Doorway States As Principal Decay Pathway In ^{12}C(^{12}C,γ) Radiative Capture

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Abstract. The heavy-ion radiative capture reaction, ^{12}C(^{12}C,γ), has been investigated at beam energies around 16 MeV. Three different experiments were performed. Capture cross-sections were obtained by measuring fused ^{24}Mg residues using the FMA at ANL. These were found to significantly exceed values reported earlier. Subsequently, the decay pathways associated with radiative capture were studied in two separate measurements: one with the high-resolution Gammasphere array and a second with a high efficiency BGO array, where gamma rays were recorded in coincidence with ^{24}Mg residues detected at the focal plane of the DRAGON recoil separator at TRIUMF. Both measurements indicate that a substantial fraction of the decay is mediated through high-lying doorway states, possibly associated with the long-predicted shape-isomeric band in ^{24}Mg.

INTRODUCTION

Radiative capture – the complete fusion of beam and target nuclei with subsequent cooling solely by gamma-ray emission – is a common and well-understood process for light nuclei such as protons and alpha 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 gamma 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,γ) [3, 4, 2], ^{12}C(^{16}O,γ) [5] and ^{90}Zr(^{90}Zr,γ) [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 gamma 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. Since 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 since 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.

We have reopened the study of heavy ion radiative capture by performing three separate experiments: one to directly

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ascertain the total radiative fusion cross-section by counting ^{24}Mg residues, and two further studies 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 intriguing to investigate whether the cooling passes through a few highly deformed 'doorway' states which have a strong overlap with both the entry resonance and the ^{24}Mg ground state. The best candidates for these doorway states are highly-deformed states comprising a so-called shape isomeric band, whose band-head is consistently predicted by a wide range of theoretical prescriptions to lie around 10 MeV [7, 8]. Such a structure is yet to be established experimentally.

EXPERIMENTS

Total Cross-Section Measurements

In order 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 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 ($E_{c.m.} \sim 8$ 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 break-up of ^{24}Mg into two ^{12}C nuclei [9]. To first order, the break-up and radiative capture reactions might be expected 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 centre-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 due to the low masses involved. Unwanted residues from A=23 nuclei were removed by closing physical slits at the focal plane. Since 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 $2^+ \rightarrow 0^+$ groundstate transition in ^{24}Mg, in coincidence with the selected recoils, by a single germanium detector at the target position. The FMA has a large energy ($\pm$20%) and angular acceptance ($\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 only 2.1°. It is, therefore, safe to assume that the FMA efficiency for such radiative capture residues is dictated solely by the fraction of residues in the charge state selected. Simple parameterisations 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].

Earlier measurements suggest a total capture cross section to the first few excited states of ^{24}Mg of around 1.0$\pm$0.2 μb [2]. The peak cross-sections determined from the detection of ^{24}Mg residues, in the present work, are considerably higher: >3 μb near $E_{c.m.}$=7.9 MeV, <1 μb near $E_{c.m.}$=7.8 MeV and $>4\mu$b for $E_{c.m.} \sim$ 7.7 MeV. This suggests a comparable, or, indeed, stronger, mechanism competing with the known decays to low-lying excited states in ^{24}Mg.

Gammasphere Measurements

In order to investigate the alternate mechanism and measure the cooling gamma rays with good resolution, the Gammasphere spectrometer, comprising a 4π coverage of 100 Compton-suppressed high-efficiency HPGe detectors, was employed [13]. Since 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 4π solid angle of the device as a sum energy spectrometer, by using a "total energy" spectrum formed from all the 860 active germanium crystals and their contiguous BGO suppression shield elements. This was used at the trigger level to dictate which events were stored for off-line analysis. A selection of $E_{tot} > 12$ MeV suppressed the vast majority of particle emission events and prevented excessive (>30%) deadtime. A gamma ray mulitplicity of 2 modules or greater was chosen. Since the Q value for the $^{12}C(^{12}C,\gamma)$ 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 $^{12}C(^{12}C,\gamma)$ 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 has the advantage of ensuring that all the γ rays in the decay cascade must have been observed, for those events with sum energies close to the expected end point. 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. It should be noted that heavy-metal collimators were fitted to the front of each germanium detector, preventing direct illumination of the BGO shield [13].

In order to find the point of maximum capture yield, a limited excitation function was performed. A ^{12}C beam accelerated by the 88" cyclotron at LBNL was used to bombard a 47 $\mu g/cm^2$ enriched ^{12}C target. Gamma 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 centre-of-target energy of 16.1 MeV, in qualitative agreement with the cross-section measurement made with the FMA, and in excellent agreement with the location of a large peak in the excitation function measured by Sandorfi and Nathan for capture to the ground-, 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 endpoint is $\sim$22 MeV) and deconvoluted into their respective cascades. A total of 1279 such cascades were obtained from the 16.1 MeV data of which 156(12) contained a cleanly detected 1368 keV γ ray, while 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 gamma 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 $4^+ \rightarrow 2^+$ 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 would imply that there are decay cascades which pass through states around 9-11 MeV (or higher) in ^{24}Mg. This deduction is not unreasonable since there are known to be a number of states which decay almost entirely by gamma 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 the shape isomeric bands are predicted to lie. The available data are, however, insufficient to identify specific states.

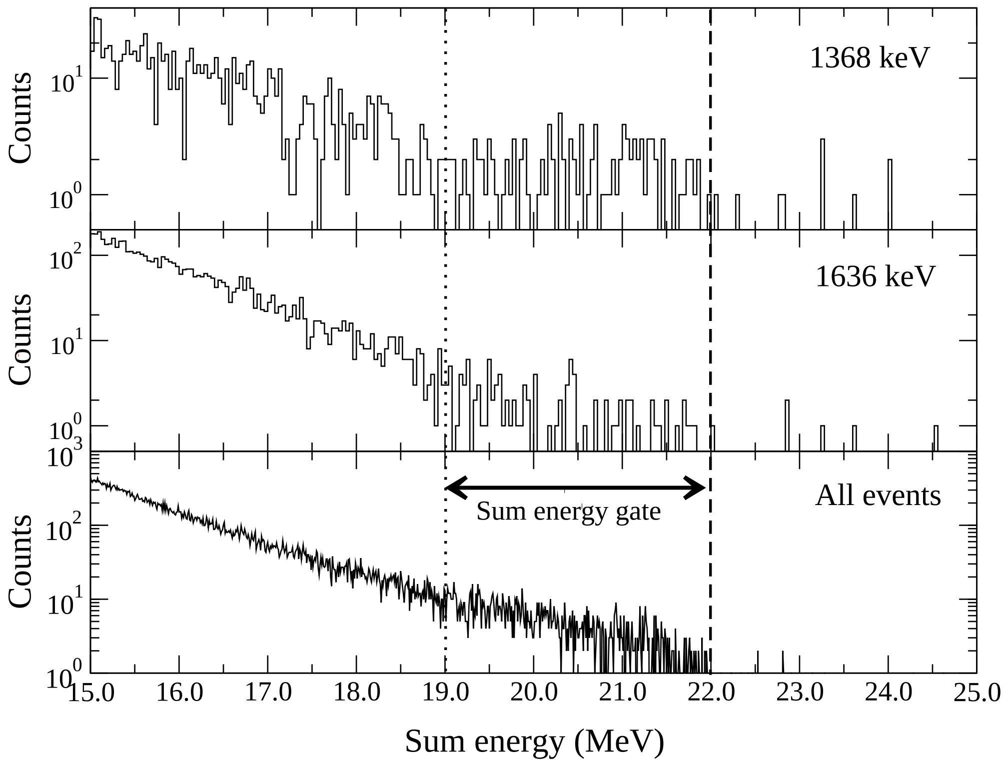

FIGURE 1. Gamma-ray sum energy spectra obtained for the $^{12}C(^{12}C,\gamma)$ reaction at a center-of-target energy of 16.1 MeV: (top) Sum energy spectra for events containing a cleanly detected 1368 keV γ ray; (middle) Sum energy spectrum for events containing a cleanly detected 1634 keV or 1636 keV 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.

Measurements With The DRAGON Separator

While our studies with Gammasphere offered the possibility of locating the high-lying states involved in the capture mechanism, these studies suffered from the intrinsically poor high energy resolution of the germanium detectors, as well as the poor efficiency of the sum energy trigger which was used. Indeed, electronic thresholds in the preamplifiers associated with the germanium detectors, meant that it was not possible to detect the high energy ($>$ 18 MeV) capture gamma rays which had been observed before. In order to detect the expected high energy gamma rays with high efficiency, and examine the distribution of decay strength to different states, we exploited the DRAGON separator at TRIUMF with its associated BGO array [15]. The DRAGON separator was principally designed for studying (p,γ) reactions with radioactive beams in inverse kinematics e.g. ^{21}Na(p,γ) [16]. Accordingly, it was necessary to replace the windowless gas target with a solid target mechanism which could handle the enriched ^{12}C foils. An additional complication in these studies is that since the DRAGON was designed for (p,γ) reactions where the recoil cone is small, the nominal angular acceptance of the separator is a cone of half angle 20 mrad. This limited acceptance means that capture recoils may miss the acceptance of DRAGON depending on the recoil kick imparted by the gamma rays emitted and so the DRAGON separator does not detect capture residues without prejudice in the same way as the FMA did. These effects have therefore been simulated using the Monte Carlo simulation code, GEANT [17].

Using the DRAGON separator, we studied the resonance in the $^{12}C(^{12}C,\gamma)$ reaction, previously identified around $E_{c.m}$=8.0 MeV, as well as resonances reported by Sandorfi and Nathan at $E_{c.m}$=6.0 and 8.7 MeV [2]. The analysis of this data is still at a preliminary stage. However, several features have emerged. Firstly, we have been able to qualitatively reproduce the early observations i.e. high energy ($\sim$ 20 MeV) gamma rays to low-lying states. Secondly, it is clear that cascade decays passing through high-lying states are very prominent at all the beam energies considered, which supports the conclusions drawn from the Gammasphere work. Furthermore, the highest energy transition in these cascades appears to increase in energy in conformity with changes in the beam energy. If we assume that this gamma

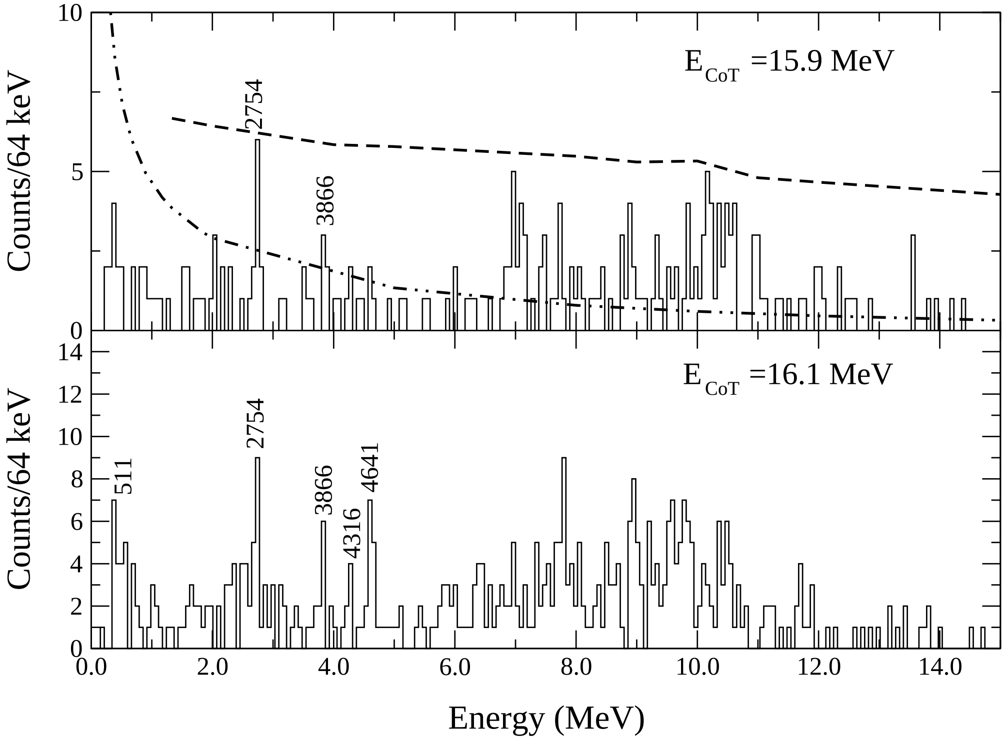

FIGURE 2. Spectra of gamma rays detected in both clean and add-back modules for cascades containing a 1368 keV γ ray (detected in a clean or add-back module) with a minimum sum energy requirement of 19 MeV: (top) Spectrum taken from the data at a centre-of-target energy of 15.9 MeV. The dashed line is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

ray is emitted first, then it would imply that the capture decay is mediated most strongly by states in a very similar excitation region, i.e. those around 10 MeV in ^{24}Mg. In the ongoing analysis, we should be able to obtain partial cross-sections for each of the possible decay branchings, correcting for the efficiency for detecting the coincident recoil on an event-by-event basis making use of the GEANT simulations.

CONCLUSION

In conclusion, we have investigated the heavy ion radiative capture reaction, ^{12}C(^{12}C,γ) using several different techniques and at several energies, particularly at an energy of 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 centre-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 dooway states to the long-predicted shape-isomeric bands in ^{24}Mg.

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