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Neutron rearrangement in reactions with light weakly-bound nuclei

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Experimental cross sections for formation of isotopes ^{44,46}Sc–in reaction (^{3}He + ^{45}Sc), ^{46}Sc–in reaction (^{6}He + ^{45}Sc), ^{65}Zn–in reaction (^{3}He + ^{64}Zn), ^{196,198}Au–in reactions (^{6}He + ^{197}Au) have been analyzed within the TDSE approach for the external neutrons of ^{3,6}He, ^{45}Sc and ^{197}Au nuclei. Fusion-evaporation was taken into account using the NRV evaporation code. Results of calculation demonstrate overall satisfactory agreement with the experimental data.

Keywords: nuclear reactions; neutron transfer; time-dependent Schrodinger equation; fusion-evaporation.

Introduction

It is well known that neutron rearrangement may play an important role in nuclear reactions. The processes of neutron transfer are extensively studied both experimentally and theoretically. The aim of this work is description of the experimental data on the formation of isotopes ^{44,46}Sc–in reaction (^{3}He + ^{45}Sc), ^{46}Sc–in reaction (^{3}He + ^{45}Sc), ^{65}Zn–in reaction (^{6}He + ^{64}Zn), ^{196,198}Au–in reactions (^{3,6}He+ ^{197}Au), where neutron transfer is one of the most important channels.

Theory

For theoretical description of neutron transfer during collisions of heavy atomic nuclei we used the time-dependent Schrodinger equation (TDSE) approach [1, 2] for the external neutrons combined with the classical equations of motion of atomic nuclei

$$m_1\ddot{\vec{r}}_1 = -\nabla_{\vec{r}_1} V_{12}(\vec{r}_1 - \vec{r}_2), m_2\ddot{\vec{r}}_2 = -\nabla_{\vec{r}_2} V_{12}(\vec{r}_2 - \vec{r}_1). \tag{1}$$

Here $\vec{r}_1(t)$, $\vec{r}_2(t)$, are the centers of nuclei with the masses m_1, m_2 , and $V_{12}(r)$ is the potential energy of nuclear interaction. We may assume that before contact of the surfaces of spherical nuclei with the radii R_1, R_2 the potential energy of a neutron $W_{\vec{r},t}$ is equal to the sum of its interaction energies with both nuclei.

The evolution of the components Ψ_1, Ψ_2 of the spinor wave function $\Psi(\vec{r},t)$ for the neutron with the mass m during the collision of nuclei is determined by the Eq. (2) with the operator of the spin-orbit interaction $\hat{V}_{LS}(\vec{r},t)$

$$ih\frac{\partial}{\partial t}\Psi(\vec{r},t) = \{-\frac{h^2}{2m}\Delta + W(\vec{r},t) + \hat{V}_{LS}(\vec{r},t)\}\Psi(\vec{r},t). \quad (2)$$

The initial conditions for the wave functions were obtained on the basis of the shell model calculations with the parameters providing neutron separation energies close to the experimental values.

The solution of the time-dependent Schrodinger equation provides the neutron transfer probability $p(b,E)$, where b is an impact parameter and E is the center-of-mass energy. The transfer cross section was calculated as

$$\sigma(E) = \int_0^\infty p(b,E)bdb. \quad (3)$$

In the analysis of experimental cross sections for formation of isotopes one must also take into account the possibility of their formation via fusion of colliding nuclei with the subsequent evaporation of nucleons and α-particles. For this purpose we used computational code of the statistical model available in the NRV knowledge base [3].

Results

Reaction (^{3}He + ^{45}Sc). Comparison of theoretical calculations with experimental cross sections for formation of isotopes ^{44}Sc and ^{46}Sc in reaction (^{3}He + ^{45}Sc) is shown in figure 1a and figure 1b, respectively. Due to the low charge of the formed compound nucleus, the cross sections for the fusion with the subsequent evaporation of an α-particle and 2p are high enough, and are respectively comparable with neutron pickup (^{44}Sc, figure 1a) and stripping (^{46}Sc, figure 1b) cross sections. The corresponding sums of neutron transfer and fusion-evaporation channels provide overall satisfactory agreement of calculation results with experimental data.

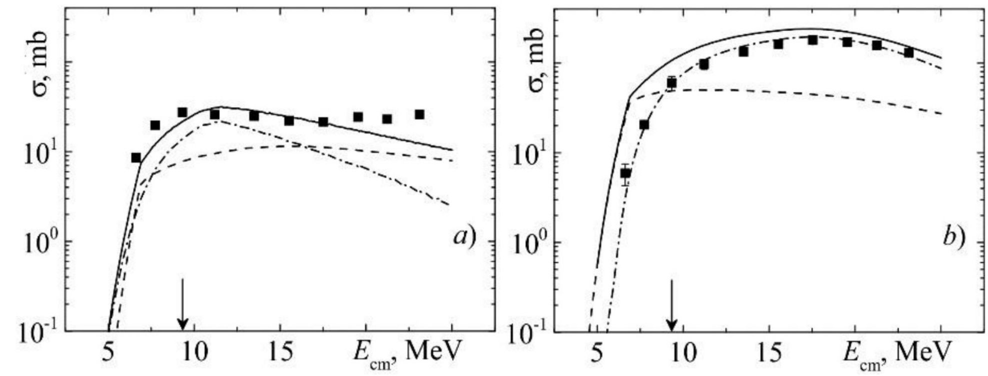

Figure 1. The cross sections for formation of isotopes ^{44}Sc (a) and ^{46}Sc (b) – in reaction (^{3}He + ^{45}Sc). Symbols are the experimental data from Refs. [4, 5], dash-dotted curves are the results of calculation of fusion-α-evaporation (a) and fusion-2p-evaporation (b) within the NRV knowledge base [3], dashed curves are the results of neutron transfer calculations within the TDSE approach, solid curves are the sums of the corresponding transfer and fusion-evaporation channels. Here and below arrows indicate the position of the Coulomb barrier.

Reaction (^{3}He + ^{197}Au). The experimental data on the formation of isotopes ^{196}Au and ^{198}Au – in the reaction (^{3}He + ^{197}Au) [6, 7] are compared to the theoretical calculations in figure 2a and figure 2b, respectively. The cross section for formation of the isotope ^{196}Au via fusion with the subsequent evaporation of the α-particle from the compound nucleus at energies above the Coulomb barrier is substantially (about two orders of magnitude) lower than the experimental data because the high Coulomb barrier prevents the emission of an a-particle from the compound nucleus with the high charge. Formation of ^{198}Au via fusion with the evaporation 2p from the compound nucleus was not observed in calculations. The calculated neutron pickup (^{196}Au, figure 2a) and stripping (^{198}Au, figure 2b) cross sections are in satisfactory agreement with the experimental data.

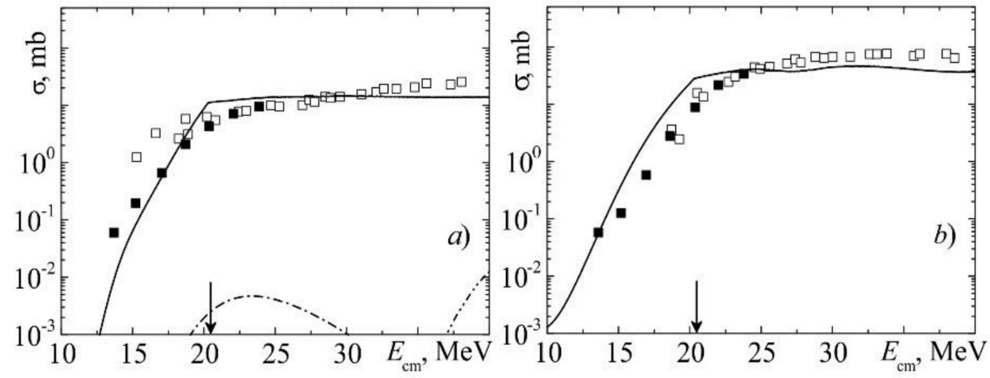

Figure 2. The cross sections for formation of isotopes ^{196}Au (a) and ^{198}Au (b) – in reaction (^{3}He + ^{197}Au). Symbols are the experimental data from Ref. [6] (filled squares) and Ref. [7] (empty squares), dash-dotted and dash-dot-dotted curves are respectively the results of calculation of fusion-α-evaporation and fusion-2p2n-evaporation within the NRV knowledge base [3], solid curves are the results of neutron transfer calculations within the TDSE approach.

Reaction (^{6}He + ^{45}Sc), (^{6}He + ^{64}Zn). Comparison of experimental data on the formation of isotopes ^{46}Sc – in reaction (^{6}He + ^{45}Sc) and ^{65}Zn – in reaction (^{6}He + ^{64}Zn) with the theoretical calculations is shown in figure 3a and figure 3b, respectively.

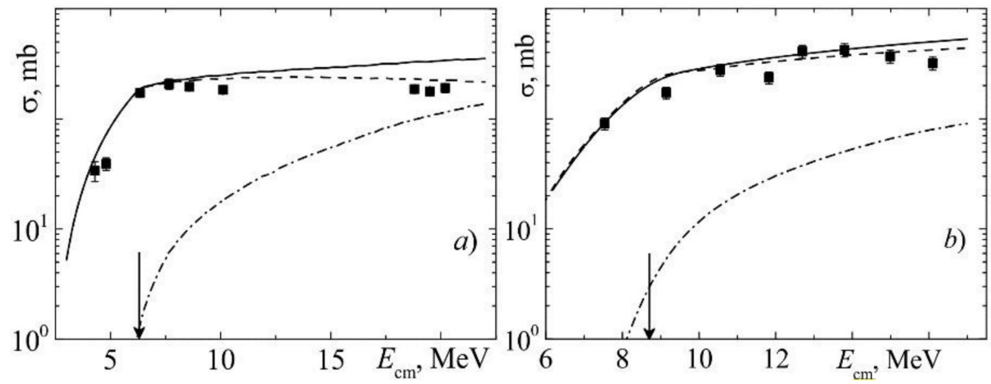

Figure 3. The cross sections for formation of isotopes ^{46}Sc – in reaction (^{6}He + ^{45}Sc) – (a) and ^{65}Zn – in reaction (^{6}He + ^{64}Zn) – (b). Symbols are the experimental data from Ref. [8] (a) and Ref. [9] (b), dash-dotted curves are the results of calculation of fusion-αn - evaporation within the NRV knowledge base [3], dashed curves are the results of neutron transfer calculations within the TDSE approach, solid curves are the sums of the corresponding transfer and fusion-evaporation channels.

The cross sections for the formation of the isotopes ^{46}Sc and ^{65}Zn via fusion with the subsequent evaporation of an is significant at energies above the Coulomb barriers due to the low charge of the formed compound nucleus. In both cases the corresponding sums of neutron transfer (stripping) and fusion-evaporation channels provide a satisfactory agreement between the calculated results and the experimental data.

Reaction (^{6}He + ^{197}Au). Comparison of experimental data on the formation of isotopes ^{196}Au and ^{198}Au in the reaction (^{6}He + ^{197}Au) with the theoretical calculations is shown in figure 4a and figure 4b, respectively. It can be seen that in this case the of fusion with the subsequent evaporation to the experimental data is negligible due to the high Coulomb barrier of the formed compound nucleus preventing the evaporation of α-particles. It should be mentioned that the yield of isotope ^{198}Au in the reaction (^{6}He + ^{197}Au) has already been studied earlier in Ref. [1], but the possible contribution of the fusion-evaporation channel was not evaluated. It is an interesting fact that the experimental yield of the isotope ^{196}Au in the higher-energy region is comparable and even exceeds the yield of the isotope ^{198}Au. Theoretical underestimation of the ^{196}Au cross section compared the experimental data at higher energies may be explained by not taking into account the processes of knock-out of neutrons from ^{197}Au by the 6 He nucleus, as well as the contributions of other reaction mechanisms. In particular, one or two neutrons from ^{6}He may be captured by 197 Au followed by evaporation of two or three neutrons, thus resulting in formation of isotope ^{196}Au in the outgoing channel. Accurate theoretical description of such processes is only possible within the solution of fully quantum many-body problem, which is associated with high mathematical complexity and requires a lot of computing power. Thus, this phenomenon requires further theoretical and experimental study.

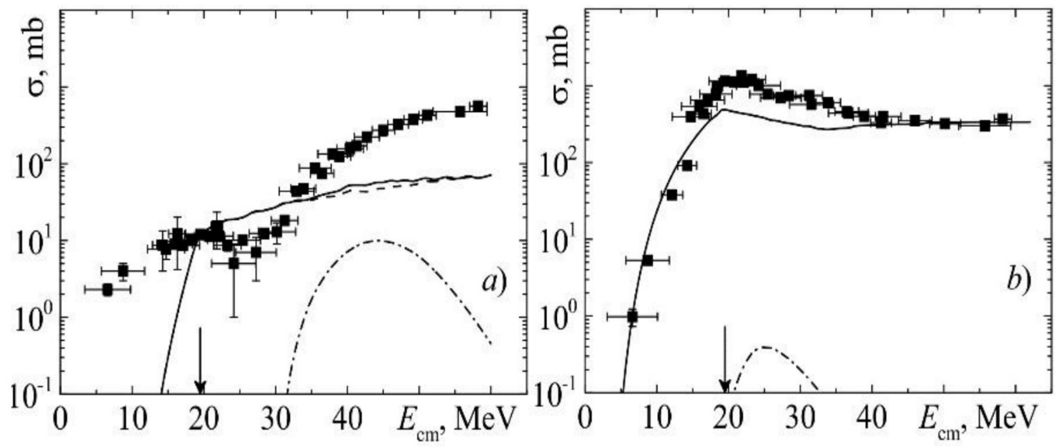

Figure 4. The cross sections for formation of isotopes ^{196}Au (a) and ^{198}Au (b) – in reaction (^{6}He + ^{197}Au). Symbols are the experimental data from Ref. [10], dash-dotted curves are the results of calculation of fusion-α 3n-evaporation (a) and fusion-α n-evaporation (b) within the NRV knowledge base [3], dashed curves are the results of neutron transfer calculations within the TDSE approach, solid curves are the sums of the corresponding transfer and fusion-evaporation channels.

Conclusion

For the analysis of experimental cross sections for formation of isotopes ^{44,46}Sc – in reaction (^{3}He + ^{45}Sc), ^{46}Sc – in reaction (^{6}He + ^{45}Sc), ^{65}Zn – in reaction (^{6}He + ^{64}Zn), ^{196,198}Au – in reactions (^{3,6}He + ^{197}Au) the time-dependent Schrödinger equation method for calculation of neutron transfer cross sections was combined with the statistical model approach using the computational code of the NRV knowledge base [3]. The sums of neutron transfer and fusion-evaporation channels provided overall satisfactory agreement of calculation results with experimental data. The method may also be applied for calculation of transfer cross sections of charged particles (e.g., protons and α-clusters).

Acknowledgments

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