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High-resolution spectroscopy of decay pathways in the $^{12}C(^{12}C,\gamma)$ reaction

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The decay branchings of a resonance in the $^{12}C(^{12}C,\gamma)^{24}Mg$ reaction at $E_{c.m.} = 8.0$ MeV have been studied with high resolution using the Gammasphere array. Radiative capture residues were discriminated from scattered beam and the dominant evaporation channels using the fragment mass analyzer coupled to a multistage Parallel Grid Avalanche Counter (PGAC)/ion chamber system. The clean selection of residues has allowed the population of excited states up to 10 MeV in ^{24}Mg to be examined in detail. Strong feeding of an excited $K^{\pi} = 0^{-}$ band is observed. A $J^{\pi} = 4^{+}$ assignment to the resonance is strongly favored.

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I. INTRODUCTION

With the advent of heavy-ion accelerators in the 1950s, the scattering and fusion of heavy projectiles like ^{12}C nuclei began to be investigated. The surprise at that time was the presence of strongly resonant phenomena for elastic and inelastic scattering of $^{12}C + ^{12}C$ [1]. The origin of these so-called quasimolecular resonances was attributed to the formation of short-lived molecular configurations of two ^{12}C nuclei. This has important consequences in nuclear astrophysics because the quasimolecular resonances in the $^{12}C + ^{12}C$ fusion cross section persist to the lowest observed energies, which makes it very difficult to reliably extrapolate to the Gamow window for realistic astrophysical scenarios [2].

Over the last 50 years, a comprehensive picture of clustering phenomena has evolved, based on the exceptional stability of the α particle and other nuclei such as ^{12}C (see the recent review by Freer [3]). Indeed, theoretical work on this topic continues to develop, and technical breakthroughs in computational techniques such as antisymmetrized molecular dynamics (AMD) have led to rich and detailed calculations of clustering phenomena. A good example of such AMD calculations would be the recent detailed theoretical description of the excited states of ^{28}Si in terms of $^{12}C + ^{16}O$ and $^{24}Mg + \alpha$ clustering by Taniguchi *et al.* [4]. In a sense, such theoretical descriptions are now far ahead of the experimental data; the latter largely deriving from reaction studies. It is in this context that heavy-ion radiative capture (HIRC) is of interest because it provides a direct connection between cluster resonances in α-conjugate nuclei and normal states. In the case of ^{8}Be, the cluster resonances, in fact, correspond to the low-lying states and electromagnetic transitions between candidate cluster states can therefore be directly extracted via the $^{4}He(^{4}He,\gamma)$ reaction. Datar *et al.* [5] have studied this reaction and were able to extract the $B(E2)$ strength for the $4^{+} \rightarrow 2^{+}$ transition, which could be compared with both α-cluster and *ab initio* structure calculations. Aside from the particular case of ^{8}Be, HIRC resonances, in general, lie at very high energy and while HIRC can afford an insightful link between capture resonances and low-lying states, studying this mechanism is challenging, as the cross sections involved are small and competition from particle evaporation channels is overwhelming.

Sandorfi *et al.* [6,7] investigated the $^{12}C(^{12}C,\gamma)^{24}Mg$ reaction at Brookhaven National Laboratory in the early 1980s, using a single large sodium iodide detector to detect the capture γ rays. Observation of capture to high-lying states was precluded by the pile-up of γ rays from particle-evaporation channels in the single detector used, allowing the observation of capture only to the ground state and the first few excited states of ^{24}Mg. Nevertheless, it was possible to observe a series of 100- to 300-keV-wide resonances in these different channels [6]. Such resonances do not have obvious counterparts in the well-measured $^{12}C + ^{12}C$ fusion cross section [8], and the presence of the capture resonances was attributed to a new kind of intermediate structure comprising the coupling of the ^{12}C-^{12}C entrance channel to the giant quadrupole resonance strength in ^{24}Mg [6]. While small variations are seen between

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the strength of different channels, it was not clear whether radiative capture proceeds in a largely statistical way to low-lying states in ^{24}Mg or whether the very strong deformation of the entry resonance (^{12}C-^{12}C dumbbell) favors preferential decay to highly deformed states at high energy in ^{24}Mg. Such a mechanism is not unprecedented. For example, Collins *et al.* [9] studied the ^{12}C(^{16}O,γ)^{28}Si reaction and found that the capture reaction proceeded preferentially to the excited prolate band in ^{28}Si rather than to the oblate ground-state band. This was attributed to the structural similarity between the capture state and the excited prolate band. While no such behavior has thus far been seen in the ^{12}C(^{12}C,γ)^{24}Mg reaction, theory supports the existence of high-lying, highly deformed bands which could, in principle, be favorably populated in the decay of the resonance.

There have been extensive attempts to describe the excited states and rotational bands in ^{24}Mg within various models involving ^{12}C + ^{12}C clustering [10–13] and α + Ne clustering [14]. Some of the more elaborated models are those presented by Baye and Descouvemont [11] who used the generator coordinate method (GCM) to calculate the properties of molecular bands in ^{24}Mg using the microscopic ^{12}C + ^{12}C interaction of Baye and Pecher [10]. In particular, they showed that two excited bands are expected—one in the ^{12}C + ^{12}C Coulomb barrier region and a second one intermediate between the ground-state band [11] and the Coulomb-barrier band; the latter may correspond to a "superdeformed" band to use the terminology of later theoretical descriptions. Baye and Descouvemont [11] further calculated transition rates within these bands and between the bands. If we identify the capture resonances with the excited band close to the ^{12}C + ^{12}C Coulomb barrier in the GCM model, then the decay branching of a such a capture resonance can be estimated. This is presented in Fig. 1 for a capture resonance corresponding to an excitation energy of 20 MeV in ^{24}Mg, under two different scenarios where $J^{\pi} = 2^{+}$ or $J^{\pi} = 4^{+}$ is assigned to the resonance. The GCM model implies a similar feeding of the "superdeformed" band relative to the ground-state band due to a cancellation between the relative transition strengths and phase-space factor (E_{γ}^{5}). The superdeformed band is not presently known experimentally, and if it lies above the particle thresholds, then depending on the structure of the band, the γ branch of its component states may be small, although there are many states in the α-unbound region between 10 and 12 MeV, which Vermeer *et al.* [15] have shown to be decaying via γ-ray emission close to 100% of the time.

Over the last decade, the topic of HIRC has been reopened with a series of measurements at Argonne National Laboratory (ANL) and TRIUMF. Measurements with the fragment mass analyzer (FMA) at ANL were carried out to determine the total cross section for radiative capture around $E_{\text{c.m.}} = 8.0$ MeV [16] and to show that it greatly exceeded that inferred from the initial measurements of Sandorfi *et al.* [6]. A parallel experiment made with the Gammasphere array investigated the capture pathways [16]. Channel selection was achieved by exploiting the very high Q value for radiative capture to define a window in sum energy where capture events could be cleanly selected. Some selectivity for population of the $K = 2$ band in ^{24}Mg in the capture process was observed but the statistics were limited due to the inefficient channel selection. To obtain high statistics for heavy-ion radiative capture, an experiment was subsequently performed with the DRAGON recoil separator at TRIUMF and its associated array of BGO detectors [17]. The fundamental limitation of the DRAGON measurements, aside from the poor energy resolution for capture γ rays, was that the angular acceptance of DRAGON is designed to be very small to be compatible with (p,γ) reactions in inverse kinematics, and so not all HIRC residues were accepted. This led to the need to carry out a detailed simulation of the response of the full apparatus using GEANT3 to interpret the results that were obtained. Despite these difficulties, some unexpected features of the HIRC process were found, such as that for $E_{\text{c.m.}} = 6.0$ and 6.7 MeV, where a large component of the radiative capture took place through $T = 1$ states around 10 MeV in ^{24}Mg, via strong isovector $M1$ transitions which prove to be a more dominant decay branch than $E2$ transitions. The capture process in this respect is somewhat analogous to Gamow-Teller β decay.

A review of the previous techniques applied to the study of the ^{12}C(^{12}C,γ) reaction suggested that the key features needed in any future study would be robust channel selection with no bias toward any class of residues, allied to a high-energy resolution for detection of capture γ rays. The goal of

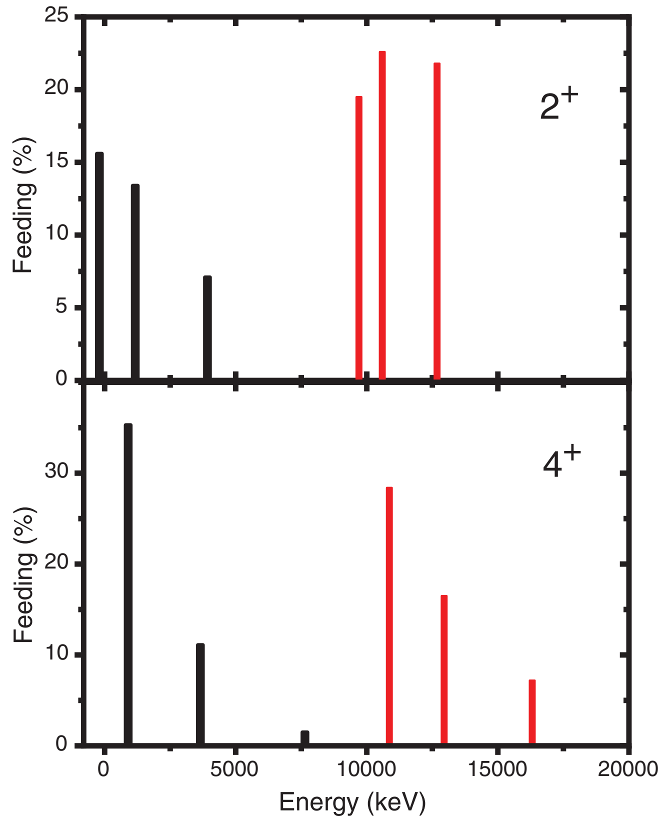

FIG. 1. (Color online) Feeding pattern from the decay of radiative capture resonances as suggested by the generator coordinate method calculations of Baye and Descouvemount [11]. The decay branches are evaluated under the assumption that the capture resonance lies at 20 MeV, for the two cases of a $J^{\pi} = 2^{+}$ resonance (top) and a $J^{\pi} = 4^{+}$ resonance (bottom).

the present experiment was to obtain high statistics for the capture process with high-energy resolution by focusing on one specific capture resonance.

II. EXPERIMENT AND RESULTS

A beam of ^{12}C was accelerated to 16 MeV by the ATLAS accelerator at ANL and incident on a 60-μg/cm^2-thick target of enriched ^{12}C. The target position was surrounded by the Gammasphere array of 100 hyperpure germanium detectors, which was used to detect the resulting γ-ray emission. Each detector comprises a germanium crystal and a contiguous BGO suppression shield and backplug. In the present experiment, suppression was not actively applied and energy was read out both from the germanium crystal and the BGO shield. The germanium crystal was read out with a full energy range of 10 MeV. Hevimet shields were fitted to the front of the individual detectors which effectively forced the first interaction to be in the germanium crystal.

Fusion residues entered the FMA where they were separated from scattered beam and dispersed according to A/q. At the focal plane of the FMA was a multistep ion chamber/Parallel Grid Avalanche Counter (PGAC) system [18] illustrated in Fig. 2. By producing a two-dimensional (2D) spectrum of the energy loss (ΔE) versus the time of flight (ToF) through each of the two transmission ionization chambers (TICs) it was possible to unambiguously identify the ^{24}Mg reaction products despite the overwhelming dominance of the particle evaporation channels. Figure 3(a) shows ΔE_1, the energy loss in the first TIC versus the ToF between the first and second PGACs (ToF$_{12}$). A 2D window was applied to this spectrum and this was used to generate a gated spectrum for the second TIC. Figure 3(b) provides ΔE_2, the energy loss in the second TIC versus the ToF between the second and third PGACs (ToF$_{23}$), gated by the 2D window from the first chamber. Residues were selected when they passed 2D windows on both of the ion-chamber spectra.

Gamma-ray spectra were generated for Compton-suppressed events correlated with ^{24}Mg residues (see Figs. 4 and 5). Some leak-through is observed from contaminant channels. For example, the 440-keV transition, which is the $5/2^+ \rightarrow 3/2^+$ transition in the strongest contaminant, ^{23}Na, appears with an intensity about 40% that of the 1368-keV $2^+ \rightarrow 0^+$ transition in ^{24}Mg. A 1634-keV peak corresponding to the $2^+ \rightarrow 0^+$ transition in ^{20}Ne is also observed with a similar intensity to the 440-keV line and has a large width attributable to the recoil kick due to the evaporation of α particles. The cross section for each of the reaction channels leading to ^{23}Na and ^{20}Ne is around 200 mb [8]. This implies that these contaminants are suppressed by around 5 orders of magnitude relative to the radiative capture channel. It is straightforward to discriminate contaminant lines from those associated with ^{24}Mg because the decay schemes for ^{24}Mg and the nuclei produced via particle-evaporation channels, ^{20}Ne, ^{23}Na, and ^{23}Mg, are all extremely well known.

The γ-ray singles data (see Fig. 5) were analyzed to produce Table I. In addition, γ-γ matrices were generated with the appropriate residue selection. The γ-γ data were extremely limited. They largely served to confirm the assignments already made from singles data. For example, a clear coincidence is seen between the 3123- and 3866-keV transitions (see Fig. 6). Some further transitions were observed in coincidence windows that were not readily seen in the singles data. For example, a coincidence of two counts was found between the 2754-keV transition and a 4316-keV one that would correspond to the minor decay branch from the 8439-keV state, already shown to be populated from its main decay branch via the 7069-keV transition to the first 2^+ state. Evidence was also seen for additional decay pathways not obvious in the singles data. A coincidence of three counts was seen between the 4641-keV transition and a 4571-keV γ-ray that could correspond to the decay of the known $(3,4)^+$ state at 10 581 keV in ^{24}Mg. This branch, however, only carries 10% of the decay of that state and we were not able to obtain clear evidence for the more dominant branches of this state.

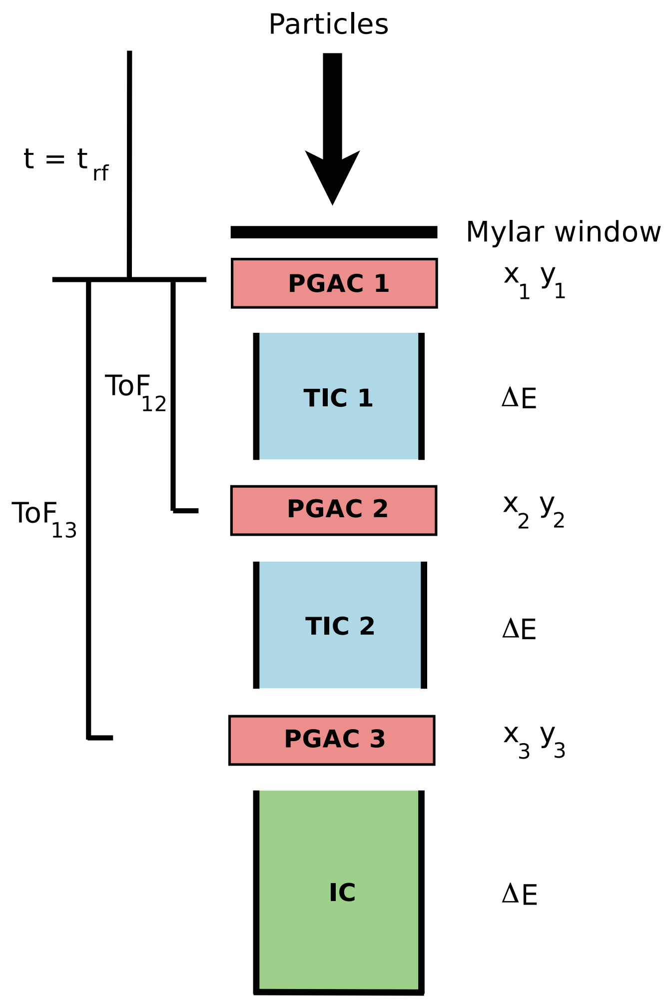

FIG. 2. (Color online) Focal plane detection system used in the present study [18]. Residues are rigorously discriminated through a set of multiple PGACs and ion chambers. The time-of-flight parameters used in the analysis are indicated.

The detection efficiency of the Gammasphere drops off rapidly as a function of energy (see efficiency curve in Fig. 4). To enhance statistics and search for potential high-energy

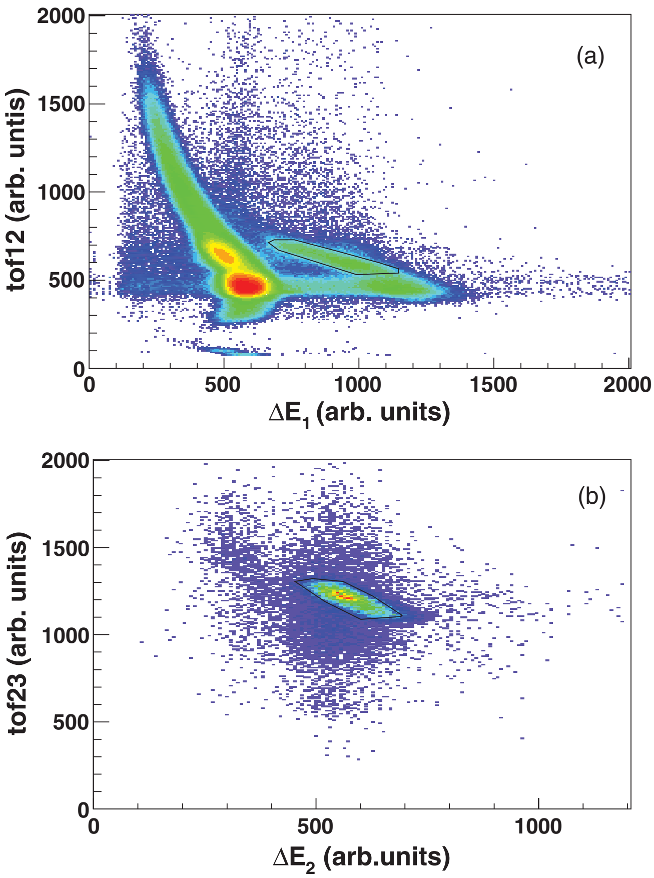

FIG. 3. (Color online) Spectra used to discriminate ^{24}Mg capture residues. (a) Plot of the time-of-flight between the first and second PGACs against the energy loss (ΔE_1) through the first transmission ion chamber (TIC1). (b) Plot of the time-of-flight between the second and third PGACs against the energy loss (ΔE_2) through the second transmission ion chamber (TIC2). The two-dimensional locus in each plot, bounded by the black line, is the region associated with ^{24}Mg residues accepted in the analysis.

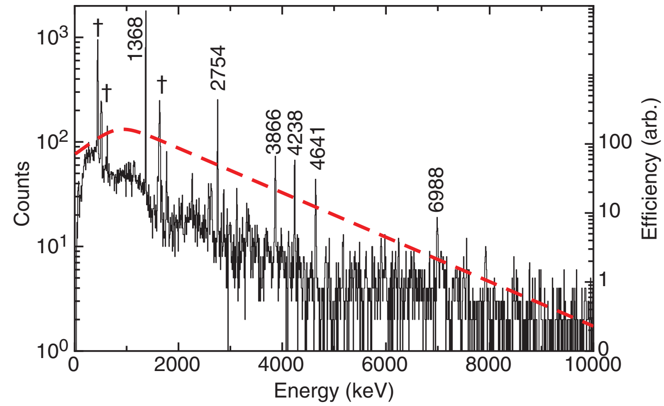

FIG. 4. (Color online) Gamma-ray spectra in coincidence with HIRC residues. Prominent transitions associated with ^{24}Mg are marked with their energy in keV, while principal contaminant lines associated with ^{20}Ne, ^{23}Na, or ^{23}Mg are marked with daggers. The red dashed curve indicates the relative detection efficiency of the Gammasphere array.

transitions, an add-back spectrum was generated for events where the BGO shield also recorded a signal (see Fig. 7). In this spectrum, high-energy γ rays such as the 6988-keV line are enhanced as pair production dominates at high energies. Unfortunately, this analysis did not reveal the presence of any additional high-energy γ rays which were not observed in the suppressed germanium spectrum. The γ-ray singles spectra and coincidence matrices were analyzed to construct a level scheme representing the population of states in ^{24}Mg following radiative capture (see Fig. 8).

III. DISCUSSION

Because the entrance channel involves the fusion of two identical bosons, the available spin/parities are even and positive. All of the states observed to be fed in the reaction could be reached by a single direct transition from a resonance with $J^\pi = 2^+$ or 4^+, if we allow transitions up to multipolarity order $E3$. In practice, we expect $E3$ to be rather hindered with respect to other multipolarities, and given that we see the population of a 5^- state at 10 028 keV, while seeing no obvious population of known 0^+, 1^+, 1^-, and 2^- states below 10 MeV, a preference for a $J^\pi = 4^+$ resonance can be drawn. We cannot observe direct feeding of the ground state in our measurement, but a resonance in this channel has been observed previously by Sandorfi *et al.* [6] around $E_{\text{c.m.}} = 8.0$ MeV. It is not clear how to reconcile this fact with the present measurement which does not favor $J^\pi = 2^+$ for the capture resonance, unless there are multiple or overlapping resonances. It should be noted that the DRAGON measurements did not lead to an unambiguous assignment to the resonance at this energy either [17]. Setting aside these issues, there is a further feature of the present data that affords a strong argument in favor of a $J^\pi = 4^+$ assignment to the capture resonance. This argument relates to the complete absence of strong isovector $M1$ transitions feeding $T = 1$ and 1^+ states around 10 MeV in ^{24}Mg. Such transitions completely dominate the radiative capture spectra obtained for the $E_{\text{c.m.}} = 6.0$ and 6.8 MeV resonances in the earlier experiments with DRAGON [17]. It was only possible to simulate this dominant component through the assumption of $J^\pi = 2^+$ for those resonances. If in the present case, the resonance has $J^\pi = 4^+$, then strong feeding via an isovector $M1$ transition might be anticipated for the 4^+, $T = 1$ state at 9516 keV, which is the analog of the ^{24}Al ground state. A single-particle isovector $M1$ transition to that state would be very fast; seven times faster than the equivalent-energy $E2$ transition. Such an $M1/(E2)$ transition is not observed above background (<0.8% of 1368-keV intensity), but there appear to be good reasons for this that are consistent with earlier work. In their study of the β decay of ^{24}Al, Warburton *et al.* [19] show that the reduced transition probability of the 9516-keV level to the first 2^+ state at 1368 keV has $B(E2) < 1.7 \times 10^{-4}$ W.u., which greatly exceeds any suppression expected for $\Delta T = 1$. This observation is interpreted as reflecting a large change in K for such a γ decay; i.e., $\Delta K = 4$, which would wipe out the transition strength owing to the K-selection rules that dictate a hindrance of $10^{2(\Delta K - \lambda)}$, where λ is the multipolarity. Taken together with nuclear structure considerations, Warburton *et al.*

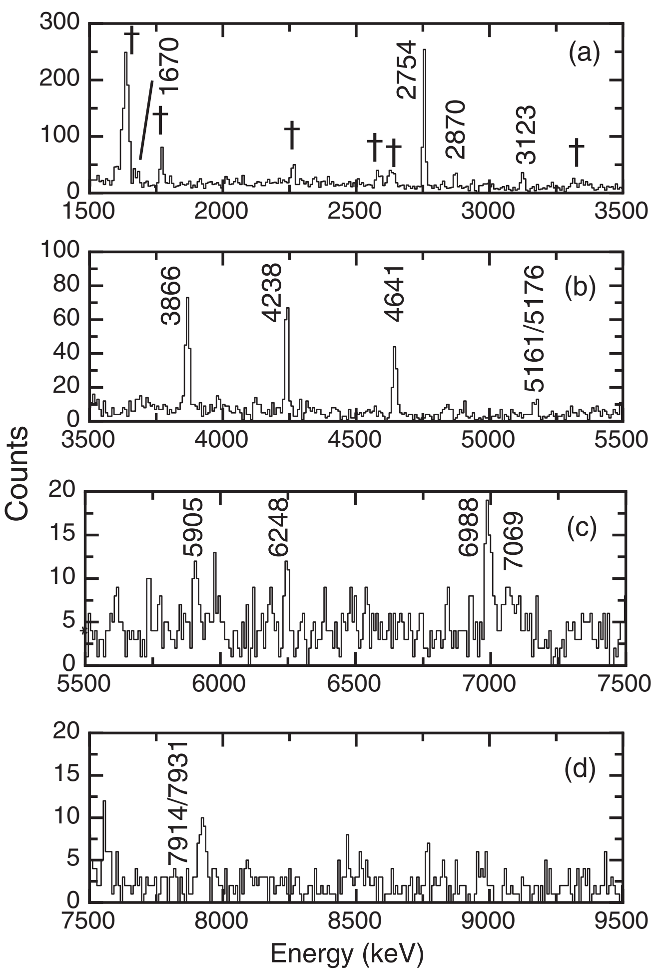

FIG. 5. Expanded γ-ray spectra in coincidence with HIRC residues. The four panels show successive portions of the total spectrum (a) from 1500 to 3500 keV, (b) from 3500 to 5500 keV, (c) from 5500 to 7500 keV, and (d) from 7500 to 9500 keV. Transitions associated with ^{24}Mg are indicated with their energy. Principal contaminant lines associated with ^{23}Na and ^{20}Ne are marked with daggers.

[19] assign the 9516-keV state as the bandhead of a $K = 4$, $T = 1$ band. The absence of a strong $M1$ transition from a $J^{\pi} = 4^+$ capture resonance to the 9516-keV state is, therefore, a natural consequence of the K-selection rules if the resonance has $K = 0$, as expected, and K is a good quantum number at this high excitation energy. While we do not observe feeding of the 9516-keV state, we do observe feeding of the 4^+ state at 8439 keV. This state was assigned by Warburton *et al.* [19] as $K = 4$, $T = 0$, and, so, similar arguments should apply as for the 9516-keV state because $\Delta K = 4$. As discussed by Warburton *et al.* [19], however, extensive mixing is observed between the 8439- and 9300-keV states; the latter being a $K = 0$ state. This mixing mitigates the hindrance expected from strict K-selection criteria.

To deduce the feeding pattern, cascade feeding was subtracted for individual states to provide a measure of the direct feeding. To get the true feeding, the feeding of each state was corrected for the additional (and often unobserved) decay

TABLE I. Energy, assignment, and intensity of γ rays observed in the γ-ray singles spectrum. Intensities are normalised to 100% for the 1368-keV transition.

Transition energy (keV)	Assignment	Intensity (%)
1368	$2_1^+ \to 0_1^+$	100
1670	$5_1^- \to 3_1^-$	1.6(4)
2346	$3_2^- \to 4_2^+$	3.1(6)
2754	$4_1^+ \to 2_1^+$	22(1)
2870	$2_2^+ \to 2_1^+$	2.6(6)
3123	$3_2^- \to 3_1^+$	4.5(10)
3866	$3_1^+ \to 2_1^+$	12.0(8)
4238	$2_2^+ \to 0_1^+$	11.0(7)
4641	$4_2^+ \to 2_1^+$	8.4(6)
5161/5176	$(2,3,4) \to 4_1^+$	2.4(4)
5905	$5_1^- \to 4_1^+$	2.7(3)
6248	$3_1^- \to 2_1^+$	2.3(3)
6988	$3_2^- \to 2_1^+$	6.0(4)
7069	$4_3^+ \to 2_1^+$	3.5(4)
7914/7931	$(2,3,4) \to 2_1^+$	4.0(4)
8963	$(3^-) \to 2_1^+$	1.5(3)

branches of the state using tabulated data [20]. The procedure where cascade feeding is subtracted should be reasonable, but in the case that there are small feeding pathways hidden in the background—a concern particularly for the feeding of the first 2^+ state—then these will not be accounted for and the direct feeding thereby will be artificially inflated. Naturally, any direct feeding of the ground state cannot be accounted for either. A further concern is whether some portion of the radiative capture proceeds to unbound states in ^{24}Mg. The present measurement is not sensitive to such branches due to the way that the residues are selected. As shown by Vermeer *et al.* [15], the majority of states above the α threshold and below 11 MeV are predominantly γ-decaying—indeed, the γ branch has been measured to be above 95% for both the 10 028- and 10 332-keV states observed in the present study [15]. Even above 11 MeV, there are many states that are almost 100% γ-decaying.

Accepting the caveats discussed above, the feeding pattern, normalized to sum to 100%, is presented in Fig. 9. The feeding of individual states appears to follow a largely statistical dependence. Most of the states are reached by $E2$ transitions for which the observed decay branching is in good conformity with the expected dependence for statistical feeding in the case

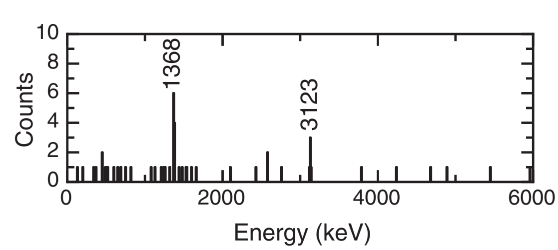

FIG. 6. Spectrum of γ rays in coincidence with the 3866-keV transition for events where HIRC residues were identified at the focal plane. Transitions in ^{24}Mg are indicated with their energy in keV.

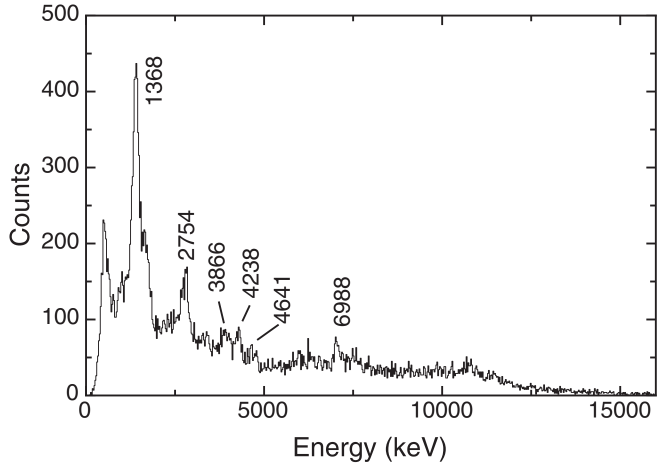

FIG. 7. Add-back spectrum correlated with HIRC residues.

of $E2$ transitions (E_γ^5) originating from a capture resonance. It is instructive to compare the present measurement with earlier measurements of the same reaction with Gammasphere but which used a sum-energy selection to identify the capture channel [16]. These earlier measurements explored two beam energies corresponding to center-of-target energies, $E_{\rm cot} = 15.9$ and 16.1 MeV. The former energy most closely corresponds to the present measurement for which $E_{\rm cot} =$ 15.85 MeV. Indeed, there are common features in the γ-ray spectrum such as a strong peak around 7 MeV. The earlier measurement gave some hints of transitions around 10 MeV but these do not appear in the present work. It is not clear if this is instrumental in origin because the selection technique is different and a sum-energy selection may favor events with

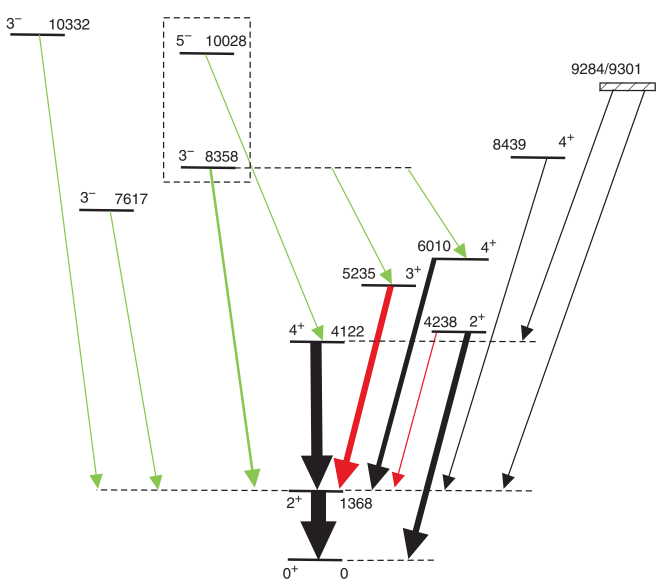

FIG. 8. (Color online) Level scheme of states in ^{24}Mg populated in the ^{12}C(^{12}C,γ) reaction. The width of the arrows is proportional to the intensity of the observed γ rays. $E1$ transitions are shown in green, $M1/E2$ transitions in red, and $E2$ transitions in black. The hashed region contains at least two states populated in the reaction (see text). The excited $K^\pi = 0^-$ band is marked with the dashed box.

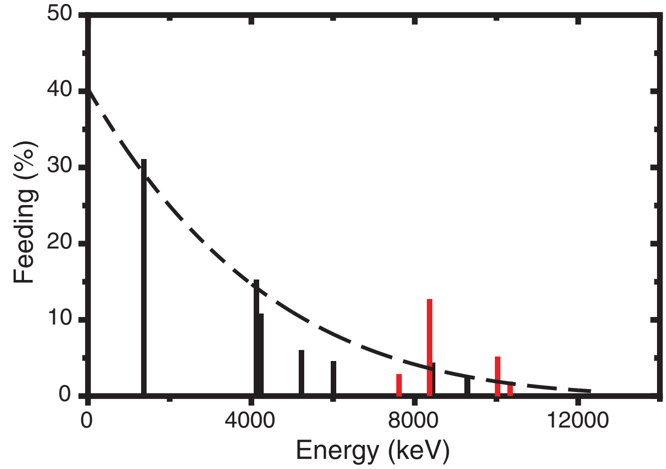

FIG. 9. (Color online) The relative feeding of excited states in ^{24}Mg following heavy-ion radiative capture; cascade feeding has been subtracted where observed (see text for details). Negative parity states are in red. The dashed curve, with arbitrary scaling, corresponds to phase space (E_γ^5) for $E2$ transitions originating from a capture resonance at 21.9 MeV.

higher energy γ rays. A clear weakness of the earlier work in comparison to the present study is the inability to determine the efficiency of different decay pathways because it would require an *a priori* knowledge of which pathways were present. Accepting this deficiency, the population of low-lying states in the earlier work seems, qualitatively speaking, to exhibit a broadly statistical distribution. Indeed this becomes clearer when compared to the data taken at the higher energy of $E_{\rm cot} = 16.1$ MeV in the earlier measurement [16], where relatively strong transitions of 4641 and 4315 keV were observed in the radiative capture spectrum, which correspond to the decay of the 4^+ states in the $K = 2$ and $K = 4$ bands, respectively. In the light of the discussion above in relation to observance of K selection in the present measurement, this may point to the presence of a resonance at $E_{\rm cot} = 16.1$ MeV, which has a higher K value such as $K = 2$ or $K = 4$. One could speculate that this could arise from inelastic excitation of the ^{12}C nuclei in the entrance channel, e.g., to the 2^+ state at 4.43 MeV. Clearly, further work would be needed to elaborate on these speculations.

A striking feature of the feeding pattern (Fig. 9) determined in the present work is the strong population of the 3^- state at 8358 keV and the 5^- level at 10 028 keV, amounting to a total of ~18% of the feeding intensity. These states were identified as members of a $K^\pi = 0^-$ band by Branford *et al.* [21] on the basis of the strong $E2$ transition connecting the two states; this assignment was subsequently reinforced through measurements by Fifield *et al.* [22]. In addition, we see weaker population of a 3^- state at 7617 keV and a state at 10 332 keV whose spin/parity is not defined in the tabulations [20]; the former state is suggested by Branford *et al.* [21] to be the bandhead of a $K^\pi = 3^-$ band, and the latter is speculated by Fifield *et al.* [22] to be the 3^- member of a $K^\pi = 1^-$ band whose bandhead is the 1^- state at 8438 keV. Assuming that the entrance resonance has even spin and positive parity, then it follows that negative-parity states can only be reached via

TABLE II. Properties of the lowest negative-parity states in ^{24}Mg caclulated within the $1\hbar\omega$ PSDPF shell model space. The components of the wave functions are given as a fraction relating to a hole in the 1p shell, and the promotion of a particle to the fp shell.

J^π	E_{ex} (exp.) (keV)	E_{ex} (calc.) (keV)	p^{-1} (%)	fp (%)
3_1^-	7617	6852	0.94	0.06
3_2^-	8358	8507	0.60	0.40
5_1^-	10 028	9495	0.06	0.94

E1, M2, or E3 transitions. The latter two possibilities may quickly be discounted since the transition strength needed would exceed the recommended upper limits by orders of magnitude. If we assume that the transition from the capture resonance to the 1368-keV, 2^+ state has a strength of 1 W.u., then the partial γ-ray half-life of the resonance is 1.2×10^{-16} s (which corresponds to a γ width of 5.4 eV). Under these assumptions, the $E1$ decays to the 7617-, 8358-, 10 028-, and 10 332-keV states are 2.1×10^{-4}, 1.1×10^{-3}, 6.7×10^{-4}, and 2.6×10^{-4} W.u., respectively. At first glance, the fact that these transitions are relatively strong is surprising, because ^{24}Mg is a self-conjugate nucleus. In such nuclei, there should be no matrix element for isoscalar $E1$ transitions and they can only appear through isospin mixing. Lawergren [23] has shown, however, that the known isospin-forbidden and isospin-allowed $E1$ transitions in ^{24}Mg, in fact, have similar strengths, in the 10^{-3}–10^{-4} W.u. range. The presence of the $E1$ transitions as a strong component of the feeding pattern in the present work is, therefore, not completely unexpected.

It is notable that the feeding of the 3^- and 5^- states in the $K^\pi = 0^-$ band is enhanced 3–5 times relative to the other 3^- states observed. An open question is whether this enhancement is structural in origin. Kato and Bando [24] find in their cluster calculations that the $K^\pi = 0^-$ band corresponds to the parity doublet of the ground-state band. As discussed by Butler and Nazarewicz [25] in their review of octupole phenomena in nuclei, there are similar predictions of low-lying $K^\pi = 0^-$ bands in many light α-conjugate nuclei. Branford *et al.* [21] note that while the candidate $K^\pi = 3^-$ band has a similar moment-of-inertia to the ground-state band, the moment-of-inertia of their candidate $K^\pi = 0^-$ band is more than double that of the ground-state band. This would imply that the $K^\pi = 0^-$ band is associated with a large deformation. It should also be noted in this context that because the 7617-keV, 3^- state is supposed to be the bandhead of a $K^\pi = 3^-$ band, this should lead to a strong hindrance in its population via an $E1$ transition from the capture resonance, in the same manner as discussed above for the $K = 4$, 4^+ state at 9516 keV. The K-selection rules imply that such a 3^- state should not be directly populated in the present work, and this implies either that the $K^\pi = 3^-$ proposition is incorrect or that there is appreciable mixing between the 3^- states at 7617 and 8358 keV.

In their transfer-reaction study, Tribble *et al.* [26] showed that the lowest 3^- state in ^{24}Mg had a structure mostly related to a hole in the 1p shell, while the second 3^- state appeared to be better explained as a particle-hole excitation into the fp shell. This observation seems to be borne out by $1\hbar\omega$ PSDPF shell model calculations, so-called because they include excitations in the p-, sd- and fp-shells [27], that were carried out in the present work to understand the structure of the lowest-lying negative-parity states in ^{24}Mg. The results of this calculation are presented in Table II. The lowest 3^- state is clearly associated with a 1p hole, while the first 5^- state is clearly associated with a particle in the fp shell. The second 3^- state is a mixture of these two configurations. Naturally, the model space is somewhat restricted and, in a deformed nucleus, the 1p-1h configurations might also be expected to have significant 3p-3h components. It is interesting that in a two-center shell model study of the ^{12}C + ^{12}C system, Chandra and Mosel [28] pointed to a major component for configuration for the molecular resonances of 4p-4h. Again, such configurations would be expected to have 2p-2h components as well. Favored decay between these particle-hole excitations might, therefore, be anticipated in comparison to a decay to the configurations based on a 1p shell hole. This could explain the favored decay to the second 3^- and first 5^- states.

IV. CONCLUSION

In conclusion, the ^{12}C(^{12}C,γ)^{24}Mg reaction has been studied at $E_{c.m.} = 8.0$ MeV. Stringent channel selection was achieved using the FMA and a multiple PGAC/ion chamber system. This allowed the capture process to be explored in detail and with high resolution using the Gammasphere array for detection of capture γ rays. In general, the capture process appears to be statistical in nature. Some exceptions are noted, including the strong feeding of an excited $K^\pi = 0^-$ band. The origin of this enhanced feeding could be related to the particle-hole structure of this band as suggested by $1\hbar\omega$ PSDPF shell model calculations. A unique assignment of $J^\pi = 4^+$ to the capture resonance at $E_{c.m.} = 8.0$ MeV is strongly favored.

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[1] K. A. Erb, and D. A. Bromley, in *Treatise in Heavy-ion Science*, edited by D. Allan Bromley (Plenum, New York, 1984), Vol. 3, Sec. 3, and references therein.

[2] Randall L. Cooper, Andrew W. Steiner, and Edward F. Brown, Astrophys. J. **702**, 660 (2009).

[3] M. Freer, Rep. Prog. Phys. **70**, 2149 (2007).

[4] Y. Taniguchi, Y. Kanada-En'yo, and M. Kimura, Phys. Rev. C **80**, 044316 (2009).
[5] V. M. Datar, S. Kumar, D. R. Chakrabarty, V. Nanal, E. T. Mirgule, A. Mitra, and H. H. Oza, Phys. Rev. Lett. **94**, 122502 (2005).
[6] A. M. Nathan, A. M. Sandorfi, and T. J. Bowles, Phys. Rev. C **24**, 932 (1981).
[7] A. M. Sandorfi, *Treatise in Heavy-ion Science*, edited by D. Allan Bromley (Plenum, New York, 1984), Vol. 2, Sec. 2, and references therein.
[8] K. A. Erb *et al*., Phys. Rev. C **22**, 507 (1980).
[9] M. T. Collins, A. M. Sandorfi, D. H. Hoffmann, and M. K. Salomaa, Phys. Rev. Lett. **49**, 1553 (1982).
[10] D. Baye and N. Pecher, Nucl. Phys. A **379**, 330 (1982).
[11] D. Baye and P. Descouvemount, Nucl. Phys. A **419**, 397 (1984).
[12] B. Buck, P. D. B. Hopkins, and A. C. Merchant, Nucl. Phys. A **513**, 75 (1990).
[13] R. A. Baldock and B. Buck, J. Phys. G **12**, L29 (1985).
[14] D. Baye and P. Descouvemont, Nucl. Phys. A **475**, 219 (1987).
[15] W. J. Vermeer, D. M. Pringle, and I. F. Wright, Nucl. Phys. A **485**, 380 (1988).
[16] D. G. Jenkins *et al*., Phys. Rev. C **71**, 041301 (2005).
[17] D. G. Jenkins *et al*., Phys. Rev. C **76**, 044310 (2007).
[18] C. L. Jiang *et al*., Nucl. Instrum. Methods Phys. Res., Sect. A **554**, 500 (2005).
[19] E. K. Warburton, C. J. Lister, D. E. Alburger, and J. W. Olness, Phys. Rev. C **23**, 1242 (1981).
[20] P. M. Endt, Nucl. Phys. A **633**, 1 (1998); **521**, 1 (1990); R. Firestone, Nucl. Data Sheets **108**, 2319 (2007).
[21] D. Branford, N. Gardner, and I. F. Wright, Phys. Lett. B **36**, 456 (1971).
[22] L. K. Fifield *et al*., Nucl. Phys. A **322**, 1 (1979).
[23] B. Lawergren, Nucl. Phys. A **111**, 652 (1968).
[24] K. Kato and H. Bando, Prog. Theor. Phys. **62**, 644 (1979).
[25] P. A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1996).
[26] R. E. Tribble, G. T. Garvey, and J. R. Comfort, Phys. Lett. B **44**, 366 (1973).
[27] M. Bouhelal, F. Haas, E. Caurier, F. Nowacki, and A. Bouldjedri, Acta Phys. Pol. B **40**, 639 (2009); Eur. Phys. J. A **42**, 529 (2009).
[28] H. Chandra and U. Mosel, Nucl. Phys. A **298**, 151 (1978).