PHYSICAL REVIEW C, VOLUME 62, 061601(R)

Folding potential for the system ^{209}Bi-^{6}He

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(Received 17 July 2000; published 26 October 2000)

The systematics of α-nucleus folding potentials is extended to the system ^{209}Bi- ^{6}He where recently anomalously large reaction cross sections have been observed. These anomalies, which have been explained by the large spatial extent of the ^{6}He wave function, can be described with systematic folding potentials in a natural way.

PACS number(s): 25.60.Bx, 25.60.Dz, 25.60.Pj, 24.10.Ht

In two recent papers anomalous properties of the system ^{209}Bi- ^{6}He at energies close to the Coulomb barrier were analyzed. The enhanced fusion probability was reported in [1]. A surprisingly large α yield was measured in the ^{209}Bi(^{6}He,^{4}He) reaction in [2], and simultaneously a huge total reaction cross section was derived from the ^{209}Bi(^{6}He,^{6}He)^{209}Bi elastic scattering data. Both papers explain the observed anomalies by the large spatial extent of the ^{6}He wave function due to the low two-neutron separation energy of about 1 MeV which may lead to an enhanced breakup of ^{6}He at low energies. In this Rapid Communication I present an alternative analysis of the data of Ref. [2] which reproduces the experimental scattering cross section and the total reaction cross section simultaneously. The above experimental observations are explained in a natural way.

The basic ingredient for the analysis of the nucleus-nucleus interaction at energies close to the Coulomb barrier is the nucleus-nucleus potential $V(r)$ which is composed of the real Coulomb potential and the complex nuclear potential. For the ^{209}Bi-^{4}He system it has been shown that huge uncertainties exist for the potential because different nuclear potentials resulted in a similar description of the experimental data at low energies [3]. Such ambiguities have been analyzed in detail by [4], and it has been shown [4–6] that the ambiguities of the potential can be reduced significantly by the use of systematic folding potentials. Additionally, it has been found that the volume integrals of the potentials for heavy nuclei show only a weak mass dependence [5,6].

The elastic scattering cross section of ^{209}Bi(^{6}He,^{6}He)^{209}Bi cannot be described by a ''standard'' Woods-Saxon potential obtained from ^{209}Bi(α,α)^{209}Bi at comparable energies [2,3] because the ''standard'' potential underestimates the total reaction cross section significantly. Therefore, a strong energy dependence of the imaginary part of the potential was proposed in [2] with the peculiar behavior of a stronger imaginary part (corresponding to stronger absorption) at lower energies. Such a behavior of the imaginary part of the potential is in strong contradiction to the systematic study of [5].

A similar description of the elastic scattering data and the total reaction cross section of the system ^{209}Bi- ^{6}He can be obtained by adapting the systematic α-nucleus potentials of [5] to the ^{209}Bi-^{6}He system. In [5] elastic α scattering was analyzed over a wide range of masses and energies. It was found that the real part of the nuclear potential has a typical volume integral of about $320-350$ MeV fm^{3} for all heavy nuclei at energies around the Coulomb barrier (see also [4,6]), and a similar value was recently obtained from ^{16}O -^{16}O scattering [7]. Therefore, such a value can also be expected for the ^{209}Bi- ^{6}He system. The strength of the imaginary part of the nuclear potential increases steeply with energy at energies around the Coulomb barrier. The absolute value is smaller for scattering of doubly magic nuclei (^{40}Ca- α, ^{208}Pb- α) and somewhat larger for systems with one semimagic nucleus (^{90}Zr- α, ^{144}Sm- α). Consequently, an even larger value can be expected for the system ^{209}Bi- ^{6}He which consists of two semimagic nuclei.

The real and imaginary part of the optical potential are coupled by a dispersion relation [8]. The adjustment of the ^{209}Bi- ^{6}He real potential to the systematics of α-scattering data neglects the difference of the dispersive influence because of the different imaginary parts in the α-nucleus and ^{6}He-nucleus systems. But the similar volume integrals J_R for the systems ^{16}O -^{16}O and α-nucleus indicate that the influence of the different dispersive couplings can be estimated to be small.

The following procedure was applied to determine the potential for the ^{209}Bi- ^{6}He system at $E=19.0$ and 22.5 MeV which are the experimental energies of [2]. E is the energy of the ^{6}He projectile in the laboratory system. First, the systematic folding potentials have been tested by calculating the ^{209}Bi(α,α)^{209}Bi elastic scattering cross section at $E \approx 20$ MeV. The calculations agree nicely with the experimental data of [3]. The folding potential in the real part of the nuclear potential V_R is given by

$$\begin{aligned} V_R(r) &= \lambda V_F(r) \\ &= \lambda \int \int \rho_P(r_P)\rho_T(r_T) v_{\text{eff}} \\ &\quad \times (E_{\text{c.m.}}, \rho=\rho_P+\rho_T, s=|\vec{r}+\vec{r}_P-\vec{r}_T|) d^3r_P d^3r_T, \end{aligned} \tag{1}$$

where ρ_P, ρ_T are the densities of projectile and target, which are derived from electron scattering for ^{209}Bi [9] and for ^{6}Li [10]. The density of ^{6}Li was used because (i) for the unstable ^{6}He no experimental density distribution is available, and (ii) the charge density of ^{6}He (as measured in electron scattering) is probably not a good estimate for the nuclear density. Note that the two-neutron separation energy

TABLE I. Summary of the potential parameters used in the analysis of the ^{209}Bi- ^{6}He system.

E (MeV)	λ	J_R (MeV fm^3)	$r_{R,\mathrm{rms}}$ (fm)	W_0 (MeV)	R_I (fm)	a_I (fm)	J_I (MeV fm^3)	$r_{I,\mathrm{rms}}$ (fm)	σ_{reac} [a] (mb)
19.0	1.044	341.8	6.54	10.0	12.5	0.60	66.7	9.94	694
22.5	1.056	345.9	6.54	17.0	11.0	0.60	77.8	8.81	1073

[a]The total reaction cross section σ_{reac} has been calculated in the strong absorption limit.

(≈ 1 MeV) of ^{6}He leading to an α core is close to the deuteron separation energy of ^{6}Li (≈ 1.5 MeV). Following [5], the effective interaction has been chosen in the DDM3Y parametrization [11,12]. For details of the folding procedure see also [13,5]. The strength of the folding potential has to be adjusted by the usual strength parameter λ with $\lambda \approx 1.0-1.3$ leading to the systematic volume integrals J_R per interacting nucleon pair of about 320 to 350 MeV fm^3 [6] (see also Table I). J_R is defined by

$$J_R = \frac{4\pi}{A_P A_T} \int_0^\infty V_R(r) r^2 dr, \tag{2}$$

the imaginary volume integral J_I is defined in a similar way. Note that in the discussion of volume integrals J usually the negative sign is neglected; also in this Rapid Communication all J values are negative.

For the analysis of the ^{209}Bi(^{6}He,^{6}He)^{209}Bi elastic scattering I use the volume integrals given by the parametrization (4.1) of [6]:

$$J_R(E_{\mathrm{c.m.}}) = J_{R,0} \times \exp[-(E_{\mathrm{c.m.}} - E_0)^2/\Delta^2], \tag{3}$$

with $J_{R,0} = 350$ MeV fm^3, $E_0 = 30$ MeV, and $\Delta = 75$ MeV. This leads to $\lambda(E=19.0 \text{ MeV}) = 1.044$ [$J_R(E=19.0 \text{ MeV}) = 341.8$ MeV fm^3] and $\lambda(E=22.5 \text{ MeV}) = 1.056$ [$J_R(E=22.5 \text{ MeV}) = 345.9$ MeV fm^3]. The Coulomb potential was taken in the usual form of a homogeneously charged sphere with a Coulomb radius equal to the root-mean-square radius r_{rms} of the folding potential.

The volume integral of the imaginary part can be roughly estimated from the systematics of [5] to be in the order of $60-80$ MeV fm^3 for the ^{209}Bi- ^{6}He system. The shape of the imaginary part was chosen as volume Woods-Saxon where the parameters depth W_0, radius R, and diffuseness a were adjusted to the experimental scattering data of [2]. The adjustment leads to $J_I(E=19.0 \text{ MeV}) = 66.7$ MeV fm^3 and $J_I(E=22.5 \text{ MeV}) = 77.8$ MeV fm^3, consistent with the expectations from α scattering. The strength of the imaginary part increases with energy which is the usual behavior for the imaginary part. The potential parameters are summarized in Table I.

The folding potential calculations are compared to the experimental data [2] in Fig. 1 (full lines). The general agreement between the experimental data [2] and the folding potential calculation is excellent and of similar quality as the calculation in [2] where the peculiar behavior of the imaginary part was used. The calculated total reaction cross sections agree perfectly with the experimental values determined from the sum of transfer/breakup [2] and fusion cross sections [1].

The most striking feature of the imaginary potential is the increase of the radius parameter R_I from $R_I = 11.0$ fm at 22.5 MeV to $R_I = 12.5$ fm at 19.0 MeV. It is not possible to describe the 19.0 MeV data with the shape of the 22.5 MeV potential and vice versa. In Fig. 1 the dotted line in the 19.0 MeV (22.5 MeV) diagram is obtained with the imaginary potential derived from the 22.5 MeV (19.0 MeV) data. This striking feature can simply be explained by a shift of the reaction zone towards larger radii at lower energies because of the low two-neutron separation energy of ^{6}He and the large spatial extent of the ^{6}He wave function. A similar phenomenon has been found for capture reactions leading to weakly bound states, e.g., in the reaction ^{16}O$(p,\gamma)^{17}$F [14].

In conclusion, it has been shown that the systematics of α-nucleus folding potentials [5] can be extended to describe the experimental properties of the ^{209}Bi- ^{6}He system at energies close to the Coulomb barrier [2]. The number of adjustable potential parameters is reduced, and therefore the proposed peculiar behavior of the imaginary potential [2] can be avoided. The only special property of the potential is the significantly increased radius of the imaginary potential at

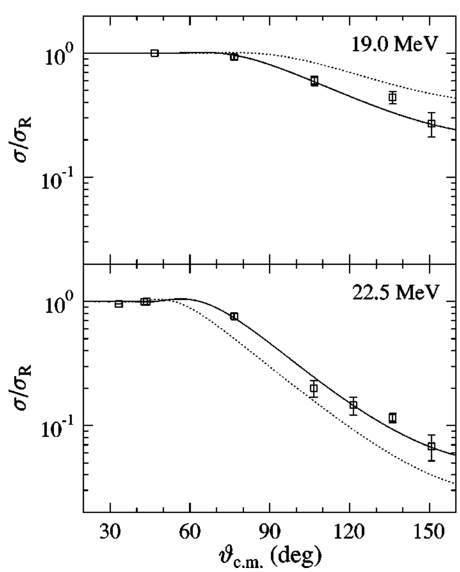

FIG. 1. Elastic scattering cross section of ^{209}Bi(^{6}He,^{6}He)^{209}Bi at $E=19.0$ (upper) and 22.5 MeV (lower part) normalized to the Rutherford cross section. The best-fit calculations are shown with full lines, whereas the dotted lines are the results at 19.0 MeV using the imaginary part of the 22.5 MeV best-fit calculation and vice versa. The experimental data points are taken from [2].

lower energies which is related to the low binding energy of the ^{6}He nucleus. The main conclusions of Ref. [2] are confirmed by this analysis.

An unusual near-threshold behavior of the optical potential has recently been found also from elastic scattering for the system ^{209}Bi- ^{9}Be [15], whereas a similar experiment for ^{64}Zn- ^{9}Be reports that [16], ''The analysis of the scattering data was not conclusive about the presence of the threshold anomaly.'' A further extension of the systematic folding potentials to these systems requires a systematic study of ^{9}Be scattering over a wide range of energies and target masses (comparable to [5] for α scattering) and is beyond the scope of this Rapid Communication.

Discussions with J. J. Kolata, G. Staudt, and A. Zilges are gratefully acknowledged.

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