Dynamics of two-neutron transfer reactions on the Borromean nucleus ^{6}He reexamined

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Microscopic calculations of cross sections with density dependent interactions employing (a) RIKEN density distributions of helium isotopes for the derivation of the real part and (b) Bachelier *et al.* and Bray *et al.* imaginary part of the optical potential have been performed for the elastic scattering of ^{6}He+^{4}He and for ^{6}He+^{1}H. The results are in very good agreement with the recent experimental data of Oganessian *et al.*

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Recently, two interesting papers appeared dealing with the experimental justification that the ^{6}He ground-state structure is composed of a core plus two neutrons in the form of a dineutron instead of cigarlike configurations [1,2]. This spatial preference of the two valence neutrons outside a rather structureless doubly closed shell nucleus creates an additional interest in studies of light exotic nuclei. In our opinion, this very fact could be considered as a precursor of a new structural physics which soon will attract more and more researchers. Through our present constructive Brief Report we find it tempting to contribute to this outstanding experiment by providing a theoretical interpretation of the available experimental data. Specifically here we present microscopic calculation of the cross sections for the elastic scattering of the ^{6}He+^{4}He and ^{6}He+^{1}H. The purpose of this Brief Report is to show that an improvement of the data description can be obtained when the specific ^{4,6}He RIKEN densities [3] and realistic density- and energy-dependent effective *NN* forces are employed for the calculations of the microscopical real optical potential (OP), instead of using the Baye *et al.* potential [1,2,4]. Indeed, we were able to describe the data of both reactions very well and the most important by strictly using published potentials and densities without any adjustment. The importance of using realistic density distributions for the target and projectile and density dependent *NN*-effective interactions for the real part of the microscopical optical potential becomes apparent. The theory employed here follows.

The RIKEN density distributions for helium isotopes [3] and the density-dependent DDM3Y realistic effective *NN* interaction [5] based on the *g*-matrix elements of the Paris [6] *NN* potential have been involved in the calculation of the microscopic real OP [7].

The general expressions [7] for the direct and exchange real parts of the microscopical optical potential, $V(\mathbf{R},E)$, in terms of the nuclear densities of the projectile and the target nuclei [$\rho_1(\mathbf{r}_1)$ and $\rho_2(\mathbf{r}_2)$], and the effective *NN* interaction $v(s=\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1)$, are [5,8]

$$V_0^D(E,\mathbf{R})=\int d\mathbf{r}_1\int d\mathbf{r}_2\rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)v_{00}^D(\rho,E,\mathbf{s}), \quad (1)$$

$$V_1^D(E,\mathbf{R})=\int d\mathbf{r}_1\int d\mathbf{r}_2[\rho_{n1}(\mathbf{r}_1)-\rho_{p1}(\mathbf{r}_1)][\rho_{n2}(\mathbf{r}_2)-\rho_{p2}(\mathbf{r}_2)]v_{01}^D(\rho,E,\mathbf{s}), \quad (2)$$

$$V_0^{EX}(E,\mathbf{R})=\int d\mathbf{r}_1\int d\mathbf{r}_2\rho_1(\mathbf{r}_1,\mathbf{r}_1+\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2-s)\times v_{00}^{EX}(\rho,E,s)\exp\left[\frac{i\mathbf{k}(\mathbf{R})s}{M}\right], \quad (3)$$

$$V_1^{EX}(E,\mathbf{R})=\int d\mathbf{r}_1\int d\mathbf{r}_2[\rho_{n1}(\mathbf{r}_1,\mathbf{r}_1+s)-\rho_{p1}(\mathbf{r}_1,\mathbf{r}_1+s)]\times[\rho_{n2}(\mathbf{r}_2,\mathbf{r}_2-s)-\rho_{p2}(\mathbf{r}_2,\mathbf{r}_2-s)]\times v_{01}^{EX}(\rho,E,s)\exp\left[\frac{ik(\mathbf{R})s}{M}\right], \quad (4)$$

where $M=A_1A_2/(A_1+A_2)$, $v_{00(01)}^D(\rho,E,s)$, and $v_{00(01)}^{EX}(\rho,E,s)$ are the direct and exchange isoscalar and isovector components of the effective *NN* interaction, $\mathbf{k}(\mathbf{R})$ is the incident relative momentum, $\rho_{n,p(1,2)}(\mathbf{r}_{1,2})$ are neutron and, respectively, proton density distributions of the projectile (1) and target (2) nuclei, while ρ_1 and ρ_2 in Eqs. (3), (4) are their corresponding density matrices.

For the calculation of the knock-on exchange term of the folded potential the approximation of Campi and Bouyssy [9], which preserves the first term of the expansion given by Negele-Vautherin [10] for the realistic density-matrix expression, has been considered:

$$\rho(\mathbf{R},\mathbf{R}+s)=\rho\left(\mathbf{R}+\frac{s}{2}\right)\hat{j}_1\left[k_{av}\left(\mathbf{R}+\frac{s}{2}\right)s\right], \quad (5)$$

where $\hat{j}_1(x)=3(\sin x-x\cos x)/x^3$, and k_{av} defines the average relative momentum [9] as function of the density distribution $\rho(r)$ and of the kinetic-energy density $\tau(r)$ for each participant in the interaction. Specifically for light nuclei the modified Thomas-Fermi approximation of Krivine-Treiner [11] has been considered for the kinetic-energy density τ leading to the following expression for the average relative momentum:

$$k_{\rm av}(r)=\left[\frac{5|\nabla\rho(r)|^2}{12\rho^2(r)}-\frac{5\nabla^2\rho(r)}{12\rho(r)}\right]^{1/2}. \quad (6)$$

The energy- and density-dependent DDM3Y effective *NN* interaction has been taken in the form [5]

$$v_{00(01)}^{D(EX)}(\rho,E,r)=g(E)F(\rho)v_{00(01)}^{D(EX)}(r), \tag{7}$$

where the direct and exchange components of the simple M3Y effective *NN* interaction $v_{00(01)}^{D(EX)}(r)$ are parametrized in terms of Yukawa functions, the energy-dependent factor is taken to be $g(E)=1\text{-}0.003E$, and the density dependent component $F(\rho)$ for the DDM3Y is given by

$$F(\rho)=C[1+\alpha\exp(-\beta\rho)];\quad C=0.2963,\quad \alpha=3.7231,$$

$$\beta=3.7384. \tag{8}$$

The frozen-density approximation [5,7,8] has been considered for the overlap density, which enters the explicit form of the density-dependent factor $F(\rho)$ (i.e., being taken as the sum of the densities of the two colliding nuclei at the midpoint of the intranucleonic separation).

The imaginary component of the phenomenological OP is taken from Bachelier *et al.* [12] for ^{6}He+^{4}He and Bray *et al.* [13] for ^{6}He+^{1}H as suggested by Oganessian *et al.* [1,2], without any adjustment here.

In Fig. 1(a) the RIKEN density distributions [3] for ^{4,6}He are shown, while in Fig. 1(b) the corresponding DDM3Y microscopical real potential is presented together with the real part of the phenomenological Bachelier's OP [12] for comparison. As one can see from Fig. 1(b) the microscopic OP is less deep at the origin than the phenomenological one, but it is stronger in the nuclear surface, thus emphasizing the effect of the surface density distributions of the interacting nuclei. The present calculations are shown in Fig. 1(c), the good agreement with the data being apparent for $\vartheta_{\text{c.m.}} \leqslant 110°$, where the potential scattering is reliable. At this relatively low incident energy (60 MeV in the center-of-mass system), as is expected [14], the interaction is localized with increased probability in the nuclear surface and the effects of the nuclear density distribution are well considered through the DDM3Y interaction. Moreover, it can be shown that a better description of the experimental data is obtained by using the DDM3Y interaction than through the simple M3Y one. The consideration here of these two aspects is the reason for the aforementioned good agreement.

Similar results have been obtained analyzing the differential elastic scattering cross sections of ^{6}He on protons, as one can see from the good agreement between the experimental data [2,15] and our calculations in Fig. 1(e). One could further refer to Fig. 17 of Ref. [2] for a good reproduction of the experimental data by using phenomenological OP of Bray *et al.* [13] and of Varner *et al.* [16]. In Fig. 1(d) the real potentials corresponding to Bray *et al.* [13] (dotted curve), from where we took the imaginary OP without any adjustment, and ours derived from RIKEN density for ^{6}He and DDM3Y *NN* effective interaction (dash two-dots line) are comparatively presented.

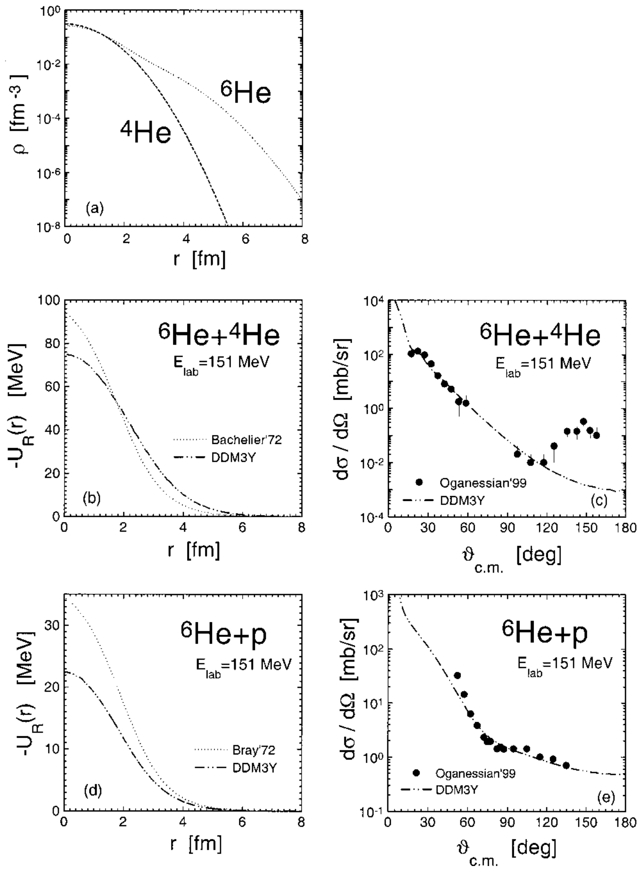

FIG. 1. Elastic scattering of ^{6}He on ^{4}He, (a)–(c), and on ^{1}H, (d), (e). (a) presents RIKEN densities for ^{4}He (short-dashed line) and ^{6}He (dotted line) while (b) presents the real parts of the phenomenological OP of Bachelier *et al.* (dotted line) and the microscopic DDM3Y potential (dash two-dots line), (c) elastic scattering differential cross sections calculated in this work, (d) the real parts of the phenomenological OP of Bray *et al.* (dotted line) and the microscopic DDM3Y potential derived in this work (dash two-dots line), and (e) elastic scattering differential cross sections calculated in this work.

The general conclusion from the present analysis of the above two reactions is that the consideration of accurate density distributions of the nuclei involved together with realistic density-dependent *NN*-effective interaction are needed for a good description of the experimental data. It is obvious that experimental data such as those of Oganessian *et al.* [1,2,15] represent an essential base for testing both the density distributions of the exotic nuclei as well as the available *NN* effective interactions.

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