# Interaction distances for weakly bound nuclei at near barrier energies

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Interaction distances were estimated for the weakly bound systems $^{6}$Li and $^{7}$Li, from elastic scattering data, as a function of energy in the vicinity of the barrier and as a function of target mass number. For comparison purposes, such distances were also estimated for some stable systems. It was found that interaction distances vary appreciably between stable and weakly bound projectiles while depending strongly on target mass number. The implications to calculations of the potential in the vicinity of the barrier are discussed.

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In the past decade the development of radioactive beam facilities gave an unprecedented boost in nuclear physics, since the rapid increase in the number of nuclei led to the discovery of phenomena that were previously unexpected [1–3]. In view of the similarities of weakly bound stable systems with their associate weakly bound radioactive ones, studies with weakly bound but stable nuclei are of critical importance as they can indicate trends and give initiatives for studies with nuclei near the drip line [4]. One of the very many problems which are found by using stable beams of weakly bound species is that of the potential threshold anomaly [5–8,10–17]. The term “threshold anomaly” [18,19] was invoked to describe for stable encounters the rapid energy variation of the real and imaginary part of the potential in the region around the Coulomb barrier, which is visualized as a peak in the real part associated with a sharp decrease in the strength of the imaginary potential. For weakly bound systems the situation, which has been recently outlined in Refs. [7–9], is, however, more complicated.

The obtained quantities of the above studies is the energy variation of the potential in the vicinity of the barrier. It is customary to obtain such quantities at the strong absorption radius. As it is discussed, however, in Ref. [9], the radial region of sensitivity may change with bombarding energy for lighter systems. Additionally the definition of the strong absorption radius is not straightforward for weakly bound systems. As it is pointed out in Refs. [4,20,21], the interaction distance of closest approach for the systems $^{6}$He+$^{208}$Pb and $^{6,7}$Li+$^{28}$Si is ~2.2 fm instead of ~1.65 fm, a value which has been obtained for several stable systems [21,22]. The importance of knowing well the interaction distance is demonstrated in Fig. 1, where we present the real and imaginary potential as a function of energy into a CDCC (continuum discretized-coupled-channel) framework [8] for the system $^{6}$Li+$^{28}$Si at various distances. In the same figure, previous data [7] obtained via the analysis of elastic scattering data in a double-folding framework are presented and compared with the calculations. It has to be noted, however, that the data originate as the best fit normalization factors (details of the fits are given in Ref. [7]) of the real and imaginary part of the potential, adopting a BDM3Y1 interaction [23], while the CDCC calculations are obtained at certain distances *d*. The variation of the energy functional dependence of the calculated potential with the distance *d* makes obvious that in order to make meaningful comparisons between theory and experiment and vice versa and, moreover, to be able to probe safely the threshold anomaly, we need to know well enough the interaction distance.

Into this context we report herewith the estimation of reduced interaction distances for weakly bound systems in comparison with stable systems as a function of energy and target mass number. For that, previous elastic scattering data [12,16,7,24–26] concerning the systems $^{6,7}$Li+($^{208}$Pb, $^{138}$Ba, $^{118}$Sn, $^{28}$Si), $^{12}$C+($^{209}$Bi, $^{28}$Si), ($^{9}$Be, $^{14}$N, $^{16}$O)+$^{28}$Si, and $^{6}$He+$^{209}$Bi were plotted as a function of the reduced distance *d*, which is defined as follows:

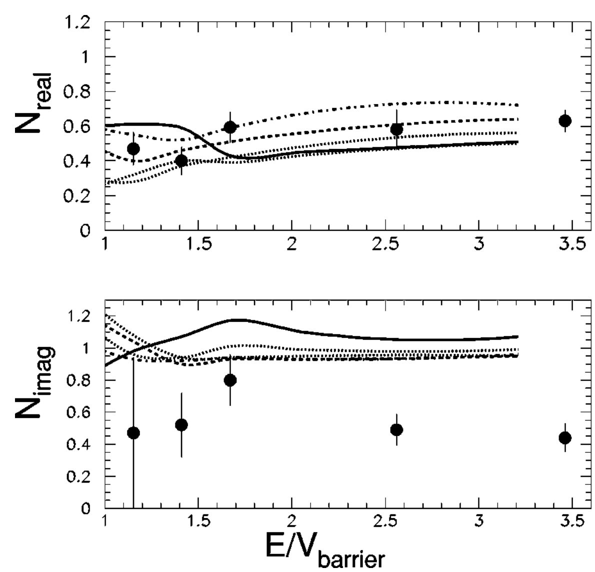


FIG. 1. Optical potential for the system $^{6}$Li+$^{28}$Si. The data designated with solid circles are from Ref. [6] and originate as the best fit normalization factors of the real and imaginary part of the potential in a double-folding framework by using a BDM3Y1 interaction. The calculations were made in a CDCC framework and ratios of $V_{eff}/V_{bare}$ were obtained at distances $D$=7.8 fm (solid line), 8.7 fm and 9.7 fm (dotted line), 10.6 fm (dashed line), and 11.6 fm (dotted-dashed line) corresponding to interaction reduced distances $d$=1.6, 1.8, 2, 2.2, and 2.4 fm $[D=d(A_1^{1/3}+A_2^{1/3})]$.

 

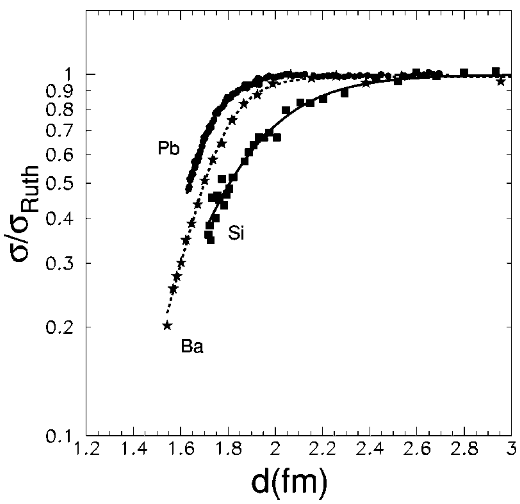


FIG. 2. Ratios of elastic scattering cross sections over Rutherford scattering, as a function of the reduced distance $d$ for the systems $^{6}Li+(^{208}Pb,^{138}Ba,^{28}Si)$ at 29, 24, and 9 MeV correspondingly. The angular distribution data are from Refs. [11,16,6].

$$D = d(A_1^{1/3} + A_2^{1/3}) = \frac{1}{2}D_0\left(1 + \frac{1}{\sin(\theta/2)}\right) \quad (1)$$

with

$$D_0 = \frac{Z_1 Z_2 e^2}{E_{\mathrm{c.m.}}} \quad (2)$$

the interaction distance of closest approach for a head on collision. As an example to our analysis, we present in Fig. 2, elastic scattering data for the systems $^{6}Li+(^{208}Pb,^{138}Ba,^{28}Si)$ at 29, 24, and 9 MeV, correspondingly, as a function of the distance $d$. In order to deduce the reduced interaction distance in a systematic way, the data are fitted with the same exponential growth function of Boltzmann type

$$y = \frac{A_1 - A_2}{1 + e^{(x-x_0)/dx}} + A_2, \quad (3)$$

where $y$ and $x$ are the ratio of cross sections over Rutherford and the reduced distance, correspondingly, and $A_1$, $A_2$, $x_0$, and $dx$ are adjustable parameters.

As it is expected for reduced distances of closest approach $d > d_s$ (where $d_s$ is a critical interaction distance), the projectile is scattered at the Coulomb scattering angle without being influenced by nuclear forces. On the other hand, as $d$ becomes smaller than $d_s$ the projectile starts to experience the nuclear force and due to absorption the ratio $\sigma/\sigma_{\mathrm{Ruth}}$ drops off unity. We define in this work the critical interaction distance at which the nuclear interaction switches on, the reduced distance $d_s$ at which the above ratio drops to 97% of the maximum, that is at a value well off the maximum taking into account the experimental errors. Also this value was chosen by taking into account that in that way we obtain similar results studying the same systems as the authors of Ref. [21] who adopt a method proposed by Christensen *et al.* [22]. In this respect we estimate the reduced interaction distance, for all the above systems and several energies in the vicinity of the barrier, where the ion moves primarily along a Coulomb trajectory. Data treated in that way are presented in Figs. 3–5. The following interesting features are observed through the plots. The reduced distance strongly depends on the mass number of the target for stable as well as weakly bound stable projectiles. This is an unexpected result which may either imply that the interaction distance does not follow the usual $A^{1/3}$ dependence or that for lighter targets the projectile is able to feel earlier (at larger distances) the nuclear interaction since the Coulomb potential is smaller than the one presented by the heavier targets and does not overbalance the nuclear potential. The argument of the first case, however, if we exclude the data for $^{6,7}Li+^{58}Ni$, stems mainly from data taken by using a $^{28}Si$ target or a $^{12}C$ projectile but these are rather deformed nuclei. Therefore further clarification is needed on that matter by studying systems which involve deformed and spherical targets and/or projectile as long as new data appear for a comprehensive analysis. Justification can be further obtained with the combination of elastic scattering data and fusion data but the last ones does not exist for the moment for the systems $^{6,7}Li+^{28}Si$. This variation of the reduced distance on target mass number seen in the present work is obvious in Fig. 3 for the weakly bound nuclei $^{6,7}Li$ and in Fig. 4 (left part) for the stable nucleus $^{12}C$. In both cases differences between reduced distances for the heavier (Pb, Bi) to the lighter targets (Si) scale by a factor of ~1.3. The dependence on the mass number of the projectile is weaker and can be seen in Fig. 3 for the scattering of $^{6}Li$ and $^{7}Li$ on the same targets Pb, Ba, Sn, Ni, and Si and in Fig. 4 (right), for the scattering of $^{12}C$, $^{14}N$, and $^{16}O$ on Si. The most interesting feature, however, that we would like to

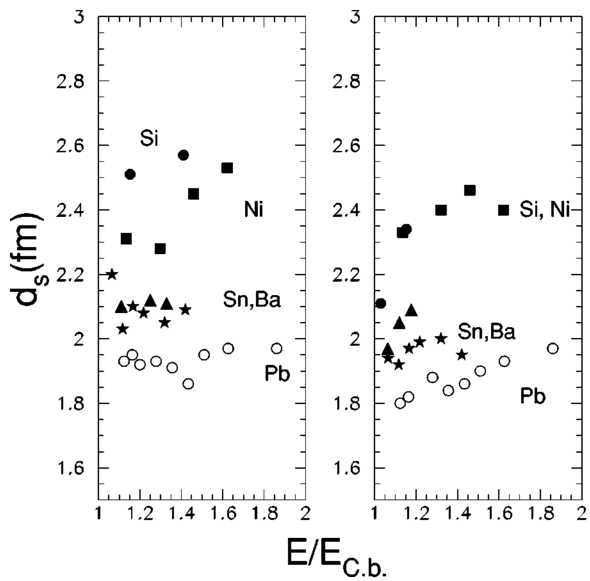


FIG. 3. Interaction distances as a function of energy over the Coulomb barrier for the systems (left plot) $^{6}Li+^{208}Pb$ (open circles), $^{6}Li+^{138}Ba$ (solid stars), $^{6}Li+^{118}Sn$ (solid triangles), $^{6}Li+^{58}Ni$ (solid boxes) and $^{6}Li+^{28}Si$ (solid circles). Right plot, same as left but where the projectile is $^{7}Li$. Coulomb barriers in the laboratory were taken as 25.8, 19.8, 18, 12.3, and 7.8 MeV for the above systems, correspondingly.

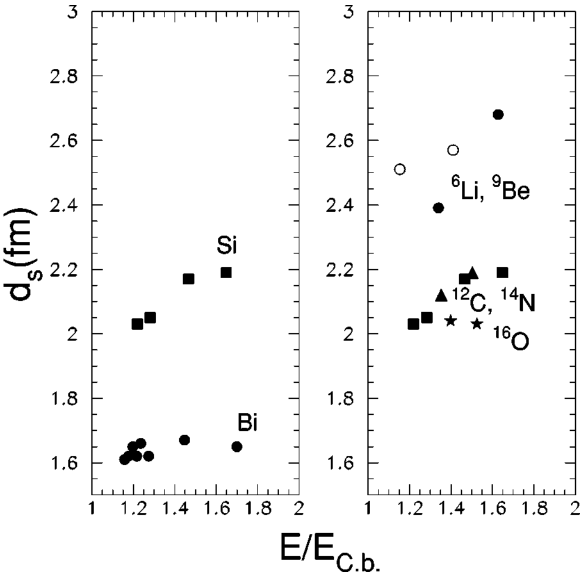


FIG. 4. Interaction distances as a function of energy over the Coulomb barrier for the systems (left plot) $^{12}C+^{209}Bi$ (solid circles) and $^{12}C+^{28}Si$ (solid boxes). Coulomb barriers in the laboratory were taken as 51.7 and 16.4 MeV for the above systems, correspondingly. In the right plot appear the systems $^{6}Li+^{28}Si$ (open circles), $^{9}Be+^{28}Si$ (solid circles), $^{12}C+^{28}Si$ (solid boxes), $^{14}N+^{28}Si$ (solid triangles), and $^{16}O+^{28}Si$ (solid stars). The Coulomb barriers in the laboratory were taken as 7.8, 10.4, 16.4, 20, and 23.6 MeV for the above systems, correspondingly.

stress here is the fact that the reduced interaction distance for weakly bound projectiles is much larger than that of the stable ones on the same target. This feature is more obvious in Fig. 5 where we compare reduced distances for three projectiles on a heavy target, either Pb or Bi. This distance for the stable nucleus carbon to Bi is ~1.6, a value which has to be compared with the one of ~1.9 for $^{6}$Li to Pb and ~2.2 for the weakly bound halo nucleus $^{6}$He to Bi. This is not an unexpected result, since the overlap between the density distributions of the interacting nuclei occurs at larger distances due to the extended distribution of weakly bound systems. Finally, an energy dependence is not obvious for scattering of stable and weakly bound projectiles on heavy targets in the vicinity of the barrier but an increasing trend is established for the scattering on lighter target systems.

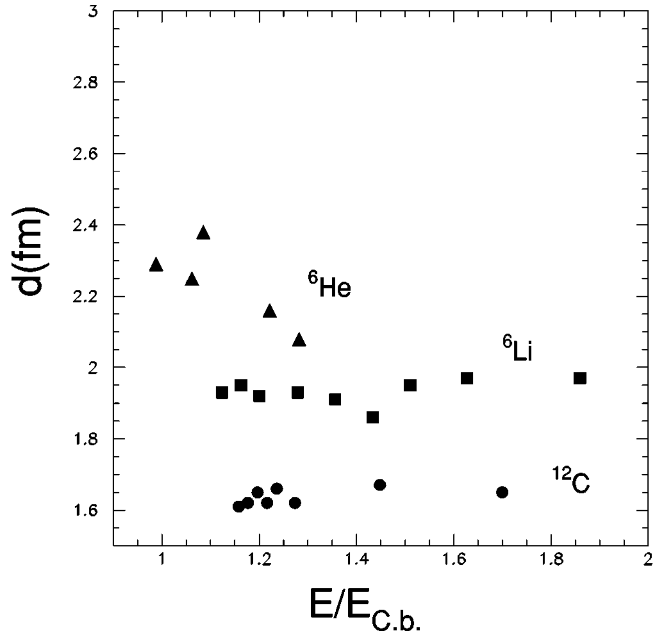


FIG. 5. Interaction distances as a function of energy over the Coulomb barrier for the systems $^{12}C+^{209}Bi$ (solid circles), $^{6}Li+^{208}Pb$ (solid boxes), and $^{6}He+^{209}Bi$ (solid triangles). Coulomb barriers in the laboratory were taken as 52.7, 25.8, and 17.5 MeV for the above systems, correspondingly.

Reduced interaction distances were estimated for weakly bound and stable nuclei elastically scattered from heavy and light-heavy stable targets at near barrier energies. It was found that a strong target mass dependence persists both for stable as well as weakly bound stable nuclei and weakly bound radioactive ones. A weak energy dependence occurs only for the lighter targets. Moreover, the point, which we intend to underline in this work, is the differentiation of interaction distances between weakly bound and stable projectiles on the same target. Under these circumstances calculations of the potential at the strong absorption radius in order to probe the phenomenon of threshold anomaly have to be made with caution.

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