Title of proposed experiment:

Evaluation of the competition between single-step and multi-step γ decay in the $^{12}C(^{12}C,\gamma)$ reaction

Name of group:

Spokesperson for group: D.G.Jenkins

E-Mail address: dj4@york.ac.uk Fax number: +44 1904 432214

Members of the group (name, institution, status, per cent of time devoted to experiment)

Name	Institution	Status	Time
D.G. Jenkins	University of York	Faculty	40%
B.R. Fulton	University of York	Faculty	20%
T. Brown	University of York	PhD Student	10%
D. Groombridge	University of York	Post-doc	10%
S.P. Fox	University of York	Post-doc	10%
J. Pearson	University of York	PhD Student	10%
R. Wadsworth	University of York	Faculty	10%
D.L. Watson	University of York	Faculty	10%
D. Hutcheon	TRIUMF	Staff	10%
L. Buchmann	TRIUMF	Staff	10%
J. Rogers	TRIUMF	Staff	10%
C. Davis	TRIUMF	Staff	10%
S. Park	TRIUMF	Post-doc	10%
J. D'Auria	Simon Fraser University	Faculty	10%
U. Greife	Colorado School of Mines	Faculty	10%
C.J. Lister	Argonne	Staff	10%
M.P. Carpenter	Argonne	Staff	10%
R.V.F. Janssens	Argonne	Staff	10%
T.L. Khoo	Argonne	Staff	10%
A.H. Wuosmaa	Argonne	Staff	10%
M. Freer	University of Birmingham	Faculty	10%
F. Haas	IReS Strasbourg	Staff, CNRS	15%
P. Papka	IReS Strasbourg	PhD Student	15%
C. Beck	IReS Strasbourg	Staff, CNRS	10%
A. Sanchez	IReS Strasbourg	PhD Student	10%
F. Azaiez	IReS Strasbourg	Staff, CNRS	10%
C. Andreoiu	University of Liverpool	Post-doc	10%
M. Chartier	University of Liverpool	Faculty	10%
R.-D. Herzberg	University of Liverpool	Faculty	10%

Start of preparations: January 2003

Date ready: April 2003

Completion date: December 2003

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
42 shifts		No

We propose to investigate the $^{12}C(^{12}C,\gamma)$ reaction using the DRAGON separator in conjunction with the BGO array. This set-up will allow the competition between single step and multi-step decays via 'doorway' states in ^{24}Mg following radiative capture to be quantified for the first time. This work will have important implications for our understanding of the radiative capture mechanism and possibly provide a tool for investigating exotic nuclear shapes. Both avenues of research would form the focus of subsequent publications.

The DRAGON separator has been designed as a powerful instrument for the measurement of key astrophysical radiative capture reactions which will exploit the radioactive beams available at ISAC. However, DRAGON also offers an amazingly powerful and indeed unique instrument for other nuclear physics experiments such as the present proposal. We note that the ability to make use of DRAGON with stable beams at times when radioactive beams are not available from ISAC, or indeed, when they are being used for the low energy program, provides better return from the investment in this unique instrument and broadens the science which can be pursued at TRIUMF.

Experimental area

DRAGON

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

Beam: 5pnA ^{12}C at various energies from 12-16 MeV including 12, 13.4 and 15.8 MeV
For measurement of the separator acceptance a 1pnA ^{21}Ne beam with energy in the range 10-15 MeV will be used.

Principal target: Various thicknesses 20-100 $\mu g/cm^2$ enriched ^{12}C

Secondary targets: Various thicknesses 50-200 $\mu g/cm^2$ enriched ^{13}C and oxide targets

Secondary channel

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

SUPPORT REQUIREMENTS	

TRIUMF SUPPORT:

DRAGON separator and BGO array
Design and construction of mechanism for changing solid targets (Design Office, Machine Shop, Controls)

NON-TRIUMF SUPPORT

Purchase or manufacture of targets. Travel expenses of off-site group members.

The targets are non-toxic (carbon or oxide) solids. The BGO and MCP detectors have applied voltages of between 1 and 3 kV: SHV connections will be used on cables and there will be no exposed parts at high voltage.

The DC terminals of the magnets are shielded by plexiglass covers. The high voltage supplies of the electrostatic dipoles are interlocked to prevent application of power if the dipole tank is vented or if a cage enclosing HV feed-throughs is open.

1 Scientific Justification

Radiative capture – the complete fusion of beam and target nuclei to form a compound system which subsequently cools solely by gamma ray emission – is a common and well-understood process for light nuclei such as protons and alpha particles. Indeed, the CNO cycle and *rp*-process which are important in the synthesis of light nuclei in stars and novae proceed by such (p,γ) and (α,γ) capture reactions, followed by β-decay. By contrast, far less is known about the process of radiative capture involving heavy ions. The existing knowledge is mostly confined to the ^{12}C(^{12}C,γ) and ^{12}C(^{16}O,γ) systems. A comprehensive review of heavy ion radiative capture (HIRC) up to the 1980s which covers these measurements has been presented by Sandorfi [1]. Very little progress has been made since.

In principle, radiative capture has many interesting aspects, both for studying the time-scale, dynamics and nature of the fusion, but also as a tool for populating interesting non-yrast states. In this regard the symmetric ^{12}C + ^{12}C system is particularly relevant as a system which has long been discussed in terms of nuclear molecule formation [2,3], being a possible precursor to relaxation into a normal compound nucleus. In this relaxation, it may be that intermediate, so-called 'doorway' states are formed, which have a strong overlap with both the initial molecular state and the final low-lying states in ^{24}Mg (see figure 1). Given the elongated nature of the entry resonance and the prolate ($\epsilon_2 \sim 0.4$) ground state of ^{24}Mg, such intermediate structure might be associated with highly extended ($\epsilon_2 \sim 1$), superdeformed or even hyperdeformed shapes; the latter being of particular topical interest. Much theoretical consideration has been given to such structures and the properties of these so-called shape-isomeric rotational bands have been calculated within the cranked Hartree-Fock [4–6], Nilsson-Strutinski [7,8], and various cluster models [9–11].

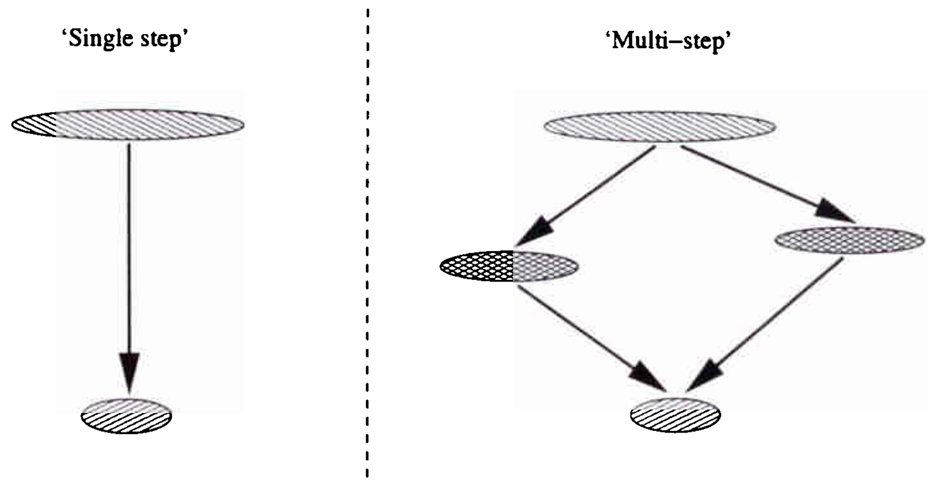

Fig. 1 Illustration of the decay possibilities following radiative capture. (left) A single step decay from the entry resonance to the ^{24}Mg ground state. (right) A multi-step decay from the entry resonance via highly deformed 'doorway' states to the ^{24}Mg ground state. The shapes are indicative of the expected nuclear deformation.

Experimental counterparts for the band-members of shape-isomeric structures in ^{24}Mg have been suggested [9,12], however, their existence is yet to be confirmed. Nevertheless, the direct relationship between the $^{12}C + ^{12}C$ entrance channel and the fused ^{24}Mg compound is already well established by Sandorfi and Nathan [14,13] and Dechant and Kuhlman [15], who measured high energy γ-ray transitions, most likely of E2 multipolarity, which directly cooled the nucleus from the capture region to the first few low-lying bound-states in ^{24}Mg (see figure 2). The origin of these species of decay was attributed to a coupling to the giant quadrupole resonance strength in ^{24}Mg [14,13,15]. Such studies, however, did not allow an investigation of a 'doorway' mechanism, involving high multiplicity decays passing through high-lying ($E_x > 5$ MeV) states in ^{24}Mg, since only a single sodium iodide detector was employed. The piling-up in the detector of low energy gamma rays from the intense particle emission channels only allowed observation of the highest energy capture γ rays. Thus, only the partial capture cross-section to the first few excited states could be studied by this method. [14,13].

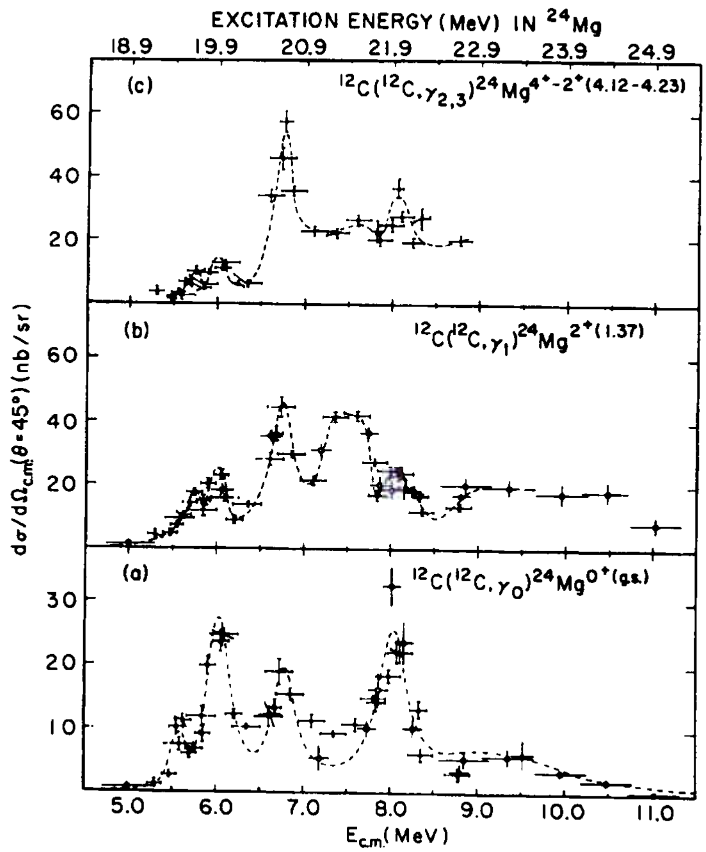

Fig. 2 Excitation functions for $^{12}C(^{12}C,\gamma)$ at θ_γ=45° as measured by Sandorfi and Nathan using a single large sodium iodide crystal - taken from ref [13].

In practice, the radiative capture of heavy ions (HIRC) is always a low probability mechanism. The high Coulomb barrier in the entrance channel, and the positive reaction Q-values mean the compound nuclei are always very highly excited, typically more than 10 MeV above the proton, neutron and alpha particle separation energies ensuring that electromagnetic cooling is never favored. The cross-section associated with the radiative capture γ rays observed by Sandorfi and Nathan was at most 1 μb [14,13] (see figure 2), while fusion channels involving particle emission have a total cross-section of around 500 mb [16] implying a partial decay width of around 10^{-6} for the radiative capture channel. The study of the radiative capture mechanism for heavy ions is therefore an experimental challenge.

2 Status of the research programme

The present research programme is directed at the search for the previously unknown process of multi-step decay via doorway states in the ^{12}C(^{12}C,γ) system and to quantify its strength relative to the known decays proceeding in a single-step to low-lying states. Once such intermediate structure is found, we aim to characterise the properties of the doorway states including their spin/parity, excitation energy and, in particular, their associated deformation. If the full decay path could be observed, with high resolution, then the experiments might also yield information on the much disputed nature of the ^{12}C+^{12}C resonances themselves, including their widths, excitation energies and spin/parities. Some progress has already been made in regard to this programme and we summarise the status below.

2.1 Gammasphere

At the outset of this research programme (May 2000), we exploited the Gammasphere array in a novel fashion in order to explore whether multi-step decays occur following radiative capture. The Gammasphere array consists of 100 high-purity Germanium detectors. Each detector comprises a high-resolution germanium crystal surrounded by a high-efficiency BGO shield which, when employed in the conventional mode of operation, is used to veto events where γ-rays Compton-scatter and fail to deposit their full energy in the germanium crystal. An alternative mode is to collect energy signals from both the germanium crystal and BGO shield and sum them to recover the full energy. We have designated each of the component detector units in Gammasphere as a 'module' and distinguish three types of such module events. A 'clean' module is one in which only the germanium crystal fired, where 'clean' implies highest possible resolution. A 'dirty' module is one where both the germanium crystal and BGO shield fired and their energy signals were added – 'dirty' implying degraded resolution. The third possibility is a 'bgo-only' module where the BGO shield fired in isolation. A 'dirty' module has substantially improved efficiency at high energies ($\sim$ 10 MeV) relative to a 'clean' module at the expense of an acceptable degradation in resolution.

Since the Gammasphere array covers the full 4π of solid angle, it forms an excellent sum energy calorimeter. The sum energy is constructed by adding the energies of all the detectors that fire in prompt coincidence. We have exploited sum energy detection as a means of separating the radiative capture channel from the competing particle emission channels whose total cross-section is five or six orders of magnitude larger. Good separation is ensured by the fact that the γ-ray sum energy associated with a radiative capture reaction is larger than that from competing particle emission channels since the reaction Q-value for the capture channel (+13.93 MeV) is much larger than that for competing particle emission channels (e.g Q-value for 1 proton emission is + 2.24 MeV).

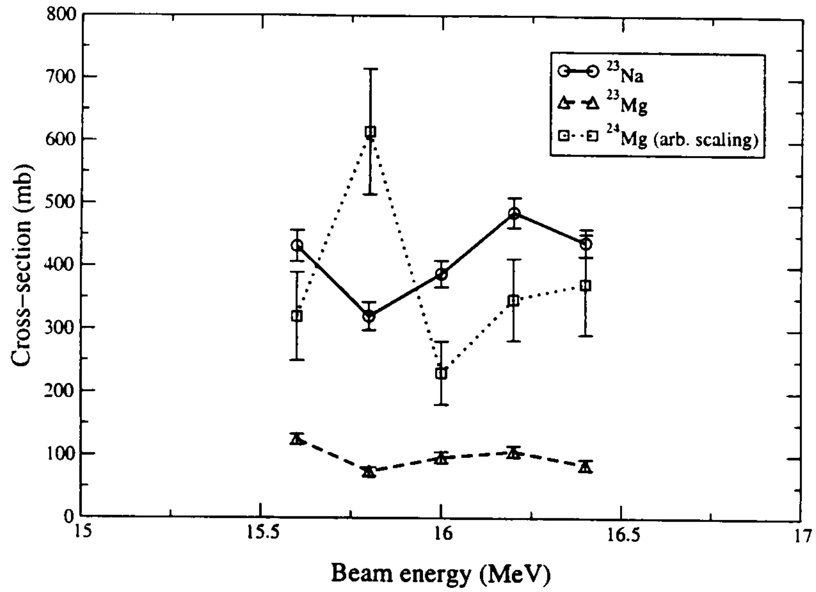

Fig. 3 Excitation function for various channels from the $^{12}C+^{12}C$ reaction. True cross-sections for ^{23}Na and ^{23}Mg are presented. Shown on the same scale but with arbitrary units is the excitation function for the capture channel leading to ^{24}Mg determined by fitting the high energy portion of the sum energy spectrum.

The $^{12}C(^{12}C,\gamma)$ reaction was investigated for beam energies near 16 MeV. This choice was motivated by two factors: the observation of resonances in the radiative capture channel around this beam energy in the earlier work of Sandorfi and Nathan [14,13] and secondly, the fact that this region corresponds to the location of known J=4 resonances in the break-up of ^{24}Mg into two ^{12}C nuclei [17]. The break-up and radiative capture reactions might be expected to be time-reversed to first order; indeed this is an aspect which our data will explore.

In order to locate HIRC resonances a limited excitation function was performed. A ^{12}C beam was delivered by the 88 inch cyclotron at Lawrence Berkeley National Laboratory and was incident on a 40 $\mu g/cm^2$ enriched ^{12}C target. Gamma rays were detected by the Gammasphere array with a trigger condition of one module. Cross-sections for the one proton and one neutron emission channels were extracted and were found to be in reasonable conformity with earlier measurements [16]. A peak in the radiative capture yield, inferred from the number of events with sum energy above 12 MeV, was observed for a beam energy of 15.8 MeV (see figure 3), corresponding to the location and width of a capture resonance previously reported by Nathan and Sandorfi [14].

Having determined the point of maximum yield for the capture channel, the array was switched to a coincidence mode where at least three γ-rays had to be detected in any given event and at least two of them in a 'clean' module. This permitted the capture events to be decomposed in detail. Data were taken both for the point of maximum yield for the capture channel (E_{beam} = 15.8 MeV) and an 'off-resonance' position (15.6 MeV). Operating in this mode, good separation between radiative capture events and particle emission events was observed in the sum energy spectrum (figure 4) with a clear excess of counts at high energies for cascades containing a cleanly detected 1368 keV γ ray –

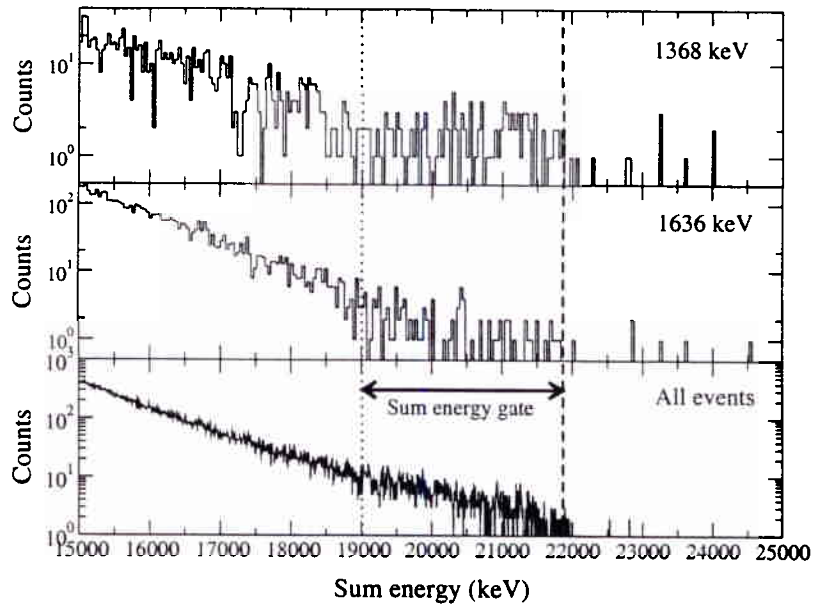

Fig. 4 Gamma-ray sum energy spectra obtained for the $^{12}C(^{12}C,\gamma)$ reaction at a beam energy of 15.8 MeV: (top) Sum energy spectra for events containing a cleanly detected 1368 keV γ-ray. (middle) Sum energy spectrum for events containing a cleanly detected 1634 keV or 1636 keV γ-ray - strong 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 (21.8 MeV) is marked with a dashed line. The high sum energy region from which capture events were selected is marked.

the characteristic $2_1^+ \rightarrow 0^+$ transition in ^{24}Mg. Moreover, the endpoint of the sum energy spectrum was in agreement with that expected from the Q value (+13.9 MeV) for the radiative capture channel and moved in conformity with changes in beam energy.

In the analysis, we selected events with sum energies above 19 MeV and unfolded them into their respective cascades. The cascades were then ordered by identifying well-known low-lying transitions in ^{24}Mg and by using certain reasonable considerations such as the largest energy γ ray in the cascade being likely to have been emitted first. Making use of the γ-γ coincidence data, it becomes clear that the decay of the entry resonance does not proceed in a statistical fashion. Moreover, the states populated in the decay differ on changing beam energy. This is illustrated in figure 5 where cascades with sum energies above 19 MeV and which contain the characteristic 1368 keV γ-ray are selected and the remaining γ rays in the cascade detected in both 'clean' and 'dirty' modules are projected. In this manner those cascades which pass through the lowest 2^+ state in ^{24}Mg may be isolated.

The population of certain states is seen to be selectively enhanced in the decay of the capture resonance. In particular, in the 15.8 MeV data, the 2^+, 3^+ and 4^+ members of the K=2 rotational band in ^{24}Mg are strongly populated. At higher energies, there is evidence for strong population of particular states around 10 MeV, which corresponds to the energy region where the shape-isomeric band is predicted to lie. These observations suggest an analogy with the decay-out of superdeformed bands to the normal deformed states in heavy nuclei where the single step decays comprise only a small fraction of the possible

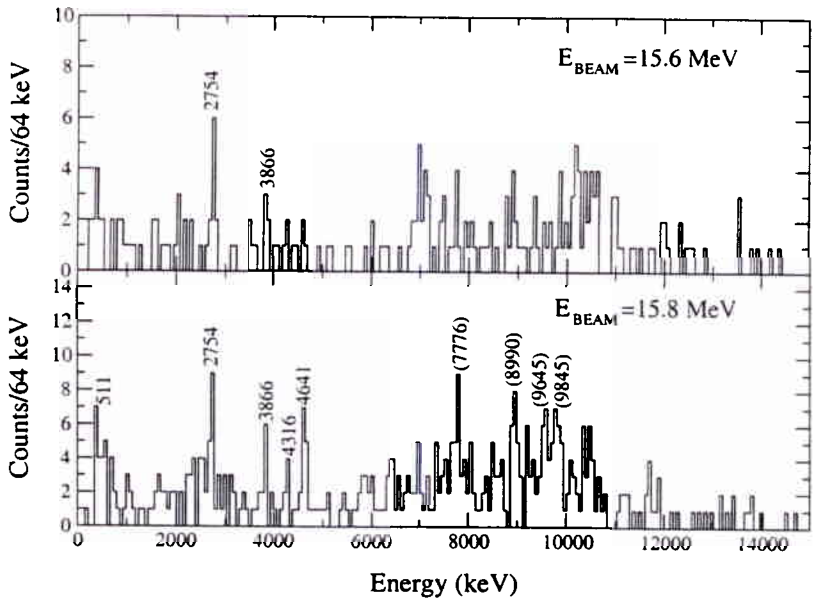

Fig. 5 Spectra of gamma rays detected in both clean and dirty modules for cascades containing a 1368 keV (detected in a clean or dirty module) with a minimum sum energy requirement of 19 MeV: (top) Spectrum taken from the data taken at a beam energy of 15.6 MeV (bottom) Spectrum taken from the data taken at a beam energy of 15.8 MeV .

decay branches, for example, the recently observed decay-out of the superdeformed band in ^{152}Dy [18].

A challenge for the analysis is to determine the cross-section associated with the multi-step decays. This is because the technique of selecting high sum energy events only samples some of the radiative capture events and the efficiency for each individual cascade differs depending on the energies of the component γ rays and the manner in which they were detected. We have investigated the efficiency of the Gammasphere array using the Monte Carlo code MCNP. Using the efficiencies suggested by the simulations we set a lower limit on the cross-section for multi-step radiative capture which passes through the lowest 2^+ state in ^{24}Mg of 10 μb. By comparison, the cross-section obtained by Sandorfi and Nathan for decays directly to the 2^+ state was around 300 nb [1]. A further difficulty in analysis arises from electronic saturation of the detector pre-amplifiers which precludes the observation of the direct 'single-step' decays reported by Sandorfi and Nathan.

These preliminary results were presented as an invited talk at the POSTYK01 Cluster Conference in Kyoto, Japan in November 2001 and as a contributed talk at the NS2002 conference in Berkeley in July 2002. On the basis of this preliminary work, further time has been awarded by the international programme advisory committee of both Argonne and Lawrence Berkeley National Laboratories.

2.2 Cross-section measurement with the FMA

Given the difficulties in deriving a cross-section from the Gammasphere data, the total capture cross-section for the ^{12}C(^{12}C,γ) reaction for a beam energy of 15.8 MeV was recently investigated (August 2002) using the Fragment Mass Analyser (FMA) at Argonne National Laboratory. A preliminary analysis suggests a cross-section around 5μb which compares favorably with that inferred from the γ-ray study using Gammasphere.

3 Description of the Experiment

Despite the success of this research programme so far in establishing that the cross-section for the radiative capture reaction is much larger than previously thought, several important questions remain in how this is reconciled with earlier measurements. In particular, the possibility arises that some or, indeed, all of the high energy (20 MeV) γ-rays detected by Sandorfi and Nathan [1] and attributed to single-step decay to low-lying states including the ground-state, might, in fact, be attributed to the spurious summing of γ-rays within the single sodium iodide crystal used in their work.

There are several possibilities. The first is that the single step decay mechanism exists with a total cross-section of around 1 μb in tandem with a multi-step decay process which carries around 90% of the total decay strength. Alternatively, some or all of the observed single step decay may have been due to the spurious summing of the multi-step γ rays into the sodium iodide detector. MCNP simulations of the sodium iodide crystal suggest an efficiency around 1% for 10 MeV γ rays. If the summing of two 10 MeV γ rays, for example, had been responsible for the appearance of a spurious 20 MeV γ ray then the 1% efficiency for the second 10 MeV γ ray might roughly account for the factor of 30 discrepancy in measured cross-sections between the multi-step (10μb) and single-step (300 nb) processes for decays to the lowest 2^+ in ^{24}Mg. Even if this proved to be the case, it would still remain an open question whether the single step decay is the dominant decay mechanism at lower energies and this issue also needs to be addressed.

The DRAGON separator in conjunction with the target BGO array comprises an excellent apparatus for resolving some of the important questions raised by this research programme so far, as well as allowing the programme to pursue new avenues of research. In comparison to the Gammasphere array, the unique and key feature of the DRAGON plus BGO array set-up is the high efficiency of the BGO array for high energy γ-rays. This will allow, for the first time, a search for multi-step and single-step high energy γ decay following radiative capture to be made simultaneously. It will then be possible to resolve key issues raised by the earlier work. Firstly, it will be immediately clear whether a multi-step decay process dominates the decay mode from the observed γ ray strength distribution. Secondly, the earlier measurements of the single step decay mode via 20 MeV γ rays may be confirmed. Any discrepancy from the earlier measurements will have profound impl! ications to our understanding of the radiative capture mechanism and overturn the "perceived wisdom" regarding these type of reactions. We emphasise that the BGO plus DRAGON set-up is the only existing set-up capable of answering these key questions. In view of the above, we would like to make the following studies:

- Perform an excitation function around 15.8 MeV beam energy to determine the total radiative capture cross-section by counting mass 24 recoils
- Deduce the relative strengths of single step and multi-step decay and verify whether multi-step decay accounts for the majority of the decay strength

- Move to lower energies to determine the relative strengths for e.g. $E_{c.m.} = 6.0$ MeV and 6.7 MeV where capture resonances have been previously reported (see figure 2).

3.1 γ ray yield estimates

We have estimated γ ray yields assuming a 40 μg/cm^2 ^{12}C target and a 5 pnA beam of ^{12}C, with a luminosity of 60 mb^{-1} s^{-1}. Taking an estimate of 200 nb for the single-step decay mechanism to the ground state (see figure 2) we calculate a reaction rate of 45/hr.

The efficiency of the BGO array for detection of a γ ray of energy $\approx$10 MeV is 40–50%. For a typical cascade consisting of 2 γ rays, each of $\approx$10 MeV, the probability of detecting *one* γ ray is about 50% and of detecting *both* γ rays is about 25% (ignoring angular correlations).

The efficiency of detection of recoils depends for the most part on the charge state distribution (we select only one charge state at a time) and the acceptance of the separator. Typically the charge-state fraction is 40–45%. The nominal acceptance is a cone of half-angle 20 mrad in the transverse direction and $\pm$2% in momentum. This corresponds to recoils for which the associated γ ray(s) carry a momentum which is less than 2% of the momentum of the incident beam.

For the case of a ^{12}C beam of 15.8 MeV and a single γ ray of energy 22 MeV (a single-step decay to the ground state), the γ-ray momentum is 3.7% of the beam momentum. We can select about 8% of the recoils, either in the forward or the backward directions in the c.m. system.

Overall, for a gamma transition to the ground state, the expected counting rate is 45 $\times$ 0.5 $\times$ 0.40 $\times$ 0.08 = 0.3 counts/hr. Experience with stable beams to DRAGON is that after overheads due to maintenance days, beam tuning and accelerator down-time, it is reasonable to expect 100 hours per week of "good beam on target" provided there are not many energy changes. This leads to an estimate of 30 counts per week for detection of recoil ^{24}Mg in coincidence with a 22 MeV gamma ray.

The separator acceptance is more favourable in the case of a cascade of 2 gammas of nearly equal energy. Now the vector sum of the gamma momentum averages $\approx$16 MeV/c instead of 22 MeV/c, with a doubling of the fraction of recoils which are accepted. On the other hand, if one demands that both gamma rays be detected, the BGO efficiency drops by about a factor 2. Thus, we do not expect a large difference in detection probability for the cascade decay compared to the single-gamma decay. However, with order-of-magnitude larger cross section the counting rates are expected to be of order 300 per week. Clearly, given the expected predominance of the multi-step decay mode, it will be necessary to take into account the possibility of γ-ray summing in the BGO counters. The BGO array has a reasonably high-level of segmentation with each counter subtending around 3% of 4π solid angle on average, meaning that the effects of γ-ray summing will be largely minimised. It will be necessary to use Monte Carlo simulations to explore the effects of γ-ray summing in this case.

It is important to make a direct measurement of separator acceptance. We propose to do this by looking for the recoil ^{12}C particles from back-angle (in the c.m. system)

Rutherford scattering of a ^{21}Ne beam. The cross section is nearly constant over the angular acceptance of DRAGON. The initial angles of the particles transmitted by DRAGON separator may be deduced from measurement of the angles at the end detector. The dependence of acceptance on the (relative) energy and mass of the recoils will be explored by scaling the separator tune at a fixed beam energy.

3.2 Background suppression

The separator selects ions according to their Mass/Charge ratio. Because the selected mass (24) is a multiple of the beam mass (12) it is necessary to select odd-numbered charge states, in order to avoid a low-energy tail of the beam in a charge state 1/2 the selected charge of Mg ions. The mass-23 isotopes of Mg and Na will be produced with large cross sections, but extensive experience with proton capture reactions suggests they should be suppressed by at least 8 orders of magnitude in the separator.

If it is assumed that every C + C reaction leads to production of one or more gamma rays, the total reaction cross section of 500 mb would mean a counting rate of order 10–20 kHz in the array. This is easily within the rate capability of even a single element of the array, but does lead to the possibility of accidental coincidences with detected heavy recoil particles. Allowable times-of-flight of the recoils span approximately 150 ns; in a TOF window of this width the probability of accidental coincidence is $1.5\text{–}3\times10^{-3}$ per detected heavy ion. To have a 1:1 signal-to-background ratio for a 3-count-per-hour signal, the background rate in the ^{24}Mg detection system must not be greater than 0.25/s.

The end detector system includes the possibility of local time-of-flight measurement, using a foil/MCP signal to Start and a silicon strip detector located 90 cm downstream as the Stop. Beam ions (mass 12) having the same energy as the Mg recoils should have a 30-ns shorter TOF.

3.3 Target issues

This is the first proposal to use a solid target on DRAGON. The standard gas target cell is mounted on the side plate of a narrow vacuum box. Its gas inlet and other services are at the bottom of the side plate, in order to allow the BGO array to fit closely around the upper part of the box, where the gas cell is located. We would replace the side plate and gas cell with a mounting system for the C targets and for apertures to be used in beam tuning. The targets and apertures would be mounted on a wheel having its axis slightly below beam height and perpendicular to the beam direction. The wheel would be driven by a chain connected to a drive near the bottom of the plate, where the vacuum feed-through and drive motor would not interfere with the BGO array.

Target impurities are of concern in this study since ^{24}Mg can be produced from reactions off ^{13}C or ^{16}O in the target. Highly enriched, oxygen-free, ^{12}C targets will be used. Target impurities may be monitored by constructing a γ ray sum energy spectrum for events with a correlated mass 24 recoil. This will allow the possibility of contamination from ^{13}C or ^{16}O in the target to be ruled out since the sum energy spectra should have very different end points. It should be noted that no evidence for such contamination was observed in the Gammasphere experiment (see above). Substituting ^{13}C or oxide targets for the ^{12}C target will allow a further cross-check to be made. Since, in principle, contamination of an enriched carbon foil with natural carbon in the vacuum chamber is a concern, it would be advantageous to change targets on a relatively regular basis.

4 Experimental Equipment

DRAGON separator with BGO array gamma detector and double-sided silicon strip detector plus MCP for recoil detection.

5 Readiness

A mechanism for changing solid targets, including remote control, must replace the existing gas target cell. Approximately 3 months after approval of the experiment will be needed for design, construction and testing of the mechanical and motor drive systems.

6 Beam Time required

We request 42 shifts (21 days) of beam-time. This would be split into two chunks of 22 and 20 shifts respectively. The first 22 shifts would include a preliminary four shifts to perform a measurement of the acceptance using a ^{21}Ne beam. We would then run for two shifts with a 15.8 MeV ^{12}C beam on each of the oxide and ^{13}C targets to assess problems of contamination. Having understood the acceptance and contamination issues, the Physics run of 14 shifts on the ^{12}C target would follow.

Following a preliminary analysis of the data, a subsequent run of 20 shifts would be carried out focusing on the lower energy resonances at $E_{c.m}$=6.0 and 6.7 MeV.

7 Data Analysis

The data will be principally analysed by the spokesperson at the University of York. In addition, analysis projects relating to the study will be carried out by students at Simon Fraser University and at IReS Strasbourg.

References

1. A.M. Sandorfi, Treatise on Heavy Ion Science Vol. 2, sec. III (ed. D. Allan Bromley) and references therein.
2. K.A. Erb and D.A. Bromley, Treatise on Heavy Ion Science Vol. 3, sec III (ed. D. Allan Bromley) and references therein.
3. N. Marquardt, Phys. Rev. C 28, 202 (1983).
4. H. Flocard, P.-H. Heenen, S.J. Krieger and M.S. Weiss, Prog. Theor. Phys. 72, 1000 (1984).
5. D. Baye and P.-H. Heenen, Phys. Rev. C 29, 1056 (1984)
6. D. Baye and P. Descouvemont, Nucl. Phys. A419, 397 (1984).
7. G. Leander and S.E. Larsson, Nucl. Phys. A239, 93 (1975).
8. I. Ragnarsson, S. Alberg and R.K. Sheline, Physica Scripta 24, 215 (1981).
9. P. Descouvemont and D. Baye, Nucl. Phys. A475, 219 (1987).
10. S. Marsh and W.D.M. Rae, Phys. Lett. B 180, 185 (1986).
11. A.A. Pilt and C. Wheatley, Phys. Lett. B 76, 11 (1978).
12. H. Schultheis and R. Schultheis, Phys. Rev. C 27, 1367 (1983).
13. A.M. Nathan, A.M. Sandorfi and T.J. Bowles, Phys. Rev. C 24, 932 (1981).
14. A.M. Sandorfi and A.M. Nathan, Phys. Rev. Lett. 40, 1252 (1978).
15. B. Dechant and E. Kuhlman, Z. Phys. A 330, 93 (1988).
16. K.A. Erb, R.R. Betts, S.K. Korotky, M.M. Hindi, P.P. Tung, M.W. Sachs, S.J. Willett and D.A. Bromley, Phys. Rev. C 22, 507 (1980).
17. B.R. Fulton *et al.*, Phys. Lett. 267B, 325 (1991).
18. T. Lauritsen *et al.*, Phys. Rev. Lett. 88, 042501 (2002).

Include publications in refereed journal over at least the previous 5 years.

- D.G. Jenkins *et al.* Phys. Lett. B 428, 23 (1998) - Magnetic Rotation in ^{106}Sn and ^{108}Sn
- D.G. Jenkins *et al.* Phys. Rev. C 58, 2703 (1998) - Magnetic Rotational Bands in ^{108}Sb
- D.G. Jenkins *et al.* Phys. Rev. Lett. 83, 500 (1999) - Confirmation of the Shears Mechanism in the Near-Spherical Tin Nuclei
- D.G. Jenkins *et al.* Phys. Rev. C 62, 021302 (2000) - First Observation of Excited States in ^{182}Pb
- D.G. Jenkins *et al.* Phys. Rev. C 64, 064311 (2001) - Stability of Oblate Shapes in the Vicinity of N=Z=34: Bands in ^{69}Se and ^{67}As
- D.G. Jenkins *et al.* Phys. Rev. C 65, 064307 (2002) - T=0 and T=1 States in the Odd-Odd N=Z Nucleus: ^{70}Br
- D.G. Jenkins *et al.* Phys. Rev. C 66, 011301 (2002) - Confirmation of Triple Shape Coexistence in ^{179}Hg: Focal Plane Spectroscopy of the Alpha Decay of ^{183}Pb.