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Searching for treasures at sub-barrier energies: the case of ^{8}B and ^{7}Be

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Abstract. Unexpected and challenging experimental results, at below barrier energies for weakly bound nuclei, are briefly reviewed in this article. The emphasis will be on our recent breakup results for ^{8}B+^{208}Pb at deep sub-barrier energies, indicating a dominance of direct mechanisms at this low energy regime. We will also present, a preliminary analysis of the ^{4}He and ^{3}He - particle production events for the ^{7}Be + ^{208}Pb reaction. These data were collected at the same experiment and at similar deep sub-barrier energies, exhibiting large yields compatible with cluster transfer processes. To confirm these results a new experiment to be performed at *TriSol* is planned, as soon as the upgrading of this facility will be completed.

1 Introduction

The investigation of reaction dynamics at near barrier energies for weakly bound nuclei was pursued systematically the last 20 years. It proved to be a fruitful play ground in relation with channel coupling effects affecting, either elastic scattering and probing a new type of the standard potential threshold anomaly -see e.g Refs. [1–3], or/and the suppression and enhancement of fusion cross sections above and below barrier energies [4–8]. On the other hand research at deep sub-barrier energies, in relation with reaction mechanisms, is mainly devoted to stable systems investigating fusion hindrance -see e.g ref. [9–11]. Recently in Ref. [12] a phenomenological description of the ratios direct to total reaction cross sections is reported, predicting an increasing trend at near barrier energies as well as a quenching in favor of the direct part for below barrier energy ratios. Moreover, a simultaneous description of elastic scattering and backscattering results [13], predicts not only an unusual behavior of the optical potential for the weakly bound nucleus ^{6}Li, with an increasing behavior at near barrier energies, but also a drop of the imaginary potential, not at near, but at deep sub-barrier energies. The last issue indicates the persistence of reaction channels at deep sub-barrier energies (see Fig. 1). These facts intrigued our interest at this low energy regime and initiated our new experiment [14] at the Notre Dame University, *TwinSol* facility [15].

In the following, we will make a brief review of our breakup results at 30 MeV for ^{8}B +^{208}Pb [14], while we will also give new results of our preliminary analysis for ^{7}Be +^{208}Pb, in relation with the ^{4}He and ^{3}He - particle production. We should note here that another important observation, for neutron rich stable and radioactive weakly bound nuclei, is the excessive α - production [16]. Research in this direction is mainly related to ^{6,7}Li and ^{6}He projectiles. An overview of existing data is given in Ref. [17]. In Ref. [18] exclusive α - production data are comprehensively analyzed and the various mechanisms are reported with emphasis on breakup following transfer. Recently inclusive measurements are also reported for the proton rich radioactive nucleus ^{7}Be on a ^{28}Si [17] and a ^{58}Ni target [19]. These measurements have been performed at near barrier energies with the conclusion that standard Continuum Discretized Coupled-Channel calculations (CDCC) and Distorted Wave Born Approximation (DWBA) calculations for breakup and transfer can not accommodate the very large measured α - production cross sections, in excess of the ^{3}He ones. A rather large ^{3}He stripping process may be inferred from these measurements.

This paper includes in section 2 details of our experiment and the results, for both secondary beams that is ^{8}B and ^{7}Be. A concluding discussion with summary will be given in section 3.

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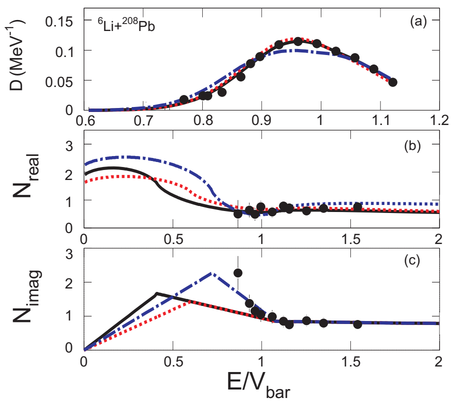

Figure 1. Determining the optical potential for ^{6}Li + ^{208}Pb via elastic scattering and backscattering measurements. (a) Barrier distributions obtained in the backscattering measurements- see Ref. [13]. (b) and (c) the real and imaginary part of the optical potential, determined in the analysis of elastic scattering data, reported in Ref. [1]. The lines represent trial potentials in a dispersive relation scheme, taking into account simultaneously the elastic scattering and backscattering measurements. Figure taken from Ref. [13].

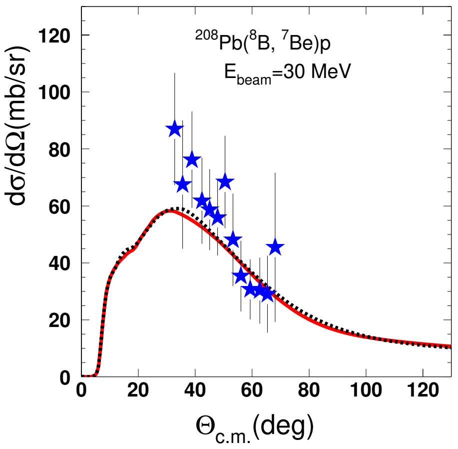

Figure 2. Angular distribution of the observed ^{8}B $\rightarrow$ ^{7}Be + p breakup yield on a lead target at a ^{8}B incident energy of $\approx$ 30 MeV (middle of the target). The solid and dashed curves denote the summed breakup angular distributions from the full (Coulomb plus nuclear potentials) and Coulomb potentials only CDCC calculations, respectively. Figure taken from Ref. [14].

2 Experimental details- Results

Comprehensive experimental details are given in Ref. [14]. Few pertinent points will be given below. The experiment was performed at the *TwinSol* facility [15] of the University of Notre Dame (UND). A cocktail secondary beam, composed of ^{8}B at the energy of 30.5 MeV, of ^{7}Li at 13.1 MeV, and of ^{7}Be at 22.5 MeV, was produced by using the ^{6}Li + ^{3}He reaction with beam fluxes in the range of 3000 to 5000 pps. The ^{8}B and ^{7}Be beams were very well separated by imposing a TOF (Time Of Flight) requirement between the occurrence of an energy signal in our detection system and the RF timing pulse from the beam buncher. The reaction products were detected in two telescopes of the SIMAS array (Sistema Móvil de Alta Segmentación), of LEMA (Laboratorio Nacional de Espectrometría de Masas con Aceleradores), the National Laboratory of the Physics Institute at the Autonomous National University of Mexico. Each telescope included a Double Sided Silicon Strip Detector (DSSSD) with nominal thickness of $\approx$ 20 μm (the effective thickness of each strip was estimated during the run and calibrations to be 24 $\pm$4 μm), backed by a silicon pad 150 μm thick. One telescope was set beam left covering an angular range between $\approx$ 25.8^{0} to 69.2^{0}, being 59.9 mm far away from the lead target, while the second telescope was set beam right covering an angular range between $\approx$28.5^{0} to 66.5^{0} being 69.95 mm away from the target. The observed reaction products were ^{7}Be for the ^{8}B+^{208}Pb studied reaction, and ^{4}He and ^{3}He - particles for the ^{7}Be+^{208}Pb one, and were detected in inclusive measurements. It is assumed that for the boron induced reaction, all ^{7}Be fragments originate from a breakup reaction mechanism, since our DWBA calculations predict a negligible proton stripping channel. Our experimental angular distribution is demonstrated in Fig. 2, together with Continuum Discretized Coupling Channel (CDCC) calculations, exhibiting a very good agreement with them. The measured cross section, obtained by integrating the angular distribution results, is $\sigma_{break}{}^{exp}$ = 326$\pm$84 mb, to be compared with the CDCC result of $\sigma_{break}{}^{theory}$ =300 mb. The very good agreement between experiment and theory, justifies the use of a theoretical value for total reaction

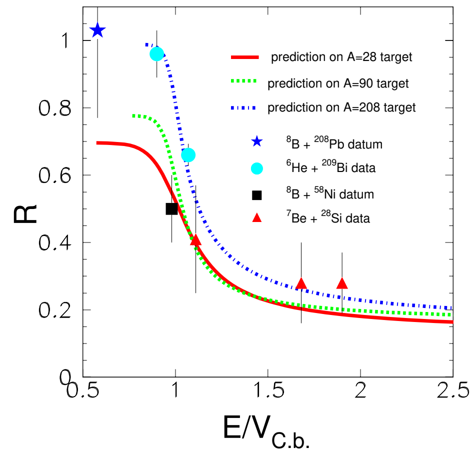

Figure 3. Ratio's, R, direct to total reaction cross section. Lines correspond to predictions obtained earlier [12], from experimental data of weakly bound neutron rich nuclei on various targets, appropriately reduced (red-solid: A=28, green-dotted A=90, blue-dotted-dashed A=208). The experimental datum for ^{8}B + ^{208}Pb [14], is designated with the blue star. A previous datum ^{8}B + ^{58}Ni with a black box [20, 21], while previous data for ^{7}Be + ^{28}Si [17] are designated with the red filled arrows, and ^{6}He + ^{209}Bi data with cyan filled circles [22].

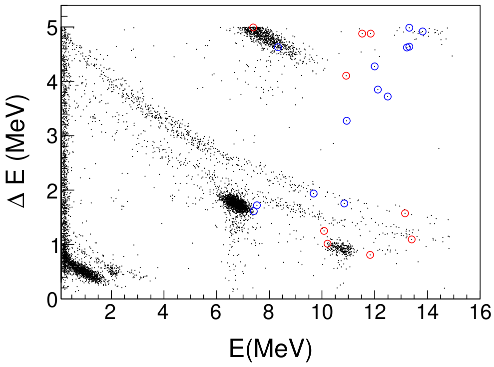

Figure 4. ΔE - E spectrum for ^{7}Be + ^{nat}Pb at 22.5 MeV. The spectrum, events denoted with black dots, is zoomed for ΔE ≤ 5 and is taken without any time window. The open circles in red and blue, denote reaction events with a time window to the ^{7}Be beam with different time bounces. The data refer to the three lower pixels of strip 27 of the DSSSD detector installed beam right, corresponding to $\theta_{lab} \approx 41°$.

cross section via CDCC of $\sigma_{tot}{}^{theory}$= 316 mb, since an experimental total reaction cross section at these energies is unobtainable. In this respect, a ratio of direct to total is determined as R=1.03±0.27. This value together with other ratios for various projectiles and targets are presented in Fig. 3. The experimental values are compared well with our phenomenological predictions [12]. The present result confirms the ratio quenching to 100% for the heavy targets, demonstrating the dominance of direct mechanisms below barrier for weakly bound projectiles and heavy targets.

We will proceed now with our preliminary analysis for the ^{7}Be + ^{208}Pb reaction at 22.5 MeV. We should note the following

α - production can originate under the following four processes.

- Breakup : ^{7}Be + ^{208}Pb → ^{4}He + ^{3}He + ^{208}Pb, S_{α} =-1.586 MeV.
- ^{3}He - stripping : ^{7}Be + ^{208}Pb → ^{4}He + ^{211}Po, Q=4.03 MeV and Q_{opt} = -10.60 MeV.
- n - stripping : ^{7}Be + ^{208}Pb → ^{6}Be + ^{207}Pb, Q= -6.74 MeV, $Q_{opt} \approx 0$ MeV.
- n - pickup : ^{7}Be + ^{208}Pb → ^{8}Be + ^{207}Pb, Q= +11.53 MeV, $Q_{opt} \approx 0$ MeV.

The ^{3}He - production can originate under the following two processes:

- Breakup : ^{7}Be + ^{208}Pb → ^{4}He + ^{3}He + ^{208}Pb, S_{α} =-1.586 MeV.
- ^{4}He - stripping : ^{7}Be + ^{208}Pb → ^{3}He + ^{212}Po, Q=-10.544 MeV and Q_{opt} = -10.60 MeV.

In Fig. 4, we present a two dimension ΔE versus E plot, zoomed in the helium area. These data are due to one strip of the DSSSD detector, corresponding to $\theta_{lab} \approx 41°$. We can observe in black, two well distinguished curves

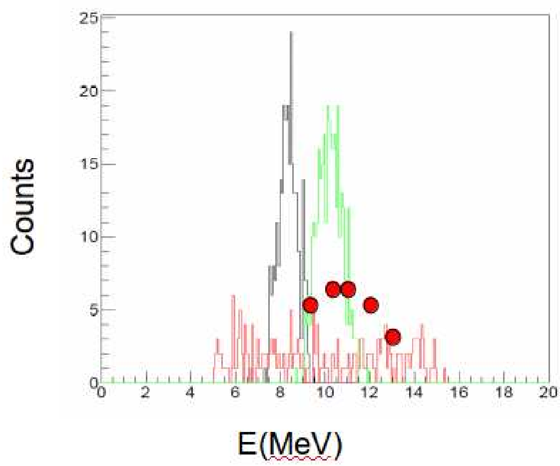

Figure 5. Simulated energy spectra for ^{3}He reaction products of the reaction ^{7}Be + ^{208}Pb at 22.5 MeV. The peaks with the black and green lines correspond to events due to elastic breakup and ^{4}He transfer, respectively. The red line correspond to non elastic breakup. The red spots correspond to our experimental energy spectra.

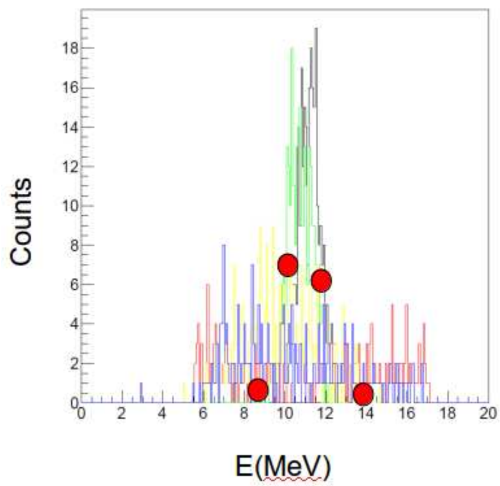

Figure 6. Simulated energy spectra for ^{4}He reaction products of the reaction ^{7}Be+^{208}Pb at 22.5 MeV. The peaks with the black and green lines correspond to events due to elastic breakup and ^{3}He transfer, respectively. Other lines correspond to all other processes underlined in the text. The red spots correspond to our experimental energy spectra.

corresponding to α- and ^{3}He - particle production. After applying the time windows corresponding solely to the ^{7}Be beam, and applying also restrictions for interstrip rejection, the only remaining events are the three ones designated with blue and red open circles (two successive rf timing pulses) for ^{4}He -particles and only one, designated with the red open circle for ^{3}He. Some events are also remaining around the elastically scattered ^{7}Be beam particles, a small part of which appears in black on the top of the Figure. The two black spots below our curves, have been identified as beam helium particles which pos-

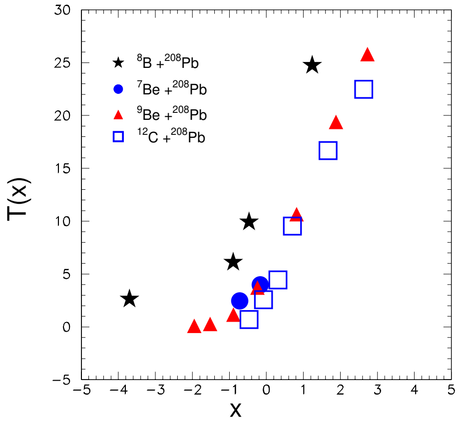

Figure 7. Reduced total reaction cross sections as a function of a reduced energy. The reduction is according to Wong relations as reported before in Ref. [23]. The cross sections are experimental or/and theoretical values from Refs. [4, 14] for ^{8}B, [24] for ^{7}Be, [25] for ^{9}Be and [26], for ^{12}C.

sibly are scattered under an angle and not perpendicular to the target and therefore accumulate in the ΔE detector less energy. Elastically scattered particles due to these beam particles, appear around the black spots.

To possibly clarify the origin of the events in the ^{3}He and ^{4}He curves by kinematics, we have performed detailed simulations. The results are included in Figures 5 and 6 for the ^{3}He and ^{4}He - particles respectively. Obviously from Figure 5 we can see that the experimental energy spectra, designated with the red spots, probe as a mechanism the cluster transfer, that is ^{4}He stripping. The situation is more complicated as expected for the ^{4}He case, where several mechanisms contribute and where the peaks due to breakup and transfer coincide. We should note here that these energy spectra is the result of events in all strips of both detectors. Also, the observed yields are quite large as we will discuss in the following section.

3 Discussion - Summary

We have outlined experimental results in relation with reaction mechanisms at deep sub-barrier energies. Two nuclei are under our investigation, by considering their induced reactions with a lead target. These are the proton halo nucleus ^{8}B, with a binding energy of only 136 keV, and the radioactive ^{7}Be nucleus with a dominant cluster structure of (^{4}He + ^{3}He) and binding energy of 1.59 MeV. The question is how these nuclei with very different structure will behave at the same deep sub-barrier energy conditions? The answer for ^{8}B was reported in Ref. [14] and it is also reviewed within this paper. In summary, the measurement of a strong and dominant breakup channel for ^{8}B on a lead target at 30 MeV, an energy corresponding to a distance of closest approach of D≈ 22 fm to be compared with a sum of radii for the two colliding nuclei of D≈ 10fm, is observed and quantified. This issue may be of paramount importance for both reaction mechanism problems but also for the structure of this challenging nucleus. At this distance of closest approach, the only interaction experienced by projectile and target nuclei, is the Coulomb one. In a simplistic approach, the proton of the halo around the compact ^{7}Be core, is tunnelling between a forbidden and allowed quantum mechanically region and at some instance of the collision, it faces the huge Coulomb potential of the lead, and scatters (breakups) to the continuum. In the conventional CDCC theory this procedure is very well accommodated and compatible results of both experiment and theory have been obtained, justifying a ratio of direct to total cross sections almost equal to one. This result is found to be in excellent agreement with our phenomenological predictions [12]. The same prediction however should apply to ^{7}Be, that is the direct cross section should almost exhaust the total reaction cross section. Our analysis is in progress in this direction. Preliminary experimental results, indicate large cross sections of the order of ≈ 100 mb. Moreover for the ^{3}He production, this mechanism is ^{4}He -stripping. Transfer mechanisms instead of a breakup process, may be well understood for ^{7}Be, from the point of view that at these large distances of closest approach, where we have no halo structure as is the case of ^{8}B, we need long range interactions, for inducing any type of reaction. Can a whole cluster of nuclei like a ^{3}He or ^{4}He nucleus tunnel through the strong Coulomb barrier of the lead target? In a conventional theoretical framework, preliminary calculations, based on elastic breakup (EBU) and non elastic breakup (NEB) mechanisms have been performed [27]. EBU is calculated into a CDCC approach, while for the NEB calculations a model proposed by Ichimura et al. [28], is employed within the distorted-wave Born approximation (DWBA). These calculations indicate total reaction cross sections of the order of ≈ 40 mb, with most of the probability to be connected with an inelastic excitation of ^{7}Be in the first excited state and only a very small probability below 1 mb, to be related with other direct mechanisms. Moreover looking to systematics of total reaction cross sections for ^{8}B and ^{7}Be, as well as of ^{9}Be and ^{12}C, presented in Figure 7, we comment the following. For stable projectiles, the total cross sections drops to zero around barrier. For the weakly bound nuclei ^{8}B and ^{9}Be around barrier starts a constant cross section quenching which for boron is close to 300 mb, while for ^{9}Be close to 10 mb. For ^{7}Be the information is limited to two points. Under an extrapolation, we expect total reaction cross sections between 30 to 170 mb, depending of the type of extrapolation and following the trend of ^{9}Be. Under the above motivation, and our preliminary results indicating large ^{3}He and ^{4}He yields, searching for a new "treasure" at deep sub-barrier energies, we plan a new experiment for ^{7}Be + ^{208}Pb in Notre Dame as long as the upgrading of *Twinsol* to *Trisol* will be complete. With the new conditions, the optimization of the secondary beam on ^{7}Be, is plausible and a clean beam of other particles, as helium beam nuclei, is expected to be produced with a high flux of the order of 10^6 pps. Such a beam could make possible the determination of cross sec-

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tions of the order of 1 mb and below. Further more another measurement will focus on the inelastic excitation of ^{7}Be by gamma spectroscopy [29].

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