Special Features of Nuclear Reactions Induced by Loosely Bound Nuclei in the Vicinity of the Coulomb Barrier Height

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Abstract. Excitation functions are measured for complete-fusion and transfer reactions induced by the interaction of $^6$He and $^6$Li with $^{206}$Pb, $^{209}$Bi, and Pt. Data obtained for fusion reactions induced by $^6$He ions deviate from the predictions of the statistical model of compound-nucleus decay at projectile energies in the vicinity of the Coulomb barrier height. A strong enhancement of cross sections for fusion reactions induced by the interaction of $^6$He with target nuclei is observed. The cross sections for reactions of cluster transfer, neutron transfer from $^6$He, and deuteron transfer from $^6$Li at deep-subbarrier energies, are also found to be enhanced. These results are discussed from the point of view of the effect of the cluster structure of nuclei on the interaction probability at energies in the vicinity of the Coulomb barrier height.

1. Introduction
Reactions involving loosely bound nuclei and occurring at energies in the vicinity of the Coulomb barrier height have many special features that have vigorously been discussed in recent years in a number of studies (see, for example, [1, 2]). These features include the enhancement of interaction cross sections in the subbarrier energy region. This effect is especially pronounced for clustering nuclei (for example, $^6$Li) [3], as well as neutron-halo nuclei (for example, $^6$He) [4]. Transfer, breakup, and complete-fusion reactions are dominant interaction channels for such nuclei. Processes in which the breakup of loosely bound nuclei in the field of a heavy nucleus is followed by the fusion of the residual nucleus with the target nucleus have been the subject of numerous theoretical and experimental investigations. In accordance with classical concepts, the fusion of interacting nuclei occurs after they overcome the barrier determined by long-range Coulomb forces and a component of the short-range nuclear potential. But in the case of the interaction of loosely bound nuclei, the fusion process has a more intricate character because of a high probability of their breakup followed by residual nucleus capture (incomplete fusion). This complicates substantially the description of the interaction of such systems and leads to new, unexpected, effects at energies in the vicinity of the Coulomb barrier height, such as deep-subbarrier fusion and reactions of cluster transfer from loosely bound nuclei, which, as a rule, have a cluster structure. At the present time, there are several theoretical approaches within which one attempts to describe the interaction of loosely bound nuclei [5, 6]. Difficulties in describing such processes stem from the need for employing a theory that would take into account the interaction of several nuclear fragments. The possibilities for studying reactions involving loosely bound nuclei at energies in the vicinity of the Coulomb barrier height have become substantially wider since the advent of relatively intense (up to $10^8$ s$^{-1}$) beams of radioactive nuclei. The first experiments along these lines involved studying the interaction of a $^6$He ion beam with heavy
nuclei [4]. Those experiments revealed an enhancement of the fusion–fission cross section in relation to the case of stable nuclei.

In recent years, experimental investigations along these lines have been developed quite intensively both with the aid of beams of radioactive nuclei and with the aid of beams of stable loosely bound nuclei, such as $^6$Li. The $^6$Li nucleus is known to have the $(\alpha + d)$ cluster structure (the energy threshold for the breakup of this nucleus into a deuteron and an alpha particle is as low as 1.47 MeV). The radius of the $^6$Li nucleus ranges between 2.32 and 2.45 fm, and this is 10% larger than the radius value expected from the available systematics. It follows that, in principle, this nucleus is also expected to manifest, in nuclear reactions, properties peculiar to other loosely bound nuclei, such as $^\alpha$He, $^\alpha$He, $^7$Li, and $^{11}$Li. The momentum distributions of nuclear residues formed upon the breakup of $^6$He and $^6$Li nuclei were investigated in [10]. From an analysis of these distributions, it also follows that, in just the same way as the $^4$He nucleus, the $^6$Li nucleus features a cluster structure, which can manifest itself in the interaction of these nuclei with other nuclei. In the present article, we describe results of investigations performed at the Flerov Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research (JINR, Dubna) in beams of accelerated $^4$He and $^6$Li ions.

2. COMPLETE AND INCOMPLETE FUSION IN THE INTERACTION OF $^6$LI IONS WITH BI AND PT NUCLEI

In this section, we present experimental results obtained at the U400 accelerator of the Flerov Laboratory of Nuclear Reactions by using a beam of $^6$Li ions accelerated to an energy of 55 ± 0.6 MeV. In order to obtain a beam characterized by a small energy spread, use was made of the method of beam monochromatization by means of a magnetic analyzer [11]. A polyethylene absorber that reduced the average energy to the required value was installed in the reaction chamber upstream of the magnetic analyzer in order to lower the initial beam energy. The energy (and the spatial distribution) of the $^6$Li-ion beam incident to the targets positioned in the focal plane of the magnetic analyzer was determined by the target dimensions (18 mm), and its value was found to be 42.5 ± 0.25 MeV. Assemblies of targets from platinum and bismuth foils were irradiated at this energy of $^6$Li ions. Aluminum absorbers were arranged in front of the targets in order to obtain different values of the $^6$Li energy. This experimental scheme made it possible to reduce the beam energy and to minimize its spread. The intensity of the beam incident to a target assembly was measured by scintillation detectors arranged downstream of the assembly. For a more detailed description of the experimental procedure, the interested reader is referred to [9]. The activation method was used to detect reaction products. The energy dependences of their production rates were measured for various reaction channels. The use of aluminum absorbers between the targets in a stack made it possible to reduce consecutively the energy of bombarding ions before each target in the stack. This method permitted simultaneously measuring a significant part of the excitation function for the reaction channels under study over a broad energy range. Products originating from the complete and incomplete fusion of $^{209}$Bi and $^6$Li nuclei are predominantly alpha-active, while the products of the respective reactions with platinum targets are gamma active. The target thicknesses were optimized in order to increase production rates for reactions having relatively small production cross sections, on one hand, and to ensure an acceptable energy resolution in measuring an induced activity, on the other hand.

2.1. $^6$Li+Bi Reactions

Induced alpha radioactivity was measured after irradiating an assembly of bismuth targets with a $^6$Li beam. The details of the procedure for identifying various isotopes appearing as reaction products and for determining their production rates can be found in [9]. The interaction of $^6$Li ions with $^{209}$Bi target nuclei resulted in the formation of $^{215}$Rn compound nuclei, whose deexcitation via neutron evaporation led to various Rn isotopes (in the case of the complete fusion reaction). Isotopes of Po and At appearing as products of reactions in which $^2$H or $^4$He fragments formed in $^6$Li breakup (incomplete-fusion reactions) are captured by the target nucleus ($^{209}$Bi) were also observed in the measured alpha-
particle spectra. The mass numbers of nuclei appearing as evaporation products were identified by the known alpha particle energy and half-lives. Some difficulty arose in the separation of the complete- and incomplete fusion channels leading to the formation of the same nucleus-for example, $^{211}$At. This isotope could be produced both upon the incomplete-fusion process $^4$He + $^{209}$Bi → $^{213}$−2$n$At and upon the electron conversion of the $^{211}$Rn nucleus formed in the channel of evaporation of four neutrons from the compound nucleus $^{215}$Rn. In that case, the reaction channels were separated by comparing the experimental and calculated excitation functions for fusion reactions [12].

The energy dependences calculated in this way for the cross sections for complete fusion followed by neutron evaporation are displayed in Fig. 1.

![Figure 1. Excitation functions for $^6$Li + $^{209}$Bi reactions resulting in the production of $^{208,210}$Po isotopes. The displayed closed symbols represent experimental data of the present study for the production of the isotopes (circles) $^{208}$Po and (boxes) $^{210}$Po. The open symbols stand for experimental data on the production of the isotopes (boxes) $^{208}$Po and (triangles) $^{210}$Po in $d^+^{209}$Bi reactions from [13] and [3], respectively.](image)

From this figure, one can see that the cross section for the production of these isotopes amounts to a few hundred millibarns and decreases smoothly with increasing energy to a value of 10 mb at an energy of 25 MeV. The cross section for the complete-fusion reaction at this energy value is 0.5 mb. For the sake of comparison, data on the fusion of deuterons with $^{209}$Bi from [3] are also presented in Fig.1. One can see that both the behavior of the excitation functions and the absolute cross-section values agree in the two cases (incomplete fusion $^6$Li with $^{209}$Bi and complete fusion of deuterons with $^{209}$Bi). The interaction of $^6$Li ions with $^{209}$Bi target nuclei resulted in the formation of $^{215}$Rn compound nuclei, whose deexcitation via neutron evaporation led to various Rn isotopes (in the case of the complete fusion reaction). Isotopes of Po and At appearing as products of reactions in which $^4$H or $^4$He fragments formed in $^6$Li breakup (incomplete-fusion reactions) are captured by the target nucleus ($^{209}$Bi). As follows from the results of the present study, the probability of the fusion reaction is relatively high in the subbarrier energy region. It is noteworthy that the experimental excitation functions for evaporation reactions agree well with their counterparts calculated on the basis of the
statistical model. In the case of incomplete-fusion reactions, the target nucleus captures fragments ($^4\text{He}$ or $^2\text{H}$) produced upon $^6\text{Li}$ breakup. The capture of product deuterons is likely to be the most probable process here. The fusion of deuterons with target nuclei in relation to the fusion of alpha particles is preferable from the point of view of the $Q$ values for these reactions:

$$^6\text{Li} + ^{209}\text{Bi} \rightarrow ^4\text{He} + ^{211}\text{Po} \quad (Q = +5.8 \text{ MeV})$$

$$^6\text{Li} + ^{209}\text{Bi} \rightarrow ^2\text{H} + ^{213}\text{At} \quad (Q = -10.7 \text{ MeV})$$

As follows from the results of the present study, the probability of the fusion reaction is relatively high in the subbarrier energy region. It is noteworthy that the experimental excitation functions for evaporation reactions agree well with their counterparts calculated on the basis of the statistical model by using the ALICE-MP code [12].

![Graph](image)

**Figure 2.** Excitation functions for the reactions $^{209}\text{Bi}(^6\text{Li}, xn)^{215-219}\text{Rn} \ (3 \leq x \leq 5)$. The displayed points represent experimental data for the (closed and open boxes) $^{209}\text{Bi}(^6\text{Li}, xn)^{215}\text{Rn}$, (closed and open inverted triangles) $^{209}\text{Bi}(^6\text{Li}, xn)^{217}\text{Rn}$, and (closed circles) $^{209}\text{Bi}(^6\text{Li}, xn)^{219}\text{Rn}$ reactions. The closed symbols stand for data of the present study, while the open boxes and open inverted triangles correspond to data from [3] for the 3$n$ and 4$n$ evaporation channels, respectively. The curves were calculated by using the ALICE-MP code [12]. The notation $B_c$ stands for the Coulomb barrier for $^6\text{Li} + ^{209}\text{Bi}$ reactions.

The cross section for the complete-fusion reaction at this energy value is 0.5 mb. For the sake of comparison, data on the fusion of deuterons with $^{209}\text{Bi}$ from [13] and [3] are also presented in Fig.2. One can see that both the behavior of the excitation functions and the absolute cross-section values agree in the two cases (incomplete fusion $^6\text{Li}$ with $^{209}\text{Bi}$ and complete fusion of deuterons with $^{209}\text{Bi}$). An analysis of $^9\text{Be} + ^{208}\text{Pb}$ and $^{18}\text{O} + ^{198}\text{Pt}$ reactions leading to the production of the same radon compound nuclei as in the case of reactions involving $^6\text{Li}$ and proceeding on a bismuth target was performed in [14]. In that case, the excitation functions are also well described by the statistical model.
As was shown in [14], the contribution of processes involving particle transfer from the target nucleus and leading to the production of Po and At isotopes is negligible (less than 2% of the complete-fusion cross section). This makes it possible to draw two important conclusions: first, the production of Po and At isotopes does not occur in the complete-fusion channel of reactions involving 6Li; second, there is a large contribution from the incomplete-fusion channel in reactions involving lithium isotopes. The fact that the isotope 210Bi corresponding to the transfer of one neutron to the target nucleus, 206Bi(6Li, n)210Bi, was not observed in our experiments indicates that the probability of this process is much lower (σ ≤ 10 mb) than the probability of neutron transfer in the reaction induced by a 3He beam [9, 13]. This can be explained by a neutron excess and a positive value of Q for the reaction in the case of 6He. Thus, the channel of 6Li-ion breakup followed by deuteron absorption by the target nuclei (incomplete fusion) is a dominant channel leading to the production of Po isotopes in 206Bi+6Li reactions, deuteron absorption being more probable than 3He absorption because of large reaction Q values. It is also noteworthy that the cross section for this process peaks at an energy close to the Coulomb barrier height.

An analysis of excitation functions for transfer reactions in 6Li beams corroborates the conclusion that the capture of the deuteron from 6Li by the target nucleus is a dominant mechanism of such reactions at energies in the vicinity of the Coulomb barrier height. The reason for this may be that the probability of deuteron capture increases upon the excitation and polarization of the projectile nucleus in the field of the target nucleus.

2.2. 6Li+Pt Reactions

The excitation functions for 6Li + Pt reactions were measured by means of the procedure identical to that in the cases described in the preceding section. After the irradiation of target assemblies of platinum foils, the induced gamma activity was measured in each target. Such reaction products include the isotope 208Tl formed in the complete fusion reaction 198Pt(6Li, 4n)202Tl and the isotopes 199Au and 195Au formed upon deuteron transfer to 198Pt nuclei. Figure 4 displays the excitation function for the reaction 198Pt(6Li, 4n)202Tl, which leads to the production of the isotope 208Tl after the evaporation of four neutrons from the compound nucleus 202Tl. The same figure also shows the results of the calculation performed by using the ALICE-MP code [12]. From this figure, one can see that the results of that calculation agree well with the displayed experimental values. This fact suggests that the code in question may provide a reasonable description of reaction-product yields and confirms additionally the correctness of the beam-monitoring method used in the experiments (that is, the method for determining, in the on-line mode, the beam energy and the flux of particles that traversed targets). Figure 3 shows the energy dependences of the cross sections for the production of gold nuclei (197Au) appearing as products of the transfer reaction induced by the interaction of 6Li ions with 198Pt nuclei. One can see that the production rate for the isotope 197Au, produced primarily upon deuteron transfer to the target nucleus has a maximum at the energy value corresponding to the Coulomb barrier height.

Therefore, there are grounds to state that direct reactions in which the capture of a deuteron from 6Li is followed by neutron evaporation must have, depending on the excitation energy of the product nucleus, a cross section larger than the cross sections for the reactions in which the capture of a proton from 6Li is followed by the evaporation of one neutron. The cross sections that we measured for 6Li + 198Pt reactions involving deuteron transfer have values close to those of d + 198Pt cross sections [15].

Commensurate values of the cross sections for 199Au production in reactions involving 6Li nuclei and deuterons (see Fig. 3) indicate that, in just the same way as in reactions involving deuterons, the polarizability of 6Li nuclei bombarded with Pt nuclei is likely to occur [16], in which case the reaction of so-called inelastic sequential breakup of 6Li followed by deuteron capture may proceed [17]. At an energy in the vicinity of the Coulomb barrier height, the fusion with a different product of the clustering of 6Li (alpha particle) is less probable, which is explained by different reaction Q values. At the same time, the process in which inelastic breakup in the vicinity of the Coulomb barrier for the
reaction in question is accompanied by the capture of a deuteron from $^6$Li by the target nucleus has cross sections smaller than those in the case of neutron transfer from $^6$He to the target nucleus [9].

The breakup of $^6$Li may occur at considerably higher excitation energies than the breakup process in reactions involving $^6$He [18]. The mechanism of deuteron stripping from $^6$Li (stripping breakup) at energies in the vicinity of the Coulomb barrier height, in which case the 6Li nucleus involved moving along the Coulomb trajectory is excited, with the result that the loosely bound deuteron is captured by the target nucleus, is discussed in [19]. The process of complete projectile capture (fusion) comes into play at higher $^6$Li energies. An analysis of excitation functions for transfer reactions confirms the conclusion that the capture of the deuteron from $^6$Li by the target nucleus is a dominant mechanism of such reactions. The mechanism of deuteron capture, for which the barrier is lower than for alpha particles, is simplified owing to the excitation of the projectile nucleus in the field of the target nucleus and its polarization. It is noteworthy that the inelastic-breakup process proceeds with the highest probability in the vicinity of the height of the reaction Coulomb barrier, where the electric field is quite strong, while the nuclear field is still weak.

3. COMPLETE AND INCOMPLETE FUSION REACTIONS INDUCED BY THE INTERACTION OF $^3$He IONS WITH Pb AND Au NUCLEI

Investigations of the interaction of nuclei involving a neutron halo are of special interest. We have investigated reactions in a $^3$He beam that result in the production of compound nuclei and their subsequent decay through the channels of neutron evaporation or fission and reactions involving neutron transfer to a target nucleus. It was indicated above that an increase in the probability of penetration (tunneling) through a potential barrier is possible for a $^3$He nucleus because of a more extended distribution of the neutron density in it in relation to ordinary nuclei. An extended distribution of nuclear matter is characteristic of neutron-rich light nuclei, in which the presence of
valence neutrons may lead to the formation of a neutron halo. Nuclei that have such a structure include $^6$He and $^{11}$Li. On the other hand, such nuclei are loosely bound, and this leads to an increase in the probability of their breakup, which may be followed by the fusion of the residual nucleus (core) with the target nucleus and nucleon-transfer reactions without a subsequent interaction of the nuclei. In principle, this wide variety of processes complicates an analysis of experimental data and requires taking into account all reaction channels. Meanwhile, a number of experiments in which attempts were made to determine the probability of fusion with $^6$He nuclei at energies in the vicinity of the Coulomb barrier height have been performed since our first experimental study aimed at exploring fusion–fission reactions involving $^6$He nuclei [4]. In the last article devoted to this problem [9], the authors stated that they did not observe an enhancement of the cross section for the reactions of fusion with $^6$He nuclei. There are some more studies that explored reactions of fusion with $^6$He nuclei [7, 8]. However, data obtained in those studies call for a higher statistical reliability; there is also want of more informative experiments that would involve separating all reaction channels. The presence of these contradictory data is indicative of difficulties in performing such experiments, primarily because of a weak intensity of beams of radioactive nuclei, which gives no way to obtain statistically reliable results, especially in the region of barrier energies. This is not the whole story, however. In order to study excitation functions over a broad energy range (5–70 MeV), the beam energy has to be reduced by means of absorbers, and this increases its energy spread. Finally, detector systems of high detection efficiency must be used at a relatively low beam intensity. We took all of this into account in preparing experiments at the Dubna Radioactive Ion Beams (DRIBs) accelerator complex [20] at the Flerov Laboratory of Nuclear Reactions at the Joint Institute of Nuclear Research (JINR, Dubna) at the beginning of 2008, where a record $^6$He-beam intensity of $5 \times 10^7$ s$^{-1}$ was achieved over a broad energy range (5–60 MeV) at an energy resolution not poorer than 1%. An optimization of the acceleration regime and of beam transportation to the measuring facility made it possible to obtain, without an additional collimation, a $^6$He$^{2+}$ beam of size 7×8 mm$^2$ directly in front of the measuring facility, the beam there having an energy of $E = 60.3$ MeV, an energy spread of $\Delta E = \pm 0.4$ MeV at a $^7$Li primary-beam current of about 3 µA. In the $^6$He beam, we performed a series of experiments aimed at studying $^6$He interaction with other nuclei. In this article, we present data obtained by measuring excitation functions for fusion reactions and neutron-transfer reactions. The yields of products originating from fusion reactions (followed by the evaporation of $x$ neutrons from the compound nucleus) and neutron-transfer reactions were measured by the activation method. The method used to determine reaction cross sections versus the energy of the $^6$He beam was described in the preceding section. In the experiments under discussion, use was made of targets from $^{206}$Pb [in order to measure excitation functions for the fusion reactions followed by the evaporation of two neutrons from the compound nucleus, $^{206}$Pb($^6$He, 2$n$) $^{204}$Pb] and $^{197}$Au [in order to measure excitation functions for fusion reactions followed by the evaporation of two to seven neutrons from the compound nucleus, $^6$He + $^{197}$Au $\rightarrow$ $^{203}$−$x$nTl, and for reactions involving the transfer of $x$ neutrons, $^6$He + $^{197}$Au $\rightarrow$ $^{197}$±$x$Au].

3.1. Complete-Fusion Reactions $^{206}$Pb($^6$He,2$n$) $^{204}$Po and $^{197}$Au($^6$He,x$n$) $^{201}$−$x$n Tl ($x = 2$–7)

Relying on the production rates measured for isotopes formed after the emission of two to seven neutrons from the compound nucleus $^{203}$Tl and taking into account the intensity of the $^6$He beam and the target thicknesses, we determined the cross sections for the production of these isotopes and their dependence on the energy of bombarding particles (excitation function). The same procedure was also used to construct the excitation function for $^{210}$Po produced in the reaction $^{206}$Pb($^6$He, 2$n$) $^{210}$Po. Figure 5 shows experimental results obtained by measuring the excitation functions for the reaction channels $^6$He + $^{197}$Au $\rightarrow$ $^{203}$−$x$nTl involving the emission of neutrons from the compound nucleus. These data were analyzed by using the ALICE-MP code [12]. The values of the parameters used in the calculations were borrowed from an analysis of experimental data on the cross sections for evaporation reactions induced by heavy ions in the region of medium-mass and heavy nuclei. In Fig. 8, the results of the calculations are represented by curves. From the figure, one can see that the experimental data on the reaction cross sections agree satisfactorily with the corresponding theoretical
curves in the region of maxima of the excitation functions for the $xn$ channels. The cross sections and excitation function for the reaction involving the emission of two neutrons and leading to the production of $^{201}\text{Ti}$ nuclei are at odds with the predictions of statistical model calculations. The calculated values proved to be markedly lower than the experimental results. The reason may be that the reaction involving the complete absorption of the $^6\text{He}$ nucleus by the $^{197}\text{Au}$ nucleus has a reaction $Q$ value of $+12.2$ MeV, with the result that the reaction involving the evaporation of two neutrons proves to be a deep-subbarrier reaction. A similar situation arises for the reaction $^{206}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$ as well (see Fig. 6). In that case, however, the reaction $Q$ value is $+4.2$ MeV, which is expected to lead to somewhat larger cross sections. The experimental and calculated data differ substantially for this reaction as well. According to statistical-model calculations (dashed curve), the cross section for the reaction $^{206}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$ at the maximum of the excitation function must be small because of a substantial suppression of this reaction channel at energies below the Coulomb barrier. However, one can see from the experimental data presented in Fig. 6 that, even at the $^6\text{He}$ ion energy 7 MeV below the Coulomb barrier for $^{206}\text{Pb} + ^6\text{He}$ reactions ($Bc \approx 21$ MeV), the cross section for the production of $^{210}\text{Po}$, a product that arises after the evaporation of two neutrons from the compound nucleus, is about 10 mb. Thus, our observation of the reactions involving the evaporation of two neutrons in the subbarrier energy region and the shape of the excitation functions for these reactions give sufficient grounds to state that there is a significant enhancement of the cross sections for the fusion of $^{197}\text{Au}$ and $^{206}\text{Pb}$ nuclei with $^6\text{He}$ nuclei near the barriers. Figure 6 also displays the fusion probability calculated on the basis of the two-step fusion model [5], which assumes a sequential transfer of neutrons from $^6\text{He}$ to the target nucleus. Concurrently, the excitation energy of the nuclear system being considered increases by $E_{\text{c.m.}} + Q_{\text{gg}}$, becoming much higher than the Coulomb barrier energy, with the result that, at the last stage, the alpha particle penetrates through the barrier. Good agreement in Fig. 6 between the experimental excitation functions and their calculated counterparts [5] (solid curve) for the reaction $^{206}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$ suggests that a sequential neutron transfer for loosely bound nuclei is likely to be a dominant factor affecting the probability for the fusion of $^6\text{He}$ and $^{206}\text{Pb}$ and increasing the reaction cross section in the deep-subbarrier region. Somewhat larger experimental cross sections in the region of minimum measured energies in relation measured energies in relation to calculated values are noteworthy. This discrepancy may be explained by the averaging of the calculated curve because of the beam-energy spread.

The mechanism of the two-step fusion model is also supported by the fact that, as will be shown below, a large value of the cross section for the reaction involving neutron-transfer to the target nucleus from $^6\text{He}$ ($\sigma \sim 1$ b) is observed at energies in the vicinity of the Coulomb barrier height. Such features of the interaction, which manifest themselves in the cross sections for cluster-transfer and complete-fusion reactions, are peculiar to many loosely bound cluster nuclei [6]. For the sake of comparison, the excitation function for the reaction $^{206}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$, which leads to the production of the same compound nucleus $^{212}\text{Po}$ as in the case of a $^6\text{He}$ beam, is also presented in Fig. 6. We performed the respective measurements at the Jyvaskyla accelerator (Finland) by using the activation procedure outlined above. On the basis of a comparison of the cross sections for the two reactions $^{206}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$ and $^{208}\text{Pb}(^6\text{He}, 2n)^{210}\text{Po}$, one can conclude that the entrance reaction channel has a significant effect on the fusion process. In the case of reactions induced by a loosely bound nucleus $^6\text{He}$, the fusion process may proceed with a high probability in the subbarrier energy region. Previously, the excitation function for the fusion reaction accompanied by the evaporation of three neutrons was measured in $^{208}\text{Bi} + ^6\text{He}$ collisions [8].
Figure 5. Excitation functions for the fusion reaction $^{197}$Au($^6$He, xn)$^{203-208}$Tl ($2 \leq x \leq 7$). The displayed curves represent the results of the calculations performed by using the ALICE-MP code [12] at the following values of the interaction-potential parameters: $r_0 = 1.29$ fm, $V = -67$ MeV, and $d = 0.4$ fm. Here, $B_C$ is the height of the Coulomb barrier for $^4$He + $^{197}$Au reactions.

Figure 6. Excitation functions for the reactions (closed box) $^{206}$Pb($^6$He,2n)$^{210}$Po and (open circles) $^{208}$Pb($^4$He,2n)$^{210}$Po involving the production of 2n-evaporation residues. The dashed and dash-dotted curves represent the results of the statistical-model calculations performed by using the ALICE-MP code [12] for the reactions $^{206}$Pb($^6$He, 2n)$^{210}$Po and $^{208}$Pb($^4$He, 2n)$^{210}$Po, respectively, while the solid curve stands of the results of the calculation within the sequential-fusion model [5] for the reaction $^{208}$Pb($^4$He, 2n)$^{210}$Po.

A comparison of the results of that study with the results of the calculations based on the statistical model of compound-nucleus formation and decay also confirms the effect of enhancement of subbarrier fusion with $^6$He nuclei. Figure 7 shows the dependence of the complete fusion cross sections obtained in the present study for $^6$He + $^{208}$Pb reactions and normalized to the interaction range $[\sigma_{\text{fus}}(r_0(A_{1/3}^1+P_{1/3}^1))]$ on the energy above the Coulomb barrier, $E_{\text{c.m.}}/B_{\text{c.m.}}$. The analogous dependences for $^6$He + $^{209}$Bi [8], $^4$He + $^{208}$Pb [21], and $^6$Li + $^{209}$Bi [16] reactions are also presented in this figure. A comparison of these reactions in the above representation reveals a strong distinction between the complete-fusion excitation function for reactions involving $^6$He nuclei and their counterparts for reactions involving $^4$He and $^6$Li nuclei. Good agreement between our data and respective data obtained in [8] at higher energies for $^6$He + $^{209}$Bi reaction catches the eye. Values quoted for the complete-fusion cross section make it possible to take into account the difference in the geometric dimensions of interacting nuclei and in the values of the interaction barriers. From Fig. 7, one can see that, in the case of reactions induced by a $^6$He-ion beam ($^4$He + $^{208}$Pb and $^6$He + $^{209}$Bi collisions), the values of the reduced cross section in the deep-subbarrier energy region are several orders of magnitude larger than their counterparts for $^4$He + $^{208}$Pb and $^6$Li + $^{209}$Bi reactions.
Figure 7. Dependence of cross sections obtained for complete fusion in (circles- data of the present study) $^6$He + $^{206}$Pb, (stars, data from [21]) $^6$He + $^{206}$Pb, (circles, data from [8]) $^6$He + $^{206}$Bi, and (closed boxes, data from [16]) $^6$Li + $^{209}$Bi reactions and divided by the interaction range $[\sigma_{\text{fus}}/(r_0(A^{1/3} t + A^{1/3} p^2))]$ on the energy above the Coulomb barrier.

In [1, 2], an attempt was made to describe fusion cross sections in the subbarrier energy region by the coupled-channel method. Within this description, the inclusion of coupling of collective degrees of freedom for loosely bound nuclei changes the complete fusion cross section and may lead, in particular, to an increase in the interaction cross section, especially in the subbarrier energy region [19]. However, further theoretical investigations relying on various approaches are required for quantitatively describing the above special features of reactions involving loosely bound nuclei—in particular, neutron-halo nuclei.

3.2. Transfer Reactions  $^6$He+ $^{197}$Au $\rightarrow$ $^{196,198}$Au.

An interesting result was obtained for the excitation functions in the reaction of neutron transfer to the target nucleus from $^6$He. Figure 8 shows the excitation functions that we measured for the reactions that are induced by the interaction of $^6$He and $^{197}$Au nuclei and where the gold isotopes $^{196}$Au and $^{198}$Au are produced in the ground state. From the data that we obtained, it follows that, in the vicinity of the barrier height, the probability of the formation of $^{198}$Au nuclei is high ($\sigma \sim 1$ b). We can also see that the cross section for the production of this isotope ($^{198}$Au) remains quite sizable at energies well below the Coulomb barrier, extending to the reaction threshold. It should also be noted that a relatively low production rate was observed in our experiments for the isotope $^{199}$Au. This may be indicative of a low population of the ground state of this nucleus upon the transfer of two neutrons. From Fig. 8, one can see that the cross section for the reaction involving the transfer of a single neutron to the target nucleus has a maximum, whereupon it decreases exponentially. The cross section for the reaction of neutron separation from the target nucleus decreases smoothly to the Coulomb barrier; after that, some kind of a separation of the cross section at a value of 10 mb occurs and then gives way to a gradual decrease. This may be explained by several mechanisms of $^{196}$Au formation ($-1n$ channel). At energies above the Coulomb barrier, neutron knockout from the target nucleus occurs predominantly. At energies in the vicinity of the Coulomb barrier height, a leading contribution to $^{196}$Au production comes from the
4. CONCLUSIONS
We will now formulate the conclusions suggested by the above analysis of the excitation functions that we measured for complete-fusion reactions followed by neutron evaporation and reactions of neutron transfer in the case where these reactions are induced by $^6$He nuclei of energy in the vicinity of the Coulomb barrier height. The excitation function measured for the reaction $^{206}$Pb($^6$He, $2n$)$^{210}$Po exhibits a significant enhancement for the fusion channel in the subbarrier energy region in relation to the predictions of the statistical model and in relation to the excitation function for the reaction $^{208}$Pb($^4$He, $2n$)$^{212}$Po, which leads to the formation of the same compound nucleus ($^{212}$Po). This is indicative of an unusual mechanism of the fusion reaction involving loosely bound nuclei. It is the opinion of the present author that special features of the interaction such that they manifest themselves in the enhancement of cross sections for cluster transfer reactions and complete-fusion reactions are characteristic of many loosely bound cluster nuclei. The reaction involving the transfer of a single neutron from $^3$He to $^{197}$Au at deep subbarrier energies ($E_{c.m.} - B_{c.m.} \leq 10$ MeV) has a relatively large cross section, and this may be indicative of the presence of quasi-free neutrons in the $^4$He nucleus. An analysis of excitation functions for transfer reactions in $^6$Li beams corroborates the conclusion that the capture of the deuteron from $^6$Li by the target nucleus is a dominant mechanism of such reactions at energies in the vicinity of the Coulomb barrier height. The reason for this may be that the probability of deuteron capture increases upon the excitation and polarization of the projectile nucleus in the field.
of the target nucleus. The results of the present study are of paramount importance for solving astrophysical problems—in particular, for obtaining deeper insight into the mechanism of the production of light elements in the Universe. In the course of nucleosynthesis, a large cross section for the interaction of loosely bound cluster nuclei ($^6$He, $^9$Li, $^7$Be) may change beta-decay chains leading to the formation of various elements [23]. For example, our results suggest that the reaction channels $^1$H($^6$He, $n$)$^6$Li, $^{12}$C($^6$He, $2n$)$^{16}$O, $^1$H($^9$Li, $n$)$^9$Be, $^3$He($^9$Li, $2n$)$^{10}$B, etc., may prove to be the most probable for the synthesis of light stable nuclei. With the aim of pursuing further investigations into special features of the interaction of $^6$He and other loosely bound cluster nuclei (such as $^6$Li, $^9$Li, and $^7$Be), we are going to measure total reaction cross sections and cross sections for cluster-transfer reactions in the subbarrier energy region. We hope that this will provide a clue to obtaining deeper insight into the mechanism of interaction of such nuclei at energies in the vicinity of the Coulomb barrier height.

ACKNOWLEDGMENTS
This work was supported in part by the Russian Foundation for Basic Research (project nos. 07-02-00271-a) and by grants from the Plenipotentiaries of the Czech Republic.

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