Breakup of ^{8}B+^{nat}Zr at the sub-barrier energy of 26.5 MeV

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Abstract. In our systematic research on reactions with weakly bound nuclei at sub- and near- barrier energies, we have studied the system ^{8}B+^{nat}Zr at the sub-barrier energy of 26.5 MeV. Our measurements, performed at the *TriSol* radioactive beam facility of the University of Notre Dame, include angular distributions of both elastic scattering and breakup, for the determination of the total reaction and breakup cross sections as well as the direct-to-total reaction cross section ratio. Preliminary results of the breakup analysis will be presented, supported by Continuum Discretized Coupling Channel calculations.

1 Introduction

The behavior of both stable and radioactive weakly-bound nuclei at energies near and below the Coulomb barrier has been a broadly studied topic for several years [1–4]. At these low energies coupling effects are expected to have significant impact on the reaction mechanisms of these nuclei [5]. These effects are especially interesting when we consider halo nuclei, characterized by extended nuclear matter distributions and low binding energies. Nuclei with a neutron halo structure have been thoroughly explored in the past [6–13]. However, this is not the case for proton halo nuclei, where data around and below the barrier are limited. Existing results for breakup and fusion measurements for ^{17}F have been reported in [14, 15] while for the ^{8}B elastic scattering and breakup measurements were reported in Ref. [16] for ^{64}Zn, for ^{120}Sn in [17] and for ^{208}Pb in [18].

The proton-halo nucleus ^{8}B, [19, 20] has attracted the interest of the scientific community, mostly regarding its involvement in the solar production of high-energy neutrinos through the radiative capture reaction ^{7}Be(p,γ)^{8}B, [21–24]. Its very low breakup threshold of 137 keV, guarantees high cross section and suggests this nucleus as a good candidate for reaction mechanism and coupling effect studies in relation with breakup measurements. Despite the large cross sections, strong couplings near and below the barrier have not been reported so far in the literature [17, 18, 25].

A second motivation for this work is a phenomenological prediction based on fusion and total reaction cross section measurements for weakly-bound nuclei, originally mentioned in [26]. According to this prediction, the ratio between the direct cross section and total reaction cross section shows the following behavior when examined as a function of the energy: at energies above the barrier the ratio is mostly constant and approximately 20%, but as the energy decreases below the barrier, this ratio increases rapidly, exhibiting target dependence. For light targets the direct-to-total ratio can reach a value of 70%, for medium mass targets a value of 80% while for heavy targets it can reach a value up to 100%. This observation suggests a possible hindrance of fusion reactions below the barrier for weakly-bound nuclei. This systematic is mostly based on stable and neutron-rich weakly-bound nuclei and so it raises the question whether a proton halo nucleus, such as ^{8}B would follow this trend.

Motivated by the above prediction, our group started a series of measurements in 2019, with the first measurement being the elastic scattering and breakup for ^{8}B on the heavy target ^{208}Pb at an energy ~ 60% of the Coulomb barrier. The results of this work are reported in [18], where the direct cross section appeared to exhaust the total reaction cross section and the direct-to-total cross section ratio value was found to be close to 1. The work reported here is a continuation of this study with the medium-mass target ^{nat}Zr. For this reaction the transfer probability is expected to be negligible and therefore breakup will be the dominant direct mechanism.

In the present experiment we have collected data for elastic scattering of ^{8}B+^{nat}Zr at the sub-Coulomb barrier energy of 26.5 MeV ($V_{C.b.}$ = 30.4 MeV) [27], and simultaneously we have performed breakup measurements. Our preliminary breakup results will be presented here. Alongside of these, elastic scattering measurements on the weakly bound nucleus ^{7}Be on the same target at five sub-barrier energies have been performed and reported in [28].

In Section 2 we will describe the experimental process for the collection of the data, in Section 3 the breakup analysis and preliminary results will be presented and discussed and finally in Section 4 a summary and conclusions of this work will be given.

2 Experimental Details

The experiment was performed at the *TriSol* radioactive beam facility, of the Nuclear Science Laboratory (NSL) of the University of Notre Dame [29]. For the in-flight production of the ^{8}B beam, with the NSL's 10 MV FN tandem accelerator, a two-proton transfer reaction was employed, with ^{6}Li as the primary beam, accelerated at 37 MeV and impinged on an ^{3}He gas target at a pressure of 850 Torr. The secondary cocktail beam consisted of ^{8}B (10%) at 27.7 MeV, ^{7}Be (22%) at 20.1 MeV and ^{7}Li (40%) at 14.9 MeV. The secondary products were focused from the three superconducting solenoids and guided to a ^{nat}Zr target with thickness 1.95 mg/cm^{2}. The reaction energies of the secondary products at the middle of the target correspond to 26.5 Mev for ^{8}B, 19.2 MeV for ^{7}Be and 14.3 MeV for ^{7}Li. The flux of the ^{8}B beam varied throughout the experiment from ~ 1500 - 6000 pps.

Details on our detection system with four two-stage ΔE-E telescopes: first stage a DSSSD (Double-Sided Strip Silicon Detectors) 15 to 20 μm thick and as a second stage a pad Si detector, 130 to 500 μm thick, are given in our previous work, [18, 27]. The telescopes were placed symmetrically around the target at a distance of approximately 6 cm, to cover an angular rage of 20^{o}-60^{o} degrees in the forward direction and 110^{o}-150^{o} degrees in the backward direction. The detector set-up can be seen in Fig. 1.

Additionally, a Time of Flight (TOF) requirement was imposed. The signal at the first stage of the telescope, the DSSSD, was used as the START signal and the rf timing pulse of the beam buncher, as the STOP signal.

The elastic scattering data were extracted using a ΔE-E technique. Data collected at ~ 25^{o} degrees are shown in Fig. 2. The elastic scattering angular distribution and total

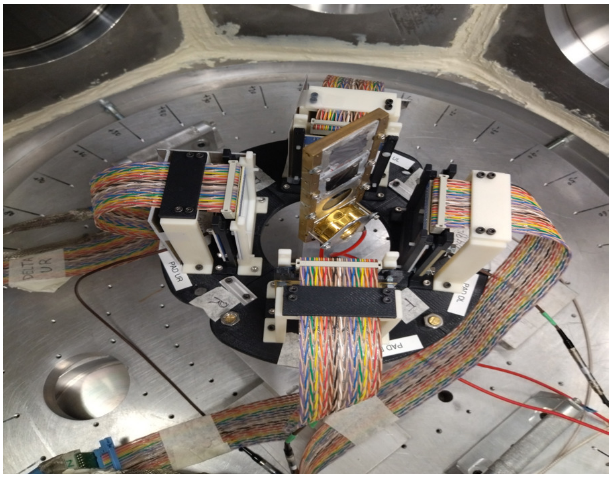

Figure 1. Detector set-up. Four ΔE-E telescopes positioned symmetrically around the ^{nat}Zr target.

reaction cross section have been obtained, as described in detail in [27]. The deduced total reaction cross section is σ = 180 ± 40 mb.

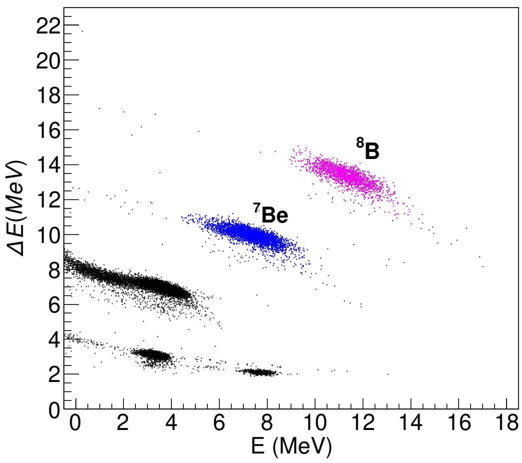

Figure 2. ΔE-E plot. The data are collected at ~ 25^{o}. Elastic ^{8}B is marked with pink and elastic ^{7}Be with blue. Fig. from [27].

3 Breakup Analysis

For the measurement of breakup cross section, it is crucial to be able to separate the breakup products from the elastically scattered ^{7}Be due to the cocktail beam including not only ^{8}B but also ^{7}Be and ^{7}Li. For this, we have used the time-of-flight method. Typical E_{tot}-TOF spectra are shown in Fig. 3. The plots contain data from three successive strips corresponding to an angular range of 24^{o}-33^{o} degrees. The breakup products appear with the same time-of-flight as the elastic ^{8}B. As can be seen in the bottom spectrum of Fig. 3, by taking the appropriated time windows related to ^{8}B, one can obtain the breakup events, clearly separated from the elastically scattered ^{7}Be.

We have analyzed the first part of the data collected during this experimental work, and obtained the breakup

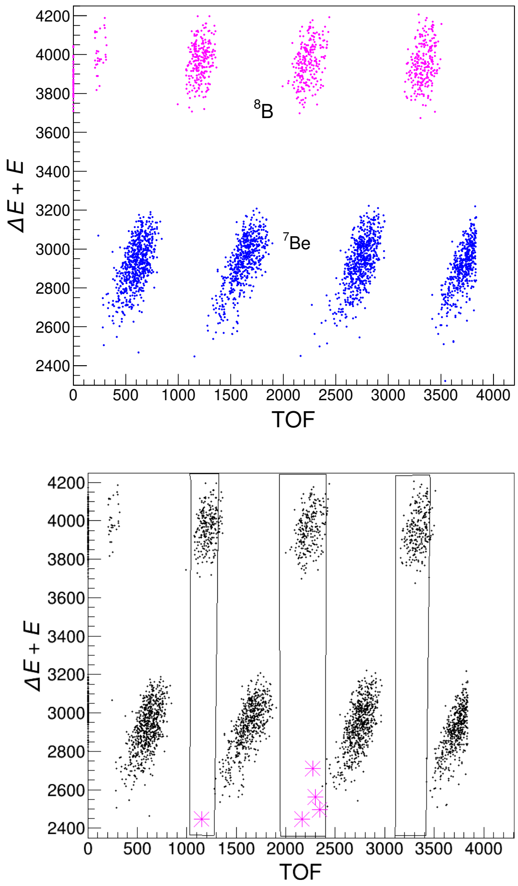

Figure 3. Time of Flight versus total energy spectra, in four rf cycles of the bunched beam. (top) ^{8}B is marked with pink and ^{7}Be with blue. (bottom) The black boxes represent time windows. The breakup products are marked with the pink stars.

events with the aforementioned method. In these runs there is the advantage of clear E_{tot}-TOF spectra allowing the distinction of the breakup events. However, the beam flux of the runs was on the lower end of the range, ~1500 pps, resulting to low statistics. We have calculated the differential breakup cross sections, $\sigma_{bu}(\theta)$, and probabilities, p(θ), according to the following equations:

$$\sigma_{bu}(\theta) = \frac{N_{bu}(\theta)\sigma_{el}(\theta)}{N_{el}(\theta)} \tag{1}$$

$$p(\theta) = \frac{N_{bu}(\theta)}{N_{el}(\theta)} \tag{2}$$

with $N_{bu}(\theta), N_{el}(\theta)$ the number of events for breakup and elastic scattering of ^{8}B respectively and $\sigma_{el}(\theta)$ the Rutherford cross section at these angles.

The obtained experimental differential cross sections are presented in Fig. 4, and the probabilities in Fig. 5, compared with CDCC calculations. Some details about the calculations are given in [27]. It is important to note here that the statistical errors are quite large due to the poor statistics.

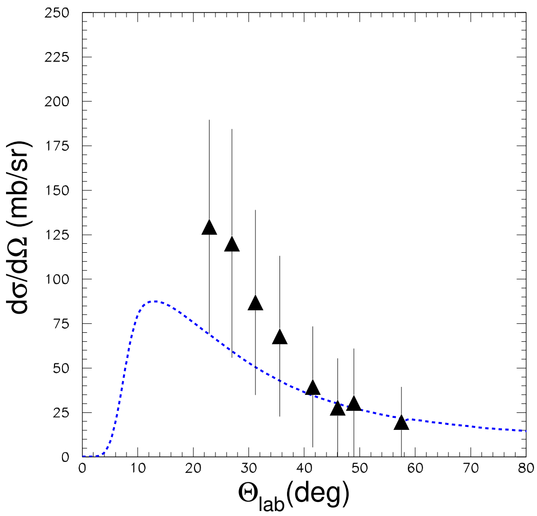

Figure 4. Breakup angular distribution. Experimental data (black triangles) are compared with CDCC calculation (blue dashed line).

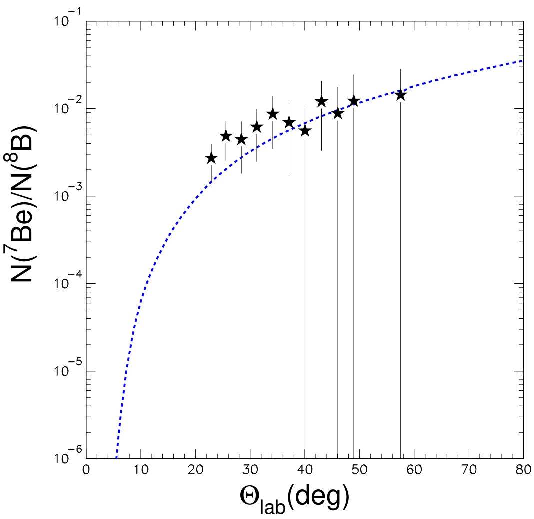

Figure 5. Breakup probabilities. Experimental data (black stars) are compared with CDCC calculation (blue dashed line)

From Figs. 4, 5 one can observe that the experimental data and the theory seem to be in fair agreement, even though the CDCC calculation appears to underestimate the breakup cross sections, especially in the more forward angles, while the agreement improves as the angle increases.

From this analysis, the integrated breakup cross section is expected to be ~ 200 - 250 mb, a value close to the total reaction cross section, deduced from the elastic scattering analysis. Breakup seems to exhaust the total reaction cross section, unlike what was expected from systematic, predicting a direct-to-total ratio value close to 0.85. Further analysis is in progress, with data of better statistics but where the separation between ^{7}Be breakup fragments and ^{7}Be beam particles is done taking into account kinematics and extensive simulations.

4 Conclusions

In summary, in this work we have presented the results for our recent breakup measurements on ^{8}B+^{nat}Zr at the sub-barrier energy of 26.5 MeV, collected at the *TriSol* facility of the University of Notre Dame. Experimental differential cross sections and probabilities have been obtained and compared with CDCC calculations.

From these preliminary results we conclude, a fair agreement between experimental data and the CDCC theory, while the breakup cross section is found to exhaust the total reaction cross section, in contradiction with systematic. This can imply that ^{8}B, as a proton halo nucleus, displays different behavior from weakly bound stable nuclei and/or exotic nuclei with a neutron halo structure.

However, within this work firm conclusions cannot be obtained, due to the large statistical errors of the experimental data. This will be further clarified with the analysis of the remaining part of the collected data, which is in progress.

Acknowledgments

K. Palli acknowledges the support by the Hellenic Foundation for Research and Innovation (HFRI) under the 4th Call for HFRI Ph.D. Fellowships, Grant No. 009194.

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