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Fusion, break-up and scattering of weakly bound nuclei

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We discuss the influence of the break-up process of stable weakly bound nuclei on the fusion cross section and on the elastic scattering at near barrier energies. The complete fusion for heavy targets is found to be suppressed at energies above the barrier, whereas this effect is negligible for light targets. The total fusion cross sections are not affected by the break-up process. The non capture break-up is the dominant process at sub-barrier energies, with significant cross sections also at energies close and above the Coulomb barrier. We also show that the break-up process is responsible for the vanishing of the usual threshold anomaly of the optical potential and give rise to a new type of anomaly, named break-up threshold anomaly (BTA).

Keywords: Break-up process; fusion cross sections; break-up threshold anomaly.

Se discute la influencia del proceso de ruptura de núcleos estables débilmente enlazados en la sección eficaz de fusión y en la dispersión elástica a energías próximas a la de la barrera de Coulomb. La sección eficaz de fusión completa para blancos pesados es suprimida para energías superiores a la de la barrera de Coulomb, mientras que este efecto es despreciable para blancos ligeros. La sección eficaz de fusión total no es afectada por el proceso de ruptura. El proceso de ruptura sin captura de residuos es el proceso dominate a energías inferiores a la de la barrera, con secciones eficaces considerables también para energías del orden de la barrera de Coulomb y supeiores. Mostramos además, que el proceso de ruptura es el responsable por la ausencia de la anomalía de umbral usual del potencial óptico y conlleva a un nuevo tipo de anomalía, llamado anomalía de umbral de ruptura (BTA).

Descriptores: Proceso de ruptura; sección eficaz de fusión; anomalía de umbral de ruptura.

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1. Introduction

The fusion process between heavy ions at energies near and below the Coulomb barrier has been extensively studied during the last four decades. During the 60's and 70's most of the investigations were concerned with the fusion at energies above the barrier. At energies not too much above the barrier, the so-called "Region I", the fusion process was found to be responsible for most of the reaction cross section, and the fusion cross section is geometrical in nature. At higher energies, the so-called "Region II", non fusion processes like deep inelastic collisions and breakup of the projectile compete strongly with fusion, decreasing the fraction of the reaction cross section corresponding to fusion, that becomes saturated. A widely used model that describes the fusion in regions I and II was developed by Glas and Mosel [1]. In these regions, barrier penetration models describe properly the experimental results. At energies below the Coulomb barrier, tunneling through the barrier has to occur in order to allow the fusion of the two nuclei. Since the end of the 70's [2] the fusion process has been studied at this energy regime, where there is a strong interplay between different reaction mechanisms that influence the fusion process, as well as the nuclear structure of the colliding nuclei. Different approaches have been used in the study of sub-barrier fusion [3], such as macroscopic degrees of freedom (deformation, surface vibrations, neck formation), coupled channels calculations, including inelastic excitations and transfer channels, and polarization potentials. A huge enhancement of the sub-barrier fusion cross section, when compared with one dimensional barrier penetration models, is found in a wide number of systems. Several review articles concerned with the sub-barrier fusion enhancement have been published [4–6].

The elastic scattering of heavy ions at near barrier energies usually shows an anomalous behavior of the energy dependence of the real and imaginary parts of the optical potential, known as threshold anomaly [7, 8]. This anomaly shows up as a localized peak of the real part and the decreasing of the imaginary part of the potential, in the neighborhood of the Coulomb barrier. It may be ascribed mainly to the coupling of the elastic and other reaction channels. There is a correlation between the real and imaginary parts of the potential due to causality and consequently they obey the dispersion relation [9].

More recently, due to the availability of beams of very weakly bound radioactive nuclei, widespread theoretical and experimental efforts have been devoted to understanding the influence of break-up of weakly bound nuclei on fusion cross sections [10]. Fusion of weakly bound nuclei differs in a fundamental way from that of tightly bound ones, since the break-up of weakly bound nuclei at energies close to the Coulomb barrier produces a strong coupling between the elastic channel and the continuum states representing the break-up channel, and therefore may reduce the fusion cross section at this regime, whereas for tightly bound nuclei this effect is felt only at higher energies (region II).

There is special interest in this subject, since reactions of astrophysical interest and leading to the production of nuclei near the drip lines are induced by very weakly bound and exotic radioactive nuclei.

Due to the low intensities of the radioactive beams, it is very convenient to produce fusion reactions with the high intensity stable beams that are weakly bound, and consequently should have a significant break-up probability. The suitable stable nuclei for this kind of study are ^{9}Be, ^{6}Li and ^{7}Li , due to their small separation energies (from 1.48 to 2.45 MeV). A full understanding of the fusion and BU processes induced by stable weakly bound projectiles is an essential step for the study of the fusion induced by radioactive beams. Most of the essential features of the importance of the break-up channel on fusion are present in both cases, although, contrary to halo nuclei, stable weakly bound nuclei do not present the very long range of the nuclear potential, with the possible lowering of the fusion barrier, and couplings to the soft dipole resonance.

2. Reaction mechanisms induced by weakly bound nuclei and theoretical challenges

Theoretically there have been conflicting predictions on whether the fusion cross sections of weakly bound nuclei are enhanced or hindered at low energies owing to the strong coupling to the break-up channel . It has been suggested [11–15] a fusion cross section enhancement when compared with the fusion induced by strongly bound nuclei, due to the presence of low lying weakly-bound or unbound states. However, it was later realized that this excitation is followed by the break-up process that produces strong couplings between the elastic channel and the continuum states which may erase the enhancement and can, therefore, inhibit the fusion cross section [16–19] when compared with one dimensional barrier penetration models, due to the loss of incident flux in this channel caused by the break-up.

So, the coupling between the relative motion and intrinsic degrees of freedom of the interacting nuclei may enhance the fusion cross section relative to one-dimensional potential predictions, or the break-up of the weakly bound nucleus before reaching the fusion barrier may inhibit it by the absorption of flux that would otherwise go to fusion. In order to have a comprehensive picture of this problem, one has to study different energy regimes, from the sub-barrier to above barrier energies and also one has to span different nuclear masses, in order to investigate the effect, on the fusion, of nuclear and Coulomb break-ups.

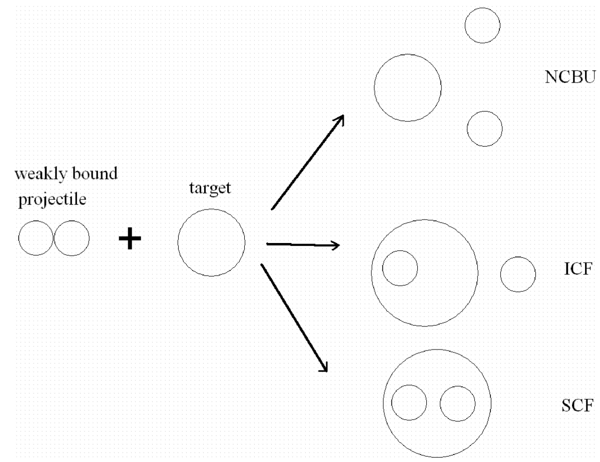

FIGURE 1. Cartoon of the reaction mechanism following the break-up of weakly bound projectiles.

In the study of this subject, several reaction mechanisms should be considered, in addition to the usual direct complete fusion (DCF), transfer and inelastic excitations. In Fig. 1 we show typical reaction mechanisms following the break-up of weakly bound projectiles: non-capture break-up (NCBU), when neither of the break-up fragments is captured by the target; incomplete fusion (ICF), when one of the break-up fragments is captured by the target; sequential complete fusion (SCF), when break-up occurs followed by the successive capture of all the fragments by the target. So, the total break-up cross section is the sum of these three contributions. Complete fusion (CF) is the sum of DCF and SCF, whereas the sum of CF and ICF is called total fusion (TF). The break-up of ^{9}Be is even more complex than that, since fragmentation of ^{9}Be into ^{8}Be + n is not the only possible ^{9}Be break-up mechanism. The unstable ^{8}Be, with a half-life of 0.7 fs, breaks-up into two alpha particles. The ^{9}Be itself may undergo a prompt break-up process ^{9}Be $\rightarrow \alpha + \alpha +$ n or breaks-up into α + ^{5}He.

Therefore, in the study of the influence of the break-up on the fusion cross section, calculations have to be performed by considering bound-continuum state couplings, with resonance or non-resonance states and continuum-continuum couplings. Coulomb and nuclear excitations have to be considered, as well as their coherent interferences. In order to account for CF and ICF, a three body theory with absorption has to be developed. As so far there is no such complete theoretical study, different approaches using approximate schemes are used. The break-up channel is described by the continuum discretized coupled channel method (CDCC) [18, 19]. By this method, the continuum is discretized into bins, which does not allow the evaluation of the contribution from the SCF and leads to inaccurate ICF cross sections. Other schematic calculations use concepts of semiclassical trajectories, survival probabilities and dynamic polarization potentials.

Among the questions on this subject that have to be answered, one finds: What are the values of σ_{NCBU} for different energy regimes, target masses and threshold break-up energies? Does the break-up affect the fusion cross section or just increase the reaction cross section? If it affects the fusion process, does it enhance or suppress the fusion cross section at different energy regimes and target masses? Is the effect on the complete fusion or total fusion?

3. Experimental difficulties and methods

Experimentally, it is impossible to discriminate the SCF from the usual DCF. Also, it is not easy to separate complete and incomplete fusion processes. Usually the emitted evaporation residues following these processes are very similar or identical, and therefore the direct identification of residues is not able to distinguish them. This similarity is even more evident for light systems for which the main evaporation channels include charged particles. This is the reason why most of the available data in the literature correspond to TF cross sections, obtained by time of flight or gamma ray spectroscopy methods [20–28], although the main interest is in the behavior of the CF cross section.

There are some measurements of CF and ICF separately, as for example [29–34]. The separation between CF and ICF in reactions involving stable weakly bound projectiles and heavy targets (^{209}Bi and ^{208}Pb) can be obtained because the compound nuclei decay by alpha emission and the characteristic energies and half-lives of the emitted alpha particles may be used to unambiguously identify the evaporation residues [29–32]. For the ^{9}Be + ^{144}Sm system, the delayed X-ray technique was used, since the residues of the compound nucleus decay by electron capture and can be separated from the one produced by the ICF [33, 34].

The measurement of σ_{NCBU} cross sections requires exclusive experiments. Coincidences between alpha particle and deuteron or tritium are used to derive break-up cross sections of ^{6}Li and ^{7}Li, respectively. The measurement of ^{9}Be break-up cross sections is more complicated, since ^{8}Be decays into two alpha particles. An indirect way to estimate σ_{NCBU} is to subtract total fusion and other direct reaction

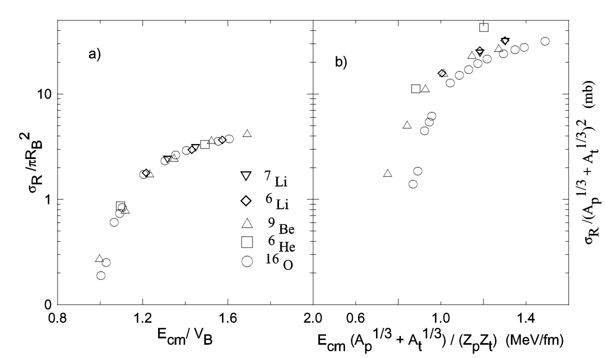

FIGURE 2. Reduced reaction cross sections for the systems consisting of different projectiles on the same ^{64}Zn target. (a) using the usual reduction procedure dividing σ by πR_B^2 and E_{cm} by V_B. (b) using the prescription described in the text and proposed by Gomes *et al.* [35].

cross sections from the derived total reaction cross section, obtained from elastic scattering measurements [24,27,28,34].

4. Difficulties in the interpretation of fusion data

We would like to mention two difficulties associated with the interpretation of the fusion data that may lead to misinterpretation of the effect of the break-up on the fusion of weakly bound nuclei. The first is concerned with the comparison of different systems in the same figure. The second is related with the choice of potential to be used when one wants to compare the data with theoretical predictions.

Since the early 80's, several works on sub-barrier fusion adopted the procedure of eliminating the geometrical factors concerning different systems by "reducing" the cross section and the center of mass energy. This reduction consists of the division of the cross section by πR_B^2 and the energy by V_B, where the barrier parameters were extracted from the fusion data at the well known "region I". The same procedure has been widely used in the study of systems with weakly bound nuclei, including halo nuclei, but this can lead to important misinterpretation of the results, since these nuclei have abnormally large radii and consequently have barrier heights that do not follow the rules and systematics of tightly bound nuclei. In Ref. 35, it was shown that the usual procedure washes out the effect of the weakly bound nuclei, as can be seen in figure 2a for the reaction cross sections for the ^{6}He, ^{6}Li, ^{7}Li, ^{9}Be and ^{16}O projectiles on the same ^{64}Zn target. In Ref. 35 it is proposed an alternative "reducing procedure", by dividing the cross sections by $(A_p^{1/3} + A_T^{1/3})^2$ and the center of mass energy by $Z_p Z_T / (A_p^{1/3} + A_T^{1/3})$. In this way the normal geometrical effects are removed and the eventual unusual values of the reduced radii are not washed out. The results of this procedure for the same systems mentioned above are shown in Fig. 2b. Here one can notice that the reduced reaction cross section is largest for the very weakly bound ^{6}He projectile, followed by the three stable less weakly bound projectiles and finally the smallest reduced reaction cross section is found for the tighly bound ^{16}O projectile, where no break-up at this energy regime is expected. This result is compatible with the concept that the smaller the threshold break-up energy, the larger the reaction cross section. Usually, experimental fusion excitation functions, both above and below the Coulomb barrier, are compared with results of theoretical coupled channel calculations. However, a critical point when one wants to compare fusion data with theory is the choice of the bare potential to be adopted. Depending on its characteristics, the conclusions concerning the effect of the break-up on the fusion may be rather different. In this sense, it is very useful the experimental derivation of the fusion barrier distribution (BD) that acts as a strong constraint to the potential parameters, since the potential should match the barrier height and shape of the BD. When BD is not available, as it happens with all available data concerning fusion of radioactive beams, it is often used a "reasonable" potential, that however might not be appropriate. Recently [36] it was shown that the parameter-free double folding non-local São Paulo potential (SPP) [37–39] is a reliable potential for studying fusion of systems involving stable weakly bound nuclei in situations in which experimental barrier distributions cannot be obtained. The SPP predictions for the fusion cross sections and BD for three systems involving stable weakly bound nuclei (^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb) coincided with those obtained from coupled channel calculations adopting potentials that matched the BD and lead to the same suppression factors of the CF cross sections reported for those systems [29–31]. In the three cases of weakly bound nuclei, the predictions overestimate the data. Then, it was found suppression factors that multiplied by the theoretical results reproduce the average behavior of the data. Figure 3 shows the theoretical fusion excitation function and barrier distribution obtained with the SPP compared to the data, for the ^{9}Be + ^{208}Pb system. The dotted and dashed lines correspond to the theoretical results obtained within BPM and CC calculations, respectively. The solid lines correspond to the CC calculations multiplied by the suppression factor (SF) values. Very good agreement is obtained for all systems. So, it was shown that the SPP can be used as a reliable bare potential for systems involving weakly bound nuclei. It is a trustful alternative to the difficult procedure of obtaining experimental barrier distributions that requires precise and high statistics measurements. These measurements are not yet available for experiments with radioactive beams and present great experimental difficulties even when high intensity stable beams are used.

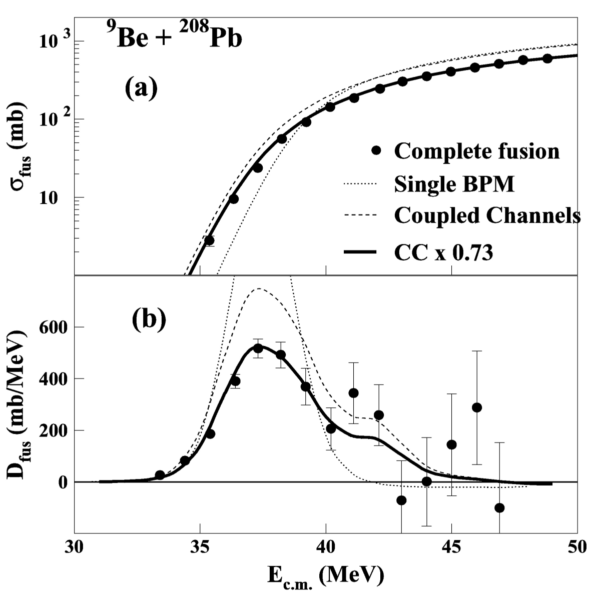

FIGURE 3. Fusion cross section data. (a) and experimental barrier distributions (b) for the system ^{9}Be + ^{208}Pb. The dotted and dashed curves correspond to theoretical results obtained with the SPP within the BPM and CC calculations, respectively. The solid curves represent the CC results multiplied by the suppression value.

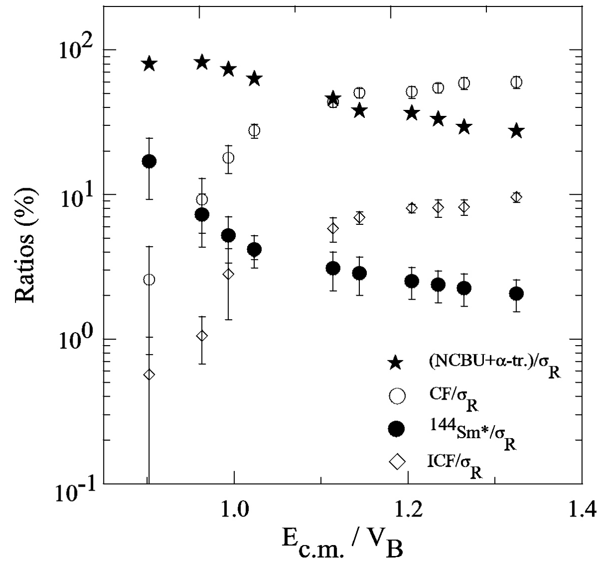

FIGURE 4. Ratios between measured and estimated cross sections and the reaction cross sections as function of reduced energy for the ^{9}Be + ^{144}Sm system.

5. Experimental results and present understanding of fusion and break-up processes

We have investigated the effect of break-up of stable weakly bound projectiles on heavy medium and light mass targets, at energies above and slightly below the Coulomb barrier. The systems studied were ^{9}Be + ^{208}Pb, ^{6,7}Li + ^{209}Bi, ^{9}Be + ^{144}Sm, ^{6,7}Li, ^{9}Be + ^{64}Zn, ^{27}Al. Other systems involving tightly bound projectiles on the same target or leading to the same compound nuclei were also investigated, in order to compare fusion cross sections. Reaction cross sections were derived from elastic scattering for most of these systems, and therefore σ_{NCBU} were estimated. The collaborative experiments were performed at the Australian National University-ANU, at the Laboratorio TANDAR, Argentina and at the University of São Paulo-USP, Brazil.

The ^{6,7}Li + ^{209}Bi and ^{9}Be + ^{208}Pb fission, CF and ICF cross sections were determined separately at ANU, by the measurement of on-line and off-line alpha particles [29–31]. Fusion barrier distributions were also derived. For the three systems, CC calculations including bound excited states, without the inclusion of any projectile break-up effect, predict larger values than the experimental ones at above barrier energies. Agreement between the measured and calculated σ_{CF} at high energies and the barrier distributions can only be obtained if the calculated cross sections are scaled by factors equal to 0.66 for ^{6}Li, 0.74 for ^{7}Li and 0.68 for ^{9}Be. The σ_{ICF} were measured for the three systems, and were found to be important in the whole energy range studied. The TF excitation functions for the three systems have similar behaviors and agree with the predictions of CC calculations [32], indicating that TF are not affected by the break-up process. The conclusions are that the ICF process is the responsible for the σ_{CF} suppression.

The ^{9}Be + ^{144}Sm CF, ICF, inelastic and reaction cross sections (σ_R) were determined separately at TANDAR [34]. Fusion was measured by the off-line X-ray method [33]. The same kind of CC calculations as for ^{209}Bi and ^{208}Pb targets were performed for the CF, ICF and TF excitation functions. The agreement between CF data and calculations at high energies can only be obtained if the calculated cross sections are scaled by a factor 0.90. The σ_{TF} is, as before, well described by the calculations. Therefore, the results for this system agree qualitatively with the previous ones, although the σ_{ICF} cross section and the CF suppression factors are much smaller. Figure 4 shows percentual contributions to the reaction cross section of different reaction mechanisms measured or derived for the ^{9}Be + ^{144}Sm system. One can observe that the NCBU is the process with largest cross section at low energies, and it accounts for most of σ_R at this energy regime. This process is also relatively important at high energies, contributing to enhance σ_R.

For medium and light mass systems it is very difficult or even impossible to separate the measurement of CF and ICF, since both processes usually lead to similar or the same residual nuclei. The gamma-ray spectroscopy method, however, may allow to infer the separation between both processes in some particular systems. σ_{TF} of ^{6,7}Li + ^{64}Zn, ^{27}Al and ^{9}Be + ^{27}Al were measured at the TANDAR by the time of flight method [22–28]. The fusion of ^{9}Be + ^{64}Zn was measured at USP by the in-beam and off-beam gamma ray spectroscopy methods [20, 21], when the derived σ_{ICF} for this system was much smaller than 10% of σ_{CF}. Elastic scattering experiments for ^{6,7}Li and ^{9}Be on ^{64}Zn and ^{27}Al were also performed at USP [20,27,41], allowing the derivation of σ_R. The fusion excitation functions, expected to correspond to CF for these systems, are not influenced by the break-up process. As discussed above, in Figure 2b is shown that the smaller the break-up threshold the larger the reaction cross section of different projectile impinging on ^{64}Zn [24]. Similar results were obtained for the ^{27}Al target. Therefore, although σ_{CF} for light systems are not affected by the BU, this process does increase σ_R. The elastic scattering data for the ^{6}He + ^{27}Al system obtained at São Paulo, not yet published, are the first measurements performed with radioactive beams in the South Hemisphere. The inverse reaction ^{12}C + ^{7}Li was studied at ANU and confirms that there is no TF suppression for light systems [40].

6. Elastic scattering and the break-up threshold anomaly

As already mentioned in this paper, the elastic scattering of tightly bound heavy nuclei at near barrier energies usually shows an anomalous behavior of the energy dependence of the real and imaginary parts of the optical potential, known as threshold anomaly (TA). Therefore, at near barrier energies, folding and phenomenological nuclear potentials that describe the elastic scattering are no longer slowly energy dependent, as they are at high energies, due to the strong coupling between reaction channels, that produces an attractive polarization potential ΔV, leading to the real potential $V_{eff} = V_{bare} + \Delta V$, where V_{bare} is the real potential at high energies. As the bombarding energy decreases and approaches the Coulomb barrier, reaction channels are closed and the strength of the imaginary potential decreases towards zero.

The situation is different when one is dealing with weakly bound nuclei, due to the strong coupling to the break-up process, that has cross section much larger than the fusion cross section at sub-barrier energies. For the scattering of these nuclei, it is expected that the TA may no longer be present, due to the repulsive polarization potential produced by the coupling of the break-up to continuum states, that compensates the attractive polarization potential arising from couplings to bound states. For these nuclei, the rapid decrease of the fusion cross section at sub-barrier energies does not mean that the main reaction channels are closing down at this regime. The analyses of the optical model parameters for the elastic scattering of ^{6}Li + ^{138}Ba [42] and ^{9}Be + ^{64}Zn [20] show the vanishing of the usual TA. Actually, for the scattering of the

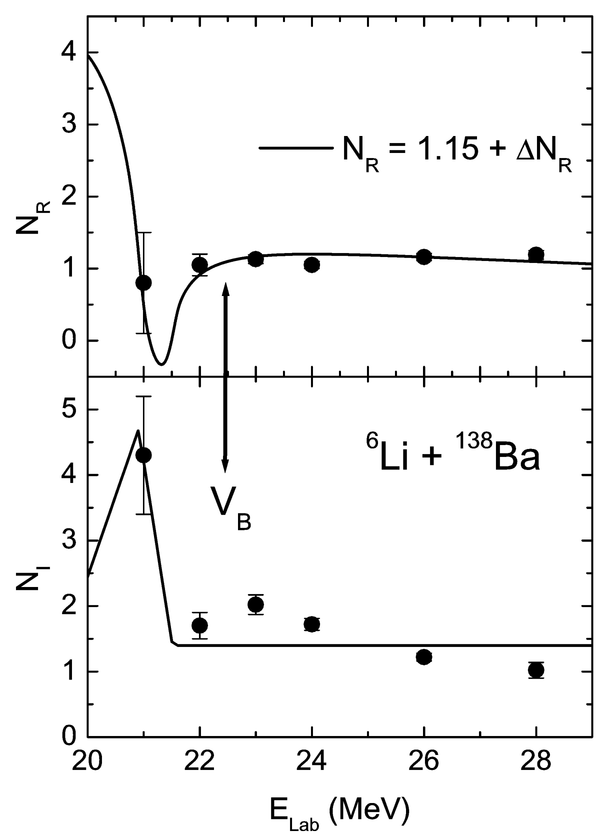

FIGURE 5. Energy dependence of the normalization factors N_R and N_I of the real and imaginary parts of the SPP for the ^{6}Li + ^{138}Ba system. The lines are compatible with dispersion relations.

weakly bound projectiles there is a dramatic deviation of the energy dependence of the optical model parameters, with the increase of the imaginary potential as the energy decreases, as can be observed in Fig. 4 for the ^{6}Li + ^{138}Ba system. Thus, the coupling to the break-up channel results in an overall repulsion, leading to a new type of TA, recently called break-up threshold anomaly (BTA) [43, 44]. The fact that the threshold for break-up extends far below the barrier in the case of weakly bound nuclei is manifested in the BTA. The break-up dynamic polarization potential, being repulsive, must lead to an increase in the barrier height, resulting in a decrease of σ_{CF} at sub-barrier energies.

7. Conclusions

Concerning the fusion of stable weakly bound nuclei ^{6,7}Li and ^{9}Be, nowadays there is a qualitative consensus on the existence of some complete fusion hindrance at energies above the barrier, for heavy targets, from 10 to 30%. Complete fusion is defined as the process in which the total projectile charge fuses and its hindrance is attributed to the incomplete fusion process. At sub-barrier energies, there is no conclusion so far, probably due to the small net effect of competition between break-up and other effects that may enhance the fusion, as it occurs for tightly bound projectiles. At sub-barrier energies the non-capture break-up is the predominant process. The σ_{NCBU} are found to be much larger than the fusion cross sections at sub-barrier energies, and depend strongly on the break-up threshold energy. Reaction cross section also increases strongly when the projectile break-up threshold energy decreases. However, the large difference between the break-up threshold for different weakly bound projectiles are not reflected in the fusion cross section.

For light and medium mass targets the situation is qualitatively similar, and the main difference is that σ_{ICF} are found to be negligible, as it is the CF suppression at energies above the barrier. The conclusions related to the negligible σ_{ICF} for medium and light mass targets may not be a priori extended to halo nucleus projectiles, due to their abnormal large radii.

The coupling of the break-up processes to the elastic channel produces a repulsive polarization potential that is responsible for the vanishing of the usual threshold anomaly of the optical potential at near barrier energies.

As perspectives for new experiments, we believe that one needs additional fusion data at sub-barrier energies and more exclusive experiments on NCBU, CF and ICF, in order to understand the overall reaction mechanisms, and to obtain precise information for the calculations. For sure, there is a strong need to extend the experiments using radioactive beams.

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