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# EXPERIMENTAL STUDY OF FISSION AND EVAPORATION CROSS SECTIONS FOR $^6$He + $^{209}$Bi REACTION

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Secondary beam of $^6$He neutron-rich nuclei was produced through a transfer reaction on the carbon target with 35.5 MeV/u $^7$Li primary beam at the U-400M cyclotron. The influence of the neutron skin of $^6$He projectile on the fusion-fission and fusion-evaporation cross sections in the reaction with $^{209}$Bi target was investigated. The $^{211}$At $\alpha$-activity following the $^{209}$Bi($^6$He, $4n$) reaction as well as fission events in the $^{209}$Bi($^6$He, $f$) reaction have been recorded by off-line methods. These results are compared with $\sigma_{\rm fis}$ and $\sigma_{4n}$ obtained in the $^4$He + $^{209}$Bi reaction.

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

## Экспериментальное изучение сечений деления и испарения в реакции $^6$He + $^{209}$Bi

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Вторичный пучок нейтроноизбыточных ядер $^6$He был получен в реакциях передачи на углеродной мишени с использованием пучка 35.5 МэВ/нуклон $^7$Li на циклотроне У-400М. Исследовалось влияние нейтронного скина $^6$He на сечения деления и испарения после слияния в реакции на $^{209}$Bi мишени. Альфа-активность ядер $^{211}$At, возникающих в реакции $^{209}$Bi($^6$He, $4n$), а также осколки деления в реакции $^{209}$Bi($^6$He, $f$) регистрировались методом off-line. Эти результаты сравниваются с $\sigma_{\rm fis}$ и $\sigma_{4n}$,, полученными в реакции $^4$He + $^{209}$Bi.

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## 1. Motivations

The neutron skin of the nucleus has been one of the central issues of nuclear structure and its existence has remained an open problem for decades. The neutron skin has been studied in detail for stable nuclei with large neutron excess such as $^{48}$Ca and $^{208}$Pb. However no significant difference in the radii between proton and neutron distributions has been observed in these nuclei [1]. It is only recently that the neutron skin for radioactive neutron-rich nuclei such as $^6$He and $^8$He has been seen experimentally and a very thick neutron skin was found [1]. The rms radius difference for both nuclei was found about 0.9 fm, but if for $^8$He it is not due to the neutron halo (the separation energy of a pair of neutrons is 2.1 MeV), for $^6$He it is more arbitrary to say whether it is due to the neutron halo or due to the skin because the separation energy of the last two neutrons is 0.97 MeV. For $^6$He radioactive nuclei there appears an interplay between the skin and neutron halo effects at energies around the Coulomb barrier.

The neutron skin is expected to have a prominent effect on nuclear reactions, for instance, the fusion reactions. The neutrons in the skin are expected to have more mobility than neutrons in normal nuclei, because:

i) A more gradual potential near the surface yields less reflection of incoming waves;

ii) A mean free path of a neutron can be longer due to lower density.

The soft dipole mode [2] is expected to occur in nuclei with the neutron skin. Combining the above effects, one can expect that such fast flow of neutrons, which can be viewed as «neutron avalanche», should occur, enhancing the reaction cross section. Takigawa et al. [3] define the fusion cross section as the sum of the incoming particle plus that of the break-up channel, but the role of the break-up channel is very contradictory. Hussein et al. [4] argue that the coupling to the break-up channel would seriously inhibit the total fusion cross section. Dasso and Vitturi in a recent theoretical work [5] have predicted that inclusion of the break-up channel leads always to an enhancement of the fusion cross section at energies close to the Coulomb barrier.

The investigation of the role played by the neutron skin of $^6$He and its influence on the fusion cross section in the reaction with $^{209}$Bi is the main motivation for this paper. The fusion process has been identified through the detection of the delayed $\alpha$-particle emitted by the decay of the ground state of the $^{211}$Po obtained from $\beta$-decay of $^{211}$At evaporation residue populated after a $4n$ evaporation. Study of the $4n$ evaporation channel is convenient because the neutron halo and skin have an insignificant overlapping energy region. Moreover, at the same time the fusion-fission cross section for this reaction in a wide energy region was measured, too [6]. Comparing the results of both experiments with the same data for the $^4$He + $^{209}$Bi reaction one could pin down the neutron skin effect for $^6$He nuclei.

## 2. The Experiment

A helium-6 isotope was produced using the primary ion beam of $^7$Li (35.5 MeV/u) at the U-400M cyclotron (FLNR, Dubna). Stripping of a proton from the $^7$Li ions on the 1.1 mm carbon target was used. The intensity of $^6$He measured by a Si(Li) detector with dimensions of $\varnothing 32\times4.15$ mm$^2$ was about 6000 pps for $2\cdot10^{11}$ pps of $^7$Li ions. The secondary beam purity up to 96% was reached due to the so-called form degrader (1.6 mm Al) positioned between the dipole magnets at the angle of 25° to the beam direction. Additionally, an $\Delta E$ detector 4150 $\mu$m in thickness reduced the energy down to 70 MeV±8% (fwhm) at the experimental target position (Fig.1,a).

The $^{211}$At($T_{1/2} = 7.22$ h) $\alpha$-activity following the $^{209}$Bi($^6$He, 4$n$) reaction as well as fission events in the $^{209}$Bi($^6$He, $f$) reaction have been recorded off-line. For fission registering the track detector method was used [7]. Special «sandwich-type» piles consisting of eight $^{209}$Bi targets (0.82 mg/cm$^2$), 55 $\mu$m-thick mylar films for registration of fission fragments and additional absorbers made of Al (60+220 $\mu$m) were manufactured. Such piles were installed perpendicularly to the incident beam between $\Delta E-E$ Si(Li) detectors that provided the secondary beam monitoring. The residual energy for $^6$He ions was 22 MeV±25% (Fig.1b). The counting error provided by the scaler was less than 2% and the losses of ions connected with the absorption inside the targets and aluminium foils and with multi-scattering were of the order of 1%. The aluminium foils and bismuth targets were tested for uranium contamination using the neutron-activation method. The analysis showed that it did not exceed $10^{-7}$ at/at

This pile was irradiated for 17 hours by a flux of $^6$He ions with the intensity of $I \approx 2500$ pps, constant within 10% variation, for the beam diameter of 15 mm. Then the $\alpha$-activity of the last four targets, which correspond to the energy range $E_{cm} \approx 20 \div 48$ MeV, was simultaneously measured by a low background $\alpha$-decay spectrometer [8]. The recording time was longer than $T_{1/2}$ of $^{211}$At. The isotope $^{211}$At undergoes $\alpha$-decay (42%, $E_\alpha = 5.87$ MeV) and in 58% of the cases goes to the short lived ($T_{1/2}$~0.5 s)$^{211}$Po which in turn undergoes $\alpha$-decay with an energy $E_\alpha = 7.45$ MeV. Figure 2 shows the total $\alpha$-yield for all targets without

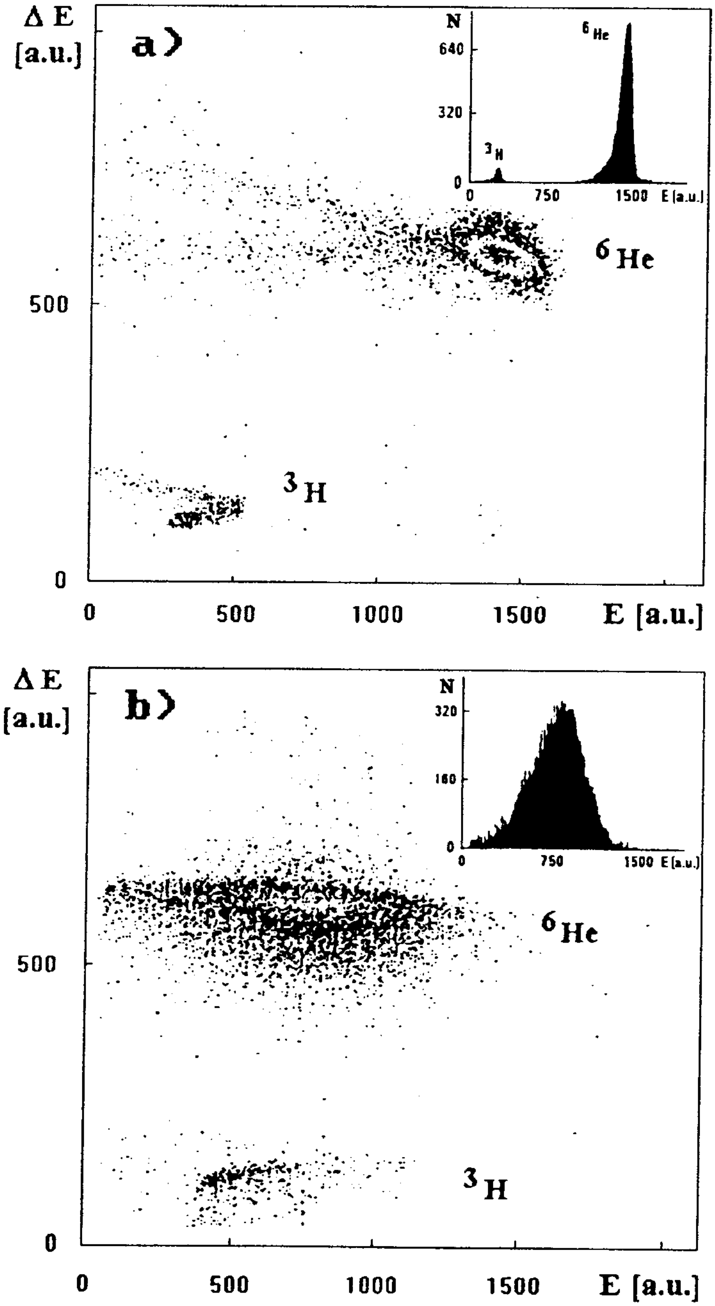

Fig.1. The secondary beam quality obtained without (a) and after (b) going through the pile

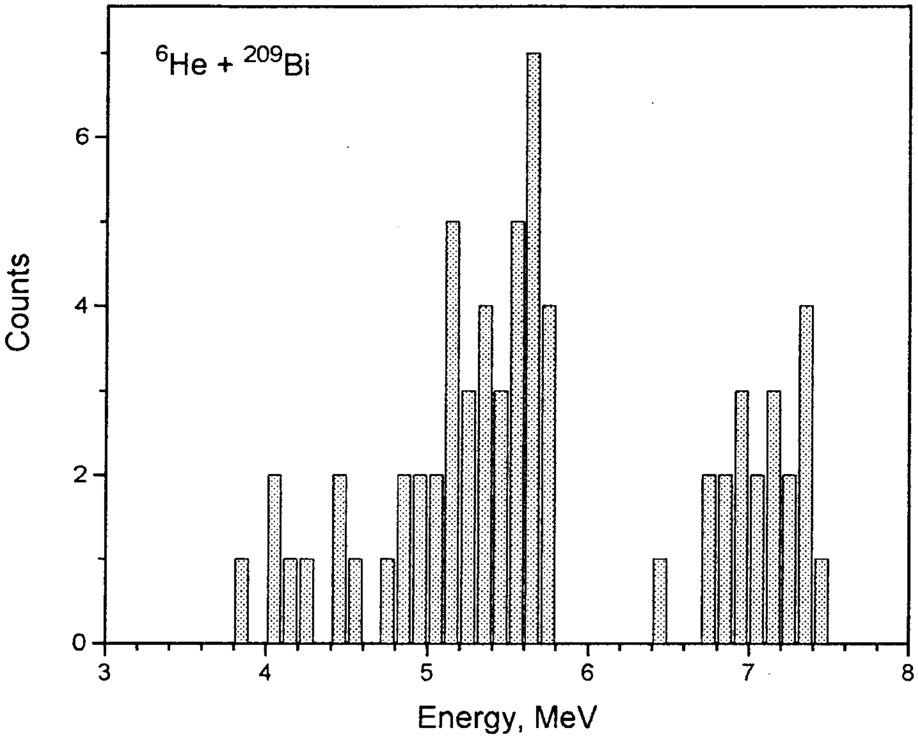

Fig.2.Alpha energy spectra from the ground state decay of the evaporation residue populated

background subtraction. The first peak ($E_\alpha$ = 5.87 MeV) belongs to the energy region where other nuclei give their contributions. The second peak ($E_\alpha$ = 7.45 MeV) with measured half-life of about 7 h corresponds to $^{211}$Po and allows good identification of the evaporation residue $^{211}$At populated after the $4n$ evaporation. Moreover in this energy region ($E_\alpha$ > 6 MeV) only one background event was registered. Unfortunately, we have imperfect information about the $\sigma_{6n}$ value because of the experimental conditions and the $\alpha$-decay properties of the $^{209}$At residue ($T_{1/2}$ = 5.4 h, $E_\alpha$ = 5.65 MeV, 5%).

To identify fission fragment events the mylar films were etched in a NaOH solution and scanned under a microscope with 100—200 magnification. For instance, in the $^6$He + $^{209}$Bi reaction the number of the observed fission events for the first film at $E_{\text{lab}} = 70$ MeV considering the detector efficiency was 228 ± 17 tracks. The total inaccuracy of the measured fission cross section was changed from 14% to 55% in the energy range of $^{6}$He nucle $E_{\text{lab}} \approx 70 \div 30$ MeV. The last film did not have any fission fragment events and one can conclude that the background from the satellite particle $^{3}$H was limited by the level of 1 mb.

## 3. Experimental Results and Discussion

The fission and the $4n$ evaporation cross sections for the $^{6}$He + $^{209}$Bi reaction as functions of the excitation energy are shown in Fig.3. The open triangles and open squares are the experimental results for the fission cross section and the $4n$ evaporation cross section in the $^{4}$He + $^{209}$Bi reaction in [9] and [10], respectively. 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 for the $^{4}$He nuclei. It was suggested [6] that this enhancement depends mainly on the entrance channel and it is connected with the neutron skin of the $^{6}$He nuclei.

The tentative excitation function of the $^{211}$At residue is presented by the solid squares in Fig.3 and the data are listed in the Table:

| $E_{cm}$, MeV | $\alpha$-yeilds ($E_\alpha = 6.75 \div 7.45$ MeV) | $\sigma_{4n}$, mb |
|---|---|---|
| 23.6±4.2 | 6 | 693±277 |
| 30.4±3.9 | 8 | 925±323 |
| 39.0±3.5 | 5 | 578±260 |
| 45.8±3.0 | 4 | 462±230 |

It is clear that the precise position of maximum of $\sigma_{4n}$ does not follow from this data but one can compare our results with the measured $4n$ evaporation cross sections for the $^{4}$He + $^{209}$Bi reaction (open squares) from ref. [10]. The absolute values of $\sigma_{4n}$ for both reactions agree well within the statistical errors. In the first approximation we can assume that the fission excitation function is more sensitive to $^{6}$He structure than the evaporation cross

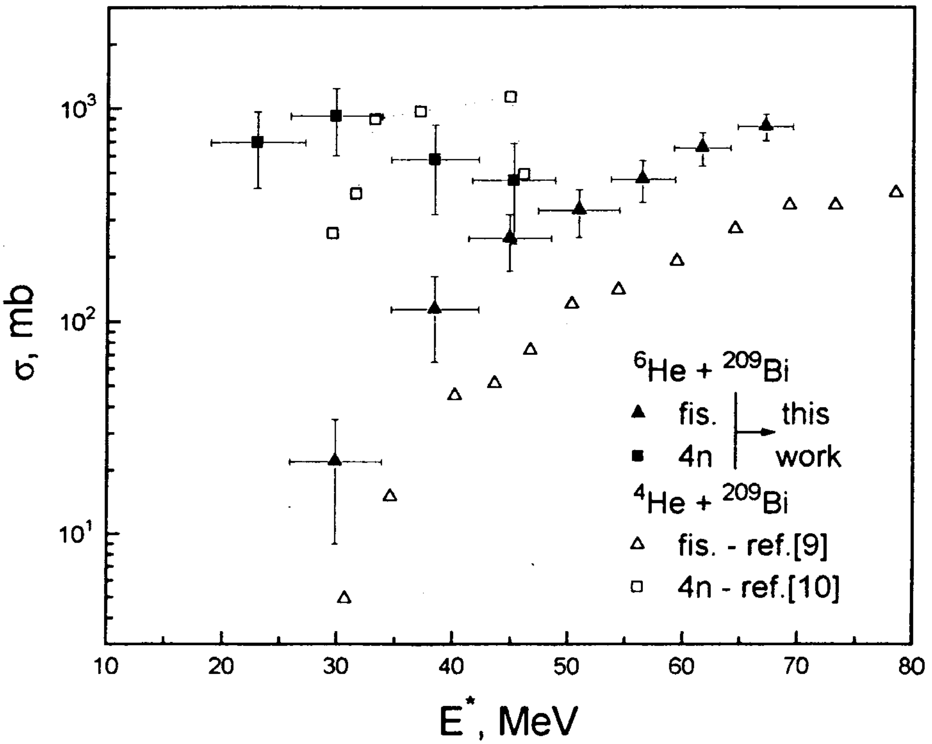

**Fig.3.** Fusion-fission (▲) and 4*n* evaporation (■) cross sections in dependence on excitation energy for $^6$He + $^{209}$Bi reaction and fusion excitation functions for $^4$He + $^{209}$Bi: (△) — fission, (□) — 4*n*

sections in the fusion reaction on the $^{209}$Bi target. Nevertheless, better statistics are obviously needed for a more detailed analysis. The nearest measurement of the ratio between $\sigma_{4n}$ and $\sigma_{6n}$ will also help to confirm our assumption about the skin effect influence of $^6$He on the fusion-evaporation cross sections.

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