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Experimental results obtained at GANIL

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Invited talk given at the Radioactive Nuclear Beams Third International Conference, East Lansing, May 24-27, 1993

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ABSTRACT

This paper presents a review of experimental results obtained at GANIL on the study of nuclear structure and nuclear reactions with secondary radioactive beams. Mass measurements by means of the GANIL cyclotrons are described. The possibilities of GANIL/LISE3 for the production and separation of radioactive beams are illustrated through a large variety of experiments.

1. Introduction

The present paper gives a review of the experimental results obtained at GANIL on radioactive beams and exotic nuclei since the 1991 Louvain-la-Neuve RNB conference.

After presenting mass measurements with the GANIL cyclotrons, the description of the LISE3 spectrometer serves as an introduction to the various experimental results obtained with secondary beams in different fields like astrophysics, nuclear structure and nuclear reaction mechanisms. Decay studies of exotic nuclei of astrophysical interest and of proton drip-line nuclei are recalled. Very recent data show the capability to produce isomeric radioactive beams. The use of highly efficient germanium detectors opens the way for extensive gamma spectroscopy of exotic species. Preliminary results on Coulomb excitation of a halo nucleus are reported. Elastic scattering and break-up reaction of light neutron-rich nuclei are presented. Near future developments of the GANIL facilities are presented in the conclusion.

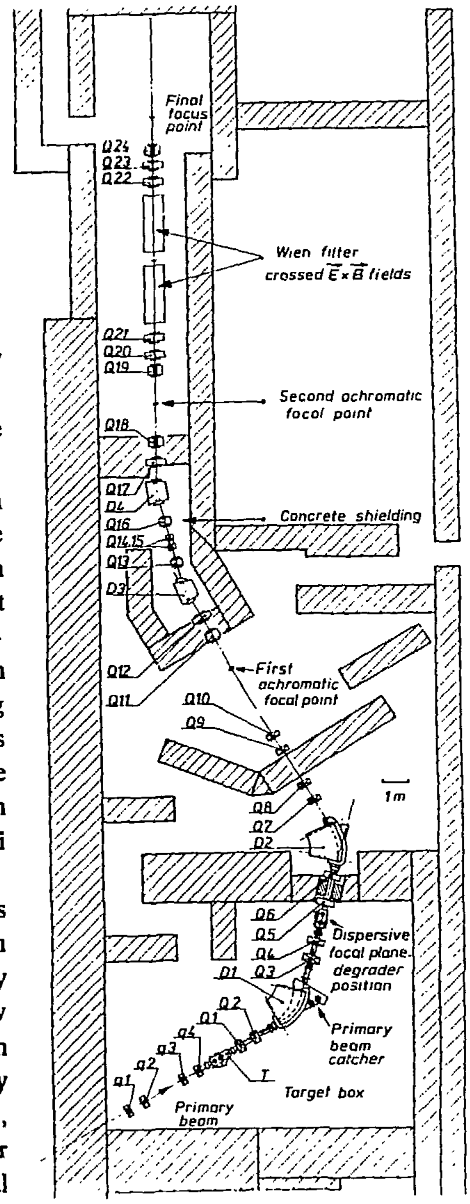
2. Mass measurements

A first step in the study of an exotic nucleus is to measure its mass. A resolution of 3.10^{-4} was achieved for the masses of neutron-rich nuclei around N=20 produced by fragmentation of a ^{48}Ca (55MeV/u) beam in an experiment performed with the alpha and SPEG spectrometers [10]. In order to reach a higher level of resolution a new method has been tested [6]: the first GANIL cyclotron CSS1 accelerates the primary beam to energies above the Coulomb barrier and the nuclear reaction takes place on a rotating and cooled target. The reaction products are injected into the second cyclotron CSS2 for selection, $B\rho$ measurement and further acceleration. The time of flight is measured between a "start" detector in front of the injector and a "stop" detector, which also identifies the outgoing nuclei, at the exit of the cyclotron .

3. The LISE3 spectrometer

The doubly achromatic spectrometer LISE, now complemented with a Wien filter, provides favourable experimental conditions for studying the radioactive decay of exotic nuclei as well as for investigating nuclear reactions with secondary beams.

The LISE spectrometer, made of two identical dipole magnets D1 and D2 (figure1), is set at zero degree with a 1msr acceptance. The incoming beam is focused on the target by quadrupole lenses. The first dipole, set at a chosen magnetic rigidity $B\rho_1$ (3.2 Tm maximum), analyses the outgoing beam in A/Z. Moveable slits located in the dispersive focal plane limit the momentum acceptance, its maximum value is equal to $\Delta p/p=\pm 2.5\%$, the momentum dispersion being D=1.71 cm / %. The object size at the target, at full primary beam intensity (several 10^{12} pps for light nuclei) is typically $x_0=\pm 0.15$ cm. This gives a resolution $\Delta B\rho/B\rho=1.3\ 10^{-3}$(the magnification is equal to G=0.75).



The second dipole compensates for the dispersion of the first one : the set-up is doubly achromatic in angle and in position. As a consequence, the flight-path between the target and the final focal point is independent of the angle of entry in the spectrometer. An energy-degrader (a bent aluminium foil of variable thickness) in the dispersive focal plane separates the nuclei according to their slowing down in matter. The achromatism is maintained for the isotope chosen by varying the thickness of the degrader. This energy-loss selection considerably reduces the number of contaminant nuclei collected at the focal plane.

Recently the performance of the LISE set-up has been enhanced by the addition of a Wien filter as shown in figure 1. By using a third selection criterion: a velocity selection, the isotopic separation is improved. The new extension is doubly achromatic in the horizontal plane (in angle and in position) and the WIEN filter, made by crossing an electrical field E with a magnetic field B, separates the nuclei in the vertical plane according to their velocity : they are focused in different points of the final focal plane.

The principal characteristics are a total length of 5 meters and a component design high voltage of ± 250 kV applied to a 10 cm gap. The electrostatic tank is, for mechanical reasons, actually divided in two 2.5 m subsections which are imbedded in the magnetic field (0.05-0.1 T and 50 cm gap). Two quadrupole triplets provide, in the center of the filter, a point-parallel relationship and an amplitude relationship in the dispersive plane. Furthermore, they allow to select the magnification in both horizontal and vertical direction at the final focal point. In order to implement the velocity filter in the given environment of the GANIL experimental hall, two 15° deviations had to be built. The isotopes selected by the moveable slits located at the exit of the WIEN filter are collected and identified in a silicon detector telescope installed at the final focal point. The time-of-flight parameter (t.o.f) along the 43 meters long flight-path, obtained between the time signal of the first silicon detector and the radio-frequency signal of the cyclotron, combined with the measured energy-loss in this detector (ΔE), gives a clear identification in A and Z for heavy nuclei.

The line directing the primary beam onto the production target, initially set at zero degree got a variable incidence (0° to 3.5°) with respect to the analysing section. This allows a very efficient suppression of remaining incompletely stripped charge-states of the primary beam and thus a more efficient use of heavier incident projectiles. Thanks to the rejection of these intense charge-states, a thin position-sensitive parallel plates counter inserted in the intermediate focal plane is able to measure the magnetic rigidity of individual fragments. This event-by-event measurement is very helpful for the unambiguous identification of heavy fragments.

These modifications of the spectrometer have substantially lowered the counting rate of the contaminant fragments on the detectors. This allows higher beam intensities on the primary production target. Therefore high-speed rotating wheel targets were made in order to accept the heat effects of very intense heavy-ion beams.

4. Decay studies

4. 1. Decay properties of exotic sulfur, chlorine and argon isotopes near N = 28: nuclear structure effects and nucleosynthesis

A kind of r process has to be invoked to explain the existence of light stable neutron-rich isotopes as ^{46,48}Ca, as they can be reached neither by O and Si burning, nor by the s process. In order to understand their synthesis and their abundance ratio, which has been found to be 50 in the solar system and 250 in refractory inclusions of the Allende meteorite, the decay properties of their progenitors have to be determined.

The theoretical predictions cannot hold for such an overabundance of ^{48}Ca without setting very strong constraints on the neutron exposure. Before 1990 ^{46}Ca was thought to be produced mainly by the decay of ^{46}Cl and ^{47}Cl (figure 2., upper part). The most striking effect of the results obtained at GANIL/LISE, using fragmentation of a ^{48}Ca beam at 60 MeV/u on a ^{64}Ni target, is the much shorter half-life of ^{45}Cl compared with the predictions. This N=28 nucleus then acts as a turning-point and drives preferentially towards ^{45}Ca. Hence the possible A=46,47 progenitors of ^{46}Ca will be produced in small amounts. Furthermore the respectively higher and lower Pn-values measured for ^{46}Cl and ^{47}Cl contribute to the reduction of ^{46}Ca production [3].

The problem of the "underproduction" of ^{46}Ca seems thus to be solved but the "high production" of ^{48}Ca will now be studied during an experiment planned at GANIL/LISE. The expected experimental values of the $T_{1/2}$ and Pn values of N>28 argon isotopes will probably explain the production of ^{48}Ca relative to ^{46}Ca.

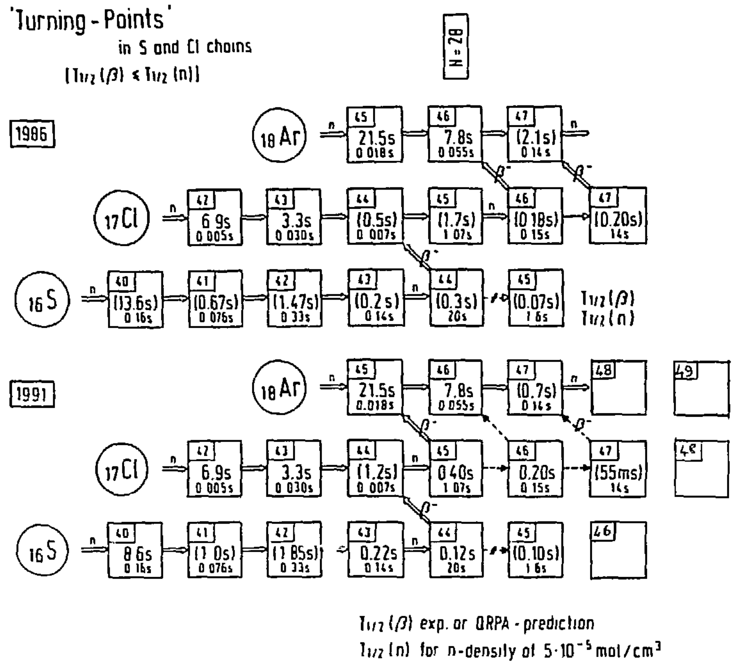


Figure 2. : Neutron-capture path in the sulfur and argon chains for a stellar temperature of T = 8 10^8K and a neutron density of 5 10^5 mol cm^{-3}. Turning-point isotopes have $T_{1/2}(\beta) < T_{1/2}(n)$. With the new experimental data, at both N = 28 "turning-point" isotopes ^{44}S and ^{45}Cl beta decay back to stability starts to dominate over further neutron capture. Hence, the possible A = 46,47 progenitors of ^{46}Ca will be produced in small amounts. Large $^{48}Ca/^{46}Ca$ ratios can be obtained, as required to explain the observed abundances[3].

4. 2. Beta-decay studies of ^{20}Na and implications for the rp process

The study of the beta decay of ^{20}Mg provides important data on the excited levels of ^{20}Na. Produced by the reaction between a 95 MeV/u ^{24}Mg GANIL beam and a nickel target, a ^{20}Mg secondary beam of high intensity and high purity was separated by the LISE3 spectrometer and implanted into an array of silicon detectors for studying beta delayed protons and gamma rays. The half-life of ^{20}Mg and six 1+ levels in ^{20}Na were determined, including the IAS ($J^\pi = 0$, T = 1). No beta feeding of the 2646 keV excited state in ^{20}Na has been observed. This level is located 450 keV above the proton threshold and may play a role in the $^{19}Ne(p,\gamma)^{20}Na$ reaction. These results will be presented and discussed in this conference by A. Piechaczek.[4]

4. 3. Decay modes of proton drip-line nuclei in the fp shell

Several decay modes are possible for this medium-light proton drip-line nuclei: a small number of them, with even atomic numbers may decay by direct two-proton emission as their predicted two-proton separation energies are slightly negative (see reference 5). Three candidates had been studied : ^{22}Si, ^{31}Ar and ^{39}Ti. They all exhibit beta-delayed proton emission decays. For the iron isotope ^{45}Fe a more negative two-proton separation energy is predicted by the mass formulas. During an experiment performed at GANIL/LISE3 this isotope was not observed, in contradiction with the predicted counting rate : its half-life may be shorter than the 250 ns time of flight.

Nuclei very close to the proton drip-line exhibit very large Q values for beta emission : about 15 to 20 MeV. This allows the feeding of numerous excited states in the daughter nucleus : some of these states are unstable to particle emission. Thus the observed decay modes are beta-delayed proton emission, beta-delayed multi-proton emission and beta-delayed alpha emission.

Important, though very partial, results were obtained on the isotopes ^{44}Cr, ^{43}V, ^{47}Fe, ^{46}Fe, and a more complete study of both ^{43}Cr and ^{46}Mn was achieved [7].

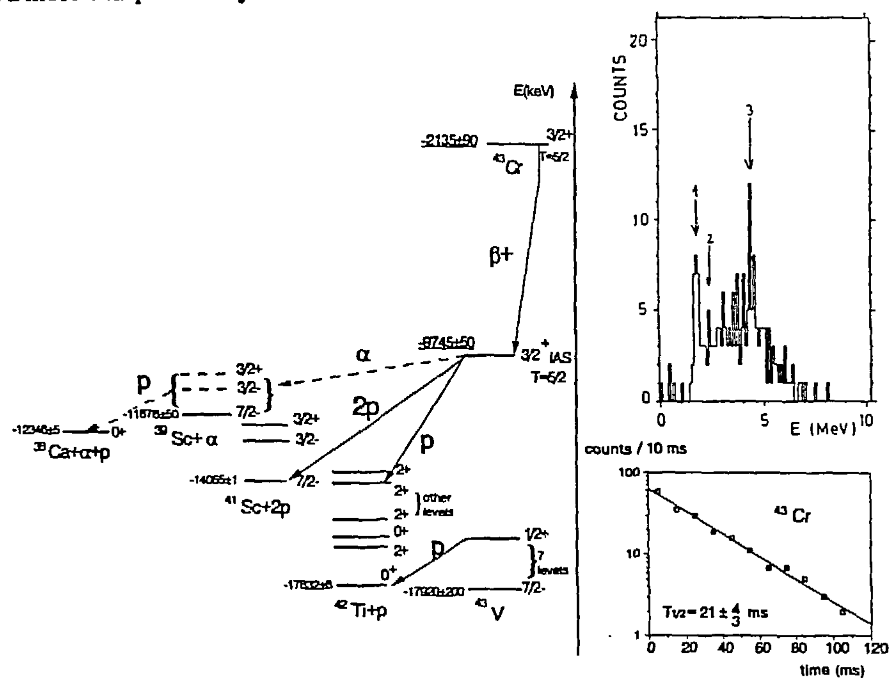


Figure 3. : Partial decay scheme proposed for ^{43}Cr. Each state is labelled with its mass-excess energy. The mass-excess values derived in the present work are underlined. The spin and parity, if known, are indicated ; otherwise, the spin and parity of the corresponding level in the mirror nuclei are adopted.

Figure 3. presents the partial decay scheme proposed for ^{43}Cr. The IAS in ^{43}V, fed by the ^{43}Cr super-allowed beta emission, undergoes proton and two-proton emission with a total absolute branching ratio of (12 ± 4) % and a possible alpha-proton decay shows up on the energy spectrum (the 2.6 MeV line is the sum of the alpha and proton energies). The experimental value of the mass excess of the IAS in ^{43}V is deduced from the energy of the beta-delayed two-proton line and the IMME, applied to the T = 5/2 states in the three nuclei ^{43}V, ^{43}Ca and ^{43}K, gives an estimation of the ground-state mass excess of ^{43}Cr [7].

4. 4. Gamma spectroscopy of exotic nuclei

A new experimental set-up (figure 4) was designed for on-line beta-gamma and gamma-gamma spectroscopy of exotic nuclei selected by the LISE3 spectrometer. The four large volume germanium detectors cover a solid angle of 1 sr and their total efficiency is about 15 % for a 1 MeV gamma line. ^{44}V was known through its beta-delayed alpha emission [15] , but most of its beta emissions, and in particular the superallowed Fermi transition, are expected to feed gamma decaying states : according to recent shell-model calculations an important part of the Gamow-Teller strength should be observed by gamma detection [17]. An isomeric level ($J^{\pi} = 6^{+}$) at low excitation energy is predicted for ^{44}V, as can be deduced from its mirror nucleus ^{44}Sc. The gamma lines following its beta decay are different from those coming from the ground-state.

^{44}V was produced in the reaction ^{58}Ni (69 MeV/u) + nickel, and its beta-delayed gammas and charged particles were recorded. Three detected gamma lines are immediately attributed, considering the known ^{44}Ti excited states : 1083 keV (first 2^+ state in ^{44}Ti to ^{44}Ti ground state), 1371 keV (first 4^+ to first 2^+) and 1560 keV (first 6^+ to first 4^+). A very preliminary calculation of their relative intensities indicates that ^{44}V is mainly produced in its isomeric state (60 to 70 percent of the detected events). A complete analysis of these results is now in progress.

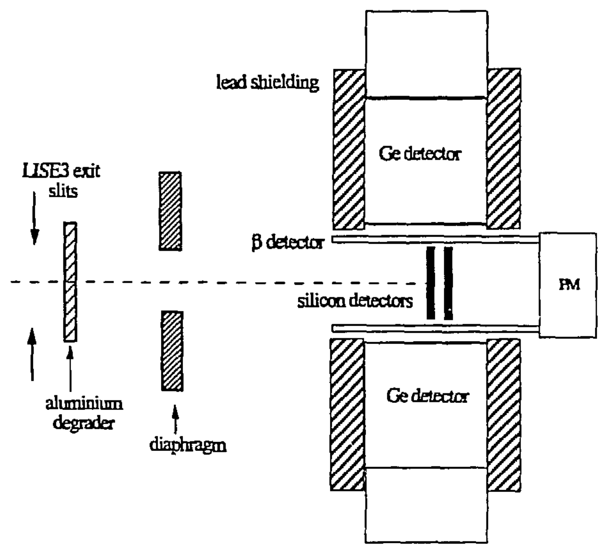


Fig. 4 : Experimental set-up for the on-line study of beta-delayed proton and gamma decay of neutron-deficient nuclei. The heavy ions selected by the LISE3 spectrometer are identified and implanted into one of the 300 μm thick silicon detectors.The latter measure the energy of the emitted charged partiles (protons, alphas). Four large-volume germanium detectors (the two that are not drawn on the figure are perpendicular to the beam axis, in the horizontal plane) surround a plastic scintillator which detects the emitted betas with an efficiency of about 93%.

5. Reaction studies with secondary beams

5. 1. Production of high spin isomeric heavy ions beams

Exotic heavy ions beams are produced mainly by the projectile fragmentation process. Transfer reactions can also produce those nuclei, with the possibility, using spin and isospin selection rules, to obtain isomeric heavy ion beams with high spins. The goal of the experiment [8] was to produce an isomeric beam of $^{42}Sc^m$ ($J^\pi = 6^+$), via the transfer of a neutron-proton pair to a ^{40}Ca projectile at 30 MeV/u. Three different targets of equivalent number of atoms were chosen : ^{12}C (5mg/cm2), and the two gaseous targets ^4He and ^3He (1 atm). $^{42}Sc^m$ ($T_{1/2}$ = 61 ms) decays by beta emission followed by three gamma rays (435.5 keV, 1227 keV and 1524.5 keV) whereas ^{42}Sc ($T_{1/2}$ = 681 ms) decays by beta emission to the ground-state of ^{42}Ca, without gamma emission. The ^{42}Sc nuclei, transmitted by the LISE3 spectrometer, were identified in a E-ΔE silicon detector telescope and the gamma rays were detected in a large-volume germanium detector. When produced with the ^{12}C target, ^{42}Sc was collected at the rate of 164 pps, and the intensities of the three gamma lines, clearly identified in the gamma spectrum, indicate, when compared with the number of implanted ions, that 76 % of the ^{42}Sc nuclei are produced in the 6^+ isomeric state.

5. 2. Elastic scattering of secondary beams

For stable nuclei, elastic scattering has been the "classical" way to obtain detailed information about the proton and neutron distributions. Concerning the halo nuclei, the idea was to investigate the nuclei in a "non-destructive" way and to appreciate the feasibility of elastic scattering experiments with weak secondary beams. Beams of 25.4 MeV/u ^{7}Li (1000 pps) and ^{11}Li (150 pps) were obtained by the fragmentation of a 76 MeV/u primary ^{18}O beam on a 3.2 g/cm^2 Be+C target. Their isotopic purity was, after separation by the LISE3 spectrometer, better than 98%.

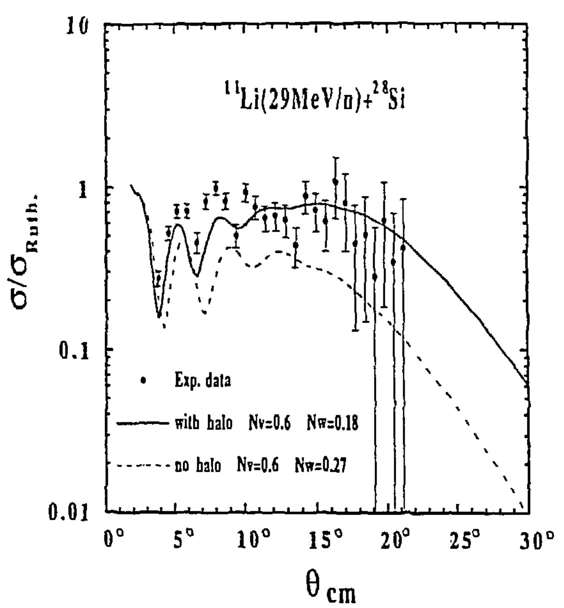


Figure 5. : Measured angular distribution and coupled-channel calculation for the elastic scattering of 29 MeV/u ^{11}Li on a silicon target [9].

The trajectory of the secondary particles was reconstructed event-by-event by two position sensitive (X-Y) silicon detectors located in the final focal plane of LISE3. The second silicon detector served as an active target. The angles and energies of the scattered particles were measured in two circular silicon stripped detectors further downstream. An array of seven BGO crystals was used to determine the residual energy of each particle.

The distribution obtained for ^{7}Li is in agreement with precise measurements in similar systems. The measured angular distribution of elastically scattered ^{11}Li exhibits a rather unusual behaviour : the ratio σ/σ_R remains almost constant over the whole angular range and its value is substantially higher than the value observed for ^{7}Li. The curves on figure 5. represent coupled-channel calculations, taking (or not) into account the presence of a neutron halo[9].

A similar set-up (fig.6.) was used recently in the study of the elastic scattering and the break-up of the proton-rich nucleus ^{8}B, which are of interest for understanding the solar neutrino problem [19].

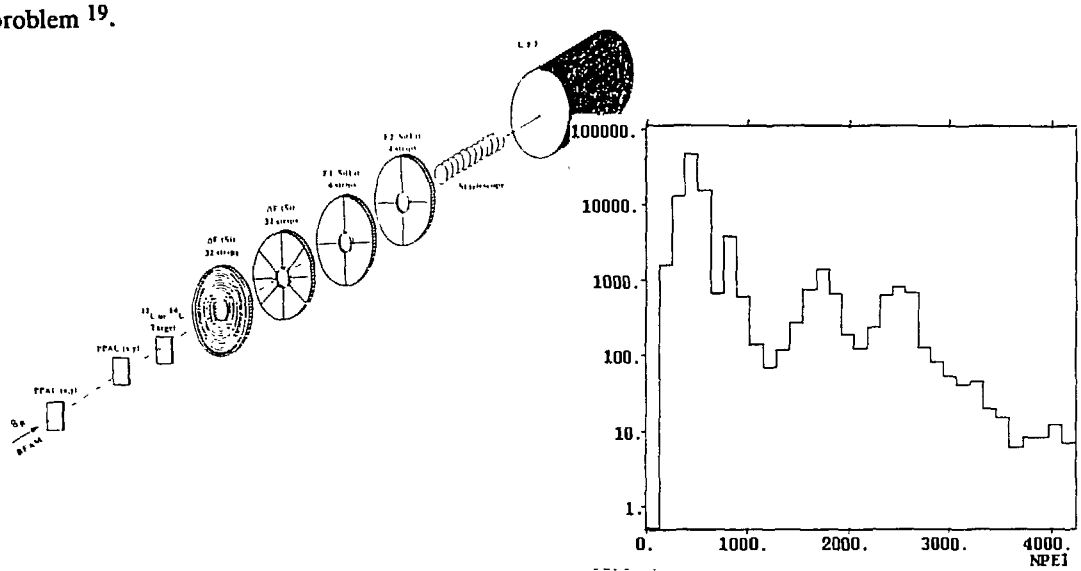


Fig.6. : This set-up is designed for the study of ^{8}B elastic scattering. The break-up reaction $^{8}B \rightarrow {}^{7}Be{+}p$ is also measured : the telescope of eleven 300 μm thick silicon detectors selects the ^{7}Be nuclei produced in the reaction. The insert shows a very preliminary angular distribution measured for the scattered ^{8}B nuclei.

5. 3. Dissociation reactions of the ^{11}Be one-neutron halo nucleus

In the reactions of a radioactive ^{11}Be beam at 41 MeV/u on gold, titanium and beryllium targets, the angular distributions of the forward emitted neutrons in the exclusive ^{10}Be + n channel were measured, as well as cross-sections. They can be accounted for, quantitatively and without free parameters, in terms of Coulomb and diffraction dissociations[14]. These results will be presented by K. Riisager in this conference.

5. 4. Coulomb excitation of bound excited states of the neutron halo

^{11}Be is the only halo nucleus with a known bound excited state (at 320 keV) : the lifetime and the B(E1) are known from a Doppler-shift experiment [12]. At GANIL this excited $1/2^-$ state has been recently populated by Coulomb excitation of a 45 MeV/u ^{11}Be radioactive beam (obtained by fragmentation of a 63 MeV/u ^{18}O primary beam and separated by the LISE3 spectrometer) on a lead target. The experimental set-up is presented on figure 8. Plastic scintillators (NE102) were used for particle identification in order to accept high counting rates. Three large-volume germanium counters detected in-flight γ de-excitation.

The γ lines arising from projectile excitation are in coincidence with a particle of the secondary beam. The mean energy and width of the peaks observed at 55 and 90 degrees are consistent with the formula $E\gamma = \frac{(E\gamma_0 \sqrt{1-\beta^2})}{(1-\beta\cos\theta)}$ and with the Doppler broadening induced by the energy spread of the secondary radioactive beam and the solid angle acceptance of the γ detectors (figure 8.). The E1 transition from the excited to the ground state is observed and the preliminary value of the cross section is in good agreement with theoretical predictions based on the measured half-life [12] and on the theory for high energy Coulomb excitation [13].

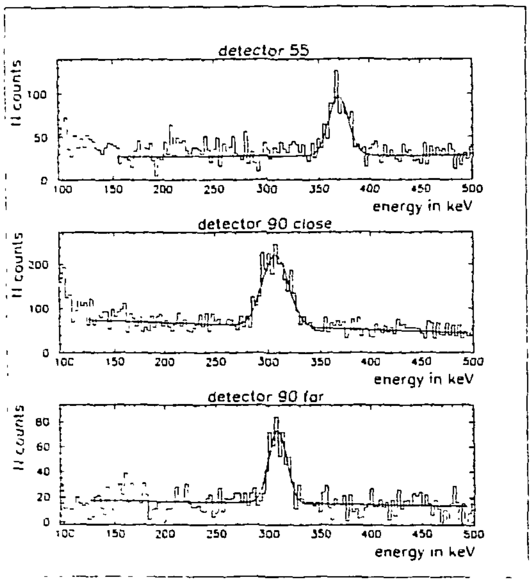


Figure 7. : Parts of the γ spectra in the relevant energy range for the 320 keV transition in ^{11}Be.

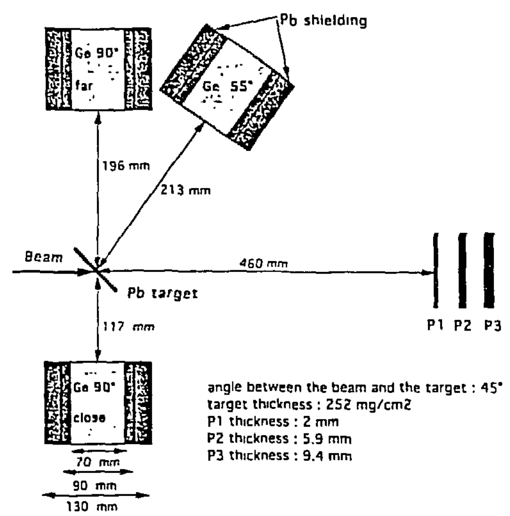


Figure 8 : Experimental set-up.

5.5. Deceleration of a secondary beam down to the Coulomb barrier

A test experiment was performed with the LISE spectrometer to determine the optimal conditions for reducing, with the minimum loss in intensity, the energy of a secondary ^{11}Be beam, produced by fragmentation of a 63 MeV/u ^{18}O beam on a ^{9}Be target, down to the Coulomb barrier. The results [18], presented in this conference by P. Roussel-Chomaz suggest possibilities for studying fusion-fission reactions induced by neutron-rich beryllium isotopes.

6. Next developments

The production of light neutron-rich secondary ions is enhanced with the highest primary beam energy (e. g. ^{18}O at 95 MeV/u), but the magnetic rigidity of the ions emerging from the target of optimum thickness is higher than the maximum Bρ of the first LISE3 dipole (3.2 Tm). The slowing down into a degrader located at the target position introduces angular and energy straggling. The maximum magnetic rigidity of the first LISE3 dipole will be increased up to 4.2 Tm in order to improve the intensity and the quality of these light neutron-rich secondary beams.

At the same time with a dipole installed at the exit of the Wien filter, the LISE3 set-up will behave as a mass separator for medium and heavy fragments (up to A=80).

Modifications of the GANIL accelerators will be made in the next future to increase the intensity of the primary beams. In order to improve the secondary beams intensity, another problem has to be solved : the secondary ions produced at GANIL by the fragmentation-like process are emitted forward inside a cone of typical half-aperture equal to 80 to 100 mrad, but the angular acceptance of the beam line is restricted to 5-10 mrad so only a small fraction of the distribution is transmitted. The purpose of the SISSI (Superconducting Intense Source for Secondary Ions) set-up is to increase the transmission of the beam line for secondary ions [15].

Therefore, the incoming beam is focused to a small size spot on the production target by a first lens and, downstream the target, a second lens with a short focal length collects the secondary ions emitted with angles up to 80 mrad and refocuses the secondary beam according to the usual beam line conditions : SISSI is made of two superconducting solenoids surrounding a fast rotating target holder (to ensure a correct heat dissipation). Its location at the exit of the second cyclotron offers three main advantages :

- the primary beam energy is as high as possible
- the moment spread of the secondary beam can be adjusted by passing through the alpha spectrometer (monochromator)
- the secondary beam can be delivered in any experimental area.

Mass measurements of heavy exotic nuclei will be achieved with the SISSI + SPEG combination. After a first selection performed by SISSI, the LISE3 spectrometer will be able to separate pure and intense secondary beams of heavy ions.

7. References

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