TRIUMF — RESEARCH PROPOSAL

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Experiment no. **1108**

Title of proposed experiment:

The ^{30}P(p,γ)^{31}S Reaction Rate in Classical Novae

Name of group: PRESOLARS

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Start of preparations:	1 August 2006
Date ready:	1 August 2006
Completion date:	6 months a.r.o.beam

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
28+1+5	DRAGON	No

Presolar grains contain unique information about the composition of material ejected from individual stars. Embedded in primitive meteorites, they have isotopic ratios which can deviate by orders of magnitude from the ratios found in the material of the solar system. Different stellar sources (AGB stars, supernovae, Wolf-Rayet stars, classical novae) with their differing nucleosynthesis and dust formation paths, are expected to produce dust grains with distinctive isotopic ratios.

Using ion microprobe analysis, Amari *et al.* have discovered a few SiC grains having a high ratio of ^{30}Si to ^{28}Si, believed to be a signature of formation in classical novae containing a heavy ONe white dwarf. As indicated in the nova calculations by Jose, Coc and Hernanz, the strength of the ^{30}P(p,γ)^{31}S reaction strongly affects the expected ^{30}Si/^{28}Si ratio because it is a way of destroying ^{30}P before it can decay to ^{30}Si. The reaction also strongly influences the model predictions for ejecta abundances of elements in the S–Ca region.

In the absence of relevant data on proton capture strengths, the calculation used rate estimates based on the Hauser-Feshbach model. The H-F model may be a poor guide to level properties near capture threshold for proton-rich nuclei in this mass region. We propose a direct measurement of the ^{30}P(p,γ)^{31}S strength using the ISAC-1 facility to produce a beam of accelerated ^{30}P and DRAGON to detect the reaction products.

Experimental area

ISAC-1

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

Proton beam, ISOL target
^{30}Si beam (OLIS)

Secondary channel

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

^{30}P: 0.2–0.5 MeV/u; $> 10^6$ s^{-1}
^{21}Na: any ISAC-1 energy; $>$ 40 epA (5+)

TRIUMF SUPPORT:

MRO support of DRAGON separator, gas target
Support from DAQ group (MIDAS, isdaq04, ROOT)

NON-TRIUMF SUPPORT

No major capital items.
Support of Canadian participants by NSERC Project grant (Nuclear Astrophysics at DRAGON, J.M. D'Auria *et al.*)

DRAGON will be operated in its standard mode. The principal safety concerns and mitigating measures are
-beam radioactivity: the two slit boxes where most of the beam routinely stops are surrounded by 5 cm thick Pb shields; a fence/gate exclusion system prevents access closer than 1 m to where radioactive beam can stop in the DRAGON system; no long-lived $A = 30$ activity is expected.
- high voltages to photomultiplier tubes: SHV connectors are used for all PMT cables.
- high currents in magnets: plexiglass shields prevent access to bare terminals; standard procedure is to lock out power supplies before working on magnets
- hydrogen gas target: PLC-controlled interlock system isolates the target from accelerator or separator sections in the event of power outage or massive leak in the target region; target roughing pump connects to a roof-mounted exhaust fan which has a backup fan and is connected to backup diesel power in case of power failure.

1 Scientific Justification

Presolar grains are "starry messengers" whose chemical and isotopic composition bring us information about the stellar conditions under which their material was produced and then condensed as dust. Embedded in primitive meteorites, these micrometer and sub-micrometer dust grains can show isotopic ratios which are orders of magnitude different from the blended abundances seen in the solar system. "Each grain is essentially a frozen piece of a single star that ended its life before the formation of the solar system." [1] A number of sites have been proposed for the origins of presolar grain material. They include AGB stars, supernovae, Wolf-Rayet stars and classical novae. Most of the carbide and oxide grains may be attributable to AGB stars, with novae accounting for only a small fraction of dust in the Galaxy. However, novae are believed to be a possible source of some anomalous isotopic ratios, such as an excess of ^{26}Mg from decay of radioactive ^{26}Al. Unambiguous identification of a nova origin for some presolar grains would allow their use in more detailed testing of theoretical models of classical novae.

Amari *et al.* [2] have performed ion microprobe analysis of a sample of SiC grains in search of isotopic abundance signatures indicative of origins in nova explosions. They found five SiC grains (and one graphite grain) which were possible candidates, having low ratios (compared to solar abundances) of ^{14}N/^{15}N and ^{12}C/^{13}C and very high ratio of ^{30}Si/^{28}Si (Fig. 1). One grain shows a ^{30}Si/^{28}Si ratio as high as 2.1 times the solar value. The high ^{30}Si/^{28}Si ratio is a feature of models for neon (ONe) novae but not for non-neon (CO) novae. In fact, as pointed out by Amari *et al.*, the calculation of Jose and Hernanz [3] predicts ^{30}Si/^{28}Si fractions 40-100 times solar abundance, requiring severe dilution by solar-abundance material to match even the highest ratio found in a presolar grain.

Jose, Coc and Hernanz [4] have investigated the dependence of the ^{30}Si/^{28}Si ratio on different inputs to their model for an ONe nova of 1.35 solar masses. They find that this isotopic ratio, as well as abundances of elements in the S–Ca region, depends sensitively on the strength of the ^{30}P(p,γ)^{31}S reaction. Proton capture destroys ^{30}P, which otherwise would β-decay to ^{30}Si with a 2.5 minute half-life. The nominal strength of the reaction was taken from the Hauser-Feshbach statistical model. It is questionable whether the level density is high enough to justify use of the H-F model in this relatively light, proton-rich nucleus [5]. If the strength was reduced by a factor 100 the calculated amount of ^{30}Si in the nova ejecta increased by a factor 5; if the strength was increased by a factor 100 there was a decrease in ^{30}Si by a factor 30. A large, if less dramatic, variation in abundance was predicted for stable nuclides between S and K: typically the abundance increased by a factor 10 for a change in reaction strength from 0.01 of nominal to 100 times nominal.

In a subsequent study [6] isotope ratios for several nova models were calculated and the processes of formation of SiC and other minerals in the ejecta of novae were considered. The authors concluded that SiC grains could be among the condensates of massive ONe novae and that mixing with solar-abundance material could account for observed ^{30}Si/^{28}Si ratios.

This picture might be modified or overturned by discoveries such as: (1) a shortcoming in the hydrodynamic model, or (2) a ^{30}P(p,γ)^{31}S reaction rate much larger than that estimated by the Hauser-Feshbach statistical model, or (3) a non-nova origin for the grains which have been assigned a nova origin [7] (although this seems unlikely to account for all of the C, N and Si isotopic signatures).

We propose to make direct measurements of the strength of the ^{30}P(p,γ)^{31}S reaction using the DRAGON facility at ISAC, with the aim of removing the rate uncertainty in the confrontation of nova models with isotopic abundance data from presolar grains.

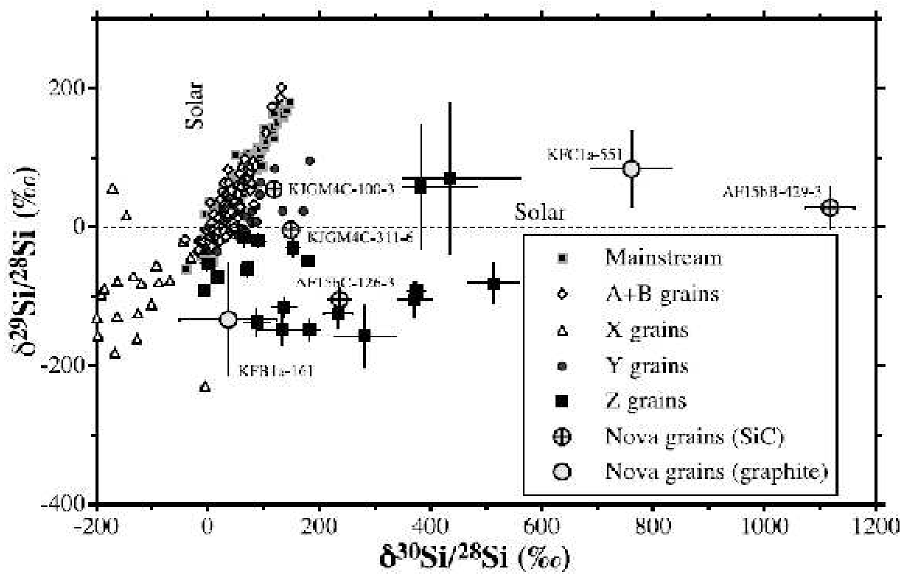

Fig. 1 Abundance ratios of silicon isotopes in selected meteoritic grains, shown as fractional deviations from solar abundances, in parts per thousand (from Ref. [6]).

2 Description of the Experiment

The proton radiative capture strength through an isolated resonance is defined as

$$\omega\gamma = \frac{2J_r + 1}{(2J_b + 1)(2J_t + 1)} \frac{\Gamma_\gamma \Gamma_p}{\Gamma}$$

where J_r, J_b and J_t are the spins of the resonance, the beam and the target, Γ_γ is the γ-ray decay width, Γ_p is the proton decay width and Γ is the total width of the resonance level (all widths in the c.m. system).

In a stellar environment where particles have a Maxwell-Boltzmann distribution of energies characterized by a temperature T (GK), the contribution to the reaction rate (cm^{3}s^{-1}mol^{-1}) from an isolated resonance is

$$N_A < \sigma v >= 154(\mu T)^{-3/2} \omega\gamma \; e^{-E_r/kT}$$

where μ is the reduced mass, E_r the resonance energy in the c.m. system, N_A is Avogadro's number, k is Boltzmann's constant and $\omega\gamma$ is in meV.

At high resonance energies Γ_p is typically much larger than Γ_γ and so $\Gamma_\gamma\Gamma_p/\Gamma \approx \Gamma_\gamma$ and $\omega\gamma$ is limited by electromagnetic transition rates. In this region of mass and excitation energy $\omega\gamma$ always is below 10 eV and usually is considerably smaller, depending on the nuclear structure of the resonance level and of lower-lying levels. At low resonance energies typically it is Γ_p which sets the limit, due to the Coulomb and centrifugal barriers. Nuclear structure in the form of poor wave-function overlap between the resonance level and beam⊕target may result in further reduction of Γ_p. The combined effect of the Coulomb barrier and the Maxwell-Boltzmann distribution of reactant energies results in the Gamow peak — the region of excitation energies most likely to contribute to the reaction rate (barring suppression due to nuclear structure issues). For ^{30}P+p at T=0.33 GK the Gamow peak comes at 0.35 MeV with $1/e$ width 0.23 MeV.

Information on the excited states of ^{31}S has come mostly from neutron pickup reactions on ^{32}S [8]; a recent heavy-ion fusion-evaporation experiment [9] excited three additional levels in the 6–7 MeV region. These levels and levels in the mirror nucleus ^{31}P are shown in Fig. 2. The number of known levels in the two isobars is about the same for each, but few spins have been established in ^{31}S.

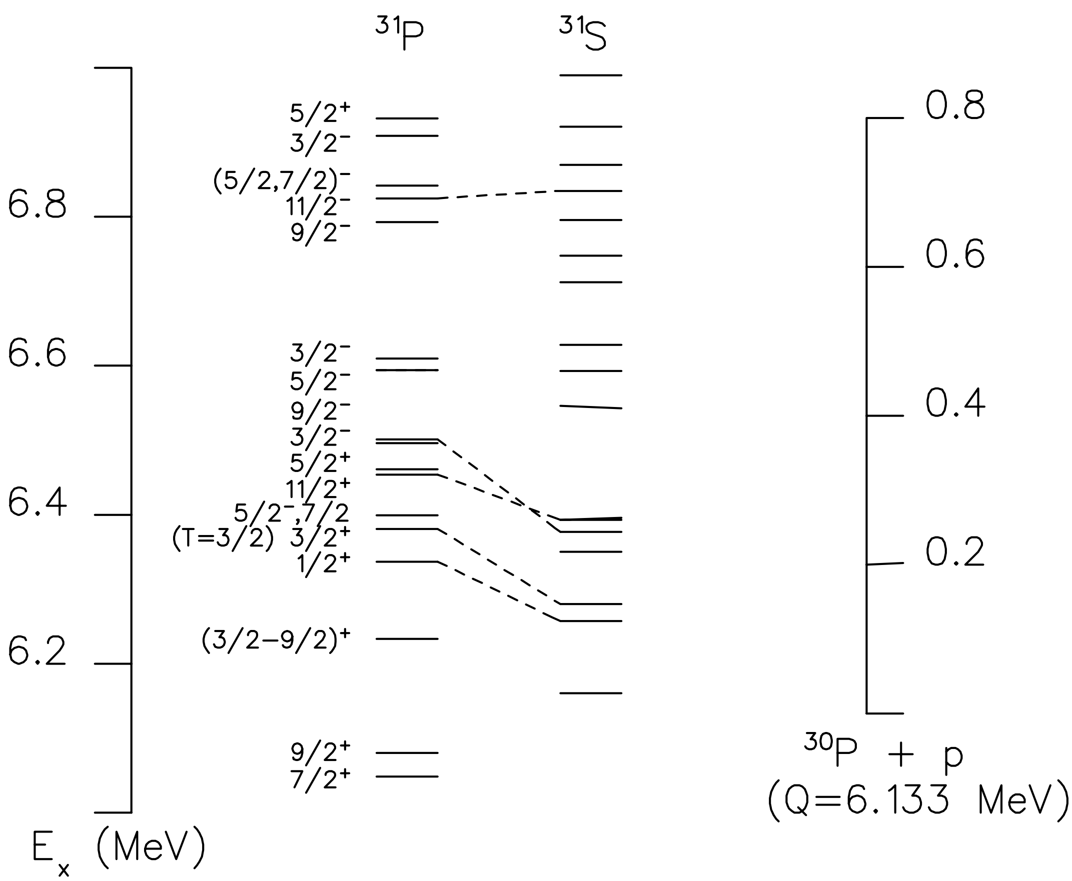

Fig. 2 Excited states of ^{31}P and ^{31}S between 6 and 7 MeV, from the tabulation of Endt [8] and the results of Refs. [9][10].

The reaction yield, the probability of a radiative capture event per incident beam particle, for a target which is thick compared to the resonance width is

$$Y = \frac{1}{2}\,\lambda^2\,\frac{M_b + M_t}{M_t}\,\frac{\omega\gamma}{\epsilon}$$

where λ is the c.m. deBroglie wavelength, M_b and M_t the masses of beam and target nuclei and ϵ is the lab-frame stopping cross section per target atom in units matching those of λ^2 and $\omega\gamma$.

In Figure 3 the solid lines show the resonance strength $\omega\gamma$ which would be required to produce a detection rate of 1 per hour at the indicated beam intensity, assuming a 20% coincidence detection efficiency. At this rate, during a 12-hour shift it would be possible to measure a resonance yield with ≈30% statistical accuracy. The broken line gives the single-resonance strength which would match the reaction rate predicted by the Hauser-Feshbach model at a temperature T=0.33 GK, the maximum reached in the nova calculations of Jose, Coc and Hernanz [4]. Open symbols plot measured strengths for two other odd-odd isospin-0 nuclei of the sd shell (^{22}Na and ^{26}Al) and for ^{30}Si, a likely contaminant. The solid triangles above the lower axis show the energies of relevant ^{31}S levels known from previous work [8].

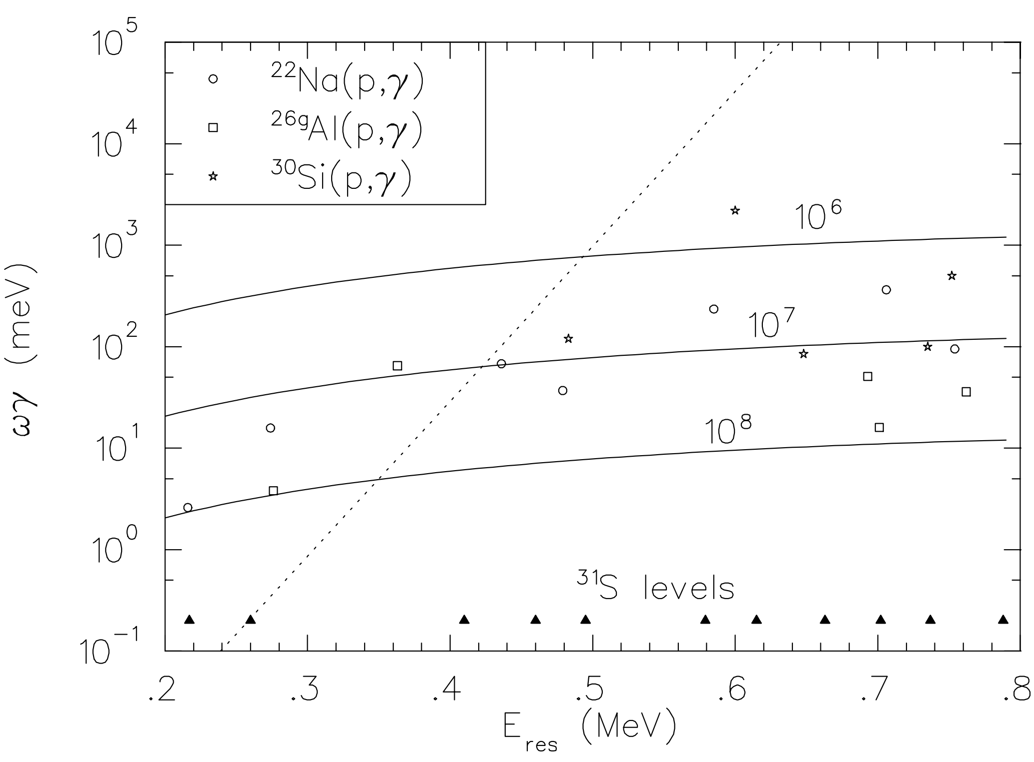

Fig. 3 The broken line is the single-resonance strength $\omega\gamma$ which matches the Hauser-Feshbach estimate for the ^{30}P(p,γ)^{31}S rate at T=0.33 GK. The solid lines show the strengths that yield 1 count/hour at the indicated beam intensities. The open symbols present measured strengths for selected nuclei, while the solid triangles indicate the resonance energies for known levels in ^{31}S (omitting high-spin levels).

It should be noted that a recent study of the ^{32}S(^{3}He,α)^{31}S reaction at beam energy 25 MeV [10] clearly saw levels corresponding to resonance energies 260$\pm$5 keV and 589/615 keV, but none of the levels at intervening excitation energies that were found at beam energy 12 MeV [11].

The simple shell model picture is that the ^{32}S ground state has 1d$_{5/2}$ and 2s$_{1/2}$ shells filled and the ^{30}P ground state is ^{32}S with 1 proton and 1 neutron removed from the 2s$_{1/2}$ shell. Reality near the middle of the sd shell is much different, with significant multiparticle-multihole configurations present in the ground states. For example, the truncated shell model calculation of Wildenthal *et al.* [12] found the amplitude-squared of the simple configurations to account for only 50% of the ground state in ^{30}P and 39% in ^{32}S. It would not be surprising to find that reactions which add nucleons to form ^{31}S excite different states from those seen in 1-neutron pickup; indeed, this was the case for the ^{29}Si(^{3}He,n)^{31}S reaction [13] which did not excite the levels at E_r=0.26, 0.46, 0.50 or 0.62 MeV. The heavy-ion fusion-evaporation reaction ^{12}C(^{20}Ne,n)^{31}S [9] excited yet other states (albeit ones which are irrelevant for proton capture because of their high spins).

The importance of the ^{30}P(p,γ)^{31}S reaction has spurred activity at various laboratories, in particular to improve our knowledge of the excited states of ^{31}S within 1 MeV of the proton capture threshold. They include ^{32}S(p,d)^{31}S [14] and a ^{31}P(^{3}He,t)^{31}S(p)^{30}P study [15] in progress. The latter study has identified at least one new level (E_x=6325 keV, E_r=192 keV) in addition to previously known levels, with <3 keV uncertainty in excitation energies. A recent experiment on β-decay of ^{31}Cl to ^{31}S [16] observed proton decay of numerous ^{31}S states, but at excitation energies 6921 keV and above which are not expected to be significant for novae.

Experiments that establish spins, parities and precise excitation energies of ^{31}S excited states can provide weak upper limits to $\omega\gamma$ but for useful upper and lower limits it is essential to do experiments with a ^{30}P beam: (a) nuclear structure effects can (and typically do) reduce $\omega\gamma$ by orders of magnitude from limits based on full overlap of wave functions or maximum gamma transition rates and (b) states important for proton capture may not have been excited in other reactions. For levels just above the proton capture threshold, a proton transfer reaction such as ^{30}P(^{3}He,d)^{31}S complements a capture experiment, because it may be able to determine wavefunction overlap without having a huge suppression due to the Coulomb barrier. A prime candidate for such a study is the $\frac{1}{2}^{+}$ level at E_x=6257 keV (E_r=124 keV). (A measurement of level meanlife and the Γ_p/Γ_γ branching ratio might, in a restricted range of excitation energies, find a ^{31}S level whose $\omega\gamma$ could be measured without use of a ^{30}P beam.)

In a recent paper [17], the ^{30}P(p,γ)^{31}S reaction rate in novae is estimated based on what is known about the excited states of ^{31}S and the mirror nucleus ^{31}P. The conclusion of the authors is that at $T \approx 0.3$ GK the rate is dominated by contributions from the resonances at 410 and 460 keV. However, it should be noted that their rate estimates for those resonances rest on the arbitrary assumption of a proton spectroscopic factor 0.1 and a gamma partial lifetime 4 fs.

A conclusive result concerning the ^{30}P(p,γ)^{31}S reaction rate at ONe nova temperatures would be that either
(1) there are one or more resonances which contribute with many times the rate estimated by the Hauser-Feshbach model ("high lower limit" scenario), or

(2) the sum of all contributions is not greater than the H-F estimate ("low upper limit" scenario).
These possibilities suggest a staged search: look first for a strong resonance at one of the known levels in ^{31}S; if that fails, scan for a strong resonance over a range of energies; if that fails, reduce the upper limit of the reaction rate to the H-F value or below.

Given our goal of determining whether or not the ^{30}P(p,γ)^{31}S reaction rate at $T \approx 0.33$ GK is many times greater than the Hauser-Feshbach estimate, it is clear from Figure 3 that resonances above 0.6 MeV cannot contribute significantly due to the limit in maximum $\omega\gamma$. The region with the greatest discovery potential for a capture experiment lies from resonance energy 0.5 MeV downward. Assuming a beam intensity of 10^7 s^{-1} and requiring the ability to set an upper limit of 0.5 counts/hour (e.g. < 5 counts in a 10-hour run) if no resonance yield is seen at a given energy, the reaction rate limit R_i at resonance energy E_i relative to the Hauser-Feshbach estimate R_{HF} is given in Table 1.

Table 1 Ratio of the rate limit R_i from a yield $\leq$0.5 count/hour for a resonance at energy E_i, to R_{HF} the Hauser-Feshbach estimate at temperature T=0.33 GK, assuming beam intensity 10^7 s^{-1}.

E_i (MeV)	0.25	0.30	0.35	0.40	0.45	0.50
R_i/R_{HF}	120	25	5	1	0.2	0.04

Our measurement sequence will be the following

- with a ^{30}Si beam, excite the resonance at E_r=0.483 MeV and use it for checkout and calibration of DRAGON detectors.
- with a ^{21}Na beam, calibrate the monitor for intensity of the positron-emitting component of the beam
- with a ^{30}P beam measure at the energies of known levels in the range 0.25 to 0.5 MeV
- scan with energy steps of 10 keV at all other energies down to 0.25 MeV or a higher limit, if dictated by available beam intensity, corresponding to R_i/R_{HF}=5

At beam intensity of 10^6 s^{-1} only a minimal experiment to measure $\omega\gamma$ for states at 0.495, 0.460 and 0.410 MeV and survey down to 0.43 MeV would be feasible. At 10^7 s^{-1} a survey down to 0.35 MeV becomes viable and at 10^8 s^{-1} to below 0.30 MeV.

If no strong resonance emerged from the study so that no useful "high lower limit" could be set, we would at least have established a (beam-intensity dependent) range of excitation energies over which the upper limit on the ^{30}P(p,γ)^{31}S rate was less than the Hauser-Feshbach estimate.

3 Experimental Details

The experiment uses the DRAGON facility at ISAC. DRAGON consists of a windowless gas target cell, a high-efficiency array of BGO γ-ray detectors, a mass separator to suppress unreacted beam and transmit the heavy reaction product to an end detector. The separator is tuned to pass one charge state of the recoils; the fraction of beam that is in the selected charge state is blocked at slits after the first of two mass-separation stages. This experiment will resemble in many ways a previous measurement of radiative capture yields in the reaction ^{21}Na(p,γ)^{22}Mg [18]. Details of the equipment and experimental techniques are presented in that reference and in facility papers [19],[20]. In the following we focus on issues which will be specific to this experiment.

Acceptance of the separator is not a concern for this experiment. The maximum lab angle of recoil ^{31}S ions is 10 mrad for 1-gamma decay to the ground state of a resonance at 0.25 MeV, and 7 mrad for a resonance at 0.5 MeV in comparison to the ≈17 mrad for full acceptance by DRAGON. Excitation energies are ≈6.5 MeV, enough energy to provide above-threshold signals in the BGO array whatever the decay scheme; the array efficiency depends upon the number and energies of γ-rays in the decay branches, which can be deduced with sufficient accuracy from the BGO data. Efficiency is approximately 50% if only a single γ-ray of the decay has energy above the trigger threshold.

The range in resonance energies spanned by a given energy of incident beam depends on the pressure in the gas target. For central cell pressure of 6 Torr the span will be ≈15 keV. When measuring at a known excited state, as many as three runs would be taken: one run would position a resonance of the nominal energy at the centre of the gas cell; if no yield was measured at that energy, a second run 10 keV lower in energy would be made; a third run 10 keV higher in energy would be made if the resonance didn't appear in the first or second run. When doing a scan at energies away from known levels, steps of 10 keV would provide good overlap in energy coverage.

Background in the BGO array comes from the room (mainly ^{40}K and ^{228}Th) plus positron decay of any beam halo which is stopped at the target cell. With a 1.5 MeV trigger threshold the room background rate is 50 Hz while the rate due to beam can be many 100's per second, depending sensitively on accelerator tune. During E989 a halo-scraping iris was installed 25 cm upstream of the target cell, where it could be shielded from the BGO array; the iris reduced background from a ^{26}Na contaminant by a factor ≈4.

Background in the recoil ion detector is "leaky beam" which is transmitted by the separator. For (p,γ) reactions it comes as a peak slightly above the energy of desired recoils, with a low-energy tail which can mask the recoils if the capture yield is much smaller than the leaky beam transmission factor. The fraction transmitted is energy dependent and is of order 10^{-9} at 0.25 MeV/u and 10^{-10} at 0.5 MeV/u. We would use a double-sided silicon strip detector; in previous (p,γ) measurements the DSSSD energy information has allowed the elimination of part of the leaky-beam background, but we do not rely on that possibility for this proposal.

Good events are identified by requiring a gamma-recoil coincidence with the correct timing. Recoil ion times-of-flight can vary within ±1% for the ^{30}P(p,γ)^{31}S reaction, as much as ±30 ns at the lowest proposed beam energy. Accidental coincidences within this time window constitute a background which, assuming BGO background rate of 100 Hz and leaky beam transmission of 10^{-9}, corresponds to a rate of ≈0.002 counts/hour at beam intensity 10^8 s^{-1}.

Isobar contamination in the form of ^{30}Si is likely to be an issue. It poses two potential problems: beam normalization is more difficult; background may increase due either to more accidental coincidences or to real events from the ^{30}Si(p,γ)^{31}P reaction (whose known resonances are plotted in Figure 3). The amount of ^{30}P in the beam will be measured using a device built by E989 to identify a beam contaminant which decays by positron emission. The device detects 511 keV γ-rays from decay of positrons emitted by the fraction of beam that is stopped on the mass-selection slits at the end of the first stage of the separator, so the charge-state distribution must be measured in order to calculate the amount of ^{30}P beam incident on the gas target.

Background due to ^{30}Si(p,γ)^{31}P at resonances below 0.483 MeV is not expected to be a problem: a survey at energies down to 0.2 MeV [21] found none using a setup which did see the $\omega\gamma\approx 80$ μeV resonance at E_p=0.225 MeV in ^{27}Al(p,γ)^{28}Si. However, a limit $\omega\gamma\leq 240$ meV for a resonance at 0.418 MeV has been suggested by Iliadis *et al.* [5] and we will use part of the setup time with ^{30}Si beam to measure yield at this energy. In radioactive beam runs, after the ^{30}Si pilot beam has been used to tune accelerators to each new beam energy, we will confirm that no ^{30}Si(p,γ)^{31}P resonance is present before switching to the radioactive beam. The exact energy of a contaminant resonance can be inferred from its position within the extended gas target, which is deduced from the hit pattern in the BGO array. If such background appears during the energy scan, the ^{30}P beam energy will be adjusted to just miss the Si resonance, sacrificing a few keV of the excitation function. If a contaminant resonance should overlay a known ^{31}S state, a separate run would be taken with the Si strip detector replaced by a gas-filled ionization chamber, to attempt E-ΔE separation of the isobars.

The stopping cross section of P ions in H_2 gas will be calculated from measurements of beam energy loss through a known thickness of target gas.

4 Readiness

The DRAGON facility is ready.

The stable beam of ^{30}Si should be available from the off-line source (OLIS) following installation in fall/winter 2006 of the recently-purchased ECR unit.

The major uncertainty is the provision of a radioactive phosphorus beam. A high-power target of TiC should be capable of producing $\approx 10^{11}$ s^{-1} of ^{30}P from a 75 μA proton beam [22]. However, a key unknown is the ^{30}P diffusion/effusion time out of the target and into the ion source, compared to the 2.5 min half-life of ^{30}P. The atomic ionization potential of P (10.5 V) rules out the existing surface ionization and laser ionization sources of ISAC. The most optimistic timetable assumes useful yield from a high-power TiC target and FEBIAD source, tests of which could take place early in the Fall 2006 beam schedule. If this combination has inadequate release and/or ionization efficiency, development of an alternative target material and an ECR source would be necessary and the timescale becomes considerably longer.

5 Beam Time required

We request 28 shifts of ^{30}P beam, 1 shift of ^{21}Na beam and 5 shifts of ^{30}Si beam.

The Si beam time is required for general checkout of the DRAGON facility and includes calibration of detector gains and TOF offsets using a known ^{30}Si(p,γ)^{31}P resonance at 0.483 MeV. The yield at resonance energy 0.418 MeV will be measured.

The ^{21}Na beam shift will be used to make a direct calibration of the efficiency of the positron detection system. We require a pure, positron-emitting beam with current at least 40 epA (5+) delivered to DRAGON.

The ^{30}P beam time will be used as follows:
12 shifts for known levels – 4 levels x 3 energies/level x 1 shift/energy
13 shifts for energy scan – 13 energies x 1 shift/energy
3 shifts for periodic major retunes of beam, plus contingency
Minimum usable intensity is 10^6 s^{-1}, optimum intensity is $\geq 10^7$ s^{-1}.

The ^{30}P time includes 2 hours tuning and check for background resonance with a Si pilot beam with each change of beam energy.

6 Data Analysis

We will use the ROOT analysis system developed for DRAGON experiments. Offline replay will be done using the DRAGON DAQ computer *isdaq04*. The existing analysis package handles the digitizers for the 30-element BGO array, the 32-channel strip detector and beam monitor counters. Analysis techniques established for experiments such as E989 (^{26}Al(p,γ)^{27}Si) cover all anticipated needs of this proposal.

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