Near-barrier neutron transfer in reactions $^3,^6$He + $^{45}$Sc and $^3,^6$He + $^{197}$Au

V V Samarín$^1$, M A Naumenko$^1$, Yu E Penionzhkevich$^{1,2}$, N K Skobelev$^1$, V Kroha$^3$ and J Mrazek$^3$

$^1$Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Moscow region, 141980, Russia
$^2$National Research Nuclear University “MEPhI”, Moscow, 115409, Russia
$^3$Nuclear Physics Institute, Czech Academy of Sciences, Rez, 250 68, Czech Republic

samarin@jinr.ru

Abstract. Experimental cross sections for formation of $^{196,198}$Au isotopes in reactions $^3,^6$He + $^{197}$Au and cross sections for formation of $^{44,46}$Sc isotopes in reactions $^3,^6$He + $^{45}$Sc have been analyzed. To calculate neutron transfer probabilities and cross sections the time-dependent Schrödinger equation for external neutrons of $^3$He, $^6$He, $^{45}$Sc and $^{197}$Au nuclei has been solved numerically. It is shown that the contribution of fusion and subsequent evaporation is significant in the case of reactions $^3,^6$He + $^{45}$Sc, whereas in the case of reactions $^3,^6$He + $^{197}$Au, it is negligible. Fusion-evaporation was taken into account using NRV evaporation code. Results of calculations demonstrate overall satisfactory agreement with experimental data.

1. Introduction
Low-energy reactions with He isotopes ($^3$He and halo nuclei $^6,^8$He) attract interest due to the new possibilities of investigating the nuclear structure of light He projectiles and heavy target nuclei, e.g. [1]. We may explore target nuclei $^{45}$Sc, $^{197}$Au by weakly bound neutrons of $^6$He and the more strongly bound neutron of $^3$He in reactions of neutron transfer from the projectile to the target as well as study the properties of external neutrons of $^{45}$Sc, $^{197}$Au in the pick-up reaction $^3$He+$^{45}$Sc, $^6$He+$^{197}$Au. We may also test some theoretical models with both simple and complicated approximations by comparing them with experimental data.

2. Experiments
The experiments were performed with the extracted radioactive beams of $^6$He obtained at the DRIBs accelerator complex, JINR, Dubna [2]. The beams of the $^3$He nuclei were accelerated by the U-120M cyclotron of the Nuclear Physics Institute, the Academy of Sciences of the Czech Republic [3, 4]. The target assemblies consisting of gold foils of different thicknesses were installed in the reaction chamber and irradiated by the beam of particles. For the reaction with $^3$He the gold target assemblies were installed in the focal plane of the magnetic spectrometer MSP-144, where it was possible to obtain the lower energy beam with a good resolution. The maximum energy of the accelerated $^6$He ions was ~10 MeV/nucleon, the intensity reached $(2-5)\cdot10^7$ s$^{-1}$. The maximum energy of $^3$He was 24.5 MeV, the beam intensity varied in the range $(5-10)\cdot10^{11}$ s$^{-1}$. After each irradiation session induced $\gamma$-
activity was measured in all Au targets. The measurements were carried out using HPGe-detectors with the energy resolution of ~1.8 keV for the gamma quantum energy of 1.3 MeV. The identification of the $^{196,198}$Au isotopes was performed by their gamma-radiation energies and half-lives. The measurements of the yields were performed taking into account absolute intensities of gamma-transitions and detector efficiency. The details of the experiment, data processing and results are described in [2 – 4].

3. Time-dependent model for neutron transfer

The experimental excitation functions for the formation of $^{196,198}$Au isotopes in the reactions of $^{3,6}$He with $^{197}$Au and formation of $^{44,46}$Sc isotopes in the reactions of $^{3,6}$He with $^{45}$Sc were analyzed and interpreted on the basis of the time-dependent Schrödinger equation [5].

3.1. Neutron states in $^{3,6}$He

Information about the structure of loosely bound nuclei may be obtained by measuring their momentum distributions after breakup in a nuclear reaction. From the momentum distribution for the $^6$He nucleus it follows that it consists of the $^4$He core and the two-neutron cluster, see e.g. [1, 6]. There are several different approaches to the approximate analysis and solution of the three-body problem [7, 8]. To determine the wave function of the ground state of the $^6$He three-body system the Schrödinger equation may also be solved by Feynman’s continual integrals method [9, 10]. Within the simple approximation we use the shell model with the experimental value of the neutron separation energy 1.86 MeV and the root-mean-square charge radius 2.065 fm (the values were taken from [11]). The shell model mean field (Figure 1a) takes into account the properties of the ground state of the system of three particles $^6$He ($\alpha + n + n$), $^3$He ($p + p + n$) and four particles $^5$He ($p + p + n + n$) calculated by Feynman’s continual integrals method [12]. The central maximum of the mean field is the effect of the repulsive core of the nucleon-nucleon interaction. Results of calculations of the charge distributions for $^3,4$He demonstrate overall satisfactory agreement with experimental data [13] (Figure 1b).

**Figure 1.** a) The mean field $V(r)$ for neutrons and the corresponding neutron levels obtained within the shell model for $^3$He (solid line), $^4$He (dashed line), $^5$He (dotted line) and $^6$He (dash-dotted line). b) The charge densities obtained within the shell model for $^3$He (solid line) and $^4$He (dashed line) compared with experimental charge densities for $^3$He (dotted line) and $^4$He (dash-dotted line) [13].
3.2. The time-dependent Schrödinger equation (TDSE) and neutron wave functions

For theoretical description of neutron transfer during collisions of heavy atomic nuclei several semi-classical models are used [5, 14, 15]. They combine quantum description of internal one-particle and collective degrees of freedom with classical equations of motion of atomic nuclei, equation (1)

\[ m_1 \dot{r}_1 = -\nabla_{r_1} V_{12} (|r_1 - r_2|), \quad m_2 \dot{r}_2 = -\nabla_{r_2} V_{12} (|r_1 - r_2|). \]  

Here \( r_1(t), r_2(t) \) are the centers of nuclei with the masses \( m_1, m_2 \) and \( V_{12}(r) \) is the potential energy of nuclear interaction [16]. 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 \( W(r,t) \) is equal to the sum of its shell model mean fields for both nuclei.

The evolution of the components \( \psi_1, \psi_2 \) of the spinor wave function \( \Psi(r,t) \) for the neutron with the mass \( m \) during the collision of nuclei is determined by the equation (2) with the operator \( \hat{V}_{ls} \) of the spin-orbit interaction

\[ i\hbar \frac{\partial}{\partial t} \Psi(r,t) = \left\{ -\frac{\hbar^2}{2m} \Delta + W(r,t) + \hat{V}_{ls}(r,t) \right\} \Psi(r,t). \]  

The evolution of the probability density for the external \( 1p_{\frac{3}{2}} \) shell neutrons of \( ^{6}\text{He} \) in the reaction \( ^{6}\text{He} + ^{197}\text{Au} \) was studied in Ref. [14]. In this case the neutron occupies free levels of the \( ^{197}\text{Au} \) nucleus. The neutron separation energies of \( ^{3}\text{He} \) and \( ^{197}\text{Au} \) are similar. In the case of pick-up to \( ^{197}\text{Au} \) the neutron occupies free levels only. The Pauli Exclusion Principle limits transfers to the unoccupied states. This principle was taken into account by two different approximations providing very similar results. Within the first, simple, approximation transfer to the occupied levels in the “frozen” shell structures of colliding nuclei is excluded. Within the second, more complicated, approximation the time-dependent few-body Slater determinant wave function is used [15]. In the case of pick-up to \( ^{3}\text{He} \) the neutron occupies the partially free \( 1s \) level of the \( ^{3}\text{He} \) nucleus and the mean field transforms from the \( ^{3}\text{He} \) shell model to the \( ^{4}\text{He} \) shell model.

The evolution of the probability density in the collisions of \( ^{3}\text{He} + ^{45}\text{Sc} \) and \( ^{6}\text{He} + ^{45}\text{Sc} \) is shown in Figures 2 and 3, respectively.

![Figure 2](image_url). Example of the time evolution of the probability density for the external neutron of \( ^{3}\text{He} \) in the collision with \( ^{45}\text{Sc} \) at \( E_{cm} = 6.5 \text{ MeV}, \) impact parameter \( b = 1.5 \text{ fm} \). Radii of circumferences equal the effective radii of nuclei \( R_1 = 2.2 \text{ fm}, R_2 = 4.5 \text{ fm} \). The course of time corresponds to the panel locations a, b, c.

After the transfer (stripping) from the \( ^{3}\text{He} \) nuclei (see Figure 4a) the neutron may occupy several initially vacant levels \( 2p_{\frac{3}{2}}, 2p_{\frac{1}{2}}, 1f_{\frac{5}{2}} \) and a partially vacant level \( 1f_{\frac{7}{2}} \) in the \( ^{45}\text{Sc} \) nucleus. The
total probability of neutron stripping and stripping probabilities to various levels of $^{45}$Sc in the reaction $^{45}$Sc($^3$He, 2$p$)$^{46}$Sc are shown in Figure 4b.

Figure 3. Example of the time evolution of the probability density for the external neutron of $^6$He in the grazing collision with $^{45}$Sc at $E_{\text{c.m.}} = 16$ MeV, impact parameter $b = 7$ fm. Radii of circumferences equal the effective radii of nuclei $R_1 = 3.0$ fm, $R_2 = 4.5$ fm. The course of time corresponds to the panel locations a, b, c.

![Figure 3](image1.png)

Figure 4. a) The neutron level scheme of $^3$, $^6$He and $^{46}$Sc nuclei for the stripping reactions $^{45}$Sc($^3$He, 2$p$)$^{46}$Sc and $^{45}$Sc($^6$He, $^5$He)$^{46}$Sc; b) The total probability of neutron stripping to $^{45}$Sc in the reaction $^{45}$Sc($^3$He, 2$p$)$^{46}$Sc taking into account the Pauli Exclusion Principle (solid line) and without the Pauli Exclusion Principle (dashed line), the probability of stripping to the states $2p_{3/2}$ and $2p_{1/2}$ (dash-dotted line), $1f_{5/2}$ (dash-dash-dotted line) and $1f_{7/2}$ (dotted line) at $E_{\text{c.m.}} = 15$ MeV. $R_B$ is the barrier position.

![Figure 4](image2.png)

Similarly, a weakly bound neutron of the $^6$He nucleus may be transferred to several initially vacant top levels $2g_{9/2}$, $1i_{1/2}$, $3d_{5/2}$, $1f_{5/2}$, $4s_{1/2}$, $2g_{7/2}$, $3d_{3/2}$ in the $^{197}$Au nucleus. The more strongly bound neutron of $^3$He may be transferred to several initially vacant levels $2f_{5/2}$, $3p_{3/2}$, $3p_{1/2}$ near the Fermi level in the $^{197}$Au nucleus.
3.3. Calculations of transfer cross sections

The total cross section of neutron transfer in the time-dependent model is calculated by equation (3)

\[ \sigma = 2\pi \int_{b_0}^{\infty} p(b) b db. \]  

(3)

Here \( b \) is the impact parameter, \( b_0 \) is the minimum collision impact parameter which is equal to zero for the energy less than the Coulomb barrier. The function \( p(b) \) is the probability of neutron transfer during the collisions of nuclei without contact between their surfaces. Without taking into account the Pauli Exclusion Principle \( p(b) \) was determined by integrating the probability density over the volume after the collision (Figures 2 and 3). With the Pauli Exclusion Principle only stripping to initially vacant levels was taken into account. In the case of \(^{6}\)He only stripping to discrete bound states of the target was taken into account.

The comparison of the experimental data and theoretical calculations for the reactions \(^{45}\text{Sc}(^{3}\text{He}, 2p)^{46}\text{Sc}\) and \(^{197}\text{Au}(^{3}\text{He}, 2p)^{198}\text{Au}\) is shown in Figures 5a and 5b, respectively. Symbols are the data from Refs [3, 4].

![Figure 5](image)

**Figure 5.** a) The excitation function for the reaction \(^{45}\text{Sc}(^{3}\text{He}, 2p)^{46}\text{Sc}\). b) The excitation function for the reaction \(^{197}\text{Au}(^{3}\text{He}, 2p)^{198}\text{Au}\). Symbols are the experimental data from Ref. [3, 4] (filled squares) and Ref. [17] (empty squares), dashed curves are fusion-2p-evaporation calculations using NRV evaporation code [11], solid curves are neutron transfer calculations taking into account the Pauli Exclusion Principle, dash-dotted curve is sum of fusion-2p-evaporation and neutron transfer. Here and below arrows indicate barrier heights.

The comparison of the experimental data and theoretical calculations for the reactions \(^{45}\text{Sc}(^{3}\text{He}, 4\text{He})^{44}\text{Sc}\) and \(^{197}\text{Au}(^{3}\text{He}, ^{4}\text{He})^{196}\text{Au}\) is shown in Figures 6a and 6b, respectively. For neutron pick-up the energy of the neutron in \(^{197}\text{Au}\) was chosen to coincide with the experimental neutron separation energy. As can be seen, in the reaction \(^{3}\text{He} + ^{197}\text{Au}\) neutrons are predominantly transferred from \(^{3}\text{He}\) to \(^{197}\text{Au}\). The comparison of the experimental data and theoretical calculations for the reaction \(^{45}\text{Sc}(^{5}\text{He}, 4\text{He})^{46}\text{Sc}\) is shown in Figure 7. The comparison of the experimental data and theoretical calculations for the reaction \(^{197}\text{Au}(^{5}\text{He}, ^{5}\text{He})^{198}\text{Au}\) has been reported in [14].
Figure 6. a) The excitation function for the reaction $^{45}$Sc($^3$He, $^4$He)$^{44}$Sc. b) The excitation function for the reaction $^{197}$Au($^3$He, $^4$He)$^{196}$Au. Symbols are the experimental data from Ref. [3, 4] (filled squares) and Ref. [17] (empty squares), dotted curves are total fusion cross sections calculated using NRV fusion code [11], dashed curves are fusion-$\alpha n$-evaporation calculations using NRV evaporation code [11], solid curves are neutron transfer calculations taking into account the Pauli Exclusion Principle, dash-dotted curves are sums of fusion-$\alpha n$-evaporation and neutron transfer taking into account the Pauli Exclusion Principle, dash-dot-dotted curves are neutron transfer calculations without taking into account the Pauli Exclusion Principle.

Figure 7. The excitation function for the reaction $^{45}$Sc($^6$He, $^5$He)$^{46}$Sc. Symbols are the experimental data from Ref. [18] (filled squares), dotted curve is total fusion cross section calculated using NRV fusion code [11], dashed curve is fusion-$\alpha n$-evaporation calculation using NRV evaporation code [11], solid curve is neutron transfer calculation taking into account only stripping to discrete bound states, dash-dotted curve is sum of fusion-$\alpha n$-evaporation and neutron transfer.

The model does not take into account the energy change associated with the $Q$-value of the neutron transfer. In the case of $Q>0$ it may lead to closer distances between nuclei and, thus, higher transfer probability resulting in higher transfer cross section. In the opposite case, $Q<0$, transfer probability is lower resulting in lower transfer cross section. This also implies the change of the structure of the projectile during the neutron transfer.

The effect of the $Q$-value and the quantum effects related to the motion of cores, e.g. tunneling, may be taken into account in the coupled channel approach [5, 12, 19] combined with the time-dependent Schrödinger equation method.

4. Conclusion
The results of calculations within the time-dependent Schrödinger equation method demonstrate overall satisfactory agreement with experimental data. The method may also be applied for calculation of reactions with cluster nuclei [20].
Acknowledgments
Authors thank A S Denikin and A V Karpov for fruitful discussions.

References
[1] Penionzhkevich Yu E 2011 Phys. Atom. Nucl. 74 1615
[2] Penionzhkevich Yu E, Astabatyan R A, Demekhina N A et al 2007 Eur. Phys. J. A 31 185
[3] Skobelev N K, Penionzhkevich Yu E, Voskoboynik E I et al 2014 Phys. Part. and Nucl. Lett. 11 114
[4] Skobelev N K, Kulko A A, Penionzhkevich Yu E et al 2013 Phys. Part. Nucl. Lett. 10 410
[5] Samarin V V 2015 Phys. of Atom. Nucl. 78 128
[6] Oganessian Yu Ts, Zagrebaev V I and Vaagen J S 1999 Phys. Rev. C 60 044605
[7] Kukulin V I, Krasnopolsky V M, Voronchev V T et al 1986 Nucl. Phys. A 453 365
[8] Zhukov M V, Danilin B V, Fedorov D V et al 1993 Phys. Rep. 231 151
[9] Feynman R P and Hibbs A R 1965 Quantum Mechanics and Path Integrals (New York: McGraw-Hill)
[10] Shuryak E V 1984 Sov. Phys. Usp. 27 448
[11] Nuclear Reactions Knowledge Base http://nrn.jinr.ru/nrv
[12] Samarin V V 2015 Phys. of Atom. Nucl. 78 861
[13] McCarthy J S, Sick I, Whitney R R 1977 Phys. Rev. C 15 1396
[14] Samarin V V 2015 Time-dependent quantum models of the dynamics of neutron transfer reactions near the barrier EPJ Web of Conf. 86 (2015) 00040
[15] Samarin V V, Naumenko M A, Penionzhkevich Yu E et al 2014 Proc. Int. Symp. on Exotic Nuclei (Kaliningrad) (Singapore: World Scientific) p 115
[16] Winther A 1994 Nucl. Phys. A 572 191
[17] Nagame Y, Sukeki K, Baba S et al 1990 Phys. Rev. C 41 889
[18] Skobelev N K, Kulko A A, Kroha V et al 2011 Eur. Phys. J. G 38 035106
[19] Samarin V V 2015 Coupling with two-center neutron states and two-surface collective excitations at fusion reactions in the vicinity of the Coulomb barrier EPJ Web of Conf. 86 (2015) 00039
[20] Samarin V V 2015 Microscopic time-dependent description of alpha-cluster transfer and incomplete fusion in reactions near Coulomb barrier Proc. Int. Conf. “Nucleus 2015” (Saint-Petersburg) (Saint-Petersburg: BBM) p 198