

## Impact of core excitations in break-up reactions with halo nuclei

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**Abstract.** We revisit the resonant break-up of  $^{19}\text{C}$  on protons at intermediate energies. In this reaction, it was found, for the first time in a halo nucleus to our knowledge, that the cross section was largely dominated by the excitation of the core. In this contribution, we study the robustness of this conclusion against the choice of different optical potentials for the core.

### 1 Introduction

Halo nuclei have been an important field of Nuclear Physics since its discovery, thanks in part to the dawn of radioactive beam facilities. Halo nuclei appear close to the neutron and proton driplines where one or two valence nucleons are so barely bound that they orbit far around the rest of nucleons that conforms a compact core. Valence nucleons wavefunction, therefore, extends far away from the core forming the matter halo that name these nuclei. Following this picture, halo nuclei are often treated within two- or three-body valence-core models, considering an inert core. Such picture breaks down in regions of the nuclear chart very far away from the stability valley which are nowadays being explored thanks to the advances in existing radioactive beam facilities. The cores of such halo nuclei will present very low excitation energies for their first excited states. Therefore, it will be also very easy to excite the core along any reaction.

Including internal degrees of freedom of the core in a few-body reaction formalism has been a tremendous challenge. Most few-body models have been recently extended to include the effect of core excitations, such as a non-recoil extension of the Distorted Waves Born Approximation (NR-DWBA) [1, 2], the Extended Continuum-Discretized Coupled-Channels (XCDCC) [3, 4], and the extension of the Faddeev/AGS equations [5]. Alongside these developments, there has been a revival of structure models which enable the incorporation of such excitations in a simple way to allow its inclusion in reaction calculations. That is the case of the particle-rotor and particle-vibrator models [6, 7]. In particular, the particle-rotor model has been successfully applied to  $^{11}\text{Be}$  [8–10], a benchmark for the case of halo nuclei. These models incorporate certain free parameters which are adjusted to reproduce the available information of the halo nucleus or that of the nucleus corresponding to its core. However,

especially with newly discovered halo nuclei, it is usual to have very little experimental information to constrain such parameters. It is also possible that the structure of the core goes beyond the picture of a rotor or a vibrator. For those cases, a semi-microscopic folding model based on core transition densities was introduced in [11]. The model succeeded to reproduce the main features of the low-lying spectrum of  $^{11}\text{Be}$  and, more importantly, of the less known halo nucleus  $^{19}\text{C}$ . In both cases, the transition densities for the respective cores were obtained with the Antisymmetrized Molecular Dynamics (AMD) method.

This model, named particle-AMD model, was also successful in the reproduction of the resonant breakup of  $^{19}\text{C}$  [12] by analyzing the  $^{19}\text{C}(p,p')$  experimental data by Satou *et al.* [13]. In [12],  $^{19}\text{C}$  resonant breakup was found to be the first case of a halo nuclei where the break up is not governed by the excitation of the valence neutron but, on the contrary, by the excitation of the core.

In the present contribution, we revisit the case of  $^{19}\text{C}(p,p')$  resonant breakup and discuss the robustness of such conclusion in detail with respect to the influence of the different optical potentials involved in the reaction calculation. The manuscript is structured as follows. In Sec. 2, we summarize the main features of the particle-AMD (PAMD) structure model. In Sec. 3, we discuss how the optical potentials enter into an XCDCC calculation. Finally, in Sec. 4 we show the different results obtain for different core-target potentials and we discuss on Sec. 5 the role of core excitations and its robustness against the core-target interaction.

### 2 Structure model

We discuss the structure of the halo nucleus in terms of a two-body core + valence-particle model where we will include the possibility of a non-inert core. Thus, a general wavefunction for the nucleus will include different eigenstates of the core,  $\Phi_{IM_I}(\xi)$ , being  $I$  the angular momentum,  $M_I$  its projection, and  $\xi$  the degrees of freedom of the core.

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If such wavefunction has total angular momentum  $J$  and projection  $M$  we can express it as:

$$\Psi_{JM}(\vec{r}, \xi) = \sum_{\alpha} [\varphi_{\alpha}(\vec{r}) \otimes \Phi_I(\xi)]_{JM}, \quad (1)$$

where the functions  $\varphi_{\alpha}(\vec{r})$  describe the relative motion between the valence particle and the core, being  $\vec{r}$  the relative distance between the two. The index  $\alpha$ , so-called channel, denotes the set of quantum numbers  $\{l, s, j, I\}$ , with  $l$ ,  $s$ , and  $j$  being the orbital angular momentum, the intrinsic spin of the valence particle, and their sum ( $\vec{j} = \vec{l} + \vec{s}$ ), respectively. Such a sum in  $\alpha$  will cover all possible channels consistent with the total angular momentum ( $\vec{J} = \vec{j} + \vec{l}$ ) and parity. Each channel will have a specific weight in each state of the nucleus. This weight can be regarded as a unit-normalized spectroscopic factor.

To obtain the eigenstates of the nucleus, we need a Hamiltonian for the system that includes a model for the internal Hamiltonian of the core  $h_c(\xi)$  and the interaction between the core and the valence-particle  $V_{vc}(\vec{r}, \xi)$ . In the weak-coupling limit we can assume:

$$\mathcal{H}_{\text{proj}} = T(\vec{r}) + h_{\text{core}}(\xi) + V_{vc}(\vec{r}, \xi). \quad (2)$$

It is important to remark that the interaction  $V_{vc}(\vec{r}, \xi)$  is the only term that connects the inner degrees of freedom of the core and the motion of the valence particle, thus being the main responsible for the coupling of the different channels, determining the relative weights in the different eigenstates of the hamiltonian. We will follow two different models for such interaction: the particle-rotor model (PRM) [7] and the semi-microscopic particle-AMD model (PAMD) [11].

For the calculation of the eigenstates of the system, we employ the Pseudo-state method, in which the model hamiltonian is diagonalized in a THO basis [14]. This basis is constructed by applying an analytical Local Scale Transformation (LST) [15] to the Harmonic Oscillator (HO). Such LST is meant to change the Gaussian asymptotic behavior of HO into an exponential one, more appropriate to tackle potentials that vanish asymptotically like a Woods-Saxon.

### 3 Reaction model

The remaining ingredients are the optical potentials between the fragments and the target:

$$V_{\text{proj-}T} = V_{vT}(\vec{R}_{vT}) + V_{cT}(\vec{R}_{cT}, \xi). \quad (3)$$

Both potentials are usually taken from global parameterizations where one evaluates the potential at the energy per nucleon of the incident projectile. Within the XCDCC framework, the interaction enters into the reaction calculation through the coupling potentials:

$$\left\langle \Psi_{J'M'}^f \left| V_{vT}(\vec{R}_{vT}) + V_{cT}(\vec{R}_{cT}, \xi) \right| \Psi_{JM}^i \right\rangle. \quad (4)$$

It can be seen that the only place in the interaction with the target that includes any information on the core excitation is  $V_{cT}$  that depends on the internal degrees of freedom

of the core  $\xi$ . In other words, by neglecting this dependence one will exclude the effect of the excitation of the core along the reaction. These effects are usually called *dynamic* effects of the core. If *dynamic* effects are neglected, the effect of the core will still be present through the weights of the different components in the projectile wavefunction,  $\Psi_{JM}(\vec{r}, \xi)$ . This other effect is usually called *static* effect.

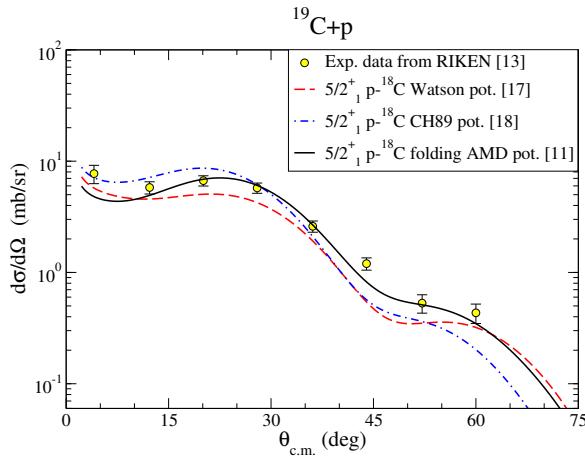
### 4 Results

We analyze the resonant break of  $^{19}\text{C}$  on protons at 70 MeV/nucleon measured at RIKEN by Satou *et al.* [13]. The resonance considered here appears as a prominent peak in the energy distribution of the breakup cross section at  $E_x = 1.46 \pm 0.10$  MeV that was assigned spin and parity  $5/2^+$  in [13]. In [12] it was found a good agreement of the angular distribution of such resonance with the first  $5/2^+$  resonance in the PAMD model and an unexpected dominance of dynamic core excitations on that break-up. We will start by analyzing within the XCDCC framework if the latter conclusion is robust against a change in the core-target potential. To do so, the other optical potential, the valence-target potential, which corresponds to the  $n-p$  potential in this case, remains the same: a simple Gaussian potential from Refs. [1, 16], whose parameters were adjusted to reproduce a Faddeev calculation of the breakup of  $^{11}\text{Be} + \text{p}$  with the more realistic  $p-n$  CD-Bonn potential.

We repeat the XCDCC calculations with two different core-target potentials. For the two choices we start from a spherical potential, namely, the Watson global parameterization [17] and the CH89 potential [18]. These two potentials are then deformed with the deformation length  $\delta$  obtained from the analysis of the AMD transition densities of  $^{18}\text{C}$  [11]. In Fig. 1, we compare the angular distributions of the resonant break-up obtained with both potentials with the original one published in [12], where a folding potential obtained from the JLM nucleon-nucleon interaction [19] and the AMD transition densities for  $^{18}\text{C}$  was used [20]. It can be seen that the three potentials provide a very similar cross section, both in shape and magnitude. Recalling that the shape of the angular distribution is determined by the coherent sum of core and valence contribution, one can infer that the relative weight of both contributions is similar in the three cases.

### 5 Conclusions

We have analyzed the resonant break-up of  $^{19}\text{C}$  on protons at 70 MeV/nucleon with emphasis in the relative importance of the core excitation mechanism and its dependence on the underlying core-target interaction. For that, have performed XCDCC calculations for the break-up to the first  $5/2^+$  resonance described in the PAMD model. Three different prescriptions have been used for the core-target potential to assess the influence of this ingredient on the results, namely Watson, CH89 and a folding potential using the same AMD transition densities for  $^{18}\text{C}$  as in the structure model.



**Figure 1.** Angular distribution of the break-up cross section for the first  $5/2^+$  resonance calculated in XCDCC with three different core-target potentials: Watson [17] (dashed red line), CH89 [18] (dot-dashed blue line) and a folding potential from AMD transition densities [11] (solid black line). The experimental data are taken from Satou *et al.* [13]. All calculations are convoluted with the experimental angular resolution.

All three calculations show a good agreement between themselves and are consistent with the experimental data, both in magnitude and shape. The best reproduction of the data is still found for the original folding potential used in [12]. The choice of the global parameterization by Watson is slightly below the experimental data but shows a very good agreement with the shape of the distribution.

Considering that the same valence-target potential is used for the three calculations and that its contribution was already found negligible in [12], in the three calculations the main mechanism that can explain the amount of break-up is the dynamic excitation of the core. This proves that such an extra break-up is not an effect of an inadequate choice of the optical potential. The only remaining free parameter is the deformation length of  $^{18}\text{C}$  which is taken from the AMD transition densities. However, such deformation length is constrained by the quadrupole electric properties of  $^{18}\text{C}$  which are well known and well reproduced by the AMD calculation. Therefore, it can be stated that the conclusion that  $^{19}\text{C}$  resonant break-up is dominated by dynamic excitations of the core is robust against the choice of core-target optical potential.

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