Decay strength distributions in $^{12}C(^{12}C,\gamma)$ radiative capture

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The heavy-ion radiative capture reaction, $^{12}C(^{12}C,\gamma)$, has been investigated at energies both on- and off-resonance, with a particular focus on known resonances at $E_{c.m.} = 6.0$, 6.8, 7.5, and 8.0 MeV. Gamma rays detected in a BGO scintillator array were recorded in coincidence with ^{24}Mg residues at the focal plane of the DRAGON recoil separator at TRIUMF. In this manner, the relative strength of all decay pathways through excited states up to the particle threshold could be examined for the first time. Isovector $M1$ transitions are found to be a important component of the radiative capture from the $E_{c.m.} = 6.0$ and 6.8 MeV resonances. Comparison with Monte Carlo simulations suggests that these resonances may have either $J = 0$ or 2, with a preference for $J = 2$. The higher energy resonances at $E_{c.m.} = 7.5$ and 8.0 MeV have a rather different decay pattern. The former is a clear candidate for a $J = 4$ resonance, whereas the latter has a dominant $J = 4$ character superposed on a $J = 2$ resonant component underneath. The relationship between these resonances and the well-known quasimolecular resonances as well as resonances in breakup and electrofission of ^{24}Mg into two ^{12}C nuclei are discussed.

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I. INTRODUCTION

Radiative capture involving heavy ions is a process that has been scarcely studied, in contrast to the well-known process of light-ion radiative capture, which plays an important role in many aspects of astrophysical nucleosynthesis. The reason that this phenomenon is relatively unexplored lies in the high Q values for such reactions, which form the compound nucleus in states of high excitation, where particle evaporation is overwhelmingly favored. Identifying the radiative capture process in heavy-ion systems is, accordingly, very challenging experimentally. Progress in the study of heavy-ion radiative capture in the 1970s and 1980s was reviewed by Sandorfi [1]. Very little further work on this exotic reaction mechanism has been carried out in the interim.

In terms of the direct measurement of capture γ rays, most attention has focused on the $^{12}C(^{12}C,\gamma)$ [2], $^{12}C(^{16}O,\gamma)$ [3], and $^{90}Zr(^{90}Zr,\gamma)$ [4] reactions. In the latter example, the process is rather statistical in nature and the initial radiative capture takes place to a high-lying, high-spin state and is proceeded by a high-multiplicity γ cascade toward the ground state [4]. By contrast, the cross sections for capture to the low-lying states for the $^{12}C(^{12}C,\gamma)$ and $^{12}C(^{16}O,\gamma)$ reactions exhibit strongly oscillatory behavior as a function of beam energy in the near-barrier region [1,2,5,6]. A series of resonances for radiative capture to the first few excited states were identified around the Coulomb barrier in both ^{24}Mg and ^{28}Si. The existence of such resonant behavior was not unexpected in the context of the strongly resonant behavior in the total cross sections for $^{12}C+^{12}C$ that has been known for nearly 50 years [7,8]. The resonances in the total cross section have been styled quasimolecular resonances as they were suggested

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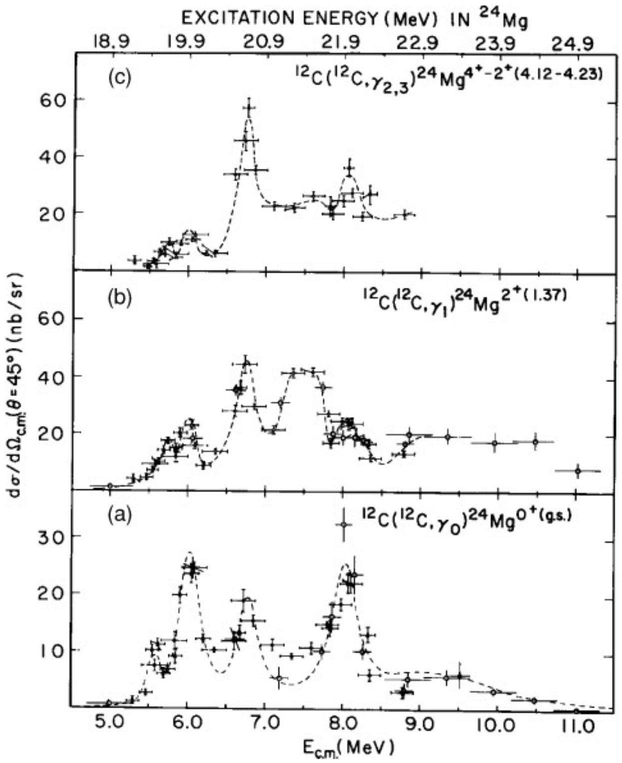

FIG. 1. Resonances in the ^{12}C(^{12}C,γ) reaction as a function of $E_{c.m.}$, measured using a large single sodium iodide detector (reproduced from Fig. 7 of Ref. [2]).

to be associated with the existence of special metastable states with a molecular ^{12}C$-^{12}$C structure. The most prominent ^{12}C(^{12}C,γ) resonances at $E_{c.m.} = 6.0$, 6.8, and 8.0 MeV (see Fig. 1), however, did not have obvious counterparts in this set of well-known quasimolecular resonances [2].

The purpose of the present work is to achieve a more complete understanding of the mechanism behind the ^{12}C(^{12}C,γ) radiative capture reaction. There are a number of key questions: Does radiative capture take place to states above the first few excited states in ^{24}Mg? Is the population of states by radiative capture statistical in nature or is favoritism shown for certain high-lying states on the basis of their structure? Does radiative capture offer a means of identifying highly deformed configurations in ^{24}Mg? Can the γ branches allow us to assign a definitive spin and parity to the observed resonances? Having answered these questions, we then aim to establish where the radiative capture mechanism fits into the context of other related phenomena such as the occurrence of quasimolecular resonances, electrofission of ^{24}Mg into two ^{12}C nuclei [1,9], and the breakup reaction ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C [10].

The initial question regarding whether radiative capture occurs to more than the first few excited states has largely been answered already at least for the resonance at $E_{c.m} = 8.0$ MeV. A study by some of our group sought to measure the total radiative capture cross section for this resonance, by recording capture residues using the Fragment Mass Analyser (FMA) at Argonne National Laboratory [11]. In this manner, the cross section could be determined independently of details of the capture decay pathway. This measurement showed that the total radiative capture cross section exceeded that inferred from earlier measurements of capture to individual low-lying states in ^{24}Mg, strongly suggesting that more complex pathways were involved in the decay process.

There is also some evidence that radiative capture proceeds to high-lying states in the case of the $E_{c.m} = 8.0$ MeV resonance. A study was carried out using the state-of-the-art Gammasphere array of 100 hyperpure germanium detectors [12], which was, at that time, situated at Lawrence Berkeley National Laboratory [11]. Because no recoil separator was available, the weak capture channel was discriminated by using the Gammasphere array as a sum energy calorimeter, summing the signals recorded in both the germanium crystals and their contiguous bismuth germanium oxide (BGO) shields. The high resolution of Gammasphere allowed the nonstatistical character of the capture decay to be determined, in particular, the preferential population of a number of states around 10 MeV in excitation in ^{24}Mg and states in the nonyrast $K = 2$ rotational band in ^{24}Mg—features not known from earlier studies [11]. A disadvantage of the approach taken in the Gammasphere studies is that it was not possible to simultaneously reproduce the original radiative capture measurements and to search for higher multiplicity pathways through highly excited states in ^{24}Mg. This limitation was due to the negligible efficiency of Gammasphere for high-energy γ rays due to the size of the germanium crystals. These restrictions provide motivation for the present work: namely to make a simultaneous measurement of all capture γ rays in coincidence with fused ^{24}Mg recoils. Only in this manner will it be possible for a complete picture of the cooling process to emerge. Moreover, by extending the study to a number of the known ^{12}C(^{12}C,γ) resonances, it will be possible to determine whether the initial findings regarding the existence of certain preferred decay pathways are particular to the $E_{c.m.} = 8.0$ MeV resonance.

There is precedence for nonstatistical decay in heavy-ion radiative capture in the case of the ^{12}C(^{16}O,γ) reaction. Collins *et al.* showed that there was very little feeding of the ground state in this reaction and the strongest decay branch was to an excited 0^+ state in ^{28}Si [3]. This observation was discussed in terms of the lack of structural overlap between the oblate shape of the ^{28}Si ground state and the intrinsically prolate nature of the entry system. The excited 0^+ state, however, is believed to be the bandhead of a well-deformed prolate rotational band, which would have a much greater structural similarity with the entry resonance [13,14]. By contrast, ^{24}Mg has a strongly prolate-deformed ground state and the known radiative capture to low-lying states is roughly similar in strength [2]. Nevertheless, for many years it has been predicted that a shape-isomeric band exists in ^{24}Mg with a bandhead around 10 MeV [15–20]. Because this band lies so far from the yrast line, it has not been possible to identify this band experimentally as it was for analagous superdeformed bands in heavier nuclei such as ^{40}Ca [21]. Baye and Descouvemont predict strong transitions between the quasimolecular resonance band and the shape isomeric band in ^{24}Mg [22].

Similar resonant phenomena to radiative capture have been observed in electrofission and more recent breakup reactions. The electrofission of ^{24}Mg into two ^{12}C nuclei is effectively the inverse of ground-state radiative capture [1,9]. The radiative capture and electrofission resonances were therefore earlier attributed to a special class of intermediate structure that had both a strong coupling to the ^{12}C+^{12}C entrance channel *and* the ^{24}Mg ground state [1,2]. Because these measurements in the late 1970s and early 1980s, there has been a further set of measurements relating to the breakup reaction ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C [10]. A whole series of resonances extending from the region of the Coulomb barrier to high excitation energy have been identified in this reaction. In principle, there should be commonality between the breakup reaction and radiative capture, although as in the case of the electrofission, the processes are only strictly the time inverse where the ^{12}C nuclei are produced in their ground state. Moreover, instrumental limitations mean that the breakup work overlaps only with the upper end of the energy region where the radiative capture resonances are known [10]. The relationship between these different classes of measurement is yet to be fully explored.

II. EXPERIMENTAL DETAILS

The heavy-ion radiative capture reaction ^{12}C(^{12}C,γ) was investigated at a series of beam energies from $E_{\rm c.m.} = 6.0$ MeV to $E_{\rm c.m.} = 8.0$ MeV at the ISAC-1 facility at the TRIUMF laboratory in Vancouver. The beams were obtained as $^{12}C^{3+}$ ions from the ISAC-1 accelerator and were incident on a series of thin self-supporting carbon foils with thicknesses in the range 20–100 μg/cm^2. Radiative capture products were identified using the DRAGON recoil separator [23]. DRAGON is a two-stage recoil mass separator with a total length of 21 m. Separation of recoils from scattered beam is achieved using a combination of electric and magnetic dipoles. A single (optimal) charge state is selected in the first magnetic dipole. Energy dispersion in the electric dipole separates the residues by mass. The second stage repeats this process, leading to an extremely high beam rejection ratio. Such a high rejection ratio is essential to DRAGON's intended application to studying proton capture reactions with short-lived radioactive species in inverse kinematics. It has successfully been employed in measurements intended to infer the astrophysical rate for the ^{21}Na(p,γ) [24] and ^{26}Al(p,γ) reactions [25]. To be optimized for such studies, the acceptance of the separator was deliberately made rather narrow; the nominal acceptance of DRAGON is a cone of half-angle 20 mrad in the transverse direction and $\pm 2\%$ in momentum. This imposes restrictions in the present study where some of the capture residues recoiled into a larger cone than the separator could accept. This could occur when the radiative capture proceeds via a single large energy γ ray that may impose a large transverse kick on the recoiling nucleus, pushing it outside of the acceptance. The effect is less severe when the multiplicity is greater than one because the vector sum of the γ-ray momenta may cancel. The fact that DRAGON does not have 100% acceptance for the residues of interest has to be considered carefully in the analysis of the data obtained and simulations were performed to interpret the results. Similar issues have been encountered in a recent study of the ^{12}C(α,γ) reaction with DRAGON [26]. The approach taken in the present work to handle the incomplete acceptance is discussed in detail below.

Fusion γ rays were detected with an array of 30 BGO detectors surrounding the target in a close-packed geometry. The layout of the detectors is described in Fig. 2. The array has a rather high efficiency due to the detector material and the large solid angle coverage. The layout of the detectors is not symmetric nor are the target-detector distances uniform, which complicates measurements of angular distributions. The γ-ray response can, again, only be understood in relation to a simulation. A hardware coincidence was applied between the recoils and γ rays.

A. Setting up DRAGON

In each case, the DRAGON separator was tuned by bending the primary beam through the first dipole so that its energy could be measured accurately after the target. This effectively calibrated the system so that the settings for the desired recoils could be obtained by scaling from this reference tune. A charge state scan was carried out to find the charge state corresponding to the largest yield of recoils, avoiding integer values of A/q. This led to the selection of recoils with $q = 7$ for each energy. Following their separation from scattered beam through the electric and magnetic elements of DRAGON, the recoils were implanted in a double-sided silicon strip detector at the focal plane, where their energies were recorded.

Several important checks were made before proceeding to general data-taking. The first concerned the key issue of whether ^{24}Mg residues could be produced from reactions with likely target contaminants such as ^{13}C and ^{16}O. The possible effect of ^{13}C contamination was investigated by replacing the enriched ^{12}C target with an enriched ^{13}C one. If the ^{24}Mg residues were coming from reactions with ^{13}C then a 100-fold increase in residue rate would have been observed; this test proved negative. A similar test for ^{16}O contamination is more difficult as a suitable target with similar characteristics to the thin self-supporting carbon foils is difficult to obtain. Nevertheless, the presence of ^{16}O was investigated by performing a full mass scan for fusion products expected from such contaminants, e.g., $A = 27$ nuclei that could only be produced from reactions with ^{16}O. No such products were convincingly identified. Additional checks were made in terms of the energy of the detected γ rays as discussed in detail below.

III. RESULTS

Data were taken at energies corresponding to previously observed resonances in the ^{12}C(^{12}C,γ) reaction at $E_{\rm c.m.} = 6.0$, 6.8, 7.5, and 8.0 MeV [2]. Data were also taken at $E_{\rm c.m.} =$ 6.4 MeV, which was known to be a minimum in previous measurements of the capture cross section [2].

A. Data analysis

The residues of interest were selected in the off-line analysis by setting appropriate gating conditions on the recoil energy

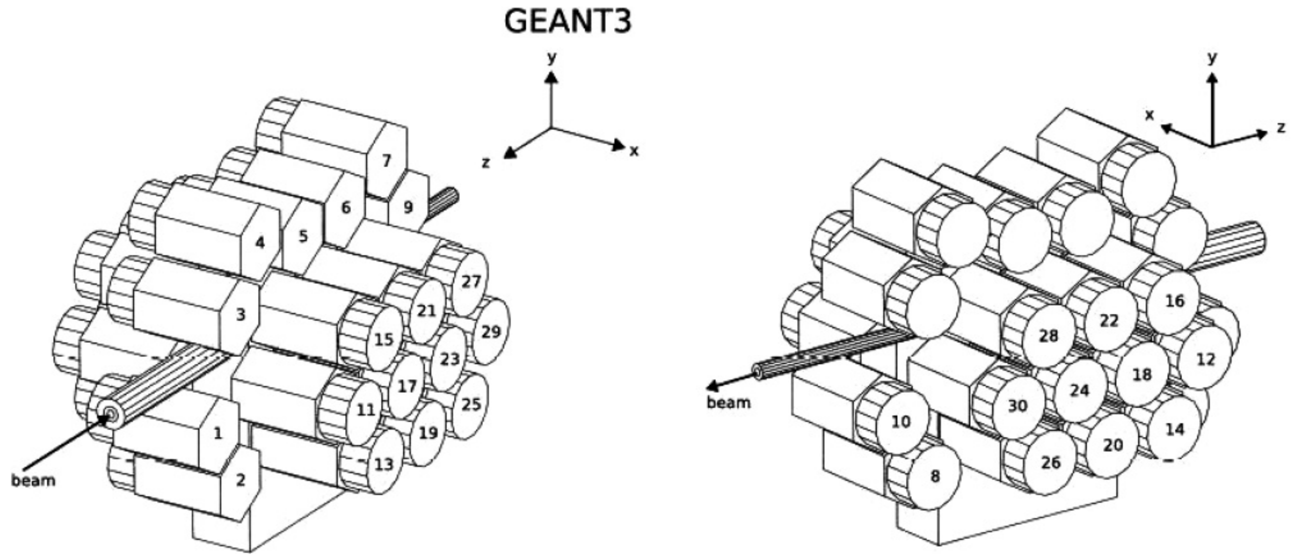

FIG. 2. Layout of the BGO detector array around the target position. The detectors are labeled according to the numbering convention used for the GEANT3 simulations (see text) from 1 to 30.

and time-of-flight through the separator. γ rays recorded in the target BGO array were then projected in coincidence with the selected recoils. There is a good probability that annihilation photons following pair production will escape an individual BGO detector, and at lower energies, this is also true of Compton scattered photons. In many events, therefore, the energy recorded from a single photon hit is spread over two or more adjacent detectors. To reconstruct the original event, a recursive clustering algorithm was applied to the γ-ray data. This algorithm starts with the highest energy event and searches for adjoining detectors that have also fired, and if this condition is satisfied, the two energies recorded are summed. The process continues recursively until no further adjacent events are found. It is then assumed that the highest energy member of the cluster corresponds to the position that the photon entered the array. The algorithm then proceeds to the next highest energy isolated event and continues the clustering process. When all possible clusters have been identified, a Doppler correction was applied. The γ events recorded are energy ordered and we refer to the highest energy γ ray in the event as γ_0, the next highest as γ_1 and so forth.

B. Resonance at $E_{\mathrm{c.m.}} = 6.0$ MeV

The lowest energy resonance considered in the present work was the one at $E_{\mathrm{c.m.}} = 6.0$ MeV. This resonance was of particular interest because earlier work suggested that the dominant resonant capture pathway should be to the ^{24}Mg ground state and first excited state [2]. In this article, we focus on this particular resonance and the observed spectra as an exemplar of the data obtained at different energies.

For the study of this resonance, a 12.12-MeV ^{12}C beam was incident on a nominally 85-μg/cm^2 ^{12}C target. The energy loss of the beam through this target was around 500 keV, implying the center-of-target energy was 11.85 MeV ($E_{\mathrm{c.m.}} =$ 5.93 MeV). The mean recoil energy was expected to be 5.31 MeV. As described above, the DRAGON separator was used to select $A = 24$ residues from the $E_{\mathrm{c.m.}} = 6.0$ MeV resonance. A well-defined recoil peak was observed in the (double-sided silicon strip detector) DSSSD at the focal plane (see Fig. 3). The energy setting of DRAGON was varied to optimize the residue yield with the best setting found to be for $E_{\mathrm{rec}} =$ 5.18 MeV. The beam current was in the range 150–250 enA and data were taken for 4 days.

To examine the decay pathways, a projection of γ rays in coincidence with the ^{24}Mg residues was made by placing windows on the recoil energy and time-of-flight through the separator (see Fig. 4). As expected from earlier measurements, a peak corresponding to capture to the ground state is observed at an energy of around 20 MeV. In the region from 15 to 19 MeV, there is evidence for capture to the first, second, and third excited states, although these are unresolved. There are also two clear peaks at around 2.5 and 4.0 MeV. We associate these with the 2.754 MeV ($4^+ \rightarrow 2^+$) and 4.238 MeV ($2_2^+ \rightarrow 0^+$)

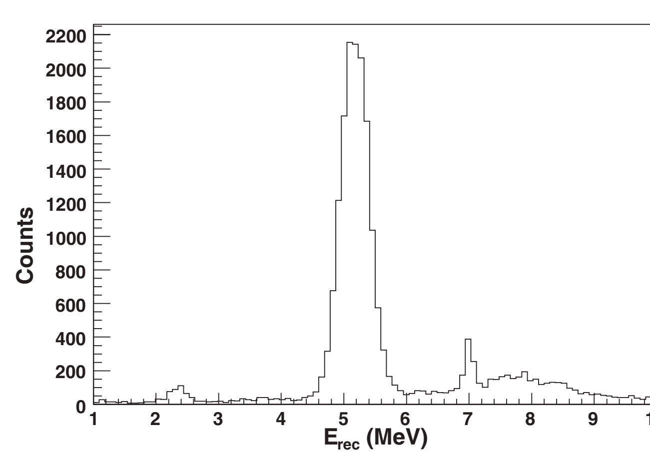

FIG. 3. Energy spectrum for $A = 24$ recoils recorded at the focal plane of DRAGON from the $E_{\mathrm{c.m.}} = 6.0$ MeV data set.

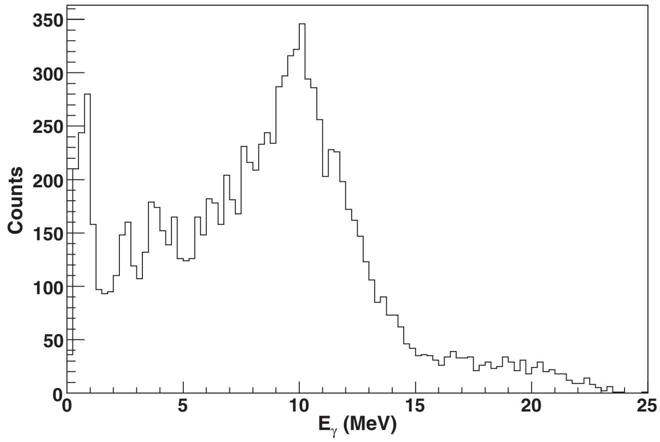

FIG. 4. Total projection of γ rays in coincidence with recoils taken from the $E_{c.m.} = 6.0$ MeV data.

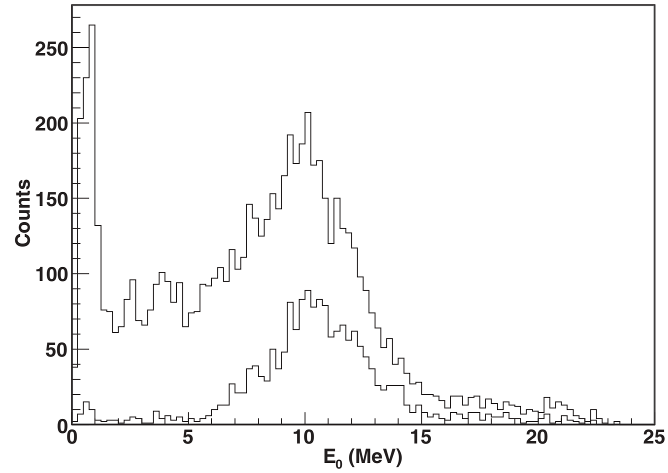

FIG. 5. Total projection of γ rays for events with two coincident γ rays taken from $E_{c.m.} = 6.0$ MeV data. The foreground spectrum corresponds to the subset of these events where the sum of these two γ-ray energies is greater than 18 MeV.

transitions in ^{24}Mg. The striking feature of the coincident γ-ray spectrum, however, is the prominent broad peak centered around 10 MeV. Such a feature was not observable in earlier measurements that used a single large sodium iodide detector due to pileup.

The first question that arises is whether the newly observed broad peak in the capture γ-ray spectrum is genuinely connected with ^{24}Mg residues coming from radiative capture or whether it could be somehow associated with contamination from a less exotic reaction channel or reaction with a target contaminant. As stated above, we were able to rigorously dismiss a contribution from reactions with ^{13}C by the simple expedient of replacing the target with a ^{13}C foil. It is somewhat more difficult to perform a similar test for ^{16}O. The ^{12}C(^{12}C,γ) radiative capture reaction, however, has the characteristic that the sum energy of emitted γ rays must equal the Q value of the reaction (+13.93 MeV) plus the center-of-mass energy of the beam. For $E_{c.m.} = 6.0$ MeV, this corresponds to a sum energy of 20 MeV. Possible reactions off contaminants such as ^{16}O have much smaller Q values, e.g., $Q = +6.77$ MeV for ^{16}O(^{12}C,α) and cannot produce a sum energy of emitted γ rays as high as 20 MeV. Figure 5 shows projections of γ rays for events where two or more γ rays were detected, comparing events where the sum energy was unrestricted with those where it was demanded that the sum energy was above 18 MeV. The two projections are structurally the same, which can be the case only if essentially all the observed events arise from the capture channel. We are therefore able to rigorously discount the role of target contamination in our observations.

The second question that emerges is whether the origin of the broad peak around 10 MeV is a resonant phenomenon in the same manner as the capture γ rays to the ground state or whether it is a nonresonant direct capture mechanism. This was investigated by raising the beam energy to $E_{c.m.} = 6.4$ MeV, which was previously believed to be an "off-resonance" position, i.e., in between the major capture resonances [1]. At this energy, the spectral shape was very different, with a strong attenuation of the 10-MeV peak relative to the high-energy capture γ rays, which can arise from direct capture at all beam energies (see Fig. 6). This demonstrates the resonant nature of the 10-MeV peak.

Although the broad feature around 10 MeV in the γ-ray spectrum is clearly a resonant phenomenon, it must be associated with a number of different decay pathways because the expected resolution of the BGO array is around 1.5 MeV. The origin of this feature may be investigated by means of an analysis of γ-ray coincidences. Figure 7 shows an energy-ordered γ-γ matrix for events where exactly two γ rays were recorded in coincidence with a ^{24}Mg residue detected in the focal-plane DSSSD. The broad region at the apex of the triangle in this E_1-E_0 plot corresponds to events where there were coincidences between two γ rays with energies close to 10 MeV and, hence, a total energy of around 20 MeV, close to the theoretical maximum allowed by the energetics of the capture reaction.

Due to the restricted acceptance of the DRAGON spectrometer, it would be expected that the distribution of high-energy γ rays to the ground state and low-lying states, and γ rays

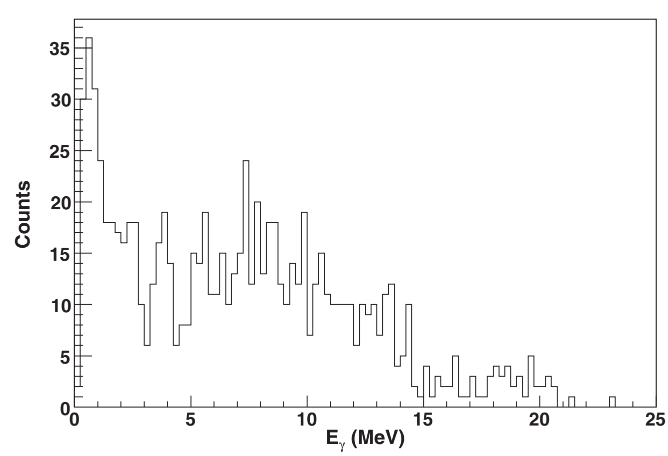

FIG. 6. Total projection of γ rays in coincidence with recoils at an "off-resonance" beam energy of $E_{c.m.} = 6.4$ MeV.

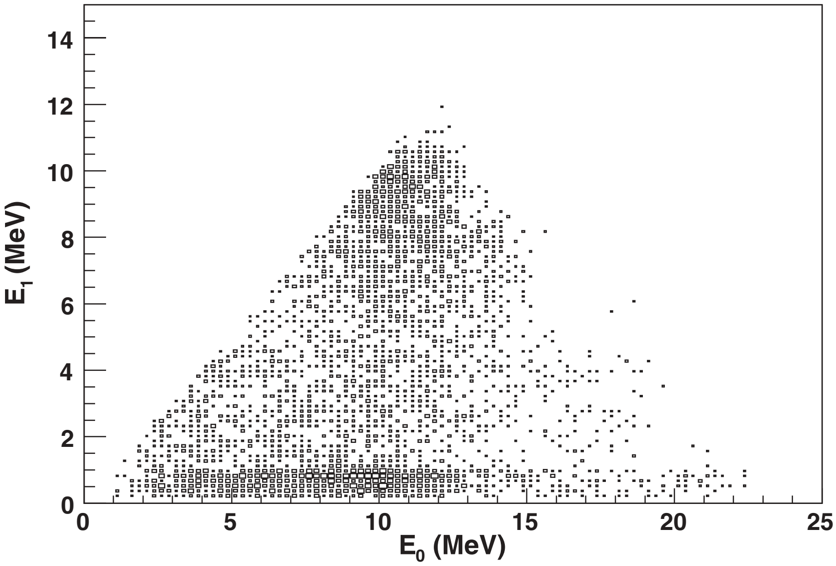

FIG. 7. Matrix of the energy of the second-highest energy γ-ray, E_1 against that of the highest energy γ ray, E_0 for events where exactly two γ rays were recorded in the BGO array. The data are from the run at $E_{\rm c.m.} = 6.0$ MeV.

forming cascades through relatively high-lying states would be rather different on the basis of kinematics, leaving aside for the moment the effect of differing angular distributions. This expectation is borne out by the striking difference observed between those events for which $E_0 > 18$ MeV (Fig. 8), compared to those events for which E_0 is between 10 and 12 MeV. This comparison clearly illustrates that only a small number of detectors are in positions where they can detect high energy γ rays in coincidence with recoils.

C. Resonance at $E_{\rm c.m.} = 6.8$ MeV

Data were also taken at a beam energy, $E_{\rm c.m.} = 6.8$ MeV, where a strong resonance has previously been observed for radiative capture to the ground, first, and second/third (unresolved) excited states in ^{24}Mg [1]. For the study of this resonance, a 13.8-MeV ^{12}C beam was incident on a 44-μg/cm^2 enriched ^{12}C target. This corresponds to a target thickness of 250 keV. The corresponding center-of-target energy was 13.68 MeV ($E_{\rm c.m.} = 6.84$ MeV). The DRAGON separator was set to accept residues with $A/q = 24/7$ and $E_{\rm rec} =$ 6.38 MeV, following an optimization of the energy settings. Data were taken for 4 days at an average beam current of around 200 enA.

The spectrum of coincident γ rays for the 6.8-MeV resonance is qualitatively very similar to that observed in the $E_{\rm c.m.} = 6.0$ MeV data. As expected from earlier work (see Fig. 1), there is more evidence for decays passing through the low-lying excited states at $E_{\rm c.m.} = 6.8$ MeV than in the data taken at $E_{\rm c.m.} = 6.0$ MeV. This can be seen by examining the γ_1 spectrum for events where a coincident γ_0 was recorded with an energy > 15.8 MeV (see Fig. 9). Clear peaks corresponding to the 2754 keV ($4^+ \rightarrow 2^+$), 3866 keV ($3^+ \rightarrow 2^+$), and 4238 keV ($2^+_2 \rightarrow 0^+$) transitions are observed. It was not possible in earlier studies to distinguish the feeding of the 4^+ state at 4122 keV and the 2^+_2 state at 4238 keV. The present measurement shows that the feeding of these is roughly

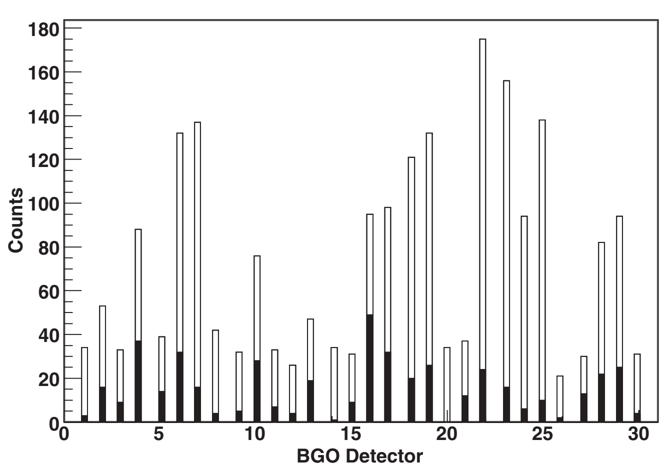

FIG. 8. Map of BGO detectors that fire for highest-energy γ-ray for $E_0 > 18$ MeV (filled histograms) and for $10 < E_0 < 12$ MeV (open histograms). Data are taken from the run at $E_{\rm c.m.} = 6.0$ MeV

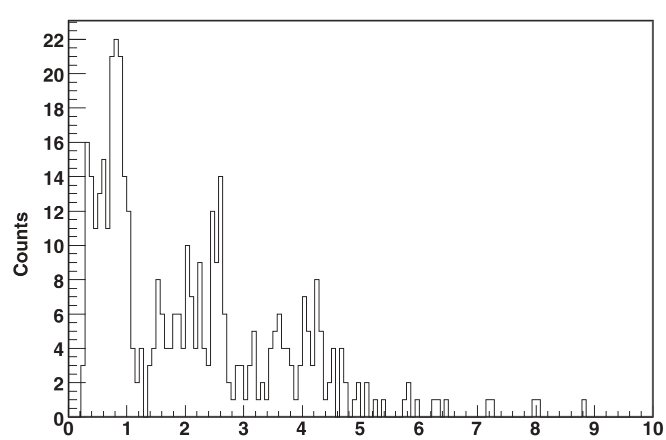

FIG. 9. Spectrum of γ_1 for events where $\gamma_0 > 15.8$ MeV and where there is a coincident recoil, taken from the $E_{\rm c.m.} = 6.8$ MeV resonance data.

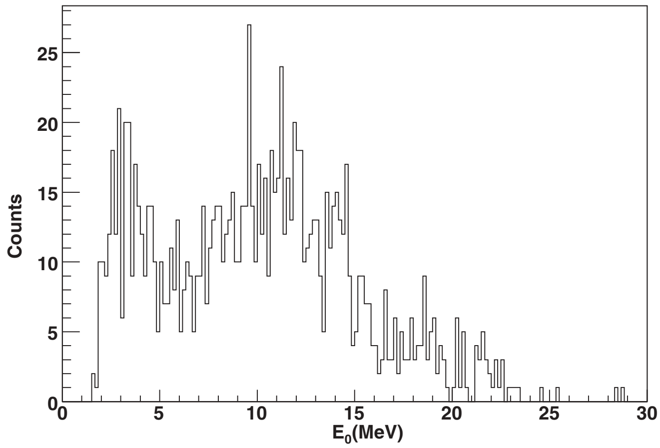

FIG. 10. Spectrum of the highest-energy γ ray in coincidence with recoils taken from the $E_{\text{c.m.}} = 7.5$ MeV data.

comparable for $E_{\text{c.m.}} = 6.8$ MeV. The dominant feature in both the $E_{\text{c.m.}} = 6.0$ and 6.8 MeV data sets, however, is the broad peak in the γ_0 spectrum around 10 MeV.

D. Resonance at $E_{\text{c.m.}} = 7.5$ MeV

A limited amount of data was taken around $E_{\text{c.m.}} = 7.5$ MeV (see Fig. 10) an energy where capture had previously been observed notably to the 2^+ state in ^{24}Mg, but there was also some evidence of enhanced capture to the 4^+ state. For this part of the run, a 15.24-MeV ^{12}C beam was incident on the 44-μg/cm^2 ^{12}C target. The corresponding centre-of-target energy was 15.12 MeV ($E_{\text{c.m.}} = 7.56$ MeV). The present data suggests that this resonance is rather different in character to the two lower energy resonances. For example, the peak around 10 MeV which dominates the γ_0 spectrum for the lower energy resonances is largely attenuated relative to capture to the low-lying excited states.

E. Resonance at $E_{\text{c.m.}} = 8.0$ MeV

A further study was carried out at a beam energy, $E_{\text{c.m.}} = 8.0$ MeV—the position of a known resonance for capture to the ground, first, second, and third excited states in ^{24}Mg [1]. To perform this study, a 16.08-MeV ^{12}C beam was incident on a 50-μg/cm^2 ^{12}C target. This corresponds to a center-of-target energy of 15.95 MeV ($E_{\text{c.m.}} = 7.97$ MeV). In fact, the $E_{\text{c.m.}} = 8.0$ MeV resonance was the one considered in the earlier studies using the FMA and Gammasphere, where evidence for strong population of higher-lying ^{24}Mg levels was observed [11]. It is unfortunate therefore that this data set suffers from contamination with what appear to be residues from $A = 23$ (see Fig. 11). Complete separation could not be achieved solely by placing conditions on the residue energy. It was necessary, therefore, to perform a normalized subtraction of the component arising from the contaminant from the coincident γ-ray spectrum (see Fig. 12). Although it is unfortunate that such a subtraction is necessary, it is still clear that the γ_0 spectrum has a very different shape to that

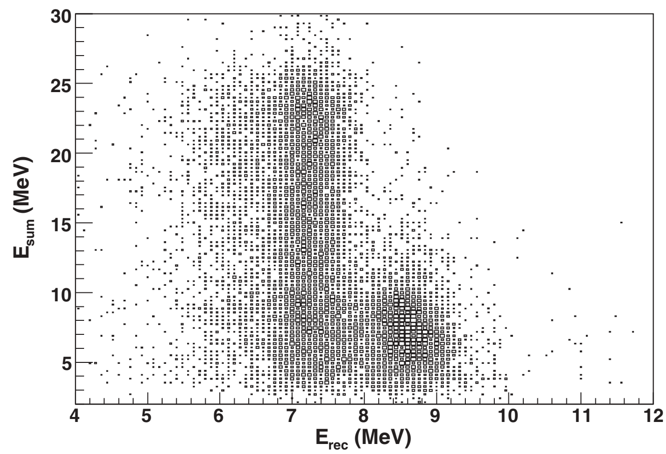

FIG. 11. Plot of the sum energy of recorded γ rays against recoil energy from the $E_{\text{c.m.}} = 8.0$ MeV data. Two regions may be identified. The lower recoil energy region corresponds to radiative capture and has high γ-ray sum energies. The higher recoil energy region is associated with $A = 23$ (principally ^{23}Na).

observed for $E_{\text{c.m.}} = 6.0$ and 6.8 MeV, and is more similar to the $E_{\text{c.m.}} = 7.5$ MeV resonance discussed above.

IV. DISCUSSION

Simulations of the combined response of the BGO array for detecting capture γ rays in coincidence with residues have been carried out using the Monte Carlo simulation code GEANT3. All of the electromagnetic components of the separator are included, allowing the residues to be tracked through and onto the focal plane. This necessarily takes account of the important effects due to the finite acceptance of DRAGON when studying coincident γ rays. It also allows the point where recoils are stopped in the system to be tracked in detail.

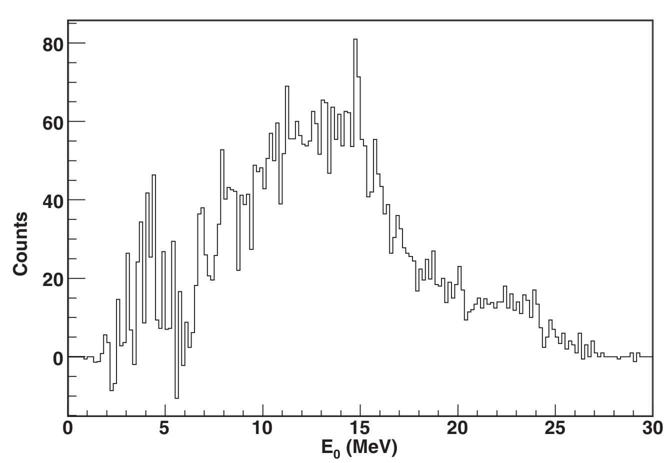

FIG. 12. Spectrum of the highest energy γ rays in coincidence with recoils from the $E_{\text{c.m.}} = 8.0$ MeV data. A normalized fraction of data originating from the higher recoil energy contaminant has been subtracted.

To carry out simulations, some approximations to the likely decay process have been made. These are largely dictated by expectations on the basis of well-known nuclear structure effects and properties. First, because the capture process is between identical bosons, the entry resonances are restricted to natural parity. Because the capture process takes place at or below the Coulomb barrier, the input angular momentum is expected to be low. The most likely spins are therefore: $J = 0, 2, 4 \cdots$. The possible decay pathways are then dictated by the choice of spin for the entry resonance. A natural choice for the $E_{\text{c.m.}} = 6.0$, 6.8, and 8.0 MeV resonances would be $J = 2$, because in each case a direct and enhanced γ-ray decay to the ground state is observed. Indeed this spin assignment was suggested previously by Nathan *et al*. [2]. The implicit assumption, however, was that there is only one resonance with a specific J value present, and the possibility of a superposition of such resonances is not considered. In the present work, we find that in some cases it is difficult to explain the data without allowing such a possibility.

The capture process could, in principle, proceed to any ^{24}Mg levels lower in energy than the resonance itself. The vast majority of such levels are ruled out because they are well above the particle-emission thresholds. From a practical perspective, the levels of interest are restricted to particle-bound states and a limited number of particle-unbound levels that, for some reason (energetics, selection rules, or structure), decay principally by γ emission. It is to our advantage that the properties of such states are well constrained by the abundant experimental studies of ^{24}Mg over the past decades. Moreover, it is possible to further restrict the states under consideration from application of γ-ray selection rules. First, for γ-ray emission, consideration of transition rates effectively restricts the range of multipolarities under consideration to $E1$, $M1$, and $E2$. The former can be safely neglected because in self-conjugate nuclei, $\Delta T = 0$ $E1$ transitions are to first order forbidden as they are purely isovector in nature [27]. In a self-conjugate nucleus, isoscalar $M1$ transitions are expected to be rather hindered, whereas isovector $M1$ transitions would be expected to be strongly enhanced [27]. Such considerations and selection rules allow us to restrict our attention to states that may be reached by either $E2$ or isovector $M1$ transitions from the entry resonance.

We note in passing a couple of more subtle nuclear structure effects that are difficult to include in the simulation. The first of these effects is the possibility of transition hindrance due to K selection rules. Some states such as the 4^+ states at 8439 and 9516 keV are believed to have high-K, i.e., $K = 4$ [28]. If K were a good quantum number at the excitation energy where the entry resonances exist and the resonance had $K = 0$, then transitions to these 4^+ states would be strongly K-hindered. A further effect not explicitly included in the simulations is isospin mixing. Although difficult to incorporate, this effect may be important in certain cases because substantial isospin mixing is reported for a number of high-lying states in ^{24}Mg [29].

Having determined which states are accessible from the entry resonance and which have a γ branch (γ branching ratios for many unbound levels are tabulated in Ref. [30]), we have considered each possible decay pathway from the entry resonance, assigning it a mean transition strength according to the values tabulated by Endt [31]. We then evaluated their corresponding intensity on the basis of the expected energy dependence for dipole and quadrupole transitions. This process continues through the intermediate states, if any, in ^{24}Mg whose γ branching is, in general, well established. The resulting spectra are convoluted with the known resolution of the BGO array before comparison with the data.

As far as possible, we have included the full angular distribution of the emitted γ rays. These correspond to analytical formula in the special case of radiative capture where full alignment is guaranteed in the entry state, because no particles are emitted. Unfortunately, it appears that the angular distribution observed is dominated by the kinematical effect due to the finite acceptance and so there is little sensitivity to γ-ray angular distributions.

A. $E_{\text{c.m.}} = 6.0$ MeV resonance

The most obvious approach to simulating the $E_{\text{c.m.}} = 6.0$ MeV resonance is to assume, in common with earlier work, that it has $J = 2$. First, we considered the role of $E2$ capture γ rays, because these were already shown in earlier work [1] to be important for capture to the first few states in ^{24}Mg. In comparison with the data, it is clear that such a component is present but it does not well reproduce the excess of strength around 10 MeV in the γ_0 spectrum (Fig. 13). The inclusion of an isovector $M1$ component greatly improves the agreement with the data (Fig. 13). The states that are important for mediating this process are the $T = 1$, 1^+ states at 9968 and 10712 keV and the $T = 1$, 2^+ state at 10059 keV, which are the isobaric analogs of low-lying excited states in ^{24}Na.

Having fixed on the general shape of the γ_0 spectrum, it is now possible to make a comparison with the γ_1 spectrum. We found that without specifying the decay pathway in some way, the γ_1 spectrum was essentially flat and featureless. Specifying for such coincident events that $E_{\gamma_0} > 15$ MeV, allows us to examine the feeding of the first few excited states (see Fig. 14). Despite the fact that the threshold for the BGO detectors was set too high to allow observation of the 1368-keV γ ray, there is good agreement between simulation and data for the 2754- and 4238-keV γ rays.

Although overall agreement between simulation and data is reasonable, there are some discrepancies such as the excess of counts at around 14–16 MeV in the simulated γ_0 spectrum (see Fig. 13), which would be associated with direct feeding of states with an excitation energy of around 4–6 MeV in ^{24}Mg. There are several states in this particular region, the 4^+ state in the ground-state band at 4124 keV; the 2^+, 3^+, and 4^+ states in the $K = 2$ band at 4238, 5235, and 6010 keV, respectively; and an excited 0^+ state at 6433 keV. There is not a unique way to achieve consistency with the measured γ_0 spectrum. One way is to adjust the flux to all of the states in this energy region down by a factor of 3 to 4. A second way is to completely remove feeding of the states in the $K = 2$ band. The effect of these two different adjustments is essentially the same and we cannot distinguish these possibilities through comparison with the data. Clearly, the second possibility is the more interesting and perhaps, physically more justifiable because the states

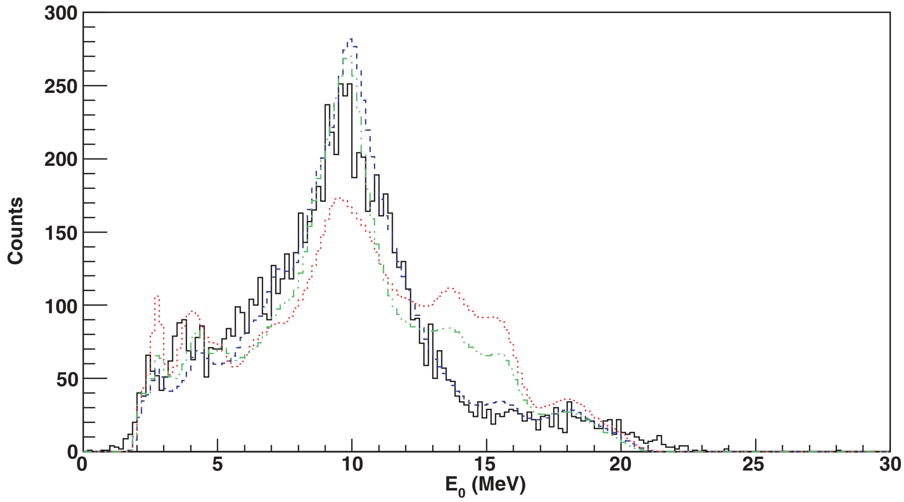

FIG. 13. (Color online) Comparison of simulated γ_0 spectra with the experimental spectrum for $E_{\text{c.m.}} = 6.0$ MeV. The red dotted line is a simulation including only $E2$ transitions and assuming that the resonance has $J = 2$. The green dot-dashed line is for both $E2$ and isovector $M1$ transitions, assuming $J = 2$. The blue dashed line has the same assumptions but the decay branchings have been adjusted to improve agreement, in the manner described in the text

involved have a similar intrinsic structure. We note that, by contrast, a strong enhancement of these same states in the $K = 2$ band was observed in a Gammasphere study around $E_{\text{c.m.}} = 8.0$ MeV [11]. We will return to this observation later.

There is also a discrepancy in the region around 12 MeV and 7–8 MeV between the experimental and simulated γ_0 spectrum. This might represent additional feeding of states around 7–8 MeV in ^{24}Mg that is not accounted for by a statistical $E2$ strength distribution. The states involved are the 2^+ states at 7349 and 8655 keV, the 1^+ state at 7748 keV, and the 4^+ state at 8439 keV, which is the bandhead of a $K = 4$ rotational band. The agreement with the experimental γ_0 spectrum can be improved by increasing the flux that reaches these states by a factor of ~ 2.5 each. However, we can achieve the same effect by increasing the flux to any one of the four states in this region by a larger amount, e.g., the branching to the 2^+ state at 8655 keV by a factor of 7. With the present resolution, it is not possible to distinguish whether a single state is responsible. We note that isospin mixing may be important in this region. The 4^+ state at 8439 keV has notably large isospin mixing due to the proximity of the 4^+ $T = 1$ antianalog state at 9516 keV [29]. Moreover, the decay branching to the 1^+ state at 7748 keV must be very sensitive to isospin mixing as the difference between isoscalar and isovector $M1$ strength should be a factor of 300 for a 12-MeV $M1$ transition feeding this level from the entry resonance.

The *ad hoc* variations of the decay branching described above lead to very much improved agreement with the data for the γ_0 spectrum (see Fig. 13). In general, the agreement between simulation and the experimental γ_1 spectrum also improves. It does not make much difference which of the possible adjustments discussed above is chosen. For the sake of argument, we show a comparison between experiment and simulation where we made general adjustments that reduce or increase the flux to a region of states rather than those that affect individual states (see Fig. 15).

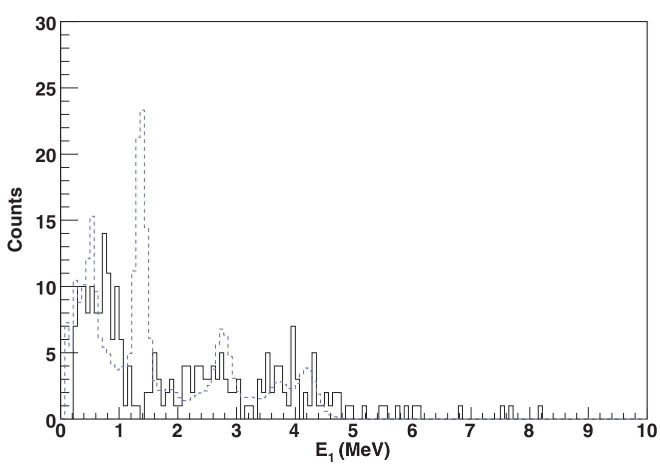

FIG. 14. (Color online) Comparison of simulated γ_1 spectrum (blue, dashed) with the experimental spectrum from the $E_{\text{c.m.}} = 6.0$ MeV data for coincident events where $E_{\gamma_0} > 15.0$ MeV. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 2$.

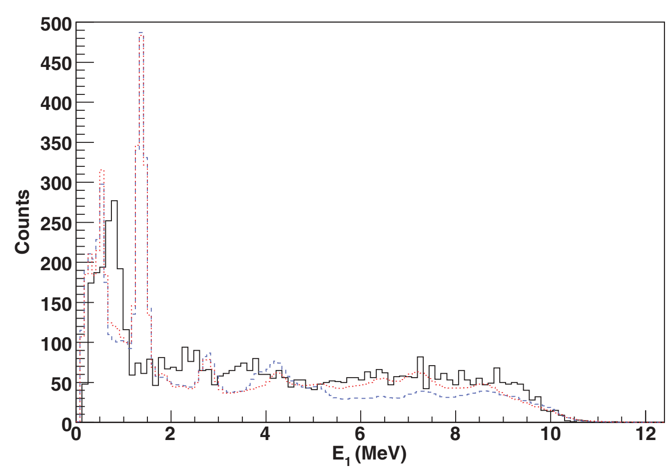

FIG. 15. (Color online) Comparison of simulated γ_1 spectrum with the experimental spectrum for $E_{\text{c.m.}} = 6.0$ MeV. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 2$. The simulation is shown both before (blue, dashed) and after (red, dotted) the decay branchings have been adjusted to improve the agreement (see text).

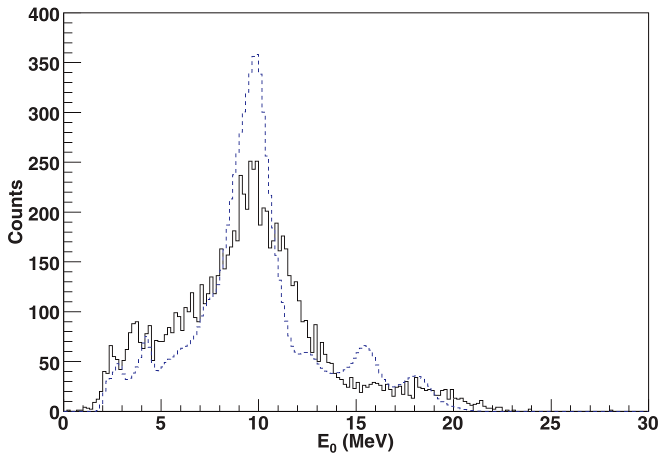

FIG. 16. (Color online) Comparison of simulated γ_0 spectrum (blue, dashed) with the experimental spectrum from the $E_{\text{c.m.}} = 6.0$ MeV data. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 0$.

Another way in which we can achieve a qualitative reproduction of the experimental γ_0 spectrum is by assuming that the resonance has $J = 0$ (see Fig. 16). Clearly such an approach would need some justification because we then have to account separately for the ground-state decay branch observed previously [1,2] and also observed in the present data, as well as the direct feeding of the 4^+ state observed in the γ_1 spectrum (Fig. 14). Both of these would need at least some $J = 2$ component to also be present. Nevertheless, we have performed a simulation assuming $J = 0$ for the resonance and adding in separately a ground-state transition. In general, the agreement with data is not so different qualitatively from the simulation assuming $J = 2$ aside from the need to add in a ground-state transition and the apparent overestimate of the contribution from states around 10 MeV, i.e., the $T = 1$ states. As with the $J = 2$ simulation, it is still necessary to increase the feeding of states around 8 MeV to improve the agreement with the data.

A third possibility would be for the resonance to have $J = 4$ but in this case the simulated spectrum is very different because the $1^+, T = 1$, states cannot be reached and so the simulation would not reproduce the strong component in the γ_0 spectrum around 10 MeV that is seen in the data. Moreover, the ground-state decay branch would again have to be added in by hand. We discuss the $J = 4$ possibility in detail for the $E_{\text{c.m.}} = 7.5$ and 8.0 MeV resonances below.

In summary, we can reproduce the experimental γ_0 spectrum only if we assume $J = 2$ or $J = 0$ for the resonance, whereas the presence of the $4^+ \rightarrow 2^+$ transition in the γ_1 spectrum for coincident events where $E_{\gamma_0} > 15.0$ MeV, makes it difficult to justify a $J = 0$ assignment to the resonance and $J = 2$ is much preferred (see Fig. 14). The low resolution of the BGO detectors, however, obscures the role individual high-lying states may play in the capture process. We are unable to evaluate the total capture cross section in an absolute manner because the beam dose and dead-time in the experiment were not accurately recorded. We can, however, obtain an approximate value for the total cross section by employing the measured cross sections obtained by Nathan *et al.* [1,2]. In a sense, the total cross section obtained in this manner represents a lower limit on the total capture cross section because we are unable to account for capture to unbound states that subsequently particle decay as we are looking at γ rays in coincidence with ^{24}Mg residues. It is also necessary to make some assumptions about the spin of the resonance and the reliability of the simulation. The summed cross section for capture to the ground and first three excited states as measured by Nathan *et al.* for the $E_{\text{c.m.}} = 6.0$ MeV resonance is ~ 700 nb [2]. Simulations carried out in the present work that have been adjusted to produce the best fit to the experimental data indicate that the part of the cross section measured by Nathan *et al.* is only $\sim 50\%$ of the total cross section $\sigma \sim 1.4\mu$b. The most recent compilation of the ^{12}C+^{12}C fusion cross section gives a total cross section of ~ 80 mb at the relevant bombarding energy [32]. This implies that $\Gamma_\gamma / \Gamma \approx 1.75 \times 10^{-5}$.

B. $E_{\text{c.m.}} = 6.8$ MeV resonance

Given the broad similarity in the γ_0 spectrum associated with the $E_{\text{c.m.}} = 6.0$ MeV and $E_{\text{c.m.}} = 6.8$ MeV resonance, a similar decay mechanism must be involved. We have therefore also simulated this resonance under the assumptions of $J = 0$ and $J = 2$ (see Fig. 17). Arguably, better agreement is found for $J = 2$ but in either case, some fine tuning of decay probabilities would be needed to completely fit the features of the experimental γ_0 spectrum. Such modifications are broadly similar to those described above for the $E_{\text{c.m.}} = 6.0$ MeV resonance, i.e., attenuation of the direct feeding of states between 4 and 6 MeV and enhanced feeding of states around 8 MeV.

As in the case of the $E_{\text{c.m.}} = 6.0$ MeV data, the γ_1 spectrum shows a prominent peak corresponding to the 2754-keV $4^+ \rightarrow 2^+$ transition (see Fig. 18), although it should be noted that

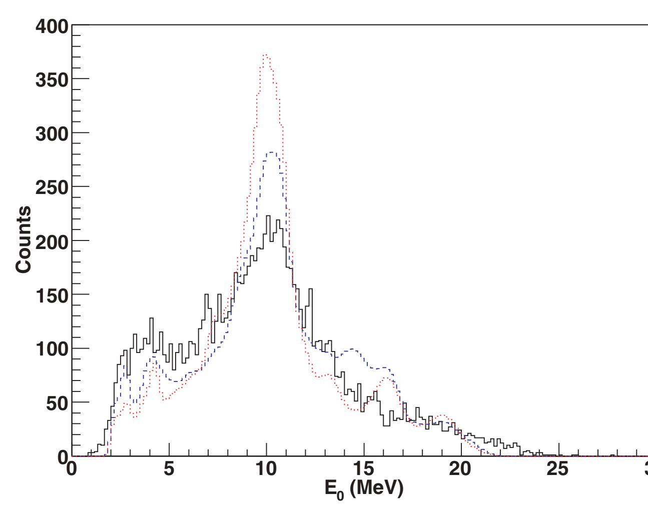

FIG. 17. (Color online) Comparison of simulated γ_0 spectra with the experimental spectrum for the $E_{\text{c.m.}} = 6.8$ MeV resonance. The simulations include both $E2$ and isovector $M1$ transitions and assume that the resonance has $J = 0$ (red, dotted) and $J = 2$ (blue, dashed).

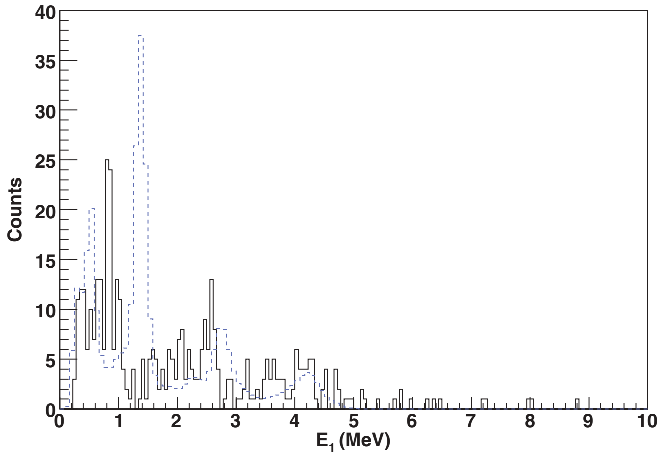

FIG. 18. (Color online) Comparison of simulated γ_1 spectra (blue, dashed) with the experimental spectrum for the $E_{\mathrm{c.m.}} = 6.8$ MeV resonance for coincident events where $E_{\gamma_0} > 15.8$ MeV. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 2$.

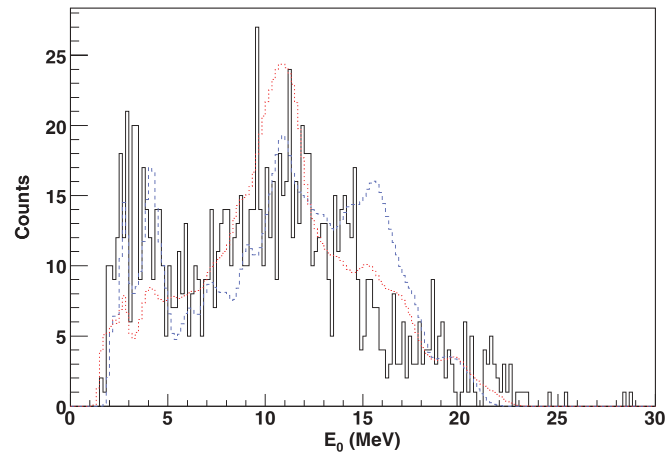

FIG. 19. (Color online) Comparison of simulated γ_0 spectrum with the experimental spectrum for the $E_{\mathrm{c.m.}} = 7.5$ MeV data. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 2$ (red, dotted) or $J = 4$ (blue, dashed).

some slight gain shift makes this peak appear a little lower in energy ~200 keV than it should. The 4^+ state could not be fed directly from a $J = 0$ resonance. It is unsurprising therefore that a simulation assuming $J = 2$ is best able to reproduce the experimental γ_1 spectrum (Fig. 18).

Although simulation prefers a $J = 2$ assignment to the $E_{\mathrm{c.m.}} = 6.8$ MeV resonance, we cannot discount the possibility of a dominant $J = 0$ resonance at a similar energy to an underlying $J = 2$ resonance that can explain some of the decay branchings such as the ground-state decay. The $J = 2$ part could come from some contribution from the nearby $E_{\mathrm{c.m.}} = 6.64$ MeV quasimolecular resonance that has a width of ~100 keV and $J = 2$ [2]. The $J = 0$ possibility is particularly relevant for this resonance energy when the early results on the electrofission of ^{24}Mg into ^{12}C+^{12}C are considered [1,9]. In general, resonances in the electrofission data are at very similar locations to the prominent resonances in radiative capture. The $E_{\mathrm{c.m.}} = 6.0$ and 8.0 MeV electrofission resonances were found to be primarily 2^+ states, whereas the $E_{\mathrm{c.m.}} = 6.8$ MeV electrofission resonance was predominantly 0^+. The latter has a particularly characteristic angular distribution. This energy also corresponds to the location of much of the giant monopole resonance strength in ^{24}Mg as measured in α scattering [40]. Clearly, some caution must be employed in relating the electrofission results to that observed in radiative capture because it is only the true time-reverse process when capture to the ground state is considered. Nevertheless, there should be some consistency between the two sets of measurements. The present work cannot unfortunately cast too much light on this speculation. In principle, it would have been straightforward to distinguish the cases from the highly characteristic angular distributions of the primary γ rays. In practice, this has not been possible due to the very limited sensitivity to angular distribution due to the design of the γ detector array. A separate possibility for resolving this discrepancy would be to search for a putative part of the capture process that proceeds by $E0$ transitions—the only allowed mechanism for $0^+ \rightarrow 0^+$ decays. At the high energies involved, such decays would proceed almost completely by internal pair transitions. This process would be somewhat analagous to the triple-α capture reaction via the excited 0^+ "Hoyle" state in ^{12}C.

C. $E_{\mathrm{c.m.}} = 7.5$ MeV resonance

Although the statistics obtained for this resonance were rather limited, it is still clear that the γ_0 spectrum for the $E_{\mathrm{c.m.}} = 7.5$ MeV resonance is differs from that seen for the nearby $E_{\mathrm{c.m.}} = 6.8$ MeV resonance. In particular, the pronounced peak in the γ_0 spectrum around 10 MeV is largely absent. This discrepancy is highlighted when a comparison is made with the expected γ_0 distribution for a simulation which assumes $J = 2$ for the resonance (see Fig. 19). If the resonance were $J = 4$, however, then it would not be possible to directly connect the resonance with the $T = 1, 1^+$ and 2^+ states via isovector $M1$ transitions. This seems a readily allowable possibilty as direct capture to the ground state did not appear to resonate at this bombarding energy in earlier measurements [1,2]. A simulation has been performed under the assumption of $J = 4$ for the resonance and it would appear to reproduce the γ_0 spectrum in the region of 10–12 MeV, but a significant discrepancy appears around 15–17 MeV. This implies that the simulation greatly overestimates the direct feeding of states between 5 and 7 MeV in ^{24}Mg such as the 3^+ and 4^+ states in the $K = 2$ band at 5235 and 6010 keV, respectively. This effect appears to be a common problem in comparing simulations with data at all energies.

It is necessary to exercise a little caution in the interpretation of this resonance as our data is somewhat limited but it is appropriate at this point to compare with the results of heavy-ion induced breakup reactions of the type ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C. A large series of breakup states has been observed in this reaction at excitation energies from around 20 to 50 MeV [10,33,34]. Angular distribution measurements for the fragments have been measured and spins assigned to many of the breakup states [10]. It has been argued that these phenomena are related to the other well-known property of the ^{12}C$-^{12}$C system, namely the quasimolecular resonances in the total reaction cross section [33].

Fulton *et al.* showed that there are a number of breakup states with $J = 4$ between 21 and 23 MeV in ^{24}Mg [10]. Curtis *et al.* remeasured these states with higher resolution and further showed their correspondence with the known quasimolecular resonances [33]. The broad (220-keV wide) $J = 4$ breakup state at 21.2 MeV and narrow (100-keV wide) $J = 4$ state at 21.6 MeV [33], which correspond to $E_{\text{c.m.}}$ energies of 7.3 and 7.7 MeV, respectively, would provide a seemingly good correspondence with the broad capture resonance observed by Nathan *et al.* [2]. It would also fit very well with the $J = 4$ assignment preferred by the present work—a possibility not seriously considered previously.

D. $E_{\text{c.m.}} = 8.0$ MeV resonance

The γ_0 spectrum for the $E_{\text{c.m.}} = 8.0$ MeV resonance is more similar to that for the $E_{\text{c.m.}} = 7.5$ MeV resonance than the lower energy resonances. Indeed, a simulation assuming $J = 2$ gives a correspondingly poor fit to the experimental data (see Fig. 20).

In common with the $E_{\text{c.m.}} = 7.5$ MeV resonance, therefore, we have also investigated a possible $J = 4$ assignment to the resonance. This is not quite as straightforward because a prominent ground-state capture transition was observed for the $E_{\text{c.m.}} = 8.0$ MeV resonance in earlier work. Nevertheless, the $J = 4$ assumption has been tested through simulation and found to provide a reasonable description of the experimental γ_0 spectrum (see Fig. 20). If we accept this J assignment then, as in the case of other resonances discussed above, it would still be necessary to introduce a $J = 2$ resonant component to account for the known resonance in capture to the ground state of ^{24}Mg at this energy observed by Nathan *et al.* [2]. To account for the observations, the centroid of these two

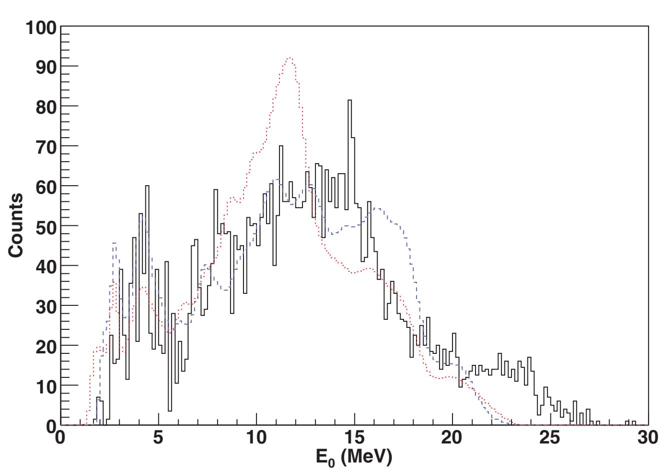

FIG. 20. (Color online) Comparison of simulated γ_0 spectrum with the experimental spectrum for the $E_{\text{c.m.}} = 8.0$ MeV data. The simulation includes both $E2$ and isovector $M1$ transitions and assumes that the resonance has $J = 2$ (red, dotted) or $J = 4$ (blue, dashed).

resonances with different spins would have to be very close in energy. We suggest that this may simply be the result of an accidental degeneracy. Comparison with the results of electrofission and heavy-ion induced breakup of ^{24}Mg tends to support this possibility. In the former case, it is favorable to fission only through $C0$ or $C2(E2)$ virtual photon excitation and so this technique is sensitive to 0^+ and 2^+ strength. The electrofission results show that there is a peak in the 2^+ strength distribution at an excitation energy of around 22 MeV in ^{24}Mg that corresponds to the $E_{\text{c.m.}} = 8.0$ MeV capture resonance [1]. By contrast, the prominent breakup states in this region have $J = 4$ [10,33]. The high-resolution measurement of the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction by Curtis *et al.* [33] reveals the presence of a series of closely spaced states each with $J = 4$ and width around 100 keV, although with varying strength, with excitation energies of 21.6, 21.8, 22.0, and 22.2 MeV ($E_{\text{c.m.}} = 7.5$–8.3 MeV). The most prominent such state is that at 22.0 MeV ($E_{\text{c.m.}} = 8.1$ MeV). It is therefore tempting to associate part of the resonant phenomenon in radiative capture at $E_{\text{c.m.}} = 8.0$ MeV with the breakup state(s). The combination of the $J = 2$ and $J = 4$ parts would explain the present and early [2] radiative capture data. Moreover, this would be in agreement with a measurement of quasimolecular resonances in ^{12}C+^{12}C that indicated the presence of both a $J = 2$ and $J = 4$ resonance at this energy [35]. We therefore achieve at least a circumstantial correspondence between the radiative capture and electrofission data and the more general phenomenon of quasimolecular resonances. We note that, in their review of fission in light nuclei, Fulton and Rae [36] have earlier tried to draw out this potential correspondence among breakup, electrofission, and the rather limited data on fission of ^{24}Mg induced by inelastic excitation with α particles [37] and protons [38].

It is appropriate at this point to review the present results in comparison to the earlier measurements of the capture cross section at this energy made with the FMA and the decay branch studies made with Gammasphere [11]. In the light of the discussion above, it is perhaps unfortunate that these earlier studies were made around $E_{\text{c.m}} = 8.0$ MeV, as the likely presence of more than one resonance introduces an undesirable element of complication. This has to be combined with the inherent difficulty of interpreting the Gammasphere data that were obtained using a sum-energy trigger to select capture events for which the efficiency varied on an event-by-event basis [11]. One of the puzzling aspects of the Gammasphere data was the strong fluctuation in the relative population of the $K = 2$ rotational band in ^{24}Mg as a function of beam energy. Indeed, at a center-of-target energy of $E_{\text{c.m.}} = 8.05$ MeV, the $K = 2$ rotational band appeared strongly enhanced relative to the ground-state rotational band. This enhancement was not seen at a center-of-target energy of $E_{\text{c.m.}} = 7.95$ MeV. The experimental conditions of the present measurement are very similar to this latter situation with a target of nearly identical thickness and a center-of-target energy of $E_{\text{c.m.}} = 7.97$ MeV. Consistency is therefore observed between the two sets of measurements in that enhancement of the decay to the $K = 2$ rotational band is not observed. Further work is clearly needed to re-examine the origin of the enhancement of the $K = 2$ band in the Gammasphere experiment. What the present

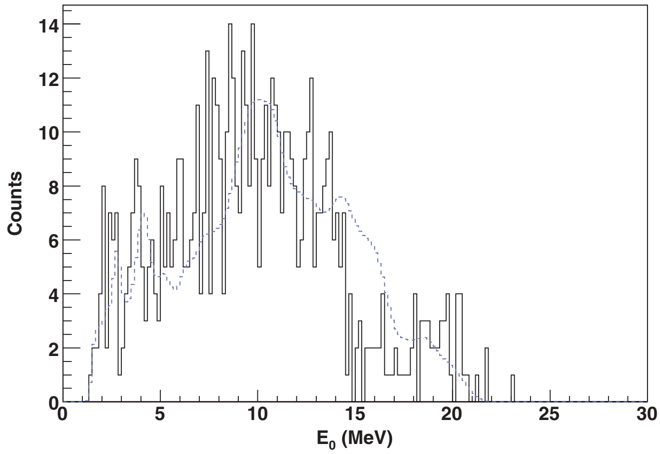

FIG. 21. (Color online) Comparison of simulated γ_0 spectrum (blue, dashed) with the experimental spectrum for the $E_{\text{c.m.}} =$ 6.4 MeV "off-resonance" data. The simulation includes only statistical $E2$ transitions and assumes that the resonance has $J = 2$.

work does show, however, is that there is at least one $J = 4$ capture resonance around $E_{\text{c.m.}} = 8.0$ MeV, whereas this resonance was previously believed to be exclusively $J = 2$. A natural way to obtain a favoritism for the $K = 2$ band, therefore, would be to have a resonance with $J = 4$ and $K = 4$ because transitions to the $K = 0$ ground-state band would then be K-forbidden. Although K might not be expected to be a good quantum number at such high excitation energies, we point out that there is good evidence for a $K = 2 J = 2$ electrofission resonance in ^{28}Si [1]. The angular distribution of fragments very clearly demonstrates that the state is excited by $E2$ excitation and therefore must have $K = 2$, breaking up into ^{12}C(2^+)-^{16}O [1,39].

E. Off-resonance: $E_{\text{c.m}} = 6.4$ MeV

According to earlier work, the data taken at $E_{\text{c.m.}} =$ 6.4 MeV should correspond to an off-resonance position [1,2]. The presumed mechanism for "off-resonance" capture would be coupling to the giant resonances. In the case of the giant quadrupole resonance this is straightforward because it lies at an appropriate energy. Youngblood *et al.* have measured the isoscalar $E2$ strength using inelastic α scattering and find that it lies at an energy of 16.9(6) MeV and has a width of 3.4(5) MeV [40]. By contrast, the isovector giant magnetic dipole resonance is concentrated in the 1^+ analog states around 10 MeV in ^{24}Mg [41,42]. This would imply that because the radiative capture considered in the present work takes place in the excitation region of 20–25 MeV, there is essentially no isovector $M1$ strength to couple to. We have therefore carried out a simulation assuming $J = 2$ but included only $E2$ statistical γ rays and we have not included the strong isovector $M1$ component (see Fig. 21). The assumption of $J = 2$ for the background is essentially arbitrary. The agreement with experimental data for γ_0, however, is encouraging.

F. Conclusions

The intention of the present work was to investigate whether radiative capture in the ^{12}C(^{12}C,γ) took place to high-lying states in ^{24}Mg and whether that process was statistical in nature. By examining the γ branching, we hoped to be able to assign spin/parities to the observed resonances. The intention was also to set the radiative capture process in the context of related processes such as electrofission and breakup reactions, as well as the more general phenomenon of quasimolecular resonances.

The present work has shown that, indeed, radiative capture takes place to high-lying excited states in ^{24}Mg at all of the resonance energies considered. In the early work of Nathan *et al.*, it was concluded that resonances in the ^{12}C(^{12}C,γ) radiative capture reaction represented strong evidence for a connection between the ^{12}C+^{12}C system and the fused ^{24}Mg nucleus [1,2]. The present work allows us to strengthen these conclusions, because we can show a connection with bound states up to 10 MeV or higher in ^{24}Mg. Moreover, the present work has shown features that could not have been examined in earlier studies such as the importance of the $T = 1$ analog states in ^{24}Mg for radiative capture in the case of the $E_{\text{c.m}} = 6.0$ and 6.8 MeV resonances.

The present measurement, when compared with Monte Carlo simulations, has allowed the spin of the radiative capture resonances to be established. For the lower-energy resonances at $E_{\text{c.m}} = 6.0$ and 6.8 MeV, the data are best reproduced for $J = 0$ or $J = 2$, with a preference for the latter assignment. At higher energies, the present data when compared with simulation suggests the dominant $J = 4$ character of the resonances at $E_{\text{c.m.}} = 7.5$ and 8.0 MeV.

As part of this work, we wanted to address the issue of the statistical character of the radiative capture process. Evidence for nonstatistial behavior had earlier been observed around $E_{\text{c.m.}} = 8.0$ MeV in a measurement with Gammasphere [11]. The present work finds this behavior to be ubiquitous to the resonances considered, and this feature has only emerged due to the ability to correlate with ^{24}Mg residues at the focal plane of DRAGON. The feeding of two regions is found to be notably different to statistical expectations. The region around 4–6 MeV where members of the $K = 2$ rotational band are situated is found to be fed less than would be expected, whereas the region around 8 MeV appears to be more strongly fed than implied by a statistical simulation. Unfortunately, the low resolution of the present measurement does not allow us to determine whether it is individual states that generate these deviations in a similar way to the notable role played by the excited 0^+ state in the ^{12}C(^{16}O,γ) reaction [3]. To resolve this issue, a further measurement where a high-resolution germanium detector array is coupled to a recoil separator is clearly warranted to sensitively identify the states responsible.

Last, let us review what the present work reveals about the connection between radiative capture and related processes such as electrofission, breakup reactions, and the general phenomenon of quasimolecular resonances. Certainly, the assignment of $J = 4$ to the radiative capture resonances at $E_{\text{c.m.}} = 7.5$ and 8.0 MeV suggests a connection with break-up states in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction that have also been assigned $J = 4$ and lie at a very similar excitation energy in ^{24}Mg [10]. This suggests also a possible connection to the quasimolecular resonances because the breakup states have been shown, qualitatively at least, to line up with known quasimolecular resonances [33]. It should be noted that in their earlier studies of ^{12}C(^{12}C,γ), Nathan *et al.* claimed that the radiative capture resonances did not appear to line up with the known quasimolecular resonances [2], although this interpretation was later disputed by Dechant and Kuhlmann, who studied radiative capture at energies closer to $E_{\text{c.m.}} = 5.0$ MeV [6]. Whether the capture resonances do indeed line up with quasimolecular resonances appears to remain an open question but if they do, in fact, correspond to the quasimolecular resonances, then it can only be with a subset of them as the capture resonances appear much fewer in number. Although a more coherent picture emerges in the present work of the connection among electrofission, breakup, and radiative capture, there is as yet not a fully comprehensive understanding of how these issues inter-relate. Clearly, the early capture measurements were sensitive only to transitions to the lowest states in ^{24}Mg that would not allow high spin capture resonances to be observed [2]. Extending the correspondence between capture resonances and breakup states to states with $J > 4$ would be a worthwhile objective for future work as it would strengthen the connection among these different pheonomena.

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