Proton- and neutron-halo breakups: Similarities and differences

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Abstract. It is shown in this paper that the decrease of the projectile ground state binding energy in a neutron-halo nucleus and the removal of the Coulomb barrier in the proton-halo nucleus, produce a similar qualitative effect on the elastic scattering cross sections. The variation of the binding energy produces opposite effects on elastic scattering and breakup cross sections. A strongly destructive Coulomb-nuclear interference owing to the decrease of the binding energy is also obtained.

1. Introduction

Despite the tremendous progress in tackling nuclear reactions induced halo and other loosely bound nuclei over the past decades \cite{1, 2, 3, 4, 5, 6, 7}, there still a number of issues that need to be addressed and new data are revealing new phenomena. Among the outstanding issues, one mentions the dynamic difference between the breakups of proton-halo and neutron-halo nuclei and their influence on other reaction channels, such as elastic scattering, fusion, among others. It is not fully understood how the absence of the core-neutron Coulomb interaction affects the breakup dynamics. There have been efforts to address this question \cite{8, 9, 10, 12, 13}. For example, the difference in the elastic scattering cross sections of \textsuperscript{8}B and \textsuperscript{11}Be induced reactions was attributed to the Coulomb and centrifugal barriers in \textsuperscript{8}B \cite{8, 9}. It was shown in these works that the removal of the Coulomb barrier greatly improves the disagreement between the different elastic scattering cross sections, despite the fact that the ground state binding energies of this two nuclei are significantly different. Similar results were reported in \cite{10}, where a strong suppression of the neutron-halo elastic scattering cross sections was obtained in the \textsuperscript{7}Be \textsuperscript{+} + \textit{p} and \textsuperscript{7}Be \textsuperscript{+} + \textit{n} reactions on the lead. On the other hand, in \cite{11}, where the same \textsuperscript{7}Be \textsuperscript{+} + \textit{p} and \textsuperscript{7}Be \textsuperscript{+} + \textit{n} reactions on a Nickel target were analyzed, it was shown that the neutron-halo breakup cross section is larger than its proton-halo counterpart, especially when the same binding energy was considered. The disagreement between the two breakup cross sections was significantly improved by increasing the \textsuperscript{7}Be \textsuperscript{+} + \textit{n} binding energy. A conclusion that was also drawn in \cite{12, 13}. This amounts to saying that the absence of the Coulomb barrier in the core-neutron potential can be, to some extent, compensated by the increase of its ground state binding energy. Intuitively, one would expect the opposite in the elastic scattering case. That is, the effect obtained in \cite{8} by removing the Coulomb barrier in the proton-halo breakup, can also be obtained in the
neutron-halo breakup by decreasing the ground state binding energy. One of the aims of this paper is to investigate this aspect.

Another important aspect as far as breakup reactions induced by loosely bound projectiles are concerned, is the importance of the Coulomb-nuclear interference. We recently analyzed its dependence on the proton-and neutron-halo ground state binding energies [11], and showed that when these energies increase, the Coulomb-nuclear interference is substantially reduced. However, this study was restricted to a single incident energy around the Coulomb barrier. It is interesting to investigate whether this conclusion holds for other reactions, as well as its dependence on the incident energy. In this paper, we analyze the breakup of $^8$Li on the lead at incident energies below, around and well above the barrier. On one hand, we are particularly interested in verifying whether the decrease of the ground state binding energy in this neutron-halo nucleus can produce a similar effect as the removal of the Coulomb barrier in the $^8$B proton-halo nucleus. Such study is crucial as it will further highlight the similarities and differences in the proton-halo and neutron-halo breakups. On the other hand, study the dependence the Coulomb-nuclear interference on ground state binding energy, considering a range of incident energy in an effort to extend the conclusion drawn in [11], and test its universality in breakup reactions induced by loosely bound projectiles. To this end, we consider five different ground state binding energies, which are obtained by adjusting the depth of the central part the Woods-Saxon $^7$Li + $n$ potential. The choice of $^8$Li is motivated, on one have by the fact that it has the same ground state quantum numbers as $^8$B, meaning that the only structural difference is the Coulomb barrier. On the other hand, the study of this nucleus has revealed unusual behavior [17, 18]. To obtain the elastic scattering and breakup cross sections, the three-body Schrödinger equation is first transformed into coupled differential equations by means of the continuum discretized coupled-channels (CDCC) method [19]. The latter are numerically solved using Fresco computer codes [20].

2. Results and Discussion

The projectile $^8$Li modeled as $^7$Li + $n$, has a ground state binding energy of $\varepsilon_0 = 2.03$ MeV, with $j^{\pi} = 2^+$, and a first excited state of $\varepsilon_{ex} = 0.88$ MeV, with $j^{\pi} = 1^+$ [14]. The bound and continuum wave functions are obtained using a Woods-Saxon potential whose parameters were taken from [14]. The depth ($V_0$) of the central component was adjusted to give the ground and bound excited energies. On the other hand, both the depths of the central and spin-orbit

![Figure 1](Image)

**Figure 1.** Elastic scattering cross section. The data points were taken from [21]

($V_{SO}$) components were adjusted to obtain the other different ground state binding energies
Figure 2. Elastic scattering cross sections for different ground state binding and incident energies.

(0.14 MeV, 0.40 MeV, 1.0 MeV, 1.50 MeV, randomly selected) well as the corresponding bound and continuum wave functions. The \(^7\)Li global parametrization of [15], was used to obtain the core-target optical potential parameters. A slight adjustment of the depth of the real part results in a satisfactory fit the experimental data (see Fig.1). The \(n+^{208}\)Pb optical potential parameters were taken from [16]. The other various integration parameters were chosen in accordance with the convergence requirement.

The elastic scattering cross sections for 0.14 MeV \(\leq \varepsilon_0 \leq 2.03\) MeV are presented in Fig.2, for incident energies below, around and well above the Coulomb barrier. Firstly, one notices that indeed, the elastic scattering cross sections are suppressed as the ground state binding energy decreases. Specifically, this suppression becomes substantial for binding energies below 1 MeV and \(E_{\text{cm}} \leq 42\) MeV. A closer look at Fig.2(d), indicates that the position of the Coulomb rainbow is not affected by the variation of the binding energy. Taking a look at Fig. 4(b) of [9], it is also noticed that the position of the Coulomb rainbow is not affected by the removal of the Coulomb barrier in the \(^8\)B nucleus. Therefore, one may conclude that the removal of the Coulomb barrier in the \(^8\)B nucleus and the decrease of the binding energy in the \(^8\)Li nucleus produce a similar qualitative effect in the elastic scattering cross sections. Furthermore, one may suggest that the lack of a Coulomb barrier in the neutron-halo nucleus can be compensated by the decrease of its binding energy. Given the fact that the breakup cross section increases with the decrease of the projectile ground state binding energy, these results reveal that a variation of the binding energy produces opposite effects on the elastic scattering and breakup cross sections.

To generalize the conclusion of [11], regarding the dependence of the Coulomb-nuclear interference on ground state binding energy, this interference is plotted in Fig.3, for the different ground state binding energies and incident energy of \(E_{\text{cm}} = 26\) MeV [Fig.3 (a)] and
Figure 3. Coulomb-nuclear interferences for different ground state binding energies.

$E_{cm} = 75$ MeV [Fig.3 (b)]. It is calculated as follows

$$\frac{d\sigma_{\text{int}}}{d\Omega} = \frac{d\sigma_{\text{tot}}}{d\Omega} - \left( \frac{d\sigma_{\text{Coul}}}{d\Omega} + \frac{d\sigma_{\text{nucl}}}{d\Omega} \right),$$

where $\sigma_{\text{tot}}$, $\sigma_{\text{Coul}}$ and $\sigma_{\text{nucl}}$ are total, Coulomb and nuclear breakup cross sections, respectively. This figure clearly shows that the Coulomb-nuclear interference is strongly enhanced and destructive as the binding energy decreases, in line with the findings of [11]. For a better analysis of Fig.3, the integrated Coulomb-nuclear interference is plotted in Fig.4, as function of the incident energy. One clearly notices in this figure that this interference is exclusively destructive where the destructiveness is strengthened with the decrease of the binding energy. These results depict a clear picture of some dynamic differences between the breakups of loosely bound and tightly bound projectiles, as far as the Coulomb-nuclear interference is concerned. In the latter case, one would expect this interference to either weaker or insignificant.

Even though Fig.4 displays unambiguously the dependence of Coulomb-nuclear interference on $\epsilon_0$, it does not reveals where does this strong destructiveness come from. Based of the assessment in [11], one can attribute this to the fact that the Coulomb breakup cross section grows quickly with lowering of $\epsilon_0$ that both total and nuclear breakup cross sections, such that $\sigma_{\text{tot}} - (\sigma_{\text{Coul}} + \sigma_{\text{nucl}}) \ll 0$ as $\epsilon_0$ decreases. To picture this, we define the ratios

$$\beta = \frac{\sigma_{\text{Coul}} - \sigma_{\text{nucl}}}{\sigma_{\text{Coul}}} \quad (2)$$

$$\gamma = \frac{\sigma_{\text{Coul}} - \sigma_{\text{tot}}}{\sigma_{\text{Coul}}} \quad (3)$$

They are displayed inf Figs.5(a) and (b), respectively. Inspecting Fig.5(a), it is noticed that $0.93 \leq \beta \leq 0.97$. In other words, $\sigma_{\text{Coul}} - \sigma_{\text{nucl}} \rightarrow \sigma_{\text{Coul}}$ as $\epsilon_0$ decreases. Also, Fig.5(b) indicates
Figure 4. Integrated Coulomb-nuclear interferences for different ground state binding and incident energies.

Figure 5. Ratios of Coulomb and nuclear breakup cross sections (a) and total breakup cross sections (b), as explained in the text.

that $0.1 \leq \gamma \leq 0.8$, meaning that $\sigma_{\text{Coul}} \geq \sigma_{\text{tot}}$. Therefore, this results in a destructive Coulomb-nuclear interference.
3. Summary
Analyzing the $^8\text{Li}^+\text{Pb}^{208}$ reaction, we have shown in this paper that the decrease of the projectile ground state binding energy in a neutron-halo nucleus and the removal of the Coulomb barrier in the proton-halo nucleus, produce a similar qualitative effect on the elastic scattering cross sections. The variation of the binding energy produces opposite effects on elastic scattering and breakup cross sections. A strongly destructive Coulomb-nuclear interference owing to the decrease of the binding energy is also obtained. This might be a general feature in reactions induced by loosely bound nuclei.

Acknowledgment
I would like to thank FAPESP grant 2016/01343-7 for financial support during my visit to ICTP-SAIFR in September 2018 where part of this work was done.

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