Effect of breakup on elastic scattering for the ^{6,7}Li + ^{59}Co systems

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The elastic scattering for the ^{6,7}Li + ^{59}Co systems was investigated in the bombarding energy range 12 MeV $\leqslant E_{\rm lab} \leqslant$ 30 MeV by means of an analysis using the São Paulo potential, through which the behavior of the real and imaginary parts as function of the bombarding energy was established. The experimental results suggest that overall there is an evidence of the usual threshold anomaly for both systems, although for the ^{6}Li + ^{59}Co system, an evidence of the breakup threshold anomaly could also be questioned.

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I. INTRODUCTION

The effect of collective degrees of freedom on the fusion process has been extensively investigated over the past few years [1]. A significant enhancement of the sub-barrier fusion cross section is often found as compared to the predictions of one-dimensional barrier penetration models. This enhancement is understood in terms of dynamical processes involving couplings to collective inelastic excitations of the target and/or projectile. A precise determination of the barrier distributions leading to the enhancement requires an understanding of the dominant channels that couple to the fusion channel [2].

The study of fusion reactions in the vicinity of the Coulomb barrier provides a fascinating challenge for theories of quantum tunneling leading to an irreversible complete fusion of the interacting nuclei into the compound nucleus [3–6]. A great experimental effort involving both (loosely bound) stable and unstable nuclei has been devoted to investigate the specific role of the breakup channel [5,7]. The weak binding of these systems can also lead to incomplete fusion and transfer processes playing an important role.

The recent availability of light-mass radioactive ion beams such as ^{6}He [8–11], ^{11}Be [12], and ^{17}F [13], and the renewed interest on reactions involved in astrophysical processes [14], motivated the investigation of fusion reactions involving very weakly bound and/or halo projectiles around and below the Coulomb barrier.

The fusion probability is sensitive to the internal structure of the interacting ions as well as to the influence of the other competing mechanisms such as breakup, which is known to affect the fusion features. The fusion cross section enhancement generally observed at sub-barrier energies is understood in terms of dynamical processes arising from couplings to collective inelastic excitations of the target and/or projectile. However, in the case of reactions where at least one of the colliding ions has a sufficient low binding energy so that breakup becomes an important process, conflicting experimental [15–17] and theoretical results are reported [18–20].

Complete fusion requires the possibility of fusion through the compound nucleus formation containing all the nucleons of both the intact projectile and the target. If only part of the projectile-like fragments may emerge from the interaction region with a compound system being formed then either incomplete fusion or transfer is defined. For incomplete fusion the breakup process is followed by fusion in a two-step process and for transfer we have a direct one-step process.

Several questions are still open regarding the interplay of breakup and fusion, the effect of breakup on complete fusion being one of the most discussed topics. The answer to this main question requires a detailed knowledge of the competing mechanisms and their contribution as a function of energy.

An alternative method for studying the influence of the breakup process on the fusion cross section of systems with weakly bound nuclei is through the elastic scattering analysis. The behavior of the energy dependences of the real and imaginary parts of the potential, at energies close to the Coulomb barrier and at the strong absorption radius, is related to the couplings between reaction channels at this energy region. The study of the elastic scattering is important as an alternative method to study the influence of different reaction channels on the fusion cross section. The elastic scattering of heavy ions at energies near the Coulomb barrier usually shows an anomalous behavior of the energy dependence of the real and imaginary parts of the optical potential, known as the threshold anomaly (TA) [21,22]. This anomaly shows up as a localized peak in the real part and the decreasing and vanishing 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 scattering to 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 [22]. Therefore, at near barrier energies, when the threshold anomaly is present, nuclear potentials that describe the elastic scattering are no longer slowly energy-dependent, as at high energies.

The situation may be different when one is dealing with weakly bound nuclei. For systems with weakly bound projectiles interacting with heavy targets, there is a strong coupling of the elastic scattering to the breakup process [22,23], which has a larger cross section than the fusion at sub-barrier energies [24,25]. Therefore, it is expected that the TA may no longer be present due to the repulsive polarization potential produced by the coupling to the continuum breakup states, which compensates for the attractive polarization arising from couplings to bound states [26,27]. 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.

Recently, a new manifestation of the dispersion relation that is unique for the breakup coupling of the dynamic polarization potential was reported, named breakup threshold anomaly (BTA) [28]. Because the coupling to the breakup in these systems continues to be important even at energies below the barrier, the threshold ceases to be the barrier itself. Thus, the imaginary part of the potential could increase at lower energies and, as the dispersion relation dictates, the real part of the dynamic potential would show a decrease, implying an overall decrease in the real part of the optical potential that fits the elastic scattering.

Within the context of studying the breakup mechanism, in this work we present an analysis of the elastic scattering for the ^{6,7}Li + ^{59}Co systems at energies near and above the Coulomb barrier. The data were analyzed with the use of the São Paulo potential [29] and the behavior of the real and imaginary parts as function of the bombarding energy was established. Our results, which involve a medium mass target, are compared to results for ^{6}Li and ^{7}Li projectiles and lighter and heavier targets.

II. EXPERIMENTAL DETAILS

The experiments were performed at the University of São Paulo Physics Institute. The ^{6}Li and ^{7}Li beams were delivered by the 8UD Pelletron accelerator in the energy range 12 MeV $\leqslant E_{\mathrm{lab}} \leqslant$ 30 MeV, and bombarded a 80 μg/cm^2 thick ^{59}Co target on a 20 μg/cm^{2}C backing.

The detection system consisted of a set of 11 triple telescopes [30]. Each telescope is composed of an ionization chamber ($\Delta E1$), one 150 μm thick surface barrier Si detector ($\Delta E2$), and one 4cm thick CsI crystal (E) with photodiode readout. The entrance windows have a 2 cm diameter and are made of aluminized polypropylene with a thickness of 150 μg/cm^2. Depending on the setup geometry, collimators can be placed in front of the windows in order to adjust the solid angle.

In order to properly identify the atomic number for light and heavy particles, for each telescope we generate four signals, namely ΔE_{gas}, E_{heavy}, $\Delta E_{\mathrm{light}}$, and E_{CsI}. The ΔE_{gas} signal comes from the two collecting rings of the ionization chamber. The E_{heavy} and $\Delta E_{\mathrm{light}}$ signals come from the Si detector with low and high gain, respectively, and the E_{CsI} signal is generated by the photodiode attached to the CsI crystal. Therefore, by using the ΔE_{gas} and E_{heavy} signals, the heavy particles can be identified. The ΔE_{gas} and $\Delta E_{\mathrm{light}}$ signals in conjunction with E_{CsI}, allow for the proper identification of the light particles, even with an isotopic separation for $Z = 1$ particles. The chosen gas for the ionization chambers was isobutane with an operation pressure of 20 torr and the anode voltage was fixed at 100 V. The average energy loss resolution of the ionization chambers is 7.6%. The typical energy resolution was around 1% for the Si detectors and 2% for the CsI detectors. In the particular case of the experiments reported here, the CsI detectors were not used.

The signals were processed using standard NIM and CAMAC electronics and the data were recorded on tape for subsequent off line analysis.

The telescopes were placed on a rotating plate and covered the angular range from 10° to 140°, spaced by 10°. The data were taken by varying the angle of the plate in 2.5° steps. The solid angles of the telescopes varied from 0.14 to 1.96 msr.

III. DATA ANALYSIS AND DISCUSSION

The experimental data were analyzed within the framework of the São Paulo potential (SPP) for which the energy dependence of the bare potential is accounted for by a model based on the nonlocal nature of the interaction. This parameter-free potential describes very well the elastic scattering of many different systems from sub-barrier energies up to 200 MeV/nucleon.

The bare interaction V_N is connected with the folding potential V_F through [31]

$$V_N(R, E) = V_F(R)\exp\left(-\frac{4v^2}{c^2}\right), \tag{1}$$

where c is the speed of light and v is the local relative velocity between the two nuclei, given by

$$v^2(R, E) = \frac{2}{\mu}[E - V_C(R) - V_N(R, E)]. \tag{2}$$

The folding potential is obtained by using the matter distributions of the nuclei, which take into account the finite size of the nucleon, with a zero range approach for $v(r)$. For the Coulomb interaction, V_C, a double sharp cutoff Coulomb potential was used. In order to obtain a global parameter-free description of the nuclear interaction, a systematization of nuclear densities was developed [32], based on an extensive study involving charge distributions extracted from electron scattering data and theoretical densities calculated through the Dirac-Hartree-Bogoliubov model. The two-parameter Fermi (2pF) distribution was adopted to describe the nuclear densities.

Within this systematization, the matter densities have an average diffuseness value of $a = 0.56$ fm, and the radius of the distribution of a nucleus with A nucleons is well described by $R_0 = 1.31A^{1/3} - 0.84$ fm.

The imaginary part of the interaction is assumed to have the same shape as the real part, with one single adjustable parameter N_I related to its strength,

$$W(R, E) = N_I V_N(R, E). \tag{3}$$

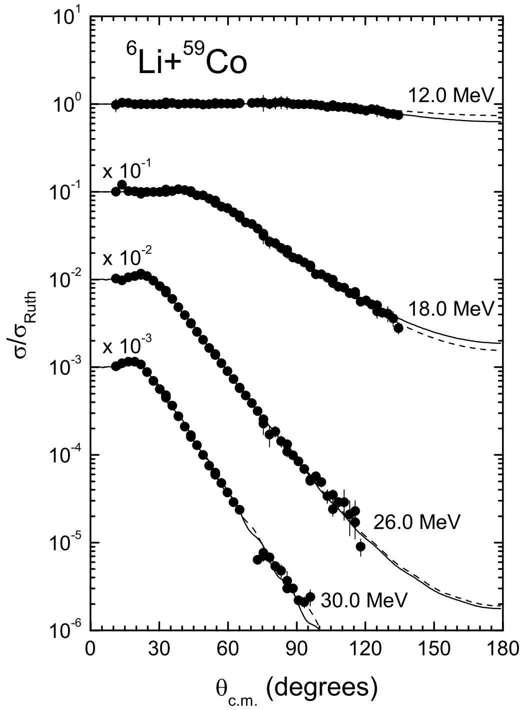

FIG. 1. Elastic scattering angular distributions for the ^{6}Li + ^{59}Co system at $E_{\rm Lab} = 12, 18, 26,$ and 30 MeV. The dashed lines correspond to fits using the São Paulo potential with the standard values $N_R = 1$ and $N_I = 0.78$. The solid lines represent best fits with the same potential, where the N_R and N_I values were allowed to vary.

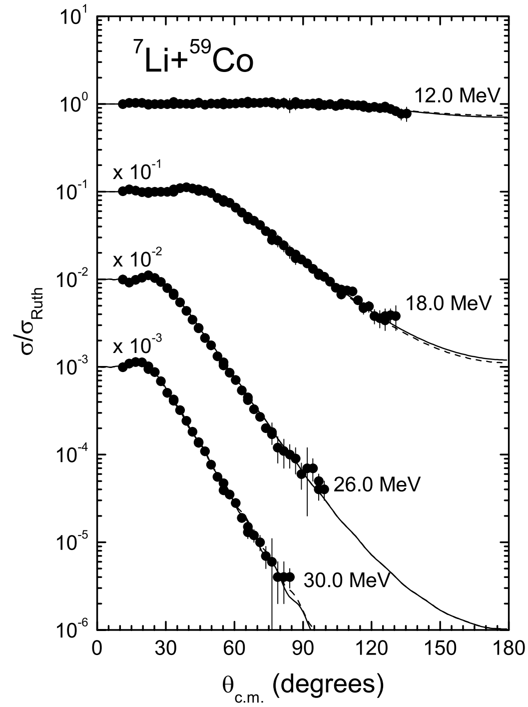

FIG. 2. The same as Fig. 1 for the ^{7}Li + ^{59}Co system.

Elastic scattering angular distributions, over wide energy ranges, were simultaneously well fitted with $N_I = 0.78$ for more than 30 systems [31]. In the general form, for $N_R = 1$ and $N_I = 0.78$, the parameter-free SPP can then be written as

$$V_{\rm SP} = (1 + i0.78)V_N(R, E). \quad (4)$$

In the first step of the analysis, we used the parameter free SPP as in Eq. (4) and the fits to the elastic scattering angular distributions are shown as dashed lines in Figs. 1 and 2 for the ^{6}Li + ^{59}Co and ^{7}Li + ^{59}Co systems, respectively.

In a second step of the analysis we considered N_R and N_I as free parameters for the fits to the angular distributions. In this situation we then have the normalized version of the SPP:

$$V_{\rm SP} = (N_R + iN_I)V_N(R, E), \quad (5)$$

where the coefficients N_R and N_I are energy dependent normalization factors and take into account the effects of the dynamical polarization potentials arising from direct channel couplings.

The results are shown as solid lines in Figs. 1 and 2. In this case we can notice that the fits are visually as good as the ones for the previous analysis step.

In Figs. 3 and 4 we present the results of the energy dependence of the best N_R and N_I values. The uncertainties in N_R and N_I were obtained through a χ^2 analysis and varied up to 10%, except for the lowest energies, for which the uncertainty was around 20%. We notice that for the real part, the results are near the standard value $N_R = 1$ for both systems, except for $E_{\rm Lab} = 12$ MeV, where the value for N_R is significantly higher than 1. For the imaginary part, the results are near the standard value $N_I = 0.78$ for both systems and slightly decrease, also near $E_{\rm Lab} = 12$ MeV. As the standard values $N_R = 1$ and $N_I = 0.78$ represent mean values obtained from data analyses of several systems, we may observe variations around the average values for some systems. Structure effects on the nuclear densities used in the folding

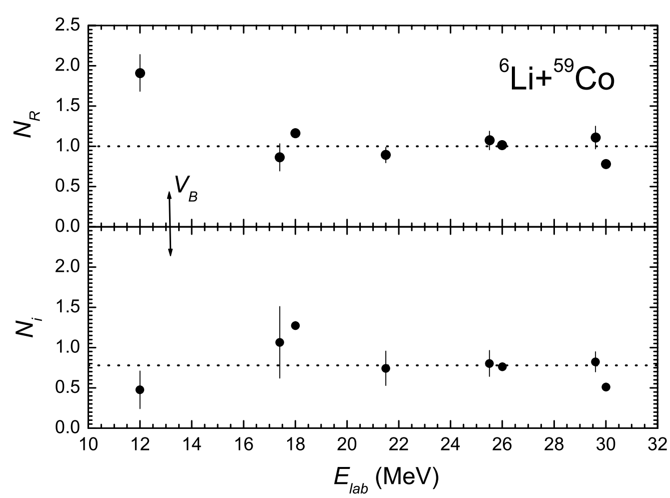

FIG. 3. Best values for N_R and N_I as a function of the bombarding energy obtained from fits with the São Paulo potential for the ^{6}Li + ^{59}Co system. The dotted horizontal lines on the standard values $N_R = 1$ and $N_I = 0.78$ serve as reference for comparison. The Coulomb barrier is indicated by a vertical line.

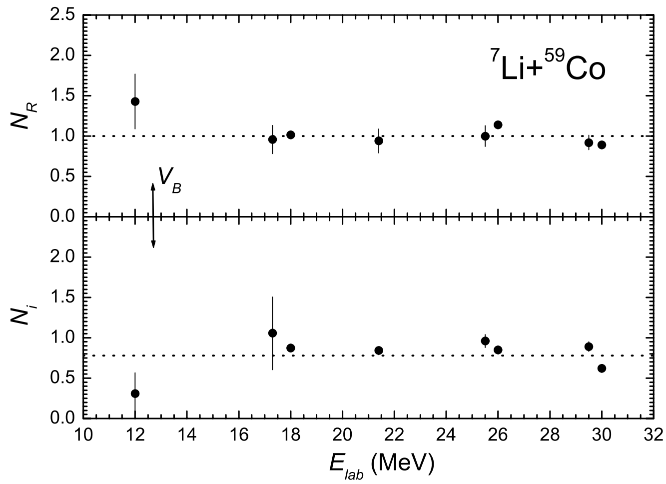

FIG. 4. The same as Fig. 3 for the ^{7}Li + ^{59}Co system.

calculations may affect N_R and different degrees of absorption from particular reaction channels may affect N_I.

Overall, the elastic scattering of ^{6}Li and ^{7}Li on the medium mass target ^{59}Co shows the same behavior as for tightly bound systems. We could in principle say that there is an evidence of the TA, i.e., a decrease in $N_I(E)$ as the energy is lowered below the barrier, accompanied by an increase in $N_R(E)$. However, if we look carefully at the behavior of N_R and N_I for the more weakly bound ^{6}Li + ^{59}Co system, for $E_{\rm Lab} \approx 18$ MeV there might be a slight decrease in N_R before it starts to increase, and a slight increase in N_I before it drops down. This could suggest the presence of the BTA, which has been observed for weakly bound systems involving targets of different masses. Taking into account the error bars, no strong conclusion can be drawn regarding the presence of the BTA for the ^{6}Li + ^{59}Co system. On the other hand, if the BTA is present for the ^{6}Li + ^{59}Co system, the behavior would be very similar to the one already observed for instance for ^{6,7}Li + ^{28}Si [33,34], ^{6,7}Li + ^{138}Ba [35], and ^{6,7}Li + ^{208}Pb [26]. For these systems the BTA seems to be present for ^{6}Li and not for ^{7}Li. The BTA was also observed for the following systems with the weakly bound ^{9}Be: ^{9}Be + ^{64}Zn [36] and ^{9}Be + ^{209}Bi [37].

For both systems investigated in this work, the imaginary potential does not decrease in a steep way, at least for the lowest energies we have measured. This could indicate that there are important direct channels still open at energies near the Coulomb barrier. This is more significant for ^{6}Li + ^{59}Co, as for the lowest energy the N_I value is higher than the one for ^{7}Li + ^{59}Co. The two most probable reaction channels still open for ^{6}Li + ^{59}Co are the ^{6}Li breakup into $\alpha + d$, and transfer.

IV. CONCLUSIONS

In this work the elastic scattering for the ^{6,7}Li + ^{59}Co systems was investigated in the bombarding energy range 12 MeV $\leqslant E_{\rm Lab} \leqslant$ 30 MeV through an analysis using the São Paulo potential. The analysis was performed in two stages. In the first stage, standard values for the real ($N_R = 1$) and imaginary ($N_I = 0.78$) parts of the potential were used. In the second stage, we considered N_R and N_I as free parameters for the fits to the angular distributions. In this situation the coefficients N_R and N_I are energy dependent normalization factors and take into account the effects of the dynamical polarization potentials arising from direct channel couplings.

The results for ^{6,7}Li + ^{59}Co suggest the presence of the usual threshold anomaly, whereas for ^{6}Li + ^{59}Co, we could also suggest the presence of the breakup threshold anomaly, although no strong conclusions could be drawn due to the error bars. If the breakup threshold anomaly is present for the ^{6}Li + ^{59}Co system, the behavior would be very similar to the one already observed for ^{6,7}Li + ^{28}Si, ^{6,7}Li + ^{138}Ba, and ^{6,7}Li + ^{208}Pb. For these systems the breakup threshold anomaly seems to be present for ^{6}Li and not for ^{7}Li.

In order to obtain more conclusive results about the presence of the breakup threshold anomaly, it would be important to perform more measurements with good statistics especially for bombarding energies near and below the Coulomb barrier.

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