Coulomb breakup of drip-liners

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Abstract. We show how to derive nuclear structure information on loosely bound nuclei far from the $\beta$ stability line from their Coulomb dissociation into the continuum. The $^{19}$C $\rightarrow$ $^{18}$C$+n$ process is taken as an example and it is shown that basic properties such as ground-state spin and parity and the neutron binding energy of the halo nucleus $^{19}$C can be derived from a comparison of theoretical calculations to experimental data.

1 Introduction

The structure of light neutron-rich nuclei close to the neutron drip-line exhibits some peculiar properties which have been the subject of numerous investigations in the most recent years. For example, a low-density extended valence neutron distribution decoupled from an ordinary nuclear core has been found in nuclei such as $^{11}$Be and $^{11}$Li. This property, the neutron halo structure, is strongly related to the extremely loose nature of the valence neutrons and to their strong spectroscopic parentage with the $2s_{1/2}$ single-particle orbit.

Coulomb breakup experiments have been used to determine the halo structure properties of neutron-rich light systems. The Coulomb breakup (or Coulomb dissociation) of a $^A$X nucleus into the $^{A-1}$X$+n$ channel is realized by using a high energy (typically radioactive ion) beam on a high-Z target. The virtual photons generated by the Coulomb field of the target are absorbed by the incident nucleus causing an electromagnetic transition from a bound state $|^A$X$>$ into the $|^{A-1}$X$+n>$ continuum. Here, $|^{A-1}$X$+n>$ denotes a positive-energy (or scattering) state of the neutron in the core of the halo nucleus. As in the case of bound nuclear states of stable or near-stable nuclei, electromagnetic transition matrix elements carry the most important information on the nuclear wave functions and hence on the structure. It follows that basic structure information are carried by the Coulomb dissociation cross section and strength distributions.

Here we will analyze the case of the Coulomb breakup of a halo candidate, $^{19}$C. This nucleus has been the subject of recent experimental and theoretical investigations because its structure presents some intriguing features. So far, nuclear breakup experiments performed at MSU [1, 2, 3] and GSI [3] have failed to provide a definitive answer even for basic properties such as the ground-state spin and parity and the neutron separation energy. The most recent experiment performed in RIKEN [4] seems to have solved these two questions but many
more on the structure of this exotic system seem to have arisen. We will explore these here, and we will show what is the theoretical ground for their definition.

2 Neutron rich Carbon isotopes

As previously mentioned, the halo structure of light neutron-rich nuclei is related to their loosely bound nature. In Figure 1, the one-neutron binding energy of the $N \geq 6$ Carbon isotopes is shown as a function of the mass number. Naturally, the binding energy decreases as the neutron drip-line is approached. The last even-odd bound isotope is $^{19}$C with a neutron binding energy of $S_n = 160 \pm 110$ KeV [5]. A more reliable estimate of his quantity, based on earlier mass measurements, is $S_n = 240 \pm 100$ KeV [6, 7, 8, 9].

In the shell model ordering, $^{13}$C has five neutrons in the $sd$ neutron shell. In the extreme single-particle picture they should occupy the $1d_{5/2}$ orbital. However, mixing with the $2s_{1/2}$ orbital is expected from the systematics of this single-particle state in the Carbon isotopes, as shown in the Figure 2. In the figure, the binding energy of the $2s_{1/2}$ orbit in the isotopic chain under consideration here is shown. It has to be reminded that, already for $^{13}$C this orbit is located below the $1d_{5/2}$. In addition, the binding itself is becoming looser and looser as the neutron number increases. This trend supports the argument which
would favor a halo structure for $^{19}$C.

In the extreme single particle picture, the structure of the $^{19}$C ground-state is given by

$$\Psi_b(J^\pi) = |^{18}\text{C}(0^+) \otimes (nlj); j^{(-)^l} >$$

where $nlj$ are single-particle orbital quantum numbers. Because of the strong effect of the orbital angular momentum on the amplitude of the tail of the radial wave function in the asymptotic region, we can expect a Coulomb dissociation cross section and $B(E\lambda)$ strength distribution completely different for the allowed configurations of the $^{19}$C ground state. We can therefore expect to derive important information on the structure of this extremely neutron-rich nucleus from the analysis of its Coulomb breakup.

### 3 Coulomb dissociation

The Coulomb dissociation cross section is related to the Coulomb field of the target nucleus by [10]

$$\frac{d\sigma_{CD}}{dE_x} = \sum_\lambda \int 2\pi bdb \frac{N_{E\lambda}(E_x, b)}{E_x} \sigma_{E\lambda}^{E\gamma}(E_x)$$

where $N_{E\lambda}(E_x, b)$ is the virtual photons number at impact parameter $b$ and excitation energy $E_x$ (defined as the sum of the neutron-residual nucleus relative kinetic energy plus the neutron binding energy) and $\sigma_{E\lambda}^{E\gamma}(E_x)$ the photo-disintegration cross section. We will specialize here to dipole radiation, i.e. $\lambda = 1$.

The photo-disintegration cross section is given by

$$\sigma_{E1}^{E\gamma}(E_x) = \frac{16\pi}{9} \frac{E_x}{\hbar c} \frac{\mu k_n}{\hbar^2} e^2 \frac{2J_c + 1}{2J_b + 1} |Q_{b\rightarrow c}^{(E1)}|^2$$
where $\mu$ is the reduced mass of the system, $k_n$ is the wave number of the neutron-residual nucleus relative motion in the continuum, $\bar{e}$ the E1 effective charge, $J_b$ is the total angular momentum of the bound state and $J_c$ the spin of the residual nucleus in the continuum.

The photo-disintegration cross section can be promptly related to the neutron capture cross section by detailed balance

\[ \sigma_{\gamma,n} = \frac{k_n^2}{k_{\gamma}^2} \sigma_{\gamma,\gamma} \]

The essential ingredients for the calculation of the Coulomb dissociation cross section are the matrix elements

\[ Q_{b \rightarrow c}^{(E1)} = \langle \Psi_c | \hat{T}^{E1} | \Psi_b > \]

where $\Psi_b$ is the bound-state wave function and $\Psi_c$ the wave function for the neutron in the continuum. These matrix elements can be easily evaluated for bound states with configurations of type $| ^4X(J^\pi) \otimes (nlj); J_b >$. In this case, they can be decomposed into the products of three factors

\[ Q_{b \rightarrow c}^{(E1)} \equiv \sqrt{S_b} A_{b,c} I_{b,c} \]

where $S_b$ is the spectroscopic factor of the bound state, $A_{b,c}$ is a factor containing only angular momentum and spin coupling coefficients and $I_{b,c}$ the radial overlap. $I_{b,c}$ can be evaluated using some potential model for the calculation of the radial wave functions $u_b(r)$ and $w_c(r)$.

4 \, \text{19C} \rightarrow \text{18C} + \text{n}

A first set of calculations of the Coulomb dissociation cross section for the $^{19}\text{C} \rightarrow ^{18}\text{C} + n$ process can be performed using a simple Woods-Saxon potential. The single-particle orbits and their relative radial wave functions can be easily calculated. The geometrical parameters of the Woods-Saxon potential well used for this calculation were $r_0 = 1.236$ fm (radius), $d = 0.62$ fm (diffuseness). In addition, a spin-orbit strength $V_{so} = 7.0$ MeV was used. With these parameters, the depth of the well was adjusted in order to reproduce a neutron binding energy of 0.240 MeV. As expected, the depths corresponding to the $2s_{1/2}$ and to the $1d_{5/2}$ were almost identical ($V_0 = 40.14$ MeV and $V_0 = 40.31$, respectively). The almost-degeneracy of these two orbits was expected.

The result of the Coulomb dissociation cross section are shown in Figure 3. It can be seen that the absolute magnitude as well as the spectral shapes of the two different configurations are completely different. From these calculation it is apparent that a measurement of the Coulomb breakup of $^{19}\text{C}$ would allow to discriminate between a $J^\pi = 1/2^+$ and $J^\pi = 5/2^+$ ground state.
Fig. 3. Coulomb dissociation cross section of $^{19}$C on a Pb target at 67.4 MeV. Only the dominant E1 contribution is included. See text for details on the other parameters used for the calculation.

Table 1. Shell model configurations of the $^{19}$C ground state, calculated using OXBASH [12] with WBP interaction. Only the configurations relevant for the present study are shown. The full set of results can be obtained upon request to the author.

| $\epsilon_{1/2} - \epsilon_{5/2}$ MeV | $J^{\pi}$ | $S_b$ | configuration |
|----------------------------------|--------|------|----------------|
| -2.22                            | $\frac{1}{2}^+$ | 0.58 | $^{18}$C$(0^+) \otimes 2s_{1/2}$ |
|                                  |        | 0.47 | $^{18}$C$(2^+) \otimes 1d_{5/2}$ |
| -0.38                            | $\frac{5}{2}^+$ | 0.32 | $^{18}$C$(0^+) \otimes 1d_{5/2}$ |
|                                  |        | 1.16 | $^{18}$C$(2^+) \otimes 1d_{5/2}$ |
|                                  |        | 0.024| $^{18}$C$(2^+) \otimes 2s_{1/2}$ |

However, this simple approximation cannot be considered sufficient for an accurate description of the $^{19}$C structure. We have then calculated the ground-state structure using the shell-model. The model space was a $\pi(p)\nu(sd)$ space with two different sets of interactions, WBP and WBT [11].

The full results of these calculations have been reported elsewhere [13] and are available upon request. Here we show only the results concerning the most important configurations obtained using the WBP interaction. In all cases, a $^{14}$C$_6$ core was assumed (5 neutrons in the sd shell).

In the table, two different set of calculations are shown for two values of the $2s_{1/2} - 1d_{5/2}$ single particle energy difference. The first one is the original value used in conjunction with the WBP interaction while the second value correspond
more closely to our situation in which the s and d orbitals are almost degenerate. In the second case, the $^{19}$C ground state turns out to be a $J^\pi = 5/2^+$ while with the 2$s_{1/2}$ orbit 2.22 MeV below the 1$d_{5/2}$ we obtained $J^\pi = 1/2^+$. This result can be understood because by lowering the 2$s_{1/2}$ orbit one favors the $|^{18}$C(0$^+$)$\otimes$2$s_{1/2}$⟩ configuration.

The results of the Coulomb dissociation cross section calculation are shown in Figure 4. There, a comparison with a recent experiment [4] performed at RIKEN RIPS facility is shown. All the configurations resulting from shell model calculations (see Table 1) were included in this calculation. From the comparison of the upper part with the lower part of the figure it is apparent that a $J^\pi = 5/2^+$ can be excluded for the $^{19}$C ground state. In fact, neither the absolute value nor the spectral shape of the experimental cross section could be reproduced with this assumption. Indeed, even allowing for larger spectroscopic amplitudes of the configurations included (up to full strengths), the experimental cross section cannot be reproduced with a $J^\pi = 5/2^+$ assumption. The integrated cross

\[ J^\pi = 1/2^+ \]

\[ J^\pi = 5/2^+ \]
section for the calculations obtained with $J^\pi = 5/2^+$ amounts to a maximum of $\sigma_{CD} \approx 450$ mb, to be compared to an experimental datum of $\sigma_{exp}^{CD} = 1.19 \pm 0.11$ b.

In turn, the experimental data are consistent with $J^\pi = 1/2^+$. This can be seen in the upper part of the figure. There, the result obtained with the dominant configuration $|^{16}\text{C}(0^+)\otimes 2s_{1/2}\rangle$ and a spectroscopic factor $S_b = 0.12$ yields a spectrum compatible with the experimental data. However, the position of the peak is located at larger energy in the experimental spectrum and the width of the distribution is larger than that resulting from the calculation. A nice reproduction of the data can be obtained using the same configuration with a neutron binding energy of 0.530 MeV and a spectroscopic strength $S_b = 0.67$, compatible with the shell model results. This value of the neutron binding, though larger than that derived from the present mass evaluations (0.240 ± 0.100 MeV), is not at all anomalous. In fact, already in the nuclear breakup experiment of Bazin et al., a value of 0.600 MeV was proposed to reproduce the width of their fragments momentum distribution data. Therefore, the result of the present analysis can be considered the confirmation of a higher value of the neutron binding energy of $^{19}\text{C}$.

5 Conclusions

In this work we have shown how the Coulomb dissociation process furnishes a unique spectroscopic tool for the investigation of the halo structure properties of loosely bound nuclear systems. Nuclear structure model calculations, such as conventional shell-model approaches are the necessary guide for the interpretation of experimental data. Quantitative answers to some of the questions posed by the exotic systems encountered in far-from-stability lands can be obtained by a close intercomparison between advanced experimental utilities with tested theoretical methodologies.

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(a) HF-SLy4d

\[ V_0 = 56.45 \text{ MeV} \]
\[ V_0 = 56.45 - 33.9(N-Z)/A \text{ MeV} \]

(b) Woods-Saxon potential

\[ \epsilon(2s_{1/2}) - \epsilon(1d_{5/2}) \text{ (MeV)} \]