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ABSTRACTS

Flerov Laboratory of Nuclear Reactions-JINR
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ABSTRACTS
The International SCHOOL-SEMINAR on Heavy Ion Physics, held by the Flerov Laboratory of Nuclear Reactions - JINR, traditionally takes place every 3-4 years. The first one was organized in 1966, and the last - in 1989. The site of these School-Seminars has been either Dubna or the Crimean town of Alushta.

The aim of the present School-Seminar is to acquaint the participants with the latest achievements and prospects of experimental and theoretical research in the field of heavy ion physics.

The scientific program covers the following main topics:

- synthesis and properties of heavy nuclei;
- synthesis and investigation of properties of exotic nuclei;
- experiments with radioactive nuclear beams;
- interaction between complex nuclei at low and intermediate energies.

It will also include reports on laser spectroscopy on exotic nuclear beams, on some applications of heavy ion beams for the problems of solid state physics, on construction of multidetector facilities, and on developing of heavy ion accelerator complexes.

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Compiled by: R.Kalpakchieva and E.A.Cherepanov.
Empirical Evaluation of Production Cross Sections for Highly Fissile Nuclei Formed in Heavy Ion Hot Fusion Reactions

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Various theoretical and semi-empirical calculations are used to choose the optimum target-projectile-energy combinations for production of heaviest nuclei via (H1,xn) reactions [1]-[3]. We tried to approach this problem on the base of systematic trends in the experimental cross section values for these highly fissile and highly excited nuclei. The data obtained by our group [4]-[6] last time and earlier results (see refs in [6], [3]) were used in the analysis. Strong correlations are observed between the values of the compound nucleus excitation energy at the fusion barrier and the positions of excitation function maxima for the (H1,4n) reactions, and only weak correlations are observed between the same values and the positions of the excitation function maxima for the (H1,5n) reactions.

Examining the dependences of the cross sections on the modified fissility parameter [7] we obtained a rather good scaling (within a factor of 3) in the drop of reduced values of the (H1,4n) reaction cross sections with the increase of the fissility parameter. The scaling breaks (within a factor 10) for (H1,5n) reactions, but the drop of cross sections is not so drastic for these reactions as for the 4n-channel. One can assume that the production cross sections of highly fissile nuclei are determined mainly by the fusion probability, for the case of 4n reactions, in the vicinity of fusion barrier. When this probability saturates (at the energies slightly above the barrier (5n-channel)), the relatively weak dependence of the cross-section on the fissility is modulated by specific features of the deexcitation of compound nuclei.

We assume that the proposed systematics can be usefull for the evaluation of the production cross sections for unknown neutron deficient nuclei in the U–Cm region and for the heaviest nuclei with \(Z \geq 105\) formed in fusion reactions, employing actinide targets.

References

Alpha-Decay Studies of Light Isotopes in Region of U-Pu

A.N. Andreyev, D.D. Bogdanov, V.I. Chepigin, A.P. Kabachenko, O.N. Malyshnev, R.N. Sagajdak, G.M. Ter-Akopian, A.V. Yeremin, S. Saro\textsuperscript{1}, M. Veselsky\textsuperscript{1}.

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In continuation of our work on \(\alpha\)-decay properties of nuclides in the vicinity of \(N=126\) shell [1] two new light uranium isotopes – \(^{218,219}\text{U}\) have been produced and identified in the complete fusion reaction \(^{37}\text{Al}+^{197}\text{Au}\). The experiments have been carried out using kinematic separator VASSILISSA and method of \(\alpha-\alpha\) time and position correlations. The \(\alpha\)-decay energies and the half-life values of \(^{218,219}\text{U}\) were determined to be \((8625\pm25)\text{ keV}\) and \((1.5^{+1.7}_{-0.3})\text{ ms}\) and \((9680\pm40)\text{ keV}\) and \((42_{-15}^{+24})\text{\mu s}\), respectively.

Reduced \(\alpha\)-widths for \(\alpha\)-decay transitions between ground states of double-even nuclei are generally taken as a reference for unhindered \(\alpha\)-decay. Sharp decrease of reduced \(\alpha\)-widths in translead region for nuclei close to \(N=126\) neutron shell is well known and is explained due to the shell structure of parent and daughter nuclei.

The reduced \(\alpha\)-widths for recently identified new isotopes of \(^{223-225}\text{U},\, ^{225-227}\text{Np}\) and \(^{230}\text{Pu}\) along with new data for \(^{218,219}\text{U}\) are discussed. Reduced \(\alpha\)-widths were calculated according to Rassmussen. It is shown that obtained \(\alpha\)-width values fit quite well to general trend for \(\alpha\)-widths in this region of nuclei.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Maximum cross section values for uranium isotopes for the reactions \(^{37}\text{Al}+^{197}\text{Au}\) (5n,6n - channels ) and \(^{20,22}\text{Ne}+^{208}\text{Pb}\) (4n,5n -channels ).}
\end{figure}

References

Actinide Based Fusion Reactions Leading to $^{263}105$ Compound Nucleus.


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The question whether the asymmetric actinide based heavy ion reactions could be used for the synthesis of heavy ($Z \geq 106$) nuclides is essential from the point of view of the study of limitation on fusion as well as because of in such reactions new nuclides can be produced close to the magic number $N=162$. Just as the issue of a hindrance to fusion still remains open the high excitation energy of the compound nucleus looks to be an obvious obstacle on the way to use these reactions.

We investigated the $^{236}U(^{27}\text{Al},5n-6n)$ and $^{232}\text{Th}(^{31}\text{P},5n)$ reactions to compare the cross-sections with the previously studied $^{209}\text{Bi}(^{50}\text{Ti},1n-2n)$ reaction. In these reactions the same evaporation residues $^{357}105$ and $^{284}105$ are produced.

For $5n$ and $6n$ reactions on $^{27}\text{Al}$ the measured cross-section values were 450 and 75 pb, respectively. The preliminary result for the $^{232}\text{Th}(^{31}\text{P},5n)$ was 100 pb. Though these cross-sections are lower than those reported earlier for the bismuth based reactions (2900 and 2100 pb for the $1n$ and $2n$ reaction channels respectively), the depletion factor does not look to be dramatic (see Figure). These observations can be explained in an assumption of the absence of a limitation on the studied fusion reactions with $^{27}\text{Al}$ and $^{31}\text{P}$ as well as on a rather visible survival probability of the highly excited compound nucleus $^{263}105$.

![Figure 1: Evaporation residues cross-sections for element 105.](image-url)
Formation of Transfermium Nuclei in Fusion Reactions of Z≥10 Heavy Ions with Actinide Targets and Possibilities to Synthesize the Element 110.

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By making use of the kinematic recoil separator VASSILISSA installed on the beam line of the U-400 heavy ion cyclotron we investigated the fusion reactions \( {}^{22}\text{Ne} + {}^{238}\text{U} \), \( {}^{26}\text{Mg} + {}^{232}\text{Th} \) and \( {}^{27}\text{Al} + {}^{232}\text{Th} \). The products of four, five and six neutron evaporation were obtained in the range of 40 – 60 MeV excitation energy of the compound nuclei \( {}^{259}102 \) and \( {}^{259}103 \). The five and six neutron evaporation products were obtained in the case of the compound nucleus \( {}^{263}105 \) formed in the fusion reaction \( {}^{27}\text{Al} + {}^{238}\text{U} \). We also obtained some preliminary results showing that the isotope \( {}^{258}105 \) was produced in the fusion reaction \( {}^{31}\text{P} + {}^{232}\text{Th} \). The analysis of the measured cross-sections did not reveal any evidence of a hindrance to fusion at the ion bombarding energy close to Coulomb barrier. A modified version of the statistical code ALICE described rather well all the existing data for fusion reactions for which the effective fissility parameter \( x_{\text{eff}} \) ranged from 0.68 (\( {}^{12}\text{C} + {}^{248}\text{Cm} \)) to 0.773 (\( {}^{31}\text{P} + {}^{232}\text{Th} \)). On this grounds, we extrapolated, the calculations to the fusion reactions leading to Z=106-110 nuclides in the vicinity of the neutron number N=162. These extrapolations demonstrate the reasonability of experiments aimed at the production and investigation of these nuclides. The best reactions, from the point of view of their cross-sections, appear to be \( {}^{22}\text{Ne} + {}^{248}\text{Cm} \rightarrow {}^{270}106^* \), \( {}^{26}\text{Mg} + {}^{248}\text{Cm} \rightarrow {}^{274}108^* \), \( {}^{22}\text{Ne} + {}^{249}\text{Cf} \rightarrow {}^{271}108^\circ \) and \( {}^{26}\text{Mg} + {}^{249}\text{Cf} \rightarrow {}^{275}110^\circ \). For the last one the extrapolation gives the maximum cross-section values of about 30 and 10 pb, for 4n and 5n reaction channels, respectively (see Figure). Some improvements of the kinematic separator VASSILISSA will enable us to carry out the experiments.

Figure 1: Maximum cross section values from calculations and experiment for the reactions
\( {}^{12}\text{C} + {}^{238}\text{U} \), \( {}^{16}\text{O} + {}^{238}\text{U} \), \( {}^{26}\text{Mg} + {}^{232}\text{Th} \), \( {}^{27}\text{Al} + {}^{238}\text{U} \), \( {}^{22}\text{Ne} + {}^{248}\text{Cm} \), \( {}^{22}\text{Ne} + {}^{249}\text{Cf} \) and \( {}^{26}\text{Mg} + {}^{248}\text{Cf} \).
Data on production and stability of heavy elements have been measured up to meitnerium (Z=109). These data are more and more scarce with increasing element number because of increasing experimental difficulties to identify the nuclei at extremely low cross-sections that decrease to a level of 10 pbarn for production of $^{266}$Mt in the reaction $^{58}$Fe + $^{209}$Bi → $^{267}$Mt. Cross-sections for production of heavy elements are mainly determined by barrier effects, pre-compound effects, fusion probabilities, fission, and evaporation of nucleons. To improve the reliability of reaction models describing the physical processes it is necessary to measure more cross-sections of various reactions and at various projectile energies. The aim of experiments being prepared presently is to measure cross-section data down to a level of 1 pbarn. Such an experimental sensitivity has to be reached also for production of element 110 and 111 in reactions with $^{208}$Pb and $^{209}$Bi targets.

Alpha-decay fine-structure lines, population and decay of isomeric states, and decay branching-ratios are most important sources of information on structure of heavy-element nuclei. The intensity ratios relative to the most intensive decay mode cover a broad range of values and can reach extremely small values. Therefore, most of these "fine structure" data could not be observed until now, although their existence is theoretically predicted. For investigation of the structure of the heaviest nuclei the experimental techniques have to be improved to be more sensitive to detect small decay branches with high resolutions of the detectors for the various decay modes.

Various types of reactions and identification techniques have been applied in the past to investigate transuranium elements. Most successful methods for production and identification of the heaviest elements known presently have been fusion-evaporation reactions with heavy targets, recoil-separation techniques, and identification of the nuclei by delayed coincidences to known daughter decays after implantation into position-sensitive detectors. These techniques can be further improved and are presently most promising for identification of new elements, search for new isotopes, and measurements of new decay data of known nuclei.
This talk will report on the development of our research into properties of heavy nuclei at the limits of nuclear stability. Here, one of the main challenges was created by theoretical predictions of the new deformed shells N=162 and Z=108 (see, e.g., Refs.[1-3] and references therein). The new shells can lead to a dramatic elevation of the stability of the "near-magic" nuclei against spontaneous fission (SF), as it is illustrated in the Figure by dashed lines drawn according to Ref.[3]. Thus, there is the possibility that SF half-lives are appreciably larger than α-decay half-lives for quite a number of nuclei around N=162 and Z=108. So far this important prediction has not been proven directly, although some indirect indications have already been collected [4]. The stabilizing effect of the ground state of nuclei close to N=162 and Z=108 can, however, be reduced by a destabilizing effect of the new fission valley leading to very compact scission shapes, which is predicted to develop close to the fragment magic numbers N=2×82 and Z=2×50 [2]. This intriguing competition between stability and instability makes experiments on probing ground-state nuclear properties around N=162 to be a task of great urgency.

To synthesize and study nuclei around N=162 and Z=108, we are preparing two different series of experiments with the Dubna gas-filled recoil separator [5]. The first one will employ the very asymmetric fusion-evaporation reaction $^{248}$Cm+$^{22}$Ne to produce the new nuclides $^{250}$Hf, $^{250}$W, $^{250}$Os, $^{250}$Ir, $^{250}$Pt, $^{250}$Au, $^{250}$Pd, $^{250}$Ag, $^{250}$Cd, $^{250}$In, $^{250}$Sn, $^{250}$Sb, $^{250}$Te, $^{250}$I, $^{250}$Xe, $^{250}$Cs, $^{250}$Ba, $^{250}$La, $^{250}$Ce, $^{250}$Pr, $^{250}$Nd, $^{250}$Pm, $^{250}$Eu, $^{250}$Gd, $^{250}$Tb, $^{250}$Dy, $^{250}$Ho, $^{250}$Er, $^{250}$Tm, $^{250}$Yb, $^{250}$Lu, $^{250}$Hf, $^{250}$W, $^{250}$Os, $^{250}$Ir, $^{250}$Pt, $^{250}$Au, $^{250}$Pd, $^{250}$Ag, $^{250}$Cd, $^{250}$In, $^{250}$Sn, $^{250}$Sb, $^{250}$Te, $^{250}$I, $^{250}$Xe, $^{250}$Cs, $^{250}$Ba, $^{250}$La, $^{250}$Ce, $^{250}$Pr, $^{250}$Nd, $^{250}$Pm, $^{250}$Eu, $^{250}$Gd, $^{250}$Tb, $^{250}$Ho, $^{250}$Er, $^{250}$Tm, $^{250}$Yb, $^{250}$Lu, $^{250}$Hf, $^{250}$W, $^{250}$Os, $^{250}$Ir, $^{250}$Pt, $^{250}$Au, $^{250}$Pd, $^{250}$Ag, $^{250}$Cd, $^{250}$In, $^{250}$Sn, $^{250}$Sb, $^{250}$Te, $^{250}$I, $^{250}$Xe, $^{250}$Cs, $^{250}$Ba, $^{250}$La, $^{250}$Ce, $^{250}$Pr, $^{250}$Nd, $^{250}$Pm, $^{250}$Eu, $^{250}$Gd, $^{250}$Tb, $^{250}$Ho, $^{250}$Er, $^{250}$Tm, $^{250}$Yb, $^{250}$Lu, $^{250}$Hf, $^{250}$W, $^{250}$Os, $^{250}$Ir, $^{250}$Pt, $^{250}$Au, $^{250}$Pd, $^{250}$Ag, $^{250}$Cd, $^{250}$In, $^{250}$Sn, $^{250}$Sb, $^{250}$Te, $^{250}$I, $^{250}$Xe, $^{250}$Cs, $^{250}$Ba, $^{250}$La, $^{250}$Ce, $^{250}$Pr, $^{250}$Nd, $^{250}$Pm, $^{250}$Eu, $^{250}$Gd, $^{250}$Tb, $^{250}$Ho, $^{250}$Er, $^{250}$Tm, $^{250}$Yb, $^{250}$Lu.
The main advantage of this reaction is given by the fact that its cross section can be reliably predicted and is expected to be fairly large, some 100 pb for the 4+5n evaporation channels. Besides, high intensities of 22Ne beams are available at the Dubna U-100 cyclotron. To prepare 248Cm+22Ne experiments, we have performed prolonged 242Pu+22Ne bombardments at E(22Ne)=114 MeV, with a typical 22Ne beam intensity of 1.5·1013 pps. For a total beam dose of 3.6·1018, we have detected between cyclotron beam pulses 38 α decays of 259104, 7 correlated α-α events of 259104→259102+α, 5254→251Fm, as well as 37 SF decays coming from 260104 and partially, 259104. At the given bombarding energy, the production cross section of 259104 in the 242Pu+22Ne reaction could be evaluated to be roughly 1.5 nb. Hence, we can estimate that the 22Ne beam dose needed to detect, for example, one mother-daughter α-SF correlation 259106→262104→SF in the 248Cm+22Ne reaction is expected to be about 1.5·1018; such dose can be reached in some 30 hours. The 248Cm+22Ne experiment will be performed jointly with LLNL, Livermore [6]; it is scheduled for April 1993.

A disadvantage of the very asymmetric reaction 248Cm+22Ne lies in the fairly low collection efficiency of the gas-filled separator for this case, which was estimated to be 6±2 % [5]. A serious complication is associated also with the use of the highly radioactive, exotic target 248Cm.

The second series of experiments we prepare is based on the use of fusion-evaporation reactions between 238U and 34S or 36S whereby the production of the isotopes 208108 and 270108 can be attempted. To explore this "sulphur" way, we have performed studies of the reactions 209,207,208Pb+34S by using two different techniques - the gas-filled separator [5] and the rotating wheel technique [7]. In this case, the collection efficiency of the separator was determined to be 35±10 %. In the 207Pb+34S reaction, for the total beam dose of 0.8·1017, it allowed us to detect between cyclotron beam pulses 46 SF events originating from the new, spontaneously fissioning isotope 238Cf with T1/2=23±5 ms [7] produced with a cross section of the order of 1 nb. This means that the sensitivity level of several pb can be reached in a 10-day 238U+34S experiment. As an additional result of our Pb+34S studies, the SF stability of the light Cf nuclei (238Cf, 240Cf, and 242Cf) was determined [7]. The dramatic effect of the neutron-deformed shell N=152 on the SF half-lives was demonstrated by revealing a Tsf decrease from 7·1010 s for 242Cf down to 2·10−2 s for 238Cf (see the Figure). A task of far-reaching importance now is to probe the effect of changing 34S to 36S on the fusion-evaporation cross sections. The semi-magic (N=20) neutron-rich projectile 36S can give a cross section enhancement similar to some extent to that known for the fusion-evaporation reactions induced by the famous projectile 48Ca.

References

Cold Multi-Nucleon Transfer between Heavy Nuclei: A Way to the Synthesis of Heavy Elements?

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Abstract

In a systematic study of neutron and proton transfer reactions in heavy systems like, $^{88}\text{Sr} + ^{144}\text{Sm}$, $^{144}\text{Sm} + ^{208}\text{Pb}$, using a magnetic spectrometer the conditions for cold multi-nucleon transfer have been established. Using semiclassical concepts for the analysis of the transfer reactions quantitative predictions for transfer probabilities can be made. The enhancement of pair transfer in superfluid nuclei is found to be strong for heavy systems if matching conditions are fulfilled.

A subsequent study of published results obtained with radiochemical methods (in particular reactions on $^{248}\text{Cm}$) shows that these results are in quantitative agreement with the data from the work using the magnetic spectrometer. Based on these systematics, predictions for reactions to produce very heavy elements ($Z > 100$) can be made.
Recent Result on Search and Study of New Neutron-Rich Heavy Nuclides in IMP

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The search and study of new neutron-rich heavy nuclides with A > 170 have been active in recent years in IMP due to the anomalous half-lives calculated and the predicted new decay modes as well as large deformation for some of them.

During the last three years, the search and study of new neutron-rich nuclides have been conducted in IMP. The $^{208}$Hg and $^{188}$Hf were identified for the first time, their half-lives have been determined to be $42^{+22}_{-13}$ min$^1$ and $3.5^{±0.6}$ min$^2$, respectively.

In order to extend our studies of new neutron-rich heavy nuclides in this region to higher Z, we made recently search for the $^{237}$Th. The present paper reports the identification of the new isotope $^{237}$Th.

$^{237}$Th was produced via the $^{238}$U (n,2p) $^{237}$Th reaction. The experiments were carried out at the 600-kV Cockcroft-Walton accelerator of IMP Academia Sinica using 14-MeV neutrons. Each sample contained an average of 16g of (NH$_4$)$_2$U$_2$O$_7$ powder and was irradiated for 15 min. Following bombardments, Th element was separated by radiochemical methods. The new activity of $^{237}$Th was first identified by following the time variation of intensity of the $γ$-rays of its daughter $^{237}$Pa. A radioactive-series decay analysing program was applied resulting in the half-life of $5.0^{±0.9}$ min for $^{237}$Th. The upper limit of production cross section of $^{237}$Th was estimated to be $5 \mu$b.

Further work is in progress.

References
[1] Zhang Li et al., High Energy Physics and Nuclear Physics, 16(1992),767.

$^1$This work has been supporting by Academia Sinica
During recent years, the interest to "hot" fusion reactions, using actinide targets, in which compound nuclei with excitation energy of 40-50 MeV are produced, has increased [1]. At present there is a great amount of experimental data on cross-sections of such reactions with evaporation of 4-6 neutrons leading to different isotopes of the trans-fermium elements up to the element 106, that allows one to carry out a systematic analysis of these data.

Figure 1 shows the values of cross-section logarithms in the maxima of excitation functions of 4n-reactions versus — the fissility parameter of the original compound nucleus. Triangles are the values of $\sigma_{4n}^\text{max}$ for reactions induced by B and C ions, squares — N, O, F, circles — Ne, Mg, Al. The "quiet", without any peculiarities behaviour of $\sigma_{4n}^\text{max}$ is noteworthy. All points are sufficiently uniformly grouped around one straight line which implies an exponential dependence of $\sigma_{4n}^\text{max}$ on $X$. A similar picture is observed for 5n-reaction cross-sections. It is seen that for the nuclei under consideration no substantial changes occur in the zn-reaction process and all experimental data can be described using an unified algorithm. Usually one uses relations of the statistical theory of nuclear reactions for this purpose, but there exist some doubts in their validity for the fission width calculations when the fission barrier and nucleus temperature are approximately equal. At the same time, the data on the precission neutrons number obtained during the recent years indicate that fission is a slow process. This circumstance and also the exponential dependence of xn-reaction cross-sections leading to transfermium nuclei on the fissility parameter $X$ indicate that one can try to use formalism of the statistical theory of nuclear reactions. In our calculations a statistical code based on the program ALICE was employed [2]. Calculations were carried out in two variants. In the first one, shell effects in evaporation and fission channels were taken into account:

$$a(E) = a \left\{ 1 + \left[ 1 - \exp(-0.0054) \right] \Delta W/E \right\}$$

where $a = A/10$, $\Delta W$ and $\Delta B$ are the shell corrections to the masses of the residual nucleus after neutron evaporation and of the fissioning nucleus, $B_f^{\text{CPS}}(l)$ is the fission barrier in the model of rotating charged drop. The ratio $a_f/a_n$ was taken equal to 1.
In the second case the relations (1) were used also, but the values ΔW and ΔB were considered to be formal parameters. For their determination the reaction $^{238}\text{U} + ^{18}\text{O}$ was used, for which excitation functions of the reactions from 4n to 8n were measured with a good accuracy. The best fit was obtained with $\Delta W = 0$ and $\Delta B = 1.1$. These values of parameters were fixed and calculations for all reactions, for which experimental data exist, were performed with them. In both variants of calculations a good fit was obtained. We consider the second variant which is more simple and more convenient for extrapolation. The results are presented in Fig.2, where there is shown a logarithm of the ratios of calculated and experimental values of cross-sections in maxima of excitation functions for reactions 4n, 5n and 6n versus fissility parameter X. Dashed lines limit interval $-0.6 < \log(\sigma_{\text{cal}}/\sigma_{\text{exp}}) < 0.6$, i.e., for the points lying between these lines $1/4 < \sigma_{\text{cal}}/\sigma_{\text{exp}} < 4$. From Fig.2 one can see that overwhelming majority of the points are within this interval.

One must note that the fission barriers of transferrium nuclei $B_f$ are substantially smaller than their neutron binding energies and therefore after neutron cascade a nucleus can be found with high probability with an excitation energy within interval $B_f - B_n$ and it undergoes fission. Only those nuclei reliably survive that after neutron cascade have the excitation energy smaller than $B_f$. Calculations show that this factor reduces yield of heavy nuclei by several orders of magnitude and that the value of $< \Gamma_n/\Gamma_f >$ ratio is smoothly varying in the transferrium region and ranges near 0.1. This result qualitatively differs from the generally accepted opinion that the ratio $\sigma_{\text{ex}}/\sigma_x$ is completely determined by $< \Gamma_n/\Gamma_f >$ value which for heavy nuclei is of the order of 0.01.

A good agreement of calculation results and experimental data for reactions induced by Mg and Al, in which isotopes of the elements 102, 103 and 105 were produced, indicates that there are no sensible limitations in fusion for this ions. Some estimates of production cross-sections of several isotopes of the elements 107-110 in maxima of excitation functions for 4n and 5n channels are listed in the table.

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<th>$\sigma$ (pb)</th>
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References

ON-LINE STUDY OF NEUTRON DEFICIENT HAFNIUM ISOTOPES AS HOMOLOGOUS OF 104 ELEMENT

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We have implanted at the Tandem accelerator in Orsay, a device similar to the one used in Dubna experiments on the chemistry of 104 element [1]. To test this rapid method of continuous separation and purification of short half-life transactinide elements [2], we have produced different hafnium isotopes of masses from 169 to 164 and half—lives ranging from 26 minutes to 76 seconds.

By irradiation with $^{16}$O ions having appropriate energy of monoisotopic gadolinium targets (masses 154, 155 and 156), and with the help of the continuous purification, by a three ion—exchanger column set up, of the hafnium fraction from its decay—products, we are able to register practically pure $\gamma$ and $X$ spectra of each $^{169-164}$Hf isotope. And so we have detected, for each isotope, much more $\gamma$ lines than the few ones reported in the litterature. By example, for $^{168}$Hf, which have only two $\gamma$ lines mentioned in NAS, more than 50 new lines have been identified.

$\gamma—\gamma$ and $\gamma—X$ correlation measurements, to precise the decay scheme of these hafnium isotopes, are in progress and will be described.

References
1. Z. Szeglowski et. al., Radiochimica Acta 51 (1990), 71.
2. Z. Szeglowski et. al., in these Proceedings.
On-line Gas Chemistry Experiments with Transactinide Elements

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The chemical properties of the heaviest elements have challenged both theoretical and experimental chemists. The reason for this special interest lies in the fact that most recent calculations of the influence of relativistic effects at these very high atomic numbers now allow detailed predictions of the chemical properties of these elements and their compounds. The investigation of the transactinide halides seems to be a very promising approach to search for relativistic effects. In a collaborative effort we have completed a series of experiments to study the volatility of the halides of elements 104 and 105, using the on-line gas chromatography technique. For our studies the nuclides $^{261}_{104}$ (T$_{1/2}$ = 65 s) and $^{262,263}_{105}$ (T$_{1/2}$ = 30 s) were produced in the reactions of $^{18}$O + $^{248}$Cm and $^{18}$O + $^{249}$Bk, respectively, at the 88-Inch Cyclotron in Berkeley and the UNILAC linear accelerator in Darmstadt. Reaction products, collected by KCl or MoO$_3$ aerosols, were continuously transported with a He/aerosol gas-jet to the on-line gas chemistry devices OLGA or HEVI. In these devices the products were collected on a quartz wool plug kept at 900 °C. Here, the halides were formed by adding various brominating or chlorinating agents. Volatile species were carried by the He flow to the adjacent, isothermal section of the column. The retention behavior of the bromides and chlorides was studied at various isothermal temperatures, ranging from 50 to 650 °C. Behind the quartz column, the molecules were reattached on new KCl aerosol particles, and transported by a second aerosol gas-jet to the counting device. The separated isotopes were directly identified by their characteristic α-decay energies, the mother-daughter α-α correlation technique, their spontaneous fission decay and their half-lives. The results of our experiments will be presented and compared with thermochromatographic data from Dubna and the newest theoretical calculations.
Experimental studies, mostly those performed at Dubna during a few last years as well as some collaborative calculational works are discussed.

With the aim of revealing possible relativistic effects in properties of the transactinoid elements, the studies have been concerned both with searching for qualitative differences in properties of the transactinoid elements and their lighter homologs (different chemical states of the elements under comparison in a given chemical environment), and with the measurements of quantitative differences in properties of the compared elements in similar chemical states.

In the gas phase chemistry research (by gas - solid thermochromatography techniques), adsorption equilibria are essentially measured. At certain conditions, the adsorption properties are very intimately related to the volatility characteristics of macroamounts of the species involved. The irregularity helps in translating the radiochemical data into the macrochemical language. In its turn, the macrovolatility is surprisingly strictly determined by purely geometrical parameters of molecules and their constituents, in the first place by the bond lengths or ionic radii; at least, this is true for the halides of transition elements with three-dimensional molecular structures. These parameters can be calculated and their values are different when using nonrelativistic and relativistic calculational approaches. At this point, the theory and experiment can be compared.

The chloride and bromide of element 104 were earlier found to be more volatile than similar compounds of hafnium and zirconium; on the basis of quantum chemistry calculations this difference could be interpreted as a manifestation of relativistic effects. The (oxo)chloride and (oxo) bromide of element 105 show slightly lower volatility than similar compounds of tantalum, while the niobium compounds are much more volatile, very probably due to a
different stoichiometry.

For the first time, element 106 has been chemically identified at Dubna. It has been separated from elements 105, 104, 103,... in the form of an oxochloride, which proved quite similar in volatility to the compounds of tungsten and chromium formed in the same experimental conditions.

For the solution chemistry studies, to compare the behaviour of homologous elements in similar chemical states, a novel fast on-line continuous chromatographic column technique has been developed. One makes use of the radioactive decay of the atoms in the column as a measure of the retention time, while the short-lived isotopes of element 104 and of hafnium are detected through measuring their longer-lived descendants. With this technique, a very high percentage of the produced atoms are detected, thus providing the best possible "statistics". A comparative study of the ion exchange equilibrium of fluoride complexes of element 104 and Hf has been performed for the first time (see G.Pfrepper et al., this Conference).
THE POSSIBILITIES OF CHEMICAL ISOLATION OF ELEMENT 106 FROM AQUEOUS SOLUTIONS ACCORDING TO THE MODEL EXPERIMENTS WITH SHORT LIVED TUNGSTEN ISOTOPES


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Four years ago, at Dubna, a study of properties of element 104 in HF solutions showed that element 104, like hafnium, forms stable anionic complexes, which are sorbed on an anion exchange resin. For this purpose, a rapid method of continuous isolation of $^{261}$Hf, produced in the bombardment $^{244}$Cm + $^{18}$O, was developed assuming ekahafnium character of element 104 [1].

Literature data show that, similar to hafnium, tungsten also forms stable anionic complexes in HF solutions, which are sorbed on anion exchangers. This fact motivated us to conduct experiments on isolation of short-lived isotopes of W from HF solutions as a model for element 106. Tungsten activities were synthesized in the reaction $^{144}$Sm($^{24}$Mg,xn)$^{163,164,165}$W (at an energy of 146 MeV or 128 MeV with a beam intensity of ~6·10$^{12}$ pps) and isolated from other nuclear reaction products obtained.

The nuclear reaction products that recoiled from the target were transported by an aerosol jet, KCl in argon (1 l.min$^{-1}$), through a 3 mm i.d., 8 m log teflon tube to an absorber, in which the KCl particulates were dissolved in 0.2 M HF supplied by a peristaltic pump to the absorber inlet. The solution containing radioactive nuclides was put successively through three combined columns filled with the ion exchange resins Dowex 50×8, Dowex 1×8, and Dowex 50×8 using another peristaltic pump at a flow rate of 1.5 to 2.0 ml.min$^{-1}$. The transportation time of radionuclides from the target to the radiochemical setup was less than 5s, and the solution passed the aerosol absorber and the columns in less than 20s. Lanthanoids were retained quantitatively on the first cation exchange column, while W isotopes on the anion exchange column. Lanthanoids activities the decay products of the W isotopes were sorbed on the second cation exchange column. Gamma spectrometric measurements of the columns were performed both in the “on line” regime when the solution was passing through the columns, and “off line” with solution flow stopped. The “on line” gamma-spectroscopic measurements showed that on the first column $^{163}$Lu and $^{165}$Lu were adsorbed, on the second column $^{163,164,165}$Hf and $^{164,165}$Ta, and on the third column $^{163,164,165,166}$Lu were collected. The initial products of $^{144}$Sm($^{24}$Mg,xn) $^{163-165}$W have not been identified in the gamma spectra of the anion exchange columns, as no data on $E_{\gamma}$ were available to us. There only the $\gamma$-lines of the granddaughters, $^{163-165}$Hf have been detected. In turn, their products, $^{163-165}$Lu, were sorbed on the second cation exchange column. Gamma spectra from the anion exchange and the second cation exchange columns indicated that $^{164}$W($T_{1/2}=8$s) was isolated from the nuclear reaction products.

Thus, a rapid method for continuous separation of W from lanthanoids has been developed. It can be used for very fast and continuous separation of element 106.

CHEMICAL IDENTIFICATION OF ELEMENT 106 BY THE THERMOCROMATOGRAFIC METHOD

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As an expected member of group VI of the Periodic System, element 106 should form volatile chloride(s) and oxochloride(s). In experiments with isotopes of tungsten, we found a chemical system for selective separation of an oxochloride of W from Ln, Hf and Ta, which, hopefully, would serve the title goal.

Element 106 was produced through the reaction $^{18}\text{O} + ^{249}\text{Cf} = ^{263}\text{106} + 4n$ (reported maximum cross section is 0.3 nb for the SF branch of $^{263}\text{106}$; $T_{1/2} = 0.9$ s). The target was 1 mg/cm$^2$ of $^{249}\text{Cf}$.

The beam intensity was about $3 \times 10^{12}$ pps, the projectile energy was close to the Coulomb barrier. The thermalized recoils were injected into a quartz thermocromatic column with 1 l/min argon gas. As chemical reagents we used air (0.2 l/min) saturated with SOCl$_2$ vapors (20 mmHg). The nuclide $^{263}\text{106}$ was registered through its SF events - the column itself served as the track detector of fragments.

In two successive experiments, reproducible zones of tracks of fission fragments were observed in a temperature region of 150-250°C, close to the deposition temperature of the 16-s $^{166}\text{W}$. Ten fission events during a 20-h bombardment and 19 events in a 32-h one were registered in this region. Essentially no tracks were found outside the indicated region of the thermal gradient. At the same time, various $\alpha$-active actinoid isotopes ($^{252-254}\text{Fm}$, $^{253,254}\text{Es}$, $^{248}\text{Cm}$) produced in "transfer" reactions were seen mostly in the start zone (≈99%), i.e., the 106/An separation was as required.

Our data seem to confirm the formation of an element 106 oxochloride similar in properties to the tungsten compound. Thus, for the first time the chemical identification of element 106 was accomplished. Both the experiments with Hf and Ta and our earlier studies of elements 104 and 105 in very similar chemical systems exclude the possibility that the other transactinoid elements might be responsible for the observed fission events.
Comparative studies of the chemical properties of transactinoids (element 104 and beyond it) and their homologues are of particular interest for understanding of relativistic effects in heavy elements [1-4].

From a volatility study of the atomic element under reducing conditions with the 3 second $^{259}$104 isotope it was concluded that element 104 behaves like a d-element rather than a p-element. This is consistent with detailed relativistic calculations [5,6]. Previous investigations of the extraction and ion exchange properties of element 104 have shown that, in general the element has the chemical character of a typical transition element of group IV [7,8]. To discuss relativistic effects in the solution chemistry, one needs quantitative data like the constants of ion exchange processes, which for transactinoid elements are yet lacking. One reason is that the conventional batch technique and elution chromatography cannot be used because of the short lifetimes and low production yields of the isotopes involved. Usually, the values of the distribution coefficient, $K_d$, for ion exchange equilibria are obtained by measuring the elution volume or time on a column.

We have proposed a novel on-line chromatographic technique of determination of the $K_d$ values for short-lived radionuclides [9]. Now the retention time, $t_R$, is evaluated from the decrease of activity of the radionuclide, the "mother nuclide", in passing through the column and/or from the growth of a non adsorbed "daughter nuclide". The latter can actually be any descendant activity while most useful is the first relatively long-lived member of the decay series. The solution applied on the chromatographic column must be completely free of the daughter nuclide (which, generally, is also formed directly in the bombardment), and the growing daughter must be completely isolated from the solution right at the exit of the column. This can be ensured by a system of ion exchange filters before and after the chromatographic column. This approach is advantageous for use under the one-atom-at-a-time conditions in the transactinoid chemistry because it can be realized as an on-line steady continuous processing of the produced transactinoid nuclei; then the time scale is the same for all the atoms that enter the column.

In the present work we used this technique to measure, in the same conditions, the sorption behaviour of element 104 and Hf in a hydrofluoric acid anion exchange system. A schematic of the apparatus and the column configuration of the filter system used in the experiments at the U-400 cyclotron are shown in Fig.1. To investigate the sorption properties of 104 and Hf in identical conditions, their short-lived $^{201}$104 and $^{186-190}$Hf were produced simultaneously by bombarding a mixed target, which consisted of $^{248}$Cm and nat. Gd with $^{18}$O. The continuous bombardment time was 24 hour at a beam intensity of $3 \times 10^{12}$ pps. The bombardment products were rapidly transported by a NH$_4$NO$_3$ gas jet. The principal chromatographic system (in column C) consisted of the anion exchanger WOFATIT HS 36 and 0.27 M HF - 0.2 M HNO$_3$ as the eluent. The columns F, A1 and A2 contained...
the cation exchanger WOFATIT KPS. The column F retained any "primordial" daughter nuclide atoms. The rate of elution was 15.9 ml/(g min). Column A1 absorbed the daughter lanthanoid and actinoid activities emerging from the mother nuclides decay in column C. The eluate from column A1 was collected for a long enough time to let the mothers decay, and then pumped through column A2, again to isolate the daughter nuclides. The retention time of 104 and Hf fluoride complexes was evaluated from spectrometric measurements of γ- and α-activity of the fractions A1 and A2. For this, the radioactive descendants of 261104 and 166-169Hf, namely, 253Fm / 253Es, 166Yb/166Tm, 167Tm and 169Lu were selectively as a group eluted from the columns and evaporated on Ta-discs.

Earlier we have shown that Zr and Hf are sorbed on the anion exchanger WOFATIT HS 36 from 0.27 M HF - 0.2 M HNO3 as Hf(Zr)F6^- complexes. Ka values of 12.9 ml/g (Zr) and 11.8 ml/g (Hf) were found by batch technique, 12.9 ml/g (Hf) by conventional elution chromatography, and 13.9 ml/g (Hf) by on-line chromatography [9,10]. The Ka value 13.9 ± 2.2 ml/g was obtained for the HfF6^- complex by γ-measurement of the samples A1 and A2 that agrees well with the data obtained by other methods. The α - particle spectra in the region 6521 - 6720 keV give a total of 31 α - events registered during 12 day of measurements of sample A1 (descendants from the decay of element 104 in column C, during tR ) and in 14.7 days in the case of sample A2 (descendants from the decay of element 104 nuclei surviving after passing the chromatographic column C). The α - activity of both samples in this region of energy decreased with a half life similar to that of 263Es. From the results, we calculated the Ka value for the 104 fluoride complex to be 10.5 ± 3.3 ml/g, that, within the experimental uncertainties, agrees with the value for HfF6^- obtained in the present work and with the Ka values for Zr and Hf measured by other techniques. Thus in the anion exchange resin - HF solution system, element 104 shows sorption properties of a close homologue of the known transition elements of group IV. Very probably it forms the complex 104F6^- . Relativistic effects, if any, could not yet be seen.

References

Dirac-Slater Calculations of Element 104(Ku) Tetrachloride, and Basic Properties of Volatile Molecules

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New Dirac-Slater Xα-scattering waves(SW) computations of 104Cl₄ as well as tetrachlorides of other IV-group elements were performed. The nature of "relativistic effects" in these molecules and the influence of electronic structure on volatility is interpreted. The previous conclusion/1-3/ that 104 Element is a typical d-element is confirmed.

A model for determination of dissociation energy(D) of volatile molecules, basing on Xα-computation is suggested:

\[ D = a E_p - b E_{\text{ion}} - c E_{\text{cov}}, \]

\( E_p \) - is the energy of promotion from the ground state of atoms to the electronic configuration into the molecule;

\( E_{\text{ion}} = 20.96 Q^2_M/R \) - is the ionic component of chemical bonding, were \( Q_M \) is effective charge of the central metal sphere in \( X_\alpha \)-SW calculations, \( R \) is interatomic distance;

\( E_{\text{cov}} \) - is the covalent component of chemical bonding, calculated as the difference between the energy levels (eigen values ) of the molecule and the exited atoms.
Since systematic uncertainties in the calculations of energy components were assumed, empiric fitting parameters $a$, $b$, and $c$ in the equation are introduced.

Calculations for Si, Ge, Sn, Ti, Zr, Hf, Th and Xe tetrachlorides were performed. The figure demonstrates a good agreement between the calculated and experimental values of $D$ with the fitting parameters: $a = 0.615^{+0.055}_{-0.055}$, $b = 0.980^{+0.045}_{-0.045}$, $c = 0.368^{+0.030}_{-0.030}$.

The dissociation energy for $^{104}\text{Cl}_4$ according to this model is predicted to be $18.0^{+0.9}_{-0.9}$ eV.

References:
Resonance Ionization Spectroscopy on $^{242}$Am Fission Isomers$^*$


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The optical hyperfine spectroscopy of fission isomers has been a challenge since Bemis et al.\textsuperscript{1} measured the isomer shift on $^{240}$Am. An ultra-sensitive laser spectroscopic method is required for such experiments because the production rates of fission isomers are very low (a few per second), and the half-lives are very short ($\leq 14$ ms). We have developed such a method which is based on resonance ionization spectroscopy (RIS) in a buffer gas cell and radioactive decay detection of the ionization process (RADRIS)$^{2,3}$.

In this contribution we report on RADRIS measurements at $^{242}$Am fission isomers. The $^{242}$Am fission isomers with a half-life of 14 ms have been produced via the $^{242}$Pu(d,2n)$^{242}$Am reaction ($\sigma = 8 \pm 3 \mu$b) at the MP tandem accelerator of the MPI für Kernphysik in Heidelberg. The recoils are transported into a buffer gas cell filled with 35 mbar argon. About 13\% of the ions neutralize during the slowing down process. The resulting atoms are resonantly ionized using an excimer dye laser combination with a repetition rate of 300 Hz and transported with the aid of a suitable electric field in front of a fission fragment detector.

The first resonant step proceeds through terms which correspond to wavelengths of 468.17 nm or 499.08 nm. The second non resonant step is achieved with the 351 nm radiation of the excimer laser itself, running with XeF. The frequency scans of the tuneable dye laser at 468.17 nm (shown in Fig. 1) and 499.08 nm exhibit broad resonance ionization signals, with a large isotope shift between $^{242}$Am and $^{243}$Am of $\delta \nu_{468\text{nm}} = -34.0(2.8)$ GHz and $\delta \nu_{499\text{nm}} = +83.1(2.8)$ GHz, respectively. For the purpose of a precise normalization with respect to the isotope shift $\delta \nu_{243-241}$ between the $^{243,241}$Am isotopes, we performed measurements in a reference cell yielding $\delta \nu_{468\text{nm}} = -1.35(12)$ GHz and $\delta \nu_{499\text{nm}} = +1.95(15)$ GHz. The ratio of the isotope shift $X = \delta \nu_{242-241}$/$\delta \nu_{468\text{nm}}$ amounts to $X_{468\text{nm}} = 2.2(3.1)$ and $X_{499\text{nm}} = 43.6(3.8)$ for the two transitions. This disagreement is not understood.

The resonance ionization efficiency defined as the ratio of the detected fission fragments and the fission isomers coming to rest in the optical cell amounts to $\approx 10^{-3}$. The measurement has been performed with totally $\approx 10^6$ fission isomers only.

\begin{itemize}
  \item $^3$ H. Backe et al., Hyp. Int., 74, 47 (1992).
  \item *) Work supported by the BMFT under contract 06 MZ 188 I
\end{itemize}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Resonance ionization signal for the $^{242}$Am fission isomer (upper part) and for $^{243}$Am (lower part). The width of the resonance results from the magnetic hyperfine splitting. The background of the $^{242}$Am fission isomer signal originates exclusively from a quasi resonant ionisation with the excimer laser alone through a level at 28451 cm$^{-1}$.}
\end{figure}
Recent Experimental Investigations on Low Energy Ternary Fission
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Abstract

A precedent report on low energy ternary fission given here in Dubna during the International School Seminar on Heavy Ion Physics (Oct. 1989) will be shortly summarized. (proceedings D 7-90-142)

In October 1989 mainly results obtained from a multiparameter measurement on alpha associated fission with the kinematic spectrometer DIOGENES [NIM A278 (1989) 452] were presented. Only yields and average kinetic energies of other light charged particles were treated.

Now the emission of clusters, heavier than alpha particles, is in the focus of interest. New results on charged particle yields up to silicon and kinetic energy distributions have been obtained and will be presented. It will be shown, how they contribute to our understanding of the ternary fission process.

Two theoretical approaches for the description of charged particle associated fission will be discussed:

- the modified double neck rupture model of Rubchenya and Javshits from St. Petersburg
  and

- the radioactive alpha emission model of Fliessbach and Schäfer.

The latter model is an elaboration of the one presented already in October 1989. Alpha emission is calculated with quantummechanical and classical methods as a kind of a radioactive decay from a time dependent nuclear potential with the shape parameters of the fissioning nucleus.

The most prominent difference between both models is that in the first case particle emission occurs after in the latter before scission.

An attempt will be made to show that under certain conditions the latter model goes asymptotically over into the first, if one stays within the framework of classical physics.
Abstract: The most interesting phenomenon of collective flow of nuclear matter is the fusion fission process. The time-scale of this process at moderate to high excitation energies is determined by the shape dependent and most likely also temperature dependent nuclear dissipation. Most of our present knowledge on the time scales of nuclear fission has been deduced from the measurement of multiplicities and energy spectra of neutrons, light charged particles and γ-rays evaporated or emitted prior and post scission. Together with complementary data like for instance fission probabilities it is possible to obtain a reasonable description of the time evolution of nuclear fission.

A systematics of experimental pre- and post-scission neutron multiplicities associated with nuclear fission will be discussed. The magnitude of nuclear dissipation deduced from pre- and post-scission neutron multiplicities are compared with theoretical estimates. The status of experimental results pointing to a relatively slow fission process and cold scission as well as the corresponding theoretical interpretation of these findings will be reviewed.
We calculate the correlation diagrams for $\Lambda$ hyperonic levels in $^{238}U$ along several fission paths with different asymmetry. Several mechanisms are discussed which control the occupation probability of the hyperonic states during fission: non-adiabatic effects, induced by the rate of change of the mean field and collisions of the hyperon with thermally excited nucleons and with thermal surface phonons. Only if the $\Lambda$-nucleon residual interaction is strong enough to establish thermal equilibrium before fission does the attachment probability as function of the mass split allow to determine a fission velocity between saddle and scission and a temperature. However for that purpose the statistics of measured data has to be improved considerably.
INVESTIGATION OF NEUTRON EMISSION AT FISSION OF EXCITED COMPOUND NUCLEI WITH \( Z \geq 92 \)

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The recent progress in studying the fission of excited compound nuclei is connected with the more detailed study of fission product characteristics including the possibility to reveal the pre-scission \( (\nu_{\text{pre}}) \) and post-scission \( (\nu_{\text{post}}) \) components from the total spectra of fission neutrons [1]. The essential excess of \( \nu_{\text{pre}} \) compared to statistical model [2,3] calculations and, also, the unusual dependence of \( \nu_{\text{pre}} \) and \( \nu_{\text{post}} \) on excitation energy have led to the understanding of the important role of nuclear viscosity not only at the first stage of the reaction induced by heavy ions, i.e. the fusion stage, but also in the fission channel of excited compound nucleus. On the basis of the data obtained recently in a number of works on \( \nu_{\text{pre}} \) a conclusion was made that fission is a slow process while evaporation processes become faster as the energy increases [4].

A diffusion model modification called LFDD (the Langevin function dissipative dynamics) has been widely developed. However, in an attempt to describe \( \nu_{\text{pre}} \) in a wide range of \( Z^2/A \) and excitation energy with only one set of parameters, this model met with difficulties. Hence one should insert a sufficiently unusual dependence of viscosity parameters on the fissioning nucleus deformation [5].

Therefore, in spite of the great quantity of experimental and theoretical works in this region up to now there is no full conception of the behaviour of energy dissipation in the fission process and one needs additional measurements of the characteristics of fission neutron emission. One also can mark that in the region of compound nuclei \( Z \geq 92 \) there are only separate experiments on studying of \( \nu_{\text{pre}}, \nu_{\text{post}} \) and \( \nu_{\text{tot}} \) values.

In the present work the first results are presented of experiments on measuring of differential characteristics of fission neutron emission in the region of compound nuclei with atomic number \( Z \geq 92 \), carried out at HMI (Berlin) on the VICKSI accelerator and on the FLNR U-400 heavy ion cyclotron. At HMI, 47- and 82-MeV \( \alpha \)-particle beams and 66.6-, 85.8- and, 104.2-MeV \( ^{12}\text{C} \) beams were used. At the FLNR, 95- and 120-MeV \( ^{16}\text{O} \) beam was used and earlier measurements of \( \nu_{\text{pre}}, \nu_{\text{post}} \) and \( \nu_{\text{tot}} \) values in reaction \( ^{238}\text{U} + ^{12}\text{C} \) (105 MeV) were carried out.

The time-of-flight technique was applied for identification of fission fragments at HMI. Fission fragments were detected by two position-sensitive low-pressure multiwire proportional counters MWPC. One small MWPC of active area 61mm x 61mm was located on one side of the beam, at a distance of 236.7 mm from the target. On the other side of the beam, there was a large area MWPC (219.5 mm x 109.8 mm) located at 261.5 mm from the target. The detectors provided better than 0.1 cm position resolution and better than 200 ps time resolution.

For the neutron multiplicity measurement 10 liquid scintillator neutron detectors were used. They were placed outside the 1m diameter scattering chamber at different angles to the ion beam. Eight of them were placed in the reaction plane, two of them out of the plane,
at distances ranging from 550 to 1150 mm. The time resolution of the detectors varied from 0.9 to 2 ns, depending on their size and lower threshold setting. The energy spectra of the neutrons were measured by time-of-flight techniques and pulse-shape discrimination between neutrons and γ-rays were used.

At the FLNR, the $E_1 \times E_2$ correlation technique of registration of pair fragments was used. The set-up includes two identical fragment detection systems which detect the reaction products in mutually perpendicular planes. Each system consists of two position-sensitive semiconductor detectors located at the fission-fragment correlation angle.

To detect neutrons scintillation detectors prepared on the base of stilbene monocrystals of 50 mm diameter and 30 mm height are used. In the given set-up two identical neutron channels located at the angles of 0 and 90 degrees with respect to each fragment tract are used. The measurement of the neutron energy spectra at angles of 0 and 90 degrees with respect to the fission axis allows one to separate neutrons emitted by the double nuclear system or the compound nucleus from neutrons emitted by the excited fragments.

The set-up includes also a spectrometer for measuring γ-quanta multiplicity in reactions induced by heavy ions. This spectrometer consists of six NaI(Tl) detectors of Ø63 x 63 mm which are located in lead collimators and set in the back hemisphere at a distance of 20 cm from the target. The full γ-quanta registration efficiency is 3 percent.

At present, the obtained information is in the stage of processing. As an example of the obtained results one can give the dependence of $\nu_{\text{pre}}, \nu_{\text{post}}$ and $\nu_{\text{tot}}$ on the $A_1/A_2$ value for the fission of $^{250}\text{Cf}$ with an excitation energy of 75 MeV.

References


MASS–ENERGY DISTRIBUTIONS OF FRAGMENTS
AND FISSION DYNAMICS

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The verification of theoretical notions about the main factors, which determine the dynamics of nuclear fission, is one of the most important tasks of experimental studying of fission fragment energy distributions (ED) [1]. One can hope that information about high ED momenta of fragments with fixed mass $M$ (coefficients of disymmetry $\gamma_1(M)$ and excess $\gamma_2(M)$) could make easier the decision of such known problems as the clearing up the mechanism of nuclear viscosity and the choice of scission criterion of the compound nucleus. Our assumptions, that research of coefficients $\gamma_1$ and $\gamma_2$ would be very important, have been confirmed by theoretical calculations [2]. In this work the following different assumptions about the scission criterion of the fissioning nucleus were used: a) neck radius is zero ($r_n = 0$); b) equal forces of Coulomb and nuclear interactions between fragments ($F_c = F_n$).

The results of these calculations proved to be strongly sensitive to the choice of the scission criterion for compound-nuclei $\gamma_1, \gamma_2$ and $\sigma^2$ in the region $Z^2/A < 33$ sharply differ both by absolute value and character of their dependence on $Z^2/A$. In order to verify these theoretical predictions we have carried out precise measurements of ED of fragments produced in proton-, $\alpha$-particle- and $^3$He-induced reactions on target-nuclei from $W$ to $Th$.

Fig.1 shows the dependence of $\gamma_1(A/2)$ and $\gamma_2(A/2)$ on excitation energy at the saddle-point $E^*_p$ for all studied nuclei. From this data one can conclude that $\gamma_1$ and $\gamma_2$ practically depend neither on excitation energy nor on nucleon composition. Fig.2 presents the comparison of our experimental results with theoretical calculations: open circles -- criterion a), closed ones -- b); signs “+” -- experiment [3], “x” -- the results of our work. Obviously, experiment rejects scission criterion $r_n = 0$ for $\gamma_1$ and $\gamma_2$. However, the calculation in the case of $F_c = F_n$ gives too small values in comparison with the experiment. This contradiction probably could be avoided if in the calculations one takes into account the fluctuations before the saddle-point and after the scission-point. Scission configurations with $r_n = 0$ lie outside the field where in the liquid drop model prolate shapes exist [4]. Therefore, the scission criterion $F_c = F_n$ is physically more preferable than $r_n = 0$, which has been used in the dynamic calculation of Nix et al [5].

References

Fig. 1

Fig. 2
FISSION OF NUCLEI WITH $A = 100-200$

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The research of headed nuclei's fission gives us rich information about drop properties of nuclear matter and might be used for verification of different modifications of liquid-drop model (LDM). The stiffness on the relation to mass-asymmetric deformation is one of the main parameters of LDM and this one is required to be checked experimentally by measuring the dispersion of mass distribution $\sigma^2_M$, which is connected with mentioned deformation directly. Earlier we have taken magnitudes of stiffness $(d^2\tilde{V}/d\eta^2)$ in region of heavy nuclei with $A > 200$. Now the results of researches of mass and energy fragment's distributions in fission of nuclei with $A < 200$ formed in reactions with heavy ions are reported. This region is important and interesting with the fact that in this region of fissioning nuclei ($A = 100 - 140$) the existence of Businaro–Gallone point $(d^2\tilde{V}/d\eta^2 = 0)$ is predicted by all variants of LDM.

Our measurements were carried out with time-of-flight spectrometer DEMAS and accelerator U–400 FLNR JINR. The reactions $^{20}\text{Ne} + ^{99}\text{Ru}$, $^{106}\text{Cd}$, $^{110}\text{Cd}$, $^{112,118,124}\text{Sn}$ have been studied. Reactions $^{12}\text{C} + ^{112}\text{Sn}$ and $^{25}\text{Mg} + ^{99}\text{Ru}$ (fissioning nucleus $^{124}\text{Ba}$) were investigated for clearing up the influence of angular momentum $\ell$ on mass and energy distributions. It was shown that magnitude of coefficient $d\alpha^2/d\ell^2 < 0$ is in agreement with theoretical predictions for this nuclei’s region. Having taken into account this fact the information about $d^2\tilde{V}/d\eta^2$ for nuclei with $A = 100 - 200$ has been obtained and analyzed and then compared with predictions of different variants of LDM.
Study of the delayed and prompt fission in reactions with relativistic heavy ions

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Some aspects of studying fission isomers and heavy hypernuclei in reactions with relativistic heavy ions are discussed. The experimental study aimed to search for the delayed fission resulting from the decay of fission isomers or heavy hypernuclei was carried out at SIS by using a setup of six low-pressure multiwire proportional counters. The preliminary results on the momentum transfer in the reaction $^{240}_{\text{Pu}} + ^{161}_{\text{Dy}}$, $^{238}_{\text{U}} + ^{208}_{\text{Pb}}$, and $^{209}_{\text{Bi}} + ^{16}_{\text{O}}$ are presented.

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The General Radioactive Decay Law

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The law for spontaneous transmutations, such as radioactive decay processes in atomic and nuclear physics, has been derived for the general case where the decay rates may be time dependent. The general formula for the ingrowth and decay in successive steps of radioactive decay chains, with multiple branches at each step, are given. As an example of current interest, the formalism is applied to the decay cascade of highly excited nuclei, where a time delay of the fission decay width is caused by the dynamics of the fission process.

Several frequently used forms of the time dependence of the fission decay width are explored and discussed in connection with measurements of pre-scission gamma- and particle emission. The general formalism developed may have applications for problems involving spontaneous transmutations in physics, chemistry, and biology.

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Influence of angular momentum and structure effects on the fission process

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It is known that the fission cross section strongly depends on the following spin-dependent quantities: (i) the compound nucleus fusion cross section, (ii) level densities in the nucleon emission and fission channels, (iii) the fission barrier also including the shell corrections. None of these quantities is, however, entirely available for the experimental investigations. The fusion cross section can be determined experimentally, by measuring cross sections in all exit channels, but its spin distribution remains a subject of theoretical speculation. Similarly, level densities can be studied experimentally only in a very limited range of low spins and energies, far from the values typical for the HI reactions. The same also holds for the spin dependence of a fission barrier which usually relies on the liquid drop model predictions. The angular momentum effects in the nuclear reactions that lead to the fission are analyzed in terms of the statistical model including collective effects in the non-adiabatic approach, avoiding all the usual numerical approximations, also accounting for the accurate angular momentum and parity coupling, and allowing for a fission preceded by a multiparticle emission [1]. Moreover, the dependence of the shell corrections on the angular momentum and nuclear temperature of the fissioning nucleus are studied by a theoretical analysis of the total fission probability for spherical and deformed nuclei. Clear evidence of the disappearance of the shell correction with increasing spin and temperature is found [2]. The result of this study may be used to explain the difference between the fission barrier extracted from the heavy-ion reaction and the ones obtained using
light-particle induced fission. Moreover, it is also found that the shell effects remain almost constant up to a nuclear temperature of about 1.65 MeV, corresponding—for example—for $^{210}$Po (that has $N=126$) to a thermal energy of about 35 MeV, after decreasing by an exponential law and reducing the shell correction to half its value at a temperature of 2.3 MeV. This result is not in agreement with the statement that the shell effects influence on fission barrier completely disappears at an excitation energy of about 20 MeV (see for example reference 3).

References


WHAT ARE SENSITIVE PROBES FOR NUCLEAR FRICTION IN HEAVY-ION INDUCED FISSION?

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We study the influence of nuclear friction on heavy-ion induced fission with a model, which combines Langevin Fluctuation-Dissipation Dynamics with a modified statistical approach. Using as an example the $^{16}O + ^{208}Pb$ induced fission of $^{238}Th$ the following quantities are investigated: prescission neutron, proton, $\alpha$-particle, deuteron, and $\gamma$-multiplicities, the spectra of these particles, fission time-distributions, multiple chance fission distributions, evaporation residue and fission cross sections. It turns out that in particular prescission $\gamma$-multiplicities and evaporation residue cross sections are by far more sensitive probes for nuclear friction in fission of hot nuclei than the most often discussed prescission neutron multiplicities.

We perform the trajectory calculations with the one-dimensional overdamped Langevin equation (LE). The driving force of the LE is calculated from the entropy which is constructed from the Fermi gas expression with a liquid drop potential [1] following the bottom of the fission valley. In constructing the entropy we use the deformation-dependent level density parameter according to [2]. Reduced friction parameter $\beta$ is the other important ingredient of LE. In order to reproduce in a satisfactory way the excitation functions of both the prescission neutron multiplicities $\langle n_{pre} \rangle$ and the fission probabilities $P_f (= \langle n_{pre} \rangle / \sigma_n)$ we have introduced a strong universal coordinate dependence of $\beta$. A constant $\beta = 2 \times 10^{24}$ sec$^{-1}$ is used from the ground state to the deformation where the necking in starts to occur and for larger deformation a linear increase of $\beta$ is assumed up to a value of $\beta = 30 \times 10^{24}$ sec$^{-1}$ at scission [3]. In order to obtain a feeling for the sensitivity of the different quantities on $\beta$ we also compare in many cases with results for deformation-independent $\beta = 20 \times 10^{24}$ sec$^{-1}$, which was proposed for the interpretation of the prescission $\gamma$-spectrum measured in [4].

The pure dynamical treatment in practice is restricted to systems which have reached a fission probability close to 100% when stopping the integration after e.g. $2 \times 10^{-2}$ fm/c as done in [5]. In order to overcome this restriction we have proposed in [6] to switch over from the Langevin description of the fission mode to a statistical one, when a stationary flow over the barrier is established after a certain delay time $t_d$. When switching to the statistical branch we apply a modified formula [3] for the fission rate which in order to be consistent with the dynamical calculations also contains the entropy as the crucial quantity and includes besides the position of the saddle point also the position of the scission point.

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So, three runs of the calculations are made: i) dynamically-statistical with deformation-dependent $f_0 (SPS)$, ii) dynamically-statistical with deformation-independent $f_0 = 20 \times 10^{27} \text{sec}^{-1} (SB)$, and iii) standard-statistical model calculations (SSM). The numerical results are confronted with each other and with experimental data. The comparison show that neutron and charge-particles multiplicities as well as the energy spectra of these particles are not very sensitive to the friction parameters we have used. However, it is clear that one needs friction and a dynamical description for the reproduction of data for these quantities because the SSM code fails to describe the data.

The other important result is that prescission $\gamma$-multiplicities and spectra are by far more sensitive probes for nuclear friction in fission than the particle multiplicities. The calculations show that evaporation residue cross sections seem to be even more sensitive probes for friction. Unfortunately the experimental situation for $^{208}O + ^{208}Pb$ system seems not to be so clear. It would be extremely interesting also to have direct data on average fission lifetime $\langle t_f \rangle$, because SPS and SB calculations give for $\langle t_f \rangle$ results which differs by orders of magnitude.

REFERENCES

The notion of "scission" being the last and the quickest stage of the fission process is used at present time as a conventional one. Usually it is supposed that the fissioning nucleus ruptures when reaches a "scission line". Mainly two scission lines are being employed. The first one is defined by the condition that radius of the neck is equal to zero (let us call the corresponding scission line \(r_{\text{neck}}\)-line). The second line called henceforth "F-line" is obtained from the condition that nuclear attractive force between future fragments has to be equal to the Coloumb repulsive force. These scission conditions can be regarded as the "extremal" ones in the sense that they lead to the families of the most stretched (\(r_{\text{neck}}\)-line) and of the most compact (F-line) scission configurations.

It is clear that the experimentally measured fission-fragment kinetic-energy distribution \(W(E_k)\) should contain a valuable information on which scission condition is realized in nature. Yet extensive calculations performed using different versions of Langevin approach failed in simultaneous reproduction of \(Z^2/A\) - dependence of two first moments of \(W(E_k)\) \([1, 2, 3]\). In particular, it turns out impossible to reproduce the variances of \(W(E_k)\), \(\sigma_{E_k}^2\), for \(Z^2/A = 25 - 32\) with either two-body and "surface"-one-body dissipation mechanisms.

An example of such results obtained in framework of the Langevin fluctuation-dissipation dynamics are shown in fig.1 (two-body viscosity \([1]\)) and in fig.2 ("surface" one-body dissipation). The numerical results corresponding to \(r_{\text{neck}}\)-line exceed by far the experimental data on \(\sigma_{E_k}^2\) irrespectively of the dissipation mechanism used. Contrary, the results of the calculations using F-line underestimate \(\sigma_{E_k}^2\) for \(Z^2/A \leq 32\) once again for both dissipation mechanisms.

We have presumed that the contradictions between the numerical results and experimental data concerning \(\sigma_{E_k}^2\) appear because one treats the scission conditions defining either \(r_{\text{neck}}\)-line and F-line as the deterministic ones. In fact the neck rupture should occur with a certain probability when the nucleus has a deformation somewhere in between of these two scission lines. We accept this probability is equal to the ratio of the length of one step in the configuration space to the "distance" between F-line and \(r_{\text{neck}}\)-line. Results of the corresponding calculations are shown in figs.1, 2 by closed diamonds and seem to be in reasonable agreement with the experimental data on fission-fragment average kinetic energy \(<E_k>\) and on \(\sigma_{E_k}^2\), in particular for the light nuclei.
Fig.1 Two first moments of $W(E_k)$ calculated using two-body viscosity in comparison with experimental data [4]. Left: the average value of fission-fragment kinetic energy versus $(Z^2/A^{1/3})$; right: the variance of fission-fragment kinetic energy versus fissility parameter. Open circles - experimental data, closed symbols - results of the calculations: circles - f-line, squares - r$_{neck}$-line, diamonds - probabilistic approach. Solid line - $<E_k> \sim Z^2/A^{1/3}$, i.e. $<E_k> = 0$ for $Z = 0$, dashed-dotted line - Viola systematics [5].

Fig.2 Same as in fig1., but for "surface" one-body dissipation.

References

Fission Barriers of Z>82 Nuclei Inferred from Heavy Ion Fusion-Evaporation Reactions

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A great body of the results about the formation cross-section of heavy ion fusion evaporation residues obtained in the experiments making use of the kinematic separator VASSILISSA are discussed in terms of fissility of heavy nuclei. The experimental results are compared with calculations of the de-excitation process of compound nuclei based on a modified version of the statistical code ALICE. The reliability of individual nuclides is discussed alongside of the obtained considerable difference between the obtained isospin dependence of the macroscopic fission barrier component and prediction of the liquid drop model. The problem of the survival of the shell effect for the fission barrier at a high excitation energy is considered on the basis of the date obtained for Z=89–91 compound nuclei having neutron numbers near the magic number N=126. The subject of a separate discussion is the issue of a sharp anomaly in the ratio of (xn) and (α,xn)-reaction cross-sections which was noted for Pa and U compound nuclei with the neutron number around N=126.

Figure. Systematics of the maximum values of the xn-cross sections. The circles and triangles alternate in order facilitate the recognition of data obtained for evaporation residues having different atomic numbers. Our results are presented by closed symbols.
Statistical Model Analysis of Level Densities and Fissilities of Excited Compound Nuclei for Heavy Ion Induced Nuclear Reactions

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The experimental data on excitation energy dependences of the level density and fissility of excited compound nuclei have been analysed in the framework of the statistical model. A systematic review and comparison of the main existing phenomenological approaches and models for describing the level density parameter and fission barriers are given. The effects of angular momentum and the excitation energy dependence of fission barriers are discussed.

The experimental data on excitation energy dependence of the level density $\rho(E^*)$ (see, fig. 1) and fissility $V_f$ (see, fig. 2) of compound nuclei are analyzed by using different models for fission barriers [1]-[7], shell and pairing corrections [8]-[10] and level density parameters [11]-[15] in order to identify their reliability and range of applicability for Monte Carlo calculations of the decay of highly excited nuclei with large angular momenta produced in heavy ions induced nuclear reactions.

![Fig. 1. Energy dependence of the level densities of nuclides $^{209}$Po and $^{230}$Th. Points are the experimental data from the summary table 2 of ref. [14]. The curves denoted as 1, 2, 3, 4, and 5 are the results of calculation with Malyshev's [11], first Ignatyuk's et al. [12], first Cherepanov and Ilijinov's [14], first and third Ilijinov, Mebel's et al. [15] systematics for the level density parameter, respectively. In the left, center, and right parts of the figure the results of calculations with Cameron's [9], Truran, Cameron and Hilf's [10], and Myers and Swiatecki's [9] shell corrections, respectively, are shown.](image)

Our estimation of the reduction of the fission barrier heights with increasing the excitation energy $E^*$ has shown that "thermal" effects may cause about a tenfold increase of the nuclear fissility for medium weigh and light nuclei with the excitation energies above 50 MeV.

It was shown that for high values of the angular momentum $L$ of fissioning nucleus a simple phenomenological approach provides results similar to those obtained by Mustafa's et al. [17] and Sierk's [2] models, but needs about ten times shorter computing time in comparison with the subroutine BARFIT of Sierk, and, therefore is more convenient for Monte Carlo calculations.
The analysis of level densities and nuclear fissility has shown that Malyshev's [11] systematics for $a(Z, N)$ provides a satisfactory description of the experimental data only for low values of excitation energies $E^*$. Cherepanov and Iljinov's [14] and Iljinov, Mebel's et al. [15] systematics for $a(Z, N, E^*)$ allow one to obtain a good description of the data in a larger interval of $E^*$, reproduce very close results and seem to describe the data better than the systematics of Ignatyuk et al. [12].

Fig. 2. Excitation energy dependence of the fissility $\Gamma_f/\Gamma_{tot}$ of different nuclei (left figure) and dependence of the fissility of the exited $^{188}\text{Ir}$ compound nucleus on the value of its angular momentum $L$ (right figure). Curves are our calculation results with KNS79 [7] fission barriers, C70 [10] shell corrections, the third Iljinov, Mebel et al. [15] systematics for the level density parameter. Experimental points were taken from the review [16].

References
We present here some preliminary results of one of the four experiments carried out at the Holifield Heavy Ion Research Facility with the 20 Compton suppressed Ge detector Close-Packed Ball. In this experiment a germetically closed $^{252}$Cf source giving 50,000 spontaneous fission events per second was placed in the central working position of the Ball and all the events of coincident $\gamma$-rays with multiplicity $\geq$ 2 were recorded during a time interval of about one week. Two types of $\gamma$-ray spectra were formed. In the first type the $\gamma$-rays were presented obtained in coincidence with $\gamma$-transitions between known low-lying states of fission fragments. The spectra of the second type, the two-gate spectra, were formed on the basis of events with multiplicity $\geq$ 3. Each spectrum of this type displayed those $\gamma$-rays obtained in coincidence with a pair of $\gamma$-rays: one of the members of this pair being emitted by a chosen fission fragment and other - by its coincident partner.

Detection of the coincident characteristic $\gamma$-rays of partner fission fragments appears to be an informative indication of fission allowing for $Z$ identification of a fissioning nucleus. All the $\gamma$-lines obtained in the spectra mentione above had the shape well fitting the known resolving power of the detector, the line overlap appears to be a rather rare event. This, together with the very low background of two-gate spectra, demonstrates the power of the pair $\gamma$-ray trigger which can be used for revealing the fission events of a given nucleus against the background of $\beta$-decay and fission of other nuclides. The present and future $4\pi \gamma$ detector arrays will provide for a good detection efficiency. We evaluated the detection efficiency for our case which makes up 0.2% of the sum of the independent yields of $^{148}$Ce and $^{146}$Ce, if the $\gamma$-lines of these fission fragments are detected in coincidences with the lines of their partner $Zr$ fragments.

The high single $\gamma$-ray detection efficiency of the Close-Packed Ge Ball, high collected statistics and unambiguity and selectivity of the method of fission event triggering resulted in observation of new, higher spin states in many nuclei. Much data providing new insights into the changing structures of neutron-rich nuclei remain to be analyzed. In the following we present some examples of the data illustrating the information about the spontaneous fission which can be extracted from experiments of this sort. Table 1 shows the normalized (to the $2^+\cdot 0^+$) intensities of the transitions between the levels of the ground state rotational bands of some complementary fission fragments formed as a result of two charge divisions of $^{252}$Cf: Zr-Ce ($Z=40$ and 58) and Mo-Ba ($Z=42$ and 56). The last two columns give the mean values of the angular momentum for the obtained level population ($<j>$) and for the states populated just after the scission ($<J>$). The values of $<J>$ are calculated taking into account the angular momentum carried by evaporated neutrons and statistical $\gamma$-rays.
Compared with previously obtained results [3, 4, 5, 6] our data can give a detailed picture of dependence of the angular momentum on the mass and atomic numbers of fission fragments.

<table>
<thead>
<tr>
<th>Fission fragment</th>
<th>Intensities of the transitions (%)</th>
<th>$&lt;j&gt;$</th>
<th>$&lt;J&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{144}$Ce$^1$</td>
<td>100 41 11 4 6.5 7.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{140}$Ce$^1$</td>
<td>100 85 58 36 21 8.4 11.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{146}$Ce$^2$</td>
<td>100 78 46 36 20 7.2 11.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{148}$Ce$^3$</td>
<td>100 75 46 31 19 7.4 11.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{100}$Zr$^4$</td>
<td>72 61 21 4.4</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>$^{102}$Zr$^4$</td>
<td>78 50 21 4.8</td>
<td>4.8</td>
<td>7.9</td>
</tr>
<tr>
<td>$^{104}$Zr$^5$</td>
<td>92 61 24 5.3</td>
<td>5.3</td>
<td>7.9</td>
</tr>
<tr>
<td>$^{144}$Ba$^6$</td>
<td>92 85 52 15 5.1 11.9</td>
<td>5.1</td>
<td>11.9</td>
</tr>
<tr>
<td>$^{104}$Mo$^7$</td>
<td>76 48 15 4.9</td>
<td>4.9</td>
<td>6.7</td>
</tr>
</tbody>
</table>

1) average over Zr isotopes, 2) with $^{100}$Zr, 3) with $^{102}$Zr, 4) with $^{146}$Ce, 5) with $^{144}$Ce, 6) with $^{104}$Mo, 7) with $^{144}$Ba. 2-7)-these results are derived from two-gate spectra (see text).

The angular momenta of different specific fission fragments are provided in combinations with the angular momenta of their separate partner nuclides representing different numbers of emitted prompt neutrons. It is well known that this number is directly related to the initial fragment excitation or, in other words, to the fragment elongation at the scission point.

Table 2 shows the mass distributions of Zr isotopes obtained in coincidence with $^{146}$Ce and $^{148}$Ce. These distributions are deduced from the detected intensities of transitions between the lowest excited and ground states of Zr fragments corrected for the known $\gamma$-ray energy dependence of the detection efficiency $(E_{\gamma})$ of the Close-packed Ce detector Ball. Assuming the small variation of the $\gamma$-ray multiplicity with the mass numbers of Zr fragments we deduce from the data of Table 2 that the most probable Zr mass numbers are shifted by two mass units (from $^{100}$Zr to $^{102}$Zr) at the transition from $^{148}$Ce to $^{146}$Ce, whereas the mean value of Zr fission fragment mass varies rather slowly.

<table>
<thead>
<tr>
<th>Ce partner</th>
<th>Normalized yields of the Zr isotopes</th>
<th>$&lt;\lambda&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{148}$Ce</td>
<td>$^{98}$Zr 0.05 $^{99}$Zr 0.15 $^{100}$Zr 1.00 $^{101}$Zr 0.52 $^{102}$Zr 0.64 $^{103}$Zr 0.14 $^{104}$Zr 0.06 100.9</td>
<td></td>
</tr>
<tr>
<td>$^{146}$Ce</td>
<td>$^{98}$Zr 0.20 $^{99}$Zr 0.60 $^{100}$Zr 0.55 $^{101}$Zr 1.00 $^{102}$Zr 0.26 $^{103}$Zr 0.20 101.4</td>
<td></td>
</tr>
</tbody>
</table>

References

To investigate the process of dissipation of collective degrees of freedom to single-particle degrees for excited nuclear matter, which plays an important role in relaxation of charge and mass distributions in HI-collisions, we measured the yields of high energy gamma-rays, accompanying spontaneous fission of 252-Cf.

For register of gamma-quanta in energy region from 4 to 25 MeV the BGO-detector with diameter ~ 4 cm and thickness ~ 15 cm was used. The fission fragments were detected by means of solid state detector. The scheme of fast coincidence between gamma-quanta and fragments was used. The time resolution of this method was ~ 10 ns. The geometry of experiment was chosen near 2π for each detector.

It was obtained that the slope of low-energy part of γ-rays spectrum for all masses of fission fragments was connected with effective temperature of fragments \( T = 1.2 \pm 0.2 \) MeV. The analysis of experimental data for different groups of fragments (group of symmetric fission - \( 120 < A < 126 \); asymmetric fission - \( 100 < A < 120 \) and superasymmetric fission - \( A < 100 \)) was shown that if the mass of light fragment was reduced, the yield of γ-rays in the high energy part of spectrum began to increase. This fact is related with known dependence of giant dipole resonance (GDR) energy \( E_R \) versus mass number \( A : E_R \sim \text{const} \cdot A^{-1/3} \) MeV.

To describe the experimental data we used the preequilibrium model of γ-rays emission in nuclear reactions \([1,2]\), transformed to the spontaneous fission process. We suggested that the total excitation energy of fission fragments was obtained by means: 1) division of total heating energy (which obtained during motion of fissioning nucleus from point of exit under barrier of fission to
the point of scission between two fragments in proportion of its masses: 
\[ E_{\text{heat}}_{1,h} = E_{\text{heat}}_{\text{total}} \cdot \frac{A_{1,h}}{A_{1} + A_{h}} \] (where \( A_{1,h} \) are the mass numbers of light and heavy fission fragment);

ii) dissipation of surface deformation energies \( E_{\text{def.}} \) of fission fragments into intrinsic degrees of freedom, when energies of fragments excitations, owing to this process - \( E_{\text{def.}}_{1,h} \) are inversely to the rigidities of fission fragments \( C_{\text{def.}}_{1,h} \):

\[ E_{\text{def.}}_{1,h} = E_{\text{def.}}_{\text{total}} \cdot \frac{C_{\text{def.}}_{1}}{C_{\text{def.}}_{1} + C_{\text{def.}}_{h}} \]

These mechanisms are in character with different mass distributions of excitation energies of fragments [3].

The analysis of theoretical calculations shown that the slope of curve for probability of \( \gamma \)-rays emission for high energy region is depended from the magnitude of density level parameter \( g \), which was chosen as \( A/8 \text{ MeV}^{-1} \). Because the energy position of GDR-peak in cross section of \( \gamma \)-ray emission is depended from the value of constant in formula for \( E_{R} \), the best agreement between theory and our experimental data was obtained for \( \text{const} = 70 \text{ MeV} \). The another value of \( E_{R} = 40.3/A^{0.2} \text{ MeV} \) [4] gives us the same result.

The fitting to the experimental data for \( \gamma \)-rays emission probability in the region of fission fragment GDR's gives us the value of heating of 252-Cf fissioned nucleus \( E_{\text{heat}}_{\text{total}} = 7 \pm 3 \text{ MeV} \). This value is in agreement with theoretical predictions [3].

We also calculated the yields of \( \gamma \)-rays in the low energy region (up to 10 MeV) by using some wellknown codes - ALICE91, EXIFON and GNASH-LANL. The best agreement between theory and experiment is for code "GNASH-LANL", but in the region of \( \gamma \)-rays energies \( \sim 6 - 8 \text{ MeV} \) near the threshold of neutron emission, the experimental yield of gamma's was overestimated the theoretical one.

REFERENCES

In recent years many attempts have been made to study the nature of high energy \(\gamma\)-emission in heavy ion collisions at intermediate energies. In general two well-determined components of this emission exist: i) incoherent bremsstrahlung accompanying collisions of nucleon-nucleon pairs in the hot-spot region of the composite nuclear system and ii) coherent nucleus-nucleus bremsstrahlung.

It was suggested that the best conditions for investigation of nucleus-nucleus bremsstrahlung mechanism occur in the case of spontaneous fission of heavy nuclei and the first experimental evidence was obtained for isotope \(252\text{-Cf}\) \cite{1}.

The aim of this work is to obtain reliable experimental data of bremsstrahlung emission accompanying the spontaneous fission of \(252\text{-Cf}\) at photon energies well over 50 MeV and to observe in detail the structure of the energy spectrum of the coherent bremsstrahlung component caused by the interference of the electromagnetic waves emitted from the two moving fission fragments.

The source with activity \(\sim 3\times10^3\) fission events/s was put into a vacuum chamber. The \(\gamma\)-ray spectra were measured by a BGO detector. The energy calibration and the efficiency of the BGO detector were accomplished by using a Pu-Be neutron source and \(\gamma\)-rays of energies up to 20 MeV, which were produced by reactions of 2 MeV protons on light targets at the EG-8 accelerator of Moscow State University. The fission fragments were detected by a silicon surface barrier detector. The time resolution of the experimental fragment-\(\gamma\) coincidence apparatus was about 10 ns. The measurements were collected in two runs of \(\sim 400\) hours each. No background coincidence events were measured in the 30 - 100 MeV region for additional run (\(\sim 200\) hours in duration) without the
radioactive source.

In the table 1 there are shown the measured $\gamma$-ray emission probabilities for a fission events. As one can see there is a minimum-like behaviour of emission probability in the energy region near 55 MeV.

Table 1. Emission probability of $\gamma$-rays in sp. fission of 252-Cf.

<table>
<thead>
<tr>
<th>Energy Interval $\Delta E_{\gamma}$, MeV</th>
<th>Number of $\gamma$-quants $N_\gamma$</th>
<th>Probability of emission, $(\text{MeV} \times \text{sr} \times \text{fission})^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 - 30</td>
<td>9</td>
<td>$(1.5 \pm 0.5) \times 10^{-8}$</td>
</tr>
<tr>
<td>30 - 40</td>
<td>3</td>
<td>$(2.8 \pm 1.6) \times 10^{-9}$</td>
</tr>
<tr>
<td>40 - 50</td>
<td>9</td>
<td>$(9.4 \pm 3.1) \times 10^{-9}$</td>
</tr>
<tr>
<td>45 - 65</td>
<td>1</td>
<td>$(0.25 \pm 0.25) \times 10^{-9}$</td>
</tr>
<tr>
<td>60 - 70</td>
<td>2</td>
<td>$(2.6 \pm 1.8) \times 10^{-9}$</td>
</tr>
<tr>
<td>70 - 80</td>
<td>4</td>
<td>$(5.8 \pm 2.9) \times 10^{-9}$</td>
</tr>
<tr>
<td>80 - 90</td>
<td>1</td>
<td>$(1.6 \pm 1.6) \times 10^{-9}$</td>
</tr>
</tbody>
</table>

To investigate the nature of the possible minimum in the energy spectrum of $\gamma$-rays we assumed that the origin of high energy $\gamma$-emission was the bremsstrahlung radiation of the two accelerated fragments after the scission of the fissioning system. In our calculations we used the classical bremsstrahlung theory [2] in the two extreme cases [1] of sudden acceleration model (SA) and Coulomb acceleration model (CA). The SA-model suggests that the fission fragments are instantaneously produced at their final kinetic energies, while in the CA-model the fragments are accelerated in the Coulomb field assuming that the initial velocities are zero. The comparison of the SA- and CA-model calculations shown that the SA-model overestimated and the CA-model underestimated the value of the bremsstrahlung yield of a factor $\sim 10$ with respect to the experimental data. Position of minimum is related with initial distance between centers of fragments ($\sim 20$ fm) and model independent.

REFERENCES

Investigations on cluster decay at the FLNR, JINR are mainly developed in two directions.

1. Investigation of cluster nuclei decay near the shells with Z=82, N=126.

   In collaboration with the Kurchatov Institute there are being carried out experiments on cluster decay of $^{242}\text{Cm}$. The experiments are difficult due to high background of spontaneous fission. At present there has been achieved cluster detection sensitivity with respect to a decay $\lambda_c/\lambda_n < 8 \cdot 10^{-17}$ that corresponds to $\lambda_c/\lambda_{sf} < 10^{-5}$ [1].

   Measurements on cluster decay probabilities of $^{230}\text{U}$ and also $^{236}\text{Pu}$ are being performed in collaboration with the group of Prof. M.Hussonois (Orsay, France). For $^{236}\text{Pu}$ in joint experiments with the Kurchatov Institute there was earlier detected cluster decay with $\lambda_c/\lambda_n \sim 2 \cdot 10^{-12}$ [2]. However, statistics included only two cases.

   In collaboration with the group of Prof. R.Bonetti (Milan, Italy) the treatment of solid state track detectors exposed on $^{232}\text{Th}$ at the Gran Sasso underground laboratory is being carried out.

2. Investigations in the new region of cluster decay near the shells with Z=50, N=50.

   The first experiments on production of $^{114}\text{Ba}$ in reaction $^{58}\text{Ni} + ^{58}\text{Ni} \rightarrow ^{114}\text{Ba} + 2\nu$ have been performed on internal beam on the FLNR, JINR U-400 cyclotron [3].

   There have been registered about 10 events which can be referred to cluster decay of $^{114}\text{Ba} \rightarrow ^{12}\text{C}$. The effect corresponds to $\lambda_c/\lambda_{total} \leq 10^{-4}$. However, the background level turned out to be a rather high one. At present the experiments with a new technique are being prepared on extracted beam of the U 400 cyclotron. We are planning to use recoil atoms collection of $^{114}\text{Ba}$ showed down in gas directly towards surface of solid state track detectors.

References

Abstract: Alpha emission energy of $^{114}$Ba is deduced by extrapolating tendencies of experimental $Q_\alpha$ decay energies of neighbouring isotopes which differ by one nucleon and one nucleon pair. The mass excess of $^{114}$Ba, calculated from the experimental mass excess of $^{110}$Xe and deduced $Q_\alpha$ energy, is finally used to predict the most probable emission energy for $^{12}_C$ radioactivity. We get for $^{114}$Ba nucleus the following results:

$$Q_\alpha = (3.601 \pm 0.062)\text{MeV} \quad \text{and} \quad Q_\alpha^{12}_C = (20.62 \pm 0.7)\text{MeV}.$$ 

The complete-fusion reactions between two complex nuclei followed by multinucleon transfer reactions is an efficient way of producing neutron deficient isotopes of many elements [1]. These reactions opened up the possibility of an advance towards the limit of the proton line of stability of nuclei where several new decay modes have been discovered: delayed proton emission, delayed fission, proton emission from ground state and very recently [2] $^{12}_C$ emission from $^{114}$Ba.

A summary of $\alpha$ decay energy measurements for neutron deficient trans-tin isotopes is given in Table 1 together with our estimations for $^{113}$Cs, $^{114}$Ba and $^{115}$Ba nuclei.

Firstly from experimental $Q_\alpha$ values, we extract for a given nucleus contributions related by the addition to a of one nucleon and one pair of nucleons. Such contributions remain practically constant for nuclei differing by one or two nucleon masses. This allows us to use the measured $Q_\alpha$ values in predicting decay energies for neighbouring nuclei with one additional nucleon and one additional nucleon pair.

For example, we get $Q_\alpha = 3.601 \pm 0.062$ MeV for $^{114}$Ba by adding to the $Q_\alpha$ value of $^{113}$Xe, the two proton contribution estimated from the difference between the $Q_\alpha$ of $^{113}$Cs and $^{111}_I$ both nuclei having $N = 58$ as $^{114}$Ba. If the difference is taken from the nuclei with $N = 59$, $^{114}$Cs and $^{112}_I$, we can
obtain another less exactly approximation \( Q = 3.693 \pm 0.083 \text{ MeV} \). The mass excess of \(^{114}\text{Ba}\) may be calculated now from the experimental mass excess of \(^{110}\text{Xe}\) [3] and \( Q \) value. We immediately get \( \Delta M(^{114}\text{Ba}) \approx -45.56 \text{ MeV} \).

Finally, we calculate the emission energy of \(^{12}\text{C}\) from \(^{114}\text{Ba}\) using the previous mass excess of \(^{114}\text{Ba}\) and mass excess of \(^{12}\text{C}\) and \(^{102}\text{Sn}\) [3]. One obtains \( Q_{^{12}\text{C}} = (20.62 \pm 0.7) \text{ MeV} \).

These results restricted only to g.s. - g.s. transitions will be used in decay rates calculations in trans tin region [4].

We hope these results serve as a guidance in detecting the cluster radioactivity at medium nuclei and to study exotic nuclei.

**Table 1** Summary of \( \alpha \)-decay energy measurements [1] and present calculations (underlined values) in trans tin-region. The \( Q_\alpha \) values are given in MeV and the experimental errors (in keV) are given in parenthesis.

<table>
<thead>
<tr>
<th></th>
<th>( Q_\alpha ) (MeV)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba</td>
<td>( 3.601 )</td>
<td>( 3.379 )</td>
<td></td>
</tr>
<tr>
<td>Cs</td>
<td>( 3.565 )</td>
<td>( 3.361 )</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td>( 3.878 )</td>
<td>( 3.714 )</td>
<td>( 3.321 )</td>
</tr>
<tr>
<td></td>
<td>(30)</td>
<td>(50)</td>
<td>(31)</td>
</tr>
<tr>
<td>I</td>
<td>( 3.570 )</td>
<td>( 3.285 )</td>
<td>( 2.989 )</td>
</tr>
<tr>
<td></td>
<td>(16)</td>
<td>(31)</td>
<td>(52)</td>
</tr>
<tr>
<td>Te</td>
<td>( 4.323 )</td>
<td>( 3.406 )</td>
<td>( 3.444 )</td>
</tr>
<tr>
<td></td>
<td>(30)</td>
<td>(50)</td>
<td>(16)</td>
</tr>
<tr>
<td>N</td>
<td>54</td>
<td>55</td>
<td>56</td>
</tr>
</tbody>
</table>

**References**


Clustering aspects of heavy nuclei deformation process
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The consistently cluster model was suggested in [1] to describe the deformation process for actinide nuclei at the descent from the fission barrier. In the frameworks of this model the irreversible elongation of the fissile system, described by the shell-model wave function, is supposed to combine with the process of probabilistic clusterization. This clusterization may take place at the bifurcation points determined by the energy conservation law and the spectroscopic factor and results into two big highly-coupled clusters and a light neck fragment.

The recent experimental data, obtained in our experiments at the MEPhI spectrometer [2], seem to confirm such an approach. In Fig. 1 the yield of fragments with the selected nuclear charge is plotted vs. their kinetic energy. One can see definite structure in this distribution with the interval of peculiarities about 4 MeV. The similar structure can be observed for each charge from the range 33-41 of the light group. This structure is well correlated with one in the dependence of measured proton odd-even effect vs. kinetic energy for fission studies of $^{232}$U(n$_{th}$,f), $^{235}$U(n$_{th}$,f), $^{239}$Pu(n$_{th}$,f) [3].

The possible forming mechanism is explained in Fig. 2. In Fig. 2a the schematic chart of the neck nuclei potential energy is shown as a function of deformation for different temperature. The horizontal line shows the excitation energy value when the clusterization of the light nuclei starts. This process seems to take place not only at prolate deformation, as stated in [4], but at oblate deformations too. The fissile system configurations for the valley with two large spherical clusters corresponding to the different states of the neck nuclei are shown under Fig. 2a, while the kinetic energy distributions are shown in Fig. 2b. So, the structure observed in Fig. 1 is related to the presence of three possible types of the fission barrier descent with different internal excitation and substantially quantum (clusterization) mode of rupture.

4. K. Ikeda, Proc. 5th Int. Conf. on Clustering aspects, in nuclear and subnuclear systems, Kyoto 1988, p.232
Fig. 1. Yield of fragments with the selected nuclear charge vs. their kinetic energy.

Fig. 2. General scheme of heavy nuclei deformation process. For details see text.
PROMISING AND CRUCIAL EXAMPLES OF CLUSTER RADIOACTIVITY PROCESSES

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General problems of cluster radioactivity: adiabatic or nonadiabatic character of process, connection with fission and $\alpha$-decay, even-odd effects, fine structure, heavy and light cluster mass limits etc. are discussed. A special attention is paid to the problem of crucial experiments, which are able to distinguish an optimal theoretical approach. Wide-scale looking for new examples, promising for measurements was carried out using our theoretical scheme [1]. Not so many cases of cluster decay are more or less perspective in the traditional $A > 208$ parent nuclei mass region. In fact, in the table most of them are presented.

<table>
<thead>
<tr>
<th>No.</th>
<th>Decay</th>
<th>$\log(T_{\text{theor}}^{1/2})$ (sec)</th>
<th>$-\log(T_{1/2}/T_{\alpha})$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^{220}$Ra $\rightarrow ^{12}$C</td>
<td>11.1</td>
<td>$\geq 12.7$</td>
<td>$T_{1/2}^\alpha \leq 1$sec</td>
</tr>
<tr>
<td>2</td>
<td>$^{221}$Ra $\rightarrow ^{13}$C</td>
<td>14.7</td>
<td>13.2</td>
<td>short-lived (sl)</td>
</tr>
<tr>
<td>3</td>
<td>$^{221}$Fr $\rightarrow ^{14}$C</td>
<td>16.2</td>
<td>7.7</td>
<td>$T_{1/2}^\alpha$</td>
</tr>
<tr>
<td>4</td>
<td>$^{223}$Ac $\rightarrow ^{14}$C</td>
<td>14.3</td>
<td>12.2</td>
<td>$T_{1/2}^\alpha \approx 10$ 2sl</td>
</tr>
<tr>
<td>5</td>
<td>$^{224}$Th $\rightarrow ^{14}$C</td>
<td>17.4</td>
<td>12.4</td>
<td>$T_{1/2}^\alpha \approx 1$sec</td>
</tr>
<tr>
<td>6</td>
<td>$^{226}$Th $\rightarrow ^{14}$C</td>
<td>17.5</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$^{226}$Th $\rightarrow ^{18}$O</td>
<td>18.5</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$^{230}$U $\rightarrow ^{22}$Ne</td>
<td>19.6</td>
<td>13.3</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$^{232}$Th $\rightarrow ^{26}$Ne</td>
<td>30.1</td>
<td>12.5</td>
<td>long-lived (ll)</td>
</tr>
<tr>
<td>10</td>
<td>$^{235}$U $\rightarrow ^{25}$Ne</td>
<td>30.1</td>
<td>13.8</td>
<td>l, and other clusters 2ll</td>
</tr>
<tr>
<td>11</td>
<td>$^{236}$U $\rightarrow ^{30}$Mg</td>
<td>29.1</td>
<td>14.4</td>
<td>ll</td>
</tr>
<tr>
<td>12</td>
<td>$^{237}$Np $\rightarrow ^{30}$Mg</td>
<td>29.3</td>
<td>15.5</td>
<td>ll</td>
</tr>
<tr>
<td>13</td>
<td>$^{234}$Pu $\rightarrow ^{26}$Mg</td>
<td>21.1</td>
<td>15.4</td>
<td>$T_{1/2}^\alpha = 17$</td>
</tr>
<tr>
<td>14</td>
<td>$^{236}$Np $\rightarrow ^{28}$Mg</td>
<td>28.7</td>
<td>14.7</td>
<td>ll</td>
</tr>
<tr>
<td>15</td>
<td>$^{238}$Cm $\rightarrow ^{31}$Si</td>
<td>21.3</td>
<td>14.9</td>
<td></td>
</tr>
</tbody>
</table>

Even these examples are rather hard for measurement. For obtaining a result it is necessary to measure the cluster decay of short - (No. 2-5), very short - (No. 1,6) and long-lived (No. 10-13) isotopes. Sometimes (No. 5,14), $\beta$-decay influence seriously. For some cases it's rather difficult to obtain the parent nucleus. Consequently we may hope to get data really for the few cases only. The most interesting of them would be No. 1, 2, 8, 9-14 - giving the emission of new clusters, including of lightest (1,2) and heaviest (16) ones, as well as (5,15) getting the examples of odd-odd nuclei decay. Some of the results, possibly, will serve as indications for more adequate variant of a theoretical approach or will be a surprise for any theory.
In spite of the difficulties of measurements for another parent nuclei some of them merit an active efforts of experimentalists. Even an obtaining of upper limit of a branching ratio for the emission of very a light cluster $^8$Be ($-\log(\Gamma_x^{\text{theor}}/\Gamma_o) = 14.3$) from $^{214}$Ra, or very heavy cluster $^{34}$Si from $^{240}$Pu (17.6), $^{241}$Am (19.2), $^{242}$Cm (18.7) and superheavy cluster $^{46}$Ca from $^{249}$Cf ($\sim 30$ in accordance with our estimations) will give some indications on cluster mass dependence of the branching ratios and will produce additional test of the known theoretical approaches.

Due to the difficulties of real measurements in the discussed mass area it is useful to look for new regions of cluster radioactivity. Just one, first indicated in /2/, was confirmed by our approach. This region includes processes with daughter nuclei, close to $^{100}$Sn and relatively light clusters $^{12}$C, $^{16}$O, etc. The folding procedure of cluster-nucleus potential evaluation was used. The initial potential was the same as we used for the $A > 208$ region /1/.

The obtained results are strongly different from those in the $A > 208$ region. For example in the case of $^{114}$Ba $\rightarrow ^{12}$C + $^{102}$Sn decay the branching ratio $\log(\Gamma_x/\Gamma_o) = -0.4$. The half-life of $^{12}$C-decay $T_{1/2} = 6 \times 10^3$ sec and the ratio $(\Gamma_x/\Gamma_o) \approx 10^{-4}$ make this decay not unobservable. The characteristics of another example $^{118}$Ct $\rightarrow ^{16}$O + $^{102}$Sn : $\log(\Gamma_x/\Gamma_o) = +3.7$, $T_{1/2} = 8.8 \times 10^2$, $(\Gamma_x/\Gamma_o) \approx 10^{-3} \div 10^{-4}$ are as well as previous one. Other variants of cluster decay in this region do not possess such good characteristics but may be preferable to give a possibility for obtaining the parent nucleus.

It is interesting that the other theoretical approaches /3,4/ give the width values for emission of $^{12}$C and $^{16}$O clusters many (respective $4 \div 8$ and $8 \div 12$) orders of magnitude lower than in our calculation. So, further experiments may serve as a test of different theoretical approaches.

Reference


THE DECAY TIME OF EXCITED $^{233,232}$Pa

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According to Strutinsky's shell correction method [1], a fission barrier of actinide nuclei has a double-humped structure with the second deep well between the humps, and the nuclei have two classes of excited states in the first and second potential wells, respectively. It was shown in ref. [2], the states in the second potential well can influence greatly the fission dynamics caused increased mean decay time via the fission channel compared with any other decay channels. These states are populated because of dissipations of fission mode kinetic energy.

The result of the fission time experiments with the reaction $^{232}$Th (d,xnf) are reported. Measurements were made with the single crystal ThO$_2$, using the blocking technique. The fission times of $^{233,232}$Pa in the excitation energy range of 6 to 14 MeV were determined. For the fission of these isotopes the time delay of the induced fission reaction relative to decay of the excited nuclei via any other channel was observed. The time delay is connected with the nuclear lifetime of the excited states in the second potential well. The second well depths of $^{233,232}$Pa were varied to provided the best description of the experimental fission lifetime data, and resulted in (3.5±0.8) MeV and (2.0±0.5) MeV, respectively. The experimental lifetime data was used to extract the absolute magnitudes of the level densities in the second well of $^{233,232}$Pa. The obtained level densities data are analysed in the level densities phenomenological model [3]. It was shown a satisfactory description of the second well densities data for Pa isotopes is achieved if the axial and reflection shape symmetry of the nuclei is assumed to be broken in the excited states of the second potential well.

There was an important assumption in the analysis of the experimental lifetime data. It was the great probability of the second well states occupation. This probability has been evaluated in the framework of the diffusion model [4]. It was shown, for all actinide nuclei the probability of the second well states occupation is more then 0.8 in the excitation energy range of 10 to 20 MeV.

References

Lifetimes of cluster radioactivity of neutron deficient trans-tin isotopes

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Abstract: The interplay between superfluid effects in cluster formation and resonance effects in barrier penetration in the cluster radioactivity (CR) phenomenon of neutron deficient trans-tin nuclei is analysed in detail. A superallowed $^{12}\text{C}$ emission from $^{114}\text{Ba}$ is found with the halftime $T = 10^{5.2}$ s and branching ratio relative to $\alpha$ decay $B \approx 10^{-4}$. The possibility of $^{16}\text{O}$ radioactivity is also discussed.

The cluster emission at relatively low decay energies may be looked as the result of a sensible interplay of nuclear structure effects especially dominated by two body interactions and resonance effects occurring in the dynamical evolution by unstable systems [1].

The main results for $^{12}\text{C}$ and $^{16}\text{O}$ emissions of neutron deficient trans-tin nuclei obtained within the framework of superfluid resonance approach [1,2] are presented in the Geiger-Nuttal plot in fig. 1. The emission energies are estimated: a) using available nuclear mass extrapolations [3], b) by combining the measured $Q_\alpha$ values [4] and known mass excess of the daughter nucleus [3], c) by combining the extrapolated $Q_\alpha$ value with the measured mass excess of the daughter nucleus [3].

Summarizing, we mention the following conclusions:

a) Cluster radioactivity half-lives considerably decrease with increasing neutron deficit;

b) A superallowed $^{12}\text{C}$ emission from $^{114}\text{Ba}$ is found in agreement with the preliminary measurements [5].

c) The alflives of $^{16}\text{O}$ emission in the trans-tin region are very close to halflives of $^{14}\text{C}$ emission in the actinide region but for more reduced energies.

d) The energy constant from Geiger-Nuttal decay low seems to be the same for all CR while the structure constant considerably differs from one to another CR by many orders of magnitude.

Parallel experimental and theoretical intense work allows to focus and sharpen the efforts in studying and understanding the CR phenomenon of nuclei near and far-away the line of nuclear stability.
Fig. 1. Dependence of the half-life on the decay energy for measured (•) and expected (○) cluster radioactivities. Each solid line corresponds to a specific emission. The dashed line connects the emission leading to the double magic clusters $^{100}$Sn and $^{208}$Pb.

SPONTANEOUS FISSION STABILITY OF NUCLEI

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We proceed from the idea that the spontaneous fission (s.f.) is a tunnel process whose probability depends mainly on the energy of fission $Q_{sf}$ and also on fragment charges. Moreover, the filling of nuclear (especially proton) shells is important. If we suppose that both fragments ($Z_1, N_1$) and ($Z_2, N_2$) are in the same intermagic region (limited by adjacent (sub)magic numbers both for protons and neutrons) where the binding energy $B(Z_i, N_i)$ is a quadratic function of $Z_i$ and $N_i$ ($i=1,2$) [1]:

$$B(Z_i, N_i) = B_0 + a_1 Z_i^2 + a_2 Z_i N_i + a_3 N_i^2 + a_4 Z_i + a_5 N_i$$

then the energy released by the fission of the parent nucleus $(Z, N)$ turns out the quadratic function of $Z_1(>Z/2)$ and $N_1(>N/2)$ too:

$$Q_{sf}(Z, N, Z_1, N_1) = Q_{sf}^0 + (2a_1 - a_2/2a_3)(Z_1 - Z/2)^2 + 2a_3(N_1 - N(Z_1))$$

where $N(Z_1) = N/2 - a_2/2a_3(Z_1 - Z/2)$ is the line of maximum energy release, $Q_{sf}^0$ being the energy of symmetric fission. The numeric values of parameters in above formulas are such (see [2]) that $Q_{sf}$ has maximum in the case of symmetric fission for $Z \geq 100$ and asymmetric for $Z < 100$. The tendency to asymmetry increases when the probability of s.f. is considered as it depends also on $Z_1(Z - Z_1)$. The formula containing the dependence of both factors assures a resonable discription of fragments. After summation over all canals of s.f. we obtain the approximative formula for periods of s.f. [3]:

$$\log T_{sf} \text{(sec)} = 61.2 \cdot Z (Q_{sf}^0)^{-1/2} - 381.5 - \delta + \Delta,$$

where $\delta = 0$ for $Z < 100$ and for $Z = 100$ if $146 < N < 158$ and $\delta = 6$ otherwise, $\Delta = 0$ for even-even nuclei and $\Delta = 3.5$ for other parities. The last formula assures the description of all experimentally known $T_{sf}$ with mean deviation 1.55 if $Q_{sf}$ is calculated from experimental masses of nuclei or according to accurate mass formula.

References
The study of the very deficient neutron nuclei by observing the evaporation residue (ER) allows the investigation of the formation of isotopes far from the $\beta$-stability line where the competition of fission is higher with respect to neutron emission. Therefore, the formation cross sections of neutron deficient heavy evaporation residues appear to be sensitive to the parameters that describe the fission process when a small charge symmetry parameter $(N-Z)/A$ is present. In our analysis we take into account the exact angular momentum coupling, the collective effects in the level density in the nonadiabatic approach [1,2] and the evolution of nuclear shapes with increasing spin [3]. Moreover, we consider the level density parameter that include the shell correction and both the nuclear temperature and angular momentum dependences of the shell correction in the fission barrier [4]. In order to explain the trend of the residual nuclei formation cross sections we also used an oscillating dependence of the shell correction as the angular momentum increases. The comparison between calculation and experimental data will be discussed.

References
HIGH-SPIN NUCLEAR TARGET OF $^{178m}_{2}$Hf: CREATION AND NUCLEAR REACTION STUDIES

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A long-lived (31 year) four-quasiparticle isomer $^{178m}_{2}$Hf (I, K$^*$=16,16$^+$) was produced in microweight quantities using the nuclear reaction $^{176}$Yb(²He,²n). The producing reaction was chosen in order to optimize the absolute yield and isomeric ratio values. Also target construction and long intensive irradiation conditions were optimized. As a result total number about $10^{15}$ of $^{178m}_{2}$Hf atoms were produced during two years. Methods of precision chemistry and mass-separation for the purification of the produced Hf material have been developed. All processing of this activity has to ensure the high efficiency of separation and high purity from ballast Hf and other contaminating elements. Thin targets of isomeric hafnium-178 on carbon and aluminium backings were prepared and used in experiments on γ-ray, neutron, proton and deuteron beams.

First nuclear reactions on a high-spin exotic target were observed: $^{178m}_{2}$Hf(n,γ)$^{179m}_{2}$Hf and $^{178m}_{2}$Hf(d,d'). The thermal neutron radiative capture leading to the activation of $^{179m}_{2}$Hf (T$_{1/2}$=25 d) has the cross section about 50 barns. The large value of the resonance integral (800 barns) was also measured for this reaction, it opens up a possibility to search experimentally for high-spin neutron resonances using a prompt γ-ray multiple detector systems combined with the time-of-flight technique. Such an experiment was performed recently and some preliminary results were obtained.

In reaction of inelastic scattering $^{178m}_{2}$Hf(d,d') the first excited level of the band built on the 16$^+$ isomeric level was revealed at the excitation energy of 353 keV. The moment of inertia of this band could be estimated immediately J=48 MeV$^{-1}$, which is much higher than moment of inertia evaluated for the first level in the ground state band J=32 MeV$^{-1}$. This result demonstrates quantitatively the antipairing influence of four quasi-particles in the even-even nucleus.

Experiments on electromagnetic interactions of the isomeric hafnium using methods of the collinear laser spectroscopy as well as of the nuclear orientation of hafnium implanted into a crystalline media were started. The electromagnetic moments, the mean radius, and the deformation of the isomeric nucleus are expected to be measured. Also the amplitude of P and PT parity violation in an electromagnetic decay can be studied as proposed by Princeton group.

Future investigations in the frame of the hafnium-178 isomer problem are a new promising scientific direction from the point of view of the development of fundamental knowledge both in the field of the nuclear structure and of nuclear reactions. The completed experiments give grounds for hopes to study the influences of the target high spin on the cross sections of nuclear reactions, to find and investigate neutron resonances with high spin, to measure their density, to study a giant resonance built on the high spin state, and to clarify in detail the role of the structure hindrances in nuclear reactions.
Spectroscopic study of the $K=8$ and $K=16$ isomeric states in $^{179}$Hf

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Yu.Ts. Oganessian, S.A. Karamian, Z. Szeglowski (JINR-Dubna, Russia)  
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M. Hussonnois, O. Constantinescu, S. Fortier, L. Rosier, G. Rotbart (IPN-Orsay, France)

The present interest in nuclei at high spin is partly motivated by a desire to understand how nuclei behave under the stress of large angular momentum. In deformed nuclei, collective rotation has been commonly observed to be energetically the most favourable mode for generating spin. However, in $^{179}$Hf it has been found [1] that some 2- and 4-quasiparticle (qp) states can occur lower in energy than members of the ground state band with corresponding spin. Figure 1 shows the partial level scheme for $^{179}$Hf with the $K^*=0^+$ ground state band, the $K^*=8^-$ 2-qp band and the $K^*=16^+$ band head of a 4-qp state. The quantum number K is the projection of the total nuclear angular momentum I on the symmetry axis.

![Level Scheme](image)

**Fig. 1:** Partial level scheme for $^{179}$Hf

In a first experiment an enriched $^{179}$Hf target was bombarded with a pulsed $^{130}$Te beam at three beam energies of 560, 590 and 620 MeV below the Coulomb barrier. The population of the ground state band and the $K^*=8^-$ isomer at 1147.4 keV was observed with the Darmstadt-Heidelberg Crystal Ball consisting of 153 NaI detectors and six additional Ge detectors. This result confirms the measurement of [2] and their suggestion that the excitation of the isomer is caused by Coulomb excitation. If the K selection rule is valid, a direct transition from the $K=0$ ground state band to the $K=8$ isomeric state and the rotational states built on it is forbidden. However, an admixture of the different K-quantum numbers in the
wave functions could allow for direct transitions to the isomer band in $^{176}$Hf. If one includes a small $K=0$ component in the wave function of the isomeric band, the population of the isomer can be reproduced via direct E3 excitation from the rotational band built on the ground state.

In a second experiment at the Munich tandem accelerator we used inelastic proton and deuteroh scattering at incident energies of 22 MeV and 26 MeV in order to search for excited states built on the $K^*=16^+$ isomer. Microweight quantities of $2 \times 10^{14}$ atoms in the isomeric state have been produced by a Dubna-Orsay-GSI collaboration using the $^{178}$Yb(a, 2n) reaction [3] From the irradiated material a target was prepared after chemical separation of the hafnium from the bulk material and by electro-spraying of the Hf-solution onto a thin carbon backing. The elastic and inelastic scattered projectiles have been measured with the Q3D-spectrograph in connection with a 1.2 m long focal plane detector [4] at laboratory angles of 100° and 135°. Fig. 2 shows the energy spectrum for the (d,d') reaction measured at 100° and an incident energy of 22 MeV. All stable hafnium isotopes can be identified by the population of the first excited states in their ground state rotational bands. In addition target impurities of platinum isotopes are observed, which are mainly due to the target preparation process. The only peak which can not be assigned to either hafnium or platinum isotopes is marked with an asterisc. Under the assumption that this state belongs to the $K^*=16^+$ rotational band in $^{176}$Hf an excitation energy of 353 keV can be deduced. This result has to be confirmed by the analysis of the measured cross section which is in progress.

![Fig. 2: Spectrum of inelastically scattered deuterons at 22 MeV for an isomerically enriched Hf-target measured at a laboratory angle of 100°.](image)


65
Collinear Laser Spectroscopy of $^{178m2}$Hf

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The optical study of the high K isomer $^{178m2}$Hf gives access to the magnetic moment $\mu$, the spectroscopic quadrupole moment $Q$, and to the isomer shift as a change of the charge radius $\delta < r^2 >_{1S}$.

The structure of this long lived ($T_{1/2} = 31y$) high spin state $I^* = 16^+$ is of particular interest: A selective preparation of microgram quantities of $^{178}$Hf samples with up to 5% isomer enrichment is described in [1]. A research program has been started using these samples as targets for nuclear reactions and Coulomb excitations.

We have set up a collinear laser experiment using the P.A.R.I.S. mass separator at the CSNSM in Orsay. The hafnium ions are neutralized in a sodium charge exchange cell and the atomic line ($6s^2 \cdot 2P_2 - 6s6p \cdot 1P_1$, $\lambda = 572$ nm) is excited with a single mode dye laser stabilized on a $^{127}$J$_2$ molecular absorption line. The Doppler shifted fluorescence spectrum is recorded by a voltage sweep applied to the charge exchange cell. The filtered fluorescence light from the $\lambda = 378$ nm line is recorded with special care for the suppression of background light from the fast atomic beam. Details of the detection system are found in [2].

With calibrated stable Hf samples a sensitivity of $5 \cdot 10^{-3}$ (photons/separated ions) has been obtained for $I = 0$ isotopes and the atomic parameters for hyperfine structure and isotope shift have been completed by the analysis of signals from stable odd and even isotopes.

In a first run we have used the sample No.1 produced at the U200 cyclotron at Dubna and introduced $1.6 \cdot 10^{13}$ atoms $^{178m2}$Hf ($I^* = 16^+$) in the ion source together with a twentyfold amount of $^{178}$Hf ($I = 0$) and a highly enriched stable tracer of $^{178}$Hf for the operation of the mass separator.

Signals have been recorded at mass 178 and two almost coinciding resonances above a 3$\sigma$ level are attributed to $^{178m2}$Hf. Their position relative to the groundstate has been extracted in a preliminary data analysis. The comparison with all possible hfs patterns and isomer shifts indicates that our partial result does not support the previous measurement of $\mu$, by nuclear orientation [3].

The particular interest in the hafnium arises from the existence of a unique range of high $K$ isomers, the investigation of which may provide some insight into the competition between quasi-particle and collective behaviour of the nucleons. There has been considerable progress in producing relatively large samples of long-lived isomers as, e.g., $^{178m}_{2}$Hf [1]. In the course of preparing measurements of the optical hyperfine structure and isomeric shift of long-lived isomer $^{178m}_{2}$Hf (Dubna-Karlsruhe collaboration), the series of experiments with stable Hf isotopes, radioactive $^{172}_{2}$Hf and $^{170}_{2}$Hf have been performed using the method of laser spectroscopy of Hf$^{+}$ions stored in RF trap [2]. Optical resonance fluorescence is induced by ultraviolet light at $\lambda=301.2$ nm; it is generated by intracavity frequency doubling in a modified type 699 cw dye laser. The overall sensitivity is such that about 100 stored $I=0$ ions are sufficient to record smooth spectra within minutes. The isotope shifts of all stable Hf isotopes and radioactive $^{172}_{2}$Hf where measured and the differences in root mean square charge radii ($\delta<r^2>$) where determined. The value of $\delta<r^2>$ we obtained for the isotope pair $^{172}_{2}$Hf, $^{174}_{2}$Hf ($\delta<r^2>^{172}_{2}=0.115(16)$) is somewhat different from one for the stable neighboring even isotopes ($\delta<r^2>\approx0.6-0.7$). This corresponds the case if there no the change of deformation between hafnium nuclei with atomic mass 172 and 174. From data obtained for isomer it may be estimated that parameter of deformation for $^{178m}_{2}$Hf should be either bigger than $\beta=0.4$, or smaller then $\beta=0.2$. Another possibility if the signal of isomer is shaped by stable Hf isotopes then $\beta$ volume belongs to the interval of $0.24\leq\beta\leq0.29$. Experiments are in progress to obtain more detail information concerning $^{178m}_{2}$Hf by using mass-separated isomer sample.

The changes in the mean-square nuclear charge radii $\delta \langle r^2 \rangle^{A'}_A$ along an isotopic chain can be extracted from the isotope shifts (IS) in the optical spectra of an element. Here we report the results for $^{174,176-180}$Hf obtained in the ongoing investigations of hafnium isotopes at LNR.

The technique of laser excited resonance fluorescence in a well collimated atomic beam has been applied to measure the IS in the transitions 5904, 5948 and 5720 Å. Metallic samples of natural abundance as well as enriched $^{177}$HfO$_2$ and $^{179}$HfO$_2$ ones have been used. This allowed us to identify the hyperfine structure (hfs) components of the odd isotopes and to determine the hfs centers of gravity and the IS. Using the King-plot procedure with reference transition 5453 Å [1] we determined the nuclear parameter $\lambda^{A'A}$ which is expressed as:

$$\lambda^{A'A} = \sum_n \left( C_n / C_1 \right) \delta \langle r^{2n} \rangle^{A'}_A,$$

where $C_n$ are the Seltzer coefficients [2]. Following Ahmad et al. [3], the listed in Table 1, $\delta \langle r^2 \rangle^{A'}_A$ values have been obtained.

Analyses of the hfs of the odd isotopes yield ratios of the magnetic dipole and electric quadrupole moments $\mu(177)/\mu(179) = -1.240(6)$ and $Q_x(177)/Q_x(179) = 0.886(2)$, respectively.

**Table 1.**

<table>
<thead>
<tr>
<th>A</th>
<th>$\lambda^{178,A}_{\text{fm}^2}$</th>
<th>$\delta \langle r^2 \rangle^{178,A}_{\text{fm}^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>174</td>
<td>-0.121(6)</td>
<td>-0.126(6)</td>
</tr>
<tr>
<td>176</td>
<td>-0.081(3)</td>
<td>-0.063(3)</td>
</tr>
<tr>
<td>177</td>
<td>-0.045(3)</td>
<td>-0.046(3)</td>
</tr>
<tr>
<td>179</td>
<td>0.024(2)</td>
<td>0.025(2)</td>
</tr>
<tr>
<td>180</td>
<td>0.072(4)</td>
<td>0.075(4)</td>
</tr>
</tbody>
</table>

References

THE NEW SPECTROSCOPY OF EXCITED SUPERDEFORMED BANDS

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The existence of superdeformed shapes at high angular momentum has been well established in a range of nuclei in the mass region around A=150. The superdeformed bands have different characteristic moments of inertia which are understood in terms of the occupation of several high-j intruder nucleons from the proton N=6 and neutron N=7 orbitals. These high-j low-Ω orbitals are largely responsible for driving the nucleus to such large deformations and for stabilising the shape. Excited bands are expected to be particle-hole excitations and several have been reported including a proton excitation from the (301½) orbital into an N=6 state producing a band with identical γ-rays to its parent state.

The UK/French EUROGAM array has been in operation at Daresbury since October 1992. The array of 45 large Ge detectors has a full energy peak efficiency of 4.5% at 1 MeV and it reduces the limit of observation of superdeformed bands by an order of magnitude.

Data has been obtained with EUROGAM on $^{149,150}$Gd, $^{151}$Tb and $^{151,152}$Dy and a number of new excited superdeformed bands have been identified. The very high statistics of triple and quadrupole coincidences have enabled spectra of excellent quality and cleanliness to be produced. Accurate gamma-ray energies and intensities have been measured and many interesting new features observed. These include band interactions and crossings and differences in both the feeding and decay of the bands. Highlights of these results will be presented.
Studies of exotic nuclei at JYFL: First results and future prospects

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At the new JYFL K = 130 MeV cyclotron laboratory the future research program on exotic nuclei will be based on the new improved IGISOL facility and the gas-filled recoil separator RITU. In addition, a general purpose 1.5 m scattering chamber and a He-jet transport system are available. The research program in the near future will be concentrated on (i) studies of techniques and reaction mechanisms to produce exotic nuclei and radioactive beams (ii) studies of weak interaction processes in nuclei via Fermi or Gamow-Teller decays (iii) studies of very proton-rich nuclei and exotic decay modes (iv) systematic studies of nuclear structure and decay with the isospin degree of freedom of very r-rich nuclei produced in fission and n-deficient heavy nuclei produced in (HI,xn) reactions, and (v) spectroscopy of the heaviest elements with Z \approx 100. Results of first experiments along this line of work will be discussed.
Beta Decay of Deformed $A=100-120$ Nuclei

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We have studied Gamow Teller (GT)-strength and its distribution as a function of deformation in neutron-rich nuclei between strongly deformed Zr and less deformed Pd isotopes. As a general result, GT-strength has been found to be spread over many $1^+$ final states in the decay of even-even precursor in the mass region studied. Neutron-rich nuclei up to the borderline of known nuclei were produced by fission at the IGISOL-facility.

In the studied region, $110 < A < 120$, recent r-process calculations have underproduced the abundance of isotopes, which is a direct consequence of a poor estimation power of half-life models [1]. We have extended the half-life systematics to very neutron-rich nuclei, as can be seen from the table below, which shows the latest isotopes found at the IGISOL-facility [2].

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$^{106}$Zr</td>
<td>$\approx 1000$</td>
<td>-</td>
<td>$^{115}$Tc</td>
<td>130(50)</td>
<td>88</td>
</tr>
<tr>
<td>$^{107}$Nb</td>
<td>330(50)</td>
<td>835</td>
<td>$^{116}$Ru</td>
<td>740(80)</td>
<td>1300</td>
</tr>
<tr>
<td>$^{109}$Mo</td>
<td>530(60)</td>
<td>2250</td>
<td>$^{170}$Pd</td>
<td>500(100)</td>
<td>1600</td>
</tr>
<tr>
<td>$^{110}$Mo</td>
<td>250(100)</td>
<td>1560</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The uncertainties of the half-life predictions come mainly from the difficulty to predict binding energies. With this in mind we have done series of decay energy measurements for n-rich even-even Pd, Ru, Mo and Zr isotopes. First results of Ru-isotopes showed that the recent mass models underestimate $Q_\beta$-values of Ru isotopes [3,4]. When this is taken into account, the excellent agreement between theory and experiment can be achieved.

Preliminary results from the analysis of the decay of $^{106-110}$Mo and $^{102,104}$Zr will also be presented.

References

* Supported by the Academy of Finland.
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ROTATIONAL PROPERTIES OF OSMIUM NUCLEI
IN THE A=180 MASS REGION

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In order to get more insight into the strongly varying rotational properties of the neutron deficient transitional Os nuclei we studied the high-spin states in $^{179,180,185,186}$Os. They are expected to be susceptible to shape changes. Configuration dependent deformation effects are expected in this region [1].

The high-spin states in $^{179,180}$Os have been populated in the $^{150}$Nd$(^{34}$S, xn) reaction at 158 MeV in an experiment at the VICKSI accelerator at the HMI and studied with the gamma-spectrometer OSIRIS. The $^{181,182}$Os nuclei were studied at the NSF, Daresbury utilizing the $^{150}$Nd$(^{36}$S, xn) reaction. The gamma-radiation was measured with the ESSA30 spectrometer. The high-spin states in $^{185,186}$Os were populated in the $^{166}$W$(^{4}$He, xn) reaction in an experiment at the KFA Juelich and studied with the OSIRIS spectrometer. Bands, which are build on different quasiparticle orbitals, were identified in these nuclei and their properties are systematized in these studies. The results indicate strong influence of the position of the Fermi surface on the rotational properties of these nuclei. The results are discussed within the framework of the cranked shell model [2].

Configuration dependent deformation changes were found in $^{179}$Os. The bands show large differences in the crossing frequencies. Their alignment behaviour is determined by shape effects and the rotational alignment of an i13/2 quasineutron pair. For the rotational band build on the 1/2(521) configuration and increase of the quadrupole deformation was established, which corresponds to a stretching of the nucleus. For the positive parity band the observed discrepancy between the experimental signature splitting of the quasiparticle Routhians and the signature dependence of the reduced B(M1) transition probabilities is considered as a possible sign of triaxial shape in this configuration [3]. It is consistent with a negative value of the gamma-deformation. The inversion of the crossing frequencies, which has been found in the two branches of this band is interpreted as experimental evidence for hexadecapole deformation, corresponding to $0.05 < e4 < 0.07$ for the above values of gamma.

Gamma-bands have been established for all the Os nuclei with even mass numbers and $N > 100$. A most interesting question emerging from their study concerns the fluctuations of the deformation parameter $g$. The even spin members of these bands are depressed with respect to the odd-spin ones. The study of the changes in the relative displacement of these levels, as suggested by D. Bonatsos [4], helps to approach the problem of the possible $g$-softness of the Os nuclei. Changes of the deformation susceptibility of the Os nuclei take place with the increase of the neutron number. The isotopes with $N > 106$ tend to approach the vibrational limit of the IBM model, while these with $N=106$, 108 are better rotors. For the lighter isotopes there is another change of the behaviour. Thus, it might be concluded that the nuclei with $N=104$ and $N > 110$ are $g$-soft, while the nuclei $^{182}$Os ($N=106$) and $^{184}$Os ($N=108$) are stiffer. This result helps to understand the rotational behaviour of these nuclei.

The ground state in $^{186}$Os is known to have prolate deformation. The rotational band which is build on this state was found to terminate at $I=18^+$. Several transitions were
found to feed this level. Their multipolarity was established using the DCO method. For all of them a spin difference of two may be excluded. The irregular level sequence above the 1493.6 keV (I=18+) is possibly connected with slightly-to-moderately oblate shape of the nucleus, which means that a prolate-oblate shape change takes place in this band. Another rotational band was found to coexist with this non-collective structure. It is not yrast and is very weekly populated. This is considered as an example of prolate-oblate shape coexistence at high spin in this nucleus. This work is supported in part by the Bulgarian Scientific Foundation under contract No. F-210/2090.

Reference

The wave function \( \psi \) of highly excited nuclear state has a complicated form. In statistical model \( \psi_{\text{st}} \) is described as:

\[
\psi_{\text{st}} = \sum_{k} C_k \psi_k
\]

where \( \psi_k \) - is the wave function of "simple" configuration, \( C_k \) - is the random number, \( n \gg 1 \). The nuclear levels spacing is small and different configurations are mixed.

The nonstatistical wave function \( \psi_{\text{Nst}} \) is expressed as:

\[
\psi_{\text{Nst}} = C_0 \psi_0 + \sum_{k} C_k \psi_k
\]

i.e., at least one "simple" configuration \( \psi_0 \) dominates [1]. From the phenomenological point of view, the nonstatistical effects at the excitation energy \( E > 5 - 10 \text{ MeV} \) in the medium and heavy nuclei indicate conservation of some symmetry.

Isospin of the isobaranalog state is not equal to that of many levels near it. Isospin symmetry prevents mixing of the isobaranalog state with other levels. Isobaranalog state has basic "simple" configurations such as proton-particle and a neutron-hole coupled to angular momentum \( 0^+ \) and nonstatistical effects are well known for it.

The nonstatistical effects connected with the \( (p,n^-)_{1^+} \) and \( (n,p^-)_{1^+} \) configurations can be associated with spin-isospin SU(4) symmetry. One of the consequences of the SU(4) symmetry is [2]: \( E(\text{IAR}) = E(\text{GT}) \), where \( E(\text{IAR}) \) - is the energy of the isobaranalog resonance, \( E(\text{GT}) \) - is the energy of the Gamov-Teller resonance. The calculated values of the energy difference \( \Delta E = E(\text{IAR}) - E(\text{GT}) \) as a function of neutron excess \( (N-Z) \) are given in [3], experimental results - in [4].
The values of $\Delta E$ depend strongly on the shell structure and on the average $\Delta E$ decreases when $(N-Z)$ value increase. Hence, SU(4) symmetry [2] and nonstatistical effects can be manifested in exotic nuclei with large $(N-Z)$.

In present paper, questions associated with the investigation of the nonstatistical effects for $\beta$-decay and delayed particles emission in exotic nuclei, are considered. We plan to apply the total-absorption gamma-spectrometer [5] in the nonstatistical effects studies.

References
HYDRODYNAMIC CALCULATION OF EFFECTIVE MASS OF TWO COLLIDING IONS

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Let us consider collision of two identical heavy ions as a collision of two liquid bodies each having the shape of sphere of radius \(2^{-1/3} R_0\) in the initial moment and finally fuse into unique sphere of radius \(R_0\). In order to describe the shape of two liquid bodies at all stages of the fusion process one can use the Cassini's ovaloides

\[
\rho^2 = -z^2 - a^2 s^2 + (a^4 + 4a^2 s^2 z^2)^{1/2}
\]

or

\[
\rho^2 = -z^2 + a^2 (1-s)/2 + a(a^2 (1-s)^2 + 12sz^2)^{1/2}/4.
\]

Under condition of volume conservation the both types of parametrization depend upon only one parameter \(s\) which varies from 0 to \(\infty\) in the first case and from 0 to 1 in the second one. Assuming irrotational flow of the unviscous liquid, the effective mass is calculated numerically by the appropriate formula

\[
\mu = \frac{3}{2} \mu_0 R_0^{-5} \int \left( \left( \frac{d\Phi}{d\rho} \right)^2 + \left( \frac{d\Phi}{dz} \right)^2 \right) \rho d\rho dz.
\]

Here \(\Phi\) is the velocity potential, which satisfies the Laplace equation and the boundary condition

\[
(dF/d\rho)(d\Phi/d\rho) + (dF/dz)(d\Phi/dz) = ((dF/da)(da/ds) + (dF/ds)(ds/db)),
\]

where \(F(p,z,s,t)=0\) is the equation for liquids surface, \(\mu_0\) is the mass of compound nucleus, \(b\) is the distance between ion centres of gravity.

The calculations were carried out using three methods: the method of momenta\(^3\), the spectral method\(^3\) and the method of Wheeler\(^4\). The results of calculations coincide well enough that is shown in the figure. From this figure one can see that the dependence of effective mass from the distance between ion centres of gravity has peculiarity in the point of tangency. In the case of Cassini's parameterization, the effective mass is continuous.
The effective mass in terms of $\mu_0$ versus $\beta$ in terms of $R_0$.

a) Cassini's ovaloides; b) parameterization/2/.

near the point of tangency. Under the other parameterization the effective mass is non-continuous near the point of tangency because the transition from $s \leq 1$ to $s > 1$ is not continuous.

The variation of effective mass near the point of tangency leads to arising of additional force

$$F_\mu = -p^2 \frac{d\mu}{db}/\mu(\beta)^2,$$

where $p$ is the momentum of system. Depending upon the sign of derivative $d\mu/db$, force $F_\mu$ influences the process of fusion as follows. When ions approach the point of tangency, the force $F_\mu$ accelerates the process of fusion. After passing the point of tangency, the force $F_\mu$ slows down the fusion process and in this way increases the lifetime of double nuclear system. Then it accelerates the fusion process again.

The stability of nuclei to $\alpha$, $\beta$, and $p$-decay is determined mainly by their decay energies. One of the approaches to the problem of binding energies is based on the division of all system of nuclei into intermagic regions (limited by (sub)magic numbers both for protons and neutrons) in each of which the separation energies of proton and neutron are approximated by linear functions of $Z$ and $N$ for every parity of nuclei [1]. Values of parameters in the formula for binding energies and submagic numbers themselves result from the solution of the inverse problem of best description of experimental data by a continuous everywhere energy surface. The rms deviations for $Q_\alpha$ and $Q_\beta$ from experiment are 0.1 MeV [1]. It follows in particular that the region of $p$-instability is $A_p<2.77-Z-\Delta$, where $\Delta=41$ for odd $Z$ and 45 for even $Z$.

Nevertheless in regions where any information about energies is fully absent another approach based on systematics of beta-decay energies has advantage. As was shown in [1] $Q_{\beta\pm}$ for every parity of nuclei are well approximated (rms\!\approx\!0.2 MeV) by linear functions of $Z$ and $A$ in sufficiently large regions limited by magic and a few submagic numbers of nucleons: $Q_{\beta\pm}=D_\pm\alpha_\pm(Z-Z^*(A))$, where $\beta$-stability line itself is a linear function of $A : Z^*=\eta A + \zeta$. Therefore $Q_{\beta\pm}$ is determined by six parameters whose values for the regions: (1) $50\leq Z\leq 74$, $82\leq N\leq 89$, (2) $50\leq Z\leq 74$, $89\leq N\leq 108$, (3) $74\leq Z\leq 82$, $89\leq N\leq 108$, (4) $74\leq Z\leq 82$, $108\leq N\leq 126$, (5) $Z\geq 82$, $N\geq 126$ are correspondingly: $\alpha_+ = 1.25; 1.25; 1.3; 1.3; 1.12$ MeV, $\alpha_- = 1.25; 1.365; 1.1; 1.1; 1.375; 1.12$ MeV, $D = 2.75; 2.4; 2.4; 2.45; 1.95$ MeV for even-even nuclei and $D = 0.95; 0.7; 0.7; 0.75$ for even-odd nuclei, $\eta = 0.3636; 0.35; 0.35; 0.356; \zeta = 7.9; 9.85; 9.55; 10.0; 9.1$. The calculated values of $Q_\alpha$ and $Q_\beta$ were used for estimation of $T_\alpha$ and $T_\beta$ according to formulas proposed in [2].

References
Spectroscopy of Neutron-Rich Light Nuclei with Multi-Nucleon Transfer Reactions

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Multi-nucleon transfer reactions have been used to study light nuclei beyond the borderline of stability. These nuclei are extremely neutron-rich and they exist only as resonances in a core+1n or 2n system. Typical examples are $^9$He, $^{10}$He or $^{10}$Li, which are reached from stable target nuclei by the transfer of 3-5 nucleons. Naturally, this method can also be used to study unbound excited states of nuclei, which are particle stable in their ground state, like $^8$He or $^{11}$Li. The two-body character of the reaction allows to observe the resonances of the recoil system in the spectrum of the outgoing particle. The neutron-rich recoiling nucleus is produced by picking up protons from the target and by stripping neutrons from the projectile into resonant states of the recoil system. A detailed investigation of the reaction mechanism on the basis of contributing reaction amplitudes shows that the transfer of protons is decoupled from the transfer of neutrons, since they move in opposite directions. The cross sections can be understood mainly as the product of the strength of the proton and the neutron transfer in a two-step reaction. In a full analysis of the experimental spectra it is important to include also the resonances of the unbound neutron (or 2n) with the ejectile in addition to those in the recoil system. The giant dipole resonance contributes the strongest in this case. The decay of the ejectile system is described as a sequential decay in flight.

Several nuclei of He-, Li- and Be-isotopes have been studied with this method at the Q3D magnetic spectrograph at Vicksi in collaboration of the Hahn-Meitner-Institut, Berlin, the Kurchatov-Institute, Moscow, and the Joint Institute for Nuclear Research, Dubna. A $^{14}$C-beam has been setup to obtain larger cross sections, since the Q-values are less negative as compared to most other reactions.

In the spectroscopy of He-isotopes the $2^+$-state of $^8$He could be identified, the mass and excited states of $^9$He have been measured with high resolution and first attempts have been made to measure $^{10}$He-resonances. In the case of Li-isotopes we could show that Wilcox et al. [1] did not observe the ground state of $^{10}$Li, but an excited state. We could identify the resonances in $^{10}$Li, which are built up by the coupling of the odd 1p3/2-proton and the odd 1p1/2-neutron. The application of the measured resonance energies improved the structure calculations for the halo nucleus $^{11}$Li. Finally we have investigated the unbound nucleus $^{13}$Be and found three resonances. The structure of Be-isotopes has a strong 2α-cluster component and is for this reason of special interest. Further studies including the 3n-system are in progress.

One of the most interesting discoveries in the structure of the light nuclei was the observation of the giant neutron halo [1] in the nuclei $^{11}\text{Li}$, $^{11}\text{Be}$, $^{14}\text{Be}$ and $^{17}\text{B}$. Recently convincing indications have been obtained that such structure is also realized in the $^6\text{He}$ and $^8\text{He}$ nuclei, in which the compact tightly bound $\alpha$ core and two or four valence neutrons, respectively, can be distinguished.

From the presence of a halo in $^6\text{He}$ some features associated with the exotic nuclei have been expected, in particular the possible appearance of collective states similar to giant resonances but at much lower energies than in normal nuclei [2]. Particular interest was sparked off by the prediction of a soft dipole mode in nuclei with two weakly bound valence neutrons which may have been observed [3] in $^{11}\text{Li}$ at excitation energy about 1 MeV. A soft dipole mode in $^6\text{He}$ has been suggested at excitation energy $5\div7$ MeV [4, 5] and a remarkable softening of the giant isovector monopole resonance (at excitation energy about 13 MeV) has also been predicted [6].

The most natural way for the observation of the soft collective modes in exotic nuclei is their inelastic scattering on the hydrogen target in the inverse kinematics conditions. The low intensity of such beams however does not make the job easy and the corresponding experiments are only in progress. Among the exotic nuclei $^6\text{He}$ is the only one which allows more simple way of study - the excitation of the indicated states in the charge-exchange reaction of the $(n,p)$ type on $^6\text{Li}$.

The aim of this work was to search for the low-lying collective states of $^6\text{He}$, in particular a soft dipole mode, via the reaction $^6\text{Li}(^7\text{Li},^7\text{Be})^6\text{He}$. The main problem here is that the quest must be conducted in the continuum region where it is difficult to separate the wide resonances from the background. Some indication on the possible existence of the low-lying dipole resonance was obtained in the $(n,p)$ reaction at $E_n=60$ MeV [7] in which a wide bump was observed at $E_x \approx 7$ MeV. However these measurements have not been made at small angles.

The measurements were carried out at the isochronous cyclotron of the Kurchatov Institute. The energy spectra of the $^7\text{Be}$ nuclei were taken in the angular range $0^\circ \div 10^\circ$ at $E=82$ MeV by a magnetic separator MASE. The form of the experimental spectra at small angles ($\Theta < 5^\circ$) strongly deviates from the simple phase space estimate. Besides of the $0^+$ ground state and the $2^+$ resonance, three broad structures appear to be present at excitation energies 6, 12 and 19 MeV, in agreement with what was observed [7] in the reaction $^6\text{Li}(n,p)^6\text{He}$. The bump at $E_x \approx 6$ MeV ($\Gamma \approx 5$ MeV) falls in the energy region predicted for soft dipole transitions.
The angular distributions for transitions to the ground state ($0^+$) and resonances at 1.8 ($2^+$), 6, 12 and 19 MeV were also measured.

Theoretical angular distributions, which include the sum of the transitions to the ground ($J^* = \frac{3}{2}^-$) and first excited ($E_x = 0.43$ MeV, $J^* = \frac{1}{2}^-$) states of $^7$Be were calculated in the framework of the microscopic DWBA assuming that a direct one-step reaction mechanism dominates. In the case of transitions to the excitation region about 6 MeV the comparison of theory and experiment allows the transferred angular momentum to be determined. The satisfactory description is obtained only assuming a dipole excitation.

Calculating the strength of $E1$ transitions in $^6$Li with the wave functions used to describe the dipole charge-exchange reaction makes it possible to obtain the value of the wave function normalization, necessary for exhausting the energy weighted sum rule (EWSR). Comparison of this value with the normalization used for describing the absolute charge-exchange reaction cross sections gave for the dipole strength an estimate of about 13% of the EWSR.

Thus, studying the charge-exchange reaction $^6$Li($^7$Li,$^7$Be)$^6$He at 82 MeV we observed broad noticeable structures in the excitation spectra of $^6$He. The structure at $E_x \approx 6$ MeV ($\Gamma \approx 5$ MeV) has the angular distribution of the dipole type and can be associated with the predicted soft dipole mode. At present time the nature of the excitations at $E_x = 12$ and 19 MeV are being analyzed.

References


Microscopic description of neutron halo in light nuclei

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Neutron halo phenomenon in light exotic nuclei can be defined as a significant difference between the matter root-mean-square radius and the proton distribution r.m.s. radius for the defined state of the same nuclei. Calculations of these quantities are not so sensitive to form of a nucleon-nucleon potential, but are essentially depending on quality of wave function. By no doubts at first it must be antisymmetric and translationally invariant. The results in the oscillator shell model (OSM) or the Hartree Fock approximation with moving centre of mass of nuclei are not so good in comparison with the results, obtained even in the translationally-invariant shell model (TSM). From another point of view, calculations in the three point-particle approximation (core + two neutrons) are giving too optimistic results [1], [2], because the antisymmetrization leads to growing up size of core and extremely large halo effect disappearance.

To clarify effects of wave-function quality in exotic nuclei \(^{6}\)He and \(^{11}\)Li description we are using fully antisymmetric and translationally-invariant one [3]. In such a case halo effect is growing up even in TSN approximation. To improve results we formulated three-cluster equations (core + two neutrons) in resonating group approximation with single nucleon-nucleon potential, not producing bound two-neutron system and assuring good enough matter and proton r.m.s. radius for core nuclei. In such a case it appears the halo effect, but it is not so large as in the three point-particle approximation.

References.
P-N INTERACTION AND MASSES OF NUCLEI WITH $Z > N$

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It is well established now that the values of many physical qualities, for example $E_{2s}$, $E_{21} / E_{22}$, $B(E2)_{0+} - 21^+$ which characterize the collectivity of nuclei are changing in a smooth and monotonous way with the product of valence nuclei $N_pN_n$ taken as a measure of the integral quadrupole p-n interaction.

It is customary to present the nuclei masses calculated in macroscopic-microscopic model as a sum of two components: the macroscopic one which is based on the concept of deformed liquid drop and the microscopic one, which takes into account the nonuniform distribution of single-particle levels in the nucleus. If one calculates the macroscopic component ($M_{\text{spk}}$) of nuclear mass using the assumption that the nucleus is spherical than the residual part ($M_{\text{res}}$) of the full mass ($M$) is equal to $M - M_{\text{spk}}$. It was suggested in [1] that ($M_{\text{res}}$) depends on the quadrupole p-n interaction. We used this suggestion to calculate the masses $M(Z, N)$ of nuclei with $Z > N$.

In the case of mirror nuclei $(Z, N)$ and $(N, Z)$ (the first figure in brackets stands for the number of protons) the values of $N_pN_n$ are equal and it follows that the ($M_{\text{res}}$) values for mirror nuclei are equal as well and hence $M(Z, N) = M(N, Z)_{\text{exp}} - M_{\text{spk}}(N, Z) + M_{\text{spk}}(Z, N)$, where $M(N, Z)_{\text{exp}}$ is the full mass value of initial nucleus measured in an experiment. The values of $M_{\text{spk}}$ were derived using the expression for $M_{\text{spk}}$ given by Möller et al. in [2]. A total of 494 mass values of nuclei with $Z > N$ calculated in different approaches are prescribed in the update summary of calculated and experimental masses [2]. For the lack of the evidence on $M(Z, N)_{\text{exp}}$ values for some nuclei the values of $M(Z, N)$ in our approach were calculated only for 451 nuclei.

We calculated root mean square deviations ($\delta$) which characterize the discrepancies between theoretical mass values established in various works and experimental ones known for 95 nuclei. The approaches may be classified under two groups. The agreement with experiment in the first group ($\delta = 0.18 \pm 0.32$ MeV) is much better than for approaches of the second group ($\delta = 0.9 \pm 1.5$ MeV).

The $\delta$ values calculated using our results and the results given by Möller et al. in [2] amount 0.31 and 1.24 MeV, correspondingly. Hence it follows that the application of our approach essentially improves mass values prescriptions for nuclei with $Z > N$ comparing the data reported in the initial macroscopic-microscopic model [2].

All approaches belonging to the first group share the common property that they use one or another relation linking the mass of initial nucleus known from the experiment and the mass of the mirror nucleus with $Z > N$. 

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It is essential, that the division of different approaches into two groups is preserved if the values $M(Z, N)$ calculated in different works are compared not with experimental masses but between themselves. The $\delta$-values calculated for the same 95 nuclei mentioned above lie in the range $0.1 \div 0.4$ MeV when either two approaches belonging to the first group are compared and they turn out in the range $0.9 \div 1.6$ MeV when first group approaches are compared with any one approach belonging to the second group.

To trace the dynamics of differences between $M(Z, N)$ values obtained in different approaches we calculated $\delta$-values taking into consideration all nuclei for which in [2] along with $M(Z, N)$ values calculated in different approaches the $M(Z, N)_{exp}$ values are given too. The division of all approaches into two groups and their composition remained unchanged. The values of $\delta$ which characterize the discrepancy of mass values derived in different approaches belonging to the first group did not exceed 0.6 MeV. In particular the $\delta$-values obtained by comparing mass values calculated in our approach and ones calculated by Pape and Antony [2] and by Comay et al. [2] amount 0.3 and 0.4 MeV correspondingly. At the same time $\delta$-values exceed 1 MeV if a similar comparison is made in the case of approaches belonging to the second group. The foregoing allow us to consider the approaches of the first group (namely Comay et al. [2], Jänecke and Masson [2], Pape and Antony [2] and our approach) as the best suited to predict the masses of nuclei with $Z > N$. The use of above mentioned approaches significantly reduce the mass values scatter for nuclei with $Z > N$ listed in [2].

References
THE MICROSCOPIC STUDY OF THE MULTINEUTRON $^{12}$Li SYSTEM.

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Recently, a new approach has been developed to describe loosely bound nucleon systems /1/ which allows one to take account of closed cluster channels. Using this approach, the microscopic calculation of the $^{14}$Li isotope has been carried out to examine its radial matter density far from center of mass. The matter density was found to have a long tail which accounts for the anomalously large r.m.s. radius. It is revealed that the amplitude of that halo effect becomes more intensive as the number of particles increases. This property stimulates the study of heavier nucleon systems.

The present work is aimed at the microscopic study of the nearby isotope $^{12}$Li. But the existence of intensive neutron halo in $^{14}$Li create an entirely new situation. If we add one more neutron to this system, indeed, we can think of this long-tail density as a source of long-ranged effective potential for the excessive neutron. This can lead to an existence of quasi-stationary states of $^{14}$Li, which are characterized by even more intensive neutron halo than $^{14}$Li core itself.

To tackle the problem, we first treat and develop the ground approximation of the hyperspherical harmonic method. In terms of this approximation, there are two unclosed shells, represented by one proton in P-shell and one neutron in SD-shell. Due to the strong spin-orbit splitting, orbitals with maximum possible moment J dominate in a ground state of such a system (J=3/2 for proton and J=5/2 for neutron). Using linear combinations of the ground harmonics with these single particle states, we determine the quantum number $J^{\pi}$ of the lowest level of $^{12}$Li. The central, spin-orbit and tensor components of the realistic NN-potential are taken into consideration.

In the framework of the sawing procedure, developed in ref. /3/, we then evaluate the admixture of cluster channel $^{14}$Li+n.

References
Production of $\Lambda$ Hypernuclei with a Large Neutron Excess

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We discuss the strange and double charge exchange ($S&DCX$): ($K^-, \pi^+$) reaction as a source of the neutron rich nuclei.

At present hypernuclei are widely produced in the controlled way by a simple strangeness exchange reaction

$$K^- + n \rightarrow \Lambda + \pi^-,$$

$$A^+Z(K^-, \pi^-)A^+Z.$$

The missing mass spectrum of emitted pions (at a fixed angle) was recognized as a convincing signature of hypernucleus production.

There are many examples of the stabilizing role of the $\Lambda$ hyperon:

- stable hypernuclei with unstable nuclear core: $^5_Hc = s_A * ^5Hc$.
- bound excited state of $\Lambda$-hypernuclei with particle unstable nuclear core:

$$\Lambda^+Li(5/2^+; 2.02MeV) = s_A * ^6Li(3^+0; 2.2MeV).$$

A substantial progress in the hypernuclear physics is expected in the nearest future when new facilities such as KAON (Canada), CEBAF (USA), and $\phi$-factory DAΦNE (Italy) start to operate. Then it will be possible to study more complicated reactions, for example, two step strangeness and double charge exchange reaction. There are two paths how to arrive at the $\Lambda np^{-2}$ state: either

$$K^- + p \rightarrow \Lambda + \pi^0; \quad \pi^0 + p \rightarrow n + \pi^+,$$

or

$$K^- + p \rightarrow \pi^+ + \Sigma^-; \quad \Sigma^- + p \rightarrow n + \Lambda.$$

We see that in a process of this type one may produce a hypernucleus with a large neutron excess.

One can estimate the binding energy ($B_\Lambda$) of the new hypernuclei easily. As the dependence of $B_\Lambda(A)$ is very smooth, it is sufficient to extrapolate the experimental data. The net result is presented as a chart of hypernuclei (see below).

Few comments are in order:

1. All $\Lambda$-hypernuclei produced in a $S&DCX$ reaction (marked by $\blacklozenge$) are new.
2. The possibility of production of very HEAVY HYPERHYDROGEN isotopes $^8H$ and $^9H$ is also predicted.
Chart of light Λ hypernuclei with binding energies $B_\Lambda$ and particle instability thresholds.

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THE STRUCTURE OF FEW-BARYON SYSTEMS IN THE CHIRAL SOLITON MODEL

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In the low-energy region of quantum chromodynamics, effective chiral Lagrangians put at the disposal of theoreticians "convenient" colorless degrees of freedom bosonic fields for describing events in strong-interaction physics. Although the use of chiral Lagrangians is usually restricted to the semiclassical approximation, the success attained by the Skyrme model in the last few years in describing nucleons as quantum states of chiral solitons provides justification for using it or generalizations of it in nuclear physics.

It is important to develop a nuclear model of chiral solitons using a formalism and, even more importantly, variables which are the same as these used in the current nonlinear field theory of nucleons.

The construction of a nuclear model of chiral solitons is also important in connection with existing and projected experimental programs to study the structure of light nuclei far from the $\beta$-stability line. The Skyrme model stresses the uniqueness of the structure of each individual nucleus, in contrast to potential models. The Skyrme model gives a new view of such problems as the existence of compound nuclear states involving antinucleons in their structure, shape isomers, and high-lying $0^+$ vibrations in light nuclei [1], [2],[3].

It is also important to develop variational approaches to solving the nonlinear problems which arise. The variational approach to understanding the physics of various phenomena requires considerably less time for numerical calculations than the direct search for solutions, even when supercomputers are used. The exclusivity of each individual state in the chiral soliton model is also emphasized by the strong dependence of the effective quantum Hamiltonian on the topological sector. Not only the inertial parameters of the effective Hamiltonian, which are functionals of the solutions in a given sector, but also the actual form of the effective Hamiltonian depend on the baryon number. Here we should point out the difficulty with the overbinding of states with the quantum numbers of the lightest nuclei. It should also be noted that reproduction of the details of the electromagnetic form factors obviously requires studies with generalized Skyrme models including the additional scalar (dilaton and gauge vector fields of a hidden symmetry), although the Skyrme model already qualitatively reproduces the existing experimental data on such details as the deuteron polarization tensor in electron-deuteron scattering.

It seems to us that the model of chiral-field solitons will be a useful tool in the future theory of light nuclei which will allow the study of the familiar problems of the theory of few-particle systems from a completely new point of view. And a new view of a problem implies new solutions.

References

ELASTIC SCATTERING OF $^{11}\text{Li} (29 \text{ MeV/N})$ ON $^{28}\text{Si}$


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The elastic scattering of a secondary $^{11}\text{Li}$ beam (29 MeV/N) on a $^{28}\text{Si}$ target has been measured for the first time and compared with elastic scattering of $^{7}\text{Li}$ (25.4 MeV/N) beam on the same target [1].

The measured angular distributions for $^{7}\text{Li}$ is in qualitative agreement with measurements at lower energies. However, for the case of $^{11}\text{Li}$ the behaviour of experimental data is quite unusual - the ratio $\sigma/\sigma_R$ is almost constant in the measured angular range. It lies higher than that observed in elastic scattering of the weakly-bound nuclei $^6\text{Li}$ [2] and $^9\text{Be}$ [3] on $^{28}\text{Si}$ at approximately the same relative energies.

The analysis of elastic scattering of $^{7,11}\text{Li}$ was carried out in the framework of optical model. As the inelastic events have not been resolved by the detection system, the estimation of the inelastic cross section for the excitation of the $2^+$ (1.78 MeV) state in $^{28}\text{Si}$ (made in the framework of DWBA) was added incoherently to the elastic one. From the calculations it follows that the contribution due to inelastic processes may be important at the end of the measured angular range.

The $^{7}\text{Li}$ experimental data can be described very well using usual optical potentials [5].

In the case of $^{11}\text{Li}$ the situation is different. In fig.1 the elastic cross section of $^{11}\text{Li}$ (dotted line), calculated with the optical potential from global parametrization [4], is shown. Better agreement can be obtained only using an anomalously large value of surface diffuseness of the real part of the optical potential (long-dashed line). The contribution from inelastic scattering is shown by the short-dashed line and the total cross section by the solid line. The unusual large value of surface diffuseness of the real part is apparently a reflection of the "neutron halo" in the $^{11}\text{Li}$ density distribution.

The coupled channel (CC) optical potential was calculated in the semimicroscopic double folding model using the density and energy dependent effective interaction (DDM 3Y). The nuclear density was constructed by standard Hartree-Fock calculation using Skyrme II parametrization of the effective interaction or taken from Bertsch et al. [3] for the "halo" density. As can be seen in fig. 2 significant differences appear by using different density distributions for $^{11}\text{Li}$. At practically the same normalization of the effective interaction and at the same total reaction cross section, the halo density reproduces better the data than the no halo density.

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References:
Elastic scattering of exotic nuclei on proton and nuclear targets within the frameworks of various theoretical approaches.

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S.Yu.Shmakov and V.V.Uzhinski
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The recent progress in the light radioactive beam technique provides unique possibilities to study the nuclear structure near the neutron drip line. The $^{11}$Li nucleus is partially interesting, the existence of a neutron halo having been experimentally proved. Apparently, the $^6$He nucleus is another candidate for a neutron halo nucleus which has properties similar to $^{11}$Li (abnormally large electromagnetic dissociation cross section, a very large radius in the nuclear scale, twofold component momentum distribution of $\alpha$-particles for fragmentation of $^6$He on light targets [1]).

The experimental studies of the $^{11}$Li + $p$ [2] and $^{11}$Li + $^{28}$Si [3] elastic scattering are in the very beginning, experiments of the $^6$He + $p$ elastic scattering are also in progress. These studies will certainly probe the extension of the halo, but being a highly integrated (inclusive) observable, elastic scattering may not carry much information on the detailed halo-structure of the exotic nuclei such as $^{11}$Li.

Detailed information on the structure of these weakly-bound states can be extracted from one- or two-nucleon transfer reaction (see, for example, [4]). But, discussions of the latter made in standard theoretical approaches rely on elastic channel information for their optical potentials. The main ingredient in the conventional treatment of elastic scattering is the single particle densities evaluated in some nuclear models.

Details of the $^{11}$Li density are still somewhat a matter of debate. The situation is more clear-cut for $^6$He, also a halo-like nucleus. Contrary to $^{11}$Li the existing experimental data for N-N and N-$\alpha$ scattering allow us to extract the corresponding potentials and hence we can calculate reasonably correct wave functions for the system N+N+$\alpha$ in the framework of the microscopic three-body approach [5]. In ref. [6] the calculated wave functions and corresponding densities were tested against a variety of weak and electromagnetic data as well as nucleon- induced quasielastic reactions $(p,p')$, $(n,p)$ and $(p,n)$ on $^6$Li as a target. An additional possibility to test the resulting wave functions is to compare $^6$Li and $^6$He elastic scattering on proton and nucleus targets; the structures of these nuclei are comparable in a global sense (in the framework of a three-body model) but differ in the correlations of the extra nucleons which may be examined experimentally. Therefore, we carried out a comparative analysis of elastic scattering of $^6$Li and $^6$He, $^{11}$Li and $^{12}$C on proton and nucleus targets at intermediate energies within the frameworks of various level theoretical models – from phenomenological optical
model analysis to microscopic Glauber calculations using methods elaborated in [7, 8]. The main aim of this paper is to describe the theoretical procedures and to discuss the effect of the halo-like structure of $^6$He and $^{11}$Li on elastic scattering.

References

CROSS-SECTION MEASURMENTS OF \textsuperscript{6}He-INDUCED FISSION OF BISMUTH

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Experiments with the use of secondary radioactive beams allow one to investigate atomic nuclear structure near the neutron and proton drip-lines. In particular, at present, a series of experiments on studying the properties of neutron-rich nuclei such as \( ^{6,8}{\text{He}}, ^{11}{\text{Li}}, ^{11,14}{\text{Be}}, ^{17}{\text{B}} \) has been carried out. Furthermore, the available intensities of secondary radioactive beams allow one to study the properties of exotic nuclei using for this purpose nuclear reactions on such beams. Up to now experiments on measuring total interaction cross-sections \cite{1} and also on elastic scattering of the exotic nuclei \( ^{6}{\text{He}}, ^{9}{\text{Li}} \) \cite{2} and \( ^{11}{\text{Li}} \) \cite{3} have been carried out.

In spite of numerous data about neutron-rich \( ^{4,6}{\text{He}} \) isotopes at present there is no unambiguous opinion concerning the existence of a neutron halo in \( ^{6,8}{\text{He}} \) nuclei. So, on the one hand, there is an assumption that in a \( ^{6}{\text{He}} \) nucleus there are a \( ^{4}{\text{He}} \) core and two neutrons \cite{4}. On the other hand, there is an assumption about the existence in \( ^{4,6}{\text{He}} \) of a neutron skin \cite{5}. Irrespective of model considerations, estimates show that for the \( ^{6}{\text{He}} \) nucleus a difference of 1 fm should exist in the mean-root-square radii of neutron and proton density distributions \cite{5}. The extended distribution of the neutron density and the excitation of a soft mode in the \( ^{6}{\text{He}} \) nucleus can lead to a decrease in the fusion barrier and, as a consequence, to an increase in the fusion cross-section near the Coulomb barrier. The much higher value of the angular momentum involved in the \( ^{209}{\text{Bi}} \) interaction with the \( ^{6}{\text{He}} \) nucleus in comparison with \( ^{4}{\text{He}} \) also can lead to a change of the fusion cross-section value, which in its turn affects the fissility of the compound nucleus. On the other hand, the relatively low value of the separation energy of the last two neutrons \( (S_{2n} \cong 0.97\text{MeV}) \) for \( ^{6}{\text{He}} \) can lead to its break up in the field of the target nucleus thus reducing the fusion cross-section.

From this point of view the investigation of fusion cross-sections and heavy nuclei fission using a \( ^{6}{\text{He}} \)-beam is of interest.

In the present work, cross-sections for the fission of \( ^{209}{\text{Bi}} \) induced by a secondary beam of \( ^{6}{\text{He}} \) and by \( ^{4}{\text{He}} \) are measured in analogous conditions. The \( ^{6}{\text{He}} \) beam was produced in the \( ^{11}{\text{B}} (20\text{MeV/A}) \)-primary beam interaction with a thick rotating tantalum target \cite{2}. The produced \( ^{6}{\text{He}} \) nuclei were separated from the other reaction products with the help of dipole magnets. The use of an aluminium degrader \( (100\mu) \) in the focal plane between the two dipoles allows one to get a relative purity of 95\% of \( ^{6}{\text{He}} \) with an intensity of about 250-300 pps. The \( ^{6}{\text{He}} \) beam with an energy of 56 MeV, having an energy spread of 2.5\%, irradiated a stack of bismuth targets separated by mylar detectors for fission fragment registration and by aluminium absorbers for degrading the energy of \( ^{6}{\text{He}} \). The \( ^{209}{\text{Bi}} \) targets were prepared by vacuum metal deposition on Al backing. The uranium contamination in such a target assembly was less than \( 10^{-7} \text{ atom/atom} \).

In the figure, the fission cross-sections measured in the reactions \( ^{4,6}{\text{He}} + ^{209}{\text{Bi}} \) are presented. Solid lines are drawn to guide the eye. For the case \( ^{4}{\text{He}} \), open square present data taken from ref.\cite{6}, stars are data obtained in the present work.
It is seen from the figure that there is a good agreement of the measured data on fission cross sections with literature values [6] in the case of fission induced by α-particles. The data obtained in the present work for $^6He$-induced fission are shown by black squares. It can be seen that the measured cross sections of the fission of $^{209}Bi$ induced by $^6He$ are significantly higher than the corresponding α-particle-induced fission cross-sections. The analysis of the observed effect on the basis of different approaches is also given.

References


4. M.V.Zhukov et al. Ibid. ref.2, p.84.


New perspectives in Nuclear structure studies with secondary isomeric heavy ion beams at intermediate energies.


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ABSTRACT

With the advent of new technologies, the feasibility of exotic heavy ion beams is now available and offers the opportunity to better understand nuclear structure far from stability. While fragmentation processes are used extensively to construct these exotic heavy ion beams (1), transfer reactions can also be used experimentally to produce such nuclei (2). Furthermore, with these last mechanisms, it is possible, using spin and isospin selection rules, to obtain isomeric heavy ion beams with high spin. Presently, our group is working on such an experiment which will be performed at the GANIL facility in March 1993.

The main idea is to produce an isomeric beam of $^{42}$Sc via the transfer of a neutron-proton pair to a $^{40}$Ca projectile at 30, 20 MeV/u. Three targets will be used, namely $^3$He, $^4$He and $^{12}$C. The two last targets, because of zero isospin, must yield the isomeric state while $^3$He target will favor the production of $^{42}$Sc in its ground state. In order to select and collect these nuclei, the 0° spectrometer LISE (3) will be used. Results of this experiment will be presented and discussed. Future investigations, depending on the success of this experiment, will be also presented.

References:

(1): The SISSI Project. Preprint GANIL.

(2): J.L. Uzureau and al.. Experience proposal GANIL E199.

ISOMER BEAMS: SPIN AND EXCITATION OF THE HOT PREFRAGMENTS

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Production rates of various PLF nuclei in their isomer and ground states are measured using fragment separator A1200 at the NSCL. The results of the model calculation interpreting the observed ratio of isomer to ground state population are reported here. Geometric model is used to describe primary fragment distribution. For the specific projectile-target combination the number of nucleons removed from the projectile and target, as well as production cross section is determined by impact parameter that defines the "participator" zone. The model gives geometrically defined prefragments where part of the projectile and target nucleons keep on moving almost undisturbed with their initial velocities. The nucleon orbits in prefragments may be considered in a diabatic picture as orbits that do not adopt to the specific deformation.

The ensemble of prefragment nucleons may be then characterized by spin value and an excitation energy, that may be determined from shell model considerations. Prefragment spin value $J$ is given by $J^2 = J^2_G$, where $J^2$ is an average quadratic spin of the nucleon in the nucleus, and $G=A(A_p-A)/(A_p-1)$ is the Goldhaber factor. Prefragment excitation is determined as $E_x = E_h$, where $E=\text{average energy per hole in the relevant energy domain}$, and $h$ is the number of holes produced in the reaction by vacation of the single particle levels. Statistical model calculations were used to determine the population of the isomer and ground states at the final fragment distribution. The results of the model calculations are presented and compared to the experimental observation. Model calculations are sensitive to the modelling of prefragment spin and excitation. This feature is used to deduce prefragment spin and excitation from the measured production cross-sections and relative populations of the isomer states.

SPECTROSCOPY OF NEUTRON-RICH NUCLEI BY USE OF RADIOACTIVE BEAM

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Abstract

Recent theoretical calculations and experimental results were used to highlight the present-day interest in secondary radioactive beams.

Spectroscopy of fission-fragments, structure of neutron halo nuclei, formation of thick neutron skin, Coulomb dissociation of $^{11}$Li and $^{11}$Be are also present.

Several qualitative features of Radioactive Ion Beams nuclear science make it very exciting: Access to extend isochains of nuclei, versatility to study specific exotic orbits, possibility to obtain access to special nuclear region, access to exotic matter distributions at extreme N/Z ratios, opportunity to observe higher spin states than usually studies, opportunity to obtain new features in nuclear reactions.

The important results obtained for the PYGMY resonance and fusion reaction of a nucleus with a neutron halo are discussed.

It is predicted that the fusion barrier is reduced to the extended neutron halo. It may thus provide the enhanced cross section to the super heavy elements and cluster radioactivity.

A brief review is presented of recent efforts that have led to an improvement of our knowledge of astrophysical studies with neutron-rich nuclei. The construction and characteristics of a Recoil Mass Spectrometer (RMS) for the Institute of Atomic Physics (fig. 1) are described. The question that can be addressed by use of RMS are also discussed.
$^{16}_{\text{O}}(\text{argon}) + ^{27}_{\text{Al}} \rightarrow ^{40}_{\text{X}}$

$O_1(\text{PA}) \rightarrow B=0.89\text{Kg}$  $O_2(\text{M}) \rightarrow B=1.02\text{Kg}$  $WF$  $B=4.0\text{Kg} U=72\text{Kv} (136\text{Kv})$

$DM$  $B=57\text{Kg}$  $O_3(\text{HV})$  $O_4(\text{HV})$  $O_5(\text{HV})$  $B=0.0$

Fig.1
Previous work on reaction mechanism in light nuclear systems, in the energy range 4-10 MeV/n, suggested that a significant contribution to the nonfusion cross-section could be related to the deep inelastic collisions. One of the basic assumptions concerning the deep inelastic process is the two-body character of the interaction. However recently it was shown that three-body final state processes turned out to be important at bombarding energies close to 125 MeV for the $^7$Li($^3$He, X) reaction. It was suggested on the basis of kinematic considerations, together with analysis of the inclusive energy spectra of reaction products, that the mechanism responsible for interaction is the direct breakup process in the present work, an evidence for three-body final state breakup, in the reaction $^{27}$Al($^3$He, X) at 116 MeV bombarding energy, is presented. The experiment was performed at the Kiev І-240 cyclotron, which produced a $^{14}$N beam at 116 MeV. Self supported $^{27}$Al foils 470 µg/cm² thick, were used as targets. In the aim to facilitate the monitoring, a thin gold layer (~ 10 µg/cm²) was deposited by vacuum evaporation on the aluminum foils. The thickness of the gold layer was determined by using the scattering of a 50 MeV $^{16}$O beam, at the Bucharest FN Tandem accelerator. The thickness of the target was checked, by measuring the energy loss of alpha particles. The reaction products with charges ranging between 3 and 13 were identified by use of $\Delta E$-E detectors filled with high purity Krypton at pressures 100-150 mbars. These detectors were operated in closed circuit. Typical resolutions of 60 KeV were obtained for the ionization part of the detector for alpha particles stopping in the gas. The E detector was a 1 mm Si surface barrier detector. The entrance window of the ionization chamber, consisted of mylar 2 µ thick. The $\Delta E$-E signals from the chamber, set in coincidence were recorded as bidimensional matrices by the aid of a SH-2 computer. Due to the high resolution of the detection system, good charge group separation was obtained. The inclusive angular distribution measurements were performed at angles between 15° and 50°, in steps of 2.5° up to 30°, and in steps of 5°, for the rest of angles. In Fig.1 it is shown a typical inclusive spectrum for the reaction product B measured at 15°, 17.5°, and 22.5°. The histograms represent the experimental data, compressed at about 1.5 MeV/channel. In order to improve the accuracy per channel. The solid curves in Fig.1 represent the three-body final-state calculations, using a formalism based on deuteron breakup model of Serber, and developed by Matsuoka et al., and by Tabor et al., for heavier systems. In this calculation it is assumed that the target behaves as a spectator during the interaction and only provides a field for projectile breakup. During the interaction, the target can be excited, but remains intact, while the projectile breaks up into 2 fragments, leaving a three body final state. In Fig.1 the arrows 1 and 2 indicate the beam velocity energies corresponding respectively to masses 10 and 11. The arrow 3 indicates the maximum energy corresponding to the two-body final state breakup, $^{14}$N+$^{27}$Al → $^{16}$O+$^{3}$p.
Fig. 1 shows a reasonable agreement of the three-body final state calculations with the experimental spectrum. An attempt to evaluate the contribution of the two-body final state breakup has led to a value less than 10%. Experiments performed on the same reaction but at lower bombarding energy, 62 MeV, show that the energy distributions of the reaction products are compatible with the predominance of a two-body final state process. The recent experiment performed at 55 MeV at Bucharest, supports entirely this view. It follows from these results that between 62 MeV and 116 MeV, there should be a transition with rising energy, from predominant two-body final state processes to predominant three-body final state processes. It would be certainly of interest to check experimentally this tendency, by measuring this reaction at additional energies. The measured angular distributions for Li to C products were integrated to yield the total breakup cross-section. This cross-section was then added to the fusion cross-section, estimated by Glass and Mosel calculations. This fusion + breakup cross-section was compared with an estimate for the total reaction cross-section obtained by an optical model calculation, using the program Genoa. From this comparison resulted that the points at 55 and 116 MeV do not reach the limit imposed by the optical model. This is understood because in the product cross-section are not included inelastic cross-sections, and cross-sections for heavier products O-Al. Another point is the dramatic increase of the cross-section for the charged groups in passing from 55 MeV to 116 MeV. (see fig. 2)

References
2 V. V. Volkov, Yadernie Reaktsii Glubokoveprugih Peredach, Energoizdat, Moscow, 1982
4 R. Serber, Phys. Rev. 72, 1008 (1947)
CORRELATION OF PARTIAL WAVES IN DEEP INELASTIC REACTIONS
AND FISSION

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Semi classical theory of cross section of inelastic nuclear reaction is considered. Particular attention is paid to correlation of partial amplitudes both in the entrance and exit states as providing quantum mechanical formulation of macroscopic features in such processes as direct nuclear reaction and nuclear fission. For deep inelastic processes this coherency is represented by statistical correlation functions of quantum mechanical amplitudes. Quantum mechanical helicity representation for the reaction amplitude is used. Relationship between quantal helicity and analogous macroscopic quantities is discussed and some effects related to quantum mechanical dispersion of helicity are indicated.
TOWARDS THE NEW MODEL OF NUCLEAR FUSION

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The generalized virial theorem method is applied to the study of nuclear fusion. Starting with the kinetic equation for the distribution function in the phase-space of a nucleon, a closed set of equations is obtained describing in a classical way the process of fusion. This is achieved by making simplifying assumptions of the following nature: i) restrictions are imposed on the shapes and collective flow of the composite system; ii) the nuclear mean field is assumed at each moment to be the same as in the equilibrated nuclear matter; iii) the collective motion energy dissipation is described through a collision term issuing from a mean relaxation time approximation. The theory is applied to the fusion of two identical spherical nuclei experiencing the head-on collision. It shows in particular that the Fermi-surface deformation affects both the force driving the system to the equilibrium and its dissipative properties.
Evaporation Residues from Complete and Incomplete Fusion of $^{20}$Ne with $^{197}$Au and $^{208}$Pb at E/A = 8.6 to 15.0 MeV/u

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Nuclear fusion reactions at bombarding energies above 10 MeV/u are characterized by a gradual transition from complete to incomplete momentum transfer. A large quantity of data is present for fusion-fission reactions or for "light" compound nuclei, while the information on the production of evaporation residues from "heavy" composite systems (A > 200) were rather scarce up to now.

We present results from recent experiments aimed to investigate velocity distributions and formation cross sections of residues from fusion-like reactions of $^{20}$Ne + $^{197}$Au, $^{208}$Pb at bombarding energies between 8.6 and 15 MeV/u. After separation from the projectile beam by the velocity filter SHIP, the evaporation residues were implanted into semiconductor detectors and identified by means of α-spectroscopy. Velocity distributions were measured at SHIP by varying the ratio of the electric field strength E to the magnetic field strength B.

For both target-projectile combinations we observed at all bombarding energies reaction products having mean velocities systematically smaller than the compound-nucleus velocity $v_{\text{cw}} = (m_{\text{proj}}/m_{\text{cw}}) \times v_{\text{proj}}$. The mean velocities decrease with increasing beam energy, while at a specific energy a "fine structure" is evident: The mean velocities of the reaction products depend on their masses. Heavier residues tend to have lower mean velocities (fig. 1). Qualitatively this behavior can be understood by the emission of preequilibrium particles, emitted in forward direction with velocities close to the projectile velocity. The intensity of the slower component observed for $^{20}$Ne + $^{197}$Au at E/A = 11.4 MeV/u, however, is lower than expected from the intensity of the preequilibrium particles measured by Fuchs et al. /1/ for the same system. Therefore we assume, that preequilibrium particle emission is closely connected to high angular momenta, for which the survival probability of heavy compound nuclei is low due to vanishing fission barriers.

For two systems, $^{20}$Ne + $^{208}$Pb at E/A = 8.6 and 11.4 MeV/u, we observed an additional residue component with a velocity distribution peaking around half of the compound-nucleus velocity. Preliminary we assign it to residues from fusion after a break-up of the projectile into massive fragments (fig. 2).
Our measured evaporation residue cross sections are several orders of magnitude higher than expected from pure statistical model calculations. The enhanced stability of the nuclei is possibly due to reduced fission probability at high excitation energies.


Fig. 1 Mean velocities of evaporation residues as a function of their masses for $^{20}$Ne + $^{197}$Au at $E/A = 14.9$ MeV/u

Fig. 2 Measured velocity distribution of $^{212}$Rn observed for $^{20}$Ne + $^{208}$Pb at $E/A = 8.8$ MeV/u (preliminary data)
ENERGETIC PARTICLE EMISSION IN THE
^{16}\text{O} - \text{INDUCED REACTION ON } ^{27}\text{Al} \text{ at } E/A = 19.3 \text{ MeV}

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In the past decade light particle energy spectra have been intensively studied in inclusive and (semi)-exclusive heavy ion reactions [1] in the intermediate energy region (10 < E < 100 MeV/u). The present experimental information is consistent with the concept of statistical particle emission from highly excited subsets of nucleons which are in the process of equilibration with the remaining composite system. Besides sequential emission from target-like and projectile-like sources, the existence of non-equilibrium emission has been observed. However, little is known about the relative importance of dynamical and statistical aspects of the reactions which should reflect the interplay of the collective motion in the mean nuclear field and the randomization of the particle velocities by individual nucleon-nucleon collisions. The relative importance of these effects is expected to change dramatically in the transition energy regime where the relative velocity between projectile and target nuclei is of magnitude comparable to the Fermi velocity. It is expected that these effects can be revealed in the emission of more energetic light particles (p, d, t, a) in ^{16}\text{O}-induced reactions on an Al target at an incident energy of 310 MeV.

Fig. 1
The high intensity (10^{12} - 10^{13} ppa) beams at the U-400 isochronous cyclotron make it possible to study these effects. In the present paper we present the first experiments intended
to observe light particle emission using the beams of the U-40C cyclotron.

The measurements were carried out using a 19.3 MeV/u $^{16}O$-beam with an average current of 100 particle nA, which bombarded an Al target with density of 5.4mg/cm$^2$. In this experiment, to detect the light particles we used a plastic scintillator range-telescope. The telescope was placed outside a vacuum scattering chamber at $\theta_{lab} = 30^\circ$ in the horizontal plane and covered a solid angle of 8 mrad.

The telescope consists of 12 plastic scintillators with increasing thickness and area. It allows to detect protons up to 200 MeV. Light particles were separated by means of $E - \Delta E(E)$ correlation and time-of-flight. The energy losses in all counters and the time-of-flight were measured for all the outgoing particles. Common analysis of time-of-flight, total energy and energy losses for each event allows to quite reliably identify the outgoing charged particles and to determine their energy. Fig.1 shows an example of the $E - \Delta E$ distribution measured with the telescope in the $^{16}O$-induced reaction on $^{27}Al$. One can see quite reliable separation of light particles.

The high energy parts of the energy spectra for protons, deuterons and tritons are presented on fig.2. Light particles with such a high energy have not been observed earlier in the same reaction [2].

![Fig.2](image)

At present attempts are in progress aimed to study in greater detail this interesting phenomenon.

References:
The two-mode theory of DWBA in which direct and exchange processes are included, has been shown to be a significant improvement for certain reactions over a one-mode treatment where there is use of only the direct transitions. Direct processes normally have their strength at forward scattering angles and fall off rapidly at larger angles. Exchange processes normally have angular distributions which are flat or backward peaked. Failure of direct calculation to reproduce the magnitude of back angle data can thus be a clue that exchange mechanisms might be making significant contributions.

In the studies of the elastic scattering of heavy ions such as \(^{12}\text{C} + ^{13}\text{C}\) with \(^{12}\text{C}\) as identical cores, the exchange process is as multiple transfer of the valence neutron between the cores during the collision. The folding model calculations for \(^{12}\text{C} + ^{13}\text{C}\) elastic scattering with full recoil and exchange contributions for \(L=0\) and \(L=0,1\) are shown in FIG 1. Purely exchange contributions shown between 90° to 180° by dotted curve for \(L=0\) and dot-dash curve for \(L=1\) separately. The total direct plus exchange contributions for \(L=0\) and \(L=0,1\) are shown by dashed and solid curves respectively. Here the contributions due to \(L=1\) seems to be important at back angles. For folding potentials, the model independent charge distribution of \(^{12}\text{C}\) is considered.

Further extension of this model for the treatment of the elastic scattering of heavy ions involving at least an unstable nucleus is considered [1]. In particular the projectile and the target are considered to be respectively composed of a neutron and a proton outside identical cores. Because of indistinguishability of nucleons, the elastic scattering cross section measured will contain in addition to scattering with no exchange of particles, the probability of the exchange of two identical cores and the contribution from the transformation of a neutron into a proton due to pion exchanges.

At energies close to the coulomb barrier, exchange amplitude may not simply comprise of a single exchange but could involve the pion exchange any number of times because the mass exchanged is very small relative to the mass of target or projectile, and the relative velocity between the colliding partners is extremely small at the classical distance of closest approach. Thus, one would expect that if the charge exchange between the heavy ions is of importance at all, it should manifest itself in the elastic scattering of isobars at projectile energies close to the coulomb barrier.

As an example, we consider the case of \(^{12}\text{C} + ^{13}\text{N}\) elastic scattering which may be useful to understand the energy dependence of the interference pattern of \(^{13}\text{C} (^{15}\text{N}, ^{12}\text{N}) ^{13}\text{C}\) reaction [2] around \(\theta=90°\) close to the coulomb barrier.
In many heavy ion collisions the folding model or DWBA does not include all the possible exchange contributions. In contrast the generator coordinate method (GCM), wherein the full antisymmetry of the problem is exploited (even for heavy nuclei) would automatically include the exchange processes. If GCM techniques is extended to include many channel effects as is done in light ion transfer reactions using realistic potential overlap [3] and modified to treat the collisions of heavy ions would provide a more accurate treatment of exchange effect. The above model is of particular current interest since collisions of mirror nuclei involving at least one unstable nucleus could be explored with new radioactive beam experiments and would provide a source for extracting effective nucleon-nucleon interaction.

LOW ENERGY HEAVY ION INTERACTION AND EXCHANGE EFFECTS

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The semimicroscopic approach (SMA) [1,2] to low energy heavy ion interaction is presented. The real optical potentials and the formfactors of the inelastic transition are constructed in a closed form on the basis of the effective nucleon-nucleon force. The single-nucleon exchange effects are taken into account in the local approximation of the density matrix formalism. The density matrix is taken in the modified Slater approximation with the account of the surface effects. It has been shown in the framework of the SMA that the role of the single-nucleon exchange effects is most important in the description of the rainbow scattering where both elastic and inelastic scattering data can be reproduced only with the explicit account of the Pauli principle [2,3].

In this work the SMA is generalized to take into account the isospin effects and the difference in proton and neutron matter distributions for both nucleus-projectile and nucleus-target. The real parts of the optical potentials have been calculated for the systems $^7\text{Li}+^{40}\text{Ca}$, $^7\text{Li}+^{44}\text{Ca}$, $^7\text{Li}+^{48}\text{Ca}$ by using the full finite-range effective M3Y interaction [4]. Both the isoscalar and isovector channels are under consideration. The energy dependence of the obtained interaction is studied for all cases. For the system $^7\text{Li}+^{48}\text{Ca}$ the influence of the neutron skin effect of the target-nucleus on the properties of the isospin part of the heavy ion interaction is investigated. It has been established that the exchange effects are essential in the surface region.

The possibilities of application of the SMA are considered to describe reactions with radioactive nuclear beams and interaction between exotic nuclei at low energies.

References
Incomplete fusion (mass transfer) of $^{20}$Ne with $^{165}$Ho is treated in the energy interval 20-40 MeV/A for projectile Ne. The number of nucleons transferred from the projectile to the target depends on to what measure nuclei are overlapped in momentum space, as it was presented in /1/. Three channels observed in experiments for the energy 30 MeV/A are obtained in the model. The number of emitted nucleons depends in a linear manner on velocity of light nucleus. The radial energy dissipation according to the window-formula is also treated, taking into consideration that only portion of all nucleons getting through the window, make contribution to the dissipation process /2/. For head-on collisions and for collisions with $l=87$ the energy dependence of ratio for transferred linear momentum to projectile’s linear momentum is calculated. It is shown that Viola parametrization for such heavy asymmetrical nuclei is not completely satisfied.

References
METHOD FOR CALCULATION OF YIELDS OF NEUTRON-RICH HEAVY NUCLEI IN INCOMPLETE FUSION REACTIONS

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To estimate the production cross sections of different nuclides we have to calculate primary isotope distribution and to obtain the final distribution taking into account particle evaporation. The evaporation process is calculated within the statistical code [1]. We take into account the emission of γ-rays, neutrons, protons, ²H, ³H, ³He, α-particles, and fission. After this two-step calculation we can compare theoretical and experimental results.

The experimental data had been obtained which demonstrated the influence of the shell effects on the multiple nucleon transfer process. The interpretation of this effect required the formulation of the microscopical model of the process. A variant of that approach has been suggested in [2].

Consider a dinuclear system after the relative motion kinetic energy damping. Let \( P_{Z,N}(t) \) be a probability to find the system at the moment \( t \) in the state with the mass \( A = N + Z \) and the charge \( Z \) of the light fragment. In [2] the master equation for \( P_{Z,N}(t) \) has been obtained.

\[
P_{Z,N}(t) = \Delta_{Z+1,N}^{(-0)} P_{Z+1,N}(t) + \Delta_{Z-1,N}^{(+0)} P_{Z-1,N} + \Delta_{Z,N+1}^{(0,+)} P_{Z,N+1}(t) + \Delta_{Z,N-1}^{(0,-)} P_{Z,N-1}(t)
\]

where the transport coefficients have been calculated microscopically. In this model the single-particle proton (index \( Z \)) and neutron (index \( N \)) transfers are considered.

Solving this equation we obtain the primary nuclides distribution which is in a good agreement with \( Q_{gs} \)-systematics. Due to this the following parameterization of isotope production probabilities can be used [3]

\[
p(i) \sim \exp \left[ \left( Q_{gs} - \delta + \Delta E_c \right)/\gamma_0 \right],
\]

where \( \Delta E_c \) is the change of the Coulomb interaction energy due to the charge transfer, \( \delta \) is the so-called "nonparing" energy correction, the parameter \( \gamma_0 \) characterizes the slope of the exponent. Therefore, the microscopic model gives exponent slope which is used in the further statistical evaporation calculations. The calculation results are presented in fig. 1.

The term incomplete-fusion reaction was suggested to reactions in which the major part of the projectile transfers to the target. We used "sum-rule" model which was suggested in [4] for calculating cross sections of yields fragments in transfer reactions. According to this model incomplete-fusion reactions are localized in successive \( l \)-windows above the critical angular momentum for a complete fusion, in a sequence beginning with the capture of the heaviest fragment of a projectile, followed by the capture of lighter fragments at higher angular momenta [4]. For the cut-off in angular momentum space a smooth cut-off is taken \( P_i = \{1 + \exp[\left( l - l_{crit} \right)/\Delta l]\}^{-1} \) to calculate \( l_{crit} \) use is made of the estimate [4].

The reaction probabilities \( p_i \) for all incomplete fusion reactions \( i \) are calculated, then this calculation is parametrized to the exponential factor, by variation of parameter \( \gamma_0 \). The angle-integrated cross section for a particular incomplete-fusion channel then is

\[
\sigma(i) = \pi \lambda^2 \sum_{l=0}^{l_{crit}} (2l+1) \gamma_0 \frac{p_i^R(i)}{\sum_{i}^R p_i^R(i)}
\]
where $T_l$ is the ordinary optical-model transmission coefficient, $l_{max}$ limiting the sum is defined as the largest angular momentum for which the colliding system gets into the region where total nucleus-nucleus potential is attractive.

The energy spectra of reaction products show the presence of deep inelastic and quasielastic components. So, we presented the excitation energies of primary heavy fragments as a superposition of two Gaussian distributions. One of these corresponds to energy distribution in quasielastic process, and the other - to deep inelastic one. The widths and relative contributions of these components are used as parameters. By means of random number the value excitation energy is performed. For different decay channels of the excited nucleus the maximum of residual energy is defined in the following way $E_{v}^{max} = E^* - E_r - E_v - V_i$; $E_{\gamma}^{max} = E^* - E_r - B_f$. Here $E^*$ is the excitation energy of the excited nucleus, $E_r$ is its rotational energy, $V_i$ is the exit Coulomb barrier for a particle of the kind $\nu$, $E_v$ is the kinetic energy of the particle, $B_f$ is the fission barrier. For all $E_{v}^{max} > 0$ the type of the emitted particle or $\gamma$-ray is drawn. For partial widths of the particle $\nu$ emission, for the fission and of the $\gamma$-quanta emission the expressions of [1] have been used. The disappearance of shell effects in the nuclear level density $\rho$ with increasing $E^*$ is accounted for in the framework of the Fermi-gas model using a phenomenological dependence [6].

The free parameters of the model used in the calculation are: parameter $\Delta_1$ of the angular momentum distribution and nuclear parameters $r_0$ of exit and entrance reaction channels. The results of calculations performed with realistic parameters' values are in agreement with experimental data on the production of some isotopes of heavy actinides (see fig.2).

**Fig.1** Calculated primary isotope yields as a function of $Q_{\gamma\gamma}$ are presented by solid signs. The results of approximation are presented by dashed lines.

**Fig.2** Calculated isotope distribution for Fm is presented by solid line. Experimental data are shown by solid dots [5].

References

CALCULATION OF EVAPORATION RESIDUE CROSS-SECTIONS IN THE REACTIONS $^{100}$Mo$+^{100}$Mo AND $^{110}$Pd$+^{110}$Pd ON THE BASIS OF THE MODEL OF COMPLETE FUSION AND QUASIFISSION COMPETITION

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By calculating the evaporation residue cross-sections $\sigma_{ER}(E)$ in the reactions $^{100}$Mo$+^{100}$Mo and $^{110}$Pd$+^{110}$Pd there have been taken into account: a) competition between complete fusion and quasifission for the initial dinuclear system (DNS); b) competition between fission and emission of light particles and $\gamma$-quanta at the compound nucleus de-excitation. The capture cross-section $\sigma_C(E)$ in both reactions has been calculated by the optical model, competition between complete fusion and quasifission - by our model. The compound nucleus de-excitation has been analyzed in the framework of the statistical model on the basis of the Monte-Carlo method.

Fig. 1. Calculated $\sigma_{CN}(E)$ for the reaction $^{110}$Pd$+^{110}$Pd in the framework of the optical model (dotted line), surface friction model (short dashed line), dynamical macroscopic model (long dashed line) and by using our model of complete fusion and quasifission competition (solid line).

Fig. 2. Calculated $\sigma_{ER}(E)$ for the reaction $^{110}$Pd$+^{110}$Pd in the framework of different models. The designations as in Fig. 1. The experimental data are denoted by solid squares.

In the figures the results of calculations $\sigma_{CN}(E)$ and $\sigma_{ER}(E)$ in the reaction $^{110}$Pd$+^{110}$Pd are presented. For the comparison the data calculated in the frame of the existing complete fusion models are given[2]. The formation of potential barrier $B_{fu}$ on the way to the compound nucleus and the competition between complete fusion and quasifission in the DNS lead to a sharp decrease of $\sigma_{CN}(E)$ in reactions between massive nuclei. The agreement between the calculation and the experimental data obtained while using our model of competition between complete fusion and quasifission indicates to the reality of interpretation of nucleus formation mechanism suggested in[3]. Just this interpretation is the basis of this model.

References
ANALYSIS OF MASSIVE NUCLEI FUSION IN THE FRAMEWORK OF EXISTING MODELS OF COMPLETE FUSION

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The complete fusion of massive nuclei is a sensitive test of the reality of our conceptus about the process of a compound nucleus formation in reactions induced by low-energy heavy ions. The calculation of evaporation residues cross-sections \( \sigma_{ER}(E) \) in the reactions \(^{100}\text{Mo}^+^{100}\text{Mo} \) and \(^{110}\text{Pd}^+^{110}\text{Pd} \) in the framework of existing models of complete fusion has been performed. Experimental data for these reactions have been obtained in[1]. The calculation of \( \sigma_{ER}(E) \) included: a) calculation of cross-section of compound nucleus production \( \sigma_{CN}(E) \), b) analysis of compound nucleus de-excitation. \( \sigma_{CN}(E) \) were calculated in the framework of the optical model[2], the model with surface friction[3], the dynamical macroscopic model[4]. The compound nucleus de-excitation has been analyzed in the framework of the statistical model with the use of the Monte-Carlo method[5]. The obtained results in comparison with experimental data[1] are presented in the figure. A dramatic discrepancy between the results of the calculation and the experimental data is seen, for the reaction \(^{110}\text{Pd}^+^{110}\text{Pd} \). The reason of this discrepancy is quasifission, which is a predominant channel of nuclear systems decay, formed in these reactions.

The competition between complete fusion and quasifission in the optical model and the model with surface friction is not taken into account. The dynamical macroscopic model takes into account the competition between different nuclear processes in the entrance reaction channel. However, in the calculations using this model the discrepancy with the experimental data in the reaction \(^{110}\text{Pd}^+^{110}\text{Pd} \) is about three orders of magnitude. Thus, one cannot succeed in describing the fusion of massive nuclei in the framework of existing complete fusion models.

Fig. Calculated \( \sigma_{ER}(E) \) for the reaction \(^{110}\text{Pd}^+^{110}\text{Pd} \) in the framework of optical model (dotted line), surface friction model (shot dashed line) and dynamical macroscopic model (long dashed line). The experimental data are presented by solid squares.

References

MODEL OF COMPETITION BETWEEN COMPLETE FUSION AND QUASIFISSION FOR MASSIVE SYMMETRIC DINUCLEAR SYSTEMS

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The analysis of complete fusion channel is performed on the basis of the concept of compound nucleus formation mechanism suggested in [1]. After the dissipation of the kinetic energy a dinuclear system (DNS) is formed. The complete fusion is the DNS evolution, during which all nucleons of one of the nuclei, are transferred shell by shell to another nucleus. Due to the shell structure the individuality of DNS nuclei is conserved all through their evolution to the compound nucleus. The DNS evolution is defined by the system potential energy as a function of its charged asymmetry and angular momentum of a collision – V(z,l). Fig.1 shows the potential energy of the DNS formed in the reactions: ¹⁰⁰Mo+¹⁰⁰Mo and ¹¹⁰Pd+¹¹⁰Pd. In calculations of V(z,l) there have been used the liquid-drop masses and the nucleus-nucleus potential which included the nuclear, Coulomb and centrifugal potentials:

\[ V(R) = V_N(R) + V_C(R) + V_I(R), \]

where R is the distance between the nuclei centres. The DNS was taken in the form of two spherical nuclei with overlapping surfaces. The distance between the nuclei centres in V(z,l) corresponds to the bottom of the "pocket" in potential V(R). The potential of nuclear interaction V_N(R) has been taken in the form of the folding potential [2]. In the Coulomb potential V_C(R) there has been taken into account the partial overlapping of the nuclei volume [3]. The centrifugal potential V_I(R) has been calculated for two sticking nuclei and a rigid body moment of inertia.

As seen from fig.1 the initial DNS in both reactions appears to be in the minimum of the potential energy formed a similitude of a giant nuclear molecule. For the fusion to occur the DNS on its way towards a compound nucleus has to "cross" via the maximum of the potential energy (the Businaro-Gallone point), i.e. to overcome the potential barrier. It is natural to call this barrier as a fusion barrier – B_fus. One should emphasise that the fusion barrier B_fus radically differs from the extra-extra push of the dynamic macroscopic model [4]. The extra-extra push is an additional kinetic energy above the Coulomb barrier due to which the system achieves a more compact form than that of a fissionable compound nucleus in the saddle point.

![Fig.1. Potential energy of the DNS in the reactions: ¹⁰⁰Mo+¹⁰⁰Mo (left part) and ¹¹⁰Pd+¹¹⁰Pd (right part). Atomic number of one of the DNS nuclei is indicated.](image-url)
The energy for overcoming the fusion barrier $B_{fu}$ is derived from the DNS excitation energy.

Usually, in quasi-fission asymmetric nuclear systems are considered [5]. In the reactions $^{100}$Mo+$^{100}$Mo and $^{110}$Pd+$^{110}$Pd the initial DNS just from the moment of their formation possess the symmetric form favourable for the decay. Therefore, for the analysis of the symmetric massive DNS decay, as it seems to us, one can use a sudden approximation. In this approximation the DNS while decaying has to overcome the potential barrier $B_{sf}$, due to the "pocket" existing in the interaction potential $V(R)$.

Fig. 2. Nucleus-nucleus potential $V(R)$ in the reactions: $^{100}$Mo+$^{100}$Mo (left part) and $^{110}$Pd+$^{110}$Pd (right part).

Fig. 2 presents the potential $V(R)$ for the systems $^{100}$Mo+$^{100}$Mo and $^{110}$Pd+$^{110}$Pd.

The thermal equilibrium (partial equilibrium) in the DNS is set rather quickly during few units per $10^{-22}$s therefore the statistical approach for the analysis of the competition between the complete fusion and quasifission can be applied. The probability for the DNS to go into the channel of the complete fusion or quasifission is determined by the DNS state densities on the tops of fusion and quasifission barriers. To describe the DNS state densities there has been used the expression suggested in [6]:

$$
A_i(E^*) = \left( \frac{g_i}{g_2} \right)^{1/2} \frac{q}{\sqrt{6j/4(2ge)^{3/4}}} \exp \left[ 2(aE^*)^{1/2} \right]
$$

where $i$: $B_{fu}$, $B_{sf}$; $g_1$ and $g_2$ are the densities of single-particle states near the Fermi surface for two DNS nuclei, $2g$ is the density of single-particle states for a compound nucleus. The ratio $\rho_{B_{fu}}/(\rho_{B_{fu}} + \rho_{B_{sf}})$ characterizes the quasifission probability, $\rho_{B_{fu}}/(\rho_{B_{fu}} + \rho_{B_{sf}})$ characterizes the probability of the complete fusion. By estimating the DNS excitation energy $-E^*$ we proceed from the data of work [7] where it has been shown that in quasifission in contrast to fission the light particles emission does not succeed in taking away a noticeable part of the system excitation energy, $E^* = E_{i}(c.m.) - V(a,l)$.

PARTITION OF EXCITATION ENERGY BETWEEN REACTION PRODUCTS IN HEAVY ION COLLISIONS

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The large value of kinetic energy losses is an inherent feature of deep inelastic heavy ion collisions. Originally, the results of several early experiments were consistent with the assumption of a very rapid establishment of the thermal equilibrium in a dinuclear system. In this case the excitation energy is divided approximately proportionally to the fragment masses. However, later experiments demonstrated that this assumption is not correct. Moreover, in reactions $^{52}$Cr+$^{208}$Pb [1], $^{238}$U+$^{124}$Sn, $^{110}$Pd [2] a large part of the excitation energy is concentrated on light fragments even for a large range of total energy losses. Nearly equal sharing of the excitation energy has been observed in reactions $^{56}$Fe+$^{168}$Ho [3] and $^{74}$Ge+$^{168}$Ho [4] for relatively large values of the total kinetic energy loss. With increasing total kinetic energy loss the division of the excitation energy approaches but never reaches the thermal equilibrium limit. Thus, these new experiments generated great interest in problem of kinetic energy dissipation.

It is clear that the structure of excited states in nuclei and magnitude of the coupling of different excitation modes with the relative motion influence the energy distribution between fragments. The main effect of the nuclear average fields is the multinucleon transfer between fragments and inelastic processes (particle-hole mechanism) in fragments. The conception of the conservation of individual properties of interacting nuclei has been used in our model. The model allows us to compare the relative role of the particle-hole excitation and nucleon exchange in the process of dissipation and to calculate the correlation between the nucleon exchange and total excitation energy of nuclei.

To consider the consistent evolution of the intrinsic and relative motion, to separate dissipative and kinetic energies from the total excitation energy of the system, it is convenient to present the total Hamiltonian of the dinuclear system $\hat{H}$ in the following form

$$\hat{H} = \hat{H}_{rel} + \hat{H}_{in} + \hat{V}_{int},$$

where $\hat{H}_{rel}$ is the Hamiltonian of relative motion and $\hat{H}_{in}$ is the intrinsic Hamiltonian of nuclei while $\hat{V}_{int}$ denotes a coupling of relative and intrinsic motions. In the second quantization form we can write [5]

$$\hat{H}(R(t)) = \hat{H}_{in}(R(t)) + \hat{V}_{int}(R(t)),$$

$$\hat{H}_{in}(R(t)) = \sum_P \hat{\varepsilon}_P(R(t)) \hat{a}_P^+ \hat{a}_P + \sum_T \hat{\varepsilon}_T(R(t)) \hat{a}_T^+ \hat{a}_T,$$

$$\hat{V}_{int}(R(t)) = \sum_{P\neq P'} \chi_{P,P'}^{(T)}(R(t)) \hat{a}_P^+ \hat{a}_{P'}, + \sum_{T\neq T'} \chi_{T,T'}^{(P)}(R(t)) \hat{a}_T^+ \hat{a}_{T'} + \sum_{T,P} g_{P,T}(R(t)) (\hat{a}_P^+ \hat{a}_T + \text{h.c.}).$$

The equation for the single particle density matrix looks like

$$i\hbar \frac{\partial \hat{n}(t)}{\partial t} = [\hat{H}, \hat{n}(t)] - \frac{i\hbar}{\tau} \{\hat{n}(t) - \hat{n}_{eq}(R(t)),$$

where $\tau$ is a parameter of the relaxation time, $\hat{n}_{eq}(R(t))$ is a local quasiequilibrium distribution at fixed distance between the centers of nuclei $R(t)$. The last term is the linearized two
body collision integral. To solve this equation we used the following approximative iteration procedure \( (\Delta t = t - t' < \tau) \)

\[
\tilde{n}_i(t) = \tilde{n}_i^{(t+\Delta t)}(R(t)) \left[ 1 - \exp \left( \frac{-\Delta t}{\tau} \right) \right] + n_i(t) \exp \left( \frac{-\Delta t}{\tau} \right)
\]

where occupation numbers \( n_i(t) \) are solutions of the equation which does not include the term of two-body collisions. To find \( n_i(t + \Delta t) \) the value of \( \tilde{n}_i(t) \) is used instead of \( n_i(t) \). This expression allows us to construct the iteration procedure to calculate excitation energy

\[
E_{\text{PLF(TLF)}}^*(t) = E_{\text{PLF(TLF)}}^*(t-\Delta t) + \sum_{i(F,T)} [\tilde{\epsilon}_{i(F,T)}(R(t)) - \epsilon_{F_i}(R(t))] [\tilde{n}_{i_r}(t) - n_{i_r}(t-\Delta t)]
\]

where \( \epsilon_{F_i}(R(t)) \) is the Fermi energy of projectile- nucleus "P" or target-nucleus "T".

The results of calculation for the reaction \( {\text{Fe}}^{56}(505 \text{ MeV}) + {\text{Ho}}^{165} \) are presented in fig. 1. It is seen that agreement between the theoretical and experimental results is quite good.

![Fig. Theoretical (solid line) and experimental results (triangles) for the ratio of the projectile-like fragment excitation energy \( E_{\text{PLF}}^* \) to the total excitation energy for reaction \( {\text{Fe}}^{56}(505 \text{ MeV}) + {\text{Ho}}^{165} \) as a function of the total excitation energy \( E_{\text{loss}} = E_{\text{PLF}}^* + E_{\text{TPE}}^* \).](image)

MECHANISM OF LIGHT PARTICLE PRODUCTION IN FUSION REACTIONS

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There are two possible channels of nucleus fusion. One of them can be connected with the dinuclear system evolution to compound nucleus [1]. The other one corresponds to the form change of the initial configuration. In this channel the system evolution coincides with the evolution of the deformed mononucleus. The channel of the dinuclear system evolution is dominant in the fusion of massive nuclei when the initial distance between the nucleus centers is more then the distance corresponding to the saddle point of compound nucleus.

In the fusion of light nuclei the initial configuration is more compact then the compound nucleus form in the saddle point. To find the relation between two fusion channels we can compare the light particle yield with the results of evaporation calculation. The channel of dinuclear system evolution gives additional contributions into the production cross section of light nuclei. For example, in the experiments with the Ar and Cr ions the very large $\alpha$—particle production cannot be explained by the evaporation from the compound system [2]. The pre-equilibrium decay of the dinuclear system due to dynamic reasons is the reason of enhanced yield of the light nuclei. It was established that with the increasing mass-asymmetry the forces aries which make the system approaching the decay barrier. The source of these forces is the coupling of the radial ($\tilde{R}$) and mass-asymmetry ($\eta$) modes of motion.

The simple analytical method was developed to calculate the diagonal and nondiagonal components of the mass tensor for the dinuclear system. To take into account the influence of the shell structure of interacting nuclei on the mass coefficients we have made the calculation in the framework of cranking model. The mass coefficients can be obtained from the following expressions

$$B_{RR} = \frac{X_\eta}{X_\eta X_R - X_\eta^2}, \quad B_{\eta\eta} = \frac{X_R}{X_\eta X_R - X_\eta^2},$$

$$B_{R\eta} = -\frac{B_{RR}X_{R\eta}}{X_\eta},$$

where

$$X_\eta = -\frac{1}{\hbar^2} \langle 0 | \{ \hat{H}, \tilde{\eta} \}, \tilde{\eta} | 0 \rangle, \quad X_R = -\frac{1}{\hbar^2} \langle 0 | \{ \hat{H}, \hat{R} \}, \hat{R} | 0 \rangle, \quad X_{R\eta} = -\frac{1}{\hbar^2} \langle 0 | \{ \hat{H}, \hat{R} \}, \tilde{\eta} | 0 \rangle.$$

Here $|0\rangle$ is the ground state of the dinuclear system, $\hat{H}$ is the microscopic Hamiltonian of this system. For these calculations the knowledge of the single particle matrix elements is need [3]. The obtained results confirmed the previous ones [4] that the nondiagonal component of the mass tensor which connects the relative motion and mass asymmetry mode increases strongly with the increasing mass asymmetry parameter.

The main mechanism of the enhanced light nucleus production is the kinematical coupling of the relative motion and the collective motion connected with the mass.
asymmetry degree of freedoms. With the increasing mass asymmetry the decay probability of the evolving dinuclear system increases (see fig.). Therefore, in the fusion reactions the enhanced light nucleus production demonstrates the presence of the dinuclear system channel.


Fig. Calculated dependence of probability decay $\Lambda_Z$ of dinuclear system on charge number of light fragment in the reaction $^{58}$Ni+$^{58}$Ni ($E_{cm}$ =150 and 120 MeV) at $J = 30\hbar$. 

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UNEXPECTED FEATURES OF REACTIONS BETWEEN VERY HEAVY IONS
AT INTERMEDIATE BOMBARDING ENERGIES

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ABSTRACT

Exclusive measurements of massive projectile-like fragments (PLF), intermediate-mass fragments (IMF), light charged particles (lcp), and neutrons, performed for two very-heavy-ion reactions at the lower boundary of the Fermi energy regime, provide compelling evidence for very simple underlying reaction dynamics dominated by collective degrees of freedom. For the reaction $^{209}$Bi + $^{136}$Xe at $E/A = 28.2$ MeV, $4\pi$ coverage was achieved for IMF, lcp, and neutrons, in a first experiment of its kind. In the $^{197}$Au + $^{208}$Pb experiment at $E/A = 29$ MeV, mainly kinematical coincidences between PLF’s and neutrons were studied. Both reactions exhibit features that are not commonly anticipated by current reaction models.

The experimental invariant emission patterns of neutrons or lcp’s demonstrate that both the $^{209}$Bi + $^{136}$Xe and the $^{197}$Au + $^{208}$Pb reactions are dominantly binary processes leading to massive projectile-like (PLF) and target-like (TLF) primary fragments that sequentially decay via the emission of neutrons, lcp’s and IMF’s, or by fission. Very hot primary fragments may loose a major fraction of their mass. In addition to particles produced in sequential evaporation, relatively small multiplicities of light particles and IMF’s, emitted instantaneously in a non-evaporative process, are observed.

The measured correlations between the multiplicities of neutrons and lcp’s suggest that, for a heavy system, the multiplicity $m_n$ of neutrons provides a good measure of the dissipated or thermal energy generated in a collision, for the entire range of impact parameters. The lcp multiplicity provides similar information with somewhat less accuracy, for intermediate to small impact parameters. Like at lower bombarding energies, it is found that the kinetic energy loss $E_{\text{loss}}$, as measured by $m_n$, is a variable that selects different reaction features and is, hence, strongly correlated with the impact parameter. The experimental correlations between particle multiplicity and massive-fragment energy, deflection angle, as well as PLF Z distributions indicate the presence of multi-nucleon exchange processes leading to dissipative reaction phenomena. Due to the rather complete information available on lcp’s and IMF’s in coincidence with

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PLF's, it is possible to reconstruct the characteristic Z distribution of primary PLF's, in the case of the $^{209}$Bi + $^{136}$Xe reaction. Unexpectedly, the experimental angle-$E_{\text{loss}}$ correlation of PLF's, available only for this latter system, exhibits two branches, indicating either dissipative orbiting or nuclear rainbow scattering. In addition, it appears that for both the $^{197}$Au + $^{208}$Pb and the $^{209}$Bi + $^{136}$Xe reactions, the initially available kinetic energy can only partially be dissipated, although some small cross section associated with full damping may have been missed in the measurement. Possibly, these effects are due to non-adiabatic effects in the nucleus-nucleus interaction.

Non-evaporative light particles and IMF's are observed most distinctly in peripheral $^{197}$Au + $^{208}$Pb and the $^{209}$Bi + $^{136}$Xe collisions, respectively, but with small multiplicities. A Fermi jet mechanism cannot adequately account for the energy spectra of non-evaporative neutrons from the $^{197}$Au + $^{208}$Pb reaction, although it predicts approximately correct multiplicities. Non-evaporative, cold IMF's observed in peripheral $^{209}$Bi + $^{136}$Xe collisions are seen to have velocities intermediate between those of PLF and TLF. Their kinematical properties are consistent with a scenario in which these IMF's are produced in the contact region between PLF and TLF, possibly due to the non-adiabatic rupture of the neck formed transiently in a reaction.

The results of these experiments on two very heavy systems provide a picture of the reaction mechanism at the lower boundary of the Fermi energy regime that is quite different from the reaction scenarios considered in the explanation of nuclear reactions involving lighter systems. Combined, the present data indicate a surprising dominance of a dissipative reaction mechanism that is, to some extent, reminiscent of the low-energy damped mechanism but exhibits also quite unexpected, new features challenging current reaction models.

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Fast light particles in Kr + Au collisions at 43 MeV/u


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The mechanism of peripheral collisions between heavy nuclei such as Kr + Au has been shown to be strongly dissipative and of two-body nature even at bombarding energies as high as 43 MeV/u [1]. On the other hand, growing evidence for multifragmentation has been found in central collisions for such systems [2]. Therefore, dissipative collisions in the Fermi energy domain seem to be a suitable tool to test the behaviour of nuclei when they come close to the limit of stability. In particular, light particles emitted in coincidence with the fragments should reflect the various aspects of the dynamics.

The present experiment was performed with the four multidetectors of Nautilus at GANIL: XYZt and DELF which measure fragments at forward angles and around the target, and the MUR and the TONNEAU which detect light particles in the same angular ranges.

To investigate the particle emission by the projectile-like nucleus, the analysis is restricted to events in which the projectile-like nucleus has been detected in XYZt. Moreover, the particle spectra measured in MUR and TONNEAU are incremented event by event not in the laboratory system but in a system bound to the fast fragment. The energy, velocity and angle in this system are $E_{sys}$, $V_{sys}$ and $\theta_{sys}$. In a $dM/dE_{sys} \cdot sin\theta_{sys} \cdot dV_{\parallel,sys} \cdot dV_{\perp,sys}$ spectrum, it has been checked that circular isocontours centered at $V_{sys} = 0$ are observed, demonstrating isotropic decay into a light particle-fast fragment pair. A non-isotropic component appears only at $\theta_{sys} > 90^\circ$ and is probably due to pre-equilibrium particles.

The energy spectra corresponding to the isotropic component are shown in Fig.1 for consecutive windows on the charge of the fast fragment $Z_p$, which was found to be a good scale on the impact parameter [1]. They exhibit the expected maxwellian shape. The minimum at $E_{sys} = 0$ and the maximum not far from the Coulomb barrier confirm that the fast fragment was the emitter of the particles. The long tail toward high $E_{sys}$ values however shows that this emission was not pure evaporation. Indeed, a fit with a $dM/dE_{sys} = M_0(E_{sys}-B) \exp[(-E_{sys}-B)/T] \cdot \chi^2$ formula yields fairly high $\chi^2$ and values for $T$ which are too high and depend too much on $Z$ ($T = 5-6$ MeV for $Z = 1$, 7-13 MeV for $Z = 2$ and more than 15 MeV for $Z = 3$). To improve the fit, we have followed the idea of Friedmann [3] and have added a fragmentation contribution (dashed curves) to the evaporation one (dotted curves). This fragmentation component has been calculated with the Goldhaber formalism modified to take into account the velocity damping and the Coulomb repulsion between the emitted particle and the rest of the projectile:

$$dM/dE_{sys} = M_0 \exp(-(p-p_0)/2\sigma^2)$$

where:

$$\sigma^2 = A_{part} (A_p - A_{part}) \sigma^2/\chi^2 (A_p - 1)$$

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\[ p = A_{\text{part}} m_N \frac{V}{c} \]
\[ p_0 = A_{\text{part}} m_N \frac{V_{\text{coul}}}{c} \]
\[ V = (A_p - A_{\text{part}}) \frac{V_{\text{sys}}}{A_p} \]
\[ E_{\text{sys}} = \frac{1}{2} A_{\text{part}} m_N \frac{V_{\text{sys}}^2}{c^2} \]

and \( A_{\text{part}} \) is the mass number of the particle, \( A_p \) that of the beam, \( c \) the velocity of light and \( m_N \) the nucleon mass. The agreement seen in Fig.1 is quite satisfactory. The parameters used are the following: for \( Z = 1 \), \( B = 0.6 \) MeV, \( T = 3.55 \) MeV, \( \sigma_0 = 70 \) MeV/c, \( V_{\text{coul}} = 3.57 \) cm/ns. For \( Z = 2 \), \( B = 5.0 \) MeV, \( T = 5.5 \) MeV, \( \sigma_0 = 90 \) MeV/c, \( V_{\text{coul}} = 2.45 \) cm/ns. For \( Z = 3 \), the evaporation contribution was not necessary, and \( \sigma_0 = 100 \) MeV/c, \( V_{\text{coul}} = 2.40 \) cm/ns. The only parameters which were varied in Fig.1 are the normalizing factors \( F_c \) and \( F_f \).

It should be stressed once more that the fragmentation component is isotropic in the frame of the projectile-like nucleus, and corresponds therefore to sequential emission. The data definitely show that the emitter had a velocity close to that of the projectile after slowing down. They do not allow to decide if this nucleus was fully reaccelerated after reseparation.

Chemical and Kinetic Temperatures Extracted in Reactions of $^{14}\text{N} + ^{112}\text{Sn}$ and $^{14}\text{N} + ^{124}\text{Sn}$ at 32A MeV.

CHIC Collaboration

Inclusive cross sections of fragment $^{1,2,3}\text{H}$, $^{3,4,6}\text{He}$, $^{6,7,8,9}\text{Li}$, $^{7,9,10,11}\text{Be}$ emitted at lab angle 60° in $^{14}\text{N}$ induced reactions in $^{112}\text{Sn}$ and $^{124}\text{Sn}$ targets at 32 MeV/nucleon have been measured. The initial 'chemical' temperature of $T_{ch} = 4.94 \pm 0.35$ MeV is determined from the yield ratios of fragments emitted in the two reactions. The slope of energy spectra, i.e. apparent 'kinetic' temperature ($T_{kin} \approx 14-10$ MeV) seems to reflect a superposition of the equilibrium distribution and a decay distribution from the two-body break up of the 'cold' residue. The difference in $T_{kin}$ of fragment spectra for two targets is well reproduced by the ratio of the Fermi momenta $p(^{124}\text{Sn})/p(^{112}\text{Sn}) = 1.03$.

Parameters related to the reactions $^{14}\text{N}(32\text{ MeV/nucleon}) + ^{112}\text{Sn}$, $^{124}\text{Sn}$

<table>
<thead>
<tr>
<th>Compound system</th>
<th>$E_{cm}$</th>
<th>$t_{crit}^{(1)}$</th>
<th>$&lt;I^2&gt;^{1/2}$</th>
<th>$E_{ret}^{(2)}$</th>
<th>$U-E_{ret}^{(3)}$</th>
<th>$T_{ch}^{(4)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MeV)</td>
<td>(h)</td>
<td>(s)</td>
<td>(MeV)</td>
<td>(MeV)</td>
<td>(MeV)</td>
</tr>
<tr>
<td>138</td>
<td>401</td>
<td>$\approx 80$</td>
<td>56</td>
<td>8</td>
<td>396</td>
<td>4.79</td>
</tr>
<tr>
<td>126</td>
<td>397</td>
<td>$\approx 81$</td>
<td>56</td>
<td>9</td>
<td>378</td>
<td>4.90</td>
</tr>
</tbody>
</table>

1) Complete fusion
2) Critical (max) angular momentum of system is defined when $B_{\text{int}} = 0$. $<I^2>$ computed by code ASIERK
3) Moment of inertia was taken as $2/5MR^2$, with $M$ the mass of nucleus and $R = 1.2A^{1/3}$ fm for the matter radius
4) $U = E_{cm} + Q -$ primary excitation of compound nucleus, $U - \omega_0 = aT^3$, level density parameter $a = (A/8)MeV^{-1}$

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Fig.1. "Chemical temperature", $T_{ch}$ as derived from the ratio of fragment cross sections for the reaction $^{14}$N(32 MeV/nucleon) + $^{112}$Sn, $^{124}$Sn at $\Theta_{lab}=60^\circ$. The lines are the fit to the data by $\exp(\Delta Q_f/T_{ch})$ for given $Z_f$. The thick line is the weighted average $T_{ch}=4.94 \pm 0.35 \text{ MeV}$. Here $\Delta Q_f$ is the difference in the ground-ground energies for given $Z_f$, $A_f$ fragment emitted from the first and second target in binary decay process.

Fig.2. Single particle inclusive cross sections measured at $\Theta_{lab}=60^\circ$ for $^{14}$N induced reactions on $^{124}$Sn target at 32 MeV/nucleon. The dashed curves are the result of parametrization of spectra by single Weisskopf distribution with $T_{ch}=4.94 \text{ MeV}$ and Coulomb reduction factor equal 0.6.

Solid lines—the calculated Maxwell-Boltzmann distribution with "kinetic temperature", $T_{kin}$, which is due to the combination of $T_{ch}$ and Fermi momentum. High-energy fragments are emitted in the process of break up of a cold part of the target after it absorbed nucleons from the "hot" zone /2/.

$$T_{kin} = \frac{2mT_{ch} + \frac{3}{2}p_f^2A_f}{2mA_f},$$

where $A_f$ denotes target mass number and $p_f$ denotes the Fermi momentum, $p_f$ is taken 270 MeV/c for $A_f=124$.

Fig.3. Experimental and calculated ratio of differential cross sections for some fragment for two studied targets. In the calculations it was supposed that $p_f(\text{112Sn})/p_f(\text{124Sn})=1.03$ with $p_f=270 \text{ MeV/c}$.

The parameters (energy, width and strength) of the Giant Dipole Resonance (GDR) built on highly excited states can reveal novel information on the shapes and the collectivity of hot nuclei. Recently, several experimental programs \(^1\)\(^2\) have focused on following the parameters of the GDR in medium mass nuclei \((A\approx110)\) between 50 and 600 MeV excitation energy. The energy of the GDR remains remarkably stable over this extended range, while the yield of the \(\gamma\)-rays from GDR decay seems to saturate above approximately 300 MeV excitation energy. Divergent interpretations give rise to very different results concerning the width and the strength of the resonance above 150 MeV. The aim of the present experiment was to pursue investigations of the GDR at very high excitation energies by measuring its \(\gamma\) decay in coincidence with evaporation residues and light charged particles, in order to pin down as precisely as possible the excitation energy and temperature of the hot nuclei in which the resonance is excited.

A \(^{94}\)Zr target was bombarded with the 27 MeV/u \(^{36}\)Ar beam from the GANIL facility in Caen, France. \(\gamma\)-rays and light charged particles (LCPs) were detected in the 180-element BaF\(_2\) ball of the MEDEA detector\(^1\) operating under vacuum. A combination of a time of flight measurement with a shape analysis of the BaF\(_2\) pulse yielded an unambiguous separation of \(\gamma\)-rays, neutrons and LCPs. Evaporation residues were measured in two parallel plate avalanche counters covering between 6° and 22°.

From the time of flight spectrum of the residues, a mean linear momentum transfer of 80% of full momentum transfer is deduced, which, according to the massive transfer model, corresponds to an average excitation energy of 560 MeV for the hot nuclei produced. The time spectrum is broad, allowing to divide the data into three bins corresponding respectively to 50%, 70% and 90% of full momentum transfer. Moving source fits to the coincident proton spectra show that the initial temperature of the compound nucleus source increases from 6 MeV at 50% momentum transfer to 7 MeV at 90%, demonstrating that the selection of high momentum transfer events is a reliable method to focus on the hottest nuclei.

A typical \(\gamma\)-ray spectrum measured in coincidence with evaporation residues, without any selection on momentum transfer, is presented on the figure. Apart from the statistical and bremsstrahlung components which can be fitted by exponentials, the GDR shows up very clearly, even at this very high temperature, as a bump centered at .5 MeV. In order to investigate the evolution of the GDR yield as a function of excitation energy, similar spectra were

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extracted for each momentum transfer bin defined above. Exponential functions were fitted to the low energy statistical and bremsstrahlung regions of each spectrum and then subtracted in order to estimate a GDR γ yield. The low energy statistical gamma multiplicity is constant as a function of increasing linear momentum transfer while the bremsstrahlung multiplicity, measured simply by integrating the experimental spectra above $E_γ = 35 \text{ MeV}$, increases strongly. Since the bremsstrahlung yield is due to nucleon-nucleon collisions during the first stages of the reaction, such a behavior is in agreement with a simple geometrical picture in which the hottest nuclei are formed in the most central collisions. The most remarkable feature is that, within the errors, the GDR γ multiplicity is constant for all three momentum transfer bins, confirming the saturation of the GDR yield at these high excitation energies.

Extraction of the parameters of the GDR requires comparison with a statistical model. Preliminary calculations using the code CASCADE have been performed with standard parameters ($E=16\text{ MeV}, \Gamma=13\text{ MeV}, S_{EW/SSR}=100\%$)\cite{J.J.Gaardhøje} which were kept fixed along the decay chain. Assuming an initial excitation energy of 500 MeV, such a calculation grossly overpredicts the γ-spectrum in the region of the GDR. More sophisticated calculations including the variation of the GDR parameters along the decay chain following the most recent theoretical developments\cite{J.J.Gaardhøje} are currently in progress and will be presented.

References

Figure Gamma spectrum measured in coincidence with fusion like events. Dashed lines correspond to exponential fits to the low energy statistical part and bremsstrahlung part of the spectrum. The solid line is the sum of these two exponentials. The insert displays the difference between the experimental spectrum and the solid line.
Projectile Fragmentation and Energy Dissipation in Peripheral Heavy-Ion Collisions

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ABSTRACT

Studies of peripheral heavy ion collisions are common in many different areas of nuclear science. On one hand, there is particle spectroscopy, which relies on the correlation between exit channel kinetic energy and target excitation to probe nuclear structure and characterize modes of nuclear motion. On the other, there are mechanism studies, which are generally aimed at investigating the dynamics of nuclear collisions and the properties of highly excited nuclear systems. Our understanding of peripheral processes could benefit significantly from experiments utilizing techniques common to both particle spectroscopy and mechanism studies. With this in mind, two widely different approaches have been employed to investigate peripheral heavy ion reactions. In one class of experiments, high resolution techniques have been used to study projectile breakup of 30 AMeV $^{18}$O and $^{20}$Ne. In other work, energy dissipation in peripheral reactions induced with 30 AMeV $^{20}$Ne have been investigated with the aid of a 4-$\pi$ neutron detector.

In the breakup experiments, two particle correlations were studied using a broad range, magnetic spectrograph. With this technique it was possible to investigate the breakup of the projectile into an alpha particle and the complementary heavy fragment for Q-values ranging from near the particle threshold down to about -100 MeV. The data show that the elastic breakup reaction are dominated by the sequential decay of known states in the projectile. The states which are most strongly populated correspond to a cluster states in the projectile. The dominance of sequential breakup persists over the entire range of measured energy losses. Little evidence is observed for the direct breakup of the projectile into non-resonant states. Similar results are obtained for...
the other α-heavy-ion correlations observed in the measurements. The data will be discussed in terms of the cluster structure of the excited fragment. In addition, questions about the excitation energy partition between the fragments and the possibility of extracting temperatures from the excited state populations will be addressed.

In other experiments, quasi-elastic processes in the $^{20}$Ne + $^{208}$Pb system were studied using an array of ΔE-E telescopes mounted inside a neutron ball. Event-by-event neutron multiplicity distributions were obtained for a variety of isotopes with Z's in the range of 4-11. Because of the correlation between excitation energy and neutron multiplicity, the results of these measurements provide insights into energy dissipation mechanisms and the competition between transfer and breakup processes. In addition, these studies may also clarify the possible role of the excitation of multiphonon excitations in dissipative reaction mechanisms.4

References
Multifragmentation:
Surface and Coulomb Instabilities
of
SHEETS, BUBBLES, and DROPS.

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ABSTRACT

Multifragmentation observed in intermediate energy heavy ion reactions has been attributed either to a variety of statistical processes, or to the onset of instabilities. We shall consider here only static instabilities, which can be divided into volume and surface instabilities. A volume instability can develop within an infinitely extended medium. An example of these is the spinodal instability, leading to the breakup of an homogeneous fluid into droplets of liquid embedded into its vapor. Surface Instabilities require either a finite system, or a two-phase system. The Rayleigh instability of a cylinder of liquid is a surface instability that leads to the breakup of the cylinder into droplets. Landau-Vlasov and BUU simulations of heavy ion collisions have shown the formation of disks and bubbles, which eventually break up into fragments. This made us consider the possibility of a surface instability as the cause for the break-up. An infinite sheet of liquid is the simplest approximation to both a disk and a bubble. In the limit of a sharp surface, a sheet is metastable with respect to perturbations of all finite wave-lengths. However, we have found that the introduction of a finite range surface-surface attractive interaction (e.g. proximity) makes the sheet unstable for all the wave-lengths above a critical value. The critical wave-length depends exponentially upon the ratio of the sheet thickness to the range of the force, so that, as the thickness is reduced to a value near the range of the force, the instability sets in rapidly. This instability, which is totally general, has not been described before. We call it "sheet instability". The introduction of geometrical boundaries leads to a further selection of the unstable frequencies, like those associated with eigenmodes. We have seen evidence of this in Landau-Vlasov calculations.

Regarding the formation of bubbles, we have determined the condition of formation and stability of bubbles within nuclei, including both Coulomb interaction, and vapor pressure inside the bubble.

The presence of the Coulomb interaction can destabilize (and sometimes stabilize!) droplets and bubbles. In the case of droplets, we have determined the critical values for the fissility parameter X for the onset of instability for all multipolarities, and established the fastest instability among them. In the case of bubbles, the radial modes are eventually destabilized, but the crispation modes are actually stabilized by the Coulomb interaction.
DYNAMICS OF FLUCTUATIONS AND MULTIFRAGMENTATION

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We introduce a general method to evaluate fluctuations of the semiclassical one-body distribution function based on the picture as a statistical ensemble of phase-space elements. Time evolutions in stable and unstable dynamical regions for realistic heavy ion collisions are presented. A general procedure to identify instability regions is discussed, which covers all possible sources of dynamical instabilities. A way to control the numerical noise is proposed, which eventually allows the development of a fully dynamical picture of fragmentation processes.

Hybrid models of dynamics-statistics type are also discussed with reference to event by event analyses of interest for multidetector systems. The possibility of observing intermittency effects is studied also in comparison with non dynamical models of percolation type.

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Quantum Dissipative Phenomena
in Nucleus–Nucleus Interaction

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In heavy ion induced nuclear reactions both the coherent (self-consistent nucleon motion inside the fragments, cluster transfer, subbarrier tunneling, the Pauli exclusion principle, etc.) and the dissipative phenomena are revealed simultaneously. It forces us to consider these dissipative phenomena within a quantum channel coupling approach.

Using the multi-dimensional multi-channel semiclassical approximation [1] parallel with exact solution of stationary and non-stationary Shrödinger coupling equations we examine the following questions. What are the main reasons and mechanisms of nuclear viscosity? May a simple quantum system with a few degrees of freedom display the dissipative features at slow external influence upon it? What is the mechanism of subbarrier dissipative motion? How can we account for friction forces within quantum theory of collision?

First of all, it was found that even very simple quantum system (of only one or two degrees of freedom) can reveal the viscous properties at slow relative motion. As the calculations show, just the chaotization of internal energy spectra (not of the coupling matrix elements!) is the main reason for dissipative response of such system, and the coupling of two intrinsic degrees of freedom having the different stiffness is another reason for its dissipative response.

Exploring the quantum subbarrier motion of nuclear clusters under conditions of strong channel coupling (dissipative tunneling) we found out besides the well-known enhancement of the total penetrability also the unusual effect of facile tunneling in inelastic channel with a large kinetic energy loss. It was found also a new effect of wave packet sticking to a potential wall due to its tangling and time delay inside the inelastic channels. Such an effect can be displayed experimentally, for example, in formation of short-living nuclear molecules at subbarrier energies.

Having an experience in solving of quantum and semiclassical multi-channel problems we try again to deduce a new one-body Shrödinger equation with a friction. One of such equation is proposed and examined in this work.


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LIGHT PARTICLE EVIDENCE OF THE DYNAMICS OF NUCLEUS–NUCLEUS COLLISIONS

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Since 1961 when Britt and Quinton detected for the first time an intensive yield of α particles in reactions with heavy ions, hundreds of experimental and theoretical papers have been devoted to the problem of light particle production in nucleus–nucleus collisions. But there is still no common viewpoint on the complex nature of this process. The great interest to the problem has several reasons. First of all, the cross section of light particles yield is very big and thus their production is a general property of nucleus–nucleus collisions without understanding the mechanism of the particle production. Secondly, the experimental regularities of mass, angular and energy distributions of light particles turned to be unexpected enough and some times even difficult to explain [1]. And last, it is well established that a great part of these particles are produced just in the first phase of the nucleus–nucleus interaction and thus they contain information on the dynamics of this interaction in contrast to the decay products of a compound nucleus forgetting the whole path of its formation.

The paper contains a critical review of the main experimental results on the light particle yield in nucleus–nucleus collisions at low and intermediate energies. It analyzes also inclusive spectra of light particles and their coincidences with the characteristic X–radiation, γ quanta, neutrons, projectile–like fragments and other light particles, with fission fragments and evaporation residues.

The main theoretical approaches used to describe nuclear reactions producing light particles are considered and their advantages and drawbacks are noted. The model of the dissipative (multistage) decay of a projectile and of the mass transfer developed in [1] has been successfully used for the analysis of the available experimental data in the energy region from 5 to 30 MeV/nucleon and for the explanation of the observed regularities of light particle production and extraction of dynamic characteristics of a nucleus–nucleus collision.

The final part of the paper discussed the yet unsolved problems of light particles production and, in particular, of the dynamics of nucleus–nucleus interactions in general. A series of new experiments which could clarify some of these problems is suggested.

ON THE DYNAMICS OF PION PRODUCTION IN NUCLEAR COLLISIONS AT INTERMEDIATE ENERGIES

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Among the various observed characteristics that enable to study the interaction of heavy ions (HI) at intermediate and high energies, the major importance has the process of pion production. Here we consider the process of pion emission within the Vlasov-Uehling-Uhlenbeck (VUU) method[1]. The VUU equation for a one-particle distribution function
describes the development in time of the interaction process of two colliding ions. In solution of (1) alongside with two-particle stochastic collisions the account of time-dependent selfconsistent field \( L\{\rho(\vec{r}, t)\} \) and the Pauli principle in final states plays an important role. When describing the process of dynamics the main point lies in choice of \( N N \) interaction and approximation of the particle interaction cross-section in nuclear medium.

It is the choice of \( N N \) interaction in the form of Skyrme forces that is common at present. The latter consist of two- and three-particle forces, the finite range Yukawa-type forces and those of Coulomb interaction. The parameters choice is connected with the equation of state (EOS) for nuclear matter and for \( U(\rho) \) we chose the dependence[2]

\[
U(\rho) = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^2
\]

with two sets of parameters, that provide different values of nuclear compressibility: hard \((K = 380MeV)\) and soft \((K = 200MeV)\) EOS.

For the solution of equation (1) we use the method of test particles. In this case for the particle formfactor parametrizing we use the method of solution of kinetic equations for the plasma[3]. Our solution method is close by its essence to [4,5] and it can be called a lattice one, since the phase space is broken into cells of definite dimensions. The solution method provides an accurate performance of laws of conservation of energy and momentum. We use the parallel ensemble algorithm in which collisions are allowed only between particles in the same ensemble.

The pions are supposed to be produced only through the resonance \( \Delta \) and \( N^* \), therefore the following reactions are taken \( NN \leftrightarrow N\Delta, NN \leftrightarrow NN^*, \Delta \leftrightarrow N\pi, N^* \leftrightarrow N\pi \). For the reactions \( NN \rightarrow N\Delta \) and \( NN \rightarrow NN^* \) the VerWest and Arndt[6] parametrizing is used, and for the inverse reaction the principle of detailed balance is applied. Thus the solution (1) comes to the solution of equations system for \( N, \Delta, N^*, \pi \) with various distribution functions for each isospin. It is supposed that \( \Delta \) and \( N^* \) propagate in the same potential as the nucleons, whereas pions are
treated as free particles. Because of a rather large width, the mass of resonances $\Delta$ and $N^*$ are distributed according to the Breit-Wigner distribution with momentum dependent width\cite{7}.

The decay probability of the resonances is determined by an exponential decay law using their proper time, the decay is assumed to be isotropic in their rest frame. The branching ratio of decay probabilities of $\Delta$ and $N^*$ on $N + \pi$ is determined by the ratio of the corresponding Clebsch-Gordon coefficients. Because of pion's strong interaction with the nuclear medium some papers (see for example\cite{8}) introduce the length of the free path for the phenomenologic account of the absorption possibility. In our paper the pion absorption is considered obviously through the reaction $\pi N \rightarrow \Delta(N^*)$, $N\Delta(N^*) \rightarrow NN$, with the maximum of cross-sections taken from the experimental data and correspond to a case, when the invariant mass of $\pi N$ system is close to the average resonance mass.

An important moment in the calculation process is an account of the Pauli blocking and not only for the two-particle collisions, but also for the resonance decay final states. Thus, the proposed method of VUU equation solution, similar to other codes and permits to describe with good accuracy the dynamics of heavy ion interactions, the calculation of spectral characteristics of the produced particles. As one of the characteristics, the production of pions in the reaction $^{40}\text{Ar} + ^{40}\text{Ca}$ at the energy 1 GeV/nucleon is studied here.

The picture shows the evolution in time of pion production. First the production of $\Delta$ and $N^*$ prevails, the life time of which is equal to a few fm/c, and then the decay process to $N + \pi$ occurs. The process $NN \rightarrow N\Delta$ reaches rapidly the asymptotics and reaches the maximum at the greatest overlapping of the interacting nuclei. It is interesting to compare number of produced and absorbed pions. In the present reaction during the interaction process there were formed 42 pions and 24 were absorbed. If we compare the number of cases of $NN \rightarrow N\Delta$ and $N\Delta \rightarrow NN$, the first one takes place earlier in time and exceeds the second one by ratio of 3/1. It should be noted, that $\Delta$ resonances play the main part in pion production at the given energies, meanwhile the role of $N^*$ is not that important, but it increases with the growth of the incident particles energy.

References

Experimental studies of heavy-ion reactions at the intermediate energy stimulate the great interest in large amplitude collective phenomena and new modes of motion in nuclear systems. The possibilities of occurrence of shock waves in nuclear matter was first predicted about 30 years ago. Around 1980 it has been shown quantum shock waves and solitons in cold nuclear matter are possible. Recently, nuclear theory has predicted the formation of the new very exotic objects, such as "disks" [1,2], unstable hollow "bubbles" and "rings" [3], which decay by intermediate mass emission.

In this report, we analyze the pure vortical motion excluding the usual approximation on smallness of the excitation amplitude and the additional assumptions on the shape of the nuclear system. We use the semiclassical nuclear hydrodynamics based on the current \( \mathbf{j} \) and density \( \rho \) algebra and hydrodynamic representation for the nuclear hamiltonian, which is equivalent in view of the equations of motion for \( \mathbf{j} \) and \( \rho \) to the initial hamiltonian. Gradient terms of the "pressure" drop out from the equations of motion on separating the curl component of the velocity field and the equation of motion for \( \text{rot} \mathbf{v} \) are formally reduced to the pure kinematic form, at least for the Skyrme type forces.

For an incompressible (\( \rho \equiv \rho_0 \)) nuclear vortical flow it is convenient to turn to the vorticity \( \zeta \), and the vector potential \( \mathbf{A} \)

\[
\mathbf{v} \equiv \text{rot} \, \mathbf{A}, \quad \text{div} \, \mathbf{A} = 0, \quad \frac{\partial}{\partial t} \mathbf{\zeta} + \mathbf{v} \cdot \nabla \mathbf{\zeta} + \frac{1}{r} \frac{\partial}{\partial \phi} \mathbf{\zeta} = 0,
\]

\[
\zeta \equiv \text{rot} \mathbf{v} = \text{rot} \, \text{rot} \mathbf{A} = \text{grad} \, \text{div} \mathbf{A} - \Delta \mathbf{A} = -\Delta \mathbf{A}.
\]

We restrict ourselves to the simplest rotational flow, two-dimensional motion \( \mathbf{v}(r, \phi) = v_r \mathbf{e}_r + v_\phi \mathbf{e}_\phi \), \( \mathbf{A} = A \mathbf{e}_z \), \( \zeta = \zeta \mathbf{e}_z \), where \((r, \phi)\) are polar coordinates of a point.

The velocity projections \( v_r, v_\phi \) can be determined by differentiating \( \mathbf{A}(r, \phi) \) with respect to \( r \) and \( \phi \)

\[
v_r(r, \phi) = r^{-1} \partial A / \partial \phi, \quad v_\phi(r, \phi) = -\partial A / \partial r.
\]

The current function \( A(r, \phi) \) can be derived from the Poisson equation with the help of the two-dimensional Green function for the Laplace operator

\[
A(r, \phi) = (2\pi)^{-1} \int d\phi' d\psi' \ln(|r - r'|) \zeta(r', \phi').
\]

In this report we consider two-dimensional analog of the nuclear "disks" - a plain nuclear vortexes - a new type of a pure vortical state of incompressible nuclear matter. They are the finite areas of the constant vorticity on a plane \((r', \phi', t) \equiv \zeta_0\), within the uniform-rotating contour \( \Gamma(r, \phi) \equiv r - R(\phi) = 0 \). These states can be considered as the generation of the Elliptic Kirchhoff Vortex [4]. The dynamical condition on the contour \((\mathbf{n} \cdot \mathbf{v}) = (\mathbf{n} \cdot \mathbf{v}_{\text{contour}})\) and the normal vector \( \mathbf{n} \) are given by

\[
\mathbf{n} = \frac{\sigma \nabla \Gamma}{|\nabla \Gamma|} = \sigma \left( e_r - S(\phi) e_\phi \right) \left( 1 + S(\phi)^2 \right)^{-1/2}, \quad S(\phi) = \frac{1}{R} \frac{dR}{d\phi},
\]

\[
\Omega \frac{dR}{d\phi} + v_r - v_\phi \left( \frac{1}{R} \frac{dR}{d\phi} \right) = 0,
\]

where \( \Omega \) is an angular velocity of the uniform-rotation of the contour, and \( \sigma = \pm 1 \) defines the orientation of the contour.
The equation for the vortex boundary may be cast into the form of the nonlinear integro-differential equation

\[
\frac{2\pi \Omega dR}{\zeta_0} \frac{d\phi}{d\phi'} = \int_0^{2\pi} \frac{d\phi'}{\zeta_0} R(\phi') \ln(1 + S(\phi)S(\phi')) \sin(\phi - \phi') + (S(\phi) - S(\phi')) \cos(\phi - \phi') + ((1 + S(\phi)S(\phi')) \sin(\phi - \phi') + (S(\phi) - S(\phi')) \cos(\phi - \phi')) \cos(\theta - \phi'),
\]

(1)

For a quantitative analysis of the equation (1) it is necessary to build its discrete analogue. Such investigations are in progress. In this report, we restrict ourselves to the qualitative analysis, which can be done by analogy with the well known elliptic Kirchhoff vortex and the solution for small perturbations of the circle \([4]\).

The small rotationless perturbation \(\delta A(r, \phi) = \alpha(\zeta_0/2)R_0^2(r/R_0) \cos(l\phi - \omega t)\), where \(l\) is an integer, gives us the following contour equation \(R(\phi) = R_0(l + \alpha \cos(l\phi - \omega t))\) for small \(\alpha \ll R_0\). So the small perturbation given by trigonometrical functions, is a crimp moving along the circle vortex with the angular velocity \(\Omega = \omega/l = (l - 1)\zeta_0/2l\). For instance, at \(l = 2\) the perturbed shape is an ellipse, rotating about its center with the angular velocity \(\zeta_0/4\), that is half of the velocity of the fluid into the contour. Perturbations of the higher symmetry \(l \geq 3\) are rotating still slower. For the ellipse \(x^2/a^2 + y^2/b^2 = 1\) one can derive the following connection between the frequency of the contour rotation and the vorticity \(\Omega = (ab/(a + b)^2)\zeta_0\).

Thus, from the above solutions it follows that:

(i) Despite the internal part of the vortex is rotating with a constant angular velocity, this motion differs from the motion of a rigid body, because the contour is rotating with a different velocity, more slowly.

(ii) The contour velocity depends on the symmetry of a perturbation and the solutions may be classified by the parameter \(l = 2, 3, 4, \ldots\), or the symmetry relative to the turn by the angle \(2\pi/l\). These vortexes are the two-dimensional analog of the rotating nuclear systems, which have stable quadruple, octuple, hexadecuple deformation accordingly.

(iii) The fixed ratio \(\Omega/\zeta_0\) and the symmetry of states define completely the shape of the contour (for instance, for the elliptic vortex its eccentricity).

Eq. (1) together with the definition of the velocity fields will describe the motion of the contour as the propagation of a nonlinear dispersion wave on a plane. At the beginning the moving contour will be inevitably distorted. However, if this state is stable, then the interference between the nonlinearity and the dispersion will lead to the return of the initial contour shape. If one could prove the existence of these states, then these vortexes will be an analogue of the solitons on a plane.

(iv) The parameter \(\Omega/\zeta_0\) will be the bifurcation parameter and will determine the stability of a vortex. The integrals of motion are the square of the "disk" which is a two-dimensional analogue of the particle number, and the circulation of the vortex defined by the help of \(\zeta_0\). If the contour motion is unstable, one may expect the disintegration of the "disk" into the separate rotating vortexes and into the vortex filaments - two-dimensional analog of the rotating intermediate mass fragments.

Nuclear processes are very rapid therefore ordinary (equilibrium) thermodynamics as employed, for example, in ref.[1] can not provide their adequate description. An expansion of the framework of thermodynamics was suggested [2] via introducing the temperature continuum $0 \leq T \leq T_0$ with a large temperature variance given as

$$< (\Delta T)^2 > = T^2 / \alpha. \quad (1)$$

The expression (1) is known in macroscopic physics with essential restriction $\alpha \gg 1 \ (\Delta T \ll T)$, however in nuclear physics values $\alpha < 1$ can occur. Thus we deal with large temperature variance and large nonequilibrium effects (we regard this case as super–nonequilibrium thermodynamics).

The new approach has exhibited a similarity between the view of nucleons and nucleon clusters as constituents in nuclear collisions and the view of partons as constituents in hadron processes. For the momentum distribution of the constituents we have got

$$n(p)axp(-\xi) / \xi, \quad \xi = a(1 + p^2 / amT)^{1/2}, \quad (2)$$

which transforms into the Maxwellian when $a \to \infty$ (limit of equilibrium thermodynamics). The new approach proved applicable to a wide range of nuclear phenomena both at low and high energy. We have got a good description for nuclear fission, carbon–type radioactivity, projectile breakup reactions, high–energy $p(p)–p$ scattering [3–7].

References
GRAPH APPROACH TO THE
COALESCENCE MODEL FOR LIGHT
FRAGMENT PRODUCTION IN
NUCLEUS-NUCLEUS COLLISIONS

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A theoretical approach is presented which enables to substantiate and generalize the
phenomenological coalescence model used successfully for the description of light fragment
production in hadron-nucleus and nucleus-nucleus interactions. Simplest Feynman graphs,
corresponding to fusion of several nucleons to a light fragment, are shown to provide the
dynamical basis of the coalescence model.

In the first stage we use only the fact that the inclusive nucleon spectra generally have
a dropping nature and can be approximated by the Gaussian form

$$Ed^3\sigma/dp_N^3 \sim \exp(-p_N^2/Q^2)$$

in the wide regions of momenta. For this reason alone the coalescence radius in momentum
space $p_0$ ceases to be a fitting parameter. In our approach it is expressed in terms of the
slope of the inclusive nucleon spectrum and parameters which describe the wave functions
of few-nucleon systems at small distances. As an example for deuteron production

$$p_0^2 = 36\pi^2 \left[ \int \frac{d^3q}{(2\pi)^3} \phi_d(q) \exp\left(-\frac{q^2}{Q^2}\right) \right]^2,$$

where $\phi_d(q)$ is the deuteron wave function in momentum space. Expression (2) leads
to the nontrivial dependence of $p_0$ on $Q$: firstly steep increase up to $300$ MeV/c at $Q$
increasing to $400-450$ MeV/c, then broad maximum and shallow decrease. Predicted
region of $p_0$ variation coincides with the one obtained in experimental data processing.

Empirically observed universality of the coalescence radius, i.e. approximate equality
of its values as required for the description of $d$, $t$, $^3$He and $^4$He spectra at the same
kinematical conditions, is reproduced. Account of nontrivial dependence of $p_0$ on the slope parameter enables to describe in a unified way the regions of both small and large transverse fragment momenta. Successful descriptions of the $\alpha$-particle and $^3$He spectra are exemplified.

At second stage, when considering heavy nuclei fragmentation, a method is proposed for the account of the additional nucleons correlations due to identity of particles and to the finite dimension of the production region. The trend of $p_0$ diminishing with the increase of the parent-nucleus mass is investigated. Account of various reasons for $p_0$ nonconstancy makes possible to extend the region of applicability of the concept that the light fragments are formed as the result of fusion of independently borned nucleons.

“Nonsymmetrical” case is separately investigated, when slope parameters of coalescing particles are substantially different. The formulae are obtained for hypernuclei production as well as for more “exotic” cases of antideuteron and quasinuclear nucleon-antinucleon states production in nucleus-nucleus interactions.

SEMI-CLASSICAL METHOD FOR DESCRIPTION
OF HEAVY ION COLLISIONS

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The method is suggested for calculating both elastic and inelastic scattering of light and heavy ions on nuclei and also for description of simple transfer reactions. It is based on the three-dimensional representation of the relative motion (e.g. distorted waves), when the typical conditions \( kR \gg 1 \) and \( V/E \ll 1 \) are fulfilled. The second important point is that it suggests to decompose the operators in matrix elements in a set of trial functions which have simple poles in the complex \( r \)-plane. Thus, we intend to get the resulting amplitudes in a simple analytical form, expressed through the corresponding residues.

First, we start with elastic scattering. Here the known problem is that the three-dimensional semi-classics cannot give scattering waves in the region out of classical angles of scattering \( \theta > \theta_c \approx V/E \). So, to get the scattering amplitude, we represent the total wave function as composed of three parts: the plane wave, the semi-classical function for the initial channel \( \Psi_k^{(+)} = u_f(\mathbf{r})e^{i\mathbf{S}_f} \) and the additional term \( \Phi(\mathbf{r}) \). The latter obeys the nonhomogeneous equation, and gives in asymptotics the following scattering amplitudes: for small angles \( \theta < 1/kR \)

\[
f_1(\theta) = -ik \int_0^\infty dp \rho J_0(kp\theta)[e^{-ikp} \int_{-\infty}^{+\infty} U(\mathbf{r}+\mathbf{k}p) - 1]
\]

and for large angles \( \theta > 1/kR; V/E \)

\[
f_2(\theta) = -\frac{1}{4\pi} \int d\mathbf{r} \Psi_{k_1}^{(-)}(\mathbf{r}) U(\mathbf{r}) \Psi_k^{(+)}(\mathbf{r})
\]

The first is the known Glauber-Sitenko formula. The second formally looks like the amplitude in the distorted wave Born approximation (DWBA), inherent only in inelastic processes. This expression is of the main interest because it works in a wide region of scattering angles. Now, if one uses e.g. the Saxon-Woods form for the nuclear potential and the Fermi...
charge density distribution for the Coulomb one, it gives the possibility to use the above-mentioned poles of these functions.

The inelastic amplitude can be obtained using the shock approximation (if $E_{\text{excit}}/E < 1$):

$$f^{in}(\theta) = \langle f|f^{el}(\theta, \xi)|i \rangle$$

where $|i \rangle$ and $|f \rangle$ are initial and final states of a nucleus depending on its internal variables $\{\xi\}$. Here the amplitude $f^{el}$ corresponds to elastic potential scattering on a nucleus having "frozen" internal coordinates $\{\xi\}$:

$$f^{el}(\theta, \xi) = f^{el}(U(\vec{r}) \to U(\vec{r}, \xi))$$

This form of inelastic amplitude contains all the interaction orders. If we extract the interaction term $U = U_0(r) + U_{\text{int}}(\vec{r}, \xi)$ and limit oneself to the first order in $U_{\text{int}}$ we get, e.g. the expression

$$f^{inel}_{ji} = -\frac{1}{4\pi} \int d\vec{r} \Psi_j^{(-)*} < f|U_{\text{int}}|i \rangle \Psi_i^{(+)}$$

that coincides with the traditional DWBA formula. Here we also can use the poles of $U_{\text{int}}$ because it is usually represented as the derivative with respect to $R$ of the Saxon-Woods potential.

The DWBA for transfer reactions is based on the following expression

$$T_{fi} = \int d\vec{r} \Psi_f^{(-)*} u_{\lambda} Y_{\lambda\mu} \Psi_i^{(+)}$$

Integration over angular variables is usually made by the stationary phase method. Then, the form factor $u_{\lambda}$ may be decomposed in a set of derivatives with respect to $R$ of the trial fermi function. This permits one to use the poles of the latter and to calculate the final integral analytically.
A new approach, applied successfully for the description of nuclear multifragmentation in proton-nuoleus reactions /1/, is generalized now for the case of nucleus-nucleus collisions. The nuclear collision process is assumed to consist of three successive stages: 1) intranuclear cascade proceeding in the both nuclei and described by the Intranuclear cascade model (ICM) /2/; 2) multifragment break-up of excited residual nuclei (RN) described by the Statistical multifragmentation model (SMM) /1,3/; and 3) deexcitation of hot primary fragments considered in two ways - either by conventional evaporation of light particles or by secondary break-up leading to the set of cold fragments /3/. The combined model, which we call cascade-fragmentation-evaporation (CFE) model, allows us to simulate the whole reaction and to calculate all observable characteristics of particles and fragments. The experimental data at collision energies \( E \geq 100 \text{ MeV/nucleon} \) have been analyzed. Some experimental characteristics can be reproduced by CFE model fairly well. The main part of the discrepancies is related to the uncertainties in masses and excitation energies of the RN after the cascade stage. The better agreement can be obtained if we select the appropriate RN's masses and energies (see, for example, in fig.1 the comparison with experimental data of the 197-Au(600 MeV/n) + 12-C reaction /4/). Such an analysis gives way to determining parameters of highly excited RN.


Fig.1. Correlation between the mean multiplicity of the intermediate mass fragments (with charges \( Z=3-30 \)) \( <M_{\text{int}} \) and the summary charge bound in the fragments with \( Z>1 \). The dots are the experimental data from /4/. The solid and dashed curves are the CFE calculations with different description of preequilibrium emission. The dashed area corresponds to the SMM calculation of the break-up of the selected residual nuclei.
Nuclear Two-Body Fragmentation:
From Spontaneous Decay To Multifragmentation
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The generalized treatment of the two-body fragmentation both from the ground and excited states is proposed. The model takes its origin from an assumption of a direct correspondence between properties of nucleonic collective motion in the decaying nucleus and characteristic of exit channel, the correspondence being defined by the overlap integral of the corresponding wave functions. The collective wave function is found from the Schrödinger's equation solution with anharmonicity corrections due to both the shell effects and nuclear rotation for spontaneous and induced fragmentation, correspondingly. The detailed calculations of the spontaneous decay half-lives were performed and it was shown the good accordance between experimental and theoretical data. The role of the different collective modes in the decay mechanism was considered and the strong dependence of the structure effects (except fine structure in fragment spectra) on the isovector mode of density oscillations was shown.

The emission widths, energy spectra and fragment multiplicities were calculated at the excitation energy from 50 MeV till 500 MeV. As the excitation energy grows, the emission width is rapidly increasing, too, and near the nuclear temperature about 4-5 MeV, the emission half-lives are close to the characteristic nuclear times; the process of the multiple fragmentation by means of the successive binary decays is here undistinguishable from the simultaneous break-down mechanism. It is shown, too, that well-known reduction of coulomb barrier happens mainly due to the thermal properties of the collective potential energy and in a less extent due to the thermal properties of nuclear density.
Experiments with Relativistic Heavy Ion Beams at the GSI Projectile Fragment Separator

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The fragmentation of relativistic heavy ions in peripheral nuclear collisions is not only a method to create exotic nuclei at energies far above the Coulomb barrier suitable for secondary nuclear reactions but also a process interesting in itself. At the GSI projectile fragment separator the fragmentation of heavy nuclei throughout the whole periodic table from oxygen to uranium and in an energy range between 500 to 1000 MeV/u was investigated for the first time systematically including reaction cross-sections and reaction kinematics. The experimental results were compared to improved spallation systematics and macroscopic as well as microscopic models such as the abrasion-ablation and the intranuclear cascade models. A reaction of special interest turned out to be the nucleon exchange. The high resolution of the GSI projectile fragment separator allows to investigate directly nucleonic excitation. At relativistic energies the Coulomb induced fission of uranium seems a promising processes to produce neutron rich isotopes. With the projectile fragment separator it is possible to investigate simultaneously complete series of isotopes along cuts of constant A/Z in the nuclear charge and mass distributions of the fission products. At these high energies where atomic nuclei are bare or almost bare new data on the interaction of heavy ions with matter such as energy loss and ionic charge distributions were measured and compared to theoretical predictions. First steps towards reactions with secondary beams were investigations on the halo nuclei $^7$Li and $^{11}$Be and a first experiment on elastic proton scattering in reversed kinematics on the unstable doubly magic nucleus $^{56}$Ni. The study of fragmentation of secondary beams has been started and gives interesting results on the evaluation of the nuclear charge distributions in dependence of the proton abundance in the projectile. A new and interesting field in the investigation of the fission process has been opened with the possibility to investigate the fission of the heavy secondary products produced by uranium fragmentation.
MULTIFRAGMENT EMISSION IN THE REACTION $^4$He + Au
AT THE ENERGIES 0.985 AND 3.65 GeV/A

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Multifragmentation is a dominant decay mode of highly excited nuclei. We performed the experiments to study multifragmentation in the system $^4$He+Au at incident energies of 0.985 and 3.65 GeV/nucleon. The advantage of $^4$He as a projectile is that intermediate mass fragments (IMF) originate from the only source — a target spectator. The new 4π-setup FASA installed on the JINR synchrophasotron was used [1]. This detector system includes a FMD - fragment multiplicity detector (55 scintillation counters with thin CsI(Tl) films), 5 time of-flight telescopes (TOF) and a large position-sensitive avalanche chamber (PPAC). Every TOF serves as a trigger of the system, giving the masses and velocities of the fragments detected. As for FMD, a rough selection of the fragment charges is possible. With off-line thresholds on the amplitude of the scintillation detectors protons, helium nuclei and heavy fragments are suppressed and the IMF multiplicity (3 < Z < 15) is deduced from the measured multiplicity. The following values were obtained for the average primary IMF multiplicities: 3.6±0.6 and 5.3±0.8 for the beam energies 0.985 and 3.65 GeV/A, respectively.

By use of TOF and PPAC the relative velocity distribution of coincident fragments has been determined for large correlation angles. It is sensitive to the size of the decaying system. For $\theta_{corr} > 164°$ we have found that $V_{rel} = (3.95±0.09)$ cm/ns and $(3.77±0.02)$ cm/ns for two beam energies used. These values are explained in the framework of the statistical model considering the multifragment break-up of a diluted nucleus (with $R = 2.2 \cdot A^{1/3}$) [2]. The value of $V_{rel}$ is slightly decreasing with the increase of the fragment multiplicity.

The FMD gives the spatial distribution of the fragments in the event. The small angle correlations are sensitive to the time scale of the multifragmentation process. Fig. 1 presents the two fragment correlation functions $R_{12}(\theta_{rel})$, defined as $R_{12} = C Y_{1,2}(\theta_{1,2})/Y_{1,2}$, where $Y_{1,2}$ is the yield of coincidences between trigger 1 and fragment 2. The denominator $Y_{1,2}$ gives a coincidence rate for the same counter of FMD, but for another trigger 1′ for which $\theta_{1,2} > 90°$. This normalization reduces a systematical error due to uncertainties in the detector efficiency. These distributions show a significant depletion of the coincidences at the small relative angles. This effect is caused by the coulomb repulsion of the fragments, therefore it depends on the Z values of the fragments detected. The magnitude of this effect also depends on the average time interval between emission of the IMF's, which is expected to be around $10^{-21}$ s. Quantitative analysis of the data is in progress now.
Fig. 1. Two fragment correlation functions measured for the $^4\text{He} + \text{Au}$ reaction at 3.65 GeV/A. The ranges of Z-values of the detected fragments are shown in the upper part of fig.

References
COLLECTIVE EFFECTS AND NUCLEON EMISSION IN Bi+Pb COLLISIONS AT 1 GeV/NUCLEON

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Abstract

The collective sideward’s emission of nuclear matter in relativistic heavy ion collisions was first predicted on the basis of hydrodynamics [1]. Their occurrence, magnitude and dependence on in-plane and out-of-plane polar angles was connected to the degree of nuclear matter compressibility and consequently to the parameters of the Nuclear Equation of State (EOS). The aspect, which is not addressed in current models, is the comparison between the collective behavior of different particle’s species. Therefore we concentrated in our study to the quantitative comparison of 'squeeze out' and 'side splash' of neutrons, protons and deuterons in \(^{208}\text{Bi} + ^{209}\text{Pb}\) collisions at 1 GeV/nucleon. Experimental details were published elsewhere [2]. We unambiguously confirmed the persistence of the 'squeeze-out' of particles in relativistic heavy ion collision at 1 GeV/u, a phenomenon previously observed at 400 MeV/u \(^{197}\text{Au} + ^{197}\text{Au}\) collisions [3,4]. We also find that the magnitude of the 'squeeze-out' is similar for neutrons, the collision.

REFERENCES

2. A. Kugler et al., Proc. of the INTERNATIONAL WORKSHOP ON GROSS PROPERTIES OF NUCLEAR EXCITATIONS XX, Hirshegg, (1992),57
STUDY OF PERIPHERAL NUCLEAR COLLISIONS AT RELATIVISTIC ENERGIES


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The projectile fragmentation of relativistic heavy ions is an important method for the production of radioactive nuclear beams. A crucial point in the understanding of these peripheral heavy-ion collisions at high kinetic energies is the question how much excitation energy is induced in the spectator parts of the colliding nuclei. Generally, the projectile fragmentation can be described as a two-step process. In the first step some nucleons of the projectile are abraded in the nuclear collision. During the second step the spectator parts of the colliding nuclei, the prefragments, thermalize their excitation energy. They finally deexcite by evaporating additional nucleons, losing their initial properties and end up as projectile fragments which are observed experimentally. Nevertheless, some prefragment properties can be derived because it is possible to reliably describe the evaporation part by means of the statistical model. A crucial point in the understanding is the question, how much excitation energy is induced in the spectator. Experimental information on this point is still very scarce.

With this aim we studied the production cross sections and the longitudinal-momentum distributions of projectile fragments produced by 0.8 A GeV $^{136}$Xe and 1 A GeV $^{197}$Au projectiles impinging on targets of beryllium and aluminum, respectively. The experiment was carried out at the Fragment Separator at GSI. The excited prefragments which are produced in these reactions preferentially emit neutrons. Thus, the isotopic distributions of elements close to the projectile are directly related to the prefragment excitation-energy distributions. Our analysis of the distributions of Pt and Ir isotopes from $^{197}$Au projectiles yields an average excitation energy of about 26 MeV per nucleon removed in the nuclear collision. This is about twice as much as predicted by the statistical abrasion model which does not include final-state interactions between participant and spectator nucleons.

Another possibility to directly measure prefragment properties is to study reaction channels in which only protons have been removed from the projectile. As the evaporation of neutrons is excluded, the reaction products may be assumed to be directly produced below the neutron threshold in the nuclear collision. The measured cross sections for the observed proton-removal products from $^{136}$Xe and $^{197}$Au projectiles can be reproduced by model calculations using this assumption. As the properties of the proton-removal products are not influenced by evaporation, their longitudinal-momentum distributions should reflect the momenta of the removed protons prior to the nuclear collision. The measured momentum widths agree astonishing well with the predictions of the independent-particle model using the average Fermi momentum of the protons. In contrast, the momentum distributions of other measured reaction channels including neutron loss have appreciably lower widths which can be attributed to the influence of the evaporation process.

With this new experimental data, the conventional picture of a universal dependence of the projectile-fragment properties on the mass loss relative to the projectile must be refined. The study of specific reaction channels clearly reveals the different influence of the abrasion and the ablation step of the reaction.

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NEUTRON SPECTRA AND ANGULAR DISTRIBUTIONS FROM THE
$H + ^{40}Ca$ REACTION AT $E_{inc} = 400$ and $600$ MeV/amu

The Transport Collaboration


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A $^{40}Ca$ ion beam produced at the BEVALAC accelerator of LBL was sent onto a natural liquid hydrogen target (LH$_2$). Beam energies were 400A and 600A MeV. Charged particles and neutrons were detected in coincidence in a wide CM angular range.

To detect neutrons, measuring their energy spectra and angular distributions, a new modular neutron spectrometer, MUFFINS$^1$, was used. Its modules are 3 centimeter thick, 50 centimeter radius discs of NE102A scintillator, each seen by 5 fast photomultipliers coupled to TDC and ADC devices. Time of flight and position of each hit can be deduced from TDC values with a resolution of 130 ps and 3 cm, respectively. For this experiment we mounted 3 such discs (the largest available configuration consists of 30 discs) in a coaxial packet along the beam axes, 9 meters downstream of the target, so subtending 3.2° around 0 degrees. Each disc has an intrinsic neutron efficiency of about 3%.

Charged particles were deflected by a superconducting magnetic spectrometer (HISS) towards a 45-plane drift chamber followed by a highly segmented scintillator time of flight wall.

In this contribution we report some results obtained with the neutron spectrometer MUFFINS.

As a matter of fact, while charged particle emissions have been extensively studied, neutron emission has been essentially neglected so far for neutron energy $E_n > 100$ MeV or, at most, it has received little attention. Only a few papers refer to this subject 2), which instead seems very interesting for different reasons, mainly related to the insensitivity of neutrons to the Coulomb field:
i) Neutrons are one of the best tools to measure nuclear densities in the intermediate stage of a collision through Hanbury-Brown/Twiss effect.

ii) Neutrons are emitted by evaporation with much lower relative energy and consequently in much larger number than protons. So their energy spectra and angular distributions can be better related to prefragments than those of protons or more massive charged particles. Differences between proton and neutron spectra and variations in multiplicity ratio at different nuclear temperatures can then help to discriminate between sequential and direct fragmentation.

iii) Neutron multiplicity can be also a very good index of centrality of collision.

We will show energy spectra and angular distributions of neutrons emitted in the \( \text{H} + \text{Ca} \) reaction at \( E_{\text{inc}} = 400 \) and 600 MeV/amu

References

ELECTROMAGNETIC PROCESSES IN RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

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The Weiszacker-Williams method of virtual quanta has recently been applied to the study of many different electromagnetic processes in high energy nuclear collisions. These include studies of nucleon removal, relativistic Coulomb fission, Higgs boson production, lepton pair production as well as many other processes. These studies will be reviewed in the context of the equivalent photon method. Emphasis will be placed on the recently observed very large electromagnetic dissociation cross sections for nucleon removal where the Weiszacker-Williams method appears to break down.
A hadronic transport model and its applications
in relativistic heavy ion collisions

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Abstract

A hadronic transport model and its applications for relativistic heavy ion collisions will be presented. The model is developed by solving numerically a coupled set of transport equations for the phase space distribution functions of nucleons, baryon resonances ($\Delta, N^*$) and pions. The model has been used to study pion multiplicity distributions and combinants in relativistic heavy ion collisions, mechanisms of intermittency, pion collective flow, the phenomena of the concave shape of pion spectra found at Bevalac and SIS/GSI. The main ingredients and the numerical techniques of the model will be discussed, typical results of model applications in studying the particle production mechanism and the heavy ion reaction dynamics as well as the nuclear equation of state of the high temperature, high density nuclear matter formed in relativistic heavy ion collisions will be presented.

References

   B.A. Li and W. Bauer, Phys. Rev. C44, 450 (1991);
Abstract

The HELIOS-3 (NA34) experiment at the CERN SPS consists of a muon spectrometer based on a large superconducting dipole magnet, scintillator hodoscopes and MWPCs, a hadron absorber made out of a low Z material ($\text{Al}_2\text{O}_3$) located 25 cm behind the target and two silicon ring detectors of suitable granularity to measure the event multiplicity in the dimuon acceptance.

The focus of this experiment is on dimuons at low $M_T$ (low mass and $p_T$), but the mass range up to the $\Psi$ is also covered by the experiment. Dimuons are measured over a wide rapidity interval, ranging from nearly central to very forward rapidities.

The dimuon mass spectrum of p-W is compared to central S-W interactions and an impressive difference is observed in the spectral shape and in the ratio of the $\rho/\omega$ resonance production relative to the dimuon continuum. We will discuss the experimental result, normalized to charged pion production, in different kinematic regions and as a function of the charged multiplicity.

The observed dimuon spectra are compared to conventional sources of lepton pair production: decays of the known resonances, including charmed mesons, and those due to the Drell-Yan process. Whereas the dimuon mass spectrum in p-W interactions can be fully described by these processes, the observed continuum in central S-W interactions exceeds significantly the level which is expected from decays as normalized to the $\rho/\omega$ production. The measured excess is well above our experimental systematic uncertainties.

Both the pure experimental observation that the reaction $SW \rightarrow \mu\mu X$ differs from the reaction $pW \rightarrow \mu\mu X$, and the comparison with conventional dimuon sources seem to be a strong indication for physical processes which do not follow simple extrapolations from proton nucleus interactions.
The process of single fragment production and the multifragmentation in the interaction of 1 GeV protons with Al, Ni, Ag and Au targets has been investigated at PNPI synchrocyclotron. The identification of fragments on M and Z was performed by two identical systems consisting of time-of-flight spectrometers and Bragg ionization chambers measured values of the maximum ionization losses (Bragg peak), the energy and the range of particles. These spectrometers were placed at the angles of 30° and 126° to beam direction. The multiplicity of fragments was measured by two parallel plate avalanche counters covering solid angle of 0.1 sr in coincidence at least with one of TOF spectrometers.

The parameter of slope of the energy spectrum in moving frame ("temperature"), the value of Coulomb barrier, the velocity of emitting source and yields of IMF have been determined for Au, Ag and Ni targets from simultaneous approximation of the energy spectra of the fragments at forward and backward angles by modified Maxwellian distribution. Yield of fragments as function of the charge in the range of \( Z = 3-20 \) are defined and fitted by a power law \( \sigma(Z) \sim Z^{-\zeta} \). For Ni and Ag target \( \zeta = 2.7 \pm 0.2 \). However for Au target the charge yields are not described by a power law and cross section for \( Z > 10 \) remains almost constant. The result of energy spectrum approximation agrees with the assumption that only one source of fragments is enough to describe the most part of the experimental data. The values of longitudinal component of the source velocity \( \beta_\parallel \) are practically independent on the charge for Au, in the case of Ni and Ag targets one can see increasing of \( \beta_\parallel \) until \( Z = 8 \).

The evaluation of fragment multiplicity from coincidence measurements indicates that the number of coincidence events increases from Au to Ni and does not exceed a few percent of inclusive cross section (0.4%, 1.6% and 2.4% for Au, Ag and Ni target, respectively).
K4-K10 PROJECT
TREBLE: TWO RING EXOTIC BEAM LABORATORY

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TREBLE is a modification of the Dubna project of the heavy ion storage ring complex K4-K10 [1]. It is predestinated to provide high precision beams of exotic nuclei with mass numbers of A<50 in an energy range from few MeV to about 200 MeV/nucleon. The availability of beams of very short lived nuclear specimen is a unique feature of this project. Due to the electron cooling, the beam quality will be improved to a level of a very high momentum resolution (ΔP/P=10⁻⁶) and transverse emittance (ε=0.1 μm⋅mrad) for the nuclei having the lifetime of >50 ms. For the beams of the nuclei with much shorter decay time, close to one millisecond, a considerable monochromatisation to the level of ΔP/P=10⁻⁴ will be available either on the ring orbit or due to the beam rebunching just before its injection in the ring.

We preserve for TREBLE the principal conception of the K4-K10 project which is based on the idea to use two storage rings both equipped with electron cooling. The first ring is intended to accumulate the primary beam from the sector focusing heavy ion cyclotron U400M, to cool this beam and to increase the energy to about 120-170 MeV/amu. The high quality primary beam obtained from the first ring as a result of fast extraction is used to produce secondary beams of exotic nuclei which, after separation by an energy loss achromat, are injected in the second ring. Here exotic beams are cooled, and one can, depending on the lifetime, either to accumulate and control the beam energy (i.e. to accelerate or, rather, decelerate), if the lifetime of exotic nuclei is more than one second, or to irradiate an internal or external target with the high precision beam immediately after cooling, if the lifetime of the exotic beam nuclei is less than one second.

The beams of very exotic nuclei, even such as ⁷¹Li, ¹⁷B, ²⁸Ne etc having life times in the millisecond region, will be accessible to experiments at TREBLE. The luminosity values will be accessible ranging between 10²⁴ and 10³⁰ cm⁻²*s⁻¹ depending on the life time and displacement of exotic nuclei from the drip line.

We specify the first stage of the project which implies the building of the first ring K4. The high peak primary beam currents provided by the injector cyclotron U400M give us favorable conditions to produce the secondary beams which can be effectively accumulated and cooled.
in K4. In Table we give parameters of some exotic beams which will be obtained after the completion of the first stage.

**Exotic Beams in K4**

<table>
<thead>
<tr>
<th>BEAMS</th>
<th>( T_{1/2} ) (sec)</th>
<th>( N-N_{\text{drip}} )</th>
<th>( E_{\text{min}} ) (MeV/amu)</th>
<th>( E_{\text{max}} ) (MeV/amu)</th>
<th>NUMBER OF IONS ON ORBIT</th>
<th>( L ) (s(^{-1}) cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^6)He</td>
<td>0.808</td>
<td>2</td>
<td>42</td>
<td>80</td>
<td>( 10^4 )</td>
<td>( 10^{24} )</td>
</tr>
<tr>
<td>(^8)He</td>
<td>0.122</td>
<td>0</td>
<td>43</td>
<td>50</td>
<td>( 10^2 )</td>
<td>( 10^{22} )</td>
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<tr>
<td>(^8)Li</td>
<td>0.84</td>
<td>3</td>
<td>41</td>
<td>105</td>
<td>( 10^4 )</td>
<td>( 10^{24} )</td>
</tr>
<tr>
<td>(^9)Li</td>
<td>0.178</td>
<td>2</td>
<td>44</td>
<td>80</td>
<td>( 10^3 )</td>
<td>( 10^{23} )</td>
</tr>
<tr>
<td>(^{11})Be</td>
<td>13.8</td>
<td>2</td>
<td>44</td>
<td>100</td>
<td>( 10^4 )</td>
<td>( 10^{24} )</td>
</tr>
<tr>
<td>(^{12})B</td>
<td>0.02</td>
<td>5</td>
<td>40</td>
<td>125</td>
<td>( 10^5 )</td>
<td>( 10^{25} )</td>
</tr>
<tr>
<td>(^{16})C</td>
<td>0.75</td>
<td>6</td>
<td>42</td>
<td>105</td>
<td>( 10^3 )</td>
<td>( 10^{23} )</td>
</tr>
<tr>
<td>(^{14})O</td>
<td>70.6</td>
<td>2</td>
<td>36</td>
<td>225</td>
<td>( 10^4 )</td>
<td>( 10^{24} )</td>
</tr>
<tr>
<td>(^{24})Ne</td>
<td>225</td>
<td>8</td>
<td>20</td>
<td>125</td>
<td>( 10^6 )</td>
<td>( 10^{26} )</td>
</tr>
<tr>
<td>(^{28})Mg</td>
<td>( 7 \times 10^4 )</td>
<td>12</td>
<td>20</td>
<td>130</td>
<td>( 10^7 )</td>
<td>( 10^{27} )</td>
</tr>
<tr>
<td>(^{38})S</td>
<td>( 1 \times 10^4 )</td>
<td>14</td>
<td>17</td>
<td>130</td>
<td>( 10^7 )</td>
<td>( 10^{27} )</td>
</tr>
<tr>
<td>(^{44})Sc(^{m})</td>
<td>( 2 \times 10^5 )</td>
<td>9</td>
<td>22</td>
<td>160</td>
<td>( 10^8 )</td>
<td>( 10^{28} )</td>
</tr>
</tbody>
</table>

**References**

The advent of Radioactive Nuclear Beams (RNB) in this decade may rival in importance the development of heavy ion beams in the 1960’s. Radioactive projectiles remove the restraint to the natural N/Z ratios of stable beams in nuclear-, astrophysical-, atomic-, and material science experiments and add the new dimension of isospin to the two classical dimensions of nuclear spin and temperature. A group of scientists has recommended that the North American nuclear physics community should seriously pursue the construction of a dedicated, flexible, broad-range RNB facility that would provide intense beams of nearly all elements for a program of scientific studies in nuclear structure, nuclear reaction dynamics, astrophysics, high spin physics, nuclei far from stability, material- and surface science, and atomic- and hyperfine-interaction physics. The initiative has, tentatively, been given the name IsoSpin Laboratory (ISL) to underscore the key feature of this new physics tool.

Several RNB facilities, utilizing the fragmentation of heavy ion projectiles, are in operation; others are planned. They produce RNBs in the energy range of 10’s of MeV/u to ~1000 MeV/u. For the North American Project a complementary approach to RNB production has been chosen. The ISL is based on the coupling of two accelerators: the first to deliver a high current light ion beam to a thick, hot spallation- or fission target and the second to accelerate the emanating radioactive species to energies in the range from a few keV to ~25 MeV/u with excellent beam qualities, typical of modern heavy ion accelerators. New technical developments have made it possible to achieve RNB intensities and purities adequate for meaningful experiments. The key advances are in high current light ion machines, new ion sources (Laser, ECR), low-β accelerating structures, RFQs, and super conducting LINACs. Many of these will be incorporated in the proposed IsoSpin Laboratory. Expected beam intensities will vary from ~10^11 to a few ions per second, depending mainly on how far the beam is removed from the line of beta stability and on the physical/chemical properties of the element. Due to the inherently low intensities and the radioactive nature of the beams experiments have to be highly efficient and insensitive to background radiation.

An overview of the ISL and a brief summary of the proposed scientific program will be given and the state of the planning activities will be discussed.

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THE PIAFE PROJECT AT GRENOBLE.

The PIAFE Collaboration

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ABSTRACT Grenoble is characterized by the existence, in nearby sites, of a possible source of exotic nuclei, the high flux reactor of the Institut Laue Langevin (ILL) and of a low to medium energy heavy ions accelerator complex, SARA. We propose to couple these two facilities, in order to obtain intense radioactive beams at a moderate cost.

The aim is to produce neutron rich nuclei with masses between 75 and 150 amu and energies between 2 and 20 MeV/amu (or 30 KeV immediately after the mass separator). The accelerated intensities will depend on the production rates, extraction efficiencies and final energies and should range between $10^5$ and $10^9$ particles per second.

For the fission source, we consider two target arrangements. The first source, using surface ionization and electron impact ionization is specialized for alkalines and earth-alkalines: a 1 gram amount of $^{235}U$ mixed with graphite is immersed in a $6 \times 10^{12}$ neutrons/cm$^2$/sec. flux. This would lead to approximately $7.5 \times 10^{12}$ fissions/sec.

The second target-source arrangement is specialized for rare gases, and possibly, halogen production: a 1 gram amount of $^{238}U$, possibly in oxide form, mixed with emanating material such as alumina or magnesia is immersed in an $1 \times 10^{14}$ n/cm$^2$/sec yielding $1.25 \times 10^{14}$ fissions/sec. A 2.5 meters long transfer tube, guides the emanated gases to an ECR source situated in a low flux environment.

After acceleration between 10 and 30 KeV, the singly charged ions should be mass analysed in a standard mass separator, directly situated outside the reactor biological shield. The $q=1^+$ ions would be transported, under vacuum, from the mass separator output to the SARA site, where they would be injected into the ECR source. In order to reduce the cost of the 400 m transfer line between the ILL and SARA, we consider using Septier type quadrupoles which are, essentially, massive conductors through which currents flow with opposite signs. Simulations show that recencting of the beam each 50 meters will probably be needed in order to insure acceptance of the beam guide exceeding 100 mm.mrad.

The 30 KeV $1^+$ beam would impinge on a heated catcher from which the atoms would be evaporated into the plasma of the high charge state ECR source of the SARA system. The multiply charged ions are injected into the first K=88 cyclotron (energy range between 1.9 and 5 MeV/amu, depending upon the charge states).

The present gain of the second cyclotron is equal to 5.4. We plan to modify the extraction system in order to make the gain continuously varying between 2 and 4.2. With this modification the beam energies for Krypton could be varied continuously from 2 to 20 MeV/amu, and that for Xenon from 2 to 10 MeV/amu.
At L.N.S. heavy ion beams with energies in the range $20\div100$ MeV/a.m.u. will be available in the near future: the 15 MV Tandem beam will be radially injected into the K-800 Superconducting Cyclotron, which is now being completed. In a few years the Cyclotron will be operated in stand-alone mode: a superconducting ECR source has been designed to be coupled to the machine and is under construction.

Two different radioactive ion beam facilities, covering different energy ranges, are planned to be developed after the commissioning of the Cyclotron.

The intermediate energy facility, based on the FRS method, is completely designed. Secondary radioactive beams will be produced from the Cyclotron beams by projectile fragmentation on a thin target. A fragment recoil separator will collect the recoils and analyze them with respect to A and Z by the degrader technique.

The general lay-out of the low energy facility, based on the ISOL method, has been fixed, but R&D work still needs to be accomplished on each component. This facility will be developed by exploiting the LNS accelerator facility (including the beam lines): the Cyclotron will provide the primary beam for the production of radioactive recoils on a thick target. A proper source will ionize negatively the recoils, which will be mass analyzed and then accelerated by the Tandem.

The main features of the design for the two facilities are here presented. Estimates for the secondary ion beam intensities are discussed.
Research at the Fragment Mass Analyzer at ATLAS*

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The Fragment Mass Analyzer (FMA) is a triple-focussing (x, y, energy) recoil mass spectrometer currently in use at the ATLAS heavy-ion facility located at Argonne National Laboratory. It separates nuclear reaction products from the primary heavy ion beam and disperses them by mass/charge (M/q) at the focal plane. It has a solid angle of about 8 msr, an energy acceptance of ±20% around the central energy, and an M/q acceptance of ±4% around the central mass.

The figure shows an M/q spectrum taken at 0° to the primary beam with fusion products from 215-MeV $^{58}$Ni on $^{64}$Ni. A mass resolution of 525:1 was obtained.

Because of its high mass resolution and large acceptances in solid angle, energy, and M/q, the FMA is particularly suited for the study of weak reaction channels. The FMA is equipped with a ten-element Compton-suppressed germanium detector array and a sixteen-element neutron detector array around the target, as well as implantation detectors at the focal plane. Results of experiments at the FMA will be presented, and future plans will be described. These include studies of heavy element production and nuclei far from stability.

*Work supported by the U. S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.
THE COMBAS PROJECTILE FRAGMENT SEPARATOR
PRESENT AND FUTURE


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The COMBAS projectile like fragment separator is being constructed at the Flerov Laboratory of Nuclear Reactions JINR (Dubna) for experiments with intermediate energy heavy ions of the U-400M cyclotron or the tandem of U-400M and U-400 cyclotrons. Equipped with a high efficiency ECR source, the U-400M cyclotron can accelerate rare isotopes 16O, 22Ne, 26Mg, 36S, 48Ca up to 50-60 MeV/A with high intensity (10^{14} - 10^{12} pps).

Our efforts were mainly concentrated on designing a high resolution fragment-separator with a high efficiency of collecting the exotic nuclei which are produced with a wide energy and angular distributions. A high intensity primary beams of heavy ions, a wide assembly accelerated ions (especially rare isotopes) on the U-400M cyclotron in conjunction with high effective COMBAS fragment-separator determine advantages of this project. For radioactive nuclei with ultrasmall yields and very short-lived the efficiency of the COMBAS separator can exceed a few tens or hundred times of the efficiencies for L1SE and RIPS separators.

"On-line" with the COMBAS separator we plan to use the next unique of a detecting systems:
- the three-dimensional track detector multiplicity in the mode detector gas target-detector,
- the 4\pi - \gamma and 4\pi-charge particles spectrometer FOBOS,
- the laser set-up,
- the 4\pi-neutron detector.

The combination of a high efficient and high resolution COMBAS separator with high luminescence and informative of detecting systems offer a unique possibilities for a full-scale of nuclear- and atomic-physicals, astrophysicals and applied of investigations with unstable secondary projectiles.

At present the main magnets components of the facility and their vacuum chambers are ready and are being prepared for testing.

In this contribution the status, the commissioning phase and the first planned experiments will be described.
The electron cooling become to-day a practical and widespread instrument for obtaining the beams of the very high quality in the energy domain between a few and some hundreds of MeV/nucleon. This is achieved by exploiting cooler electron beams of the energy between a few and some hundreds of keV. Unique parameters of cooled heavy ion beams are their high density and monochromaticity which can not be achieved in any other way. This provides for principally new possibilities in nuclear physics experiments. At present, several coolers - one storage ring of antiprotons (LEAR, CERN) and eight heavy ion storage rings are working in different laboratories in the world.

The progress of electron cooling proceeds along the following directions leading to the increase of the rate and degree of cooling and widening of the region of the beam parameters where the electron cooling is applicable. This implies the following:
- use of cooling electron beams with ultimately high intensity,
- development of cooler systems with the space charge neutralization of the electron beam,
- extension of the electron energy maximum value to few units and even to tens of MeV,
- efficiency increase of the electron beam energy recuperation.

One specifies three topical applications of cooler rings:
- accumulation and control of antiproton (proton) and heavy ion beams, respectively, for experiments in particle and nuclear (atomic) physics,
- accumulation and precooling of proton and heavy ion beams for further acceleration to TeV energy region (the projects LHC and SSC).

Nontraditional applications of the electron cooling method are discussed. In particular, this is the cooling of circulating beams of positrons which could be a source of antihydrogen beams.
In connection with experiments on electron cooling of ions in storage rings [1] it is of interest to consider the inverse process — namely, stimulated recombination of atoms (ions) with subsequent population of hyperfine-structure (HFS) components. Effects involving stimulated recombination of atoms in proton-electron beams were considered in Refs. [2] and [3]. It was shown that under certain conditions, ensured by the method of electron cooling, the rate of stimulated recombination considerably exceeds the rate of spontaneous recombination. In view of this, it is natural to expect that in the case of stimulated recombination in the field of a circularly polarized wave it will be possible to observe effects involving the optical polarization of nuclei. This effect is considered for the case of the proton-electron beams used in the method of electron cooling. An estimate is obtained for the maximum degree of polarization of the protons on components of the HFS of the 2s-state of the hydrogen atom.

References
At the Flerov Laboratory of Nuclear Reactions in Dubna the ECRIS DECRIS is being built beginning with 1990. The source, like classical MINIMAFIOS, has two stages. In the first one a cold plasma is ignited and then it diffuses towards the second stage with the "minimum B" configuration. The axial magnetic field is produced by water cooled solenoidal coils which consume a power of 130 kW. The radial magnetic field is produced by a NdFeB hexapole with a magnetic field on the ionization chamber surface of about 0.8 T.

Recent results of extracted beams from the ion source DECRIS for argon, oxygen, nitrogen and helium are near to ion currents from MINIMAFIOS but there are some ways to improve an ion source performance. These include gas mixing effect or "ion cooling", the improvement of first stage construction and rising the total level of magnetic field by using additional soft iron.

Of special interest is the production of a short multicharged ion pulse for injection into a heavy ion storage ring, which is being designed at the FLNR now. For this reason the previous experiments on the DECRIS operation in the so called "afterglow mode" were carried out.

The estimates of energies and intensities of accelerated ion beams which can be produced by coupling an ECR source to FLNR cyclotrons in comparison with those accelerated from PIG ion source shown that the use of an ECR ion source results in gains in both the energy and intensity of high charge state ion beams in all cyclotrons, as for the U-400M, it will be possible to operate it in autonomous regime to accelerate ions up to Xe.
THE 4π-FRAGMENT SPECTROMETER FOBOS - STATUS AND FIRST PRELIMINARY RESULTS


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The FOBOS spectrometer (collaboration Dubna - Rossendorf - Berlin) is intended for heavy ion reaction studies in the bombarding energy range of 10...100 AMeV /1-3/. In its final stage it will consist of a "gas ball" of 30 position-sensitive avalanche counters and 30 axial ionization chambers behind them. A TOF base of 50 cm and a sensitive depth of 25 cm determine their dimensions. A shell of 210 CsI(Tl) scintillation counters surrounds the gas ball. As forward array, the ARGUS detector system /4/ is planned to be used.

CAMAC and FASTBUS front-end electronics have been connected via a central VME crate to a Micro-VAX computer for data acquisition. The respective software developed on the base of the HOOPSY system has been tested in an experiment at VICKSI (HMI Berlin).

All detector types have been tested at the "mini"-FOBOS set-up, a small reaction chamber at a U-400 beam line. This set-up allowed also to test the front-end electronics

1 This Project is financially supported by the Bundesministerium für Forschung und Technologie, Contract No. 06 DR 100
Fig. 1: Cut of the FOBOS Array

1. Vacuum chamber  
2,3. Detector module cases  
4. Position sensitive avalanche counters  
5. Bragg ionization chamber  
6. Scintillation counter  
7. Forward wall

and the first-level trigger with two avalanche counters and two ionization chambers, as well as a model of the remote-controlled evacuation and gas-supply system. The data recorded in test runs with radioactive sources and heavy-ion beams were used for generation and test of simulation, calibration and analysis routines.

First results have been achieved concerning near-barrier reaction cross sections (4.5AMeV $^{84}$Kr on $^{116}$Sn and $^{118}$Sn) and fission after incomplete fusion (10AMeV $^{40}$Ar on $^{198}$Pt), demonstrating the advantage of an independent mass determination for each registered product.

Presently (February 1993) the FOBOS detector is equipped with 6 of 30 modules. The whole system is being prepared for first commissioning runs.

References


Upgrades to the Michigan State University 4\pi Array
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The original 4\pi Array [1] covers the sphere with 32 sectors (20 hexagons and 12 pentagons) arranged like the sectors in a soccer ball. One pentagon is reserved for the entrance of the beam and for the target mechanism and TV camera. Originally, the opposite pentagon was left empty to allow for the exit of the beam. Among the upgrades described below are arrays of particle detectors for this forward-angle sector. Each of the 30 modules in the original design consist of three layers of detectors. The inner layer is a position-sensitive, low-pressure multiwire proportional counter. The middle layer is a 15 cm deep ion chamber that functions as a Bragg curve detector [2] which measures the Z of particles that stop in it. The outer layer is a set of phoswich telescopes, 6 in each hexagon module and 5 in each pentagon module, a total of 170 independent detectors. Each phoswich is a 3 mm thick, \Delta E, fast plastic scintillator followed by 25 cm of plastic scintillator with a longer time constant. The detectors and the photomultipliers for the phoswiches are located inside the vacuum. This is different from the similar FOBOS array in Dubna where the photomultipliers and part of the scintillators are outside of the vacuum.

The five hexagon modules surrounding the forward angle pentagon extend to within 16.5° of the beam and so have a large counting rate. One of the upgrades was the division of the Bragg curve detectors into six segments to match the phoswich detectors. Another upgrade replaced the argon-methane gas in these detectors with heavy fluorocarbons, C\textsubscript{2}F\textsubscript{6} and C\textsubscript{3}F\textsubscript{8} [3]. A gas recirculator-purifier system was developed so that the expensive gas could be reused indefinitely. The heavy gas allowed the use of lower pressures which increased the reliability of the gas windows.

Two types of detector arrays are used in the forward pentagon. One is a set of 45 phoswiches. This array can be used with high counting rates without pulse pileup or radiation damage. A more expensive array, with a lower energy threshold and better energy, charge, and mass resolution is now being constructed by the University of Iowa and the University of Maryland. It uses silicon \Delta E detectors with CsI(Tl) or phoswich E detectors. For angles extending down to 5°, there are 60 CsI(Tl) crystals, read out with silicon photodiodes, arranged in three pentagonal rings of 20 crystals each. The silicon \Delta E detectors are combined into larger, segmented detectors with two or four segments. This allows a larger solid angle to be covered by the silicon by eliminating some of the dead area around the edge. The angles from 5° to 2.5° are covered by a position sensitive, annular silicon detector in front of a ring of 16 phoswich detectors.

All of the ADCs and QDCs are located in CAMAC crates and are read through fast ECL outputs. These are collected in a buffer and processed by a set of transputers before they are sent to the main data acquisition computer. The dead time per event is 50 μs. A 16 bit ADC with a large dynamic range and an ECL readout is being developed at Michigan State University for use with the new forward array.

INVESTIGATION OF INTERACTIONS OF RELATIVISTIC NUCLEI AT SPHERE 4π DETECTOR

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SPHERE (fig.1) is a 4π detector designed to obtain as much detailed information as possible on multiple cumulative particle production at the JINR Synchrophasotron and Nuclotron [1,2]. The spectrometer contains three major components: a central detector for the detection of particles from the target-nucleus fragmentation region, a forward detector covering the projectile-nucleus fragmentation region, and a target for the generation of muon pairs with a beam absorber. The detector system consists of electromagnetic calorimeters, dE/dx and time of flight scintillator hodoscopes and Cherenkov counters identifying γ, e, π, K, p, d, t, α etc. The tracks are measured with MWDC’s and MWPC’s.

The status of the spectrometer SPHERE is as follows: the first line of the forward detector was operated since 1990, it is hoped that the 4π detector will be completed by the middle of 1996. The main problems to be solved are to investigate the reactions of the production of two and more particles in the region corresponding to resonance production (in particular, the production of vector particles in the cumulative region), to study the production of lepton pairs in collisions of relativistic nuclei, and to investigate spin effects in large transverse momentum reactions.

In 1990 a beam dump experiment on production of low-mass cumulative muon pairs by 9.0 GeV/c deuteron beam was performed at the JINR Synchrophasotron by means of the forward detector of the SPHERE spectrometer [3].

In 1991 the power value of A-dependence of cross-section for 9.0 GeV/c deuteron fragmentation into cumulative pions was measured on carbon, aluminium, copper, and lead nuclei.
for cumulative numbers within $0.8 - 1.2$ [4]. The mean value is equal to $0.27 \pm 0.09$ in this interval. The target atomic weight dependence significantly differs from the volume type dependence on the atomic weight of fragmenting nucleus (fig.2).

In March 1992 the experimental data on cumulative pion production have been acquired for a $9 \, \text{GeV}/c$ polarized deuteron beam bombarding polyethylene, carbon, tin and lead targets. Measurements of the target fragmentation multiplicity, correlating with straightforward flying cumulative pion, are added to our experimental facility. The detailed analysis of these experimental data is in progress now.

References


   A.I. Malakhov. In Proceeding of International Conference on Nuclear and Particle Physics, Liverpool, April 8-11, 1991, p.44.


THE DUBNA GAS-FILLED RECOIL SEPARATOR:
A FACILITY FOR HEAVY ELEMENT RESEARCH


Joint Institute for Nuclear Research, Dubna

The separator was put into operation in 1969. Its D-Q-Q design, main parameter values as well as first tests at the U400 cyclotron were described in Ref.[1]. Since then many significant improvements and numerous model experiments were accomplished to develop the separator into a facility for heavy element research. Owing to its underlying principle, the separator shows excellent qualities for fusion-evaporation reactions induced by $^{40}$Ar and similar projectiles. Therefore the main goal of our recent developments was to achieve a reliable application of the separator to highly asymmetric fusion-evaporation reactions induced by much lighter projectiles like $^{18}$O or $^{22}$Ne on targets of the transuranium nuclides. Special emphasis was laid on the possibility of applying very intense beams of these lighter projectiles to strongly radioactive and rather exotic target species like $^{242}$Pu or $^{244}$Cm.

Being very attractive from the viewpoint of heavy element research, the highly asymmetric reactions represent the most difficult case for studying these with recoil separators. As compared, e.g., to $^{40}$Ar-induced reactions, the asymmetric reactions are characterized by much broader angular distributions of evaporation residues (EVRs) recoiling out of a target of a finite thickness; thus, only some 15 to 30% of the EVRs are accepted by the D-magnet (see the Figure). The large angular divergency of the EVRs restricts effective target thicknesses by values of about 0.2 mg/cm$^2$ or less. Other complications originate from low kinetic energies $\langle E_R \rangle$ of EVRs recoiling out of the target as well as from large dispersions of $E_R$. Perceptible $\langle E_R \rangle$ losses occur in the 3.7-m long path of EVRs through the gas filling the separator (usually H$_2$ at $\approx 1$ Torr), as well as in the exit window and in pentane gas filling the detection module. As it was shown in our measurements with the $^{244}$W+$^{22}$Ne reaction, the transmission of EVRs through the separator and hence the efficiency $e_e$ of the EVR collection onto the focal plane Si detector array falls down rapidly with Lay-out of the separator. The detection system of the separator involves six individual 20 mm wide by 30 mm high Si detectors covering an area of 120x30 mm$^2$ at the focal plane. Two large-area (120x60 mm$^2$) multiwire proportional chambers placed in pentane at $\approx 1$ Torr are used for time-of-flight measurements of EVRs and background particles arriving at the Si detectors. The 0.5-μm mylar exit window separates the detection module from the gas media of the separator.
<table>
<thead>
<tr>
<th>Target Projectile Z of EVRs</th>
<th>( ^{24}\text{Ne} )</th>
<th>( ^{235,238}\text{U} )</th>
<th>( ^{238}\text{U} )</th>
<th>( ^{242}\text{Pu} )</th>
<th>( ^{206,207}\text{Pb} )</th>
<th>( ^{207}\text{Pb} )</th>
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<td>( ^{16}\text{O} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( ^{18}\text{O} )</td>
<td>93</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>( ^{20}\text{Ne} )</td>
<td></td>
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<tr>
<td>( ^{22}\text{Ne} )</td>
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<td>( ^{26}\text{Mg} )</td>
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<tr>
<td>( ^{30}\text{S} )</td>
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<td>( ^{34}\text{S} )</td>
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<td>( ^{40}\text{Ar} )</td>
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<td>Beam energy, MeV</td>
<td>112</td>
<td>11.0</td>
<td>122</td>
<td>114</td>
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<td>196</td>
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<tr>
<td>( &lt;E_R&gt; ), MeV</td>
<td>11.0</td>
<td>5.8</td>
<td>8.7</td>
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<tr>
<td>( q )</td>
<td>3.3±0.1</td>
<td>2.1±0.1</td>
<td>2.3±0.1</td>
<td>6.2±2</td>
<td>6.2±2</td>
<td>10±0</td>
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<tr>
<td>( \epsilon_c ), %</td>
<td>16±3</td>
<td>3±1</td>
<td>6±2</td>
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<td>-full energy</td>
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<td>-scattered projectiles</td>
<td>2-10^{16}</td>
<td>7-10^{16}</td>
<td>5-10^{18}</td>
<td>10^{14}</td>
<td>5-10^{12}</td>
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<td>-target-like products</td>
<td>&gt;10^{3}</td>
<td>&gt;10^{4}</td>
<td>&gt;10^{4}</td>
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<td>Image size (FWHM)</td>
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<td>8.7±1.4</td>
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<td>-horizontal, cm</td>
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<td>-vertical, cm</td>
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<td>2.1±0.1</td>
<td>3.5±0.2</td>
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Decreasing \( <E_R> \), from \( \epsilon_c=18% \) at \( <E_R>=12.5 \) MeV down to \( \epsilon_c=8% \) at \( <E_R>=4.5 \) MeV. Furthermore, a decrease in \( <E_R> \), i.e., in the average EVR velocity, causes a lowering of the average charge state \( <q> \) of EVRs in the gas media and seems to give rise to significant fluctuations of \( q \). Appreciable \( q \) fluctuations at the low \( <q> \) values characteristic of EVRs from very asymmetric reactions are supposed to give additional reasons for fairly low EVR collection efficiencies \( \epsilon_c \) in these cases as well as for extended image sizes at the focal plane.

A summary of measured or estimated (starred) characteristics of separation is presented in the Table (here \( <E_R> \) values are given for EVRs recoiling out of the middle of the target used in a particular experiment). It is seen that collection efficiencies \( \epsilon_c \) for heavy EVRs produced by highly asymmetric fusion-evaporation reactions range between 3% and 10%. However, despite the fairly low \( \epsilon_c \) values, the net sensitivity of experiments can be essentially improved by applying very intense beams of \( ^{16}\text{O}, ^{22}\text{Ne} \) and other lighter projectiles, up to \( (2-4)\times10^{13} \) pps, which are provided by the Dubna U400 cyclotron. To accept such intense beams, the separator is equipped with beam wobbling systems, fast rotating entrance windows, rotating target wheels, etc. We stress also that for asymmetric reactions a very favourable separation quality lies in the extremely strong suppression of both full energy and scattered projectiles.

The potentialities of the separator for heavy element research with very asymmetric reactions can be exemplified by our recent experiments on the production of isotopes of element 104 in the \( ^{242}\text{Pu}+^{22}\text{Ne} \) reaction [2]. In these experiments, the \( ^{22}\text{Ne} \) beam with a typical intensity of \( 1.5\times10^{12} \) pps applied to a rotating target of \( ^{242}\text{Pu} \) allowed us to reach, in several days, a total beam dose of \( 3.6\times10^{14} \) and to detect between cyclotron beam pulses many tens of \( \alpha \) and SF decays of the isotopes \( ^{259}104 \) and \( ^{260}104 \) which are produced in the given reaction with cross sections of the order of 1 nb. A remarkable long-term stability of the separator operation was revealed in the 104 experiments.

References
SELECTIVE TRACK RADIOGRAPHY OF Bi-Pb AND Au-Pt IN MINERALS WITH ACCELERATED $^{12}$C IONS

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Moscow Physical Engineering Institute, Moscow, Russia

Abstract

The problem of low concentration selective measurements of the elements Bi, Pb and Au, Pt with the aid of accelerated heavy ions in minerals is discussed. In many cases it is necessary to determine not only the average contents of the heavy elements in a sample but also to determine its local distribution with spatial resolution at about 10 $\mu$m [1,2].

Our approach in solving that problem is based on the measurements of the yield of prompt fission fragments and induced $\alpha$-activity produced at the interaction of accelerated $^{18}$O ions with Bi, Pb, Au and Pt nuclei. The $^{12}$C ion exposures of metal foil targets of these elements and polished mineral samples were performed at the external beams of the accelerators U-200, U-400 of Flerov Laboratory of Nuclear Reactions, JINR at the energies 9.1 and 13.2 MeV/nucl correspondingly. The specimens were placed perpendicularly to the $^{12}$C beam. Before the exposure they were covered with 15-20 $\mu$m thick muscovite mica; the total $^{12}$C ion fluxes were between $3\times10^{12}$ and $10^{14}$ ions/cm$^2$.

After carbon ion exposure induced $\alpha$-activity of Po isotopes was registered by CR-39 plastic track detectors. Exposure time was 1.5 hour and 144 hours to detect short-lived and long-lived components, respectively for Bi, Pb, Au and Pt ethalons and for mineral samples.

It was established, that the yield of fission fragments in "2$\pi$-backward" geometry was within $\pm10\%$ the same for all the heavy elements being investigated. The observed local microdistribution of fission fragment tracks in muscovite mica was determined with the precision up to $\pm10$ $\mu$m. By examining of $\alpha$-sensitive CR-39 plastic track detectors it was found, that the yield of $\alpha$-particles for metallic Au and Pt targets was $\leq 10$ tr/cm$^2$, for Bi and Pb targets $\geq 10^6$ tr/cm$^2$.

Thus we can resolve the local microdistributions due to Bi, Pb and due to Au, Pt inclusions by comparing of fission fragment and $\alpha$-particle tracks microdistributions.


Analysis of equilibrium charge-state distributions for heavy ions after passing through carbon foils

A.G. Popeko, R.N. Sagaidak, A.V. Yeremin
Flerov Laboratory of Nuclear Reactions, JINR, Dubna

Precise knowledge of the mean equilibrium charge $\bar{q}$ and charge distribution width $d_q$ of ions after traversal of carbon foils is especially important for correct operation of on-line recoil separators of heavy ion induced nuclear reaction products like VASSILISSA [1].

Experimental data on $\bar{q}$ and $d_q$ reported before 1972 are summarized by Wittkower and Betz [2]; those between 1972 - 85 are compiled by Shima et al. [3], and more recent data after 1985 are included in [4].

The analysis of the data has revealed that the observed values have not always been well reproduced by existing formulae.

We have developed new semiempirical formulae for evaluation of the mean equilibrium charge and charge distribution width of ions after traversal of carbon foils. Our parameterization allows one to get more confidence in prediction of $\bar{q}$ and $d_q$.

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