Outstanding features of reactions with halo nuclei

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Abstract. Recent results for total reaction and fusion excitation functions for halo systems are compiled. The striking similarity in the behavior of total cross sections for proton-halo ($^8$B) and neutron-halo ($^6$He) systems is pointed out. Static and dynamic halo effects are elucidated by comparing data for a neutron-halo nucleus and its core. Fusion cross sections are discussed in terms of a maximum angular momentum for fusion, $L_f$. A linear energy dependence for $L_f$ is consistent with the data for all the existing measurements so this might actually be a characteristic feature of true halo systems. A qualitative difference between the fusion of neutron-halo and proton-halo systems also is pointed out.

1. Introduction
In the context of nuclear physics research, one of the most relevant events of the last few decades was the advent of physics with radioactive ion beams, a field that is now just over 25 years old. The existence of nuclear halos, which was realized soon after the first experiments, remains as probably the most outstanding discovery in this field. While nuclear halos were actually discovered through reaction measurements at intermediate energies, where static effects are dominant, the respective dynamic effects are expected to become more evident at lower energies, near the corresponding Coulomb barrier. Under these conditions the nucleons in the halo may have time enough to rearrange themselves in the force field of the target so that, for instance, dynamic polarization effects may appear. Up to date, many low energy measurements have been performed with light halo systems, thus giving one the opportunity to search for possible patterns in the respective behavior.

Such a pattern has been found, for instance, in the case of total reaction cross sections, $\sigma_R$, for systems involving the neutron-halo projectile $^6$He. The corresponding excitation functions, when properly scaled to eliminate trivial effects of size and charge, follow a well defined path for all systems studied, which includes a wide range of bombarding energies and target masses. A comparison with respective data for the corresponding core nucleus, $^4$He, leads to interesting conclusions about the static and dynamic effects of the halo. Although only one excitation function has been measured for the proton-halo projectile $^8$B, it is quite remarkable that the observed behavior is similar to that of $^6$He insofar as total reaction cross sections are concerned.
Fusion excitation functions at near barrier energies also have been measured for a few of these systems. Because of the increased importance of direct processes in low energy reactions with halo nuclei, the fusion cross sections are lower than the respective total reaction cross sections. By using a simple single-barrier penetration model, the fusion data can be described in terms of a maximum angular momentum for fusion, \( L_f \). Surprisingly, for all the halo systems analyzed so far, the data seem to indicate a linear energy dependence for \( L_f \).

A discussion of the above topics is the subject of the present work. A compilation of recent results will be presented, showing some of the most prominent halo effects. In the first part, it will be shown that the excitation functions for total reaction cross sections of different systems having as projectiles either the neutron-halo nucleus \(^6\text{He}\) or the proton-halo isotope \(^8\text{B}\), do follow a common systematic trend. In the second part, the existing measurements for fusion of halo systems will be presented and, through the introduction of a simple model to analyze them, a characteristic behavior will be pointed out.

2. \( \sigma_R(\mathcal{E}) \) for reactions induced by \(^6\text{He}\) and \(^8\text{B}\)

The two-neutron halo nucleus \(^6\text{He}\) was the first halo projectile for which reaction measurements were done [1], and it is probably the one that has been most extensively studied so far [2]. A recent survey of respective measurements in the low energy regime is given in Ref. [3], where the results of a systematic comparison of total reaction cross sections for systems with different targets are reviewed. However, this kind of comparison was actually motivated originally by the idea of looking for possible signatures of proton-halo effects, as shall be discussed below.

2.1. Comparing reaction cross sections for different systems

Earlier evidence for a possible systematic behavior of total reaction cross sections was observed in Ref. [4], where elastic scattering angular distributions for the proton-halo projectile \(^8\text{B}\) on a \(^{58}\text{Ni}\) target were reported. The measurements were performed at five near barrier energies, using the radioactive ion beam facility TwinSol at the University of Notre Dame [5]. The typical \(^8\text{B}\) beam in this facility is contaminated with substantial amounts of \(^6\text{Li}\) and \(^7\text{Be}\), so it was possible also to get the respective angular distributions (Fig. 1). The solid curves in the figure correspond to optical model calculations, which in turn give the corresponding total reaction cross sections. So, three total-reaction excitation functions were obtained, one for each system. This was actually the first study of this kind for a proton-halo projectile, which was indeed the main interest of this work, but the other two projectiles are also intrinsically interesting. They are both weakly-bound and \(^7\text{Be}\) is actually a radioactive nucleus, which in addition happens to be the core for \(^8\text{B}\). It was thus interesting trying to compare to each other the results for the three systems. For this purpose, the cross sections and energies were reduced according to the expressions

\[
\sigma_{\text{Reduced}} = \frac{\sigma_R}{(\mathcal{A}_p^{1/3} + \mathcal{A}_t^{1/3})^2}, \quad E_{\text{Reduced}} = \frac{E_{\text{c.m.}}}{[Z_p Z_t/(\mathcal{A}_p^{1/3} + \mathcal{A}_t^{1/3})]}.\]

This reduction of data is expected to eliminate trivial effects of size and charge without washing out other important effects [6], thus making data for different systems directly comparable to each other.

Intuitively, one would expect this reduction to work better for similar systems, so it was decided to include in the comparison previous data for other halo- and weakly-bound systems having targets of similar masses. The comparison showed very interesting features. In addition to the three systems measured in Ref. [4], data for the weakly-bound projectiles \(^6\text{Li}\) and \(^9\text{Be}\) were also included, with targets in the neighborhood of \(^{58}\text{Ni}\). As shown in Fig. 2, all data for weakly-bound projectiles fall on the same trajectory, which is indicated with the lower solid curve. As for halo projectiles, in addition to \(^8\text{B}\), data for the neutron-halo nucleus \(^6\text{He}\) were included, the main intention being to spot possible differences between reactions induced by proton-halo vs neutron-halo projectiles. In this case a heavy target (\(^{209}\text{Bi}\)) was also considered, mainly because the respective data were easily available [7, 8]. In spite of the big difference in
Figure 1. Elastic scattering angular distributions for the \( (8B, 7Be, 6Li) + ^{58}Ni \) systems. Taken from Ref. [4].

Figure 2. Reduced cross sections from Ref. [4] compared to other data. The curves are to guide the eye.

target masses, all data for halo systems did also fall on a common path, which lies above that for the weakly-bound systems. So, two outstanding features of reactions with halo nuclei can be pointed out from this plot: a) The respective reaction cross sections show a strong enhancement with respect to those corresponding to weakly-bound projectiles, and b) Reactions with the proton-halo projectile \( 8B \) show similar enhancement as those with the neutron-halo projectile \( 6He \), despite important differences in structure, binding energy and reaction mechanisms for these two projectiles.

2.2. Characterizing halo, weakly-bound and strongly-bound systems by respective reduced barriers

The previous results suggested a more extensive comparison including further systems [9]. As shown in Fig. 3, additional data for one more halo system, \( 6He + ^{27}Al \), as well as data for a strongly-bound projectile, \( ^{16}O \), were also included. The data for \( ^{27}Al \) extended the energy range of the halo systems to higher reduced energies, corroborating the previous trend, while the data for \( ^{16}O \) defined a new path, lying further down in the plot. So, in the space of reduced quantities there are three trajectories, one corresponding to halo systems, one for weakly-bound systems, and one for the strongly-bound projectile. These trajectories can be characterized by Wong’s model [10] with appropriate barrier parameters. This model is based on the simple idea that a reaction between two interacting nuclei will occur as long as the corresponding Coulomb barrier is passed. In the present situation, a reduced barrier can be defined [11] which serves to characterize each curve. Wong’s formula in this case is written as

\[
\sigma_{\text{Red}}^W = \frac{\epsilon_0 \omega^2}{2E_{\text{Red}}} \ln \left\{ 1 + \exp \left[ \frac{2\pi}{\epsilon_0} (E_{\text{Red}} - V_{\text{Red}}) \right] \right\}. \tag{1}
\]

The reduced radius \( r_{0b} \) is simply the barrier radius divided by \( (A_p^{1/3} + A_t^{1/3}) \), and both the
Table 1. Reduced barrier parameters for each curve in Figs. 3, 4.

| Fig. | curve | \( V_{Red} \) | \( r_{0b} \) | \( \epsilon_0 \) |
|------|-------|----------------|-------------|-----------|
| 3    | dash (halo projectiles) | 0.79          | 1.79        | 0.49      |
|      | solid (weakly-bound proj.) | 0.82          | 1.64        | 0.34      |
|      | dash-dot \((^{16}\text{O}+^{64}\text{Zn})\) | 0.87          | 1.56        | 0.14      |
| 4    | solid \((^{6}\text{He} \text{ projectiles})\) | 0.780±0.014   | 1.79±0.04   | 0.43±0.06 |
|      | dash\((^{4}\text{He} \text{ projectiles})\) | 0.913±0.005   | 1.39±0.05   | 0.175±0.006 |

Table 1: Reduced barrier parameters for each curve in Figs. 3, 4.

The barrier curvature parameter \( \hbar \omega_0 \) and the barrier height \( V_b \) are reduced in the same way as the energy (see above) to obtain \( \epsilon_0 \) and \( V_{Red} \), respectively. The curves in Fig. 3 correspond to fits of eq. 1 to the respective experimental points, yielding the parameter values indicated in the first three lines of Table 1.

Figure 3: Comparison of reduced cross sections for twelve different systems. Figure adapted from Ref. [9].

Clearly, all the halo systems studied here can be characterized by a single reduced barrier, from which the actual barrier parameters for each particular system can be deduced (an equivalent statement holds for the respective weakly-bound systems). The existence of this systematic behavior suggests that, for a given halo nucleus, the effects of the halo can be investigated by comparing the reduced plots for both, the halo projectile and its core. Since \(^{6}\text{He}\) is the halo nucleus for which the largest number of measurements exist, it was only natural to start by doing the mentioned comparison for data corresponding to this neutron-halo projectile, as discussed below.

2.3. Static and dynamic effects of the halo

A comparison between total reaction data for systems with \(^{6}\text{He}\) projectiles and similar data for systems where the projectile was the respective core, \(^{4}\text{He}\), was the subject of Ref. [11]. Further discussion on the same topic was included also in Ref. [3]. For the sake of completeness, a brief summary of the main results is given here.
Figure 4 shows total reaction data for a large variety of $^6\text{He}$ systems. In addition to the three $^6\text{He}$ systems of Fig. 3, data for six other targets were included. As a result, both the mass and the reduced energy ranges for the corresponding systems of the previous figure were considerably extended. A fit of eq. 1 to the more complete data set yielded the barrier parameters shown in line 4 of Table 1, where estimated uncertainties taking into account data spread and respective error bars are also indicated. By comparing lines 1 and 4 of the table, one can conclude that the previously observed trend of the data for halo systems is corroborated in the new analysis, even though the $^8\text{B}$ data were excluded here for obvious reasons.

An analysis of experimental data for total reaction cross sections was also done for $^4\text{He}$ systems covering the same mass and energy ranges as those for $^6\text{He}$. The respective reduced points (not shown in the figure) do also show a well defined trend, which is quite different from the previous one. The trajectory followed by the $^4\text{He}$ systems can also be characterized by a reduced Wong curve, shown by the dashed line in Fig. 4, with parameter values given in the fifth line of Table 1. It can be seen that the reduced cross sections fall systematically lower in this case and the slope for fall-off at low energies is steeper. The differences observed in lines 5 and 3 of Table 1 for the reduced barrier parameters of $^4\text{He}$ and $^{16}\text{O}$, respectively, might be a consequence of the eccentric character that has been observed for the nuclear density of $^4\text{He}$ [12], but further study is required to corroborate this point.

A consideration of the big differences in reduced radii for systems with $^6\text{He}$ and $^4\text{He}$ (lines 4 and 5 of Table 1), lead to the conclusion that the shift of the $^6\text{He}$ cross sections to higher values with respect to those corresponding to $^4\text{He}$ systems, is consistent with a static effect of the halo. The larger nuclear size associated to the halo would “push” the barrier away to longer distances, at the same time lowering the barrier height [3, 11]. Likewise, the smaller slope shown by the $^9\text{He}$ data at low energies is most probably a signature for dynamic effects of the halo. Such effects have been observed experimentally as an enhanced probability of transfer and/or breakup near and below the barrier. Within the context of Wong’s model, they would be simulated by an extremely narrow barrier. Indeed, it can be seen from Table 1 that the $\epsilon_o$ value for $^6\text{He}$ systems is much larger than the one associated to $^4\text{He}$ (by a factor of 2.5). This parameter determines the respective barrier curvature and it is also closely related to the low-energy slope of the corresponding curve in Fig. 4. It can be shown that a large value of $\epsilon_o$ (or $\hbar \omega_0$) corresponds to an increased diffuseness of the absorption in $l$ space [9], consistent with a higher probability for peripheral processes.

3. $\sigma_{fus}(E)$ for halo systems
Near-barrier fusion excitation functions, $\sigma_{fus}(E)$, have been measured for three of the halo systems mentioned above. These are the $^6\text{He} + ^{209}\text{Bi}$ system [13], the $^6\text{He} + ^{64}\text{Zn}$ system [14, 15], and the $^8\text{B} + ^{58}\text{Ni}$ system, which was measured very recently [16]. In this section, a quite interesting common behavior found from these measurements, which is different from the behavior for normal systems, will be pointed out.

Since direct processes are quite important for halo systems at near barrier energies, the fusion cross sections are always lower than the total reaction cross sections, $\sigma_{fus}(E) \leq \sigma_R(E)$ (see Fig. 5). For the latter, we already have a good description in terms of a Wong function with well defined barrier parameters (Table 1). These parameters should be associated not to a bare potential but to some sort of effective interaction potential taking into account all possible interactions. In principle, one could also fit a Wong function to the respective fusion data and the resulting parameters should then be associated instead to an effective fusion potential. These two potentials should be consistent with the same bare potential, connected to it through respective polarization potentials simulating the effects of the involved channel couplings in each case. This subject is presently being investigated and some results will be published elsewhere [17].
Alternatively, one may wonder whether for a given system it is possible to describe both the total reaction and the fusion data within the same framework, i.e., by using the same barrier parameters. In fact, it is possible to show that, by using the barrier parameters extracted from the total reaction data, it is possible to describe also the fusion data [18]. Briefly, while the total reaction cross sections are calculated from a sum of terms of the form $(\pi/k^2)(2l+1)T_l$ over all partial waves ($T_l$ are the involved transmission coefficients), the respective fusion cross sections can be estimated from the same sum, but restricted to a maximum angular momentum for fusion $L_f$. Under this assumption, it was shown in Ref. [18] that the fusion cross section can be approximately calculated by using an analytic function similar to the one obtained in

**Figure 5.** Total reaction $\sigma_R$ and fusion data $\sigma_{fus}$ for three halo systems. The solid (dashed) line corresponds to the Wong (linear $L_f$) model, both of them calculated with the indicated barrier parameters. Adapted from Ref. [18].

**Figure 6.** Values of $L_f$ extracted from the fusion data for $^6$He + $^{209}$Bi, $^6$He + $^{64}$Zn and $^8$B + $^{58}$Ni. The dashed lines are linear fits to the respective points while the dash-dotted curve illustrates what would be expected for normal systems. Adapted from Ref. [18].
Wong’s model:

\[ \sigma_{\text{fus}}(E) = \left[ \frac{\hbar \omega_0 R_c^2}{(2E)} \right] \ln \left[ \frac{1 + e^{-y_0}}{1 + e^{-z}} \right], \tag{2} \]

where

\[ y_0 = 2\pi(V_0 - E)/(h\omega_0), \quad \text{and} \quad z = y_0 + [\pi \hbar / (\omega_0 \mu R_c^2)]L_f(L_f + 1). \tag{3} \]

The barrier parameters for each system in Fig. 5 can be obtained from the values given in the first line of Table 1. It is then straightforward to obtain the energy dependence of \( L_f \) from the fusion data. For each measured fusion cross section \( \sigma_{\text{fus}}^{\text{exp}} \), one can find the \( L_f \) value that, when substituted in eq. 2, reproduces \( \sigma_{\text{fus}}^{\text{exp}} \). This was done for the three halo systems mentioned above, with the results shown in Fig. 6. All three halo systems show a linear energy dependence for \( L_f \). This is surprising, especially because it turns out to be quite different from what would be expected based on observations for many other systems.

For the case of “normal” systems, if one goes to relatively high energies above the barrier, fusion starts being lower than the total reaction cross section. It was shown a long time ago that a critical distance of approach is the relevant quantity limiting fusion in this case (see discussion in Ref. [18]). In other words, only those nuclei that reach a critical distance \( R_c \) get fused. In the \( L_f \) plot, the critical distance condition looks like the dash-dotted curve shown in Fig. 6 for the case of the \( ^6\text{He} + ^{209}\text{Bi} \) system. Clearly, this cannot explain the behavior of the halo system. A critical distance that increases with decreasing energy would be needed in order to reproduce the data points. Therefore, a new mechanism for fusion should be found in order to describe the previous observations for halo systems. It is worth mentioning that weakly-bound systems are probably on the verge of the transition between the behavior predicted by the critical distance model and that of the linear-\( L_f \) model [18].

The predictions of the linear-\( L_f \) model for the respective fusion excitation functions can be calculated by replacing the corresponding functions \( L_f(E) \) (see insets in Fig. 6) in eqs. 2, 3. The obtained description of the experimental data is very good, as shown in Fig. 5 by the dashed lines. It will be interesting to measure near barrier fusion excitation functions for additional halo systems and verify whether a linear-\( L_f \) model does also describe the corresponding data.

With respect to the comparison between fusion of neutron-halo vs proton-halo systems, we may mention a qualitative difference in the respective excitation functions for fusion induced by \( ^6\text{He} \) and \( ^8\text{B} \), which can be observed in Fig. 5. While fusion tends to saturate the total cross section at high energies for the \( ^8\text{B} \) case, the corresponding curves \( \sigma_{\text{fus}}(E) \) and \( \sigma_R(E) \) stay rather parallel to each other in the respective plots for the \( ^6\text{He} \) projectile. Apparently, there is a strong fusion enhancement in the proton-halo case which is not present for neutron halos. This remarkable difference, first noticed in Ref. [16] and further discussed in Ref. [18], may result from the different role played by Coulomb polarization in the cases of charged and neutral halos.

This section may be summarized by stating two conclusions: a) By introducing a maximum angular momentum for fusion, \( L_f \), it is possible to describe both the fusion and the total reaction cross sections for halo nuclei within the same framework, \( i.e. \), by using the same barrier parameters, and b) A linear energy dependence of \( L_f \) seems to be the new ingredient describing the fusion data for halo systems. This simple energy dependence works well for all cases considered, which suggests that this is an important step towards a more detailed understanding of the underlying reaction mechanism.

4. Conclusions

Recent experimental results for total reaction and fusion cross sections of halo nuclei are discussed. A comparison of \( \sigma_R \) with corresponding data for weakly-bound and strongly-bound systems shows three different trajectories in a reduced plot, one for each group. The strong
enhancement observed for halo systems can be interpreted in terms of static and dynamic effects of the halo. While static effects are associated to an increased barrier radius and produce an enhancement of $\sigma_R$ in the whole energy region, dynamic effects are important only in the near barrier region and are simulated by an extremely small barrier width which in turn produces a slower fall off of the data at low energies.

The existing experimental results for fusion of halo systems are discussed by using a simple analytic model which describes the fusion cross sections in terms of a maximum angular momentum for fusion, $L_f$. It is shown that a linear energy dependence for $L_f$ gives a surprisingly good description of the experimental fusion excitation functions for both proton-halo ($^8\text{B} + ^{58}\text{Ni}$) and neutron-halo ($^6\text{He} + (^{209}\text{Bi}, ^{64}\text{Zn})$) systems. This behavior is different from that expected for normal systems so it is possibly a characteristic feature of true halo systems. Finding a fusion mechanism that explains this behavior should help to improve our present knowledge of these exotic nuclei.

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