Core excitation in halo nucleus breakup

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Abstract. We estimate the magnitudes of core excited state cross sections, following halo nucleus dissociation on a light target. Calculations of integrated partial cross sections for the ${}^9\text{Be}({}^{11}\text{Be}, {}^{10}\text{Be}\gamma)$ reaction at 60 MeV/nucleon are presented and some sensitivities to inputs discussed. Reasonable agreement is obtained with preliminary experimental estimates for this system.

1. Introduction

A conventional experimental arrangement for the study of halo nuclei has been to detect a heavy fragment, with the mass and charge of the core of the halo nucleus, following the dissociation of the incident beam. So, in the case of a ${}^{11}\text{Be}$ beam, ${}^{10}\text{Be}$ fragments are detected with velocities close to that of the beam velocity. The measured cross sections for the detection of this heavy fragment, both total and differential, have been used to attempt to clarify the halo nucleus structure, for example in analyses of the widths of the core momentum distribution [1]. These usually assume a dominance of the cross section corresponding to the halo particle removal from the core (ground) state. Recent experiments, such as discussed here by Hansen, in which decay photons from excited states of the heavy core fragment are identified, would indicate that, potentially, a significant contribution to these measured core distributions arises from excited and not ground state core configurations.

A preliminary analysis of measurements of the ${}^9\text{Be}({}^{11}\text{Be}, {}^{10}\text{Be}\gamma)$ reaction with a 60 MeV/nucleon ${}^{11}\text{Be}$ beam [2] is shown as the experimental points in Figs. 1 and 3. It is consistent with about 25% of the cross section going to the 1^- (5.960 MeV) and 2^- (6.263 MeV) excited core states while the cross section to the 2^+ (3.368 MeV) state is consistent with zero.

2. Eikonal model calculations of nuclear breakup

To provide a first theoretical orientation, eikonal model calculations are carried out for both the diffraction dissociation and stripping [3] contributions to the integrated partial cross sections for a particular ${}^{10}\text{Be}^*$ core state c following ${}^{11}\text{Be}$ breakup. For the calculation of each final state cross section $\sigma(c)$ the projectile ground state $|\phi_{IM}\rangle$ is described as a valence neutron, with single particle quantum numbers $(nj\ell)$ and

an associated spectroscopic factor, with respect to the specific core state. Such configurations are written $|\phi_{IM}^c\rangle$, with I the intrinsic spin and M the spin projection of the ground state. These component cross sections will be computed from the integrals over the projectile c.m. impact parameter $\mathbf{b}$,

$$\sigma(c, \text{diff}) = \frac{1}{2I+1} \int d\mathbf{b} \left[\sum_M \langle \phi_{IM}^c | (1 - S_c S_n)^2 | \phi_{IM}^c \rangle - \sum_{MM'} |\langle \phi_{IM'}^c | (1 - S_c S_n) | \phi_{IM}^c \rangle|^2 \right], \quad (1)$$

and

$$\sigma(c, \text{strip}) = \frac{1}{2I+1} \int d\mathbf{b} \sum_M \langle \phi_{IM}^c | (1 - |S_n|^2) |S_c|^2 | \phi_{IM}^c \rangle. \quad (2)$$

The S_c and S_n are the profile functions [4, 5] for the core and neutron, functions of their own impact parameters, determined by the assumed core- and neutron-target interactions. While the diffractive dissociation and stripping contribution are comparable for weakly bound (n-halo) states, the stripping contribution dominates in the case of non- s -wave and more tightly bound neutron removal – as for excited core states. Clearly only $\sigma(c, \text{diff})$ is sensitive to the refractive components of the core and n-target interactions and so details of the real parts of the interactions are of little importance when $\sigma(c, \text{strip})$ dominates. The core-target interaction is in any case highly absorptive at the energies of interest and S_c has often been replaced (without loss of accuracy) by a sharp cutoff (black disk) form.

$\sigma(c, \text{strip})$ on the other hand is sensitive, through the n absorption probability $(1 - |S_n|^2)$, to the assumed geometry and absorptive character of the n-target interaction, a sensitivity which is assessed qualitatively in the following.

3. Application to ^{11}Be breakup

We estimate partial cross sections $\sigma(c)$ to the 0^+ , 2^+ , 1^- , and 2^- ^{10}Be final states in the $^9\text{Be}(^{11}\text{Be}, ^{10}\text{Be}\gamma)$ reaction at 60 MeV/nucleon. The 0^+ and 2^+ states are assumed to arise from dissociation/stripping of the $(2s_{\frac{1}{2}} \otimes 0^+, S_n=0.504 \text{ MeV})$ neutron halo, and the $(1d_{\frac{5}{2}} \otimes 2^+, S_n=3.872 \text{ MeV})$ excited core configurations, respectively, in the $^{11}\text{Be}(\text{g.s.})$. The spectroscopic factors for these two configurations, in both the shell model [6] and simple excited core cluster models [7], are essentially in agreement. We take $S(2s_{\frac{1}{2}} \otimes 0^+)=0.74$, and $S(1d_{\frac{5}{2}} \otimes 2^+)=0.20$ [6].

The excited $J^\pi=1^-$ (5.96 MeV) and 2^- (6.26 MeV) $^{10}\text{Be}^*$ final states are considered as arising from the removal of a tightly bound $(1p_{\frac{3}{2}} \otimes J^\pi, S_n \approx 6.5 \text{ MeV})$ neutron. These states are themselves less than 1 MeV from the $^9\text{Be}+n$ breakup threshold (6.8 MeV) and might be thought of as resulting from the stripping of a $1p_{\frac{3}{2}}$ neutron from the $^{10}\text{Be}(0^+)$ core of the $^{11}\text{Be}(\text{g.s.})$ – producing a $[2s_{\frac{1}{2}} \otimes ^9\text{Be}(\frac{3}{2}^-)]1^-$ or $[2s_{\frac{1}{2}} \otimes ^9\text{Be}(\frac{3}{2}^-)]2^-$ halo-like $^{10}\text{Be}^*$ core. This same nucleon stripping mechanism was used previously to study the unbound ^{10}Li system [8], in that case by the removal of a proton from the ^{10}Be core.

The spectroscopic factors for the 1^- and 2^- configurations in the $^{11}\text{Be}(\text{g.s.})$ are estimated as $S(1p_{3/2} \otimes 1^-) = 0.69$ and $S(1p_{3/2} \otimes 2^-) = 0.58$ [6]. For the $\frac{1}{2}^+ {}^{11}\text{Be}$ case we have an additional simplification in Eqs. (1) and (2), and

$$\langle \phi_{IM'}^c | \phi_{IM}^c \rangle_{\text{spins}} = [u_{nj\ell}^2(r)/4\pi] \delta_{MM'}, \quad (3)$$

where $u_{nj\ell}$ is the neutron radial wave function. All neutron single particle states are calculated in a central Woods-Saxon well with radius and diffuseness parameters (1.15 fm, 0.5 fm). This calculates a $^{11}\text{Be}(\text{g.s.})$ with rms radius of 2.90 fm, assuming a $^{10}\text{Be}(\text{g.s.})$ rms radius of 2.28 fm [4].

Cross sections are calculated from Eqs. (1), (2) and (3). The profile functions for the core- and n-target(^9Be) systems are calculated using the optical limit of Glauber theory [4]. We assume a finite-range NN formfactor f_{NN} (see Eqs. (2) and (3) of [5]), free nn and np cross sections, real to imaginary ratios of the forward scattering amplitude due to Ray [9] (at 100 MeV) and a Gaussian finite range parameter $\beta_{nn} = \beta_{np} = 0.5$ fm. Using this NN formfactor, and matter densities with rms radii consistent with electron scattering, we reproduce the measured $\sigma_R(^{12}\text{C} + ^{12}\text{C})$ and $\sigma_R(^{12}\text{C} + ^{27}\text{Al})$ at 83 MeV/nucleon [10] and calculate $\sigma_R(p + ^9\text{Be}) = 29.1 \text{ fm}^2$ at 60 MeV/nucleon, consistent with experiment [11]. Calculations using these profile functions are denoted NN in the following.

The calculated $\sigma(c, \text{diff})$, $\sigma(c, \text{strip})$, and their sum, before multiplication by the spectroscopic factors, are shown in Figure 1 when using the NN based profile functions. The dominance of the stripping term, for other than the 0^+ halo core state, is evident. The full curve shows the summed cross sections multiplied by the stated spectroscopic factors and is in reasonable agreement with the trends of the preliminary data for this system.

Figure 1. Calculated and deduced $\sigma(c)$ for the indicated $^{10}\text{Be}^*$ core states in the $^9\text{Be}(^{11}\text{Be}, ^{10}\text{Be}\gamma)$ reaction at 60 MeV/nucleon, calculated using the NN description of the profile functions.

In the case of the 1^- and 2^- final states the calculation of the core profile function S_c assumed the $^{10}\text{Be}^*$ core state to be an extended $[2s_{\frac{1}{2}} \otimes ^9\text{Be} (\frac{3}{2}^-)]$ halo-like entity, with $S_n=0.5$ MeV and wave function φ , thus approximating the removal of a $p_{\frac{3}{2}}$ neutron from the $^{10}\text{Be}(0^+)$ core of the $^{11}\text{Be}(\text{g.s.})$. S_c is then calculated to include breakup of this composite core [4], as

$$S_c(b) = \langle \varphi | S_9 S_n | \varphi \rangle, \quad (4)$$

with the ^9Be -target profile function S_9 calculated assuming a ^9Be rms radius of 2.28 fm.

As expected, in these cases with a fragile halo-like core state, the core survival probability is reduced compared to calculations which assume a normally sized ^{10}Be core. The cross sections are 10–15% smaller when using S_c given by Eq. (4) rather than the S_c used for the ground state. The calculations presented in the Figures are based on the use of Eq. (4).

Figure 2. Calculated n absorption probability ($1 - |S_n|^2$) as a function of impact parameter from phenomenological optical potential and optical limit NN descriptions of the n- ^9Be profile function.

To assess the sensitivity of calculations to the assumed n- ^9Be interaction, referred to earlier, S_n is also calculated using the phenomenological nucleon- ^9Be optical potentials 7, 8 and 9 of [12] and (b) of [13]. The qualitatively very different inputs to the stripping calculations which result, through the $(1 - |S_n|^2)$ factor, are shown in Figure 2 for these phenomenological and the NN profile function cases. The less volume and more surface absorptive nature of the phenomenological interactions is evident and it is clear that this theoretical/experimental input will be a very important one – in particular for calculations of the absolute magnitudes of the stripping cross sections.

The averages of the cross sections computed with these phenomenological S_n are compared with those using the optical limit NN description in Figure 3. The calculated cross sections are different typically by a factor of two in cases where the stripping

Figure 3. Calculated and deduced $\sigma(c)$ for the indicated $^{10}\text{Be}^*$ core states in the $^9\text{Be}(^{11}\text{Be}, ^{10}\text{Be}\gamma)$ reaction at 60 MeV/nucleon. Calculations use the phenomenological and the NN descriptions of the n - ^9Be profile function.

cross section is dominant. The two very different descriptions of the profile function do however encompass the preliminary data and the trends, and the relative sizes of the halo state and core excited cross sections, in the two cases are very similar. The summed calculated cross sections are 30 and 18 fm², respectively, compared to the experimental estimate of 22 fm².

Other applications, to test the consistency of such model calculations against the still rather limited experimental data for other projectile systems, are in progress and will be discussed elsewhere [2, 14].

4. Summary

The magnitudes of integrated core excited state cross sections following halo nucleus dissociation on a light target are estimated within the eikonal approximation. We describe model calculations of partial cross sections in the case of the $^9\text{Be}(^{11}\text{Be}, ^{10}\text{Be}^*)$ reaction at 60 MeV/nucleon which provide a reasonable qualitative description of preliminary experimental information for this system. These calculations support the possibility that a significant fraction of measured core fragment cross sections arise from excited core configurations in the final state.

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