Appropriate bare potentials for studying fusion induced by ^{6}He

E. Crema,[1] P. R. S. Gomes,[2] and L. C. Chamon[1]

[1]*Departamento de Física Nuclear, Instituto de Física da Universidade de São Paulo, Caixa Postal 66318, 05315-970, São Paulo, SP, Brazil*

[2]*Instituto de Física, Universidade Federal Fluminense, Av. Litorânea s/n, Gragoatá, Niterói, R.J., 24210-340, Brasil*

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We analyze fusion cross sections induced by the ^{6}He halo projectile in the framework of the double-folding São Paulo potential, which has already been shown to be a reliable potential for the analysis of fusion cross sections induced by stable weakly bound nuclei. The results show that the fusion cross sections of ^{6}He+^{209}Bi, ^{238}U, ^{64}Zn are suppressed at energies above the barrier when compared with coupled-channels calculations that do not take into account the projectile breakup, whereas they are in agreement with the calculations at subbarrier energies. The results for the ^{6}He+^{209}Bi system are contradictory to those reported previously.

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There are some recent studies questioning the use of the same optical potential to explain, simultaneously, fusion and quasielastic experimental data [1] or even, during recent decades, to explain deep subbarrier and above-barrier fusion [2] but the bare nuclear interaction between the nuclei at near barrier energies has been widely represented by a frozen potential with a Woods-Saxon shape. Another well-established fact is the strong dependence of nuclear reaction calculations on the choice of the primary interaction. Of course, comparisons between data and theoretical calculations are strongly potential dependent. So, the choice of an appropriate bare nuclear interaction between two colliding nuclei, although it is a difficult task, is a crucial step in the data interpretation. As one does not have direct access to the "true" bare potential, some procedures have been developed to constrain the choice of the bare potential to be used.

The first procedure is the analysis of the elastic-scattering data within the context of an optical potential, where an imaginary potential is added to the real potential, to take into account the flux deviated from the elastic channel. The optical potential that gives the best fit to the elastic-scattering data is then used to describe other reaction channels, even in coupled-channels calculations (CCC), including inelastic and transfer reactions in the coupling matrix. This kind of calculation suffers from several inconsistencies: (i) as the imaginary and real parts of the optical potential are not completely independent, the real part carries information on the complete reaction mechanism, and therefore, it cannot be used as the bare potential; (ii) the elastic scattering at forward angles is governed by the external part of the potential and cannot test the inner region of the interaction where fusion takes place; (iii) as CCC aim to understand the role of each reaction channel in the global reaction mechanism, it is senseless to perform CCC using an imaginary potential that had already accounted for these channels.

Another procedure that has been widely used to obtain the bare potential is the fit of the high-energy fusion data by a single barrier penetration model (BPM). However, this method also has its uncertainties, because there may be channels that hinder the fusion cross section at energies near and above the Coulomb barrier or, like the deep inelastic process, even at energies well above the barrier. Hence, the bare potential extracted through this method can be contaminated by different processes.

The derivation of experimental barrier distributions probably is the best way to constrain the choice of the bare potential to be used, because their heights and shapes should be reproduced by the calculations. However, much experimental work is demanded to obtain the barrier distribution, so far not achieved with low-intensity radioactive beams.

Of course, the true bare potential could be derived from a complete CCC, where all reaction channels were explicitly included in the coupling matrix. However, as one knows, this complete calculation is not possible, for practical reasons. By reducing the model space in the CCC, the resulting potential is the bare potential added to a polarization-potential arising from the channels that were not included in the calculation. This situation becomes even more complicated when a weakly bound nucleus is involved in the reaction, because the breakup channel might couple strongly with other degrees of freedom.

To overcome these difficulties, we have shown recently [3] that the parameter-free São Paulo potential (SPP) [4,5] is a reliable bare interaction for studying the fusion of systems involving stable weakly bound nuclei in situations in which experimental barrier distributions cannot be obtained. As it is deduced from fundamental principles, the SPP does not contain the limitations discussed above and does not contain any adjustable parameter. In this Brief Report we propose to adopt the SPP as the bare potential in the study of fusion reactions induced by the radioactive weakly bound nucleus ^{6}He.

At the present time, the available conclusions in the literature about the role of ^{6}He on the fusion reaction mechanism are contradictory. Kolata *et al*. [6] claim that there is a large sub-barrier fusion enhancement for the ^{6}He+^{209}Bi system, whereas Raabe *et al*. [7] suggest that there is no enhancement in the sub-barrier fusion of the ^{6}He+^{238}U system. In a recent article, Penionzhkevich *et al*. [8] claim that there is a large sub-barrier enhancement for the ^{6}He+^{208}Pb system. Could these opposite conclusions be due to target structure differences? This Brief Report offers a contribution for resolving this question.

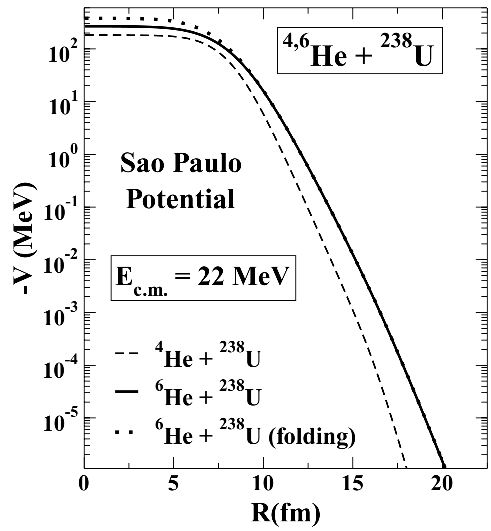

FIG. 1. The SPP for the ^{4,6}He+^{208}U systems at $E_{\text{c.m.}} = 22$ MeV. The dotted line represents the contribution of the double-folding part of the effective potential for the ^{6}He system.

The basis for the calculations with the SPP is reliable knowledge of the matter distributions of the interacting nuclei. As the ground-state density of ^{6}He has been determined from several experimental and theoretical studies [4,9–13], one can calculate the SPP for the ^{6}He+^{238}U, ^{6}He+^{209}Bi, and ^{6}He+^{64}Zn systems, for which the fusion excitation functions were already measured [6,7,14]. We did not perform calculations for the ^{6}He+^{208}Pb system, because in Ref. [8] the fusion cross sections were not available. To show the influence of the ^{6}He halo structure on the reaction mechanism, a comparison between fusion data taken with the projectiles ^{6}He and ^{4}He was used in the previously mentioned works. We also performed the calculation of the SPP for the ^{4}He projectile on ^{238}U, ^{209}Bi, and ^{64}Zn targets. Figure 1 compares the results of the SPP at $E_{\text{c.m.}} = 22$ MeV for the ^{4}He+^{238}U (dashed line) and ^{6}He+^{238}U (solid line) systems. The observed difference between the two potentials around the barrier radius ($R \approx 11$ fm) is mainly due to the characteristics of the ^{4}He nucleus, which has its two Fermi density parameters far from the systematic average values, contrary to the situation for the ^{6}He nucleus. It is important to observe in Fig. 1 that the potential diffuseness is much larger for the ^{6}He system, which should have a strong influence on the reaction mechanism. The dotted line in Fig. 1 shows that, even when a halo nucleus is involved, at energies around the Coulomb barrier, and around the barrier radius, the SPP for this system is essentially its double-folding part.

The aim of the present work is not to improve the CCC performed in Refs. [6,7,14]. Instead, to show the effect of the potential choice on the conclusions, we coupled the same channels as in those references. The following excited states were coupled: (a) for the ^{6}He projectile, the resonance state at the continuum at $E^* = 1.8$ MeV, with $\beta_2 = 0.90$ and $r_0 = 1.06$ fm; (b) for the ^{238}U target, $E^*(2^+, 4^+, 6^+, 8^+) = 0.049$, 0.148, 0.307, 0.518 MeV, respectively, and the $E(3^-) = 0.7319$ MeV, with the deformation parameters $\beta_2 = 0.37$ and $\beta_3 = 0.1213$, with $r_0 = 1.06$ fm; (c) for the ^{209}Bi target, $E(5/2^+) = 2.62$ MeV and $E(7/2^+) = 3.09$ MeV, with $\beta_3 = 0.153$ and $\beta_5 = 0.110$, with $r_0 = 1.06$ fm; and (d) for the ^{64}Zn target, $E^*(2^+) = 0.991$ MeV and $E^*(3^-) = 2.998$ MeV, with $\beta_2 = 0.333$ and $\beta_3 = 0.366$, with $r_0 = 1.06$ fm. We used the FRESCO code [15] in the CC calculations, with the SPP interaction supplied numerically. To show the sensitivity of the results with the spread of the Fermi density parameters around their corresponding average values, calculations were performed with the strength of SPP varied by ±10%. From now on, all theoretical results will be represented in this Brief Report by broad lines representing the regions covered by the variation of ±10% in the strength of the bare potential. For comparison purposes, we have first analyzed the fusion induced by the ^{4}He projectile on the same targets. We expected that the SPP could describe the fusion excitation functions of those systems.

The comparison of the SPP prediction and the ^{4}He+^{238}U fusion data [16] is shown in Fig. 2(a). The coupling scheme of the target states was already mentioned. The predictions slightly underestimate the data, but that can be understood, because the data are not for fusion cross sections but rather fission cross sections, which should be slightly larger than fusion, due to the presence of transfer channels.

In Fig. 2(b) we show the results of the SPP predictions for the ^{6}He+^{238}U system. In these calculations, the ^{6}He

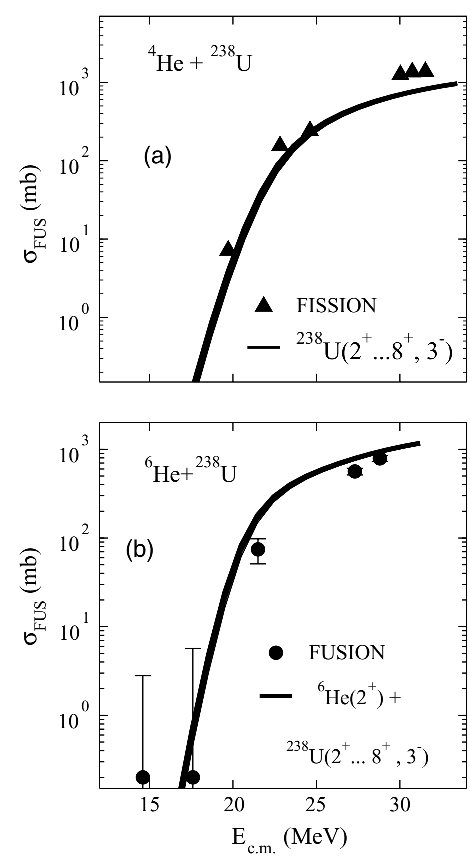

FIG. 2. Fusion excitation functions for (a) ^{4}He+^{238}U and (b) ^{6}He+^{238}U. The bands shown in the figure represent the region of variation of the theoretical cross section obtained when the strength of the optical potential is varied by ±10% relative to the standard SPP in the coupled-channels calculations.

resonance state was also considered. One can observe fusion cross-section suppression at energies above the barrier, whereas the behavior at sub-barrier energies is predicted by the SPP. The suppression factor of the fusion cross section is determined to be SF = 0.84 if one uses the usual strength of the SPP. If one reduces the SPP strength by 10%, which is within the uncertainty of the SPP, the suppression factor becomes SF = 0.86. Therefore, from the present analysis one observes a suppression of the fusion cross section for the ^{6}He-induced reaction of the order of 15%, similar to the values obtained for stable weakly bound nuclei. In the original work by Raabe *et al.* [7], CCCs were performed with a bare potential calculated by a double-folding procedure (M3Y). Results similar to those presented here for ^{4}He and ^{6}He were obtained, although the behavior of the fusion cross sections has not been explicitly explored in that article.

For the ^{6}He+^{209}Bi system [6,17–19], the coupling scheme included the resonance state of the projectile and excited states of the target mentioned above. The results are shown in Fig. 3. Figure 3(a) shows that the behavior of the ^{4}He + ^{209}Bi fusion excitation function is predicted by the SPP. In Fig. 3(b), for the ^{6}He + ^{209}Bi system, one can observe a behavior similar to that obtained for the ^{238}U target: fusion cross-section suppression at energies above the barrier, with SF = 0.81 for the usual SPP strength and SF = 0.83 if the strength is reduced by 10%; at sub-barrier energies the predictions are in agreement with the data. Kolata *et al.* [6] use the data above the barrier to derive

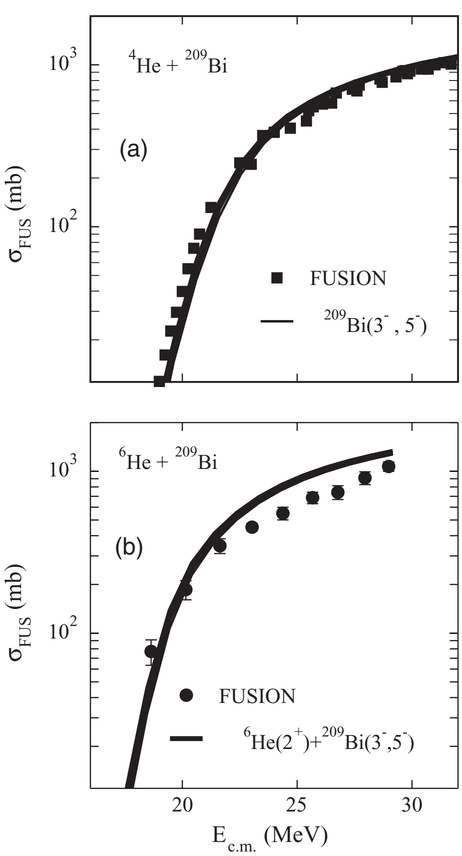

FIG. 3. The same as in Fig. 2 for (a) ^{4}He+^{209}Bi and (b) ^{6}He+^{209}Bi.

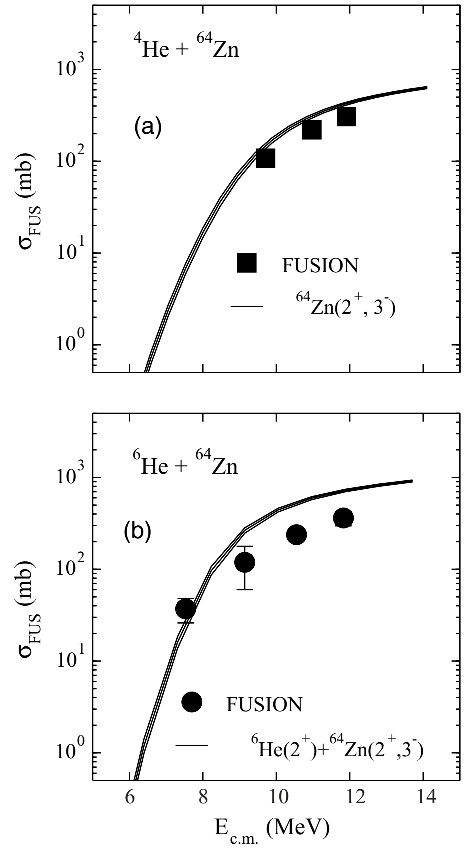

FIG. 4. The same as in Fig. 2 for (a) ^{4}He+^{64}Zn and (b) ^{6}He+^{64}Zn.

the barrier height and deduce that this value was reduced by around 5 MeV, compared with the average value for this mass region. They concluded that there is a large sub-barrier fusion enhancement for this system. This apparent disagreement between the sub-barrier fusion cross sections for the ^{6}He+^{209}Bi and ^{238}U systems does not exist in our present analysis.

For the light ^{64}Zn target [14], the results are shown in Fig. 4. The behavior of fusion in the ^{4}He+^{64}Zn system is well predicted by the SPP, whereas a large fusion suppression is found for the ^{6}He+^{64}Zn system, corresponding to a suppression factor SF = 0.53. At sub-barrier energies, there is no enhancement of the fusion cross section. Di Pietro *et al.* [14] made no comparison with calculations, because the potentials that fit the fusion and elastic-scattering data are not compatible. The large suppression for the ^{6}He+^{6}4Zn system might be due to the experimental method for the derivation of the fusion cross section. The experimental fusion cross sections were largely contaminated by the one- and two-neutron transfer channels. As the authors used theoretical predictions of the code CASCADE to eliminate these channels, their resulting cross sections may correspond to a lower limit of the cross sections. So, a more definitive conclusion in this system should wait for new experimental data.

We have used the SPP to analyze fusion induced by the radioactive halo projectile ^{6}He. The most striking result that comes from our analysis of the fusion cross section induced by ^{6}He is the very similar behavior of the ^{6}He+^{238}U, ^{209}Bi, and ^{64}Zn systems, both above and below the Coulomb barrier. For the two heavier systems, no sub-barrier fusion enhancement is observed and a hindrance of about 15% is found at above-barrier energies. It should be stressed that similar fusion suppression factors were found for fusion induced by the stable weakly bound nuclei, ^{6,7}Li and ^{9}Be [3,20–22]. This hindrance of the fusion cross section is believed to be due to the effect of the breakup process, which produces a strong coupling between the elastic channel and the continuum states. At sub-barrier energies, there is no enhancement of the fusion cross sections, probably due to competition between breakup and other effects that may enhance fusion, as occurs for tightly bound projectiles. Our results are in agreement with the three-body calculations performed by Yabana *et al*. [23] for the ^{11}Be+^{208}Pb system. Hence, we have established a very coherent and systematic behavior for fusion induced by both stable and radioactive weakly bound nuclei. For the ^{6}He+^{238}U system, our results agree with those obtained from Raabe's analysis [7], which also used a bare potential calculated by a double-folding procedure (M3Y). However, our results for the ^{6}He+^{209}Bi system disagree with Kolata's analysis [6], where the bare potential was deduced from a BPM fit to the highest-energy data.

In conclusion, we believe that to analyze fusion data for systems involving stable and radioactive nuclei taken around the Coulomb barrier, one needs to use a bare potential obtained from procedures based on fundamental principles, such as double-folding methods. However, to do that for radioactive nuclei, it is necessary to know (at least) the ground-state density of the radioactive nucleus involved.

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