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NUCLEI
Experiment

Effect of Nuclear-Reaction Mechanisms on the Population of Excited Nuclear States and Isomeric Ratios

N. K. Skobelev*

Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia

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Abstract—Experimental data on the cross sections for channels of fusion and transfer reactions induced by beams of radioactive halo nuclei and clustered and stable loosely bound nuclei were analyzed, and the results of this analysis were summarized. The interplay of the excitation of single-particle states in reaction-product nuclei and direct reaction channels was established for transfer reactions. Respective experiments were performed in stable (^{6}Li) and radioactive (^{6}He) beams of the DRIBs accelerator complex at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, and in deuteron and ^{3}He beams of the U-120M cyclotron at the Nuclear Physics Institute, Academy Sciences of Czech Republic (Řež and Prague, Czech Republic). Data on subbarrier and near-barrier fusion reactions involving clustered and loosely bound light nuclei (^{6}Li and ^{3}He) can be described quite reliably within simple evaporation models with allowance for different reaction Q-values and couple channels. In reactions involving halo nuclei, their structure manifests itself most strongly in the region of energies below the Coulomb barrier. Neutron transfer occurs with a high probability in the interactions of all loosely bound nuclei with light and heavy stable nuclei at positive Q-values. The cross sections for such reactions and the respective isomeric ratios differ drastically for nucleon stripping and nucleon pickup mechanisms. This is due to the difference in the population probabilities for excited single-particle states.

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1. INTRODUCTION

Interest in the mechanisms of nuclear fusion and nucleon transfer at low energies has grown considerably in recent years in view of the problem of synthesis of superheavy transuranium elements and other nuclei in the vicinity of the nuclear stability boundary. In contrast to what was thought earlier, it turned out the mechanisms of nuclear reactions near the Coulomb barrier have not been understood conclusively. Meanwhile, these investigations are of paramount importance for astrophysics, since, in considering the problem of nucleosynthesis, it is necessary to know fusion cross sections in order to get a clearer idea of the scenario via which there arise chains of nuclei. Any new information about the effect of subbarrier processes on the interaction of nuclei can change radically our ideas of a successive chain of formation of new nuclei in nucleosynthesis. Investigation of reaction mechanisms for halo nuclei and loosely bound nuclei is of great interest both for theorists and for experimentalists. In turn, the cross sections measured for nuclear reactions are of importance for testing models used to describe the excitation and deexcitation of nuclear states in newly arising systems.

Reactions involving extremely light nuclei like those of deuteronium and helium have received the most adequate study. These and other extremely light nuclei are used in reactions as bombarding particles. At the same time, they are detected as products of various reactions not less frequently.

It is well known that the deuteron binding energy is 2.2246 MeV [1]. Despite its low binding energy, the deuteron is a stable nucleus. On the other hand, the binding energy of the triton (^{3}H), which is a radioactive hydrogen isotope, is 8.48 MeV, while its binding energy per nucleon, $E_{\rm bind}/A$, is as small as about 2.83 MeV [1, 2]. However, the separation energy for one neutron in this nucleus is 6.26 MeV. The Coulomb barrier $B_{\rm Coul}$ for the ^{3}H+^{197}Au reaction is 10.88 MeV, while the energy deposition Q in the production of a ^{200}Hg compound nucleus is 13.31 MeV; for the reaction $^3{\rm H} +^{197}{\rm Au} \to^{198}{\rm Au} + dQ$, $Q = 0.255$ MeV.

The ^{3}He nucleus, which is an isobaric analog of the triton, is a stable nucleus, and its binding energy of about 7.718 MeV ($E_{\rm bind}/A \sim 2.57$ MeV) is lower than the binding energy of the ^{3}H nucleus. In the

*E-mail: skobelev@jinr.ru

^{3}He nucleus, the separation energy for one proton is 5.493 MeV, while that for two protons is about 7.72 MeV. The Coulomb barrier height $B_{\rm Coul}$ is higher for the ^{3}He+^{197}Au reaction than for the ^{3}H+^{197}Au reaction and is equal to 21.76 MeV in the former case. For the ^{3}He+^{197}Au reaction leading to the production of a ^{200}Tl compound nucleus, the Q value is 10.8 MeV, while, for the reaction $^3{\rm He} +^{197} {\rm Au} \rightarrow {}^{198}{\rm Au} + 2p$, $Q = -1.206$ MeV.

A low nucleon binding energy in these nuclei should lead to an increase in the contribution of direct reaction mechanisms, such as projectile breakup, and the stripping and pickup mechanisms at bombarding-particle energies in the vicinity of the Coulomb barrier.

A number of nuclear reactions with other stable and radioactive beams lead to the formation of the products of similar nuclear reactions also having a positive Q value. In reactions involving light bombarding particles (^{6}He, ^{8}He, and so on) that have a halo structure and loosely bound clustered nuclei (such as d, ^{6}Li, and ^{7}Li) that have positive Q and low breakup thresholds, the yields of complete-fusion and transfer-reaction products are sizable in the region of subbarrier energies [3–7]. For the ^{6}Li nucleus, the threshold excitation energy for $\alpha + d$ cluster decay is 1.475 MeV, while, for the ^{7}Li nucleus, $\alpha + t$ decay occurs at excitation energies above 2.47 MeV. These energies are on the same order of magnitude as the energy of two-neutron separation from the ^{6}He nucleus or the energy of ^{6}He breakup to $^4{\rm He} + 2n$ (0.975 MeV). In a number of cases, the cross sections for transfer reactions reach a maximum value at an energy close to the Coulomb barrier for the reaction [3, 4].

The objective of the present study was to explore mechanisms of reactions that proceed upon exposing various targets containing light or heavy nuclei (^{9}Be, ^{45}Sc, and ^{197}Au) to beams of light loosely bound nuclei. This is done by analyzing the excitation functions for product nuclei formed in complete fusion reactions and in reactions involving the transfer of one or a few nucleons and clusters. Experimental cross sections obtained for the production of fusion reactions and few nucleon transfer reactions in beams of radioactive halo nuclei and clustered loosely bound stable nuclei are analyzed in this study along with isomeric ratios determined for a number of synthesized nuclides. This analysis, which covers, in particular, the mass region near closed shells, made it possible to trace the relation between the resulting cross section values and reaction mechanisms.

2. DESCRIPTION OF THE EXPERIMENT

The experiments under discussion were performed in extracted deuteron beams of energy 11.7 MeV [6, 7] and ^{3}He beams of energy 24.5 MeV [8, 9] from the U-120M cyclotron of the Nuclear Physics Institute (NPI), Academy of Sciences of Czech Republic (Řež), and in ^{6}He and ^{6}Li beams from the DRIBs accelerator complex of the Joint Institute for Nuclear Research (JINR, Russia) [3–5].

Target assemblies formed by scandium and gold foils of different thickness (from 3 to 5 μm) were installed on the path of th deuteron or ^{3}He beams at the center of the reaction chamber. Aluminum foils 5 to 50 μm thick were arranged in between the targets in order to reduce the beam particle energy. In a number of cases, irradiation runs for a single assembly lasted for eight hours. All induced activity measurements were performed by using calibrated high-purity germanium (HPGe) detectors of HWHM (half width at half magnitude) energy resolution of 1.8 keV at the photon energy of 1.3 MeV. Nuclei produced in the reactions being considered were identified with allowance for the gamma-decay energy and the lifetime of these nuclei by using nuclear data compiled in [10]. Experiments devoted to studying the elastic and inelastic scattering of these ions on a ^{9}Be target were also performed in ^{3}He and ^{4}He beams [11].

The beams of ^{6}He and ^{6}Li were obtained at the DRIBs accelerator complex for radioactive beams (Laboratory of Nuclear Reactions at JINR), which is a tandem of the U-400M and U-400 accelerators (ISOL method). The maximum energy of ^{6}He ions was about 10 MeV per nucleon, while the intensity of ^{6}He within the U-400 cyclotron reached values at a level of 2×10^8 particles per second. The procedure used in irradiating assemblies of gold foils and scandium with an extracted beam of ^{6}He nuclei was described in [3, 4, 6].

3. RESULTS

The elastic and quasielastic scattering of ^{3,4}He nuclei was studied in the reactions ^{9}Be(^{3}He, ^{3}He)^{9}Be and ^{9}Be(α, α)^{9}Be at the energies of $E_{^3{\rm He}} = 24.5$ MeV (NPI) and at the energy $E_{^4{\rm He}}$ of about 40 MeV (University of Jyväskylä, Finland) [11]. The transfer reactions ^{9}Be(^{3}He, α)^{8}Be and ^{9}Be(^{3}He, ^{5}He)^{7}Be and the charge-exchange reaction ^{9}Be(^{3}He, t)^{9}B were studied in addition to these channels. For all of the reactions studied in those experiments, the experimental cross sections and angular distributions were analyzed by employing the distorted-wave Born approximation (DWBA) and the coupled channel approach. In all transfer reactions, the population of excited states was observed in addition to the population of the ground states, the respective population probabilities being different. The investigations in question revealed that, in the interaction of these light nuclei, a peculiar structure of the ^{9}Be target nucleus manifests itself clearly in the form of virtual cluster configurations—specifically, in the form of the $\alpha + \alpha + n$ three-body and α+^{5}He, t+^{6}Li, and ^{8}Be + n two-body systems.

In the reactions induced by d, ^{3}He, and ^{6}He interactions with scandium and gold nuclei, we will be interested primarily in the treatment of the resulting experimental reaction cross sections from the point of view of peripheral interactions; therefore, a detailed data analysis that is associated with the reactions of the complete fusion of interacting nuclei and which was performed earlier in [3, 12] is skipped here. Only basic conclusions deduced from this analysis are formulated immediately below.

Subbarrier and near barrier fusion reactions involving stable cluster and loosely bound light nuclei are described quite reliably on the basis of evaporation models with allowance for channel coupling (for cluster nuclei like ^{6}Li) and on the basis of relatively simple evaporation models (for ^{3}He and for other light bombarding particles). Data on cross sections for fusion reactions made it possible to conclude that the halo structure of ^{6}He manifests itself most strongly in the region of energies below the Coulomb barrier, so that it is necessary to take into account both the structural features of the nucleus involved and coupling to other reaction channels in order to explain an increase in the fusion cross section. At energies of ^{6}He particles above the reaction barrier, the character of interaction in fusion reactions shows but a slight qualitative difference from that in reactions involving other light particles. In the subbarrier energy region, direct reaction mechanisms are dominant in reactions involving ^{6}He and other loosely bound nuclei; for the majority of these mechanisms, including fusion mechanisms, the Q-value is positive.

We will now consider features of nucleon transfer and cluster transfer reactions involving light projectile nuclei and various target nuclei. Figures 1 and 2 show excitation functions for the production of scandium isotopes in the neutron transfer reactions induced by bombarding ^{45}Sc with deuterons and ^{3}He and ^{6}He nuclei [6–9]. Large values of the cross sections for the production of scandium isotopes are associated with high values of Q for all of the reactions under investigation (see table). It can be seen from the corresponding figures that the largest cross section values are observed at energies below the Coulomb barrier.

Q-values in reactions induced by various charged particles

Reaction	Q, MeV	Threshold, MeV
^{9}Be(^{3}He, p)^{11}B	10.323	
^{9}Be(^{3}He, $2p$)^{10}Be	−0.95	1.208
^{9}Be(^{3}He, t)^{9}B	−1086.63	1450.23
^{9}Be(^{3}He, α)^{8}Be	18.913	
^{9}Be(^{3}He, α)α	19.049	
^{9}Be(^{3}He, ^{5}He)^{7}Be	−0.721	0.962
^{9}B(^{3}He, αn)^{7}Be	0.14	
^{9}Be(^{3}He, ^{6}Li)^{6}Li	−1.894	2.528
^{45}Sc(d, p)^{46}Sc	6.536	
^{45}Sc(d, t)^{44}Sc	−5.069	5.296
^{45}Sc(^{3}He, p)^{47}Ti	11.507	
^{45}Sc(^{3}He, t)^{45}Ti	−2.08	2.22
^{45}Sc(^{3}He, $2p$)^{46}Sc	1.043	
^{45}Sc(^{3}He, α)^{44}Sc	9.25	
^{45}Sc(α, ^{3}He)^{46}Sc	−11.816	12.869
^{45}Sc(α, ^{5}He)^{44}Sc	−12.062	13.135
^{45}Sc($\alpha, \alpha n$)^{44}Sc	−11.33	12.335
^{45}Sc(^{6}He, αn)^{46}Sc	7.785	
^{45}Sc(^{6}He, ^{5}He)^{46}Sc	7.05	
^{197}Au(d, p)^{198}Au	4.287	
^{197}Au(d, t)^{196}Au	−1.815	1.833
^{197}Au(^{3}He, $2p$)^{198}Au	4.287	
^{197}Au(^{3}He, α)^{196}Au	−1.815	1.833
^{197}Au(α,^{3}He)^{198}Au	−14.065	14.351
^{197}Au(α,^{5}He)^{196}Au	−8.807	8.986
^{197}Au($\alpha, \alpha n$)^{196}Au	−8.072	8.236
^{197}Au(^{6}He, ^{5}He)^{198}Au	4.802	
^{197}Au(^{6}He, αn)^{198}Au	5.537	
^{197}Au(^{6}He, ^{7}He)^{196}Au	−8.482	8.741
^{197}Au(^{6}He, $\alpha 3n$)^{196}Au	−9.048	9.324

In Fig. 1, the cross sections for ^{46}Sc production in the reactions involving deuterons and ^{6}He nuclei are given versus the ratio of the particle energy to the energy of the Coulomb barrier, ($E_{\text{c.m.}}/B_{\text{c.m.}}$). This figure clearly shows that the maxima of the cross sections for the two reactions in question lie near the Coulomb barrier, this being indicative of their peripheral character.

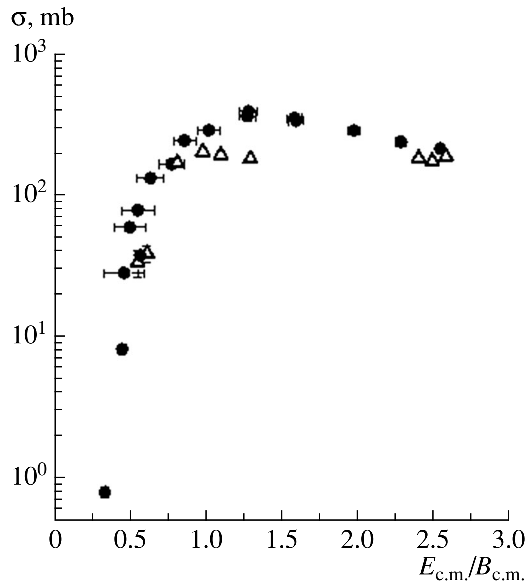

Fig. 1. Cross sections for the reactions (closed circles) $^{45}Sc(d,p)^{46}Sc$ and (open triangles) $^{45}Sc(^6He, X)^{46}Sc$ versus the ratio of the energy of projectile particles (d and ^6He) to the energy of the reaction Coulomb barrier in the c.m. frame.

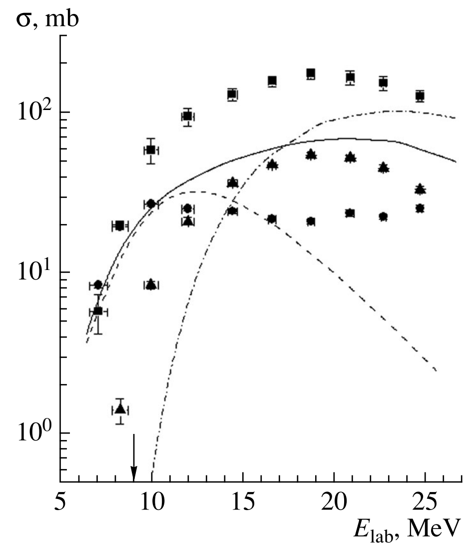

Fig. 2. Excitation functions for products of the $^{45}Sc+^3He$ reaction. The displayed points stand for experimental cross sections for the reactions (circles) $^{45}Sc(^3He, \alpha)^{44}Sc$ (reaction *1*), (triangles) $^{45}Sc(^3He, \alpha n)^{43}Sc$ (reaction *2*), and (boxes) $^{45}Sc(^3He, 2p)^{46}Sc$ (reaction *3*). The curves represent the cross sections calculated on the basis of the ALICE-MP code for (dashed curve) reaction *1*, (dash-dotted curve) reaction *2*, and (solid curve) reaction *3*. The arrow indicates the Coulomb barrier energy B_{Coul}.

Figure 2 shows the cross sections for the production of the isotopes ^{43}Sc, $^{44g+m}Sc$, and ^{46}Sc in reactions induced by ^3He nuclei versus their energy. The isotopes ^{44}Sc and ^{46}Sc are produced in one-nucleon-transfer reactions [stripping mechanism (^{46}Sc) and pickup mechanism (^{44}Sc)]. Owing to a positive value of Q, the cross sections for these reactions are comparatively large at ^3He energies below the Coulomb barrier. In the case of neutron transfer to the ^{45}Sc target nucleus from ^3He, the excitation function for ^{46}Sc exhibits a behavior characteristic of one-neutron-transfer reactions in the case of the interaction of stable nuclei and does not feel the Coulomb barrier [8, 9], as is observed in reactions involving deuterons or ^6He nuclei. The behavior of the excitation function for the reaction leading to ^{44}Sc production is somewhat unexpected. Despite a large positive value of Q (+9.254 MeV), a distinct maximum of the excitation function near the reaction Coulomb barrier is observed for the respective (^3He, α) reaction—that is, this reaction is governed predominantly by a peripheral interaction. It is also shown in [13] that the (^3He, α) reaction on ^{45}Sc proceeds through the interaction of a neutron from the target nucleus with ^3He (pickup mechanism) and leads to the excitation of a broad spectrum of excited states of ^{44}Sc.

Figure 3 shows the excitation function for the charge-exchange reaction $^{45}Sc(^3He, t)^{45}Ti$ and the results obtained by calculating it with the aid of the PACE-4 and ALICE-MP codes based on an equilibrium statistical treatment of the fusion of interacting nuclei and the deexcitation of a compound nucleus [8, 9]. The calculated curves deviate significantly from their experimental counterparts, and this is indicative of a more intricate reaction mechanism.

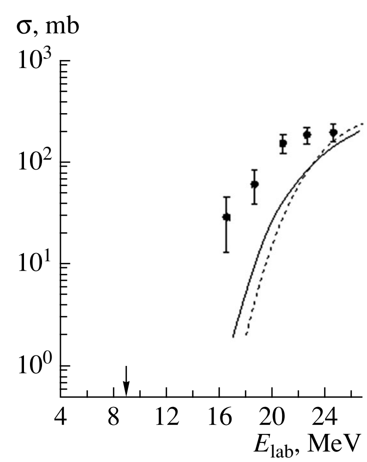

Fig. 3. Excitation function for the products of the reaction $^{45}Sc(^3He, t)^{45}Ti$. The curves correspond to calculations based on the (dashed curve) PACE-4 and (solid curve) ALICE-MP codes. The displayed points (^{45}Ti) stand for the experimental reaction cross sections.

The experimental excitations functions for the production of ^{196}Au and ^{x}Au in the ^{197}Au+^{6}He and Pt+^{6}Li reactions were analyzed earlier. The respective results were presented in [3, 7, 12].

The experimental cross sections obtained for the reactions induced by d, ^{3}He, ^{6}Li, and ^{6}He interactions with scandium, platinum, and gold nuclei were treated in [12], where peripheral interaction channels were considered, as the result of the direct stripping and pickup mechanisms. In particular, nucleon transfer both to a target and to a projectile nucleus is observed with a high probability at a positive reaction Q value.

The cross sections for neutron or cluster transfer reactions reach a maximum value at an energy close to the reaction Coulomb barrier if at least one of the reaction products is a nucleus whose binding energy is large. The energy spectra for the observed products of such reactions indicate that, in the exit channel, such a reaction admits a description within the two-body problem. The population of the ground state and excited single-particle states in the residual nucleus upon nucleon transfer is observed in this case.

As a rule, the cross sections for reactions involving nucleon stripping, pickup, and charge exchange differ strongly from one another (see Figs. 2 and 3). This is because the probabilities for a nucleon transition from a nucleus to its collision partner and the population of the ground state and excited single-particle states are different both in reactions on loosely bound nuclei [13, 14] and in the interaction of stable nuclei [15] in view of the fact that nucleon transitions occur predominantly to such states of interacting nuclei that are close in energy and spin. In the interaction of nuclei that leads to the formation of reaction products at a positive value of Q_{gg} (for the ground state), states of energy close or equal to Q_{gg} are selected among all neighboring states and are populated, which may destroy the original population of outer orbits of the projectile nucleus as it moves in the field of a heavy target nucleus [16]. As a rule, this circumstance leads to an enhanced probability for the transfer of neutral particle (neutron) from the projectile nucleus [17].

In the case of charged-particle transfer, the change in the energy should be corrected not only for the difference of the Q_{gg} values but also for the change in the Coulomb interaction energy [17, 18]. As a result, an effective change in the energy occurs; that is, $Q_{\text{eff}} = Q_{gg} - Q_{\text{opt}}$, where the second term Q_{opt} stems from the change in the Coulomb energy. The change in the energy upon charged-particle transfer is related to the quantity

$$Q_{\text{opt}} = E_i \left(\frac{Z_f\, z_f}{Z_i\, z_i} - 1 \right)$$

where E_i the c.m. projectile energy and Z_i and z_i (Z_f and z_f) are the charge numbers of, respectively, the target and projectile nuclei (charge numbers of final-state nuclei) [18].

For reactions involving light projectile nuclei and light target nuclei, in which case the charges Z_i and z_i are close, Q_{opt} will change slightly (from 0 to 1 MeV [18]) near the reaction barrier. This should lead to a predominant population of the ground state and the excited states closely lying to it in the final nucleus. As the energy of bombarding particles increases, the probability for the population of higher lying states in the acceptor nucleus grows [15].

The change in the energy Q_{opt} becomes sizable in transfer reactions governed by the mechanism of stripping of a proton (or other particles) from light projectiles to heavy target nuclei [18, 19]. For example, Q_{opt} may reach a value in excess of 6 MeV upon proton or deuteron stripping from a ^{6}Li light projectile nucleus to a ^{209}Bi heavy target nucleus in the region of energies near the Coulomb barrier.

In transfer reactions proceeding via the mechanism of nucleon pickup from a target nucleus by a light projectile nucleus, there arises a vacancy (hole) in that shell of the residual nucleus where a nucleon was before the transfer event. The filling of vacancies can lead to the rearrangement of nucleons in the shell and to the excitation of higher lying states [13, 20]. In the one-nucleon-transfer reactions proceeding through the pickup mechanism, one can observe, as a rule, smaller values of cross sections with respect to their analogs for the stripping mechanism.

The cross sections for the ^{3,6}He+^{197}Au reactions involving neutron transfer both to a target nucleus and to a projectile nucleus were recently calculated with allowance for nucleon transitions to various levels predicted by the shell model by applying the stationary strong coupled channel method and by calculating the coupling matrix for two-center neutron channels. The results of solving the time-dependent Schrödinger equation [21, 22] were used to determine the strong coupled channel constant. These estimates of cross sections for transfer reactions agree fairly well with the corresponding experimental values and do not contradict the above statements that various excited states are populated in the target nucleus upon neutron transfer from a light projectile nucleus (^{3}He or ^{6}He) to a heavy target nucleus.

4. ISOMERIC RATIOS

The difference in the population probability for excited states in fusion and transfer reactions naturally affects the decay of isomeric states of nuclei. The cross sections for the production of mercury, thallium, and gold nuclei in the ground and isomeric states were measured in [3–9]. In particular, this concerns the isomers of the isotopes ^{195m}Hg and ^{197m}Hg(7/2$^-$), ^{198m}Tl and ^{196m}Tl(7$^+$), and ^{196m}Au and ^{198m}Au(12$^-$) obtained in the reactions induced by beams of loosely bound ^{3}He, ^{6}He, ^{6}Li, and other stable nuclei. For the same nuclides of mercury, thallium, and gold, the isomeric ratios were determined in [19, 23].

The behavior of the excitation functions and isomeric ratios for the products of fusion reactions followed by neutron evaporation can be explained within models of nuclear reactions proceeding through a compound nucleus. As a rule, reactions proceeding through a compound nucleus are characterized by higher isomeric ratios [19, 24] that change in response to changes in the projectile energy and sort (owing to a change in the introduced orbital angular momentum and excitation energy) [24].

In reactions involving the emission of charged particles, isomeric ratios have different values for different reaction types, but, as a rule, they are lower than the isomeric ratios in fusion reactions accompanied by neutron emission because a higher excitation energy is necessary for the emission of charged particles and because a charged particle can take away a higher orbital angular momentum.

Isomeric ratios for direct reactions proceeding through the mechanism of neutron transfer to a target nucleus or to a projectile particle (stripping or pickup mechanism) usually have lower values [19]. The same conclusion on isomeric ratios for nuclei produced in direct reactions in beams of alpha particles was drawn in [25].

In the case of neutron transfer from a light projectile nucleus to a light or heavy target nucleus, the ground state and the closest low-lying states are populated. As was indicated above, the probability for the population of higher lying states increases with projectile energy [14, 15]. In the subbarrier region and in the vicinity of the Coulomb barrier, the isomeric ratio grows in this case with projectile energy.

In reactions where a light projectile picks up a neutron from a heavy target nucleus, this neutron leaves a vacancy (hole) in the heavy target nucleus. Excited particle–hole and isomeric states may be populated owing to nucleon rearrangement in filling this vacancy. Although the cross section for nucleon capture from the target nucleus grows with projectile energy, the population probability for the same excited particle–hole and ground states in the residual nucleus is likely to increase. Therefore, the isomeric ratios for nuclei produced in such reactions are virtually independent of the projectile energy [13, 19].

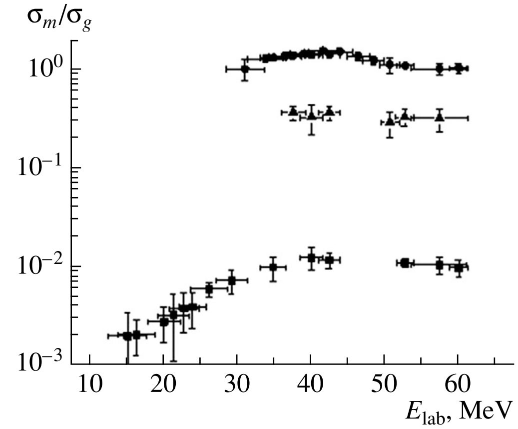

Fig. 4. Isomeric ratios versus the energy of ^{6}He for nuclei produced in the ^{197}Au+^{6}He reaction: (closed circles) ^{198}Tl, (closed boxes) ^{198}Au, and (closed triangles) ^{196}Au.

Investigation of nuclear reactions in beams of ions accelerated to an energy close to the reaction Coulomb barrier shows that the behavior of the cross sections for fusion and transfer reactions depends greatly on the reaction Q_{gg} value (see table). At positive values of Q_{gg} for reactions involving loosely bound and halo nuclei, the compound nucleus acquires a higher excitation energy even in the subbarrier region of energies. However, a positive value of Q in fusion reactions has virtually no effect on values of isomeric ratios and their behavior (isomeric ratios grow in the subbarrier energy region, thereupon reaching a plateau or decreasing in some cases). It was indicated in [25] that, for nuclei produced in fusion and transfer reactions induced by bombardment with alpha particles, isomeric ratios decrease as the difference in spins between the isomeric and ground states increases. Our group did not observe this trend for isomeric ratios in the reactions involving loosely bound nuclei (see Figs. 4 and 5).

In order to calculate isomeric ratios for products of incomplete-fusion and nucleon-transfer reactions, it is necessary to estimate the orbital angular momentum introduced by an exchanged particle or cluster and the energy transfer from it. It can be expected that low-lying single-particle levels in a newly formed nucleus are populated in the case of the transfer of particles that have a low energy or a low orbital angular momentum. This will reduce substantially the number of steps of deexcitation of this nucleus and diminish the population of isomeric states.

Let us now consider the population of isomeric states in nuclei formed in one and few nucleon transfer reactions. In [23], the excitation functions and the isomeric ratio (σ_m/σ_g) are presented for the isotope

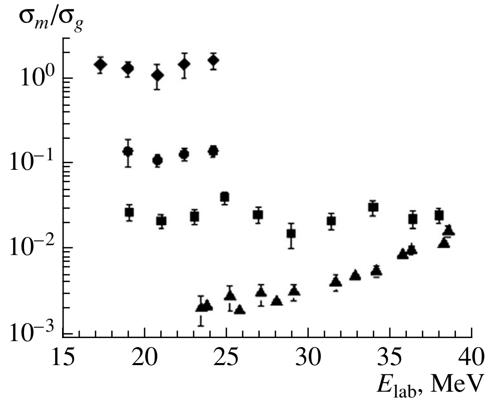

Fig. 5. Isomeric ratios versus the ^{3}He energy for nuclides produced in the ^{197}Au+^{3}He reaction: (closed circles) ^{197}Hg, (closed diamonds) ^{198}Tl (present study), (closed boxes) ^{196}Au [26], and (closed triangles) ^{198}Au [26].

^{196}Au produced in the interaction of ^{6}He with the ^{197}Au target nucleus (see Fig. 4). Over the whole measured range of energies, the isomeric ratio has a value of about 10^{-1}, which changes only slightly in response to an increase in energy. Collisions between ^{6}He and gold nuclei are accompanied by a sizable energy transfer leading to the excitation of nucleons in outer orbits and to the breaking of neutron pairs that is followed by the transfer or emission of one of the neutrons. For nuclei in the vicinity of closed shells, this results in the formation and population of excited particle–hole states, including isomeric states. As the energy of bombarding particles grows, the population probability for excited states increases, but the isomeric ratios undergo virtually no change. This approach to the formation and population of particle–hole states is considered within the shell and exciton models.

The cross sections for reactions leading to the production of ^{196}Au nuclei in the ground and isomeric states were also measured in ^{3}He beams [26]. As the energy of the ^{3}He beam changes (see Fig. 5), the isomeric ratios obtained in those measurements behave in just the same way as in reactions induced by ^{6}He beams. The absolute values of the isomeric ratios for ^{196}Au have the largest values in reactions involving ^{6}He.

The production of the isotope ^{198}Au in the ground and isomeric states was studied earlier in the reaction of neutron transfer to a ^{197}Au nucleus in the interaction with deuterons and alpha particles [27, 28], in which case the growth of the isomeric ratio with increasing energy was observed, but their values were found to be relatively low (10^{-3}–10^{-2}).

The excitation functions for the production of the isotope ^{198}Au (in the ground and isomeric states) in the ^{6}He+^{197}Au reaction are presented in [23] along with respective isomeric ratios. A possible explanation for low values of the isomeric ratios (see Fig. 4) is that the neutron transferred from a light projectile nucleus to a heavy gold target nucleus populates in it low-lying states similar in structure to respective projectile states [19], and this cannot help affecting the population of high-spin (12^-) isomeric states in the ^{198m}Au nucleus formed. As the energy of projectile nuclei grows, the probability for the population of higher excited and isomeric states naturally increases, and so do the isomeric ratios.

The population of isomeric states of ^{198}Au was also studied in other transfer reactions involving halo nuclei. Neutron transfer to a ^{197}Au target nucleus from a ^{8}He projectile nucleus was also observed with a high probability [29]. In this reaction, the isomeric ratios for ^{198}Au also grows in the subbarrier region up to a value of about 10^{-2}.

It was shown in [4, 5] that, at energies close to the reaction Coulomb barrier, the probability for deuteron transfer from the ^{6}Li nucleus to the platinum target nucleus is high, and the isomeric ratio for the ^{198}Au nucleus formed reaches a somewhat greater value of about 10^{-1} [30].

The cross sections for ^{197}Hg production in the ground and isomeric states were measured in the reaction ^{197}Au(^{3}He t)^{197}Hg, and the respective isomeric ratio was determined (see Fig. 5) and found to have a relatively high value of about 0.1 remaining virtually invariable upon the change in the ^{3}He energy [12]. Relatively large values of the cross sections for the (^{3}He, t) reactions both on scandium [8, 9] and on gold nuclei are noteworthy. This result can be qualitatively explained by the fact that, at these values of Q, the reaction in question proves to be in the region of charge-exchange resonances, with the result that the population of highly excited states in the target nucleus occurs.

5. CONCLUSIONS

The cross sections for the production of mercury, thallium, and gold nuclides in the ground and isomeric [^{195m}Hg and ^{197m}Hg($7/2^-$), ^{198m}Tl and ^{196m}Tl(7^+), and ^{196m}Au and ^{198m}Au(12^-)] states formed in reactions induced by beams of loosely bound and clustered nuclei of ^{3}He, ^{6}He, and ^{6}Li were measured, and the isomeric ratios were calculated for these nuclides. This made it possible to get a clearer idea of the relationship between the resulting isomeric-ratio values, on one hand, and different reaction mechanisms and respective distinctions between the populations of excited states, on the other hand.

The behavior of the excitation functions and isomeric ratios for the products of fusion reactions followed by neutron evaporation can be explained within the compound-nucleus model. Reactions proceeding through a compound nucleus are characterized, as a rule, by higher isomeric ratios, which change with projectile energy and sort.

A comparison of experimental values obtained for the cross-section ratios σ_m/σ_g in different reactions shows that there is a large difference in the values and in the behavior of the isomeric ratios between fusion and direct reactions.

The isomeric ratios for direct reactions that proceed through nucleon transfer to a target nucleus or to a projectile particle (stripping or pickup mechanism) have lower values. In the case of the neutron-stripping mechanism, the population of low-lying states of the final nucleus occurs; as the energy of bombarding particles grows, the probability for the population of higher lying states increases. In the subbarier region and in the region near the Coulomb barrier, the isomeric ratio therefore grows with projectile energy.

In reactions where a light projectile nucleus picks up a neutron from a target nucleus, this neutron leaves a vacancy (hole) on the level that it originally occupied in the target nucleus. Excited particle–hole and isomeric states may be populated in the residual nucleus upon filling this vacancy. As a rule, the pickup of one of the target nucleons therefore occurs from high-lying energy levels, and this leads rather small cross-section values. Although the growth of the energy of bombarding acceptor particles leads to an increase in the cross section for nucleon capture from the target nucleus and in the probability for the population of high-lying excited particle–hole states in the residual nucleus, the isomeric ratio for such reactions is virtually independent of the energy of bombarding particles.

In the case of charge-exchange reactions in beams of loosely bound nuclei, the isomeric ratios change only slightly. It seems that, in these reactions proceeding at energies close to the Coulomb barrier (with allowance for Q), the region of charge-exchange resonances is reached, so that highly excited states of the target nucleus, including isomeric states, are populated.

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