Evaporation protons from $^{8}\text{B}+^{58}\text{Ni}$ at near barrier energies

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Abstract. Yields of evaporated protons from the $^{8}\text{B}+^{58}\text{Ni}$ reaction are measured at backward angles, for several near barrier energies. Statistical model calculations using the code PACE are used to extrapolate the measurements to the whole angular region in order to get angle integrated cross sections. Fusion cross sections are deduced by using the calculated proton multiplicities. The obtained fusion excitation function shows a large enhancement as compared to BPM calculations using conventional barrier parameters.

1. Introduction
The short-lived radioactive nucleus $^{8}\text{B}$ is adjacent to the proton drip line and has a very small proton separation energy of only 0.138 MeV. It has attracted much attention because it may have a proton halo. Evidence for this, both theoretical and experimental, has appeared in the literature in recent years [1–10].

The present work is part of an effort to clarify the proton-halo wave function of $^{8}\text{B}$ as it relates to reaction cross sections at near barrier energies. For this purpose, studies of fusion, breakup and total yields are important. The kinematic regime near the barrier emphasizes peripheral reactions, where halo signatures are most probable to appear. For the $^{8}\text{B}+^{58}\text{Ni}$ system, the breakup measurement of Refs. [1, 2] did certainly show such a possible signature: Coulomb-nuclear interference at very large distances was shown to play an important role.

As for total reaction yields, very recently it was shown that the near- and sub-barrier reaction yields for $^{8}\text{B}$ show striking similarities with previous observations for the neutron-halo projectile...
2. Antecedents

For $^6$He projectiles, large enhancements were observed below the barrier for a $^{209}$Bi target [11–13], and also for targets closer to $^{58}$Ni [14, 15]. For systems with lighter targets such as $^6$He+$^{12}$C [16] and $^6$He+$^{27}$Al [17], the neutron halo effects seemed to be smaller. We will first show the data recently obtained for the proton-halo projectile $^8$B, and then a comparison with data corresponding to the neutron-halo projectile $^6$He will be done.

2.1. Total reaction yields for $^8$B projectiles

Elastic scattering angular distributions were reported for $^8$B+$^{58}$Ni at five near barrier energies [18]. Optical model fits to the data were used to extract the corresponding total reaction cross sections. Since nuclei of $^6$Li and $^7$Be were also present in the beam in substantial amounts, data for these two projectiles were also obtained and analyzed. The $^7$Be projectile is particularly interesting because it is the core of $^8$B, so a comparison between these two projectiles should in principle give information about the reactions of the halo.

In order to make the comparison, reduced cross sections and reduced energies were used, according to the expressions

$$\sigma_{\text{Reduced}} = \sigma_R / (A_p^{1/3} + A_t^{1/3})^2, \quad E_{\text{Reduced}} = E_{\text{c.m.}} / [Z_p Z_t / (A_p^{1/3} + A_t^{1/3})].$$

This reduction of data is expected to eliminate trivial effects of size and charge, thus making data for different systems directly comparable.

Fig. 1 shows the comparison for the three projectiles. The halo system seems to define a single trajectory in this plot, while the data for $^7$Be and $^6$Li seem to group also in one single trajectory, different from the previous one. An important point is that in this reduced plot the trajectory for the halo nucleus lies above that for the weakly bound projectiles, which could be an actual signature for the presence of the halo. A comparison with additional systems reported in the literature seems to corroborate this conclusion, as described in next section.

![Figure 1](image1.png)  
**Figure 1.** Total reaction cross sections for the ($^8$B,$^7$Be,$^6$Li)+$^{58}$Ni systems, plotted in reduced form. Data from Ref. [18].

![Figure 2](image2.png)  
**Figure 2.** Comparison of reduced cross sections for twelve different systems. Figure adapted from Ref. [19].
2.2. Comparison to other systems
In Ref. [19], the above results were compared to the reported data for other systems, which include the neutron-halo projectile $^6\text{He}$ as well as several isotopes of Li and Be, which are weakly bound. In addition, data for the strongly bound projectile $^{16}\text{O}$ were also included in the comparison.

We see in Fig. 2 that the reduced cross sections for all studied weakly bound (but otherwise normal) systems lie on the same trajectory when plotted as a function of reduced energy. A similar conclusion applies to the halo systems, but the respective trajectory lies above the previous one. The trajectory corresponding to the $^{16}\text{O}$ projectile, on the other hand, is the one lying lowest in the plot. In other words, if we characterize the trajectories by a mean value of the respective projectile binding energies, they lie progressively lower in the plot with increasing binding energy.

It was also shown [19] that the trajectories could be characterized by respective Wong-model [20] fits. These fits are illustrated with the curves in Fig. 2. The results of this figure seem to rule out previous conclusions [17] that for $^6\text{He}+^{27}\text{Al}$, the neutron halo effects seem to be smaller. The most striking result is the fact that the reduced cross sections for the proton-halo nucleus $^8\text{B}$ and the two-neutron-halo nucleus $^9\text{He}$ follow identical trajectories despite differences in the structure, binding energy, and reaction mechanisms [18] of these systems. It is expected that the fusion measurements for $^8\text{B}$ will help further understand the peculiarities of the proton-halo system.

3. Experimental details
The $^8\text{B}$ beam was obtained from primary $^6\text{Li}$ projectiles through the $^3\text{He}(^6\text{Li},n)^8\text{B}$ direct transfer reaction using the TwinSol radioactive nuclear beam facility at the University of Notre Dame [21]. The basic setup of the TwinSol facility consists of a production target chamber, where the primary reaction takes place and in which the radioactive $^8\text{B}$ beam is produced. Two superconducting solenoids are used to collect, transport, analyze and focus the beam into a secondary chamber, where the secondary reaction takes place. For this experiment, the secondary target was a natural Ni sheet of 2.22 mg/cm$^2$, of 8.9 cm $\times$ 8.9 cm, which was bombarded with the $^8\text{B}$ beam at three different mean fusion energies in the center of mass reference frame (19.9, 21.9 and 23.8 MeV).

The experimental arrangement is shown in Fig. 3. Four $\Delta E-E$ silicon surface-barrier telescopes (A, B, C and D) were placed at backward angles (112.5°, 127.5°, 142.5° and 157.5°) to detect the evaporated protons from the fused system, while two detectors (E and F) were placed at forward angles to monitor the beam. Before starting the experiment, another detector (G) was placed at the secondary target position to characterize the beam. The beam intensity was reduced by a factor of $10^3$ during the characterization and the detector was taken away during the real experiment. A sample of the beam spectrum for the highest experimental energy is shown in Fig. 4, where the main beam components ($^6\text{Li}$, $^7\text{Be}$ and $^8\text{B}$) are clearly separated by time-of-flight. A small contamination due to the $^7\text{Li}$ and $^3\text{He}$ components of the beam might be present in the proton yield associated to $^8\text{B}$ since the corresponding times-of-flight are similar. In contrast to $^8\text{B}$, the $^7\text{Li}$ beam energies are always below the corresponding Coulomb barrier. This, combined with the fact that proton multiplicities for $^7\text{Li}+^{58}\text{Ni}$ are about a factor of two lower than the ones for the $^8\text{B}$ beam, leads to a negligible effect on the proton yields. For $^3\text{He}$, however, there was an effect on the proton yields of about 10% so it was necessary to consider this contribution. The respective correction was only considered for the highest energy, since for the other two energies the $^3\text{He}$ could be separated from $^8\text{B}$ by time of flight.
4. Results and discussion
The results for the corresponding fusion excitation function for the three energies are presented in Fig. 5. Proton multiplicities calculated with the code PACE [22] were used to estimate these fusion cross sections. The solid line in this figure is a one-dimensional barrier penetration model (BPM) calculation and it is shown for comparison purposes. The corresponding barrier parameters ($V_b = 20.8$ MeV, $\hbar \omega = 5.53$ MeV and $R_b = 8.75$ fm) represent the typical barrier expected from the systematics for normal systems, which by comparison with the experimental data indicates a large fusion enhancement. This result seems to indicate an effect of the proton-halo of the $^8$B nucleus.

In Fig. 6, the solid line is a three parameter fit of the data with Wong’s function [20]. An integrated breakup cross section from Ref. [1] is shown by the square and a CDCC calculation,
performed for the $^8$B breakup channel [23], is represented by the dotted line. Also displayed in this figure is the experimental total reaction cross section (black diamonds), reported for the $^8$B+$^{58}$Ni system in Ref. [18]. As for the most important reaction channels associated to the present system, it can be seen that the sum of the CDCC calculations for the breakup plus the fusion cross sections reported in the present work (sum shown by the dashed line), seem to saturate the total reaction cross section. We conclude then that other possible reaction channels such as the proton transfer channel should be, at most, very weak. This conclusion was in fact anticipated both from comparison with the $^7$Be core in Ref. [18] and from respective CDCC calculations in Ref. [23].

5. Conclusions
Evaporation protons from the $^8$B+$^{58}$Ni system were measured at three near barrier energies. The proton multiplicities calculated with the code PACE were used to estimate the respective fusion cross sections. The resulting excitation function shows a large enhancement with respect to expectations for normal systems, an effect that is most probably related to the proton-halo nature of $^8$B. By considering the results for the different reaction channels for this system, evidence is presented indicating that the breakup and the fusion channels saturate the total reaction cross section. This is consistent with previous estimations [18, 23] about the proton transfer channel being weak or negligible.

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