Structure effects and dynamics in fusion reactions of light weakly bound nuclei

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Abstract. The study of fusion in collision around the Coulomb barrier, induced by radioactive or stable weakly bound nuclei, has been the subject of many experiments in the last years. From a semiclassical point of view, direct processes like break-up or transfer may be favoured by the low binding energies and one might also expect suppressed fusion cross section due to the competition with the break-up. However, according to the Coupled Channel calculations (CC), it is well known that the presence of strong open reaction channels can be responsible for a fusion cross-section enhancement with respect to the single barrier penetration calculations and the break-up should be included in such calculations. In order to further investigate on this topic, the $^6\text{Li}+^64\text{Zn}$ collision has been studied at several energies around the Coulomb barrier, to extract the total fusion and the total reaction cross sections and to study the energy dependence of the optical model potential.

1. Introduction and motivations

In the last few years, several attempts have been made to understand the reaction mechanisms in collisions of weakly bound nuclei around the Coulomb barrier [e.g. 1].

A weakly bound nucleus is a nuclear system with the ground state energy very close to the particle emission threshold. This means that a little excitation is sufficient to dissociate the nucleus into two or more parts. These peculiar nuclei can be either stable or unstable and may show a cluster structure. The low binding energy leads to a diffused mass distribution and, in extreme cases, to the halo structure [2].

In collisions involving a weakly bound nucleus direct processes like break-up and transfer may be favoured by the low binding energy and/or cluster structure. Two kinds of effects on fusion cross section may be expected: from a static point of view, a diffused mass distribution is affecting the projectile-target potential lowering the Coulomb barrier and increasing the fusion cross section; from a dynamical point of view, it is known that the strong coupling of the entrance channel with inelastic excitation or other reaction channels like transfer leads to a modulation of the barrier resulting in an enhancement of the fusion cross section with respect to single barrier penetration model. Due to the low break-up thresholds, in weakly bound nuclei the coupling to inelastic excitations may correspond to the coupling with the break-up channel, therefore...
we need to understand if the break-up is simply removing flux from fusion suppressing it or, if the coupling to break-up will produce enhancement of the fusion cross section around and below the barrier.

In order to investigate on the previously discussed topic, different authors have performed many experiments. Recently, to consistently compare all existing results, it has been developed a dimensionless universal fusion function [1, 3, 4] to be compared with the experimental data in order to look for systematic effects of the break-up on fusion cross-section. In such comparison the experimental data have been scaled to eliminate the differences due to the coupling to excited bound states, different charges, different barrier shapes and positions [1, 3, 4 and references therein].

From this analysis the authors concluded that reactions on heavy targets show a complete fusion cross-section enhancement below the Coulomb barrier and complete fusion suppression above the barrier [4]. In the case of light and medium mass targets the experimental results apparently show no effects on fusion cross section above the barrier but data are missing at energies below the barrier [3]. It has been noticed in [3] that although experimental data for different systems clearly show a consistent systematic behaviour. A few of them, such as the \(^6\)Li+\(^{64}\)Zn data on ref [6], deviate from the systematic and possible problems on the experimental data have been suggested for these systems.

In order to investigate on the previously discussed topic, the goal of the present experiment is to study the collisions induced by \(^6\)Li and \(^7\)Li on a \(^{64}\)Zn target. \(^6\)Li and \(^7\)Li are both weakly bound nuclei but there are differences in their structure: \(^6\)Li does not have discrete excited states and its binding energy is 1.4 MeV; \(^7\)Li has a bound excited state at 0.5 MeV and its binding energy is 2.5 MeV. Possible effects of these differences on reaction dynamics are discussed in [5], where are investigated the collisions induced by \(^7\)Li and \(^6\)Li on a \(^{59}\)Co target. At sub-barrier energies, it has been observed a \(^6\)Li total fusion cross-section enhancement with respect to the \(^7\)Li total fusion cross-section. The authors concluded that this behaviour could be explained only taking into account the coupling with the break-up and the different binding energy of the two nuclei. For this reason we want to measure the \(^6\)Li+\(^{64}\)Zn total fusion excitation functions down to energies far below the Coulomb barrier. Moreover, as noticed before, the \(^6\)Li+\(^{64}\)Zn collision is one of the few systems where the total fusion cross-section deviates from the systematics [3] and the presence of problems in the \(^7\)Li+\(^{64}\)Zn experimental data of [6] have been suggested in [3]. In addition, the comparison between the total fusion cross-section and the total reaction cross-section [6] shows, in this case, an unusually large elastic break-up cross-section never seen in other similar systems.

For this reason we propose a new measure of the total fusion cross-section with a different technique. Complementary information on the study of the \(^6\)Li+\(^{64}\)Zn collision has also been obtained by measuring precise elastic scattering angular distributions at several energies around the Coulomb barrier. Such angular distributions have been used to investigate on the possible absence of usual threshold anomaly on optical potentials due to the presence of break-up as suggested by several studies [8-14].

Although the complete goal of the present experiment is a comparison of the results for the systems \(^6\)Li+\(^{64}\)Zn, here we will discuss only some of the results for the \(^6\)Li+\(^{64}\)Zn system since the analysis is not yet complete.

2. Total fusion cross section

In order to measure the total fusion cross section around and below the barrier we cannot detect directly the evaporation residues because a great number of them could remain in the target or be below the detection energy threshold due to the low incident energy. For this reason we used an activation technique detecting off-line the X-rays following the electron capture decay of the evaporation residues. The experimental setup is shown in figure 1. The beam passes through a thin Au foil in order to extract the beam current profile by detecting the Rutherford scattered particles with two monitor detectors. Then, the beam impinges on the target followed by a catcher, which stops all the evaporation residues coming out from the \(^{64}\)Zn target. The target thicknesses varied between 550 \(\mu\)g/cm\(^2\) and 250 \(\mu\)g/cm\(^2\) decreasing as the beam energy reduced. At low energies the target is thinner
because below the barrier the fusion cross section changes rapidly so, a little energy loss in the target may lead to a large variation of the fusion cross section.

**Figure 1.** Experimental setup for the $^{64}$Zn activation with the $^6$Li beam. The beam passes through a thin Au foil in order to extract the beam current profile detecting the Rutherford scattered particles. Then, the beam impinges on the target followed by a catcher to collect the recoiling evaporation residues.

After the activation, the target and the catcher are placed in front of a silicon-lithium detector in order to measure the activity curve. This activation technique can be applied when the largest fraction of the evaporation residues decay by electron capture. In the activated target can be found, at the same time, several isotopes of different elements. After the electron-capture decay of the parent nucleus in its daughter, there is emission of a characteristic atomic X-ray having the typical energy of the daughter atom. Since each element has a different characteristic X-ray energy, the X-ray spectrum is the sum of different Gaussian peaks. With a multi-Gaussian fit, the different evaporation residues are identified in charge localizing the peak of their daughters but the isotopes of the same element cannot be discriminated by the X-ray energy. Each energy peak is therefore the sum of the contribution of the different isotopes of the same element. In figure 2, as an example spectrum, can be clearly seen the primary peaks (Kα) of Zn, Ga and Ge and the secondary peak (Kβ) of Ge on the right. The secondary peaks of Zn and Ga are also considered in the fit.
Several spectra from the same activated target have been measured at different times. Integrating the peak of a specific element and dividing by the duration of the spectrum acquisition run, we obtain the average activity of that element during the run. The activity curve is built by measuring at different times the X-ray spectra from the same activated target and obtaining the activity for each peak. Since different isotopes of the same element have different half-lives, the identification in mass can be done by fitting the activity curve as the sum of different half lives contribution as showed in figure 3.

As a parameter of the fit, we obtain the time zero activity for each evaporation residue that is the activity of the residue at the end of the activation.

Normalizing the time zero activity with the geometric and intrinsic efficiency of the detector, considering the beam current profile during the activation, the target thickness and the (K-alfa) fluorescence probability one can obtain the production cross section for each evaporation residue.

Adding the contribution of all evaporation residues we obtain the total fusion cross section.
Figure 3. Activity curve fit to identify different Ga isotopes by their half-live.

Figure 4. Total fusion excitation functions for the $^6$Li+$^{64}$Zn collision. The present data are plotted with the green diamonds and are compared to the previous data from the Brazilian group [6]. The disagreement between the two cross-section confirms experimental problems in the previous data.
In figure 4 our total fusion cross section with green diamonds is compared with the previous data of [6] in red dots. The error bar in our data is of the order of 10%. There is a disagreement between our data and the existing ones most probably due to detection threshold problems in the previous experiment as suggested by the authors [6]. With the activation technique, we do not have the threshold problems connected with the evaporation residues energies.

3. Elastic scattering angular distributions, total reaction cross-section and threshold anomaly.

As anticipated, we measured precise elastic scattering angular distributions at several energies around the Coulomb barrier in order to extract the total reaction cross-section and to investigate on the possible absence of usual threshold anomaly on optical potentials [8-14].

The usual behaviour of the optical potential as a function of energy is described in [7]. As the incident energy decreases below the barrier, the imaginary part is reducing and the real part shows a "bump". This behaviour is called threshold anomaly. The real and the imaginary part are linked together by the dispersion relation. The physics interpretation of the imaginary part decrease is the reaction channels closure. The bump in the real part is due to the coupling effects that introduce an attractive polarization potential. For the weakly bound nuclei it has been suggested that the coupling to the break-up may produce a repulsive polarization potential destroying the usual threshold anomaly. In some cases, we may observe the opposite behaviour with an increase of the imaginary part around the barrier [8]. Some authors called this behaviour "break-up threshold anomaly".

The available experimental data do not allow one to draw general conclusions regarding the behaviour of the optical potential around the Coulomb barrier for the weakly bound $^6$, $^7$Li nuclei. The results for different systems are often not conclusive because there are not enough data available at energies near and below the barrier. Thus, it would be important to perform measurements with small energy steps at energies in the vicinity of the Coulomb barrier. The measure of the elastic scattering angular distribution at low energy is a difficult task because, in this case, the Coulomb scattering is dominant. Therefore, to see variation with respect to the Coulomb scattering it is necessary to measure with an accuracy of the order of 1% and to go to very backward angles. The systematic error can be reduced by paying special attention to the normalization and to the mechanical alignment. For this reason, at the lowest beam energies, we measured at symmetrical angles with respect to the beam direction. The experimental setup is shown in figure 5. The scattered particles are collected by an array of five $\Delta E$(10-$\mu$m thick)-$E$(200-$\mu$m thick) silicon telescopes mounted on a rotating plate to cover a wide angular range. Absolute values of the cross sections were obtained by normalizing the data with the assumption that the scattering at small angles, where monitor detectors were placed, is purely of the Rutherford type. The ratio between the monitors solid angles and telescopes ones has been determined with a Rutherford scattering of $^6$Li on a $\sim$200 $\mu$g/cm$^2$ thick $^{197}$Au target.

The $^{64}$Zn target thickness of $\sim$400 $\mu$g/cm$^2$ is small enough to allow the discrimination of the target first excited state. Using telescopes one can easily separate the elastic events from the reaction ones. This is particularly important for very backward angles since, in this case, the low intense elastic peak is in the same energy range of the continuum alpha spectrum. In figure 6 are shown the measured elastic scattering angular distributions.
Figure 5. Experimental setup to measure the elastic scattering angular distributions. The scattered particles are collected by an array of five silicon telescopes mounted on a rotating plate to cover a wide angular range.

Figure 6. Elastic scattering angular distributions at different energies for the $^6\text{Li}+^{64}\text{Zn}$ system.
3.1. Optical model analysis and results

The angular distributions have been fitted using different optical model potentials [9]: renormalized double folding potential for both real and imaginary part (DF1); renormalized double folding potential for the real part and Woods-Saxon potential for the imaginary part (DFWS). In this last case two different density distributions have been used for the double folding potential (DF1WS & DF2WS). The results are displayed in figure 7.

![Figure 7](image)

**Figure 7.** Trend of the optical model potential obtained by fitting the elastic scattering angular distributions with two different potentials. Renormalized double folding potential for both real and imaginary part (DF1); renormalized double folding potential for the real part and Woods-Saxon potential for the imaginary part (DF1WS, DF2WS). See the text for details.

In figure 7-left we see the normalization factors from the fit using the double folding potential for both real and imaginary part (DF1). In figure 7-right we see the other fit with the Woods-Saxon potential for the imaginary part and the two different density distributions for the double folding real potential (DF1WS and DF2WS). Solid symbols, in the right picture, correspond to the DF2WS fit; empty symbols, in the same picture, correspond to the DF1WS fit. Results of independent measurements at a fixed energy, which are plotted in different colours, agree always together.

As we observe in both pictures, the optical potential trend is the same independently by the potential used for the fit. As it can be seen from figure 7, around the Coulomb barrier, indicated by the arrow, there is no presence of usual threshold anomaly.

3.2. Total reaction cross-section

Fitting the elastic scattering angular distribution with the optical model we also extracted the total reaction cross sections. These cross sections are plotted in figure 8 (red triangles) together with the corresponding ones measured by the Brazilian group [6] (yellow squares) and the total fusion cross section data already shown before. Our total reaction cross-section agrees with the previous data of [6]. The difference between the total reaction cross-section and the total fusion cross section is the break-up contribution. In the present data the deduced break-up contribution is smaller then the one extracted from the previous data [6] due to the larger fusion cross-section.

We can also observe that the relative contribution of the break-up is more important at sub barrier energies.
4. Summary and conclusions
By using an activation technique we measured the total fusion excitation function for the $^6$Li+$^{64}$Zn system. Our excitation function appears to be systematically larger than the one reported in [6]. This result seems to confirm the presence of experimental problems in the $^6$Li+$^{64}$Zn fusion data of [6] as suggested by the same authors of [6] in [3]. These problems are probably due to the energy threshold in the direct detection of the evaporation residues. The activation technique is not affected by this kind of problems. The difference between the reaction cross-section and the fusion cross-section is now smaller than in [6], leaving less space for elastic break-up cross-section. Moreover, as expected, this comparison shows that the relative contribution of the break-up to the total reaction cross-section become more important when decreasing the beam energy below the barrier.

From the analysis of the elastic scattering angular distributions within the optical model, the energy dependence of the optical potential around the Coulomb barrier has been studied showing absence of the usual threshold anomaly.

5. References
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