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# Near-barrier scattering of $^{6}$He and $^{11}$Be

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**Abstract.** Experiments on halo nuclei at energies around the Coulomb barrier can provide good quality data on elastic, inelastic, breakup and nucleon transfer reactions. This information turns out to be very important to understand the structure and dynamics of these exotic nuclei. In this work we present relevant results obtained from recent scattering experiments of $^{11}$Be and $^{6}$He on heavy targets at energies around the Coulomb barrier. Our data exhibit strong absorption effects in the elastic channel. The role played by transfer and breakup channels, and the coupling to the continuum, are studied using CDCC and DWBA calculations.

**Keywords:** Nuclear reactions; Halo nuclei; Dipole polarizability, Transfer to continuum, Breakup reactions.
**PACS:** 24.10.Eq; 24.10.Ht; 25.50+g; 25.60.Bx; 25.60.Je

## INTRODUCTION

Over the last decade there has been a notorious development of high intensity beams of loosely bound radioactive nuclei, on both neutron and proton rich sides of the nuclear chart. Among these extraordinary specimens are those that exhibit the so called "neutron halo": a rather inert core plus one or two barely bound extra neutrons, forming an extended neutron distribution. The nucleus $^{11}$Be exhibits a one-neutron halo structure, whereas the nucleus $^{6}$He is a two-neutron Borromean halo nucleus: i.e., none of the individual subsystems n-n or $\alpha$-n forms a bound state.

Some important properties of these nuclei are the very low binding energy, the extended halo structure, and the fact that they should be easily polarizable: i.e., during the collision process the system will be distorted due to the different interactions of the target with the halo and the core. These particular features affect the scattering of halo nuclei on heavy targets, even at collision energies below the Coulomb barrier. Therefore nuclear reactions at energies around the barrier exhibit some common features, like the strong absorption found in the elastic channel or the large cross sections reported for nuclear dissociation [1].

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During the previous years there has been an intense research on near-barrier reactions induced by light halo nuclei on heavy targets [2]. In this paper we discuss the results obtained in recent experiments performed with $^{6}$He beams at the Centre de Recherche du Cyclotron at Louvain-la-Neuve (Belgium) [3, 4], and with $^{11}$Be beams at the REX-ISOLDE facility at CERN (Switzerland) [5]. Theoretical calculations are presented and the relevant reaction mechanisms are discussed on the light of the analysis of these data.

## SCATTERING OF $^{6}$He on $^{208}$Pb

High intensity $^{6}$He beams in a wide range of energies are currently produced at the radioactive beam facility of the Centre de Recherche du Cyclotron (CRC). In a first set of measurements [3] the $^{6}$He beam was produced at laboratory energies of 14, 16, 18 and 22 MeV and the scattering on a $^{208}$Pb target was measured at (5°-65°) and (135°-170°) laboratory angular ranges. In a second experiment [4] we measured the scattering at 22 MeV but covering a wider angular region (5°-165°). In these experiments the LEDA array [6], the DINEX telescope array [7] and a set of two double-sided silicon-strip detector telescopes [8] were used. A detailed description of the experimental methods and analysis can be found in [9, 10]. From these experiments we were able to determine accurate values for the elastic and inclusive break-up cross sections over a wide range of angles and several collision energies.

In Fig. 1.a it is shown the angular distribution of the elastic cross section at E=22 MeV, which is close to the Coulomb barrier for this system. The data exhibits a strong reduction of the elastic flux, extending up to very small scattering angles, so that the rainbow structure typical of the scattering of stable nuclei, is completly absent. This effect can be found at collision energies as low as 16 MeV. Further investigations using Optical model (OM) calculations [10] reveal that in order to reproduce the data, large values of imaginary diffuseness (~1.7 fm) are needed. Simple semiclassical estimates [11] show that flux removal can reach distances as large as 20 fm. These effects are clear indications of the presence of strong reaction mechanisms still active in situations in which the nuclei stay well separated. This is what we call long range absorption, and it is associated to the scattering of halo nuclei.

The relevant reaction mechanisms producing long range absorption might arise from the loosely bound structure of $^{6}$He that favors the coupling to the positive energy continuum. This effect has been investigated by Continuum Discretized Coupled Channel (CDCC) calculations, and the results are shown in Fig. 1.a. The solid line is the result of a CDCC calculation similar to that reported in [12], which includes the $^{4}$He+2n continuum states of the projectile [13], and reproduces the general trend of the data. The dashed line is the result of the one-channel calculation, which now exhibits the typical heavy ion rainbow and is unable to describe the data. An important part of these couplings originate from the distortion induced in $^{6}$He by the intense dipole interaction with the heavy target. However our studies reveal that only a fraction of this absorption is actually due to the Coulomb dipole polarizability [9, 14], the rest arising from other reaction mechanisms.

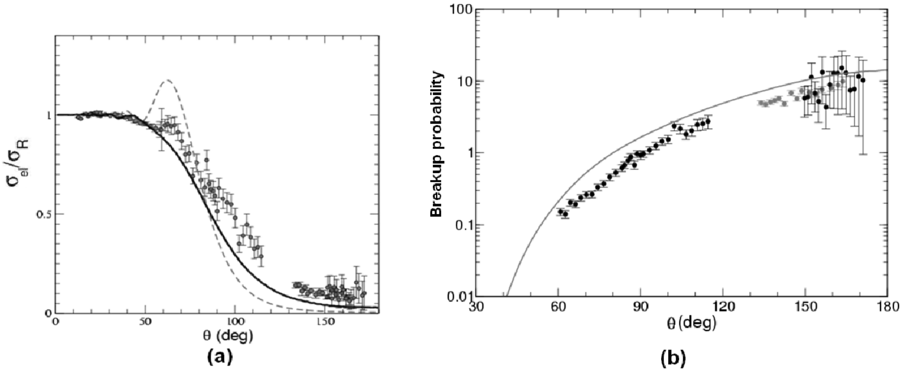


**FIGURE 1.** a) Ratio of cross sections elastic/Rutheford versus the scattering angle (lab) $^6$He on $^{208}$Pb at E= 22 MeV (preliminary). b) Angular distribution of the "breakup probability" of $^6$He in $^4$He at 22 MeV (preliminary). Data are from PH189 and PH215 experiments. See text for details.

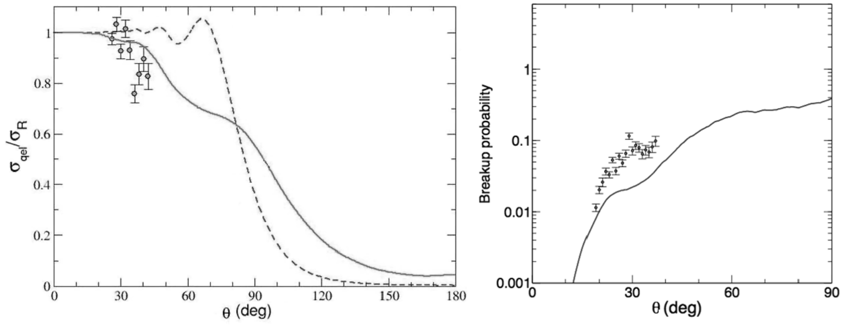
A deeper insight into the dynamics of this system can be achieved from the study of the strong alpha yields produced at near-barrier collisions. These are known to exhaust most of the total reaction cross sections [15, 16]. In Fig. 1.b we present the "breakup probability" of $^6$He on $^4$He at 22 MeV, defined as the ratio of the $^4$He fragments to the $^6$He elastic channel, as a function of the scattering angle. It is noticeable the large alpha production at backward angles, which is about ten times stronger than the elastic channel. This reaction channel remains very strong even at deep sub-barrier energies where we still find about 10% of the elastic channel at 14 MeV [10].

Our experimental results can be well described in terms of the *transfer to continuum* (TC) mechanism. In this process the two neutrons are transferred to continuum states of the lead target with very low relative kinetic energy, so that the emerging alpha gets an outgoing energy similar to that of the elastic events. Transfer calculations have been performed in a DWBA approach, including bound and unbound states of the $^{208}$Pb target and using a di-neutron model for $^6$He [12]. Preliminary results of a TC calculation are plotted with a solid line in Fig. 1.b. The calculations based on a TC mechanism show a reasonable agreement with the data, and with the energy distribution measured at backward angles (see ref. [10]). Nevertheless direct breakup and other reaction channels, like one-neutron transfer, might play a more important role at smaller angles. A detailed study of the alpha energy distributions from PH215 will shed some light to this problem. More refined TC calculations using a modified di-neutron model [17] should improve the theoretical description.

## SCATTERING OF $^{11}$Be on $^{120}$Sn

The $^{11}$Be nucleus is an interesting case to study the dynamic of nuclear haloes at near-barrier energies. The weakly bound $^{11}$Be nucleus ($S_n$ = 503 keV) has a relatively long half-life (13.8 s) suitable to be studied at REX-ISOLDE. The only bound excited state lies at 320 keV ($I=½^-$) with a strong coupling to the ground state ($I=½^+$) by E1 transitions [18]. Scattering experiments at near-barrier energies have been performed to disentangle the relative role played by different processes like transfer and fusion mechanisms [19, 20, 21, 22].

We have studied the scattering of $^{11}$Be on $^{120}$Sn at 32 MeV at REX-ISOLDE [4]. We have used an array of six DSSSD telescopes [8], arranged in a close hexagonal configuration [2]. Full details of the experimental setup and data analysis will be given elsewhere [13].



(a) (b)

**FIGURE 2.** a) Ratio of cross sections quasi-elastic/Rutheford versus the scattering angle (lab) for $^{11}$Be on $^{120}$Sn at 32 MeV (preliminary). b) Angular distribution of the "breakup probability" of $^{11}$Be in $^{10}$Be at 32 MeV. See text for details.

Due to relatively low beam intensity (≤ $10^5$ pps) we had to use a thick (3.5 mg/cm$^2$) $^{120}$Sn target. This choice limited our energy resolution to about 500 keV, spoiling the possibility of resolving elastic and inelastic channels. However the resolution was good enough to separate $^{10}$Be break-up from elastic channel using the $\Delta$E-E technique. Although the statistics achieved limited the analysis to angles below 40°, the results obtained are promising. A preliminary angular distribution for the quasi-elastic cross section is shown in Fig. 2.a.

In the forward angular region we should expect the dominance of the direct break-up channel. In order to allow a comparison with the experimental results, we have performed preliminary CDCC calculations including the coupling to the ½-excited state and the $^{10}$Be + n continuum. The results are plotted in Fig. 2.a with a solid line. The dashed line excludes the effects of coupling to continuum states and exhibits a typical rainbow structure. Our calculations predict a strong reduction in the elastic cross sections due to the effect of coupling to the continuum, which is consistent with the general trend of the data. In Fig. 2.b we present the angular distribution of the break-up probability at 32 MeV, normalized to the quasi-elastic channel. The calculation predicts lower cross sections than the measurements. This is a signature of existing reaction mechanisms not included in our calculations. In particular, neutron transfer and core excitation could play a relevant role. Part of this puzzle will be solved by looking to the energy distribution of the break-up events. This work is actually in progress.

# SUMMARY AND CONCLUSIONS

In this work we discuss recent experimental results on reactions of $^6$He and $^{11}$Be on heavy targets at near-barrier energies. The elastic cross sections show a strong absorption even at deep sub-barrier energies, suggesting the presence of long range reaction mechanisms. This feature is only partially due to the dipole part of the nuclear interaction. Other reaction processes coupled through unbound continuum states of projectile and target are very important. The analysis of the energy and angular distributions of reaction fragments suggest that "transfer to the continuum" is the dominant reaction mechanism at backward angles. More and high quality data on cross sections for elastic, inelastic and transfer channels would be needed to fully understand the near-barrier scattering of these weakly bound nuclei.

# ACKNOWLEDGEMENTS

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