Reaction rates from Coulomb dissociation:
Core excitation effects

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Abstract. A process, involving the $^7\text{Be}$ core excitation in the Coulomb breakup of $^8\text{B}$ into $p+^7\text{Be}$ has been investigated. From the experimental results recently obtained in RIKEN we have derived the mixing amplitude of the $|^7\text{Be}(1/2^-) \otimes \pi(1p_{3/2}); 2^+ >$ configuration in the ground state of $^8\text{B}$. Implications on the evaluation of the $S_{17}$ at stellar energies are discussed.

1 Introduction

Electromagnetic excitation and/or dissociation can be induced on unstable nuclei in experiments employing radioactive ion beams (RIBs). These experiments allow for a determination of capture reaction rates involving radioactive nuclei. There are, however, certain cautions which must be taken into account when applying this method. A mechanism which must be considered is the possibility of core excitation [1]. In fact, if a low-lying level of the core nucleus is present, it can be excited during the Coulomb break-up process. As an example, we have analyzed the reaction

$$p + ^7\text{Be} \rightarrow ^8\text{B} + \gamma$$

of crucial importance in solar neutrinos production. The Coulomb dissociation of $^8\text{B}$ into $^7\text{Be}+p$ has been in fact proposed and applied to derive the $(p, \gamma)$ reaction rate [2]. In this case, there is a low-lying $1/2^-$ excited state in $^7\text{Be}$ at 0.429 MeV (see Fig. 1). As well as the $^7\text{Be}$ ground state, this state can be populated by the s-wave protons in the continuum emitted during the breakup process. The relative de-excitation $\gamma$-ray has been recently detected and the production cross section derived in a breakup experiment in RIKEN [3].

Here we will present the theoretical interpretation of this mechanism together with a quantitative analysis of the experimental result obtained. Implications of this analysis on the $^8\text{B}$ ground-state structure will be discussed and the relative impact on the calculation of the $S_{17}$ will be shown.

2 Coulomb dissociation

Let us first consider that the Coulomb dissociation cross section is given by

$$\frac{d\sigma_{\text{CD}}}{dE_x} = \frac{N_{E\lambda}(E_x)}{E_x} \sigma_{\gamma,p}(E_x)$$

where $N_{E\lambda}(E_x)$ is the virtual photon number, $E_x$ the excitation energy (defined as the sum of the proton-residual nucleus relative energy plus the proton binding energy)

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\[ \sigma_{\gamma,p}(E_x) = \frac{16\pi}{9} \frac{E_x}{\hbar c} \frac{\mu k_p}{\hbar^2} e^2 \frac{2J_c + 1}{2J_b + 1} |Q_{b\rightarrow c}^{(E1)}|^2 \]  

where \( \mu \) is the reduced mass of the system, \( k_p \) is the wave number of the proton-residual nucleus relative motion in the continuum, \( e \) the proton 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 proton capture cross section (hence to the \( S_{1\gamma} \)) by detailed balance

\[ \sigma_{\gamma,p} = \frac{k_p^2}{k_{\gamma}^2} \frac{2J_c + 1}{2J_b + 1} \sigma_{p,\gamma}. \]  

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

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

where \( \Psi_b \) is the bound-state wave function and \( \Psi_c \) the wave function for the proton in the continuum. The calculation of these matrix elements is not an easy task, in general. However, they can be readily evaluated under the particular condition in which the bound state has a single particle configuration of type \( |^{\Lambda}X(J_{\pi}^c) \otimes \pi(nlj)\rangle \); \( J_b \rangle \). 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 the radial overlap

\[ I_{b,c} = \int_0^\infty u_b(r)r w_c(r) dr \]
can be evaluated using some potential model for the calculation of the radial wave functions $u_b(r)$ and $w_c(r)$.

The parameters required by these potential models are: (1) the proton-nucleus interaction potential in the continuum for the calculation of the wave function $w_c(r)$, (2) the potential for the calculation of $u_b(r)$, and (3) the spectroscopic factor $S_b$. It has to be noted, however, that in the particular case of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, the proton-nucleus potential in the continuum does not play any significant role, as far as the low energy region (say $E_p \leq 1$ MeV) is considered. In fact, it can be easily shown that even the use of a simple plane-wave approximation for the continuum wave function is sufficient to obtain a good accuracy in the calculation of the $E1$ matrix elements. Nevertheless, we will use a Coulomb+Woods-Saxon potential with the parameters fixed by the bound-state calculation in the evaluation of the wave function $w_c(r)$.

Moreover, one has to consider that in the calculation of the $E1$ transition matrix elements for loosely bound states such as the $^8\text{B}$ ground state, only the asymptotic behavior of the wave function is relevant. In fact, a Whittaker function of type

$$u_b(r) = \hat{b}_s W^+_{\eta,i}(k_b r)$$

has been shown to be sufficient in the calculation of the $E1$ matrix elements, in the low energy region [4]. This implies that, in principle, the overall normalization coefficient $\hat{b}_s$, referred to as asymptotic normalization coefficient (ANC), is the only quantity necessary for the evaluation of the $^7\text{Be}(p,\gamma)^8\text{B}$ cross section. The ANCs can be either measured by transfer reactions or, alternatively, calculated. Microscopic and/or potential models can be used to this end. Using our model parameters given below, we have obtained $\hat{b}_s = 0.75$ and 0.73 respectively for the $\pi(1p_3/2)_1$ and $\pi(1p_3/2)_2$ single-particle components (see below for their definition). Again we would like to stress here that the ANCs are more fundamental quantities as compared to the spectroscopic factors. In fact, the spectroscopic factor is model-dependent in the sense that it depends on the form-factor used in its experimental determination. On the other hand, the $\hat{b}_s$ only reflects the asymptotic behavior of the wave function and therefore it is independent on the detail of the interaction which determines the behavior itself.

### 3 Core excitation

A simple assumption in the $^8\text{B}$ ground state would consist of the following configuration

$$|^{8\text{B}; 2^+} = |3/2^- \otimes \pi(1p_{3/2})_1; 2^+ > .$$

In our analysis, we will consider an additional component in the ground state wave function, namely, we will consider the following configuration

$$|^{8\text{B}; 2^+} = \sqrt{1-\alpha^2} |3/2^- \otimes \pi(1p_{3/2})_1; 2^+ > + \alpha |1/2^- \otimes \pi(1p_{3/2})_2; 2^+ >$$

where we have introduced the mixing amplitude $\alpha$. Here, the two $\pi(1p_{3/2})_{1,2}$ single-particle wave functions are identical (derived from the same Woods-Saxon potential), except that in the second component, the binding energy is effectively increased by the excitation energy of the $^5\text{Be} 1/2^-$ state, namely by 0.429 MeV. The potential parameters we have adopted are the Barker potential [3]: $r_0 = 1.25$ fm, $d = 0.65$ fm.
and the well-depth adjusted to reproduce the proton binding energies $V_{01} = -46.54$ MeV and $V_{01} = -47.93$ MeV respectively for the two components $\pi(1p_{3/2})_{1,2}$.

A measurement of the Coulomb breakup cross section for the $^8B$ into $p + ^7Be$ process has been recently reported in which the branching ratio for the inelastic channel leading to the $^7Be$ low-lying $1/2^-$ state was measured by detecting the 0.429 MeV $\gamma$-ray in coincidence with the breakup events. The result of this experiment lead to a branching ratio

$$\frac{\sigma_{CD}(1st)}{\sigma_{CD}(gs) + \sigma_{CD}(1st)} = 5\%.$$ (10)

By calculating the Coulomb dissociation cross section for both the reaction channels, we have been able to determine the mixing amplitude defined in Eq. 9 as $\alpha = 0.36$. This value can be compared with the theoretical calculation based on a three-body model reported recently which gives $\alpha = 0.31$.

The corresponding calculation of the $S_{17}$ are shown in Fig. 2. The experimental values for the inelastic channel are only preliminary. It can be seen that there is an overall agreement of the calculation with the experimental values for both channels. In turn, this means that our $^8B$ wave function is reliable. In our calculation we obtain $S_{17} = 19.5$ eV b for the elastic and $S_{17} = 9.6$ eV b for the inelastic channel respectively, at $E_p = 20$ keV. The value of the inelastic component is much larger than expected and should be seriously considered in all the breakup experiments aimed at the determination of this fundamental reaction rate.

References

[1] Mengoni A., 1997, in Proceedings of OMEG97 in Atami, World Scientific, Singapore, in press.
[2] Motobayashi T. et al., 1994, PRL 73, 2680
[3] Kikuchi T. et al., 1997, Phys. Lett., B391, 261
[4] Xu H.M., et al., 1994, PRL 73, 2027
[5] Barker F.C., 1980, Aust. J. Phys. 33, 177
[6] Grigorenko L.V., et al., 1998, Phys. Rev. C57, R2099