MICROSCOPIC ANALYSIS OF NUCLEON TRANSFER PROCESSES IN LOW-ENERGY NUCLEAR REACTIONS WITH NEUTRON-ENRICHED NUCLEI ^{6}He, ^{18}O, ^{48}Ca

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Time-dependent Schrödinger equation is numerically solved by difference method for external neutrons of nuclei ^{6}He, ^{18}O, ^{48}Ca, ^{238}U at their grazing collisions with energies near to a Coulomb barrier. The spin-orbital interaction and Pauli's exclusion principle were taken into consideration during the solution.

1.1 Introduction

Neutron transfers in the low energy nuclear reactions allow us to obtain new isotopes of atomic nuclei with increased neutron content [1]. The probability of neutron transfer is highest during so called grazing nuclear collisions [2]. In this case, the distances between the surfaces of the atomic nuclei do not exceed the range of the action of nuclear forces (~2 fm). The most probable transition is the one between the nuclei of the external, most weakly bound neutrons. These processes have been studied in reactions with the participation of both light (e.g., ^{6}He [1]) and heavy neutron rich nuclei. The basis of the microscopic models of nucleon transfer during grazing collisions of atomic nuclei is the so called form factors [2], for which simple empirical approximations are generally used. A new possibility for specifying the form factors for definite pairs of colliding nuclei is provided by studying the evolution of the states of external neutrons by means of a numerical solution for the non stationary Schrödinger equation with allowance for spin–orbital interaction using the approach proposed and developed in [3-5]. In this work we examine a basic questions of non stationary quantum approach and it applications to some examples of nucleons transfer at low-energy nuclear reactions neutron enriched spherical nuclei ^{6}He, ^{18}O, ^{48}Ca and nuclei ^{198}Au, ^{238}U in spherical shell model [6,7].

1.2 Theory and numerical methods

In the theoretical description of the neutron transfers upon heavy atomic nuclei collisions, a few semiclassical models are used [2-5]. They combine classical equations of atomic nuclei motion

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

that are justified by smallness of a de Broglie nuclear wave length and the quantum description of internal one-particle and collective degrees of freedom. Here $\vec{r}_1(t)$, $\vec{r}_2(t)$ are nuclei centers with masses m_1, m_2 and $V_{12}(r)$ is the potential energy of nuclei interaction. Before contact between the surfaces of spherical nuclei with radii R_1, R_2 we may consider that neutron potential energy equal sum

$$V(\vec{r},t) = V_n^{(1)}(\vec{r} - \vec{r}_1(t)) + V_n^{(2)}(\vec{r} - \vec{r}_2(t)). \tag{2}$$

the centers of which can be considered moving along the classical trajectories $\vec{r}_1(t)$, $\vec{r}_2(t)$. The evolution of the components ψ_1, ψ_2 of the spinor wave function $\Psi(\vec{r},t)$ of a neutron with mass m during nuclei collisions is determined by the system of equations [7]

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\psi_1 &= \left(-\frac{\hbar^2}{2m}\Delta + V(\vec{r},t)\right)\psi_1 + i\frac{b}{2}\left(\frac{\partial V}{\partial x}\frac{\partial \psi_1}{\partial y} - \frac{\partial V}{\partial y}\frac{\partial \psi_1}{\partial x}\right) + \\ &+ i\frac{b}{2}\left(\frac{\partial V}{\partial y}\frac{\partial \psi_2}{\partial z} - \frac{\partial V}{\partial z}\frac{\partial \psi_2}{\partial y}\right) - \frac{b}{2}\left(\frac{\partial V}{\partial x}\frac{\partial \psi_2}{\partial z} - \frac{\partial V}{\partial z}\frac{\partial \psi_2}{\partial x}\right), \end{aligned} \tag{3}$$

$$i\hbar\frac{\partial}{\partial t}\psi_2=\left(-\frac{\hbar^2}{2m}\Delta+V(\vec{r},t)\right)\psi_2-i\frac{b}{2}\left(\frac{\partial V}{\partial x}\frac{\partial\psi_2}{\partial y}-\frac{\partial V}{\partial y}\frac{\partial\psi_2}{\partial x}\right)+$$
$$+i\frac{b}{2}\left(\frac{\partial V}{\partial y}\frac{\partial\psi_1}{\partial z}-\frac{\partial V}{\partial z}\frac{\partial\psi_1}{\partial y}\right)+\frac{b}{2}\left(\frac{\partial V}{\partial x}\frac{\partial\psi_1}{\partial z}-\frac{\partial V}{\partial z}\frac{\partial\psi_1}{\partial x}\right). \tag{4}$$

The constant of the spin-orbital interaction b can be presented in the form $b=0,022R_0^2\kappa$, where R_0=1 fm and dimensionless constant $\kappa\sim 30$ [4]. The numerical method of time-dependent equations (3), (4) solution is similarly to split-operator fast Fourier transform (FFT) method without spin-orbital interaction [8].

1.3 Results and discussions

We investigated collisions halo nucleus ^{6}He with spherical nucleus ^{197}Au.

The evolution of the probability density ρ for two external 1p$_{3/2}$ shell neutrons of ^{6}He with averaging on total angular moment projection Ω to some axis

$$\rho(\vec{r},t)=\frac{1}{3}\sum_{\Omega=-3/2}^{3/2}\left(\left|\psi_1(\vec{r},t)\right|^2+\left|\psi_2(\vec{r},t)\right|^2\right). \tag{5}$$

at frontal collision are shown in Fig. 1. The formation of the stable structure of maxima of the probability density indicates that the neutrons preferably occupy two center state (Fig. 1*a*). After collision (Fig. 1*b*) neutrons occupy several initially vacant levels (3d$_{5/2}$, 4s$_{1/2}$, 2g$_{7/2}$, 3d$_{5/2}$) in the ^{197}Au with an energy approximately equal to energy of external neutron in ^{6}He (about –2 MeV), therefore tunnel effect is resonant.

The probability p of neutron transfer during the collisions of nuclei without contact between their surfaces was determined in [5] by integrating the probability density over the volume and vicinity of the nucleus target after collision (Fig. 2*a*).

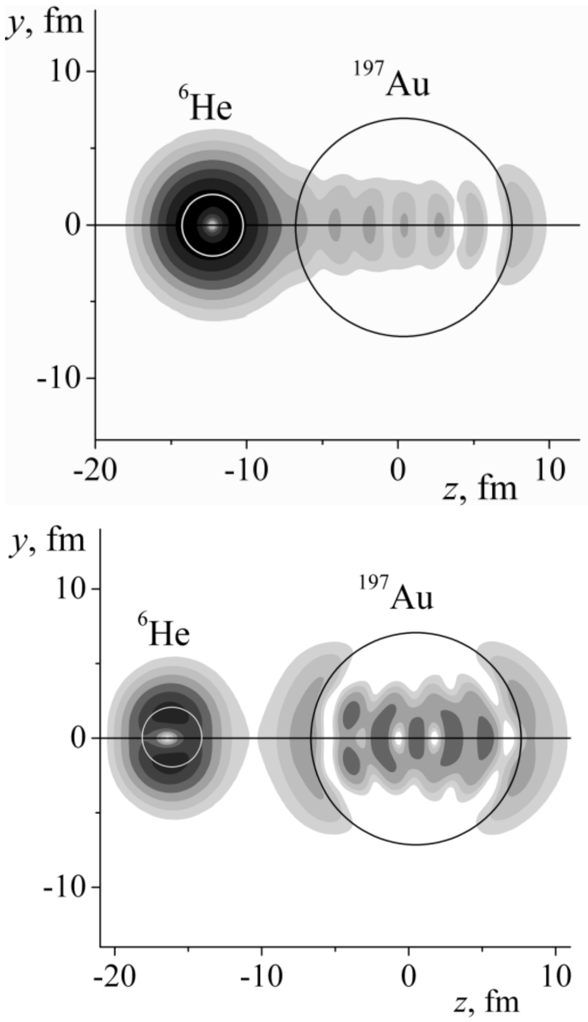


Fig. 1. Change in the probability density $\rho(x, y, z = 0)$ of the external neutrons of ^{6}He nucleus with the initial state $1p_{3/2}$ during a collision with the ^{197}Au nucleus at energy in the center of mass system E = 18 MeV, and radii of the circumferences equal radii of the nuclei. The course of time corresponds to the panels' locations from left to right.

(a)

(b)

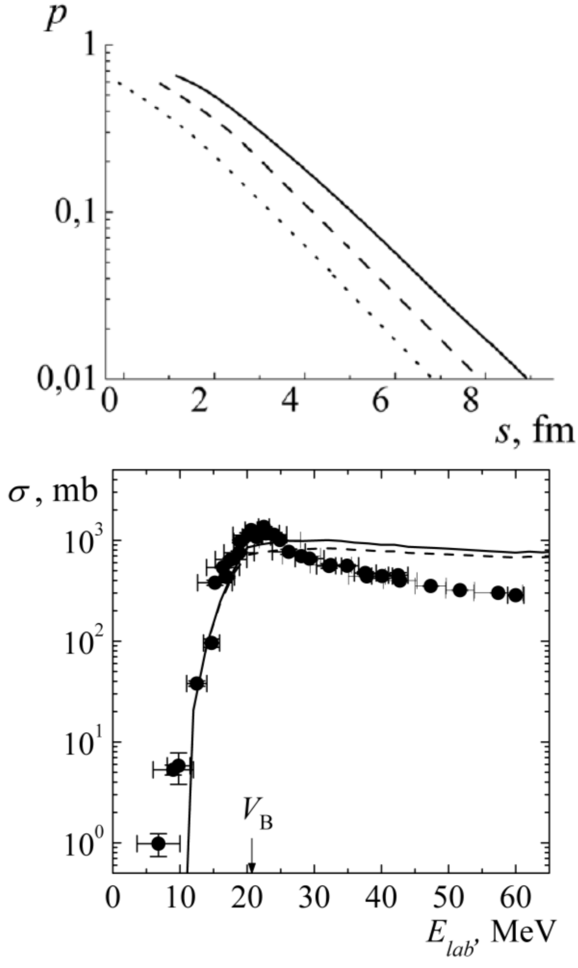


Fig. 2. *a*) The probabilities of neutron stripping at reaction ^{6}He+^{197}Au as a function of on minimum distance *s* between nuclear surfaces for energy in the center of mass system *E* = 20 MeV (solid line), *E* = 30 MeV (dashed line) and *E* = 60 MeV (dotted line).

b) Energy dependence of the cross section for the formation of the ^{198}Au isotope in the ^{6}He+^{197}Au reaction. Dots represent the experimental data from [1]; the dashed line – calculations for the transfer of one neutron; the solid line − calculations for the transfer of one or two neutrons; V_B is the Coulomb barrier.

The total cross section of the one or two neutrons transfer from shell, containing two neutrons before the collision is

$$\sigma = 2\pi \int_{b_0}^{\infty} w(b) b db, \quad (6)$$

where b_0 is the minimum collision impact parameter b corresponding to the grazing collision, when the surfaces of the nuclei approach the distance a=0.7 fm, equal to the diffusivity of the surface region of nuclei. Function $w(b)$ is probability of transfer one or two neutrons [5]. The ^{198}Au isotope can also be formed as a result of the transfer of two neutrons with the subsequent evaporation of one of them. A comparison of the experimental data on the cross section of neutron transfer during the ^{6}He+^{197}Au reaction in Fig. 2*b* and the calculation results demonstrates satisfactory agreement between them at energies near the Coulomb barrier.

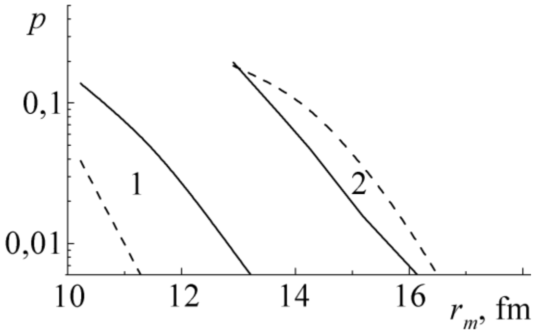
Pauli's exclusion principle limits transfers to occupied states for next studied reactions: ^{18}O+^{48}Ca, ^{48}Ca+^{238}U. This principle was taken into consideration by two approximations. On first simple approximation we except transfer to occupied levels in “frozen” shell structures of colliding nuclei, results are shown in Fig. 3*a*.

On second approximation we used time dependent a few body wave function

$$\Phi_N\left(\vec{r}_1,\ldots\vec{r}_N,t\right) = \frac{1}{N!}\det\begin{bmatrix} \Psi_1\left(\vec{r}_1,t\right) & \ldots & \Psi_1\left(\vec{r}_N,t\right) \\ \ldots & \ldots & \ldots \\ \Psi_N\left(\vec{r}_1,t\right) & \ldots & \Psi_N\left(\vec{r}_N,t\right) \end{bmatrix}, \quad (7)$$

for N=2,3. This model is similar to Hartree-Fock method [7] and time-dependent Hartree-Fock approximation (TDHF, [9]), but it easier them. For neutron transfers at reaction ^{18}O+^{48}Ca two (N=2) external neutrons ($1d_{5/2}$ from ^{18}O and $1f_{7/2}$ from ^{48}Ca) with moment projection □=1/2, 3/2 are took into account. For neutron transfers at reaction ^{48}Ca+^{238}U three (N=3) external neutrons ($1f_{7/2}$ in ^{48}Ca and $2g_{9/2}$, $1i_{11/2}$ in ^{238}U) with moment projection □=1/2, 3/2 are took into account. Results for neutron transfer probability p at reaction ^{48}Ca+^{238}U (Fig. 3*b*) demonstrate quality agreement between simple approximation with exception transfer to occupied states and a few body wave function approximation (7). At reactions ^{6}He+^{197}Au, ^{18}O+^{48}Ca neutrons are

(a)



(b)

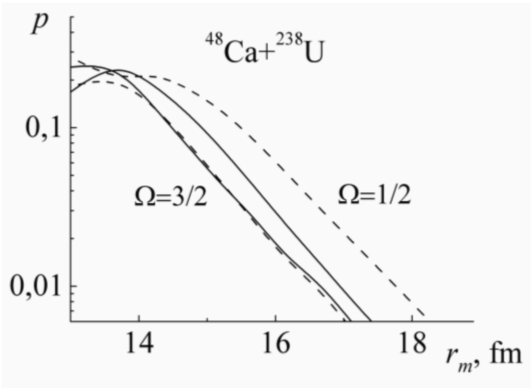


Fig. 3. *a*) Probabilities of neutrons pick-up (solid curves) and stripping (dashed curves) for ^{48}Ca at frontal collision ^{48}Ca + ^{18}O (curves 1) and ^{48}Ca + ^{238}U (curves 2) as function on minimum value of internuclear distance r_m in approximation with exception transfer to occupied states *b*) Probabilities of neutrons pick-up (solid curves) and stripping (dashed curves) for ^{48}Ca at frontal collision ^{48}Ca + ^{238}U as function r_m in approximation (7) with *N*=3 for moment projection Ω=1/2, 3/2.

predominantly transferred from a smaller nucleus to the greater nucleus. At reaction ^{48}Ca+^{238}U probabilities of neutrons stripping and pick-up are commensurable. Calculated probabilities of neutrons pick-up and stripping and similar functions may be used for cross sections for neutrons transfer reactions and experimental date analysis.

1.4 Acknowledgement

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