Systematic results of fusion, total reaction cross sections and breakup threshold anomaly with weakly bound nuclei at near barrier energies

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Introduction

The coupling between the elastic scattering and different reaction mechanisms plays the vital role for the energy dependence of the optical potential produced by polarization potentials. For systems containing only tightly bound nuclei, couplings to bound excited states or transfer channels produce an attractive polarization potential and, consequently, lead to enhancement of the fusion cross section at energies near and below the Coulomb barrier, when compared with no-coupling calculations. For these systems, the energy dependence of the optical potential shows the usual threshold anomaly (TA) [1, 2]. The TA manifests as the decreasing of the imaginary potential as the energy decreases towards the barrier, as consequence of the closing of reaction channels. But nowadays the direction have been changed by the replacement of tightly bound with weakly ones, and many aspects differing from the former ones have been developed in the recent past few years. One of the chief aspect is the possibility of the opening of other channels especially breakup using the weakly bound projectiles such as ^{6}Li, ^{7}Li & ^{9}Be in the elastic scattering experiments in the vicinity of the Coulomb barrier has attained a great attention. Here the projectile being weakly bound, couples to the breakup channel and the probability of breakup cross section stays alive. Furthermore it has been also observed that the breakup cross section becomes larger than the fusion cross section at the sub barrier energies [3] and contradicts to the usual Threshold Anomaly and this effect is named as Breakup Threshold Anomaly (BTA) [4]. Here the imaginary part shows the increasing trend with a small reduction in the real part of the potential near the barrier with the development of repulsive real polarization potential. Therefore, it is important to investigate the dependence of the breakup and total reaction cross-sections near the barrier energies.

General features of reactions with the weakly bound nuclei

An important feature of collisions of weakly bound nuclei is that the breakup mechanism may give rise to two different types of fusion. Complete fusion (CF), when the whole masses of the projectile and the target are contained in the compound nucleus (CN) and incomplete fusion (ICF), when some nucleons move out of the interaction region before the formation of the CN.

Several experiments were performed to assess the situation. In particular, fusion measurements of easily breakable stable nuclei such as ^{6}Li, ^{7}Li and ^{9}Be with heavy targets were reported and the above-mentioned reduction in the fusion cross section was confirmed. From the theory side, a detailed Continuum Discretized Coupled Channels (CDCC) calculation was reported for the fusion of ^{11}Be with ^{208}Pb [5]. It was difficult to draw definitive conclusions concerning the CF cross section since this method cannot evaluate the contribution from the sequential process. The calculation of the incomplete fusion within the CDCC, needed to obtain the CF, is still being investigated [6]. The status of the fusion of weakly bound stable and unstable nuclei is therefore that of an ongoing extensive effort both in theory and experiment.

Elastic scattering of weakly bound nuclei

Accurate measurements of elastic scattering angular distributions over a wide angular range are very important to investigate threshold anomalies and to assess the relevance of the breakup channel in collisions of weakly bound nuclei. The techniques used to measure elastic scattering are standard and will not be detailed here. Essentially, one uses sets of silicon barrier or position sensitive E–ΔE telescopes covering a wide angular range. In order to precisely determine the scattering angle, collimators or masks are frequently placed in front of the detectors. Fig. 1 shows a typical elastic scattering angular distribution for the system ^{6}Li + ^{116}Sn [7].

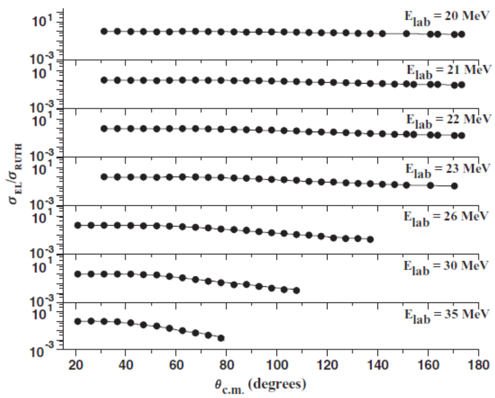

FIG. 1. Elastic scattering angular distribution for the system ^{6}Li + ^{116}Sn at different bombarding energies and their optical model fits.

Threshold and breakup threshold anomaly

The basic characterization of TA is the observation of a localized peak in the real part of the potential accompanying the sharp decrease of the imaginary part of the potential as the bombarding energy declines towards the Coulomb barrier. The name "anomaly" comes from the expectation that the real and imaginary parts of the OP are energy independent at higher energies, but not at near barrier energies. In brief, the coupling to the channels other than elastic introduces an attractive real potential and the result of the decrease of the imaginary potential is tacit by the closure of the nonelastic channels at energies near and below the Coulomb barrier. It has been shown [1] that there is a connection between the real and imaginary parts of the OP due to causality and subsequently they obey the dispersion relation.

This situation may change in the scattering of weakly bound nuclei [4]. These nuclei have very low breakup threshold energies and so, have a large breakup (BU) probability. At energies above the barrier, fusion cross sections are usually larger than BU cross sections, but at energies close to the barrier, the opposite occurs, and furthermore, BU probabilities remain large even at energies below the Coulomb barrier [8 - 11]. The BU process feeds states in the continuum and produces a repulsive polarization potential [12 - 14]. This fact is compatible with the recently demonstrated [15, 16] systematic suppression of fusion cross section of weakly bound systems at near barrier energies, due to dynamic effects of BU.

Therefore, contrary to what is written in some papers in the literature, the Breakup Threshold Anomaly (BTA) is the absence of TA at the Coulomb barrier, and not necessarily the rise of the imaginary potential when the bombarding energy decreases towards the barrier. Since the BU cross section does not decrease significantly in the vicinity of the Coulomb barrier, this is no longer the threshold of the closing of the reaction channels. When the repulsive BU polarization predominates, BTA is more clearly observed by the increasing of the imaginary potential as the energy decreases, associated with a small reduction in the real part of the potential near the barrier. In any situation, the real and imaginary parts of the OP should satisfy the dispersion relation. In Fig. 2, threshold anomaly is clearly demonstrated taken from [2] and the system used was the tightly bound projectile and heavier mass target. In this calculation imaginary part is taken to be a two-linear segment function and the non-subtracted dispersion relation. We see from Fig. 2 that the heavy-ion optical potential is dispersive and obeys the dispersion relation. In Fig. 3, BTA may be noticed and the system used was the weakly bound projectile and heavier mass target [4].

Total reaction cross sections

In order to perform a systematic study of total reaction cross-sections with different weakly bound projectiles with several targets, it is necessary to compare the cross-sections for systems with different Coulomb barriers. For this purpose, it is necessary to suppress the differences arising from the size and charges of

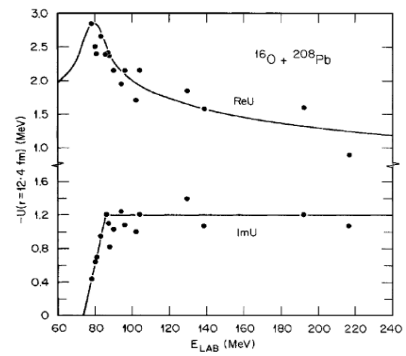

FIG. 2. Energy dependence of the real and imaginary parts of the optical potential obtained for the ^{16}O + ^{208}Pb system.

the systems. This can be done in different ways. The two most frequently used reduction procedures are to normalize the collision energy with respect to the barrier height and to divide the cross-section by its geometrical value, i.e., to plot $\sigma_R/\pi R_B^2$ against $E_{c.m.}-V_B$ or $E_{c.m.}/V_B$, where R_B and V_B are, respectively, the s-wave barrier radius and height and should be evaluated using a realistic treatment of the optical potential similar to the folding model.

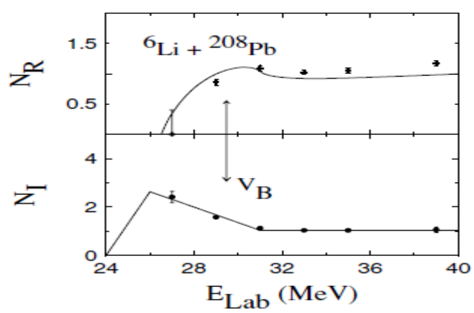

FIG. 3. Energy dependence of the real and imaginary parts of the optical potential obtained for the ^{6}Li + ^{208}Pb system.

However, this procedure does not consider the important influence of the barrier curvature at the sub-barrier energies [15]. It has been pointed out [17] that when weakly bound projectile nuclei are involved, care should be taken in order to preserve the static effects arising from the low breakup energy of the projectile. So, the reduction method should remove the dependence on the masses and charges of the collision partners but not specific features of the projectile density. The proposed reduction method [17] is to plot $\sigma_R/(A_p^{1/3}+A_t^{1/3})^2$ versus $E_{c.m.}\,(A_p^{1/3}+A_t^{1/3})/Z_p Z_t$. However, the above-mentioned reduction procedures fail to remove appropriately the static effects on the fusion reactions of different systems. In another methodology, it has been shown [18] that the fusion function is system independent when σ_F is accurately described by Wong's formula [19]. In this case F(x) becomes $F(x) \rightarrow F_0(x) = \ln\,[1 + \exp\,(2\pi x)]$. Note that $F_0(x)$ depends exclusively on the dimensionless variable x. It is a universal function which is the same for any system. For this reason it is called the Universal Fusion Function (UFF), which is shown in Fig. 4. This UFF can be used as a benchmark to which renormalized data should be compared.

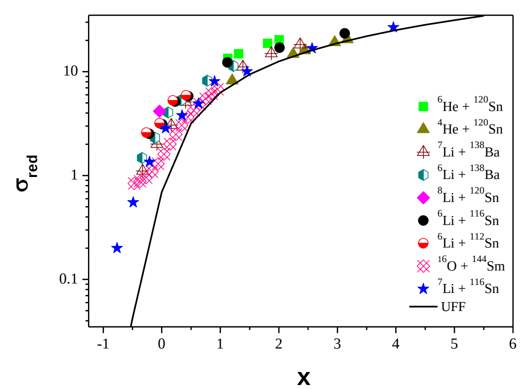

FIG. 4. Reduced reaction cross section vs reduced projectile energy for different systems involving halo, weakly and tightly bound projectiles using the prescription given in Ref. [15, 20].

In the present work we compare the total reaction cross sections derived from our experimental elastic scattering data for the ^{6,7}Li + $^{112,\,116}$Sn systems with other systems involving tightly bound, stable weakly bound and radioactive and halo projectiles with targets in the same mass range. We use both the above mentioned procedures (Figs. 4 and 5).

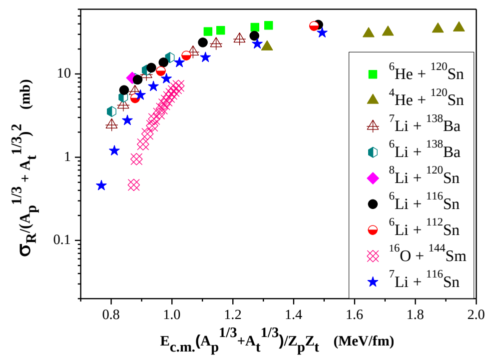

FIG. 5. Reduced reaction cross section vs reduced projectile energy for different systems involving halo, weakly and tightly bound projectiles.

Summary and outlook

Thus in order to contribute to obtain a more clear picture of a possible systematic behaviour for the optical potential in the near barrier it is required to measure elastic scattering angular distributions for the systems with weakly bound, unbound and halo nucleus and compare the results with the reactions having tightly bound projectiles. The present behavior of rapid variation of the polarization potential below and near the barrier corresponds to the presence of BTA for weakly bound nuclei. This remark is based on the fact that the imaginary part of the optical potential does not drop to zero below the barrier energies and also there is a decrease of the real potential at the lowest energies.

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