EPJ Web of Conferences **117**, 06021 (2016) DOI: 10.1051/epjconf/201611706021
NN2015

Three-body breakup of ^{22}C

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Abstract

Coulomb breakup excitation functions of ^{22}C are calculated as a function of its ground state energy. We consider three ground states that fall into the recent experimental limit $S_{2n} < 0.3$ MeV. The ground states are constructed by varying the scattering length value of a $1s_{1/2}$ virtual state in ^{21}C. We find enhanced breakup cross sections sensitive to the weakly bound character of the ground state.

1 Introduction

The breakthrough experiment of Tanaka et al. [1] gave evidenced for a large matter radius for ^{22}C of 5.4 ± 0.9 fm, characterizing this nucleus as the heaviest halo nucleus known so far. Data on high-energy two-neutron removal from ^{22}C suggest that this nucleus is Borromean with both neutrons in a $s-$orbit [2]. A recent mass measurement places a limit in the two neutron separation energy of $S_{2n} < 0.3$ MeV [3]. Mosby et al. [4] predict an experimental scattering length limit of $|a_0| < 2.8$ fm and, from this value and a zero-range three-body model, suggest a limit $S_{2n} < 70$ keV.

Halo nuclei are seen as made of two or three bodies [5]. In particular, the four-body coupled-channels adiabatic and the adiabatic plus eikonal dynamical approaches has been introduced in Ref. [6] to compute reaction cross sections around 300 AMeV of ^{22}C. Four-body models make use of core$-n$ and $n-n$ interactions to describe the three-body projectile, and core-target and target$-n$ interactions are needed into the reaction framework. A four-body study of the Coulomb breakup mechanism of ^{22}C is particularly difficult since neither the ^{20}C$-n$ potential nor the ^{22}C ground state energy is exactly known. A theoretical description of the ^{22}C breakup should clarify many aspects of the very weakly bound character of this nucleus.

In this work we apply a Coulomb corrected eikonal model [7,8] to predict breakup excitation functions of ^{22}C on ^{208}Pb at 240 AMeV as a function of the ground state energy of ^{22}C. We use three ground state energies that fall into the limit $S_{2n} < 0.3$ MeV. These ground states are computed by using ^{20}C$-n$ potentials constructed to give different scattering lengths of a ^{21}C virtual state.

The paper is organized as follows. Section 2 briefly review the eikonal model. In section 3 we exhibit the ^{22}C breakup cross section for different ground state energies. Some conclusions are shown in Section 4.

2 Four-body eikonal

In this section we briefly introduce the four-body Coulomb corrected eikonal model of Ref. [7]. For details we refer the reader to this reference.

For a three-body projectile impinging on a non-composite target the time-independent four-body Schrödinger equation is written as

$$\left[-\frac{\hbar^2}{2\mu_{PT}}\Delta_R + H_0(\xi) + V_{PT}(\boldsymbol{R},\xi)\right]\Phi(\boldsymbol{R},\xi) = E_T\Phi(\boldsymbol{R},\xi), \tag{1}$$

where μ_{PT} is the projectile-target reduced mass, ξ represents the set of internal coordinates of the projectile and $H_0(\xi)$ is its internal Hamiltonian. In Eq. (1) the center of mass coordinate has been removed, and $\boldsymbol{R} = (\boldsymbol{b}, Z)$ is the relative coordinate between the center of masses of the projectile and the target, with transverse component $\boldsymbol{b}$. The projectile-target interaction $V_{PT}(\boldsymbol{R},\xi)$ is the sum of three terms corresponding to the interaction between each body of the projectile with the target. The total energy in the center of mass system is $E_T = E_0 + \frac{\hbar^2 K^2}{2\mu_{PT}}$, with E_0 being the ground state energy of the projectile.

In eikonal models one assumes that the collision energy is much higher than the Coulomb barrier to make the following ansatz for the solution of Eq. (1)

$$\Phi(\boldsymbol{R},\xi) = \frac{1}{(2\pi)^{3/2}} e^{iKZ}\hat{\Phi}(\boldsymbol{R},\xi), \tag{2}$$

where $\boldsymbol{K}$ is the initial relative projectile-target wave vector defined along Z. In Eq. (2) $\hat{\Phi}(\boldsymbol{R},\xi)$ is a slow varying function over $\boldsymbol{R}$, which means

$$\left|\Delta_R \hat{\Phi}(\boldsymbol{R},\xi)\right| \ll \left|K\frac{\partial}{\partial Z}\hat{\Phi}(\boldsymbol{R},\xi)\right|. \tag{3}$$

Inserting Eq. (2) into the Schrödinger equation (1), using Eq. (3) and performing the adiabatic approximation which consists in replacing H_0 by E_0 [9], we find the so-called eikonal wave function

$$\Phi_{\mathrm{eik}}(\boldsymbol{R},\xi) = \frac{1}{(2\pi)^{3/2}} \exp\left[i\left(KZ - \frac{\mu_{PT}}{\hbar^2 K}\int_{-\infty}^{Z} dZ' V_{PT}(\boldsymbol{b},Z',\xi)\right)\right] \Psi_{J_0 M_0 \pi_0}(\xi), \tag{4}$$

where $\Psi_{J_0 M_0 \pi_0}(\xi)$ is the three-body projectile ground state with total angular momentum, projection over the quantization axis and parity J_0, M_0 and π_0, respectively. This state is determined here from a three-body model. For the internal coordinates ξ, we use hyperspherical coordinates (for details we refer the reader to Refs. [10, 11]).

Breakup cross sections are proportional to the T-matrix

$$T_{\mathbf{K}',\mathbf{K}} = \langle \phi_{\mathbf{K}'} | V_{PT} | \Phi^{\mathrm{eik.}}_{\mathbf{K}} \rangle \tag{5}$$

with the definition $\phi_{\mathbf{K}'}(\mathbf{R},\xi) = \frac{1}{(2\pi)^{3/2}} e^{i\mathbf{K}'\cdot\mathbf{R}} \Psi^{(+)}_{k_\xi,\xi}(E,\xi)$, where $\boldsymbol{K'}$ is the final relative projectile-target wave vector and $\Psi^{(+)}_{k_\xi,\xi}(E,\xi)$ is the three-body continuum state of the projectile. In this work, we use the three-body R-matrix method in hyperspherical coordinates to find continuum states with the appropriate boundary conditions [12]. The set of wave vectors associated to the internal coordinates of the projectile is represented by k_ξ. The projectile excitation energy E is defined from the three-body breakup threshold. The adiabatic approximation introduces a logarithmic divergence for Coulomb interactions. This problem is overcome by the Coulomb corrected eikonal model [7, 13, 14].

3 Breakup cross sections

Aiming at showing the sensitivity of the Coulomb breakup cross section of ^{22}C with its ground state energy, we consider three sets of ^{20}C$-n$ potentials. The $n-n$ potential for all cases is a central Minnesota interaction with exchange parameter $u = 1$ [15]. We take the ^{20}C$-n$ potential from Ref. [6] with $a = 0.65$ fm and $R_c = 3.393$ fm. The spin-orbit depth is modified to

$V_{ls} = 35$ MeV, which is close to the values given in Ref. [16]. We assume the existence of a $1s_{1/2}$ virtual state which scattering length is varied by modifying the $V_{l=0}$ depth. Table 1 lists the scattering lengths for three $V_{l=0}$ values and their respective three-body ground state energies and $r_{\rm rms}$ radii.

Table 1: Depths $V_0^{l=0}$ for the determined ^{20}C-n potential sets and the corresponding scattering lengths a_0 of the $1s_{1/2}$ virtual state computed with the technique of Ref. [17]. E_0 and $r_{\rm rms}$ are the ^{20}C+$n+n$ ground state energies and $r_{\rm rms}$ radii associated with each two-body potential.

	$V_0^{l=0}$ (MeV)	a_0 (fm)	E_0 (MeV)	$r_{\rm rms}$ (fm)
Set 1	33.47	-490.73	-0.23	3.95
Set 2	33.00	-47.58	-0.14	4.22
Set 3	30.50	-4.57	-	-

From Table 1 we observe that for the Set 1 and Set 2, the ground state energy falls into the experimental limit $S_{2n} < 0.3$ MeV. The scattering length $a_0 = -4.57$ fm, close to the experimental limit $|a_0| < 2.8$ fm [4] which is link to the prediction $S_{2n} < 70$ keV, from a zero-range three-body model, does not provide a bound state. However, we should note that our prediction is more accurate since we use finite-range interactions.

The breakup cross sections are computed with the ground states that reproduce $E_0 = -0.23$ MeV and $E_0 = -0.14$ MeV. As the core$-n$ potential Set 3 in addition to the $n-n$ interaction do not give a bound state, we use a three-body phenomenological potential [18] with $V_{3B_0} = -3$ MeV. This is with the aim of getting a more weakly bound ground state that the previously mentioned, with $E_0 = -0.07$ MeV.

Figure 1 shows the total Coulomb breakup cross section of ^{22}C (right) and its partial wave decomposition (left) as a function of its ground state energy. For each total breakup cross section, the bound and continuum partial waves are computed by using the same ground state Hamiltonian. We use the 1^-, 0^+ and 2^+ partial continuum states which provide the prominent contributions, and are truncated in $K_{\rm max}$ =25, 30 and 20, respectively. The ^{20}C$-^{208}$Pb and $n-^{208}$Pb potentials are taken from Ref. [19] and Ref. [20], respectively. The core-target potential uses charged and matter densities from Ref. [21]. In Fig. 1 we observe a similar behavior of the partial breakup contributions. The total breakup cross section is shifted to low energies as the more weakly bound state is used.

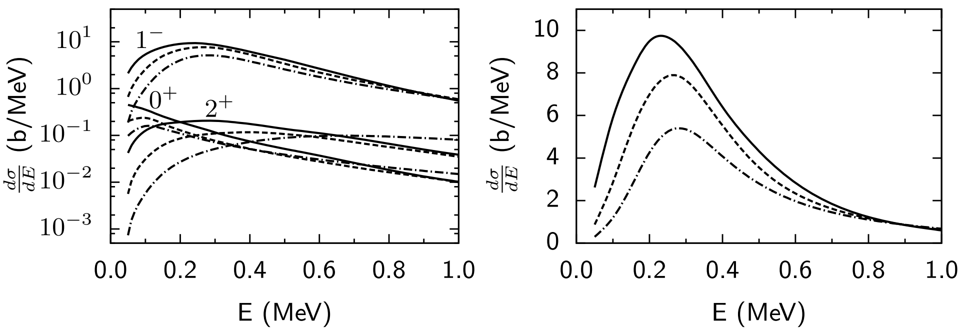

Figure 1: Dominant partial breakup cross sections (left) and total contribution (right) computed by using three-different ground state energies. The solid, dashed and dashed-dotted lines correspond to E_0=-0.07, -0.14, -0.23 MeV, respectively.

4 Conclusions

We have shown breakup cross sections of ^{22}C on ^{208}Pb at 240 AMeV as a function of the ground state energy of ^{22}C. The predictions show that if a weakly bound state exists, it should show up from the very peaked experimental breakup cross section at low excitation energies. Further analysis should be done to understand if the peaked behavior is related to a resonance or if it is related with the very weak binding of the ground state. The role of the core-target potential should be investigated too.

Acknowledgments

E.C.P. is financed by the Fondo Nacional de Financiamiento para la Ciencia, la Tecnologia y la Innovación Francisco José de Caldas and the Universidad Nacional de Colombia, Colombia. P.D. acknowledges the support of F.R.S.-FNRS, Belgium.

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