Coulomb breakup of the Borromean nucleus $^{22}$C

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Abstract. We study the Coulomb breakup cross section of the $^{22}$C nucleus and its relation with three-body resonances and ground state properties. Cross sections are computed with a Coulomb corrected four-body eikonal model and they are constructed by fixing the continuum state and varying the ground state of $^{22}$C. These states are calculated by using $^{20}$C$^-n$ potentials that provide different scattering lengths and resonance energies, of a presumed virtual state and of a $d$ resonance in $^{21}$C. We find that the breakup cross section is strongly dependent on the ground state properties and we predict the existence of a $2^+$ narrow resonance in $^{22}$C.

1. Introduction

The $^{22}$C nucleus is the heaviest Borromean nucleus known so far. Its deduced rms radius, $r_{rms}$, and two neutron separation energy, $S_{2n}$, present large uncertainties ($r_{rms} = 5.4 \pm 0.9$ fm [1] and, $S_{2n} = 0.42 \pm 0.94$ MeV [1] and $S_{2n} < 300$ keV [2]). As Borromean nuclei can been seen as a core surrounded by two neutrons, three-body models are used to study such as nuclei.

In three-body models, two-body potentials are needed. Those are obtained from experimental information of elastic scattering or by reproducing spectroscopic data. $^{21}$C is unbound and little experimental spectroscopic information is known. Recently, Mosby et al. [3] claim that if a $^{21}$C virtual state exists, its scattering length should be limited to $|a_0| < 2.8$ fm. In Ref. [4] the recently measured $^{21}$C excitation spectrum shows a presumed $d$ resonance.

An important property of halo nuclei is the enhancement of their Coulomb breakup cross sections at low excitation energies. Some theoretical calculations relate this enhancement with a $1^-$ three-body resonance [5, 6] and others with the weak binding of the ground state [7, 8] of those nuclei.

The goal of the present paper is to study if a possible enhancement in the Coulomb breakup cross section of $^{22}$C, for some suitable conditions, is related with a resonance behavior or with its ground state properties. With this aim, we choose three sets of $^{21}$C potentials that reproduce different scattering lengths and resonance energies of $^{21}$C. In combination with a fixed $n-n$ interaction, these sets provide different ground and continuum states. We fix the continuum state and vary the ground state to observe its effect on the breakup cross sections.

2. Three-body phase shifts and breakup cross sections

Breakup cross sections are computed with the four-body eikonal Coulomb corrected model of Ref. [9] (see Ref. [9] and Ref. [6] for details). This model uses three-body wave functions in
hyperspherical coordinates. Bound states are computed variationally and continuum states are computed with the correct asymptotic behavior. We follow Ref. [10] and Ref. [11], respectively.

We need core−n and n−n potentials to compute ground and continuum states of $^{22}$C. As n−n potential, we use a Minnesota central interaction with exchange parameter $u = 1$ [12].

The $^{20}$C−n potentials have the form

$$V_{^{20}C+n}(r) = -V_0^l f(r) + V_s l \cdot s \frac{d}{dr} f(r),$$

with $f(r) = 1/(1 + \exp(r/\alpha))$, $\alpha = 0.65$ fm, $R_c = 3.393$ fm, $V_s = 35$ MeV and $V_0^{l=2} = 42$ MeV. The depths $V_0^{l=0}$ and $V_0^{l=2}$ are given in Table 1. These depths are chosen to provide different scattering lengths of a 1$s_{1/2}$ virtual state and 0$d_{3/2}$ resonance energies of $^{21}$C. The three potentials provide a single bound state in each shell model orbit, which is removed by a supersymmetric transformation to approximately take into account the Pauli principle.

| $V_0^{l=0}$ (MeV) | $V_0^{l=2}$ (MeV) | $E_0$ (MeV) | $a_0$ (fm) | $E_R$ (MeV) |
|-------------------|-------------------|-------------|------------|-------------|
| set 1             | 29.8              | 47.5        | -0.10      | -2.8        | 0.83        |
| set 2             | 29.8              | 48.4        | -0.47      | -2.8        | 0.59        |
| set 3             | 33.0              | 47.5        | -0.46      | -47.6       | 0.92        |

Three ground states with each set and a single continuum wave function are computed. We use set 1 to get the continuum state. We calculate the $1^-$, $2^+$ and $0^+$ continuum partial waves, which provide the prominent contributions to the breakup cross sections. Important convergence parameters for computing the wave functions are the maximum hypermomentum, $K_{\text{max}}$, and the number of basis functions, $N$. As a basis we use the Lagrange-Legendre [13] with $a = 90$ fm and $N = 100$. We use $K_{\text{max}} = 40$ for the ground state and $K_{\text{max}} = 30, 25, 20$ for the $J^\pi = 0^+, 1^-, 2^+$ continuum partial waves.

The breakup of $^{22}$C on a $^{208}$Pb target is studied at 240 MeV/nucleon. For the breakup calculations, we need core-target and n−target potentials. The $^{20}$C−$^{208}$Pb potential is taken from Ref. [14] by interpolating the $a_{NN}$ and $\sigma_{NN}$ parameters. The n−$^{208}$Pb potential is given in Ref. [15].

Figure 1 shows breakup cross sections associated with the three sets and their respective $1^-$ partial contribution. In general, the cross sections are dominated by their dipole part. However, the cross section calculated with set 2 differs from its dipole contribution showing a bump at low excitation energies. This is related with the non orthogonality of the ground state and the $0^+$ continuum partial wave.

The cross section for the weakest bound state exhibits the larger enhancement at low excitation energies. Breakup cross sections computed with set 2 and set 3 are very different, although their corresponding $^{22}$C ground states have similar energies. Therefore, we can observe clearly a large effect of the two-body properties, $a_0$ and $E_R$, on the $^{22}$C excitation spectrum.

In Fig. 2 we present $^{20}$C+n+n+n phase shifts computed by following Ref. [11] for the $1^-$, $2^+$ and $0^+$ continuum partial waves. We observe a $2^+$ narrow resonance around 0.8 MeV. This is in agreement with the peak structure that shows up in the breakup cross sections, independently of the ground state used. In contrast, we cannot relate a $1^-$ three-body resonance with the enhancement at low excitation energies of the breakup cross sections.
Figure 1. (Color online) Total (solid lines) and dipole (dashed lines) breakup cross sections of $^{22}$C with different core−$n$ potentials.

Figure 2. (Color online) Three-body $^{20}$C + $n + n$, $J = 0^+$, $J = 1^−$ and $J = 2^+$ phase shifts computed with set 1.

3. Conclusions

We observe a large enhancement of the Coulomb breakup cross section of $^{22}$C that is due to the very weakly bound character of the ground state and that is no related with a $1^−$ three-body resonance. We also find a $2^+$ resonance that shows up in the breakup cross section consistent with the three-body phase shift calculation. Of course these results depend on the $^{21}$C and $^{22}$C properties assumed. However, the existence of a $^{22}$C $2^+$ resonance seems well established.

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