Properties of resonances in ^{12}C above the triple-alpha threshold

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Abstract. A complete kinematics study of the ^{10}B(^{3}He,p$\alpha\alpha$) and the ^{11}B(^{3}He,d$\alpha\alpha$) reactions has been performed to study the multi-particle break-up of ^{12}C resonances above the triple-alpha threshold. The values of energy and widths of some states has been improved, and in states of natural parity partial branches of decay through the ground state of ^{8}Be have been extracted. The influence of the "ghost" of the ^{8}Be ground state has been taken into account in order to clarify the partial branches.

1. Introduction

The properties of ^{12}C resonances has been the subject of several recent articles [1, 2, 3, 4, 5, 6]. The interest in gaining a better understanding of the properties of the resonances ranges from determining influences in the triple-alpha process important for the synthesis of heavy elements in the stars [7], to forming a complete picture of the resonances in ^{12}C in order to provide input for state-of-the-art ab initio calculations currently underway for ^{12}C [8]. However, to test the robustness of theoretical models the properties of ^{12}C resonances must be well-defined. In this contribution we seek to review the energies and widths of the well-known resonances, some of which have recently been called into question [6]. In addition, we give the partial branches of natural parity states which decay sequentially through the ground state of ^{12}C.

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The branching ratios in the literature have not taken into account the role of the "ghost" [9] of the ^{8}Be ground state in decays of natural parity states in ^{12}C. The "ghost" of the ^{8}Be ground state is due to the near-threshold energy of the ground state and is characterized by a high-energy tail. The ratios measured here are thus a clarification of the measured ratios with the inclusion of the "ghost" of the ^{8}Be ground state.

2. Experiment

The study of the ^{10}B(^{3}He,p$\alpha\alpha$) and the ^{11}B(^{3}He,d$\alpha\alpha$) reactions were carried out at the Centro de Microanálisis de Materiales (CMAM), located in the campus of the Universidad Autónoma de Madrid. This center houses a 5 MV tandetron that uses the Cockroft-Walton power supply system [10]. This device, due to the absence of mechanical moving parts, provides very stable beams, making the CMAM accelerator an ideal place for these types of reaction studies.

The experimental setup consisted of four Double Sided Si Strip Detectors (DSSSD) [11], each 60 μm thick, backed by a non-segmented Si-PAD 1500 μm thick. Three of the DSSSDs have 16×16 perpendicular strips, while one of the DSSSDs has 32×32 perpendicular strips. The 16×16 DSSSDs have an active area of 50×50 mm^2, giving a pixel size of 3×3 mm^2, while the 32×32 DSSSD has an active area of 67×67 mm^2, giving a pixel size of 2×2 mm^2. The telescopes were arranged to maximize multi-particle detection, placing two DSSSDs as close to 0° as possible. The detectors were located 4 cm from the target, giving a solid angle coverage of 38% of 4π. The angular resolution of the 32 × 32 DSSSD is 2° while the resolution of the 16 × 16 DSSSD is 3°. The large solid angle combined with the high segmentation of the DSSSDs gives complete kinematics information on the three alpha breakup of ^{12}C. A detailed look at the setup and the preliminary analysis techniques are described in [12].

3. Analysis and Results

The ^{12}C excitation energy can be determined either from the light-ion (i.e. the deuteron in the reaction with the reaction with the ^{11}B target and the proton in the reaction with the ^{10}B target) or from the invariant mass of the three alpha-particles. The complete kinematics information allows one to remove most random coincidences and background channels. However, background channels with the same multi-particle final states will clearly remain, as discussed in Section 3.2.

In order to fully understand the broad structures in the excitation spectrum of ^{12}C, an R-matrix calculation is necessary. However, in this analysis we have fit the peaks using a Breit-Wigner function convoluted with a Gaussian resolution on a two-degree polynomial background. Restricting our attention to relatively narrow peaks ($\Gamma < 500$ keV), we find that fitting with a Breit-Wigner function convoluted with a Gaussian distribution, plus a polynomial background, gives good fits indicating that distortion of the peak shape due to interference with hitherto unknown broad states of same spin-parity is negligible.

3.1. Analysis Procedure

The fits for each data set are done individually for each detector over angular bins of ten degrees. A systematic error of 5 keV was assigned to the excitation energies as determined by the adjustments made when re-calibrating the spectra. The systematic errors of the widths were determined individually for each state by varying the background models (e.g. one degree versus two degree polynomial).

Accurate values for the resolution were very important in fitting the peaks, especially for states with a width similar to the resolution (roughly 40 keV), and were therefore calculated for each state and at the different angular bins. The resolution was determined for states with narrow widths relative to the resolution ($\Gamma < 1$ keV), and then extrapolated to the peak energies. The energies were calibrated internally using the ground state, the 4.44 MeV state, the 9.64 MeV

state, and the 12.71 MeV for the ^{11}B target data. For the ^{10}B target data, only the 9.64 MeV state, the 12.71 MeV, and the 16.11 MeV state were used.

The quality of the data was such that the fits could also be divided into cases in which all four particles were detected and those in which only the light-ion and two of the three alpha particles were detected. Through the use of momentum and energy conservation, the third alpha particle was reconstructed without introducing significant background. These two data sets were used to determine the final values of the different resonances.

To determine the partial branches, the states which decay sequentially via the ground state in ^{8}Be were separated using the invariant mass technique. The state is situated 92 keV above the 2α threshold, and the gate imposed on the $\alpha - \alpha$ relative energy was from 0-230 keV in the case of the multiplicity three data, and between 40-150 keV in the multiplicity four data set. The procedure was then the same as that used to determine the energy and width of the resonances, with the exception that the data was not separated into different angular bins so as to accumulate more statistics.

3.2. Background contribution

As discussed above, it is very important that one has a good understanding of the background. The complete kinematics allows us to remove most unwanted background and random coincidences. It is, however, not possible to completely remove contribution from background channels with the same multi-particle final states. Both of the reactions have contributing background channels; the ^{10}B target data has the following channels

$$^{3}\text{He} + {}^{10}\text{B} \rightarrow \left\{ \begin{array}{l} p + {}^{12}\text{C} \rightarrow p + \alpha + {}^{8}\text{Be} \\ \alpha + {}^{9}\text{B} \rightarrow \alpha + p + {}^{8}\text{Be} \\ \alpha + {}^{9}\text{B} \rightarrow \alpha + \alpha + {}^{5}\text{Li} \\ {}^{8}\text{Be} + {}^{5}\text{Li} \rightarrow {}^{8}\text{Be} + p + \alpha \end{array} \right\} \rightarrow p + 3\alpha \qquad (1)$$

while for the ^{11}B target the contributing channels are

$$^{3}\text{He} + {}^{11}\text{B} \rightarrow \left\{ \begin{array}{l} d + {}^{12}\text{C} \rightarrow d + \alpha + {}^{8}\text{Be} \\ \alpha + {}^{10}\text{B} \rightarrow \alpha + d + {}^{8}\text{Be} \\ {}^{8}\text{Be} + {}^{6}\text{Li} \rightarrow {}^{8}\text{Be} + d + \alpha \end{array} \right\} \rightarrow d + 3\alpha \qquad (2)$$

It is possible to remove some contribution from different channels. In the case of the ^{11}B target data, we do not see the $\alpha + {}^{10}$B channel since the emitted deuterons are not energetic enough to be seen in the ΔE-E plot. Additionally, contribution from narrow states in ^{5}Li and ^{6}Li can be removed. The contribution from the different background reactions are best visualized by plotting E_{α_i} versus $E_{p/d}$ in the total center of mass frame. Figure 1 shows such plots for the ^{10}B target and ^{11}B target data.

3.3. Results

The preliminary values for excitation energies and widths resulting from averaging over the two targets are given in Table 1. The values for the excitation energy of the different ^{12}C resonances are within error of the literature values, with the exception of the 13.35 MeV state. However there are cases where the width of the resonances have substantial deviations from literature values. The width of the 3^{-} 9.64 MeV state is larger than that given in the compilation of [13], although the value we obtain agrees with the value of $\Gamma = 42(3)$ keV in [14]. The very large deviation between the width of the 13.35 MeV state 375(40) keV in [13] versus our value of 427(18) keV could be accounted for by the fact that the literature value is averaged over many different values: 500$\pm$80 keV [15], 290$\pm$70 keV [16], 430$\pm$100 keV [17], 355$\pm$50 keV [18], and 700$\pm$100 keV [19].
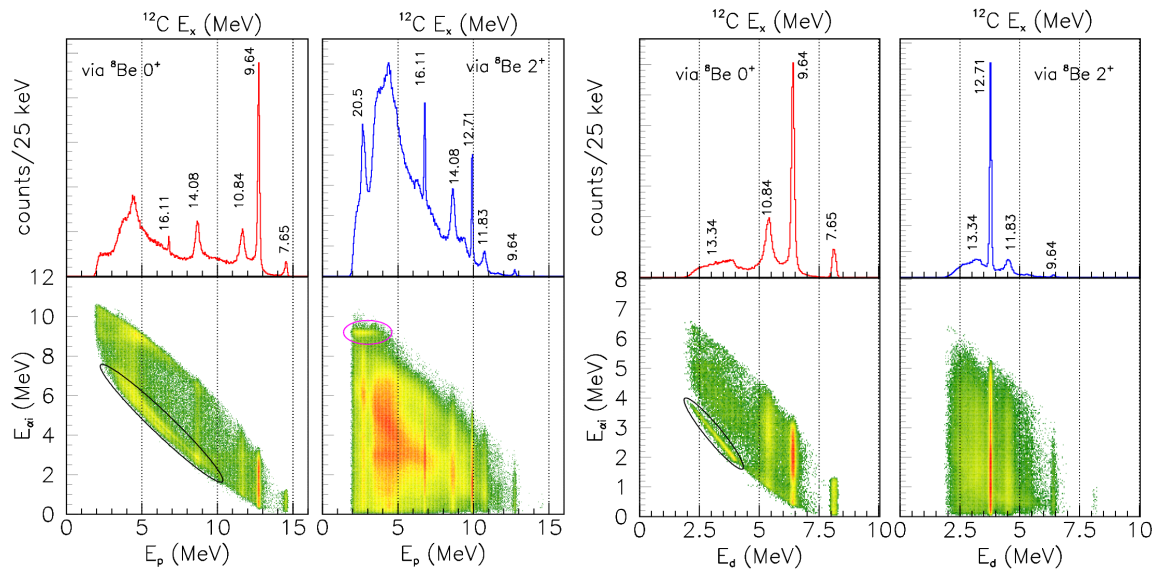
Figure 1. Multiplicity four data from the ^{10}B(^{3}He,p$\alpha\alpha$) (left) and the ^{11}B(^{3}He,d$\alpha\alpha$) (right) reaction. The data has been split in each figure into decay which proceeds via the ground state in ^{8}Be (left) and the rest (right), as explained in the text. Levels in ^{12}C can be seen as constant proton and deuteron energies, and are seen in the projections in the top of the E_{α_i} versus $E_{p/d}$ plot figure. On the left, contribution from the ground state of ^{5}Li is circled in black in the ^{8}Be ground state branch. Similarly, in the plot of decay via the 2^+ of ^{8}Be, the narrow 2.36 MeV state in ^{9}B is circled in pink. In the figure to the right, the narrow 2.19 MeV state in ^{6}Li which breaks up through the ground state of ^{8}Be is circled in black. All of these contributions have been removed when doing the fits. There are clearly structures from broader states visible in both plots which cannot be fully removed.

Table 1. Preliminary values obtained for the energy and width of resonances in ^{12}C. The literature values of J^π, Γ, and E_x are taken from [13].

E_x of ^{12}C (keV) lit.	Γ (keV) lit.	J^π	E_x (keV) this work	Γ (keV) this work
9641(5)	34(5)	3^-	—	44(4)
10844(16)	315(25)	1^-	10833(9)	274(7)
11828(16)	260(25)	2^-	11830(13)	243(6)
13352(17)	375(40)	(2^-)	13307(8)	427(18)
14083(15)	258(15)	4^+	14074(5)	249(11)
20500(100)	300(50)	(3^+)	20559(5)	252(15)

The branching ratios to the ground state of ^{8}Be were corrected for the detection efficiency of the setup. Including the sequential breakup of the resonances both through the ground state and through the broad 2^+ state was done through the use of Monte Carlo simulations. In the case of breakup through the 2^+ state in ^{8}Be, the particles were generated by making use of the CERNLIB routine GENBOD, which assumes a breakup into the available phase space.

The effects of penetrability on the decay branch through the ground state of ^{8}Be was simulated using the R-matrix formalism [20]. The choice of channel radius $a_c = r_0(A_1^{1/3} + A_2^{1/3})$ was found to have a significant impact on the partial branches, and the chosen value was that given as the

Table 2. Preliminary branching ratios of natural parity resonances in ^{12}C to the ground state of ^{8}Be. The branching ratios are shown with and without correcting for the decay via the ghost of the ^{8}Be ground state. The alpha-decay width to the ground state of ^{8}Be is calculated from the new values for the widths given in given in this work. For the 16.11 MeV resonance, the width of the state is taken from [13].

^{12}C E_x (MeV)	J^π	B.R. % (literature)	B.R. % (no corr.)	B.R. % (corr.)	Γ_{α_0} (keV)
9.64	3^-	97.2 [6]	96.3(1)	99.5(6)	44(4)
10.84	1^-	—	94.7(5)	99.4(6)	272(7)
14.08	4^+	17(4) [22]	22.8(2.0)	24.2(2.0)	60(6)
16.11	2^+	4.4 [13]	5.6(1)	6.4(1)	0.34(1)

optimal value in reference [21], with $r_0 = 2.47$ fm. An analysis is underway of the dependence of the results on the channel radius and will be discussed in a future publication [23]. Table 2 shows the calculated preliminary partial branches Γ_{α_0}/Γ to the ground state of ^{8}Be with and without corrections due to penetrability. One can see the importance of including the penetrability effects of the ground state in ^{8}Be on the partial branches of the lower-lying ^{12}C states, completely eliminating the decay branch to higher states of ^{8}Be for the 9.64 MeV and the 10.84 MeV resonances.

We note that the partial branch for the 9.64 MeV resonance given in the literature varies from our corrected branching ratio because the value cited does not include the effect of the "ghost" of the ground state of ^{8}Be. The partial branch for the 14.08 MeV state of Γ_{α_1}/Γ=0.772 $\pm$0.020 is in agreement with the values of 0.83 $\pm$ 0.04 reported in [22]. For the 16.11 MeV resonance, reference [13] gives the partial widths as Γ_{α_0}= 0.290 $\pm$ 0.045 keV and Γ_{α_1}= 6.3 $\pm$ 0.5 keV. Using a value of Γ=5.3 $\pm$ 0.2 keV for the 16.11 MeV state, we obtain Γ_{α_0}= 0.34 $\pm$ 0.01 keV and Γ_{α_1}= 5.01 $\pm$ 1.15 keV. Further analysis is needed to confirm the numbers obtained in this contribution, and the physics implications will be reported elsewhere [23].

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