Structure effects in collisions induced by halo and loosely bound nuclei

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Abstract.
Reactions induced by halo and loosely bound stable nuclei at low bombarding energies, arouse a lot of interest in the last fifteen years. Many experiments have been performed so far, using both stable and radioactive beams. These experiments are driven by theoretical expectations concerning effects, at sub-barrier energies, of coupling between relative motion and intrinsic excitation of the colliding nuclei which for the weakly bound systems lies into the continuum. In this paper some results of experiments concerning the study of reaction mechanisms with halo and loosely bound stable nuclei at energies around the Coulomb barrier will be discussed.

1. Introduction
In the last years several papers have been published where reaction mechanisms, in particular fusion at low bombarding energies, were investigated, in reactions induced by halo and loosely bound nuclei. Weakly bound nuclei and more specifically halo nuclei, are characterized for having the ground state very close to the particle emission threshold, therefore, in theoretical calculations, in order to proper describe the reaction dynamics, coupling to bound and break-up states must be considered. It is well known in fact, that in order to reproduce the behavior of the cross-section for the different reaction processes at very low energies, dynamical effects, such as the coupling of the relative motion of projectile and target to their intrinsic excitations or to other reaction channels, as for instance transfer, must be included in the calculations. In particular, since weakly bound nuclei have no or at most one bound excited state, coupling to inelastic channels implies coupling to the continuum. This coupling is calculated, within a Coupled Channel approach by performing Continuum Discretized Coupled Channel (CDCC) calculations where the continuum is considered as a sum of discrete states. CDCC calculations predict that, in reactions induced by halo nuclei, dynamical effects enhance the sub-barrier total fusion cross-section with respect to the no-coupling case. In addition, due to the break-up, a suppression of the complete fusion cross-section is predicted by CDCC calculations at energies above the barrier [1]. Conversely, different models as for example [2], based on a time-dependent wave-packet method predicts that the cross-section in the neutron halo case is slightly suppressed than in the non-halo case.
Low energy fusion cross-sections measurement with radioactive halo beams is a difficult task owing to the low intensities of the beams and the small cross-sections involved. Therefore, information on the effect of coupling to break-up can be more easily obtained either by measuring...
elastic scattering, which has a large cross-section, or using stable weakly bound beams which have much higher intensities than radioactive beams. In this paper an overview of the progress made in reaction studies with halo and weakly bound stable nuclei is presented.

2. Elastic scattering and direct processes in reactions induced by halo nuclei

Most of the existing data concerning low energy reaction studies with halo nuclei, have been performed using $^6$He as a beam. Elastic scattering and reaction data on several targets are nowadays available and this has stimulated a lot of theoretical work as well. Some data, such as quasi elastic (QE) angular distribution and fusion excitation function, exist also for collisions induced by $^{11}$Be beam and, very recently, elastic scattering data induced by the proton halo $^8$B on medium mass $^{58}$Ni have been published [3].

Low energy $^6$He induced elastic scattering on medium and heavy mass targets, shows a reduction of the elastic cross-section in the rainbow region see e.g. [4, 5] as well as at large scattering angles. In order to describe properly the reduced cross-section within the Optical Model (OM), large diffuseness parameters of the imaginary term of the optical potential must be used. Also CDCC calculations of $^6$He elastic scattering on different targets have recently been published [6, 7, 8]. According to these calculations, the reduction of the elastic cross-section at the rainbow is originated by the coupling to states into the continuum. $^6$He is a three body system, since it can be considered as formed by an $^4$He core plus two neutrons. In order to simplify the very complicated CDCC calculations of a four body reaction process, two body representations of $^6$He ($^4$He core plus a di-neutron) are in many cases considered e.g. [6]. More recently, four-body (n-n-alpha+target) CDCC calculations have been developed [7, 8] and good agreement with the data is obtained in some cases. Also these calculations show that coupling to the continuum suppresses the elastic cross-section at the rainbow. In [9], coupling to single neutron stripping and its importance in describing the low-energy scattering of a halo nucleus was investigated. According to the authors f Ref. [9] it has a significant effect on the elastic scattering of $^6$He and should not be neglected. Coupling to the 2n stripping, which was found to have a large experimental cross-section [10, 11], larger than the 1n stripping and also break-up, could have a major role on the elastic scattering. Inclusive measurements, of reaction processes with $^6$He beam, have shown that a large cross-section (about 80% of the total reaction cross-section), is due to direct processes (see e.g. [4]). Recently, Chatterjee et al. [10] measured the coincidences between outgoing $\alpha$-particles, neutrons and $\gamma$-rays in the reaction $^6$He+$^{65}$Cu. From this experiment the cross-section for the 1n, 2n transfer and the break-up was derived. The cross-section for the 2n transfer was found to be dominating the direct reaction processes (a factor of ten larger than the 1n transfer). This result is in agreement with [11] where the outgoing $\alpha$-particle was measured in coincidence with two neutrons. In the $^6$He+$^{65}$Cu experiment of [10], the elastic scattering cross-section was also measured. Coupled Reaction Channel calculations, which included coupling to 1n and 2n transfer, were performed. These calculations show that coupling to the 2n transfer has a stronger effect than the 1n transfer coupling. The inclusion of the 2n transfer allows to reproduce the magnitude of the elastic cross-section, even if the shape of the cross-section is not reproduced.

Quasi elastic scattering of $^{11}$Be+$^{209}$Bi have been measured by Mazzocco et al. [12]. This experiment was performed at Riken by using a fragmentation beam degraded in energy. The beam energy resolution was insufficient to measure elastic scattering and, as above mentioned, the QE cross-section was measured instead. The QE cross-section included the 1st excited state of $^{11}$Be, which is bound and is only 320 keV from the ground state, and the target excited states up to 2.6 MeV. The quality of the data does not allow to see whether elastic scattering induced by the halo $^{11}$Be nucleus shows a suppression in the rainbow region as observed in the elastic scattering induced by $^6$He. On the QE data, Coupled Channel calculations were performed, in order to extract the total reaction cross-section. The extracted total reaction cross-section was
compared to the reaction cross-section for the weakly bound $^9$Be isotope onto the same $^{209}$Bi target, which was measured by the same group [13]. The total reaction cross-section, for the two Be isotopes, is found to be very similar. The authors had also previously measured the fusion excitation function for $^{9,11}$Be on $^{209}$Bi target, which had also a similar cross-section in the whole energy range explored [14]. The authors concluded that since the absorption is mainly due to fusion and break-up, the breakup process, as the fusion process, must have comparable cross-sections in both $^{9,11}$Be nuclei. No difference was found in the behavior of the halo $^{11}$Be nucleus and the non-halo $^9$Be nucleus. This result was in disagreement with what previously found with $^6$He. However, since both $^9$Be and $^{11}$Be are weakly bound, the break-up channel could play a similar role for the two systems.

Recently, we measured the elastic scattering angular distribution of $^{9,10,11}$Be on a medium mass $^{64}$Zn target, at the same center of mass energy of 25.4 MeV, using ISOL $^{10,11}$Be beams. The experiment with $^9$Be beam was performed at the 14 MV Tandem of Laboratori Nazionali del Sud (LNS) in Catania. The experiments with the radioactive $^{10,11}$Be isotopes were performed at REX-ISOLDE at CERN. Preliminary results show that the total reaction cross-section deduced from OM analysis is $\sigma_R \approx 1$ b for $^9$Be and $^{10}$Be whereas $\sigma_R \approx 2$ b for $^{11}$Be. Contrary to what it has been found by [12], a much larger total reaction cross-section is measured in the halo nucleus case. This conclusion disagrees with the result of [12] but agrees with the results obtained with $^6$He.

The elastic scattering induced by the proton halo $^8$B nucleus on a $^{58}$Ni target was measured at the Twinsol radioactive beam facility of the University of Notre Dame at five beam energies [3]. The total reaction cross-section was extracted from the Optical Model analysis of the elastic data. The results show that similarly to what observed in the $^6$He data, and also in our $^{11}$Be data, the $^8$B induced reaction has a much larger total reaction cross-section if compared with the reaction cross-section of weakly-bound non-halo nuclei. The authors of [3] attribute this large reaction cross-section to the contribution of break-up and not to transfer as was experimentally observed in the case of $^6$He induced reactions.

### 3. Elastic scattering induced by loosely bound nuclei: threshold anomaly effect

Important information about dynamical effects played by the coupling with break-up states, can be obtained by studying reactions induced by loosely bound projectiles. Recently, many experiments have been performed in order to study the threshold anomaly in elastic scattering of $^{6,7}$Li and $^9$Be on different targets. The optical potential extracted from the analysis of elastic scattering of heavy ions, involving tightly bound nuclei, it is known to show a rapid variation with energy near the Coulomb barrier. This energy dependence of the OM potentials is called threshold anomaly, see e.g. [15]. The usual threshold anomaly has been ascribed to the coupling of the elastic scattering to the nonelastic channels. The real part of the OM potentials shows a bump at the barrier energy; correspondingly, the imaginary potential decreases. The decrease of the imaginary potential can be understood as being originated by the closure of nonelastic channels at energies near the Coulomb barrier. In weakly bound nuclei the breakup channel is expected to be a relevant reaction channel even at low energies, below the Coulomb barrier. The coupling to the breakup produces a repulsive polarization potential and the usual threshold anomaly may disappear. It has recently been suggested that a new type of anomaly is present in the scattering of weakly bound nuclei, named as 'breakup threshold anomaly' [16]. In this case the strength of the imaginary potential increases as the incident energy decreases, below the Coulomb barrier. The effects of the breakup channel on the elastic scattering of $^{6,7}$Li have been studied for different targets [17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. However, conclusions concerning the possible absence of the usual threshold anomaly are contradictory. Keely et al. [17] have investigated elastic scattering of $^{6,7}$Li+$^{208}$Pb at energies around the Coulomb barrier. It was found that the energy dependence of the optical potential is consistent with
the existence of the usual threshold anomaly for the $^7$Li projectile and its absence for the $^6$Li projectile. According to CDCC calculations [27] the difference for these systems is mainly due to the difference in their breakup thresholds, $S_{\alpha} = 1.48$ MeV for $^6$Li and $S_{\alpha} = 2.45$ MeV for $^7$Li. The data for the $^6$Li+$^{208}$Pb system were reanalyzed by Hussein et al. [16] and the results for the energy dependence of the optical potential have been interpreted as an evidence of a new type of threshold anomaly, named as mentioned above, 'breakup threshold anomaly'. Maciel et al. [18] measured the elastic scattering of $^{6,7}$Li+$^{138}$Ba at near barrier energies. The results of the optical model analysis are similar to those for the $^{208}$Pb target [17]. The presence of the usual threshold anomaly for the $^7$Li elastic scattering has been interpreted as the effect of the strong couplings with the 1$^+$ excited state of $^7$Li (0.48 MeV) as well as other inelastic and direct channels. The $^6$Li nucleus has no bound excited state, for this reason the breakup channel is expected to be the dominant direct reaction channel. The repulsive polarization potential produced by breakup may compensate the attractive polarization potential produced by other direct and inelastic channels. Gomes et al. [24] reanalyzed the $^{6,7}$Li+$^{138}$Ba data and the results suggest the presence of the breakup threshold anomaly for both projectiles. Elastic scattering of $^{6,7}$Li nuclei on light targets $^{28}$Si and $^{27}$Al was measured by Pakou et al. [19, 20] and Figueira et al. [21, 22], respectively. In the case of the $^{28}$Si target, no usual threshold anomaly was observed [19, 20]. Similar results were obtained for the $^7$Li+$^{27}$Al system [21]. On the other hand, the $^{6,7}$Li+$^{27}$Al scattering suggests the presence of the breakup threshold anomaly [22].

The study of the threshold anomaly in the elastic scattering of $^{6,7}$Li on the medium mass target $^{59}$Co has been performed by Souza et al. [23]. The experimental results suggest the presence of the usual threshold anomaly for both systems. On the contrary elastic scattering of $^6$Li on medium mass nuclei $^{58,64}$Ni [25] and $^{90}$Zr [26] is consistent with the presence of the breakup threshold anomaly. Summarising, for the $^6$Li scattering on several targets, the results seem to indicate the presence of a break-up threshold anomaly, whereas this is not clear for $^7$Li where in some analysis the optical potential seem to show the regular threshold anomaly. The different result has been justified as due to the higher break-up threshold of $^7$Li and to the coupling to the 1$^+$ excited state which, in $^7$Li is bound and in $^6$Li is unbound. The behavior of $^9$Be elastic scattering, should be very similar to that of $^6$Li. In fact, they have similar break-up thresholds and both do not have bound excited states. However the results for $^9$Be are rather controversial as for $^7$Li [28, 29].

At low bombarding energies, below the Coulomb barrier, the elastic cross-section deviates very little from the Rutherford cross-section and the OM analysis is very sensitive to small variation of the cross-section. Therefore, one has to be sure that all systematic errors in the elastic scattering angular distribution measurement are minimized. We recently measured at LNS in Catania, the elastic scattering $^6$Li+$^{64}$Zn in the energy range 10 MeV$\leq$$E_{c.m.}\leq$ 20 MeV. Particular care was taken in order to reduce all source of systematic errors. The OM analysis was performed using a double folding potential. The same shape of the real and imaginary potential was used and the parameters of the fit were the two normalization constants $N_R$ and $N_I$. The results of the analysis are consistent with the so called 'break-up threshold anomaly' thus confirming the previous results of $^6$Li measurements.

4. Fusion cross-section in halo and weakly bound induced reactions

Typical intensities of radioactive beams are $10^4$-$10^7$ pps, these are several orders of magnitude smaller than the ones of stable beams. For this reason, in experiments with radioactive beams it is extremely difficult to measure at sub-barrier energies where cross-sections are very small. In particular the fusion cross-section decreases exponentially as the energy decrease below the barrier. Therefore, due to the low measured yield, fusion excitation function do not extend down to deep sub-barrier energies. An open issue is how to evidence, static effects due to the halo as well as the above mentioned dynamical effects due to the coupling to the continuum.
The ideal would be having realistic CDCC calculations to be compared with the experimental data. These, especially in the case of $^6$He, are still missing owing to the complicated three-body structure of this nucleus. The experimental data have been compared with calculations of single barrier penetration, standard CC calculations, or with data involving reactions induced by well bound nuclei on the same target or by comparing data of a reaction with different projectile and target but forming the same compound nucleus [30, 31, 4, 32, 33]. However the result (enhancement/suppression of the cross-section) will depend upon the type of comparison. As an example of discrepancy originated by the different procedure of comparison, in the case of $^6$He+$^{64}$Zn of [4, 32] the data are compared with the reaction $^4$He+$^{64}$Zn. From that comparison no differences of the two measured fusion excitation function are found in the energy range explored. In [34] the same $^6$He+$^{64}$Zn data, are compared with CC calculation without coupling to the continuum. From that comparison, a suppression of the fusion cross-section of the order of 50% at energies above the barrier is claimed and no effect at energies below the barrier is found.

Experiments performed using weakly bound stable nuclei may help to investigate the specific role played by the break-up channel. Reactions induced by the least bound stable nuclei ($^6$, $^7$Li, $^9$Be) have been studied on several targets see e.g. [35, 36, 37, 38]. The quality of the data is, of course, much better than the one obtained with the radioactive beams. In reactions on heavy targets a reduction of the complete fusion (CF) cross-section is observed at energies above the barrier, whereas no clear effect is observed below the barrier. The reduction was attributed to the projectile break-up in the strong Coulomb field of the target nucleus, followed by incomplete fusion (ICF). No effect was found in the total fusion cross-section, which agrees with the CC calculations [35].

Reactions on medium mass targets have produced different results. Owing to the lower charge of the target nucleus, the ICF process is expected to be small (within the experimental errors). For $^6$, $^7$Li and $^9$Be on $^{64}$Zn [38] the total fusion cross-section seems not to be affected by the break-up process. For $^9$Be+$^{64}$Zn collision the total reaction cross-section was found almost equal to the total fusion cross-section at energies around the barrier. Conversely, the reaction induced by $^6$, $^7$Li on the same $^{64}$Zn target has shown a total reaction cross-section much larger than the total fusion cross-section [38] which is unexpected. However, in a recent publication by Gomes et al. [39] where a universal fusion function (UFF) is derived in order to search for systematic trends in the total fusion excitation function, it is argued that there are problems with the $^6$, $^7$Li+$^{64}$Zn data. We recently measured the $^6$Li+$^{64}$Zn total fusion excitation function at near and sub-barrier region. The experiment was performed using the same activation technique used to measure $^6$He+$^{64}$Zn [4]. This technique is particularly suitable to measure fusion cross-sections when the evaporation residues (E.R.) are so slow that can get stopped into the target. To use this technique, of course, the produced E.R. must be radioactive, and this is the case for $^6$Li+$^{64}$Zn total fusion reaction. In figure 1 our results are compared with the data of [38]. As one can see from the figure there is a disagreement between our data and the previously published data. This discrepancy could be originated by the time of flight technique used by Gomes at al. [38] to obtain the fusion cross-section. The low energy heavy fragment produced in fusion or incomplete fusion processes are partially stopped into the target, threshold effect can be responsible for the lower cross-section measured in [38].

5. Summary
In conclusion, reaction studies with halo and weakly bound nuclei at energy around the barrier are currently being extensively performed and a lot of data are becoming available. Elastic scattering of halo nuclei showed a reduced cross-section in the rainbow region. Such a suppression is due to long range absorption that within the CDCC approach can be reproduced once the coupling to the continuum is considered. Coupling to break-up seems also responsible for the
absence of the threshold anomaly in the OM potentials in reactions with weakly bound nuclei. Fusion studies with halo nuclei still shows controversy about possible enhancement/suppression effects, depending upon how the experimental data are compared to extract the searched effect. With weakly bound beams very detailed measurements exist with heavy targets where a suppression of the complete fusion cross-section was found at energies above the barrier. On medium mass targets, measurements do not extend down to energies below the barrier and in some cases it seems that the measured cross-section is underestimated. The anomalously large elastic break-up cross-section observed in $^{6,7}$Li+$^{64}$Zn seems indeed to be related to a problem with the previously measured data. Our recent measurement, where a different experimental approach was used, do not show this effect.

6. References

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