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SETUP FOR FISSION AND EVAPORATION CROSS-SECTION MEASUREMENTS IN REACTIONS INDUCED BY SECONDARY BEAMS

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1. INDRODUCTION

The presence in a nucleus of a neutron skin or halo is expected to have strong influence on the cross section of reactions induced by such nuclei. This cross section is enhanced due to the diffuse density distribution of the valence neutrons. On the other hand, reactions induced by nuclei with neutron excess may have large Q-values and, therefore, fusion can lead to a highly excited compound nucleus. A question may arise whether the valence neutrons can serve as a bridge for nucleon transfer with the consequence of enhancing the fusion cross section below the barrier or they will be lost in a break-up process before fusion takes place, by this decreasing the total complete fusion cross section at and below the barrier.

One of the surprises in the physics of secondary radioactive beams was the observation of the enhanced fusion-fission cross sections. Theoretical and experimental efforts have been devoted to study this phenomenon. However, a full understanding remains elusive due to various experiments, which had been aimed to registration of different interaction channels.

A few experiments have been carried out with a ^{6}He beam [1-5]. The increased interest in the ^{6}He nucleus lies in that it has a neutron skin. If the structure of this nucleus influences the reaction parameters, one should, comparing the results to similar results obtained with a ^{4}He beam, find a difference. One way to look for any such effect is to measure the characteristics of the evaporation residues produced after complete fusion in xn-evaporation channels. Another way is to measure the fusion-fission excitation function in a wide energy range.

Formerly we studied ^{6}He-induced fission using a stack of thin ^{209}Bi-targets (0.5-0.7 mg/cm^{2}) separated by solid-state Mylar track-detectors [4], allowing the detection of fission fragments with high efficiency (about 80%). The excitation function for the fission of ^{209}Bi as well as the cross section for the ^{209}Bi(^{6}He,4n)^{215}At-reaction were measured in a wide energy range.

Later a similar experiment [5] was carried out at two values of the excitation energy equal to 32 and 34 MeV. Despite the conclusion of the authors of [5] that there was disagreement between their experimental fission data and ours, we should point out that taking into account the large experimental errors characteristic for experimental data at low values of the cross sections, the difference between the data is not large. Moreover, their conclusion was qualitatively consistent with statistical-model calculations of ref. [6] in that the ^{6}He-induced fission yield is smaller than that for ^{4}He. However, this type of calculation has not been able to reproduce the experimental data, for instance the experimental data on ^{4}He+^{209}Bi fission from ref. [7]. We have found out that the behaviour of the fission excitation function for the ^{6}He + ^{209}Bi reaction is the same as for the ^{4}He + ^{209}Bi reaction, but the fission cross-section for the ^{6}He isotope is significantly higher than that for ^{4}He nuclei. In ref. [2] it was suggested that this enhancement depends mainly on the entrance channel and is connected with the neutron skin of ^{6}He nuclei. In order to get a clearer idea of the interaction, one should in principle measure all channels of the interaction: complete fusion, few nucleon transfers, fission after complete and incomplete fusion, etc.

In the present paper we describe a new experimental setup designed for simultaneous measurement of fission and neutron-evaporation cross-sections in reactions induced by secondary beams.

2. THE EXPERIMENTAL SETUP

A schematic view of the experimental setup is presented in Fig. 1.

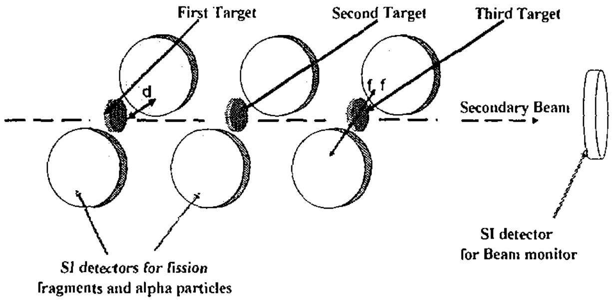

Fig. 1. Layout of the experimental setup.

The setup has been built for detecting both evaporation residues and fission fragments in parallel. The setup can hold up to three targets. The targets are placed at 45^0 with respect to the secondary beam direction. Two silicon detectors (diameter 5 cm), located at 90^0 to the beam direction, face each target from either side. This makes it possible to increase the effective solid angle up to 30% and thus get sufficient statistics in a shorter period of irradiation. The ^{209}Bi-targets were about 330 $\mu g/cm^2$ thick on a 2.5 μm thick Mylar backing. This array of three targets allows increasing the statistics by a factor of three, as the maximum energy loss of the beam particles between the three targets is less than 1 MeV. If energy degraders are inserted between the targets, it would be possible to get measurement at three different energies of the beam in one run.

The silicon detectors measure the energy of the α-particles emitted by various evaporation residues and also the energy of the fission fragments. The signals from the silicon detectors are divided for the fission fragments and for the evaporation residuals decay. For this purpose, for each detector channel two spectroscopic amplifiers (operating at various gains) are used.

Because of the quite large solid angle, this setup is suitable to use in studies of secondary-beam induced reactions as it makes possible the investigation of reactions with cross sections less than 10^{-26} cm^2 at a mean beam intensity of about 10^4 pps.

2.1. Secondary beam production

The bombardment of a thick ^{9}Be primary (production) target, as shown in Fig. 2 [8], with an intense ^{7}Li-beam at about 35 MeV/A has led to the production of relatively intense (10^4 -10^6 pps) secondary beams of ^{6}He with energies 10-30 MeV/A at the U400M cyclotron of FLNR, JINR. The separation of the products produced in the target to form the secondary beam is achieved using the main beam-transport line of the accelerator. It has been specially modernized and supplemented with some new elements according to the ion-optical calculations for the transport of the mentioned light ions. Slits, a beam profiler (a multiwire proportional chamber) and a polypropylene degrader are used to control and improve the quality of the secondary beam. Its energy dispersion and angular convergence are thus minimized with a small loss of intensity only. The purity of the beam usually obtained is not worse than 98%. Using two profilers for diagnostics makes it possible to focus the beam on the physical target, located in the reaction chamber, as well as to control the size of the beam spot.

The secondary beam is monitored by means of position-sensitive Si-detectors installed downstream of the targets.

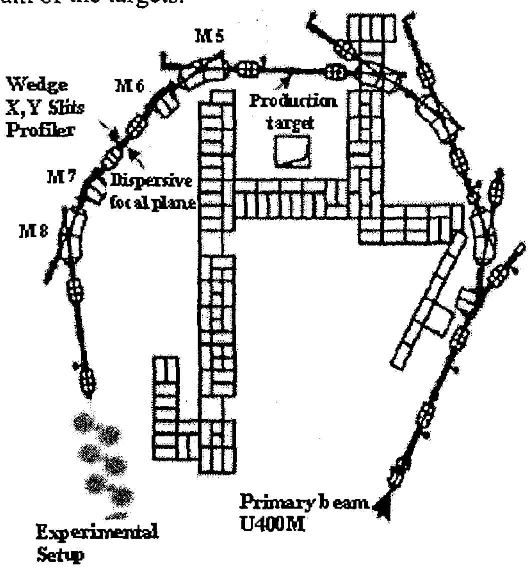

Fig. 2. Schematic diagram of the beam-line for producing the secondary beam with the position of the present setup.

2.2. Registration of α-particles and fission fragments

This experimental setup has been tested using a Pu-Am-Cm source. The energy spectrum of the emitted α-particles, measured with one of the detectors, is shown in Fig. 3 (upper panel) as an example. We observe three peaks, corresponding to the strongest α-transitions 5.15 MeV, 5.48 MeV and 5.80 MeV in the decay of ^{239}Pu, ^{241}Am and ^{244}Cm, respectively. On the basis of this measurement we have been able to determine the energy resolution for α-particles equal to FWHM ≈ 280 keV. The spectrum of the fission fragments are also shown in Fig. 3 (lower panel). We can see that the energy distribution for the fission fragments allows distinguishing the two mass groups characteristic for spontaneous fission of the ^{244}Cm isotope.

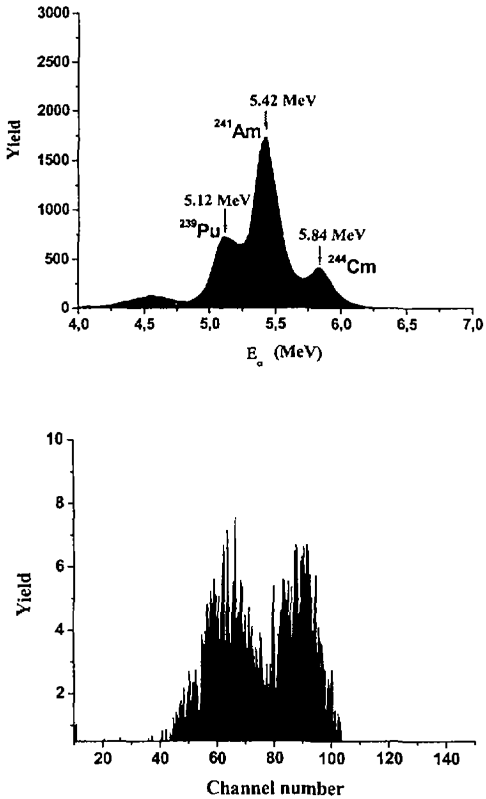

Fig. 3. Energy spectrum of α-particles emitted by a Pu-Am-Cm source (upper panel) and energy distribution of fission fragments from the spontaneous fission of ^{224}Cm (lower panel).

3. EXPERIMENTAL RESULTS

3.1. Fission fragments in the ^{7}Li+^{209}Bi-reaction

We have tested the setup at the U400M accelerator using a ^{7}Li-beam with an energy E=80±1 MeV. The ^{7}Li-beam energy was chosen by tuning the magnetic rigidity of the beam line. Two correlated fission fragments were registered in coincidence by each couple of silicon detectors, located at 90^0 to the direction of the beam-line (see Fig. 1). These detectors were calibrated with fission fragments from a thin ^{244}Cm source and alpha particles from a ^{226}Ra source. The two-dimensional plot of the energies of the fragments, corresponding to the fission of the compound nucleus ^{216}Rn, is presented in Fig. 4.

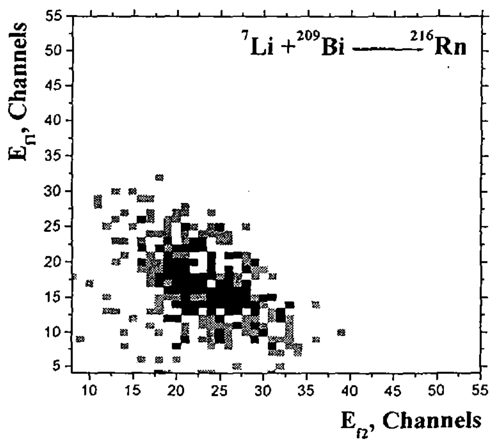

Fig. 4. The two-dimensional plot of the energies of the two correlated fission fragments obtained in the ^{7}Li+^{209}Bi-reaction.

3.2. Alpha particles of evaporation recoils in the ^{6}He+^{209}Bi-reaction

The described setup was also used to study the interaction of the secondary ^{6}He beam with the ^{209}Bi target nuclei. The energy of the beam was 50±3 MeV. At this bombarding energy the excitation energy of the formed compound nucleus ^{215}At is $E^* \approx 49\pm3$ MeV. Thus we can expect the formation of evaporation residues with the emission of up to 6 neutrons.

Most of the residual nuclei produced in He-induced reactions on ^{209}Bi, due to their closeness to the N=126 and Z=82 closed shells, are short-lived α-particle emitters. The characteristics [9] of the main α-decay modes of the nuclei, which can be formed in our case in the ^{6}He-induced reaction, are shown in Table 1. It is seen that the α-decay half-lives of these nuclei are generally short and the α-decay energy is reasonably well spaced in the energy region 6-10 MeV.

Table 1. α-decay characteristics of the nuclei, formed in the $^{6}He + ^{209}Bi \rightarrow ^{215-xn}At$ reaction.

xn	Evaporation residue	$T_{1/2}$	E_{α} (MeV)
1*n*	^{214}**At**	558 ns	8.82
2*n*	^{213}**At**	125 ns	9.08
3*n*	^{212}**At**	314 ms	7.68
4*n*	^{211}**At**	7.21 h	5.87 7.28 (^{211}**Po** 516 ms)
5*n*	^{210}**At**	8.1 h	5.36 - 5.52 5.3 (^{210}**Po** 138.4d)

In Fig. 5 the α-particle energy spectrum, measured in the reaction $^{6}He + ^{209}Bi$, is shown. The 4n-evaporation channel, with the formation of ^{211}At, can be identified in two ways. The isotope ^{211}At ($T_{1/2}$ = 7.21 h) undergoes α-decay with E_{α} = 5.87 MeV with a probability of 41.8%. In 58.2% of the cases it decays by electron capture into the short-lived ^{211}Po ($T_{1/2}$= 0.516 s), which in turn undergoes α-decay with E_{α} = 7.28 MeV. In fact, two lines are observed in the energy spectrum of the α-particles, which can be attributed to the decay of ^{211}At: The first one ($E_{\alpha} \approx$ 5.74 MeV) is located in the energy region where other nuclei contribute, whereas the second peak ($E_{\alpha} \approx$ 7.53 MeV), corresponding to the decay of ^{211}Po, allows good identification.

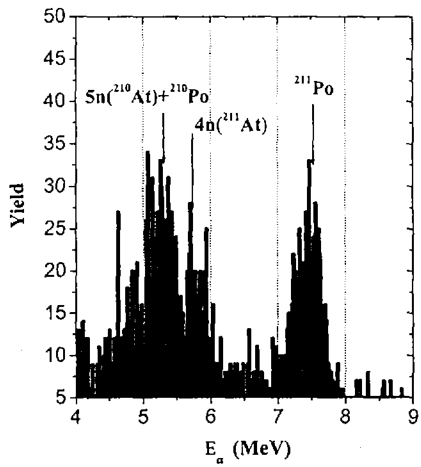

Fig. 5. Experimental α-particle energy spectrum, measured after the emission of different number of neutrons from the compound nucleus ^{215}At.

The evaporation of 5 neutrons leads to the production of the isotope ^{210}At ($T_{1/2}$ = 8.1 h). With about 99.8% probability it decays by electron capture to ^{210}Po ($T_{1/2}$ = 138.4 d) and only in 0.18% of the cases undergoes α-decay with an average energy $E_\alpha \approx 5.4$ MeV. The ^{210}Po isotope is an α-emitter with $E_\alpha = 5.3$ MeV. As we can see in Fig. 5, there is third peak in the spectrum at $E_\alpha \approx 5.28$ MeV, which can be explained by the decay of ^{210}At and its daughter isotope ^{210}Po.

4. CONCLUSIONS AND PERSPECTIVES

We have here reported on a set of measurements of prompt ^{7}Li-induced fission of ^{209}Bi and various evaporation residues produced in the ^{6}He+^{209}Bi reaction, performed by detection of fission fragments and α-particles emitted from the produced nuclei. The described setup is to be used in excitation function measurements. We plan to measure the excitation functions of fission and fusion reactions. The fusion cross sections are determined from the sum of the xn evaporations cross sections and the fission cross sections.

For a better performance we plan to improve the described setup by introducing CsI-detectors and position-sensitive parallel-plate avalanche counters for the control of the spot size and the quality of the secondary beam, and for the identification of the reaction products. Also, some experiments of this type using other secondary beams are to be carried out at the DRIBs facility at JINR.

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Хассан А. А. и др. Е7-2002-118
Установка для измерения сечений деления ядер
и сечений образования испарительных продуктов
в реакциях с вторичными пучками

Представлена установка для изучения реакций, вызванных вторичными радиоактивными пучками. Она позволяет проводить одновременное измерение энергетических спектров α-частиц и осколков деления при распаде образовавшихся в реакциях ядер. Идентификация ядер-продуктов испарительных реакций проводится по измеренным спектрам α-частиц. Для увеличения статистики используется набор из трех мишеней. Два кремниевых детектора, расположенных под углом 90° к направлению вторичного пучка, перекрывают 30 % телесного угла. Эта экспериментальная установка может использоваться для измерения функций возбуждения реакций слияния–деления и реакций, приводящих к образованию испарительных продуктов.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 2002

Hassan A. A. et al. E7-2002-118
Setup for Fission and Evaporation Cross-Section Measurements
in Reactions Induced by Secondary Beams

A setup for studying reactions induced by secondary radioactive beams has been constructed. It allows simultaneous measurement of α-particle and fission fragment energy spectra. By measuring the α-particles, identification of evaporation residues is achieved. A set of three targets can be used so as to ensure sufficient statistics. Two silicon detectors, located at 90 degrees to the secondary beam direction, face each target, thus covering 30 % of the solid angle. This experimental setup is to be used to obtain excitation functions of fusion–fission reactions and of reactions leading to evaporation residue production.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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