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Doorway states as a principal decay pathway 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 beam energies around 16 MeV. Two different experiments were performed. Capture cross sections were obtained by measuring fused ^{24}Mg residues and were found to significantly exceed values reported earlier. Subsequently, the decay pathways associated with radiative capture were delineated using the Gammasphere array. A substantial fraction of the decay was found to proceed through a few high-lying doorway states near 10 MeV in excitation.

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Radiative capture—the complete fusion of beam and target nuclei with subsequent cooling solely by γ-ray emission—is a common and well-understood process for light nuclei such as protons and α particles. Indeed, radiative capture reactions are important for nucleosynthesis in astrophysical objects such as novae and x-ray bursters, in which heavier nuclei are synthesised by the rapid-proton capture (rp) process, which proceeds principally by (p,γ) reactions, followed by β decay. In contrast, the process of radiative capture between heavy ions is far less well understood. The high mutual Coulomb barrier between ions suppresses fusion and the very high excitation in the compound system leads to strong competition from particle emission.

Sandorfi has reviewed the possible mechanisms for heavy-ion radiative capture (HIRC) [1]. The radiative cooling can arise from giant resonance enhancement of γ widths, may involve structural enhancement through wave-function overlap in doorway states, or can involve trapping near the yrast line leading to the suppression of other mechanisms. Each process has a different excitation energy, structure, and mass dependence, so the various contributions are not easily predicted. The $^{12}C(^{12}C,\gamma)$ [2–4], $^{12}C(^{16}O,\gamma)$ [5], and $^{90}Zr(^{90}Zr,\gamma)$ [6] systems have been the most extensively investigated. In their study of $^{12}C+^{12}C$ radiative capture, Sandorfi and Nathan used a single large NaI detector to observe high-energy capture γ rays to low-lying states in the fused system ^{24}Mg. They found that the fusion cross section was strongly resonant, with peak cross sections for capture to individual excited states of the order of 20 nb/sr [2]. The observation of high-energy γ rays was attributed to a coupling to the giant quadrupole resonance strength in ^{24}Mg. Because a single NaI detector had been used, it was necessary to avoid the piling up of low-energy γ rays from particle emission channels in the detector, and only the observation of the very highest energy γ rays to low-lying excited states in ^{24}Mg was possible. This was unfortunate because it did not allow the total radiative capture to be deduced nor was it possible to establish whether there might also be higher multiplicity decays passing through high-lying ($E_x > 5$ MeV) states in ^{24}Mg. In this Rapid Communication, we report two separate experiments: one to directly ascertain the total radiative fusion cross section by counting ^{24}Mg residues and a second study to investigate the pathways of radiative cooling. If the capture resonance is associated with a ^{12}C-^{12}C nuclear molecule, and the capture proceeds to low-lying states, it is interesting to investigate whether the cooling relaxes through a few "doorway" states or through a more conventional statistical process involving many levels. If a doorway mechanism is important, then the best candidates would presumably be the highly deformed states predicted by a variety of theoretical approaches [7,8] to lie around 10 MeV in excitation. Such states would have a good overlap with both the entry resonances and the ground state.

To determine whether the total capture cross-section was larger than that inferred from measurements of high-energy capture γ rays, an experiment was performed using the

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TABLE I. Total cross sections for ^{12}C(^{12}C,γ) from a series of runs detecting ^{24}Mg residues. The given energy range corresponds to the target thickness.

Target thickness (μg/cm^2)	$E_{\text{c.m.}}$ (MeV)	σ (μb)
99	7.66–7.90	3.8(3)
66	7.74–7.90	3.3(1)
52	7.77–7.90	2.0(1)
20	7.85–7.90	2.3(1)
14	7.87–7.90	3.0(2)

Fragment Mass Analyser (FMA) at Argonne National Laboratory (ANL) to detect ^{24}Mg residues following the ^{12}C(^{12}C,γ) reaction. We elected to investigate an energy region ($E_{\text{c.m.}} \sim$ 8 MeV) where resonant capture to low-lying states in ^{24}Mg had previously been reported [2]. This region also corresponds closely to the location of known $J = 4$ resonances in the breakup of ^{24}Mg into two ^{12}C nuclei [9]. To first order, the breakup and radiative capture reactions might be expected to be time inverse, and the relationship between these very different sets of experimental measurements provided another motivation for this project.

A ^{12}C beam accelerated to 15.8 MeV by the ATLAS accelerator at ANL was incident on thin self-supporting enriched ^{12}C foils with various thicknesses: 14, 20, 52, 66, and 99 μg/cm^2. The FMA was employed to separate fusion residues from the primary beam and to disperse them by mass/charge (M/q) at the focal plane. At the focal plane, the residues passed through a parallel-plate avalanche counter (PPAC) and into an ion chamber, containing isobutane at a pressure of 1.5 torr. They were subsequently implanted into a thick silicon detector. The higher energy loss of the fusion residues in the ion chamber gas allowed them to be cleanly discriminated from scattered beam particles in a plot of energy loss (ΔE) versus energy (E) deposited in the silicon detector. The FMA was set up to focus ^{24}Mg residues, produced via radiative capture, onto the center of the focal plane. The selected recoils had $A/q = 24/5$ and a recoil energy corresponding to half the center-of-target energy—as expected for the radiative capture channel. The 5^+ charge state was selected to avoid A/q ambiguities from the expected $A = 23$ (^{23}Mg and ^{23}Na) and $A = 20$ (^{20}Ne) residues. Under these conditions, residues with different values of A/q were found to be well separated at the focal plane because of the low masses involved. Unwanted residues from $A = 23$ nuclei were removed by closing physical slits at the focal plane. Because the FMA is isochronous, calibration of the energy and time of flight could be used to verify that the selected residues did correspond to $A = 24$; this identification being confirmed by the detection of the 1368-keV $2^+ \rightarrow 0^+$ ground-state transition in ^{24}Mg, in coincidence with the selected recoils, by a single germanium detector at the target position. Cross sections were derived on the basis of the expected FMA efficiency (see Table I).

The FMA has a large energy ($\pm$20%) and recoil cone acceptance ($\pm 3^\circ$). For events where the recoil effect of the emitted photon is maximal (i.e., a single 22-MeV γ ray emitted at 90° to the beam axis), the maximum corresponding recoil angle is 2.1°. Simulations using the code SRIM-2003 demonstrate that the probability of a recoil ion produced at the center of the target being scattered to an angle greater than 1° is less than 4%, even for the thickest carbon target (99 μg/cm^2) employed in this work. Similarly, the energy spread because of the possibility of the reaction taking place at any depth in the thickest target is $\pm$10%, whereas the spreading because of multiple scattering is nearly always less than 1%, according to SRIM-2003 calculations. These considerations taken together indicate that it is safe to assume that all radiative capture residues will fall well within both the angular and energy acceptance of the separator. The FMA efficiency should therefore be solely limited by the fraction of ions in the particular charge state transmitted to the focal plane. Simple parametrizations of the charge-state fraction [10] predict that 17% of residues have charge state 5^+ at this energy [10], in good agreement with data tabulated by Shima *et al.* [11]. Back *et al.* [12] have shown that the FMA transport efficiency is only 85% of the theoretical maximum and this has been taken into account along with losses associated with ions hitting the wire planes of the PPAC (2% per wire plane, i.e., 8% for four wire planes). The integrated charge for each run was corrected for dead-time losses.

The production of ^{24}Mg from contaminants in the target must be carefully considered. In the case of ^{13}C contamination, ^{24}Mg can be copiously produced in the ^{13}C(^{12}C,n) reaction. To investigate this possible extra souce of ^{24}Mg, we compared the yield of ^{24}Mg produced in our highly enriched (>99.9% ^{12}C) targets with a test experiment using a 73-μg/cm^2 ^{12,13}C target, enriched to >90% in ^{13}C and using exactly the same FMA settings. If the primary source of ^{24}Mg were ^{13}C contamination, then a very dramatic increase in ^{24}Mg residue yield would have been expected. In fact, after taking account of the difference in target composition and thickness, the yield was unchanged. Contamination of ^{16}O in the target is an issue, because carbon foils would be expected to have some low level of oxygen content arising from, for example, water adsorbed on the surface. Fortunately, the ^{16}O(^{12}C,α)^{24}Mg reaction has a large positive Q value (+6.77 MeV), leading to rather different kinematics as compared to the carbon-carbon radiative capture. The energy and angular acceptance of the FMA strongly suppresses most ^{24}Mg production from oxygen contamination, because off-axis emission of the α particles deflects the ^{24}Mg out of the separator acceptance, whereas on-axis emission produces ^{24}Mg ions with velocities higher or lower than those expected from radiative capture. Only one kinematic solution can produce ^{24}Mg ions which pass both the energy and angular acceptance of the separator. This solution involves the ^{24}Mg being excited to a narrow region of excitation energy around 14 MeV, with low-energy α particles being emitted at backward angles in the lab frame. This specific solution cannot be rigorously excluded on kinematic grounds though it represents a very small fraction of the total cross section. A careful inspection of data taken with the germanium detector at the target position was made to attempt to identify any γ rays from reactions involving ^{16}O, but none were found. The time dependence of ^{24}Mg production was also studied to determine whether there was an effect related to beam heating

of the target which might drive water vapor out of the target, but no time-dependent effect was found over many hours of running. Thus, all our systematic checks were consistent with the detected ^{24}Mg residues arising from ^{12}C-^{12}C radiative capture and not from contaminant reactions. This hypothesis is supported by the second experiment reported below, where calorimetric techniques were used to deduce a capture cross section.

Earlier measurements suggest that the total capture cross section to the first few excited states of ^{24}Mg peaks at 1.0(0.2) μb and varies strongly with energy [2]. The peak cross sections determined from the detection of ^{24}Mg residues, in the first part of this work, are considerably higher: >3 μb near $E_{\mathrm{c.m.}} = 7.9$ MeV, <1 μb near $E_{\mathrm{c.m.}} = 7.8$ MeV, and $>4\mu$b for $E_{\mathrm{c.m.}} \sim 7.7$ MeV (see Table I). This suggests that the "single-step" decays discovered in earlier work [2] represent a small part of the total radiative capture cross section near 16 MeV beam energy, that other mechanisms are playing a major role in the capture process, and that these processes also vary rapidly with beam energy.

To investigate the alternative mechanism and measure the cooling γ rays with good resolution, the Gammasphere spectrometer, comprising 100 Compton-suppressed, high-efficiency high-purity germanium (HPGe) detectors with almost complete angular coverage, was employed [13]. Because the Gammasphere array was situated at Lawrence Berkeley National Laboratory (LBNL), where no recoil mass spectrometer was available, it was necessary to devise a different methodology for selecting radiative capture events. The latter methodology exploited the high solid angle of Gammasphere to measure the total energy released as photons in the reaction. A "total energy" spectrum was formed from the energy signals from all 860 active germanium crystals and their contiguous bismuth germanate (BGO) suppression shield elements. This was used at the trigger level to dictate which events were stored for off-line analysis. A selection of $E_{\mathrm{tot}} > 12$ MeV suppressed the vast majority of particle emission events and prevented excessive ($>30\%$) dead time. A γ-ray multiplicity of two modules or greater was chosen. Because the Q value for the ^{12}C(^{12}C,γ) reaction is large and positive (+13.93 MeV), and greatly exceeds that associated with competing particle evaporation channels, the end point of the sum energy spectrum associated with the ^{12}C(^{12}C,γ) channel should be the highest end point in the spectrum. Selecting the highest sum energy events, therefore, allowed the radiative capture channel to be cleanly selected and subsequently deconvoluted into its constituent γ rays. This technique had the advantage that those events which passed the high energy-sum condition had, by construction, deposited almost the full energy of the radiative capture cascade somewhere in the Gammasphere array.

The γ-ray detection efficiency may be improved, albeit at the cost of energy resolution, by summing the energy recorded in the germanium detector with that measured in the surrounding BGO Compton-suppression shield. In practice, the reduction in energy resolution is tolerable. In the remainder of this discussion, we distinguish between "clean" modules where the suppression shield did not fire and "add-back" modules where the summing procedure was applied. Modules where only the BGO shield fired were not considered useful in the analysis of the decay pathways but were included in the construction of the γ-ray sum energy. Heavy-metal collimators were fitted to the front of each BGO shield to prevent direct illumination. This lowered the efficiency of the calorimetric sum-energy trigger, as at lowest order, all photons needed to first pass into germanium, which is 40% of the full 4π solid angle. Such an arrangment, however, greatly improved the response of the device, especially the "add-back" resolution, because it retained many events in which the majority of the energy deposition was in germanium, which has much superior energy resolution.

Gammasphere was optimized to detect radiation below 10 MeV, where its absolute photopeak efficiency falls to 1%. Unfortunately the analog electronics used in conjunction with the germanium and BGO components saturate at 16 and 10 MeV, respectively, so single photons of very high energy cannot be detected with useful efficiency. This prevented a direct remeasurement of the earlier observations of direct decays to the first few excited states in ^{24}Mg [2], which have energies around 20 MeV. The present work can only complement these earlier measurements by locating previously unobserved and higher multipicity cascades, which our cross-sectional data suggest comprise a substantial fraction of the total decay pathways.

To find the point of maximum capture yield, a limited excitation function was performed. A ^{12}C beam accelerated by the 88-in. cyclotron at LBNL was used to bombard a 47 μg/cm^2 enriched ^{12}C target. γ rays were detected by the Gammasphere array with a trigger condition of one module firing in coincidence with the beam. A peak in the capture yield, inferred from the number of recorded events with a sum energy above 12 MeV, was found for a center-of-target energy of 16.1 MeV, in qualitative agreement with the cross-sectional measurement made with the FMA, and in excellent agreement with the location of a large peak in the excitation function previously observed by Nathan *et al.*, for capture to the ground-state and first-, second-, and third-excited states [2]. Having located the point of maximum yield, the array was switched to a coincidence mode where three γ rays had to be detected in any event and at least two of these in a "clean" module. The beam current was increased to 100 pnA, and high statistics were obtained both for the point of maximum yield (16.1 MeV) and for an "off resonance" position (15.9 MeV). Good separation of radiative capture events and particle emission channels was observed in the sum energy spectrum (see Fig. 1), with a clear excess of counts at the high sum energies for cascades containing a 1368-keV γ ray, the $2^+ \rightarrow 0^+$ transition in ^{24}Mg. Moreover, the end point in the sum energy spectrum moved up and down in conformity with changes in beam energy (not shown).

In the subsequent analysis, events were selected with sum energies larger than 19 MeV (the end point is $\sim$22 MeV) and deconvoluted into their respective cascades. This restrictive selection was imposed to exclude possible contributions from any ^{24}Mg nuclei produced in other reactions, such as ^{13}C(^{12}C,n), which could produce events with a sum energy of up to 17 MeV. Employing the high sum energy condition, a total of 1279 cascades were obtained from the 16.1-MeV data, of which 156(12) contained a cleanly detected 1368-keV γ ray,

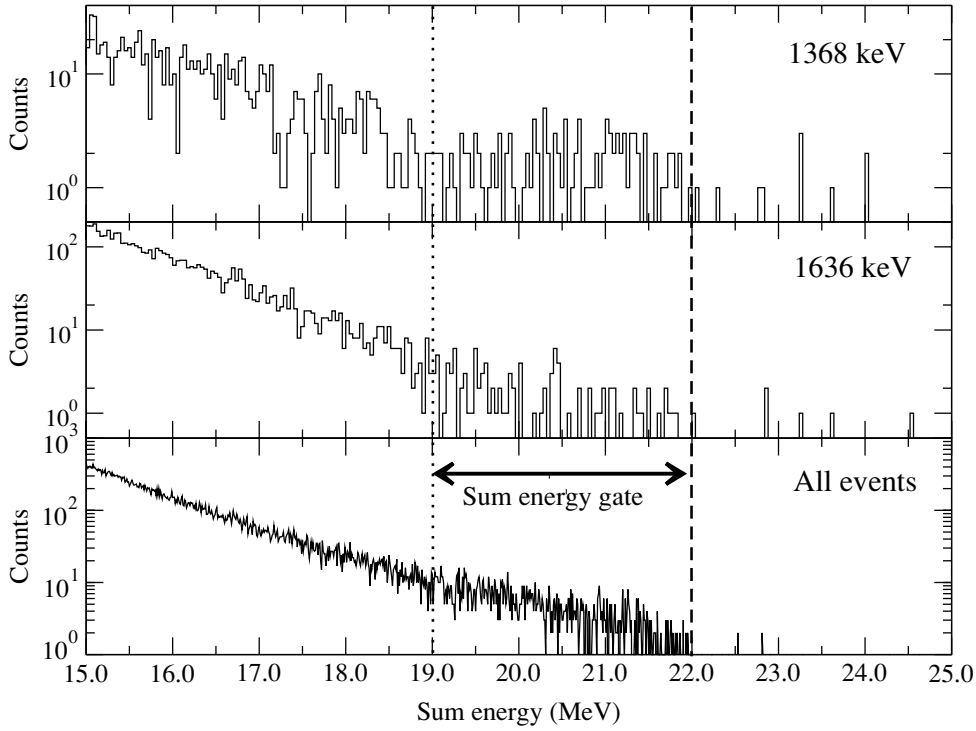

FIG. 1. γ-ray sum energy spectra obtained for the ^{12}C(^{12}C,γ) reaction at a center-of-target energy of 16.1 MeV: (top) sum energy spectra for events containing a cleanly detected 1368-keV γ ray; (middle) sum energy spectrum for events containing a cleanly detected 1634- or 1636-keV γ ray (strong transitions in ^{20}Ne and ^{23}Na, respectively); (bottom) sum energy spectrum for all events. The expected end point in sum energy for the radiative capture channel (22.0 MeV) is marked with a dashed line. The high sum energy region from which capture events were selected is marked.

whereas 913 cascades were selected from the 15.9-MeV data, of which 118(11) had a 1368-keV γ ray. The cascades were sorted into matrices of clean modules vs clean modules and clean modules vs add-back modules, each with the relevant sum energy criterion. These coincidence data indicate that the decay following capture does not proceed in a statistical fashion. This is illustrated in Fig. 2, where cascades containing the 1368-keV γ ray are selected, and the remaining γ rays in both clean and add-back modules are projected. Clear differences are seen between the "on" and "off" resonance data, and the population of certain states in the decay of the capture resonance is seen to be enhanced. In particular, in the 16.1-MeV data (bottom of Fig. 2), 3866- and 4641-keV γ rays, corresponding to the decay of the 3^+ and 4^+ levels in the $K = 2$ rotational band to the first 2^+ state in ^{24}Mg, are observed with intensity comparable to that of the 2754-keV $4^+ \rightarrow 2^+$

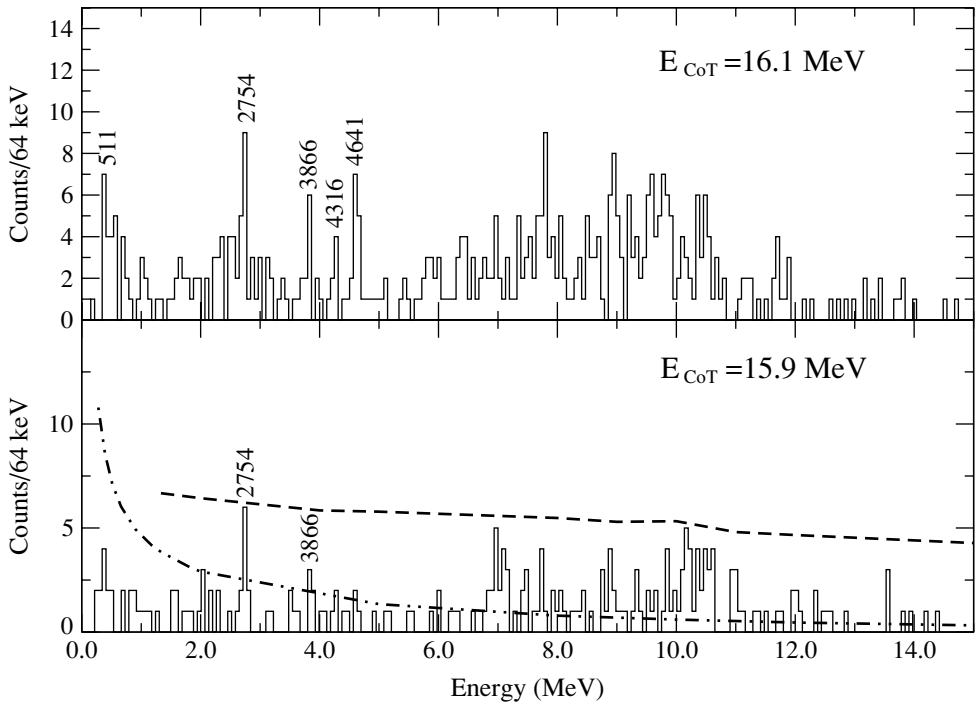

FIG. 2. Spectra of γ rays detected in both clean and add-back modules for cascades containing a 1368-keV γ ray (detected in a clean or add-back module) with a minimum sum energy requirement of 19 MeV: (top) spectrum taken from the data at a center-of-target energy of 16.1 MeV; (bottom) spectrum taken from the data at a center-of-target energy of 15.9 MeV. The dashed line is the simulated efficiency curve for add-back modules, whereas the dot-dashed line represents the relative efficiency for clean modules. The efficiencies are scaled to a measured absolute efficiency of 9.0% at 1.333 MeV for clean modules.

transition. In fact, the ratio I_{4641}/I_{2754} changes from around 1:1 off-resonance to 4:1 on-resonance. This indicates very strong population of the $K = 2$ band relative to the ground-state band.

Higher energy transitions around 8–10 MeV are also observed in coincidence with the 1368-keV transition. This observation implies that some of the decay cascades pass through states located around 9–11 MeV (or higher) in ^{24}Mg. This deduction is not unreasonable because there are known states decaying almost entirely by γ decay in the particle-unbound region up to 12 MeV in ^{24}Mg [14]. It would be very interesting to determine which specific states are involved, especially in view of the fact that this is the energy region where low-spin members of shape isomeric bands are predicted to lie [7]. The available data are, however, insufficient to identify specific states. However, they cannot be high-spin states but, rather, must have $J \leqslant 4$, because they decay to the 2^+ state in ^{24}Mg.

We note that favored feeding of specific structures in light nuclei has been observed before. For example, Collins *et al.* reported very enhanced population of a 0^+ state at 6.69 MeV in ^{28}Si in the ^{12}C(^{16}O,γ) reaction [5]. Under a very different reaction mechanism, namely the symmetric fission of ^{56}Ni, the rotational band built on top of the same 0^+ state in ^{28}Si was also found by Sanders *et al.* to be populated much more strongly than expected, based on a purely spin-weighted, statistical decay [15]. This enhanced population, observed in two very different studies, was explained by both sets of authors as being because of the presence of a highly deformed prolate rotational band built on the excited 0^+ state in ^{28}Si. Such an attribution may be the key to explaining the favored population of highly excited states in ^{24}Mg.

It is difficult to extract a reliable capture cross section for the ^{12}C(^{12}C,γ) reaction, as each decay pathway has a different detector efficiency, dependent on the constituent γ-ray energies and multiplicity. Further, the absolute response of Gammasphere in "add-back" mode and with a calorimetric event selection has yet to be experimentally verified. MCNP Monte Carlo simulations have been made for the response of Gammasphere to the cascades of interest (see Fig. 2). For a fixed multiplicity, the response is rather insensitive to how the energy is shared between the constituent photons, as there is a compensation in efficiency between detecting a high- and low-energy photon as opposed to two photons of similar energy. The efficiency for a particular cascade falls very rapidly with increasing multiplicity. Making use of the observed decay patterns and relying on the simulated response, we extract a cross section of $\sim$5–10 μb, consistent with that obtained from the direct measurement of ^{24}Mg residues. Technically, the Gammasphere experiment alone gives a lower bound for the radiative capture cross section, as conceivably there is a significant contribution from cascades with high multiplicity comprising low-energy γ rays. The consistency between the Gammasphere study and the cross-sectional measurement with the FMA argues against this being a substantial contributor. Moreover, the observed pathways associated with radiative capture suggest the entry resonance must have relatively low spin, $J = 2$ or 4. Taken together with considerations of phase space and level density, very high multiplicity decay cascades associated with radiative capture would seem unlikely.

In conclusion, we have investigated the heavy-ion radiative capture reaction, ^{12}C(^{12}C,γ), using two different methods and at several energies around 8 MeV in the center of mass. We have found that the total radiative capture cross section is strongly oscillatory with a peak of 5–10 μb at a center-of-target energy of 16.1 MeV and so is considerably stronger than generally assumed. The main decay mechanism appears to be through intermediate "doorway" states lying at $\sim$10 MeV in excitation in ^{24}Mg and not by the previously observed "giant-resonance" assisted single step pathway. For resonances near 8 MeV in the c.m., over 80% of the flux appears to proceed through a few isolated doorway states. There is distinct preference for decay to the well-known low-lying $K = 2$ rotational band in ^{24}Mg, indicating that there is selectivity in the doorway mechanism. Further work is in progress aimed at firmly linking the doorway states to the long-predicted shape-isomeric bands in ^{24}Mg.

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