POPULATION OF ISOMERIC STATES IN FUSION AND TRANSFER REACTIONS WITH BEAMS OF RADIOACTIVE AND WEAKLY BOUND NUCLEI*

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The influence of the mechanisms of nuclear reactions on the population of isomeric states ^{44m}Sc (6^+), ^{196m}Au (12^-), ^{198m}Au (12^-), ^{195m}Hg $(13/2^+)$, ^{197m}Hg $(13/2^+)$, ^{198m}Tl (7^+), ^{196m}Tl (7^+) obtained in reactions induced by beams of weakly bound and radioactive nuclei ^{3}He, ^{6}Li, ^{6}He are studied. In direct reactions involving cluster transfer, the isomeric ratio is lower than in reactions, where fusion with evaporation of nucleons occurs. In the case of charge exchange reactions with beams of weakly bound nuclei, the isomeric ratios change only slightly. If the reaction Q-value is positive, neutron transfer is observed with high probability in interactions of all weakly bound nuclei with both light and heavy stable target nuclei. Cross sections and their isomeric ratios differ for nucleon stripping and pickup channels owing to the difference in population of excited single-particle and collective states.

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1. Introduction

An isomeric state was first discovered by Hahn [1] in 1921 in the atomic nucleus ^{234}Pa formed in the uranium salt after the β decay of ^{234}U. The first explanation of this phenomenon was given in 1936 by Weizsäcker [2]. By now, more than 100 isomeric states in atomic nuclei with lifetimes of more than 1 s are known [3]. There are several types of isomers: spin isomers, shape isomers, and K-isomers.

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In this paper, we consider the population of isomeric states corresponding to spin isomers. The ratio of the probabilities of population of the ground and isomeric states in the atomic nucleus, defined as σ_m/σ_g and called the isomeric ratio (IR), depends on a number of factors, in particular, on the excitation energy of the nucleus formed in the reaction and on the transferred angular momentum l [3, 4]. The measurement of the IR in various nuclear reactions allows one to obtain important information both on the structure of the nucleus under study and on the degree of its excitation, as well as on the spins of excited nuclear states.

The purpose of this work is to study the influence of the mechanisms of fusion and transfer reactions in the interaction of weakly bound ^{3}He nuclei, cluster ^{6}Li and halo ^{6}He nuclei with stable nuclei on the excitation of new nuclei, resulting in the population of excited and isomeric states in the process of transferring individual nucleons and clusters. The experiments were performed with the extracted ^{3}He beams at the U-120M cyclotron, Nuclear Physics Institute of the Czech Academy of Sciences, Řež [5–7] and with the ^{6}He and ^{6}Li beams obtained at the DRIBs accelerator complex, Joint Institute for Nuclear Research, Dubna [8–10].

2. Isomeric ratios for ^{44}Sc

From the point of view of studying isomeric ratios, ^{44}Sc is an interesting nucleus near the shells $Z = 20$, $N = 20$ and 28. The half-lives and intensities of the γ transitions in ^{44m}Sc (6^+) and ^{44g}Sc (2^+) decays are convenient for measurements.

Figure 1 shows the excitation functions we measured for the formation of ^{44}Sc in the ground and isomeric states in the reaction ^{45}Sc(^{3}He, α)^{44}Sc and the dependence of the IR on the energy of the bombarding particles ^{3}He [6, 7]. In such reactions with weakly bound nuclei with a positive

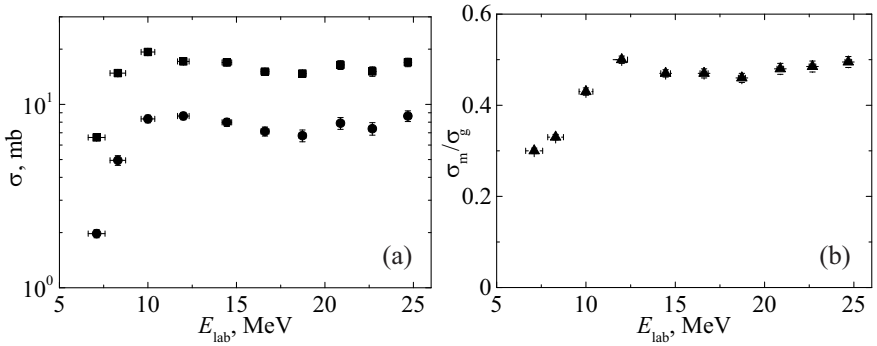


Fig. 1. (a) Excitation functions for the ^{45}Sc(^{3}He, α)^{44}Sc reaction products: ^{44m}Sc (6^+) (circles), ^{44g}Sc (2^+) (squares). (b) Isomeric ratio σ_m/σ_g (triangles).

Q-value, in addition to the ground state, a wide range of excited states within the Q-window is populated [11]. The measured IR for ^{44}Sc is lower than that for fusion reactions and practically does not change with the increase of energy of ^{3}He above the Coulomb barrier.

3. Formation of isomers of nuclei near shells $Z = 82$ and $N = 126$ with beams of weakly bound and radioactive nuclei

3.1. Complete fusion reactions followed by evaporation of neutrons and charged particles

Let us now consider the formation of atomic nuclei in the ground and isomeric states near shells $Z = 82$ and $N = 126$. Almost spherical ^{197}Au and ^{194}Pt were chosen as target nuclei.

The ^{198}Tl isotope was obtained [7, 12] in the reaction ^{197}Au(^{3}He, $2n$)^{198}Tl in the ground (2^{-}) and isomeric (7^{+}) states. The corresponding IR [Fig. 2 (a)] is slightly different from the IR for the same isotope obtained via the fusion reaction in the bombardment of gold by α-particles [13].

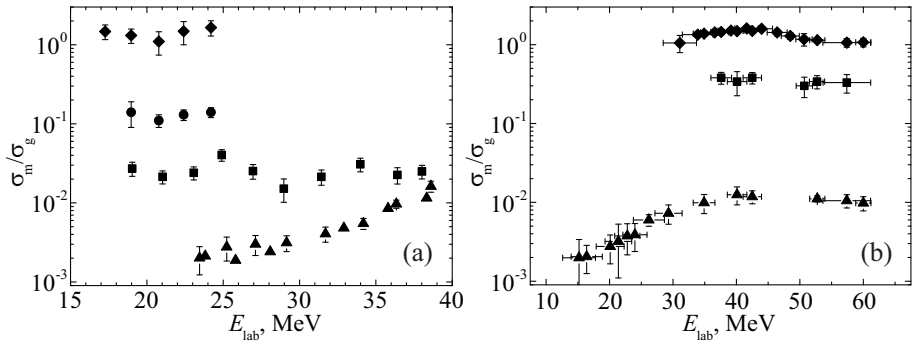


Fig. 2. (a) Dependence of the IR on ^{3}He energy for nuclides formed in the reaction ^{3}He + ^{197}Au: ^{197}Hg (circles), ^{198}Tl (diamonds), ^{196}Au (squares), ^{198}Au (triangles). (b) Dependence of the IR on ^{6}He energy for nuclei formed in the reaction ^{6}He + ^{197}Au: ^{198}Tl (diamonds), ^{196}Au (squares), ^{198}Au (triangles).

In [8], excitation functions were measured for the formation of ^{198}Tl in the ground and isomeric states via fusion reaction ^{197}Au(^{6}He, $5n$)^{198}Tl. The value of the IR [Fig. 2 (b)] increases with the increase in energy of the bombarding particles, reaches a maximum at 45 MeV and, in general, remains greater than unity in the entire studied energy range. The results of calculations of the IR for ^{198}Tl within the statistical model practically coincide with the experimental values [14]. In the calculations, we used the generally accepted expressions for the dependence of the level density on the excitation energy and the angular momentum l.

The cross sections for formation of ^{196}Tl in the ground (2^-) and isomeric (7^+) states were also measured at two ^{6}He energy values above 50 MeV [8]; the obtained IRs are close to the maximum IR value for the ^{198}Tl isotope. It should be noted that the obtained IRs for both ^{196}Tl and ^{198}Tl are slightly lower than the ratios of "statistical weights" $(2J_m + 1)/(2J_g + 1)$.

At higher energy of the bombarding ^{6}He particles, the population of the isomeric state in the ^{195}Hg nucleus was also observed in the reaction channel ^{197}Au(^{6}He, $p7n$)^{195}Hg [14]. This channel involves deexcitation of the compound nucleus by evaporation of a charged particle (a proton); in this case, the IR does not change over a wide energy range.

We also measured the IR [Fig. 2 (a)] for the ^{197}Hg isotope formed in the channel ^{197}Au(^{3}He, t)^{197}Hg [6, 7]. For this charge exchange channel, the IR has a relatively low value ~ 0.1 and slightly varies with the energy of ^{3}He.

3.2. Nucleon and cluster transfer reactions

The population of isomeric states in gold isotopes ^{196}Au, ^{198}Au is of great interest, because these isomeric states have higher spins ($J^\pi = 12^-$).

The excitation functions for ^{196}Au formed in both ground and isomeric states in the interaction of ^{6}He with the target nucleus ^{197}Au were measured in [14, 15]. The values of the IR for ^{196}Au [Fig. 2 (b)] slightly vary with energy in the entire studied energy range.

The cross sections for formation of ^{196}Au in the ground and isomeric states were also measured with beams of ^{3}He and α-particles [7, 16]. The resulting IRs [Fig. 2 (a)] behave similarly to those for reactions with ^{6}He, *i.e.*, when the energy of particles exceeds the Coulomb barrier, the IR remains almost constant.

The excitation functions for the formation of ^{198}Au in the ground and isomeric states were measured and σ_m/σ_g was determined in the transfer reaction ^{6}He + ^{197}Au [14]. The low IR values can be explained by the fact that the neutron transferred from the light nucleus to the heavy target nucleus populates the ground and low-lying states [17]. With an increase in the energy of incident particles, the probability of populating higher excited states increases, and so does the IR [Fig. 2 (b)]. As can be seen from Fig. 2 (a), the IR for ^{198}Au measured in the reaction with ^{3}He [16] has the same behavior as that obtained in the reaction with ^{6}He.

The population of isomeric states of ^{198}Au has also been studied in other transfer reactions involving nuclei with a halo structure. Neutron transfer from the ^{8}He projectile nucleus to the ^{197}Au target nucleus was observed with approximately the same probability [18]. In this reaction, the IR for ^{198}Au grows in the sub-barrier region and then reaches a plateau $\sim 10^{-2}$.

At the energies near the Coulomb barrier, a deuteron is transferred from ^{6}Li to the target nucleus ^{198}Pt with a high probability [9, 19, 20]. As in reactions with deuterons, the isomeric states of ^{198}Au are populated and the IR for ^{198}Au reaches $\sim 10^{-1}$ indicating transfer channels with the population of single-particle and collective states [21]. The IR was also measured for the reactions ^{6,7}Li + ^{209}Bi [22] with transfer of α-particles and d or t from ^{6}Li and ^{7}Li, respectively, with the formation of ^{212}At and ^{211}Po isomers. For transfer of α-particles from Li, the IR changes smoothly with the change of Li energy, and the maximum is close to the value of the IR obtained in fusion reactions with α-particles. In the case of transfer of tritium from ^{7}Li and formation of ^{211m}Po, the IR is $\sim 10^{-1}$ and, as for capture of d, practically does not change with an increase in the energy of ^{7}Li.

4. Discussion

In order to examine in detail the yields of products in particular reaction channels and understand the behavior of the isomeric ratios for the studied nuclei formed in the ground and isomeric states, it is useful to estimate the excitation energies of these nuclei.

In the case of transfer of one or several neutrons, for estimating the maximum excitation energy $E_{\rm exc}$, one can use a rough assumption

$$E_{\rm exc} \approx Q_{gg} + n\frac{E_{pcm}}{A}\,, \tag{1}$$

where Q_{gg} is the Q-value for the reaction with transfer of one or n neutrons to the ground state, $\frac{E_{pcm}}{A}$ is the kinetic energy of the transferred neutron (or n neutrons).

In the case of transfer of a charged particle, the change in energy must be corrected not only by the difference in the value of Q_{gg}, but also by the change in the energy of the Coulomb interaction [23, 24], so that the effective change in the energy is $E_{\rm eff} = Q_{gg} - Q_{\rm opt}$, where the second term corresponds to the change in the Coulomb energy. The excitation energy for nucleon transfer can be roughly estimated as $E^{*} = E_{\rm eff}$ [25].

The change in the energy for transfer of a charged particle is

$$Q_{\rm opt} = E_{\rm i}\left[\frac{Z_{\rm f}z_{\rm f}}{Z_{\rm i}z_{\rm i}} - 1\right]\,, \tag{2}$$

where E_i is the projectile energy in the center of mass system, $Z_{\rm i}$, $z_{\rm i}$ ($Z_{\rm f}$, $z_{\rm f}$) are the atomic numbers of the nuclei in the initial (final) reaction channels [24]. The change in the excitation energy is reflected in the population of the excited states of the nuclei.

Calculations of neutron stripping and pickup in reactions ^{3,6}He + ^{197}Au have recently been performed by solving the time-dependent Schrödinger equation for the neutrons of the colliding nuclei [26, 27]. These calculations also require taking into account the shell structure of the studied nuclei and changes in the neutron level populations as a result of the collision.

Note that high Q-values for neutron and cluster transfer channels lead to the increase in the values of the corresponding transfer cross sections.

The peculiarities of transfer reactions with weakly bound and halo nuclei at projectile energies near the Coulomb barrier can be understood if we turn to studies of transfer reactions with beams of stable nuclei ^{12}C, ^{16,18}O at energies 5–6 MeV/nucleon [28] and ^{11}B, ^{12}C, ^{14}N at energies above 10 MeV/nucleon [29]. In these studies, channels corresponding to transfer of various numbers of nucleons were investigated and energy spectra of detected ions were measured. The study of a large number of one-nucleon and multinucleon transfer reactions with heavy ions [21, 28, 29] showed that

— the cross sections for transfer of nucleons and clusters in reactions with heavy ions depend on the energy of accelerated ions, the reaction Q-value, and the angular momentum;

— reactions proceed via direct transfer mechanism and the energy spectra of the detected light ions indicate an unusual population of the excited states of the heavy target-like nuclei;

— only a small number of the excited states in the final nuclei are strongly populated.

For transfer reactions, there is a connection between the reaction mechanisms and the population of the excited states of the target-like nuclei, *viz.*,

— in the reactions of transfer of a single nucleon, mainly single-particle states are populated in the formed nuclei, and with an increase in the projectile energy, other highly excited states are populated;

— the reactions of transfer of two nucleons and deuterons lead to the population of the states, known as collective states, including high-spin states, typical for an elongated configuration;

— in reactions of transfer of α-particles, collective states are also populated including, in particular, (3^-) states and other high-spin states.

5. Conclusions

The cross sections for fusion and transfer reactions strongly depend on the reaction Q-values. This feature is manifested in the case of transfer of several nucleons or clusters, which is connected with the change in the structure of nuclei.

As a rule, the values of the cross sections for the reactions of stripping, pickup, and charge exchange are very different. The corresponding change in the structure of nuclei leads to different populations of the ground and excited states of nuclei.

Reactions of transfer of one nucleon have the largest cross sections. For multinucleon transfer, reactions of transfer of bound clusters are more favorable than those of unbound clusters.

Different populations of excited states in fusion and transfer reactions are naturally reflected in the population of isomeric states of atomic nuclei. A comparison of the experimental values of the IR obtained in different reactions shows that there is a large difference in the values and in the behavior of the IR for fusion reactions and direct reactions.

Reactions proceeding through a compound nucleus are usually characterized by a higher IR. The behavior of the excitation functions and the IR for the products of fusion reactions with nucleon evaporation can be explained within the statistical model.

Direct reactions with transfer of neutrons to the target nucleus or to the incident particle (stripping and pickup) usually have lower IR values.

For stripping reactions in the region near the Coulomb barrier, the IR grows with the increase in energy of the bombarding particles. The IR for nuclei formed in the pickup reactions is practically independent of the energy of the bombarding particles above the Coulomb barrier.

For the nuclei formed in charge exchange reactions, the IR varies only slightly with the energy of the bombarding particles. Apparently, in such reactions at energies near the Coulomb barrier, the region of charge exchange resonances is reached, and highly excited states of the target nucleus (including isomeric states) are populated.

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