Near-barrier fusion of proton rich systems

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Abstract. Recent near-barrier measurements for fusion of the proton-halo system 8B.58Ni (Aguilera E F et al. 2011 Pys. Rev. Lett. 107 092701) showed unexpected results. In contrast to previous results for neutron-halo systems, for instance, the respective fusion cross sections are enhanced for both, below- and above-barrier energies. The charged nature of the halo could thus have an effect on the fusion mechanism. Within this context, in the present work the fusion cross sections for several proton rich systems are compared to each other. Three of these systems correspond to the same target, 58Ni (with projectiles of 3He, 7Be, and 8B), but data for 17F + 208Pb also are included. All these projectiles lie near the proton drip line. An appropriate scaling of the data is made to do the comparison and the results are discussed.

1. Introduction
The motivation for the present work is closely attached to the recent results for the fusion of 8B.58Ni [1]. The main interest of these data comes from the fact that 8B is a proton-halo nucleus in its ground state, and these were actually the first fusion measurements reported for a projectile with such a feature. The data showed a striking enhancement, at all energies, with respect to the expectations for a bare potential. While sub-barrier enhancements are nowdays commonplace, and the mechanisms producing them are rather well established, there is no known mechanism that can produce such a big fusion enhancement above the barrier. In fact, these data fall out of the systematic behavior observed for many weakly-bound systems, including the neutron-halo systems that have been measured. Indeed, the systematics [2–4] shows that, with respect to an appropriate standard reference (see below), complete fusion (CF) of stable weakly bound nuclei is suppressed at energies above the barrier and enhanced below the barrier, while total fusion (TF) for the same systems coincides with said reference at energies above the barrier. As for neutron-halo systems, the measured total fusion cross sections with different targets seem to show a suppression above the barrier and an enhancement at sub-barrier energies.

It is important to consider some issues that might help assess the validity of the observed behavior for the proton-halo system. With respect to the method used to extract the fusion cross sections out from the measured protons, in Ref. [5] arguments are given about the reliability of the procedure. Also, other systems have been studied experimentally with the same method, with quite reasonable results. The fusion data for 3He + 58Ni published in Ref. [6], for instance, were obtained with the same technique. Also, since 6Li was the main contaminant in the 8B beam used in Ref. [1], data for fusion of the 6Li + 58Ni system were obtained simultaneously.
A preliminary analysis of these data indicates quite good consistency with previous results for the similar system $^6$Li + $^{59}$Co [7], which were obtained by another group, using a quite different technique. It is thus important to search for a mechanism that might explain the observed enhancement in the proton-halo system. From the experimental point of view, it is interesting to look at data for other systems that could possibly shed some light on this issue. As a step in this direction, in the present work a comparison is made with similar data for other proton-rich projectiles. The fact that in this context proton-halos seem to behave so differently from neutron-halos, the first showing enhancement while the latter show suppression above the barrier, leads one to think that the charge might be playing an important role.

In next section, the projectiles that will be compared are listed and the method of comparison is described. The results are presented in section 3, where a correlation between the above-barrier cross sections and the breakup threshold energy of the projectile is noticed. A discussion of the results in semiclassical terms is given in section 4 and, finally, a summary and the conclusions of the present work are presented in section 5.

2. Systems considered and method of comparison

Data for five systems were compared to each other, four of them corresponding to proton-rich projectiles and one reference system. Three of the data sets were taken by our own group, using the same technique. These are the already mentioned results for the proton-halo nucleus $^8$B [1] and newer data for the radioactive nucleus $^7$Be [8] and for the stable nucleus $^3$He [6], all of them with the same target, $^{58}$Ni. $^7$Be is actually the core for $^8$B, which can be considered as a proton weakly bound to this core, with $E_{th}=0.14$ MeV. Like $^8$B, the $^7$Be nucleus lies also on the proton-rich side of the line of stability, and it is weakly-bound, with a threshold separation energy $E_{th}=1.59$ MeV, corresponding to separation into clusters of $^4$He and $^3$He. Being stable, the $^3$He isotope is an extreme case of proton-rich nuclei; it actually lies on the edge of the proton drip-line, in the light mass end. Also, although maybe one cannot say that it is weakly-bound, its threshold separation energy ($E_{th}=5.49$ MeV, for separation into $d + t$) is below the typical value for normal nuclei. In the comparison, we included also existing data for fusion of the $^{17}$F + $^{208}$Pb system [9], whose projectile is actually known to have an excited state with a proton-halo. It is unlikely, however, that the halo state could come into play during the fusion process. Nevertheless, this nucleus certainly has a proton excess and it is weakly-bound too. Its threshold separation energy, into $^{16}$O + $p$, is $E_{th}=0.6$ MeV. Finally, as a reference, fusion data for the tightly-bound projectile $^{16}$O also were included in the comparison, with a $^{58}$Ni target [10]. All data sets considered here refer to total fusion, i.e., not only complete fusion but also incomplete fusion, if any, is included in the cross section data.

For the purpose of comparing the fusion data for different systems, we followed the prescription of Canto et al. [2, 3]. The barrier parameters $V_B, R_B, \hbar\omega_0$, are obtained from a realistic bare potential and used to reduce the cross section and the energy through the expressions

$$F(x) = \frac{2E}{\hbar\omega_0 R_B^2} \sigma, \quad x = \frac{E - V_B}{\hbar\omega_0}. \quad (1)$$

As a reference to decide whether the data present enhancement or suppression, the reduced cross sections can then be compared with the so called universal fusion function (UFF),

$$F_0(x) = \frac{2E}{\hbar\omega_0 R_B^2} \sigma^W = \ln[1 + e^{(2\pi x)}], \quad (2)$$

where $\sigma^W$ stands for the expression derived for the cross section in the one-dimensional barrier penetration model of Wong [11]. With this reduction, it makes sense to compare reduced data for different systems directly in the same plot. To get the barrier parameters, we used always
the double-folding São Paulo Potential (SPP) [12], with default values for the matter and charge densities. A summary of the systems to be compared and the respective barrier parameters is presented in Table 1. Note that the data for the $^7\text{Be} + ^{58}\text{Ni}$ system are still preliminary, but we may say that the points that will be shown are most probably in their final form.

### Table 1. Summary of systems analyzed and respective barrier parameters.

| System         | Reference | $R_B$ (fm) | $V_B$ (MeV) | $\hbar\omega_0$ (MeV) |
|----------------|-----------|------------|-------------|-----------------------|
| $^3\text{He} + ^{58}\text{Ni}$ | [6]       | 8.60       | 8.59        | 4.25                  |
| $^7\text{Be} + ^{58}\text{Ni}$ | [8]$^*$    | 8.96       | 16.58       | 3.79                  |
| $^8\text{B} + ^{58}\text{Ni}$  | [1]       | 8.92       | 20.80       | 4.14                  |
| $^{16}\text{O} + ^{58}\text{Ni}$  | [10]    | 9.41       | 31.66       | 4.44                  |
| $^{17}\text{F} + ^{208}\text{Pb}$ | [9]      | 11.65      | 85.32       | 4.76                  |

* preliminary data

In the sub-barrier region, Wong’s formula is inaccurate for systems as light as the ones considered in the present work, which would make the UFF (eq. 2) unsuitable as a reference in this region. To account for this, a renormalization of the cross sections is made $[2, 3]$ by using properly calculated cross sections, $\sigma_{\text{calc}}$. The first expression of eq.(1) is then replaced by

$$F(x) \rightarrow \frac{\sigma_{\text{exp}}}{\sigma_{\text{calc}}} F_0(x).$$ (3)

To get $\sigma_{\text{calc}}$, an optical model (OM) calculation was done for each system by using the respective SPP for the real part and an interior imaginary potential of Woods-Saxon form, with parameters $W_0 = 50$ MeV, $r_W = 1.06$ fm, $a_W = 0.2$ fm. The absorption in this potential effectively simulates an incoming wave boundary condition, thus providing a good estimation for fusion.

### 3. Results

Figure 1 shows the comparison of the reduced fusion cross sections (renormalized) for the five systems of Table 1. The universal fusion function is shown with the dotted line. Thanks to the renormalization performed, this line remains a good reference for the purpose of deciding about enhancement or suppression in the whole energy region.

For the $^8\text{B}$ data, the large enhancement already mentioned can be appreciated. An interesting new information is that for $^7\text{Be}$ there is also evidence for enhancement above the barrier. This enhancement is not as big as for boron, but it seems to be real. For interpolation purposes, a three-parameter fit using Wong’s function $[11]$ was done to each data set, shown with the solid curves. This very reasonable interpolation shows evidence for enhancement above the barrier in the case of the $^{17}\text{F}$ data also, and this enhancement seems to be even higher than that for $^7\text{Be}$. The helium data, on the other hand, seem to show a suppression above the barrier.

A clearer view of the enhancements is obtained by taking the ratios between the interpolation curves in Fig. 1 and the dotted curve, the UFF. The resulting enhancement curves are shown in Fig. 2, which includes only reduced energies above $x = -0.5$ because this is the region we want to emphasize. For energies far enough above the barrier, these enhancement curves become flat. The $^{16}\text{O}$ curve is a bit enhanced in this region, mainly due to the effect of couplings with inelastic excitations $[10]$. If one does coupled channel calculations for the boron or the beryllium systems and includes the relevant inelastic excitations, the effects on fusion are negligible. So,
Figure 1. Reduced fusion data for five systems. The solid curves are Wong function fits to the respective data while the dotted curve is the UFF (eq. 2). $E_{\text{th}}$ refers to the breakup threshold energy for each projectile.

Figure 2. Enhancement curves, with respect to the dash-dotted line of Fig. 1.

Figure 3. Correlation between the fusion enhancement at $x = 1$ and the breakup threshold energy of the projectile.

A different mechanism is needed to explain the larger enhancements observed for these systems. Indicated in Fig. 2 are the threshold energies ($E_{\text{th}}$) needed to separate each projectile into two clusters. Looking carefully, one may notice a correlation between the observed enhancements, in the region where the curves are flat, and these energies. To further investigate this point, we took the enhancements at $x = 1$, where the curves are already pretty flat, and plotted the respective values versus $E_{\text{th}}$, as shown in Fig. 3.

Quite surprisingly, this plot shows a nice correlation between the reduced cross sections at “high energy” and the breakup threshold energies of the projectiles. In the logarithmic scale of the figure, the points lie along a well defined straight line. The question remains as to the physical reasons lying behind this correlation. A complete theoretical explanation of this is beyond the scope of the present work. Instead, some simple semiclassical considerations will be made in next section, which might help to get further insight into this matter.
4. Discussion

Let’s assume temporarily that we have a projectile formed by two nearly uncoupled charged clusters, which approaches some target and gets exposed to the respective Coulomb field (see Fig. 4a). In classical terms, the acceleration on each cluster is easily calculated and its ratio is given in terms of the respective charges and masses, \( a_1/a_2 = Z_1 A_2 / Z_2 A_1 \). If this ratio is less than one, the light cluster tends to stay behind. Table 2 presents the most probable clusterization of our projectiles, and the respective values of the acceleration ratio. This ratio is less than one in all cases, so according to our classical argument, the light cluster in each case would tend to stay behind. Of course, these classical arguments are suspect for a quantum system, but Esbensen and Bertsch [13] have made breakup calculations for \(^8\text{B} + ^{58}\text{Ni}\), where the boron is treated quantically, showing that Coulomb polarization is quite important in this process.

While the hypothesis of nearly uncoupled clusters is probably valid for halo nuclei such as \(^8\text{B} [14]\), it will break down for other projectiles. Intuitively, one can expect that the binding energy of the clusters would play a role in this polarization process: the larger the binding the harder the polarization of the projectile. So, this could be the mechanism underlying the correlation that we observed in Fig. 3. But there is still the question as to how could this mechanism actually contribute to the fusion enhancement.

Suppose that we have our B-Ni system in the fully polarized configuration at a distance \( r \) between the respective centers of mass, as illustrated in Fig 4b. We can estimate how the Coulomb barrier is modified in this situation. The interaction potential can be calculated as a superposition of the contribution of the Be cluster plus the contribution of the proton

\[
V_{B\text{Ni}}(r) = V_{Be\text{Ni}}(r - r_p/8) + V_{p\text{Ni}}(r + 7r_p/8). \tag{4}
\]

For the first part, we used the S\~ao Paulo Potential for \(^7\text{Be} + ^{58}\text{Ni}\). For the p-Ni system, the nuclear potential is negligible in the region near the barrier and for the respective Coulomb part we used the potential of a point plus a spherical charge distribution of the proper radius. As a
Table 2. Projectile clusters and respective separation energies and acceleration ratios.

| Proj. Clusters | $E_{th}$ (MeV) | $Z_1$ | $A_1$ | $Z_2$ | $A_2$ | $a_1/a_2$ |
|---------------|----------------|-------|-------|-------|-------|------------|
| $^8$B $^7$Be + p | 0.14           | 4     | 7     | 1     | 1     | 4/7        |
| $^{17}$F $^{16}$O + p | 0.6           | 8     | 16    | 1     | 1     | 1/2        |
| $^7$Be $^4$He + $^3$He | 1.59         | 2     | 4     | 2     | 3     | 3/4        |
| $^3$He $^2$H + p | 5.49           | 1     | 2     | 1     | 1     | 1/2        |

reasonable estimation, for the radius of the orbit of the valence proton in boron we used $r_p \sim 3$ fm.

Figure 5 shows the obtained results, where the blue curve corresponds to the polarized barrier. Its height is considerably lower than that of the bare (unpolarized) potential, shown in black. The barrier radius is also slightly increased. Both of these effects should produce an enhancement on the fusion cross section. It is interesting to compare the importance of the nuclear and the Coulomb parts in this process of lowering the barrier. If we assume that the nuclear interaction stays the same as in the bare potential and estimate only the change of the Coulomb potential due to the dumbbell configuration, we get the red curve. Clearly, the nuclear interaction plays the main role.

To get an idea about the magnitude of the enhancement induced by the above polarized potential, a barrier penetration model (BPM) calculation using this barrier was performed. The result, shown in Fig 6 (blue curve) is rather encouraging: it almost describes well the data. Further measurements are required to corroborate the observed fusion enhancements and more rigorous theoretical calculations are needed to understand them. Based on the results of this work, it is fair to say that Coulomb polarization might be playing an important role.

**Figure 6.** BPM calculations for the bare (solid) and the polarized (dash) potentials of Fig. 5.

**Figure 7.** Visualization of the possible role of Coulomb polarization in the reactions involving halo nuclei.
5. Conclusions
The near-barrier fusion cross sections measured for several proton-rich projectiles ($^3$He, $^7$Be, $^8$B, $^{17}$F) were compared to each other and to those corresponding to a reference projectile ($^{16}$O). A reduction of data was done to make the comparison, by using the prescription of Canto et al. [2,3] and the São Paulo potential to get the corresponding barrier parameters. Evidence for enhancement above the barrier was pointed out for projectiles of $^7$Be, $^8$B and $^{17}$F while the opposite holds for the $^3$He projectile. For energies sufficiently above the barrier ($E \sim V_B + \hbar \omega$), a correlation was found between the reduced cross sections and the breakup threshold energy of the projectile. Simple semiclassical considerations point to Coulomb polarization as the possible mechanism underlying the observed behaviour.

Further pursuing this hypothesis, it is tempting trying to visualize the proton-halo effects observed so far, as opposed to the respective neutron-halo effects, by using the physical picture illustrated in Fig. 7. For neutron-halo nuclei, Coulomb polarization favors neutrons in the halo residing in the region between the core and the target, which then enhances the reaction probabilities. This is consistent, for instance, with the observation that for $^6$He + $^{209}$Bi the main reaction mechanism in the near-barrier region is 2n transfer. In contrast, polarization of the proton-halo projectile via the Coulomb force, results in the valence proton spending more time at large distances from the target, where it is shielded by the core from the full Coulex effect. In this case, core-halo breakup would occur mainly through the long range Coulomb force, and p-transfer would be suppressed. The projectile would “see” a lower barrier, thus enhancing fusion.

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