

Near-barrier fusion of proton- and neutron-halo systems

E F Aguilera

Departamento de Aceleradores, Instituto Nacional de Investigaciones Nucleares, Apartado Postal 18-1027, C. P. 11801, México, D. F., México

E-mail: eli.aguilera@inin.gob.mx

Abstract. It is shown that the behaviour of the fusion excitation functions for proton-halo and neutron-halo systems presents important differences, especially in the energy region slightly above the barrier. Measurements for ${}^6\text{He}$, ${}^{11}\text{Li}$ and ${}^{11}\text{Be}$ projectiles are discussed to exemplify the behaviour of neutron-halo systems, while experiments with ${}^8\text{B}$ beams illustrate the situation for proton-halo nuclei. With respect to a standard benchmark, neutron- (proton-) halo systems show a fusion suppression (enhancement) above the barrier.

1. Introduction

In the later two decades, fusion cross sections near the Coulomb barrier have been measured for several neutron-halo systems, but only recently a couple of true proton-halo systems (*i.e.*, having a proton-halo in its g.s.) have been studied in this context.

The aim of this work is to show that the behaviour of the fusion excitation functions for halo systems presents important differences depending on whether the halo is charged or neutral. More precisely, it will be shown that proton-halo and neutron-halo systems behave differently, especially in the energy region slightly above the barrier.

The work starts with a reminder about the behavior of neutron-halo systems, whose main feature is that they present a fusion suppression above the barrier (Sec. 2). Then, in Sec. 3 some apparently controversial data will be shown, corresponding to two proton-halo systems: ${}^8\text{B} + {}^{58}\text{Ni}$ (Sec. 3.1) and ${}^8\text{B} + {}^{28}\text{Si}$ (Sec. 3.2). These data have been critically reviewed recently, as described below. On one hand, a possible contamination in the B on Ni data was carefully analyzed. In addition, since in each case a mapping of the measured observable into the fusion cross section had to be made by using statistical model calculations, it became necessary to consider possible model dependencies. As a conclusion, it will be shown in Section 3.3 that the data for both systems are actually consistent with each other and with a fusion enhancement above the barrier. Finally, a summary and the main conclusions of this work will be presented in Section 4.

2. Neutron-halo systems

It's been long known that neutron-halo systems present a fusion suppression above the barrier. By adopting the parameter-free São Paulo Potential (SPP) [1] as an appropriate bare potential to describe fusion reactions, Crema *et al.* [2] showed that the experimental fusion excitation functions for the neutron-halo projectile ${}^6\text{He}$ on targets of ${}^{64}\text{Zn}$, ${}^{209}\text{Bi}$ and ${}^{238}\text{U}$ present very



similar behavior. They found that, for energies above the respective Coulomb barriers, the experimental fusion cross sections for all three systems were suppressed with respect to the corresponding SPP predictions. In an earlier work [3], the same authors had shown that the SPP gives reliable results in the study of fusion reactions with stable weakly-bound projectiles. A realistic density for ${}^6\text{He}$ was used in Ref. [2] for the calculation of the respective potentials.

In order to systematize this kind of results, it is convenient to use an appropriate method of data reduction that allows one to compare with each other, in the same plot, the cross sections for different systems. One method that has been successfully used to compare fusion data consists of using the following prescription to reduce the cross section and the energy [4, 5, 6, 7]:

$$\sigma_{Red} = \frac{2E}{\hbar\omega R_b^2} \sigma, \quad E_{Red} = \frac{E - V_b}{\hbar\omega}, \quad (1)$$

where $V_b, R_b, \hbar\omega$ are the corresponding barrier parameters. Extracting these parameters from a realistic bare potential for each system, such as the SPP, provides a common benchmark for a meaningful comparison of different systems [5, 6, 7]. The above prescription is based on a well-known analytic expression for the cross section, $\sigma^W(E)$, which was derived long ago by Wong [8]. If applied to $\sigma^W(E)$, one gets the so called universal fusion function (UFF) [6, 7],

$$\sigma_{Red}^W(E_{Red}) = \frac{2E}{\hbar\omega R_b^2} \sigma^W(E) = \ln[1 + e^{(2\pi E_{Red})}]. \quad (2)$$

A comparison of fusion data for the neutron-halo systems ${}^6\text{He} + {}^{209}\text{Bi}$ [9] and ${}^6\text{He} + {}^{238}\text{U}$ [10] was done in Refs. [6, 7] using this prescription. For both systems, the authors found a suppression factor of 0.7 with respect to the UFF. This is illustrated in Fig. 1, where in addition we have included data for ${}^6\text{He} + {}^{64}\text{Zn}$ [11], ${}^{11}\text{Li} + {}^{208}\text{Pb}$ [12], and ${}^{11}\text{Be} + {}^{209}\text{Bi}$ [13]. One can see that, for all these neutron-halo systems, fusion is suppressed for energies above the barrier, with suppression factors that are between ~ 0.5 -0.7.

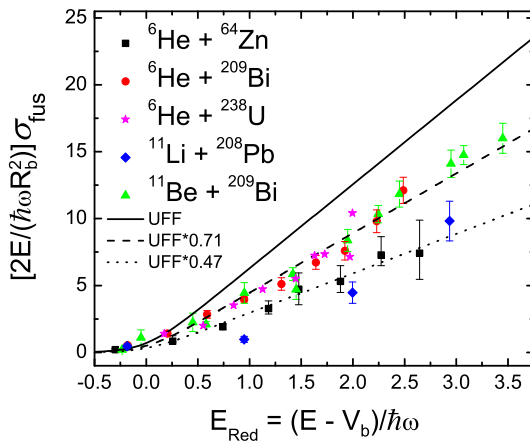


Figure 1. Reduced fusion cross sections for several neutron-halo systems. Data from: ${}^6\text{He} + {}^{209}\text{Bi}$ [9], ${}^6\text{He} + {}^{238}\text{U}$ [10], ${}^6\text{He} + {}^{64}\text{Zn}$ [11], ${}^{11}\text{Li} + {}^{208}\text{Pb}$ [12], and ${}^{11}\text{Be} + {}^{209}\text{Bi}$ [13].

The barrier parameters that were used to make the reduced plot of Fig. 1 are given in Table 1. They were obtained from the double-folding SPP, using default values for the respective matter and charge densities, which follow the systematics observed for many nuclei. The observed deviations from the UFF in Fig. 1 can thus be ascribed either to static effects related to deviations in the actual densities, or to dynamic effects, originating from some intrinsic properties of the respective nuclei.

Table 1. Barrier parameters used to reduce the data for all systems considered in the present work, obtained in each case from the respective São Paulo Potential.

System	Reference	R_B (fm)	V_B (MeV)	$\hbar\omega$ (MeV)
${}^6\text{He} + {}^{64}\text{Zn}$	[11]	9.5	8.4	2.9
${}^6\text{He} + {}^{209}\text{Bi}$	[9]	11.6	19.3	3.9
${}^6\text{He} + {}^{238}\text{U}$	[10]	11.9	27.8	4.0
${}^{11}\text{Li} + {}^{208}\text{Pb}$	[12]	12.0	31.66	3.44
${}^{11}\text{Be} + {}^{209}\text{Bi}$	[13]	11.8	38.2	4.0
${}^8\text{B} + {}^{28}\text{Si}$	[20]*	8.18	11.27	3.38
${}^8\text{B} + {}^{58}\text{Ni}$	[14]*	8.9	20.8	4.09

* reanalyzed in Ref. [17]

3. Proton-halo systems

Proton-halo systems have been far more elusive. Only two such systems have been measured, both corresponding to ${}^8\text{B}$ projectiles but with different targets. It is generally agreed that the ${}^8\text{B}$ nucleus has a one-proton halo configuration in its ground state. An apparent controversy aroused between the two datasets for these proton-halo systems, but a recent work showed that they are actually consistent with each other. This will be briefly described here.

3.1. ${}^8\text{B} + {}^{58}\text{Ni}$

Experimental cross sections for the fusion of ${}^8\text{B} + {}^{58}\text{Ni}$ were published in 2011 [14]. With respect to expectations of a simple barrier penetration model calculation, they presented a big enhancement, even for energies above the Coulomb barrier, which in this case is at 20.8 MeV. This differs from what has been observed for neutron-halo systems, as discussed in Sect. 2 above. These results were also surprising because the behaviour of total reaction cross sections for proton-halo and neutron-halo systems is quite similar. Indeed, it has been shown that the reduced total reaction cross sections for ${}^8\text{B} + {}^{58}\text{Ni}$ and for several neutron-halo systems fall on the same trajectory when plotted as a function of the reduced energy [15].

In Ref. [14], evaporation protons were measured at backward angles and the statistical model code PACE2 [16] was used to calculate the respective multiplicity, which was then used to deduce the corresponding fusion cross section. An advantage of this technique is that the respective proton multiplicities are fairly high, which enhances the probability of observing the fusion events. In addition, model calculations are expected to be more stable for high multiplicities. A possible disadvantage of the technique is related to the fact that protons are also produced in the breakup (bu) of ${}^8\text{B}$ into ${}^7\text{Be} + \text{p}$. If these bu protons reach the detectors, there is no way to distinguish them from evaporation protons.

The contribution of bu protons to the measured proton cross sections, σ_p , was estimated in Ref. [17] by using CDCC calculations available in the literature. Except for the lowest energy measured, this contribution was practically insignificant and, furthermore, the lowest energy point could be recovered by analyzing the evaporation alpha particles that were detected during the same experiment. In fact, alpha particle measurements were also liable to be analyzed for a few more energies and they gave fusion cross sections consistent with those obtained from the proton measurements at the same energies [17].

In addition, possible model dependencies in the $\sigma_p \rightarrow \sigma_{fus}$ mapping were extensively studied in Ref. [17] by using three different evaporation codes (PACE2 [16], LILITA [18], and CASCADE [19]) and carefully choosing the respective input parameters. The relevant proton multiplicities, M_p , were calculated using two different criteria. First, the three evaporation codes were run using always the same set of optical-potential parameters (OMP) to calculate the transmission

coefficients corresponding to neutrons, protons and alpha particles. The results are displayed with solid squares, circles, and up-triangles in Fig. 2. From the average of these results, a proton multiplicity $\langle M_p \rangle \pm \delta \langle M_p \rangle$ was obtained for each energy (down-triangles in Fig. 2) and corresponding fusion cross sections $\sigma_{fus} = \sigma_p / \langle M_p \rangle$ were calculated. Then, a different set of OMP's was used in CASCADE, corresponding to those recommended by the author of this code, which gave proton multiplicities M'_p (stars in Fig. 2). These latter multiplicities happened to be very similar to $\langle M_p \rangle$, which indicates a fairly low sensitivity of proton multiplicities to the OMP's used in the calculations for this particular system. In other words, the effects of model dependency in the $\sigma_p \rightarrow \sigma_{fus}$ mapping are rather weak and can be reasonably accounted for by the uncertainties $\delta \langle M_p \rangle$ assigned to $\langle M_p \rangle$. As a conclusion, the ${}^8\text{B} + {}^{58}\text{Ni}$ fusion cross sections reported in Ref. [14] did not change significantly. In addition, the respective systematic error originally reported was eliminated and replaced by a proper folding of $\delta \langle M_p \rangle$ into the global uncertainty.

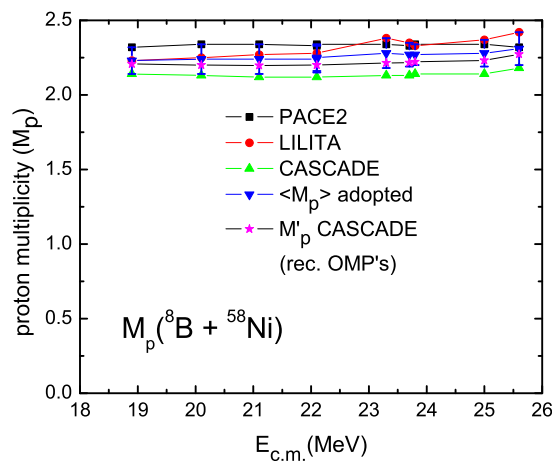


Figure 2. Proton multiplicities obtained for the ${}^8\text{B} + {}^{58}\text{Ni}$ system with the three codes PACE2, LILITA, and CASCADE, as described in the text.

3.2. ${}^8\text{B} + {}^{28}\text{Si}$

In the experiment with the Si target [20], alpha particles were measured instead of protons. The detector covered an angular range at forward angles, but no angular distribution was actually measured. The alpha multiplicity used to deduce the fusion cross section was calculated in this case with the code CASCADE [19]. A good asset in this technique is the fact that alpha particles coming from direct processes are unlikely, but the low alpha multiplicities and the necessary dependency on the detector efficiency become important disadvantages in this technique. In contrast to the results for ${}^8\text{B} + {}^{58}\text{Ni}$, the fusion cross sections reported in Ref. [20] for ${}^8\text{B} + {}^{28}\text{Si}$ showed a suppression above the barrier.

As for the detector efficiency, unfortunately this was not discussed in Ref. [20], but the respective uncertainty would probably translate into an additional systematic error larger than 15% in the corresponding data, as discussed in Ref. [17]. In addition, for this system an equivalent analysis using the same three codes (PACE2, LILITA, CASCADE) also was carried out in Ref. [17]. A higher degree of model dependency was found for the respective $\sigma_\alpha \rightarrow \sigma_{fus}$ mapping, which is most probably a consequence of the low alpha multiplicities M_α . This is illustrated in Fig. 3, where the symbols have an equivalent meaning to those of Fig. 2, but M_p is replaced by M_α and ${}^{58}\text{Ni}$ is replaced by ${}^{28}\text{Si}$. The same criteria described in Sec. 3.1 to obtain $\langle M_p \rangle$ and M'_p were used here to obtain $\langle M_\alpha \rangle$ and M'_α , respectively. In this case, the

values of M'_α fell out of the uncertainties assigned to $\langle M_\alpha \rangle$, indicating a fairly strong model dependency. This is the reason why the respective results for σ_{fus} were plotted in Ref. [17] as two separate datasets, one corresponding to $\langle M_\alpha \rangle$ and the other corresponding to M'_α . In next Section, a proper average of these two datasets for ${}^8\text{B} + {}^{28}\text{Si}$ will be plotted instead.

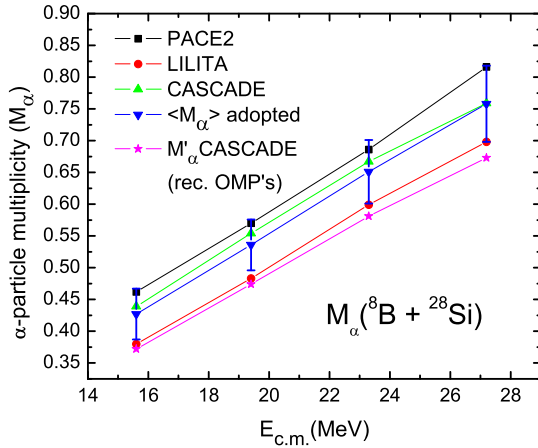


Figure 3. α -particle multiplicities obtained for the ${}^8\text{B} + {}^{28}\text{Si}$ system with the three codes PACE2, LILITA, and CASCADE, as described in the text.

3.3. Consistency of fusion data for ${}^8\text{B} + ({}^{28}\text{Si}, {}^{58}\text{Ni})$

Figure 4 shows a reduced plot of fusion data for the ${}^8\text{B} + ({}^{28}\text{Si}, {}^{58}\text{Ni})$ systems, as obtained from the reanalysis of Ref. [17] that was described in Sections 3.1 and 3.2. The barrier parameters used to reduce the data are given in Table 1. The data points for the ${}^{28}\text{Si}$ target were actually taken as the average of the values obtained under the two model assumptions which led to multiplicities $\langle M_\alpha \rangle$ and M'_α , as described above. Further details of the respective statistical model calculations can be found in Ref. [17].

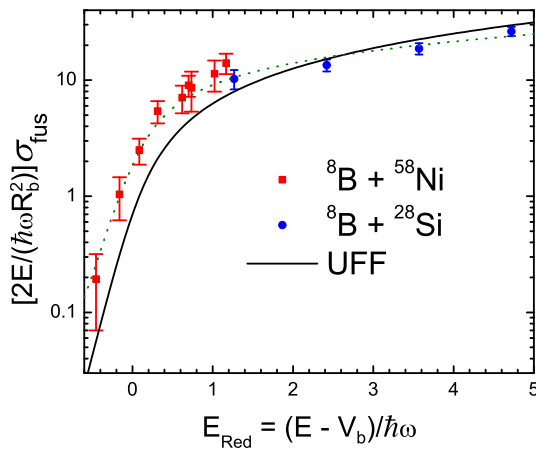


Figure 4. Reduced fusion cross sections for the proton-halo systems ${}^8\text{B} + ({}^{58}\text{Ni}, {}^{28}\text{Si})$. Datasets for both systems are from the reanalysis made in Ref. [17] of the original data [14, 20]. The dotted line is to guide the eye.

It can be seen that the reduced fusion cross sections for the two proton-halo systems are certainly consistent with each other when the effects of model dependency are properly taken into account. It is worth mentioning also that a possible systematic error larger than 15%,

associated to the respective detector efficiency, should probably be assigned to the ${}^8\text{B} + {}^{28}\text{Si}$ data. The mentioned controversy between the two proton-halo systems was thus solved. The dotted line in Fig. 4, which was drawn to guide the eye, clearly shows that both datasets are also consistent with a fusion enhancement above the barrier. For $E_{\text{Red}} = 1$, this curve indicates an enhancement factor of 1.5. This reduced energy corresponds to 4.1 MeV (3.4 MeV) above the barrier for the case of the ${}^{58}\text{Ni}$ (${}^{28}\text{Si}$) target.

4. Conclusions

The behaviour of the fusion excitation functions for halo systems is reviewed. Neutron-halo systems present a fusion suppression for energies above the barrier, which is illustrated in a reduced plot of experimental data for several systems corresponding to projectiles of ${}^6\text{He}$, ${}^{11}\text{Li}$ and ${}^{11}\text{Be}$. As for proton-halo systems, an apparent discrepancy in the behaviour of the fusion excitation functions for ${}^8\text{B} + ({}^{28}\text{Si}, {}^{58}\text{Ni})$ is shown to disappear when the effects of model dependency are taken into account. Both systems are thus consistent with a fusion enhancement for energies above the barrier. An important difference is thus confirmed in the fusion of halo systems, which depends on whether the halo is charged or neutral.

Acknowledgments

This work has been partially supported by CONACYT (México).

References

- [1] Chamon L C, Carlson B V, Gasques L R, Pereira D, De Conti C, Alvarez M A G, Hussein M S, Cândido Ribeiro M A, Rossi Jr. E S and Silva C P 2002 *Phys. Rev. C* **66** 014610
- [2] Crema E, Gomes P R S, and Chamon L C 2007 *Phys. Rev. C* **75** 037601
- [3] Crema E, Chamon L C, and Gomes P R S 2005 *Phys. Rev. C* **72** 034610
- [4] Prasad N V S V, Vinodkumar A M, Sinha A K, Varier K M, Sastry D L, Madhavan N, Sugathan P, Kataria D O, and Das J J 1996 *Nucl. Phys. A* **603** 176
- [5] Gasques L R, Chamon L C, Pereira D, Alvarez M A G, Rossi Jr. E S, Silva C P, and Carlson B V 2004 *Phys. Rev. C* **69** 034603
- [6] Canto L F, Gomes P R S, Lubian J, Chamon L C, and Crema E 2009 *Nucl. Phys. A* **821** 51
- [7] Canto L F, Gomes P R S, Lubian J, Chamon L C, and Crema E 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 015109
- [8] Wong C Y 1973 *Phys. Rev. Lett.* **31** 766
- [9] Kolata J J *et al.* 1998 *Phys. Rev. Lett.* **81** 4580
- [10] Raabe R *et al.* 2004 *Nature* **431** 823
- [11] Scuderi V *et al.* 2011 *Phys. Rev. C* **84** 064604
- [12] Vinodkumar A M *et al.* 2013 *Phys. Rev. C* **87** 044603
- [13] Hinde D J and Dasgupta M 2010 *Phys. Rev. C* **81** 064611
- [14] Aguilera E F *et al.* 2011 *Phys. Rev. Lett.* **107** 092701
- [15] Kolata J J and Aguilera E F 2009 *Phys. Rev. C* **79** 027603
- [16] Gavron A 1980 *Phys. Rev. C* **21** 230
- [17] Aguilera E F *et al.* 2016 *Phys. Rev. C* **93** 034613
- [18] Gomez del Campo J and Stokstad R G 1981 ORNL Report TM-7295
- [19] Pühlhofer F 1977 *Nucl. Phys. A* **280** 267
- [20] Pakou A *et al.* 2013 *Phys. Rev. C* **87** 014619; *Phys. Rev. C* **87** 049901(E)