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2n-Evaporation Channel In The ^{4,6}He+ ^{208,206}Pb Fusion Reactions

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Abstract. Excitation functions of the reaction products were measured for the reactions induced by ^{4,6}He projectiles on ^{208,206}Pb targets, leading to the same compound nucleus. The excitation functions for the 2n evaporation channels were obtained at energies below the sub-Coulomb barrier region. A large value of the fusion cross section was observed in the case of the reaction induced by the weakly bound ^{6}He projectile. This reflects an unusual mechanism is present in reactions induced by weakly bound nuclei.

Introduction

The investigation of the peculiarities of nuclear reactions induced by loosely bound nuclei, including those located far from the valley of stability has attracted a lot of interest [1, 2]. In particular, nuclei with large neutron excess are known to manifest a phenomenon known as neutron halo or skin. At low energies around the interaction barrier, nuclear structure manifests itself in complete fusion reactions with the formation of a compound nucleus or in the transfer of a few nucleons from the projectile to the target nucleus [3-5].

The enhancement of fusion in the sub-barrier region was predicted in some theoretical papers [6, 7]. It was shown that the probability of penetrating the potential barrier increases due to the extended distribution of neutron density compared with the ordinary atomic nuclei, situated close to the valley of stability. Such distributions, as shown in Ref. [8], may bring forth the "coupling of the collective degrees of freedom" and, consequently, the enhancement of the interaction cross section, in particular, in the sub-barrier energy region.

On the other hand, these nuclei are weakly bound, thus the probability that they breakup is high and it is quite possible that a breakup fragment can sequentially be transferred to or fuse with the target nucleus. The variety of possible processes makes it difficult to perform a straightforward interpretation of the experimental data.

Recently a series of experiments have been performed with the aim to study the fusion-fission process using ^{6}He beams with close-to-barrier energies [3-5, 9-11]. However, the obtained data were rather controversial and showed that higher statistical confidence is necessary as well as more informative experiments giving possibilities of distinguishing different exit reaction channels.

The experiment [4, 5] performed in FLNR (JINR), Dubna in 2006 at the accelerator complex for radioactive beams DRIBs [12] confirmed the results on the enhancement of fusion close to the Coulomb barrier, when halo nuclei are involved. In this experiment the cross sections for the formation of compound nuclei as a function of energy were measured. However, the energy spread of the beam after lowering the ^{6}He-projectile energy using degraders reached ±2.5 MeV.

The aim of the present work was to measure the excitation functions of the fusion reaction of ^{6}He with ^{206}Pb using the cross sections of the 2-neutron evaporation channel at energies including the region of the Coulomb barrier (12-27 MeV) with an energy resolution not worse than ±500 keV. Performing such an experiment became possible due to the production of high-intensity ^{6}He beam (up to 10^{8} pps), obtained at DRIBs [12]. For the purpose of comparison of the results from the ^{206}Pb(^{6}He,2n)^{210}Po, we measured also the reaction ^{208}Pb(^{4}He,2n)^{210}Po, which leads to the formation of the same compound nucleus ^{212}Po.

1 Experimental method

The stacked-foil activation technique was used for producing and measuring the yields of the reaction products. The identification of the Po isotopes produced in the target stack was done by the induced α-activity in the specific targets. The stack consisted of several targets (10÷14) made of the enriched ^{206}Pb material with aluminium (with thickness 5÷20 μm) degraders inserted between them. The targets were prepared by deposition of the Pb sulphide on 4 μm thick Ti-backings.

Two methods of beam monochromatization were used in the experiments. The first method implied placing the target stack on a specially designed gauge, which could be placed at different radii inside the FLNR U400 cyclotron. In this way, the initial energy of the beam was fixed, but could be changed by changing the radius. The energy resolution of the ^{6}He beam falling on the stack in this case was not worse than ±250 keV, while the intensity reached 10^8 pps. In the second method, the magnetic spectrometer MSP-144 [13] was used with the target stack situated at its focal plane. In this case, it was possible, using a polypropylene degrader in front of the entrance of the spectrometer, to decrease the initial beam energy from about 60 MeV down to 28 MeV without significantly worsening its energy spread. In this experimental method (the additional detail were given in Refs. [4, 5]), according to the size of the targets along the focal plane (20 mm) and the dispersion of the magnetic spectrometer MSP-144 (~40 keV/mm), the energy resolution of the beam amounted to ±400 keV. In this case the intensity of the beam was 2×10^7 pps. In front of the target stack a proportional gas chamber was used for measuring of the beam dose and the profile of the beam. The beam dose on the stack was also measured by a scintillation counter behind it.

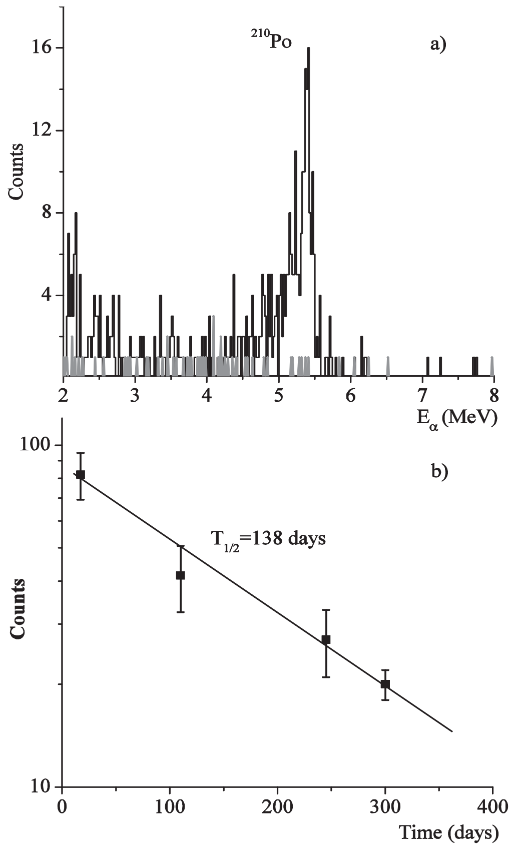

Fig. 1. a) Energy spectrum of α-particles from the evaporation residues resulting from the decay of the compound nucleus, produced in the reaction ^{6}He (15.3 MeV) + ^{206}Pb. The background events are presented by the grey histogram. b) Decay curve of the characteristic α-line, corresponding to the energy of 5.3 MeV, shown in Fig. 1a. The solid line is calculated for $T_{1/2}$=138 days.

The identification of the mass number of the evaporation residues, in particular of the 2-neutron evaporation channel, was done according to the known energy of the emitted α-particles and the half-lives.

As an example, figure 1a presents one α-particle energy spectrum, obtained after the irradiation of a ^{206}Pb target with ^{6}He ions at 15 MeV. Figure 1b shows the half-life of the activity, corresponding to 5.3 MeV from the α-decay of ^{210}Po. The calibration and the measurements of the efficiency of the detector system are described in detail in Ref. [14].

2 Experimental results and discussion

The obtained cross sections for the ^{206}Pb(^{6}He,2n)^{210}Po reaction as a function of the beam energy for the case of complete fusion accompanied by subsequent neutron emission are presented in figure 2. The excitation function for the reaction ^{208}Pb(^{4}He,2n)^{210}Po leading to the same compound nucleus ^{212}Po, as the ^{6}He-induced reaction on ^{206}Pb, is also shown in figure 2. The experimental excitation functions are compared with the theoretical calculation according to [15] (solid line in figure 2). This model [15] assumes that sequential transfer of neutrons from the ^{6}He projectile to the target nucleus takes place. In such a process the excitation energy of the nuclear system increases as $E_{cm}+Q_{gg}$, which ensures the enhancement of the probability for the α-particle to penetrate the Coulomb barrier.

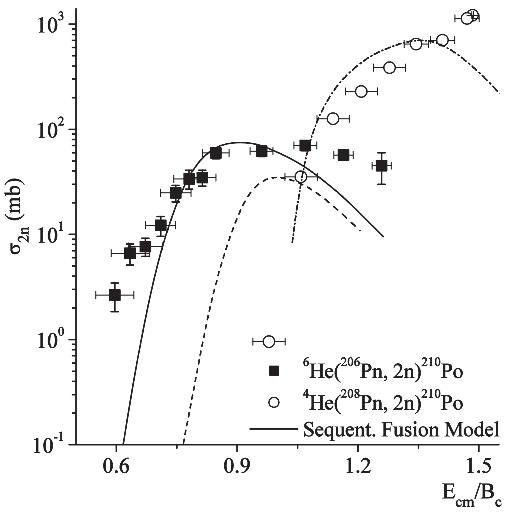

Fig. 2. Cross sections of the 2n-evaporation channels for the reactions ^{206}Pb(^{6}He,2n)^{210}Po (■) and ^{204}Pb(^{4}He,2n)^{210}Po (○) as a function of the ratio (E_c/B_c). The solid line is the result of the calculation according to the sequential fusion model [5, 15] for ^{206}Pb(^{6}He,2n)^{210}Po reaction. Dashed and dot-dashed lines show calculated the 2n evaporation excitation functions in the case of ignoring the neutron transfer channel for the ^{206,208}Pb(^{6,4}He,2n)^{210}Po, respectively.

The excitation cross section was calculated ignoring the neutron transfer channel and is shown by dashed lines. It can be seen from the figure that, even at ^{6}He energies below the Coulomb barrier of the ^{206}Pb+^{6}He reaction, the formation cross section of ^{210}Po – the isotope produced after the evaporation of 2 neutrons by the compound nucleus – is quite significant (~10 mb). Thus, from the obtained data it follows that a considerable enhancement of the cross section of the reaction of fusion of ^{206}Pb with the ^{6}He nuclei takes place around the Coulomb barrier compared to the case of ignoring the neutron transfer channel.

The feasibility of this two-step fusion model is supported by the results of Refs. [4, 5], where a strong influence of neutron transfer was observed: a high cross section (σ~1 b) for the transfer of neutrons to the target by the ^{6}He projectile was measured at bombarding energies around the Coulomb barrier. Besides, at the Coulomb barrier a maximum was observed for the excitation function of a neutron transfer reaction. We may expect that such peculiarities in the interaction between nuclei, manifesting themselves as an enhancement of the cross section of cluster transfer, as well as of complete fusion, are characteristic for many other weakly bound cluster nuclei [14].

The comparison of the cross sections from the two reactions $^{206}Pb(^{6}He,2n)^{210}Po$ and $^{208}Pb(^{4}He,2n)^{210}Po$ reveals the influence of the entrance channel on the fusion process. As can be seen from figure 2 the good agreement between the experimental and calculated [15] (solid curve in figure 2) excitation functions for the reaction $^{206}Pb(^{6}He,2n)^{210}Po$ gives evidence that the process of sequential transfer of neutrons in the case of weakly bound nuclei is the main factor influencing the fusion of ^{6}He with ^{206}Pb.

One should mention that was experimentally established that value of cross section for 0n or 1n-evaporation channels in the $^{208}Pb(^{4}He,xn)^{212}Po$ is below 0.5 mb. Thus, the 2n evaporation from the compound ^{212}Po is distinguished from the incomplete fusion of ^{4}He with the lead target, since the product in both reactions is ^{210}Po. According to the simple estimation, energy of ^{4}He after breakup is 30% less than the projectile energy, that brings interaction system $^{4}He+^{208}Pb$ deeply into sub-barrier region. So, the fusion of ^{4}He after break-up of ^{6}He with the lead nucleus does not take place at the sub-barrier energies.

It should be noted that formerly in the $^{209}Bi+^{6}He$ reaction [9] the excitation functions were measured for the decay of the compound nucleus by the emission of 3 neutrons. The comparison of the obtained results with calculations within the framework of the theoretical model for formation and decay of a compound nucleus also demonstrated an enhancement of the sub-barrier fusion induced by ^{6}He ions.

Figure 3 shows the dependence of the complete fusion cross sections divided by the interaction radius $\sigma_{fus}/(r_0(A_t^{1/3}+A_p^{1/3})^2$ for the reactions $^{6}He+^{206}Pb$ and $^{4}He+^{208}Pb$, obtained in the present work (assuming parameter r_0=1.2), together with those for the $^{6}He+^{209}Bi$ reaction [9], as a function of the energy above the Coulomb barrier E_{cm}/B_c. For comparison, the same dependence is presented for the $^{6}Li+^{209}Bi$, studied earlier in our paper [14], as well as from Ref. [16]. In order to get the values for the $^{4}He+^{208}Pb$ reaction, it was necessary to sum over the cross sections for the 1n-evaporation residues of Ref. [18] and the 2n-evaporation residues, obtained in the present work. As it follows from Ref. [19], where the reaction $^{197}Au(^{4}He,0n)$ was studied, we assume that similarly the contribution from the $^{208}Pb(^{4}He,0n)$-channel can be neglected.

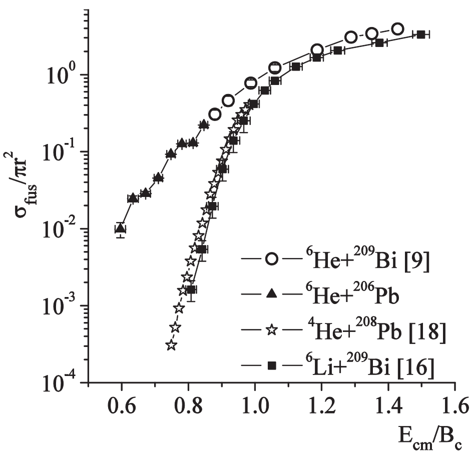

Fig. 3. The ratio of the complete fusion cross sections and the interaction radius $(\sigma_{fus}/(r_0(A_t^{1/3}+A_p^{1/3}))^2)$ for the reactions $^{4,6}He + ^{208,206}Pb$, $^{6}He + ^{209}Bi$ [9] and $^{6}Li + ^{209}Bi$ [16] as a function of the ratio of energy to the Coulomb barrier E_{cm}/B_c.

Our present data (which obtained with the better resolution) are in an agreement with of our previous study [4, 5] of the fusion reaction $^{6}He+^{206}Pb$. Both current data and previous one show the same tendency as shown in figure 3.

The comparison of these reactions demonstrates the strong difference in excitation functions for complete fusion induced by ^{6}He ions and by the nuclei ^{4}He and ^{6}Li. It is noteworthy that our data are in agreement with the data for the reaction $^{6}He+^{209}Bi$ [9], which were obtained at higher energies. The presented reduced values of the complete fusion cross sections allow accounting for the difference in the geometrical size of the interacting nuclei and in the values of the interaction barriers.

Conclusions

In the measured excitation function of the reaction $^{206}Pb(^{6}He,2n)^{210}Po$ at sub-barrier energies a significant enhancement is observed for the probability of fusion compared to expectations according to the statistical model and to the results from the $^{208}Pb(^{4}He,2n)^{210}Po$ reaction, in which the same compound nucleus ^{212}Po is produced. This reflects an unusual mechanism that is present in reactions induced by weakly bound nuclei. We further assume that the unusual mechanism, which manifests itself in the enhancement of the cross section in the transfer of clusters, as well as of complete fusion reactions, may be characteristic for many other loosely bound cluster nuclei.

It seems that for the further study of the interaction of ^{6}He, as well as of other weakly bound cluster nuclei, such as ^{6}Li, ^{7}Be, etc., we must measure total reaction cross sections and cross sections for the transfer of clusters at energies close to and below the Coulomb barrier. This will let us better understand the interaction mechanism of such nuclei at low energies.

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