FEATURES OF NUCLEAR REACTIONS WITH LIGHT WEAKLY BOUND NUCLEI AT ENERGY NEAR THE COULOMB BARRIER

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In the experiments carried out by ion beam ^{6}He of the cyclotron complex DRIBs (JINR) and ^{3}He beam cyclotron U-120M of the NPI, Czech Academy of Sciences have been investigated reaction ^{45}Sc+^{3}He,^{6}He and ^{197}Au+^{3}He,^{6}He in the energy range near the Coulomb barrier. It were obtained the experimental values of the cross sections for complete fusion reactions and direct reactions for formation of the isotopes ^{43}Sc, ^{44}Sc and ^{46}Sc also ^{196}Au and ^{198}Au as a function of the bombarding ^{3}He and ^{6}He energy. Despite the low binding energy of ^{3}He and the positive Q- values leading to the formation of isotopes ^{44}Sc and ^{46}Sc also ^{196}Au and ^{198}Au, the behavior of the excitation functions with the formation of these isotopes is different from the excitation functions for d, ^{6}He.

1. Introduction

Understanding of the mechanisms of the fusion and transfer reactions with beams of radioactive and weakly bound stable nuclei is essential for the synthesis of superheavy elements and astrophysics. A small binding energy of the valence nucleons in halo nuclei and nuclear clusters in loosely bound nuclei should influence the processes of interacting nuclei at energies near the Coulomb barrier [1-3]. In addition to on the possibility of reaction affects Q-value, which in these cases is usually positive. Like the halo radioactive nuclei, weakly bound nuclei such as $^{6,7}Li$ and others, have a low threshold for breakup on clusters, and therefore they have a high probability for clustering in the excited state. The transfer reactions may

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dominate at energy of the bombarding ions below the Coulomb barrier as from the cluster structure of nuclei well as from the large positive Q-value. Can one expect any-peculiarities in reactions with stable nuclei projectiles as ^{3}He, which has a small binding energy of 7.718 MeV (2.57 MeV / A)? Due to the smaller separation energy of the proton in ^{3}He (S_p = 5.49 MeV), low-energy separation of 2 protons S_{2p} = 7.71 MeV, reactions due to ^{3}He should lead to an increase in the contribution of direct reactions: pickup and stripping of nucleons. The purpose of this report is the comparison of the reaction mechanisms in the bombardment of targets of ^{45}Sc, ^{197}Au and Pt by ions ^{6}He, ^{3}He and ^{6}Li at energies in the vicinity of Coulomb barrier reactions. This was done by analyzing the excitation functions of reactions for formation of different nuclides as products of the complete fusion and for formation of the same radioactive nuclei in direct reactions, including those with a positive Q-value of the reaction.

2. Experimental procedure

The experiments were performed at the accelerator complex DRIBs [3], the cyclotron U-400M JINR with ACCULINNA separator [4] and the U-120M

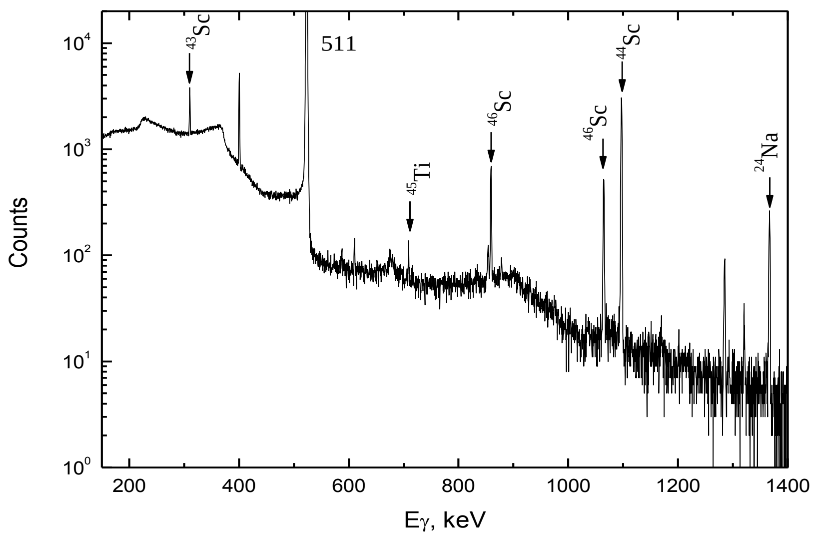


Fig. 1. Gamma-spectrum obtained in the measurement within 30 min, the irradiated foils of 3 μm ^{45}Sc ^{3}He beam with an energy of 22.7 MeV, 5 hours after the end of irradiation.

cyclotron of the Institute of Nuclear Physics of the Czech Republic in Rez [5] using the activation technique. After irradiation by a beam of accelerated ions of ^{3}He, ^{6}He and ^{6}Li of thin foils from ^{45}Sc, ^{197}Au and Pt in there are been measured the induced activities. All measurements were performed on HPGe detectors from 20 to 50% efficiency with respect to NaJ and HWHM of 1.3 to 1.8 keV for the γ-ray energy of 1.3 MeV. Identification of nuclei formed in the reaction was carried out taking into account the γ-decay energies and lifetimes of these nuclei using the nuclear data collected in [3]. In Fig. 1 shows the characteristic γ-spectra obtained in the measurement of induced activity in Sc target induced by ^{3}He beam. The calculations of cross sections for nuclides produced in nuclear reactions based on the work [3].

3. Experimental results

3.1. *Fusion reactions*

On the basis of the measured yields of the isotopes for the reaction ^{197}Au+^{6}He, formed after the evaporation from the compound nucleus ^{203}Tl of x-neutrons, taking into account the ^{6}He beam intensity and the target thickness, we could determine the cross sections for the formation of the different isotopes and their dependence on the bombarding energy (the excitation functions). Contrary to the excitation functions for x = 3-7, the cross sections for the 2n-exit channel (the nucleus ^{201}Tl is formed) are significantly higher than the values, calculated using the one-dimensional barrier between the interacting nuclei [3]. This may be connected with the fact that the reaction with total absorption of ^{6}He by the ^{197}Au target nucleus has a large positive *Q*-value, equal to +12.2 MeV.

We have observed quite a similar situation in the case of the interaction of ^{6}He with ^{206}Pb, the *Q*-value is equal to +4.2 MeV. The cross section for this reaction at the maximum, according to the statistical model calculations should be small, because the maximum is situated at energies below the Coulomb barrier [3, 5]. The agreement between the experimental reaction cross sections for the ^{206}Pb(^{6}He,2n)^{210}Po reaction with the calculated for the two-step fusion process can be considered, which influences the fusion probability of ^{6}He with

^{206}Pb and leads to the increase in the reaction cross section at energies far below the barrier.

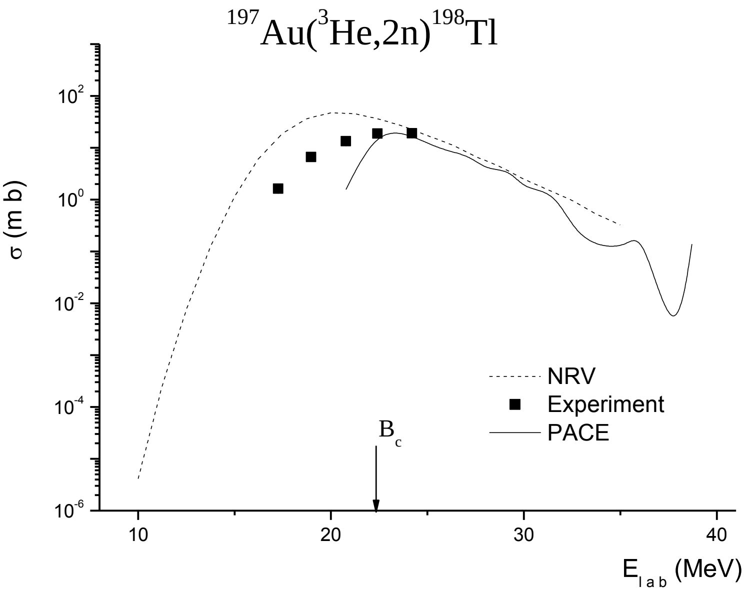


Fig. 2 Excitation functions of reactions of formation of ^{197}Au (^{3}He, 2n) ^{198}Tl. Bc = 22,4 MeV.

For these exit channels, followed by the evaporation of two neutrons (^{206}Pb+^{6}He and ^{197}Au+^{6}He) at energies close to the Coulomb barrier the cross sections differ from predictions within the framework of the statistical model for compound nuclei decay. A strong enhancement is observed and this is in agreement with the model of “sequential fusion”

In the case of a study of reaction^{197}Au+^{3}He the Q-value for the compound nucleus reaction 10.8 MeV and it is possible to observe appreciable cross sections for evaporation 2n channel in the sub-barrier energy region. The excitation function for the reaction ^{197}Au (^{3}He, 2n) ^{198}Tl are shown in Fig. 2. The results of calculations of cross sections for the same reaction on ^{197}Au using the codes NRV [7] and PACE 4 [8] are shown also.. They give the closest cross section values to experimental results for some energy range.

In the experiments [9] was been shown the absence to fusion hindrance in reaction ^{198}Pt+^{6}Li in comparison of couple- channels calculation using Woods-Saxon potential.

3.2. *Direct reactions*

First we were observed a large cross section for neutron transfer with the ^{6}He to nucleus of the target in the reactions ^{6}He + ^{197}Au at sub-barrier energies [3]. The transfer reactions of one neutron to the ^{197}Au nucleus from ^{6}He take place with relatively high probability at deep sub-barrier energies. This may be connected with the interaction of quasi-free neutrons.

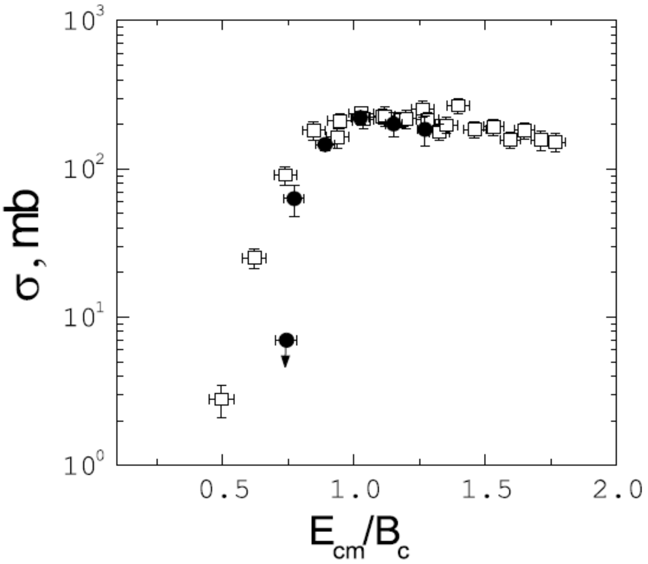


Fig. 3. Excitation function for the isotope ^{199}Au, produced in the interaction of ^{6}Li with ^{198}Pt. [8] ●- our data, for the *d* + ^{198}Pt reaction presented by □, are shown for comparison.

In the study of the reactions with ^{6}Li beam have been measured yields of isotopes with the transfer of nucleons to the target nucleus [10]. In Fig. 3 is shown the excitation function for formation of isotope ^{199}Auin the reaction ^{198}Pt (^{6}Li, X) ^{199}Au, which has a positive Q- value. Comparison of formation cross section for ^{199}Au in the reactions of deuterons and ^{6}Li indicate that, apparently, mainly in the bombardment of Pt nuclei by ^{6}Li, the reaction is the so- called inelastic sequential breakup of ^{6}Li, leading to the target capture from ^{6}Li only deuteron. These data were confirmed in articles [9].

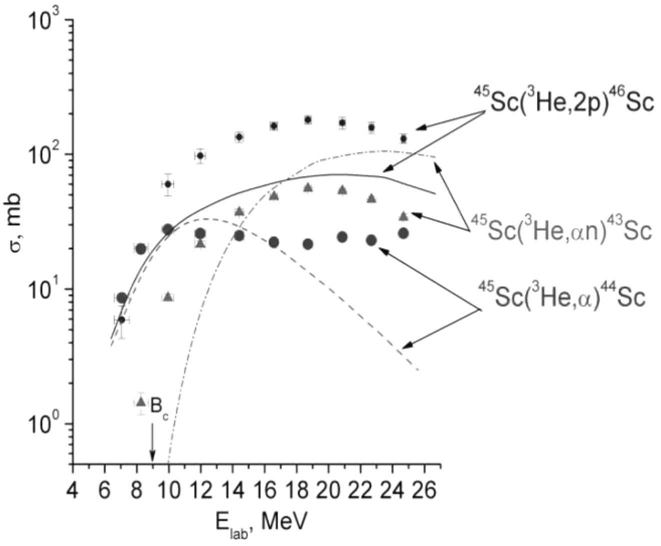
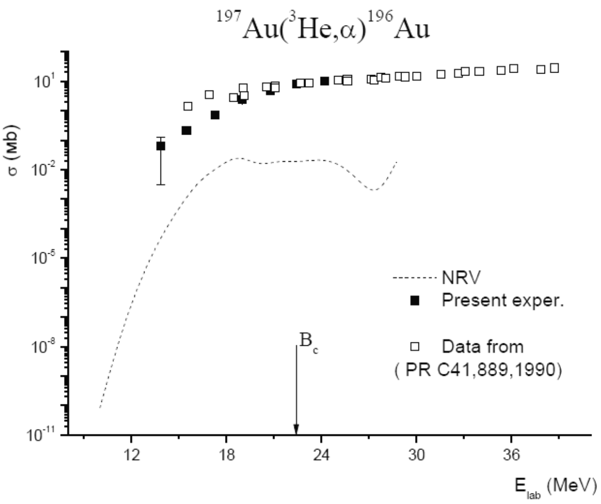


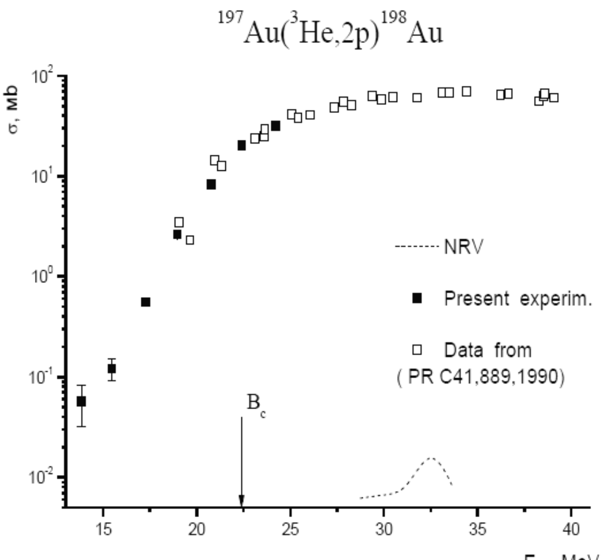
Fig.4. The excitation functions of the reaction products ^{45}Sc +^{3}He. Reaction cross sections are presented with symbols: square-cross section of the ^{45}Sc (^{3}He, 2p) ^{46}Sc, triangles-^{45}Sc (^{3}He, αn) ^{43}Sc and mugs-^{45}Sc (^{3}He, α) ^{44}Sc. Curves are calculation of cross sections for these reactions is the code ALICE-MP.

In Fig. 4 are shown the cross sections for formation isotopes of ^{44}Sc and ^{46}Sc via the energy of bombarding particles of ^{3}He by ^{45}Sc for one nucleon transfer reaction as stripping (^{46}Sc) and pickup (^{44}Sc) reactions [11].
Both these reactions due to positive Q-values well manifested at energy ^{3}He below the Coulomb barrier. In the case of transfer to the target nucleus ^{45}Sc one neutron from^{3}He excitation function (^{46}Sc) has a characteristic behavior for a single neutron transfer reactions. Some unusual behavior of excitation function is observed, when ^{44}Sc is formed. Despite on the large positive value of Q (+9,254 MeV) for the reaction (^{3}He, α) there is a clear maximum of the excitation function near the Coulomb barrier.

In reactions ^{197}Au+ ^{3}He were measured cross-sections of nuclei ^{196} Au and ^{198}Au (Fig.5). It is noted that in this case, both the reactions:
^{197}Au (^{3}He, 2p) ^{198}Au and ^{197}Au (^{3}He, α) ^{196}Au
take place at the sub-barrier energy.



(a)



(b)

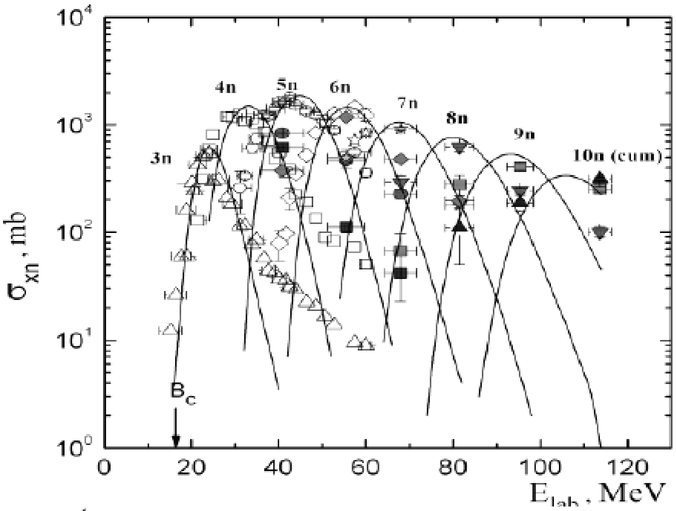
Fig. 5. The excitation functions for formation of: a) ^{196}Au, b) ^{198}Au- in the interaction of ^{197}Au with ^{3}He (Bc = 22,4 MeV).

The excitation function for ^{196}Au, it is formed the α-particle, as in the case of reactions with ^{45}Sc (Fig. 4), reaches its maximum at the Coulomb barrier of this reaction.

3.3. *Fusion reactions up to 20 MeV/ A*

We have extended the experiments [12] to study the fusion and transfer reactions at higher energy of the accelerated ions of ^{6}He about 20 MeV/A.

(a)



(b)

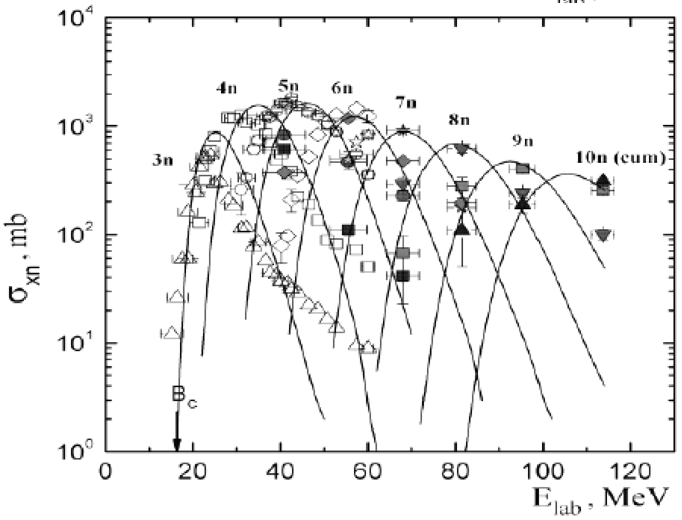


Fig. 6. The excitation functions of reactions ^{197}Au (^{6}He, xn) $^{203\text{-}xn}Tl$. Open symbols-data of [3], the dark symbols-data of the work. [9] Solid curves-calculation program ALICE [3,9] (a) and NRV [7] (b).

The results of measurements of excitation functions for complete fusion reactions with the formation of the compound nucleus ^{203}Tl and subsequent evaporation of neutrons are shown in Fig.6. Calculations were performed using the code ALICE-MP [3] and the NRV [7]. A comparison of calculations with experimental data shows that significant suppression for complete fusion is not observed.

4. Conclusion

On the basis of experimental data on the interaction of the halo nuclei ^{6}He with^{197}Au and ^{206}Pb can draw the following conclusions:

-The data on two neutrons evaporation channel in fusion reactions at energies close to the Coulomb barrier are different from predictions within the framework of the statistical model for compound nuclei decay. The strong enhancement was observed for halo nuclei and that is in agreement with the model of "sequential fusion".

- Above the Coulomb barrier, the process of fusion halo nuclei is well described by the evaporation models, the suppression in the fusion was not observed at the energy of 20 MeV /A.

- Neutron transfer reaction cross sections or cluster capture cross sections reach its maximum value at the Coulomb barrier in the case of the formation of α-particles as reaction product.

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