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Observation of γ-delayed 3α breakup of the 15.11 and 12.71 MeV states in ^{12}C

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ABSTRACT

The reactions $^{10}B(^3He, p\alpha\alpha\alpha)$ at 4.9 MeV and $^{11}B(^3He, d\alpha\alpha\alpha)$ at 8.5 MeV have been used to investigate the γ decay of states in ^{12}C. By measuring the four-body final state in complete kinematics we are able to detect γ transitions indirectly. We find γ transitions from the 15.11 MeV state in ^{12}C to the 12.71, 11.83, 10.3 and 7.65 MeV states followed by their breakup into three α particles. The relative γ-ray branching ratios obtained are (1.2 ± 0.3), (0.32 ± 0.12), (1.4 ± 0.2) and $(4.4 \pm 0.8)\%$, respectively, with the remaining $(92.7 \pm 1.0)\%$ of the γ decays going to the bound states. We obtain $\Gamma_\alpha/\Gamma = (2.8 \pm 1.2)\%$ for the isospin-forbidden α decay of the 15.11 MeV state. From the 12.71 MeV state we find γ transitions to the 10.3 and 7.65 MeV states. The relative γ-ray branching ratios are $(0.9^{+0.6}_{-0.5})$ and $(2.6^{+1.6}_{-1.2})\%$, respectively, with the remaining $(96.6^{+1.7}_{-1.3})\%$ of the γ decays going to the bound states. Finally, we discuss the relation between the β decay of ^{12}N and ^{12}B to states in ^{12}C and the γ decay of the 15.11 MeV analog in ^{12}C to the same states.

1. Introduction

The experimental detection of electromagnetic transitions in nuclei is challenging when the energy distribution of the emitted γ rays is broad, as may happen for transitions between particle-unbound states. In such situations the γ branches are usually small because they compete with particle decay channels of much larger width. In the present Letter we explore an alternative experimental approach where the γ-ray detection is substituted by the measurement of multi-particle breakups in complete kinematics [1]. In particular we have looked at γ transitions in ^{12}C followed by the breakup into three α particles. The ^{12}C spectrum just above the first unbound 0^+ (Hoyle) state contains several broad levels and is not yet resolved theoretically or experimentally [2–7]. We refer to this as the "10.3 MeV state" in the following.

The first $T = 1$ state in ^{12}C is situated at 15.11 MeV, about 1 MeV below the threshold for proton emission, and has spin and parity 1^+. It decays predominantly through the emission of γ rays. Decay through α emission is hindered by isospin conservation. Nevertheless, the existence of a small α branch has been established experimentally [8]. The majority of the γ decays from the 15.11 MeV state go to the ground state (92%), but γ branches at the percent level to the 12.71, 7.65 and 4.44 MeV states have also been measured [9]. In the present work γ transitions to broad states in ^{12}C have been detected for the first time. The broad nature of these states explains why previous experiments relying on the detection of the emitted γ rays were not able to separate them from the background.

The decay of the 1^+ $T = 0$ state at 12.71 MeV is dominated by α emission leaving a small γ branch of 2%. Before this work the

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only known γ transitions were to the ground state (87%) and the 4.44 MeV state (13%). Here we report on the first observation of transitions to unbound states.

The Letter is structured in four parts: Section 2 briefly describes the experimental setup. Section 3 is divided into a number of subsections discussing different aspects of the data analysis with all the results summarised in Table 1 and Fig. 4. Section 4 contains the discussion of the results including their link to the recently measured β decays of ^{12}N and ^{12}B [7]. Finally, Section 5 summarises and discusses the potential of complete kinematics measurements giving specific examples of γ transitions in other light nuclei that can be studied with this method.

2. Experimental procedures

The reactions $^{10}\mathrm{B}(^3\mathrm{He}, p\alpha\alpha\alpha)$ and $^{11}\mathrm{B}(^3\mathrm{He}, d\alpha\alpha\alpha)$ were studied at the Centro de Microanálisis de Materiales in Madrid [10] at beam energies of 4.9 and 8.5 MeV, respectively. The detection system consisted of four Double Sided Silicon Strip Detectors (DSSSD) [11] 60 μm thick, each backed by an unsegmented silicon detector 1.5 mm thick allowing for particle identification. The detectors were placed 4 cm from the target with two of them covering 7–75° to the beam and two others covering 98–170° thereby obtaining a total solid-angle coverage of 38% of 4π. A detailed description of the experimental apparatus and methods is given by M. Alcorta et al. [1] who also discuss the initial steps of the analysis concerned with the transformation of raw data into physics events.

3. Analysis and results

3.1. γ-delayed 3α breakup of the 15.11 MeV state

Given the observation of all four final-state particles we can reconstruct the excitation energy of the ^{12}C resonance formed in the $^3\mathrm{He} + {}^{10}\mathrm{B} \to p + {}^{12}\mathrm{C}$ reaction by two independent methods. One option is, given the energy and direction of the proton, to determine the excitation energy of the ^{12}C resonance through energy and momentum conservation. The other option is to calculate the invariant mass of the three α particles. Normally these two methods bring us to the same result, but when the ^{12}C resonance decays by γ emission to a lower-lying state before the breakup into three α particles takes place, the results no longer agree; the invariant mass method gives the excitation energy of the state populated in the γ decay whereas the proton gives the excitation energy of the resonance initially formed. The energy difference is carried away by the unobserved γ ray (neglecting the tiny recoil of the ^{12}C nucleus). In order to look for these γ-delayed 3α breakups we make a two-dimensional plot (Fig. 1) with the ^{12}C excitation energy given by the proton, $E_x^{(p)}$, along the abscissa and the excitation energy given by the invariant mass method, $E_x^{(3\alpha)}$, along the ordinate. Ordinary 3α breakups will be situated along the diagonal while γ-delayed 3α breakups will appear below it.

The momentum carried away by the γ ray, E_γ/c, is within the experimental resolution and small compared to all other momenta involved. This fact allows us to require the momentum to be conserved in the events that we include in Fig. 1, significantly reducing the background in the region below the diagonal [1].

We use the coincidence time information to remove random coincidences with a time window of 100 ns. In the present case we allow sub-threshold ($\lesssim$ 600 keV) particles without time information to pass the cut. Later, when we consider the γ decay of the 12.71 MeV state, we apply a stricter time gate which excludes sub-threshold particles. We refer to these two gates by the names “partial” and “complete”, respectively.

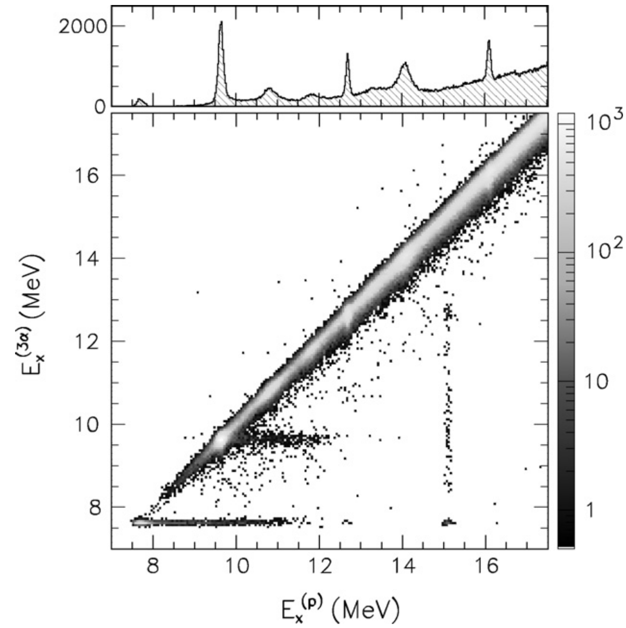

Fig. 1. Complete kinematics data from the $^{10}\mathrm{B}(^3\mathrm{He}, p\alpha\alpha\alpha)$ reaction. Only events that satisfy momentum conservation and pass the partial time gate (see text for explanation) have been included. The ^{12}C excitation energy calculated from the measured energy and momentum of the proton is along the abscissa while the excitation energy calculated from the invariant mass of the three α particles is along the ordinate.

The main feature of Fig. 1 is the high intensity along the diagonal. The projection on the abscissa clearly shows the population of a number of well-known states in ^{12}C. The four most prominent peaks in the spectrum are the 2^+ state at 16.11 MeV, the 4^+ state at 14.08 MeV, the 1^+ state at 12.71 MeV and the 3^- state at 9.64 MeV. The 2^- state at 11.83 MeV, the 1^- state at 10.84 MeV and the Hoyle state (0^+) at 7.65 MeV are also visible. Additional broad structures are present underneath these peaks caused in part by broad states in ^{12}C such as the “10.3 MeV state”, but also by the $\alpha + {}^9\mathrm{B}$ and $^5\mathrm{Li} + {}^8\mathrm{Be}$ channels, their contribution increasing towards higher ^{12}C excitation energies, see [1]. Due to its small α width the 15.11 MeV state is not visible in the projection of Fig. 1 even though the single-proton spectrum verifies that it is populated in the $^3\mathrm{He} + {}^{10}\mathrm{B} \to p + {}^{12}\mathrm{C}$ reaction at a rate comparable to the 16.11 MeV state.

The γ transitions from the 15.11 MeV state to lower-lying unbound states are visible as a narrow vertical band of increased intensity at $E_x^{(p)} = 15.1$ MeV in Fig. 1. The low background level in the region away from the diagonal is due to random coincidences which happen to survive the partial time gate as well as the requirement of momentum conservation. The origin of the background events will be dealt with in more detail when we consider the 12.71 MeV state. Close to the diagonal the effects of response tails also contribute to the background. The two bands that extend horizontally from the Hoyle state and the 9.64 MeV state in direction of increasing excitation energy (decreasing proton energy) are caused by protons that punch through the back detectors. The group of five events seen at $E_x^{(p)} = 12.7$ MeV, $E_x^{(3\alpha)} = 7.65$ MeV probably represents the detection of the $12.71 \to 7.65$ transition. However, the punch-through protons prevent any clear conclusions to be drawn. We note that the observed intensity of five events is consistent with the branching ratio of 2.6% obtained in the study of the $^{11}\mathrm{B}(^3\mathrm{He}, d\alpha\alpha\alpha)$ reaction.

The γ-delayed 3α breakups identified in Fig. 1 projected onto the ordinate give the γ spectrum shown in Fig. 2. We use the invariant mass technique to determine whether the decay proceeds

Table 1
Details on the γ decay of the 15.11 and 12.71 MeV states in ^{12}C.

Transition	Events	Det. eff. (%)	γ branch [9] (%)	γ branch present work (%)
15.11 → 12.71	39	0.74	1.4(4)	1.2(2)
11.83	8	0.57	...	0.32(12)
10.84	< 7.3[a]	1.30	...	< 0.13
10.3	65	1.09	1.6[b]	1.4(2)
7.65	70	0.36	2.6(7)	4.4(8)
0 and 4.44	40 344	9.9	94(2)	92.7(1.0)
12.71 → 10.3	3	0.40	...	$0.9(^{+6}_{-5})$
7.65	4	0.18	...	$2.6(^{+1.6}_{-1.2})$
0 and 4.44	11 660	13.9	100	$96.6(^{+1.7}_{-1.3})$

[a] Upper limit valid at 90% C.L.
[b] The 15.11 → 10.3 transition was not observed by [9]. The intensity of 1.6% is an estimate derived from the measured β-decay branching.

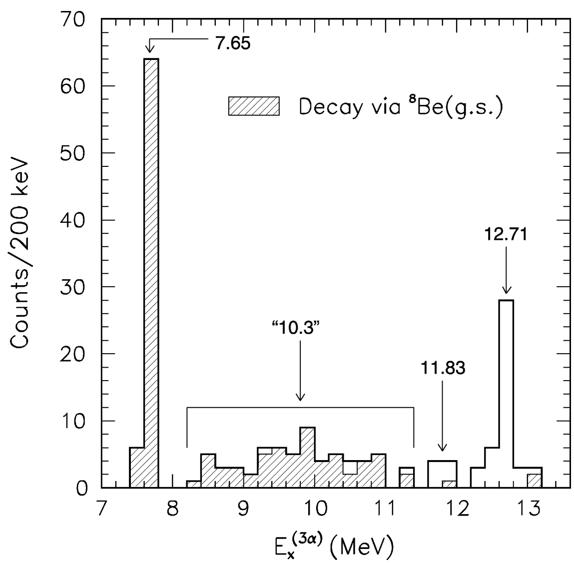

Fig. 2. The deduced γ-decay spectrum of the 15.11 MeV state.

through the narrow ground state of ^{8}Be situated 92 keV above the 2α threshold (the gate imposed on the α–α relative energy extends from 0 to 200 keV). The "10.3 MeV state" is seen to decay mainly through the ground state of ^{8}Be in line with previous observations [7]. In contrast the unnatural parity of the 11.83 MeV state prevents it from decaying via the ^{8}Be ground state. This is indeed the case for the peak identified as the 11.83 MeV state in Fig. 2 and proves that these eight events do not belong to the high-energy tail of the broad "10.3 MeV state".

The relative γ-ray branching ratios of the 15.11 MeV state derived from the present work are listed in Table 1 and compared to earlier measurements. The errors given are 1σ confidence intervals and include the uncertainty on the detection efficiency.

3.2. Detection efficiency

The probability that we detect all four charged particles in the γ-delayed 3α breakup of the 15.11 MeV state depends on the decay path. Calculating the probability is complicated and has been done through Monte Carlo simulations [1].

The broad "10.3 MeV state" and the Hoyle state are assumed to decay through the narrow ground state of ^{8}Be. Due to the similarity between M1 γ decays and Gamow–Teller β decays discussed in Section 4 we may use the β-delayed 3α spectrum measured by [7] corrected for detection efficiency and phase space to describe the shape of the "10.3 MeV state", provided we scale the spectrum by a factor of E_γ^3 to account for the phase-space factor of M1 γ transitions. The resulting spectrum is consistent with the measured one. For the unnatural-parity states at 12.71 and 11.83 MeV we find that the detection efficiencies are rather insensitive to the particular model adopted for the 3α breakup. A phase-space simulation predicts detection efficiencies that differ by less than 5% from those obtained assuming a sequential decay through the broad 2^+ first excited state in ^{8}Be, taking into account all of the effects mentioned in [12]. This can be understood as the result of a fairly uniform experimental acceptance throughout the 3α phase-space combined with a relatively large portion of phase space covered by the 3α breakup of unnatural-parity states. In contrast, decays via the narrow ground state of ^{8}Be occupy a very limited region of phase space which results in a complete kinematics detection efficiency that is—all other factors taken out—somewhat larger.

By comparison to experimental data we find that the efficiencies predicted by the simulations are correct within 10%. However, in the particular case of the 12.71 → 7.65 transition we assume an error of 20% on the efficiency estimate to account for an increased sensitivity to the ADC thresholds. The detection efficiencies are given in Table 1.

3.3. γ decay to bound states

Transitions to the ground state and the 4.44 MeV state can be identified in the experimental data by looking for events where the proton and the ^{12}C nucleus are detected in coincidence. The proton tells us which ^{12}C resonance was populated. A γ transition to one of the bound states can then be identified as a deficit in the energy balance, $E_p + E_{^{12}\mathrm{C}} - (Q + E_{^3\mathrm{He}})$, equal to the excitation energy of the populated resonance. Clearly, this method does not distinguish between transitions to the ground state and the 4.44 MeV state.

Due to their low energy and high Z the ^{12}C ions are easily stopped in the DSSSDs preventing identification by the ΔE–E method, hence leading to a large background from e.g. $p+\alpha$ coincidences. A significant reduction in background levels is achieved by imposing momentum conservation in the plane normal to the beam axis. In the case of the 15.11 MeV state the surviving background is negligible. For the 12.71 MeV state some background remains (signal-to-background ratio of 3:1) which, however, we are able to reproduce on an absolute level with simulations.

The γ transitions to the bound states enjoy a much higher detection efficiency than the transitions to the unbound states because their identification only requires the detection of two particles.

3.4. γ-delayed 3α breakup of the 12.71 MeV state

In the case of the 12.71 MeV state only a few events are observed so we must treat the background from random coincidences with great care. Time information is used to separate real coinci-

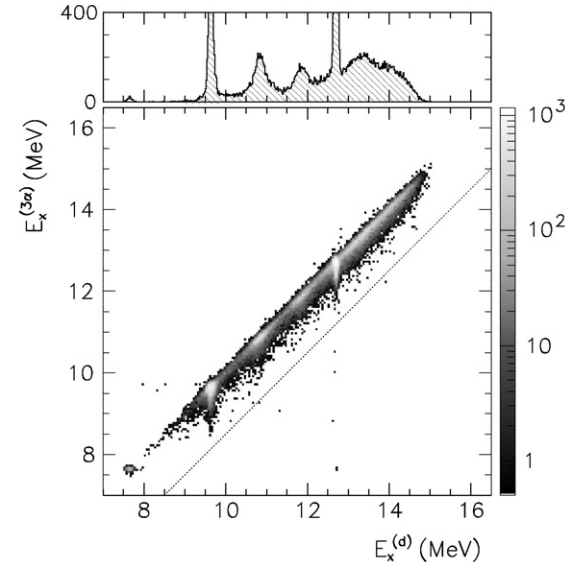

Fig. 3. Complete kinematics data from the ^{11}B(^{3}He, $d\alpha\alpha\alpha$) reaction. Only events that satisfy momentum conservation and pass the partial time gate have been included. The ^{12}C excitation energy calculated from the measured energy and momentum of the deuteron is along the abscissa while the excitation energy calculated from the invariant mass of the three α particles is along the ordinate. The dotted line 1.5 MeV below the diagonal marks the extent of the response tails.

dences from random ones, and event mixing is used to estimate the background level when time information is lacking due to sub-threshold particles.

The complete kinematics data from the ^{11}B(^{3}He, $d\alpha\alpha\alpha$) reaction is presented in Fig. 3. Only $d + 3\alpha$ events that satisfy momentum conservation and pass the partial time gate have been included. Because of the reduced Q value we do not reach as high excitation energies as with the $^3\mathrm{He} + {}^{10}\mathrm{B} \to p + {}^{12}\mathrm{C}$ reaction in spite of the increased beam energy. The dotted line 1.5 MeV below the diagonal marks the extent of the response tails. Events in the region below this line are either γ decays to unbound states or random coincidences that happen to satisfy momentum conservation and the requirements of the partial time gate.

We find seven events neatly aligned on a vertical string at $E_x^{(d)} = 12.71$ MeV, four of which are clustered together at $E_x^{(3\alpha)} = 7.65$ MeV, thus appearing as a single dot in the figure. In addition to these seven events we find two events, one at $E_x^{(d)} = 11.3$ MeV and another quite close to the dotted line at $E_x^{(d)} = 13.9$ MeV.

If the partial time gate is removed eleven additional events appear below the dotted line. Together with the single event already present at $E_x^{(d)} = 13.9$ they form a vertical band about 1 MeV wide centered at $E_x^{(d)} = 14$ MeV. These events originate from random coincidences between (i) two particles stopped in the DSSSDs and (ii) a deuteron along with the heavy fragment from one of the following reactions[2]

$$^3\mathrm{He} + {}^{12}\mathrm{C} \to d + {}^{13}\mathrm{N(g.s.)},$$
$$^3\mathrm{He} + {}^{10}\mathrm{B} \to d + {}^{11}\mathrm{C}(6.34, 6.48). \tag{1}$$

If we require all four particles to be inside the 100 ns coincidence window (complete time gate, cf. Section 3.1) the eleven events that appeared when the partial time gate was removed obviously disappear, but the single event close to the diagonal remains. If, instead, we require at least one particle to be outside the coincidence window the number of events grows from one to five. With a data taking window (ADC window) of 2.15 µs and a coincidence window of 100 ns we expect 20.5 times as many random coincidences outside the coincidence window as inside which is consistent with the observed outcomes of five outside and one inside. The method of event mixing has been applied to the experimental data to estimate the background rate from random coincidences and yields a number that is consistent with the observed background of twelve events.

The single event at $E_x^{(d)} = 11.3$ MeV disappears when the complete time gate is imposed suggesting that it is also a random coincidence.

Out of the seven events of the "12.71 MeV string", the three isolated events represent the detection of the $12.71 \to 10.3$ transition. All three events survive the complete time gate making it highly improbable that they should be random coincidences. The 90% confidence limits on the physics signal are 0.869–6.81 [13] showing that the data is consistent with the hypothesis of a non-zero physics signal. The absence of background caused by random coincidences is consistent with estimates obtained through event mixing.

The four remaining events of the "12.71 MeV string" clustered together at $E_x^{(3\alpha)} = 7.65$ MeV represent the detection of the $12.71 \to 7.65$ transition. They all disappear when we impose the complete time gate because sub-threshold α particles are present. We would like to stress that all four events survive the partial time gate, i.e. the deuteron and those α particles that do have time information are indeed inside the coincidence window. We utilise event mixing to estimate the background from random coincidences in the region of Fig. 3 occupied by the four $12.71 \to 7.65$ events. We obtain an upper limit of 0.2 at 90% C.L. making it highly improbable that they should be random coincidences. Using [13] we calculate the 90% confidence limits on the physics signal to be 1.40–8.25.

It is worth noting that the seven events of the "12.71 MeV string" all survive the ^{8}Be(g.s.) gate consistent with expectations. The relative γ-ray branching ratios of the 12.71 MeV state derived from the present work are listed in Table 1.

3.5. α branches

Using detection efficiencies derived from simulations we convert the observed ratio of α to γ decays of the 12.71 MeV state into branching ratios. The results are $\Gamma_\alpha/\Gamma = (97.4 \pm 0.3)\%$ and $\Gamma_\gamma/\Gamma = (2.6 \pm 0.4)\%$ in agreement with the value adopted in Ref. [14], $\Gamma_\gamma/\Gamma = (2.22 \pm 0.14)\%$.

The detection of the isospin-forbidden α decay of the 15.11 MeV state is complicated by a large continuum background. Yet, the $p + \alpha$ coincidence spectrum exhibits a clear signal of 500 ± 100 events on top of a background of about 4000 events. We only consider α particles emitted at laboratory angles larger than 60° in order not to include the large signal from $p + {}^{12}$C coincidences. Simulations have been used to determine the inevitable contribution from the γ-delayed 3α breakups of the 15.11 MeV state. Using the present γ-ray branching ratios we obtain 280 ± 30 events leaving a residual α-decay signal of 220 ± 100 events. This translates into a branching ratio of $\Gamma_\alpha/\Gamma = (2.8 \pm 1.2)\%$ (1σ error bars).

The complete kinematics spectrum (see Fig. 1) does not exhibit any clear peak at 15.11 MeV. However, the large continuum background present could easily be hiding a small α-decay signal. Energy conservation is imposed to eliminate the contribution from the γ-delayed 3α breakups. We assume a linear background and establish an upper bound on the Gaussian signal hiding in the background. After correcting for the detection efficiencies we arrive at an upper limit of 3.3% on the α branch of the 15.11 MeV state

[2] The ^{11}B target contains 19.8% ^{10}B (its natural abundance) and rests on a carbon foil.

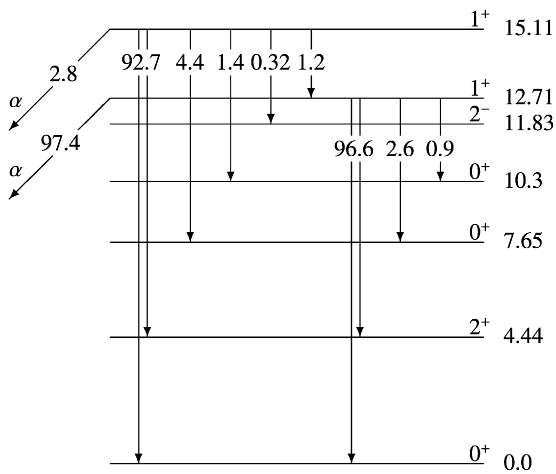

Fig. 4. Energy-level diagram showing the relative γ-ray branching ratios, in percent of the total γ width, from the 15.11 and 12.71 MeV states in ^{12}C measured in the present work. Error bars are given in Table 1. Also shown are the α-decay branching ratios, in percent of the total width. Error bars are given in the text.

valid at 90% C.L. in good agreement with the value of $(2.8 \pm 1.2)\%$ obtained above by considering $p + \alpha$ coincidences.

The value measured by Balamuth et al. [8] and adopted in Ref. [14] is $\Gamma_\alpha/\Gamma = (4.1 \pm 0.9)\%$. However, the 0.32% γ branch to the 11.83 MeV state and the 1.4% γ branch to the broad "10.3 MeV state" were not accounted for in the analysis of [8]. By subtracting these contributions from their value one obtains $\Gamma_\alpha/\Gamma = (2.4 \pm 0.9)\%$ in good agreement with our numbers.

In the framework of two-state mixing the charge-dependent matrix element connecting the 15.11 and 12.71 MeV states, $\langle H_{\mathrm{CD}} \rangle$, can readily be determined from the α widths [8]. With our new smaller value for $\Gamma_\alpha(15.11)$ we obtain $\langle H_{\mathrm{CD}} \rangle = 260 \pm 60$ keV in better agreement with the results obtained with electromagnetic and pionic probes [15].

4. Discussion

From our γ branching ratios in Table 1 partial γ widths can be calculated assuming[3] $\Gamma_{\gamma 0} = (36.9 \pm 0.8)$ eV for the transition to the ground state and using the relative γ-ray branching ratio of $(2.3 \pm 0.9)\%$ to the 4.44 MeV state measured by [9]. The reduced transition strength, $B(\mathrm{M1})$, can be calculated from the partial γ width, Γ_γ, through the formula of [18],

$$\Gamma_\gamma = 1.76 \times 10^{13} \hbar E_\gamma^3 B(\mathrm{M1}), \tag{2}$$

if we assume that the decays are purely M1 as is indeed the case for $1^+ \to 0^+$ transitions. For the $1^+ \to 1^+$ and $1^+ \to 2^+$ transitions single-particle estimates suggest that the E2 contribution is below one percent. The reduced transition strengths can be directly compared to theoretical predictions, e.g. it has recently been demonstrated [19] that ab initio no-core shell-model calculations of the $15.11 \to$ g.s. transition strength are very sensitive to the assumed three-body interaction.

Further insight can be gained by comparing the $B(\mathrm{M1})$ values to the corresponding $B(\mathrm{GT})$ values in the allowed Gamow–Teller (GT) decays of ^{12}N and ^{12}B. The major component of the two transition types is the spin term $(\sigma\tau)$, but the M1 transitions can also have contributions from orbital terms $(l\tau)$ [20,21]. In addition, both transitions can be affected by meson exchange currents (MEC); large contributions are expected for M1 transitions while G-parity conservation strongly suppresses this effect for GT transitions [22]. The combined effect of MEC and orbital parts is measured by the ratio [20],

$$R(\mathrm{M1/GT}) = \frac{B(\mathrm{M1})/2.643\mu_N^2}{B(\mathrm{GT})}. \tag{3}$$

We note that isoscalar terms (σ and l) may contribute to the M1 strength due to isospin mixing between the 15.11 and 12.71 MeV states, but their contribution must be small considering the amount of mixing that is observed [15].

The ratio $R(\mathrm{M1/GT})$ has been studied for sd-shell nuclei. Relying on theoretical calculations of the orbital contribution to $R(\mathrm{M1/GT})$ the MEC contribution was found to be modest [20]. Alternatively, by assuming the MEC contribution known conclusions can be made regarding the orbital contribution [21].

In the p-shell one is limited to the five $T = 0$ nuclei ^{6}Li, ^{8}Be, ^{10}B, ^{12}C and ^{14}N. The low number of states in the Q_β-window further limits the number of available cases (though charge-exchange reactions with high-energy radioactive beams may overcome this limitation in the future). The $A = 12$ case is the only one giving the possibility of studying several transitions in the same system. The link between M1 and GT transitions for $A = 12$ was previously explored in [9] where the orbital contribution to the M1 transitions were estimated with the shell model calculations of Cohen and Kurath and found to be less than one percent both for the 12.71 MeV state and the ground state and 10% for the 4.44 MeV state. The MEC contribution was later calculated for the ground-state transition and found to account for about 10% of the strength [23].

Recently, new experimental $B(\mathrm{GT})$ values for the decays of both ^{12}B and ^{12}N have become available [7]. For the 7.65 and 12.71 MeV states the new $B(\mathrm{GT})$ values are lower than previous measurements by factors of 2–3 which makes it interesting to revisit the $A = 12$ case. In Table 2 we give our results for the $B(\mathrm{M1})$ values together with the corresponding $B(\mathrm{GT})$ values of [7] and the ratio $R(\mathrm{M1/GT})$. Results for the bound-state transitions are included for completeness. We also give the theoretical $B(\mathrm{M1})$ predictions of the shell model of Cohen and Kurath [9] and the antisymmetrised molecular dynamics (AMD) approach [2]. The shell model is known to be unable to describe well clustered states such as the 7.65 MeV state and the "10.3 MeV state". The AMD approach is suggested to be able to describe both shell-model and cluster-type states.

The experimental $R(\mathrm{M1/GT})$ ratios are consistent with unity except for the transitions to the ground state and the 12.71 MeV state. For the ground-state transition the deviation from unity was discussed in [23]. We note that the $B(\mathrm{M1})$ value predicted by the AMD calculation is a factor of 4–5 too low. For the transition to the 12.71 MeV state both the shell-model calculation of Cohen and Kurath and the AMD calculation reproduce the experimental $B(\mathrm{M1})$ value despite neglecting the contribution of MEC's and predict the orbital contribution to be small, i.e. $R(\mathrm{M1/GT}) \simeq 1$, consistent with the experimental situation before the measurement of [7]. However, using the new $B(\mathrm{GT})$ values the ratios in Table 2 result. There is therefore presently not one theoretical approach which can reproduce the full set of $B(\mathrm{GT})$ and $B(\mathrm{M1})$ values in Table 2. The no-core shell model reproduces the new smaller $B(\mathrm{GT})$ values to the 12.71 MeV state [7], but the corresponding $B(\mathrm{M1})$ value from this approach is not yet available.

5. Summary and outlook

Detection of multi-particle breakups in complete kinematics makes the study of electromagnetic transitions possible between

[3] Weighted average of the three most recent measurements, (37.0 ± 1.1) [16], (38.5 ± 0.8) [17] and (35.9 ± 0.6) eV [15], with the error raised to compensate for the large spread.

Table 2
Comparison of the β decay of ^{12}N and ^{12}B to states in ^{12}C and the γ decay of the 15.11 MeV analog in ^{12}C to the same states.

Final state (MeV)	J^π	B(GT)		Γ_γ (eV)	B(M1) (μ_N^2)	R(M1/GT)		B(M1) theory (μ_N^2)	
		^{12}B	^{12}N			^{12}B	^{12}N	Cohen and Kurath	AMD
12.71	1^+	0.49(3)	0.450(11)	0.49(10)	3.0(6)	2.4(5)	2.6(5)	2.9	2.5
10.3[a]	(0^+)	0.203(9)	0.154(3)	0.55(10)	0.43(8)	0.80(15)	1.1(2)	...	...
7.65	0^+	0.108(3)	0.090(2)	1.8(3)	0.37(7)	1.3(2)	1.6(3)	...	0.014
4.44	2^+	0.0297(9)	0.0271(4)	0.9(4)	0.07(3)	0.9(3)	0.9(4)	0.0931	0.09
0	0^+	0.331(2)	0.2952(14)	36.9(8)	0.92(2)	1.06(2)	1.18(3)	0.768	0.17

[a] The reduced transition strengths, B(GT) and B(M1), have been calculated using the phase-space factor of a narrow state at 10.3 MeV.

broad particle-unbound nuclear states with an efficiency comparable to standard γ spectroscopy (on the order of 1%), but in an essentially background-free environment.

We have looked at the γ decays of the 15.11 and 12.71 MeV states in ^{12}C to lower-lying states that break up into three α particles. The following transitions were detected: 15.11 $\to$ 12.71, 11.83, 10.3, 7.65 and 12.71 $\to$ 10.3, 7.65. The partial γ widths obtained in the present work are in agreement with previous measurements when such exist. The value of $\Gamma_\alpha/\Gamma = (2.8 \pm 1.2)\%$ obtained for the isospin-forbidden α decay of the 15.11 MeV state is in good agreement with the literature value when corrected for the new γ branches as discussed in Section 3.5.

Finally, we have explored the relation between the M1 γ decays of the 15.11 MeV state and the analog β decays of ^{12}B and ^{12}N and the associated ratio, R(M1/GT), between the reduced transition strengths.

Looking to the future, we see a number of physics cases that could be studied with an experimental method like ours. One nearby example is the 16.11 MeV state in ^{12}C ($J^\pi = 2^+$, $T = 1$) which is known to have γ branches to the 12.71 and 9.64 MeV states at the 10^{-5} level [24] slightly below our sensitivity. Naturally, one would also expect γ branches to the broad states. Two other examples are the lowest $T = 3/2$ levels of ^{9}Be and ^{9}B. They are known to have γ branches of 2.1 and 2.5%, respectively, to the ground states [25], but γ transitions to excited states have not been observed yet. Another case of interest is ^{8}Be. The $4^+ \to 2^+$ transition was recently measured by Datar et al. [26] using an experimental technique similar to ours with the additional advantage of also detecting the emitted γ ray. A measurement of the $2^+ \to 0^+$ transition might be within reach despite an expected branching ratio of only 6×10^{-9}. With the inclusion of γ and neutron detectors in the experimental setup a wider range of physics cases will become accessible.

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References

[1] M. Alcorta, et al., Nucl. Instrum. Methods A 605 (2009) 318.
[2] Y. Kanada-En'yo, Prog. Theor. Phys. 117 (2007) 655.
[3] H.O.U. Fynbo, et al., Nature 433 (2005) 136.
[4] B. John, et al., Phys. Rev. C 68 (2003) 14305.
[5] M. Itoh, et al., Nucl. Phys. A 738 (2004) 268.
[6] M. Freer, et al., Phys. Rev. C 76 (2007) 034320.
[7] S. Hyldegaard, et al., Phys. Lett. B 678 (2009) 459.
[8] D.P. Balamuth, et al., Phys. Rev. C 10 (1974) 975.
[9] D.E. Alburger, D.H. Wilkinson, Phys. Rev. C 5 (1972) 384.
[10] http://www.cmam.uam.es/.
[11] O. Tengblad, et al., Nucl. Instrum. Methods A 525 (2004) 458.
[12] H.O.U. Fynbo, et al., Phys. Rev. Lett. 91 (2003) 082502.
[13] W.A. Rolke, et al., Nucl. Instrum. Methods A 551 (2005) 493.
[14] F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1.
[15] P. von Neumann-Cosel, et al., Nucl. Phys. A 669 (2000) 3.
[16] B.T. Chertok, et al., Phys. Rev. C 8 (1973) 23.
[17] D. Deutschmann, et al., Nucl. Phys. A 411 (1983) 337.
[18] A. Bohr, B.R. Mottelson, Nuclear Structure, vol. I, Benjamin, New York, 1975, p. 382.
[19] P. Navrátil, W.E. Ormand, Phys. Rev. C 68 (2003) 034305;
P. Navrátil, et al., Phys. Rev. Lett. 99 (2007) 042501.
[20] A. Richter, et al., Phys. Rev. Lett. 65 (1990) 2519.
[21] Y. Fujita, et al., Phys. Rev. C 67 (2003) 064312.
[22] I.S. Towner, Phys. Rep. 155 (1987) 263.
[23] P.A.M. Guichon, C. Samour, Nucl. Phys. A 382 (1982) 461.
[24] E.G. Adelberger, et al., Phys. Rev. C 15 (1977) 484.
[25] A.B. McDonald, et al., Nucl. Phys. A 273 (1976) 451.
[26] V.M. Datar, et al., Phys. Rev. Lett. 94 (2005) 122502.