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From Halo Effective Field Theory to the study of breakup and transfer reactions: reliably probing the halo structure of ^{11}Be and ^{15}C

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Abstract. In this work we study one-neutron halo nuclei, and in particular ^{11}Be and ^{15}C, which can be seen as an inert core of ^{10}Be or ^{14}C plus a loosely bound neutron. During the last decades several transfer and breakup reactions involving these systems have been measured on different targets and energies. We study these processes using one single structure model for each nucleus applying the halo effective field theory (Halo EFT) at next-to-leading order NLO. The main parameters of this EFT are adjusted on nuclear-structure data and/or ab initio predictions. We model the transfer reaction within the Adiabatic Distorted Wave Approximation (ADWA) and the breakup process applying an eikonal model with a consistent treatment of nuclear and Coulomb interactions at all orders. At high energy, our model includes a proper treatment of special relativity Our theoretical calculations are in good agreement with experiment for a variety of reaction observables, thus assessing the robustness of the structure model provided for these nuclei. This new idea enables us also to reliably estimate the nuclear-structure observables that actually affect the reaction process, and hence that can be inferred from such measurements.

1. Introduction

In this work we study reactions involving one-neutron halo nuclei. These exotic nuclei are found close to the neutron drip-line and exhibit a much larger matter radius than their isobars. This peculiar property is qualitatively understood as due to their low binding energy of one neutron, which then can tunnel far into the classically forbidden region and hence form like a diffuse halo around a compact core [1, 2]. Examples of these systems are ^{11}Be and ^{15}C, which can thus be seen as an inert core of ^{10}Be or ^{14}C plus a neutron. Due to their weakly-bound nature these systems are particularly unstable and hence their structure is studied mostly through indirect techniques, such as nuclear reactions [1].

Breakup and transfer reactions can be used as spectroscopic tools to infer information about the structure of these one-neutron halo nuclei. Breakup occurs through the interaction of the halo projectile with a target; when the reaction is measured on a heavy target the dominant interaction is Coulomb interaction and the Coulomb cross section $d\sigma_C/dE$ depends on the size

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r of the nucleus through the electric dipole excitation $dB(\mathrm{E1})/dE$ [3, 4]. Transfer processes, like the (d,p) reaction which consists in the "capture" of the deuteron's neutron by the target, are related to the halo nucleus spatial range when peripheral.
During the last decades several reactions involving these systems have been measured on different targets and at different energies [5, 6, 7, 8, 9, 10, 11]. Our purpose is to study these different processes using one single structure model for each nucleus and see if we can obtain a coherent description of a wide range of reaction observables. We first describe the structure of halo nuclei within the halo effective field theory (Halo EFT) at next-to-leading order (NLO), adjusting the main parameters on nuclear-structure data and/or ab initio calculations. We then study transfer and breakup processes at different energies and compare our predictions with experimental results.

2. The structure model

We model one-neutron halo nuclei as two-cluster systems composed of an inert compact core C plus one neutron n. The interaction between these two clusters is described by an effective potential V_{Cn}. In this model, the Hamiltonian that describes the quantal structure of halo nuclei reads

$$\mathcal{H}(\mathbf{r}) = -\frac{\hbar^2\nabla^2}{2\mu_{Cn}} + V_{Cn}(\mathbf{r}) \tag{1}$$

where μ_{Cn} is the core-neutron reduced mass and $\mathbf{r}$ is the C-n distance. We obtain a set of wavefunctions $\varphi_{jlm}(E,\mathbf{r})$ for this system by solving the eigenvalue problem

$$[\mathcal{H}(\mathbf{r}) - E_{jlm}]\,\varphi_{jlm}(E,\mathbf{r}) = 0, \tag{2}$$

where j is the total angular momentum resulting from the coupling of the orbital angular momentum l with the spin of the halo neutron and m is its projection. The bound states of the halo nucleus are then described by the eigenstates of $\mathcal{H}$ of negative energy, which are discrete and exhibit a well-known asymptotic radial behaviour

$$u_{jlm}(r) \underset{r\to\infty}{\longrightarrow} \mathcal{C}_{jlm}\; e^{-k_{jlm}r}, \tag{3}$$

where $\hbar k_{jlm} = \sqrt{2\mu_{Cn}|E_{jlm}|}$ and the parameter C_{jlm}, called the asymptotic normalization constant (ANC), regulates the strengths of the wavefunction tail. So, for the wavefunction describing the valence neutron it represents the spatial extension of the halo. Therefore the ANC gives information about the halo nucleus structure.
For positive energies we obtain a continuum of oscillating functions with reduced radial parts normalized according to

$$u_{klj}(r) \underset{r\to\infty}{\longrightarrow} \sin\left(kr - l\frac{\pi}{2} + \delta_{lj}\right) \tag{4}$$

and phaseshift δ_{lj}, that is the main parameter for constraining the V_{Cn} interaction for positive states.
To obtain the structure of ^{11}Be and ^{15}C we define the interaction $V_{Cn}(\mathbf{r})$ following the Halo EFT at NLO [12]. This theory is based on the clear separation of scales in halo nuclei: the large scale related to the size of the halo (about 7 fm in ^{11}Be) and the small scale of the order of the core radius (about 2-3 fm). This provides an expansion parameter (small scale/large scale) upon which the interaction can be expanded (see [12] for a recent review). We use narrow Gaussian potentials, so at leading order (LO) the interaction is

$$V_{Cf}^{LO}(r) = V_0 e^{-\frac{r^2}{2r_0^2}}, \tag{5}$$

where the V_0 parameter is adjusted in s waves to fit the binding energy, and $V_{Cf} = 0\ \forall l > 0$. At NLO the interaction includes the second-order derivative of the central term, and we parametrise it as [13]

$$V_{Cf}^{NLO}(r) = V_0 e^{-\frac{r^2}{2r_0^2}} + V_2 r^2 e^{-\frac{r^2}{2r_0^2}}, \tag{6}$$

and V_0 and V_2 are adjusted in s and p waves to fit binding energies and ANCs, for bound states, and phaseshifts, in the continuum, while $V_{Cf} = 0\ \forall l > 1$. The r_0 cutoff is used to evaluate the sensitivity to short-range physics: this is an estimate of the range $r < r_0$ neglected in the model. If the results are not dependent to r_0 the process under study is more sensible to the asymptotic part of the wavefunctions (3) and (4).
Both ^{11}Be and ^{15}C ground states are $1/2^+$ states, so they could be modeled as a $1s_{1/2}$ neutrons bound to a core in 0^+ state, i.e. ^{10}Be(0^+) and ^{14}C(0^+) respectively. To fit a halo EFT interaction at NLO we need the binding energies and ANC of these states. Their ground states energies $E_{g.s.}$ are known from experiment: $E_{g.s.} = -0.504$ MeV and -1.218 MeV for ^{11}Be and ^{15}C respectively. While their ANC should be determined. We follow a method to extract this feature from peripheral transfer reactions [14], which occur at low energies and forward angles. This method has been applied to extract the ANC for the two nuclei in [15, 16] using data from [5, 7]; the results obtained for the two ground states are reported in Table 1. Interestingly our results are in excellent agreement with recent ab initio calculations for these nuclei [17, 18].

	^{11}Be $C_{g.s.}$ (fm$^{1/2}$) (fm$^{1/2}$)	^{15}C $C_{g.s.}$ (fm$^{1/2}$)
our result	0.785±0.03	1.26±0.02
ab initio	0.786	1.282

Table 1. Our ANC results [15, 16] compared to ab initio predictions for ^{11}Be [17] and ^{15}C [18].

3. The study of transfer and breakup reactions

Once we have information about the binding energy and the ANC of ^{11}Be and ^{15}C ground states we are able to describe their structure within a halo EFT description at NLO. The radial behaviour of the ^{15}C ground state wavefunction is shown, as an example, in the left panel of figure 1 for different choices of the r_0 parameter: it is clear how changing the cutoff the inner part of the wavefunction changes, while the tail remains unchanged as it is related to the ANC. We use these structure models as input for reaction calculations to study transfer and breakup processes involving the two halo nuclei.

3.1. (d, p) transfer reaction

To model the (d, p) transfer reaction we use the finite-range Adiabatic Distorted Wave Approximation (FR-ADWA) [19]. We used Chappel-Hill global nucleons-nucleus potential, Reid soft core potential for the deuteron bound state, and deuteron adiabatic potentials obtained with the front code of TWOFNR [20, 21, 22]. The transfer calculations have been performed using FRESCO [23]. In [15] and [16] we show our results for the (d, p) reactions measured by [5] and [6, 7] involving ^{11}Be and ^{15}C, respectively. We report here in the right panel of figure 1 the results involving ^{15}C. We obtain a good agreement with data in peripheral conditions, i.e. low deuteron energies (below about $E_d = 17$ MeV) and forward angles (less than 20°). The difference found at higher angles indicates the region of a less peripheral reaction, as well as the need for more sophisticated reaction models [24]. For example, it seems that, at this beam energy, the excitation of the target affects the transfer cross section at large angles [25].

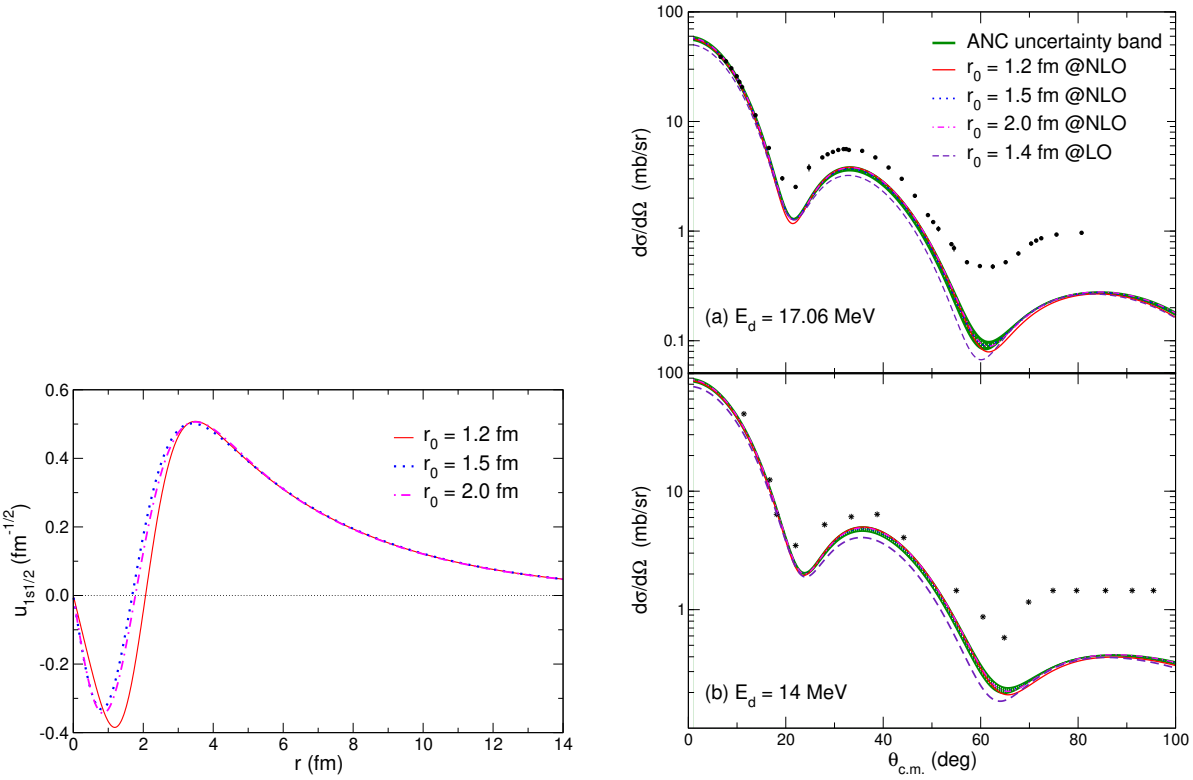

Figure 1. Left panel: radial part of the ^{15}C ground state wavefunction calculated with the halo EFT interaction at NLO using different r_0. Right panel: cross sections for the ^{14}C$(d,p)^{15}$C transfer reaction obtained at (a) $E_d = 17.06$ MeV and (b) $E_d = 14$ MeV. FR-ADWA calculations performed with the halo EFT descriptions at LO and NLO (with different cutoff r_0) of ^{15}C are compared to experimental data from (a) Ref. [7] and (b) Ref. [6]. The green band shows the effect of the uncertainty on the ANC upon the calculation.

3.2. Breakup reaction

We also study the breakup of these nuclei at intermediate (about 70A MeV) and high (at 520A and 605A MeV) energies using an eikonal model with a consistent treatment of nuclear and Coulomb interactions at all orders, which takes into account proper relativistic corrections [26]. We compare our results with measurements from RIKEN and GSI [10, 11, 8, 9], for the differential cross section as a function of the dissociation energy. In figures 2, and 3 we report our results for the cases of ^{11}Be [13, 26] and ^{15}C [16], respectively, on Pb and C targets (solid lines). The results at intermediate (high) energy are reported in the left (right) panels. We obtain a general good agreement with data at different energies and on different targets. At excitation energies between $1-3$ MeV data show some picks that could be related to resonances. As it results more evident in the case of carbon targets, the description of resonances is not included in our structure description. In the case of the high energy breakup we also report the results of calculations without the inclusion of relativistic corrections (dashed lines in right panels of figures 2 and 3): this shows the importance of considering this corrections at higher energy regimes.

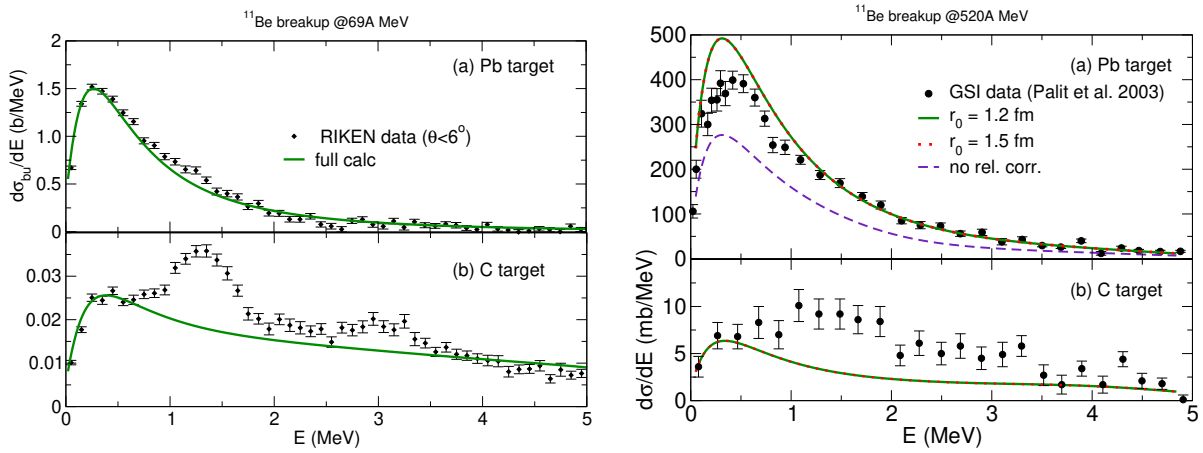

Figure 2. Left panel: ^{11}Be breakup measured at about 70A MeV at RIKEN on (a) Pb and (b) C targets [10, 13]. Right panel: ^{11}Be breakup (green solid lines) measured at 520A MeV at GSI on (a) Pb and (b) C targets, and result without relativistic corrections (purple dashed line) [8, 26]

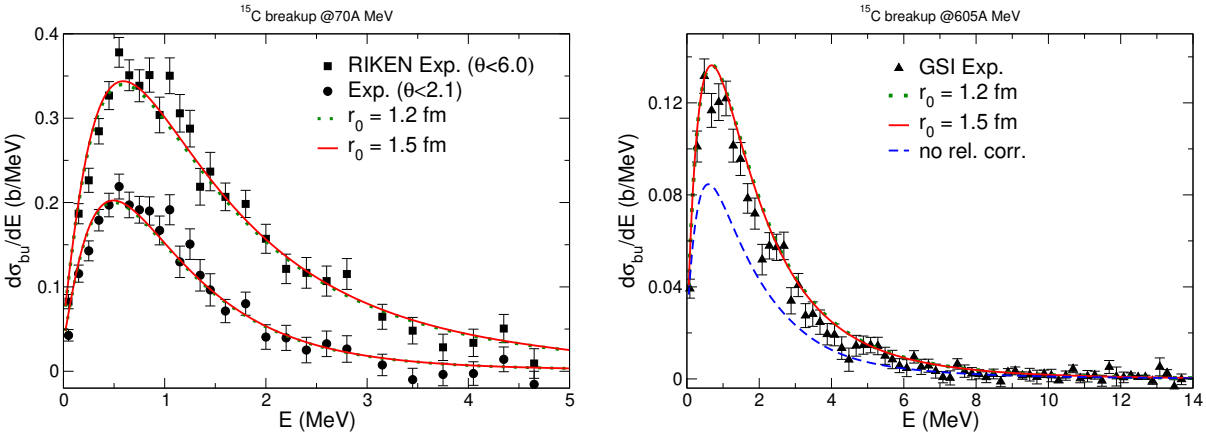

Figure 3. Left panel: ^{15}C breakup measured at about 70A MeV at RIKEN on Pb target considering different angular cuts [11, 16]. Right panel: ^{15}C breakup (red solid line) measured at 605A MeV at GSI on Pb target, and result without relativistic corrections (blue dashed line) [9, 16].

4. Conclusions

We find that our theoretical predictions are in good agreement with the experimental data for each reaction at different energies, thus assessing the robustness of the structure model provided for these nuclei. The use of Halo EFT allows to understand which elements of their structure matter in the description of nuclear reactions: binding energies and ANCs. To describe the effect of resonances, that in the case presented include d-waves, it would be necessary to go beyond NLO. Our results also allow to confirm the validity of ab initio predictions: with a description of the nuclear structure in agreement with ab initio results we are able to describe different reaction observables. Finally we show the importance of the inclusion of relativistic corrections in the case of the breakup at high energy.

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