TRIUMF – EEC

NEW RESEARCH PROPOSAL

Exp. No: S1122

Date: Oct. 27, 2006

Measurement of the $^{33}S(p,\gamma)^{34}Cl$ reaction rate with DRAGON

Name of group **DRAGON**

Spokesperson(s) for Group

A. Parikh

Email address(es)

xrayburst@gmail.com

Current Members of Group: (name, institution, status, % of research time devoted to experiment)

J. A. Clark	Yale University	Research Associate	15
B. Davids	TRIUMF	Research Scientist	5
C. Deibel	Yale University	Graduate Student	15
U. Greife	Colorado School of Mines	Associate Professor	10
D. A. Hutcheon	TRIUMF	Research Scientist	20
J. Jose	UPC/IEEC Barcelona	Associate Professor	5
A. Laird	University of York	Lecturer	10
A. Parikh	Yale University	Graduate Student	25
P. Parker	Yale University	Professor	15
C. Ruiz	University of York/TRIUMF	Research Associate	10
M. Trinczek	TRIUMF	Research Associate	10
C. Vockenhuber	Simon Fraser University/TRIUMF	Research Associate	20
C. Wrede	Yale University	Graduate Student	15

Date for Start of Preparations: Now

Beam time requested (# of 12-hr shifts): 18+3

Date Ready:
January 2007

Experimental Area:

ISAC

Completion Date:
6 months after receiving beam

SUMMARY

The analysis of miniscule inclusions in primitive meteorites has shown anomalous isotopic ratios (relative to solar) largely characteristic of the conditions thought to prevail in various astrophysical environments. AGB stars and supernovae are thought to be major sources of these “presolar” grains. Recently, several grains have been identified with isotopic signatures that have been theoretically predicted for the ejecta of nova explosions on oxygen-neon white dwarfs. A possible “smoking gun” for a grain of nova origin is a large ^{33}S abundance: nucleosynthesis calculations predict as much as 150x the solar abundance of ^{33}S in the ejecta of oxygen-neon novae. This overproduction factor may, however, vary by factors of at least 0.1 – 3 because of uncertainties in the ^{33}S(p,γ)^{34}Cl reaction rate at nova temperatures. This rate also plays a critical role in determining whether or not gamma-rays emitted in the decay of the metastable state of ^{34}Cl ($t_{1/2}$ = 32 m) may be observed from novae.

Direct examinations of the ^{33}S(p,γ) reaction in the past have only studied resonances down to E_R^{CM} = 434 keV. At nova temperatures, lower-lying resonances may play a dominant role. As such, we propose to search for resonances below E_R^{CM} = 434 keV and measure their strengths using a stable ^{33}S beam in conjunction with the DRAGON facility. We will also re-measure the strengths of those resonances above E_R^{CM} = 434 keV that are important for the ^{33}S(p,γ)^{34}Cl reaction in nova explosions.

BEAM AND SUPPORT REQUIREMENTS

PROTON BEAM/ TARGET: (energy, intensity, pulse characteristics, ion source)

Energy (in MeV): **N/A**

Intensity (in µA):

Pulse Width (in nanoseconds):

Rep Rate: Choose one of: normal; 1/5; other (Place response here):

PRODUCTION TARGET: **N/A**

$1AT_1$: 1cmC; 1cmBe or $1AT_2$: 10cmBe (Place response here):

ISAC: Ion Source: SURFACE; FEBIAD; LASER; ECR; OLIS

(Place response here): OLIS

SECONDARY CHANNEL/ISAC BEAMLINE (Place response in the space below):

1. **For Base, choose one from: M9A; M9B; M11; M13; M15; M20; 1B;2C; PIF; NIF**
2. **For ISAC, choose one from GPS1; GPS2; GPS3; TRINAT; TITAN; BNMR; BNQR;POLARIMETER;YIELD,8π**
3. **For ISAC-I, choose one from DRAGON; TUDA; HEBT**
4. **For ISAC-II, choose one from : SEBTø; SEBT1; SEBT2; SEBT3**

ISAC-1: DRAGON

SECONDARY BEAM (particle type/isotope, energy, energy width, solid angle, spot size, intensity, beam purity, target, special characteristics)

Please list all isotopes:

Beams to be produced with OLIS.

^{33}S, 0.2 – 0.6 MeV/u, 1 pnA or more at DRAGON
^{35}Cl or ^{37}Cl for charge-state studies, 0.2 – 0.6 MeV/u, 100 enA or more at DRAGON

EXPERIMENTAL FACILITY(IES) TO BE USED:

DRAGON facility in the ISAC-1 experimental hall

TRIUMF RESOURCES REQUESTED:

(Summarize the expected TRIUMF resources needed for the experiment. Identify major capital items and other costs that will be requested from TRIUMF. Note: Technical Review Forms must be provided before allocation of beam time.)

No major capital items.

Continued infrastructure support from TRIUMF for DRAGON at ISAC-1, including assigned personnel.

Special support for the production of ^{33}S beam of charge-state 2+ with OLIS.

EXTERNAL FUNDING SOURCES (Summarize expected non-TRIUMF sources of funding for the experiment.)

Support of Canadian participants by NSERC Project grant (Nuclear Astrophysics at DRAGON, J.M. D'Auria et al.)

SAFETY

(Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.)

Standard DRAGON procedures for stable beam experiments will be observed.

1 Scientific Justification

1.1 Presolar Grains of Nova origin

Presolar grains embedded within primitive meteorites can provide information on stellar evolution and nucleosynthesis in the sites where they formed. They are identified by their isotopic compositions, which may be orders of magnitude different from that of the solar system. To date, carbonaceous (e.g. diamond, SiC, graphite), oxide (e.g. corundum, TiO), silicate, and silicon nitride grain types have been identified; ratios of carbon, nitrogen, oxygen, neon, magnesium and silicon isotopes, for example, have been measured. Most of the studied grains carry isotopic signatures thought to be indicative of origins in asymptotic giant branch (AGB) stars, red giant stars or supernovae.

Recently, several grains exhibiting major-element isotopic ratios ($^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{30}Si/^{28}Si$) characteristic of classical nova explosions were discovered [Ama01]. (Previously, grains of nova origin had been identified purely by large trace $^{22}Ne/^{20}Ne$ ratios, with the excess ^{22}Ne supposedly arising from the decay of ^{22}Na created in a nova [Cla75].) Another telltale sign of a nova may be the observation of large (relative to solar) amounts of ^{33}S (stable, 0.75%) in grains [Jos04, Ama01]; models of explosions on 1.35 $M_{\odot}$ ONe white dwarfs give an overproduction factor $X_{33}/X_{33_{\odot}}$ = 150 for this isotope [Jos01]. Indeed, "the predicted ^{33}S excess may provide a remarkable signature of a classical nova event" [Jos04]. Sulfur has been observed in the ejecta of novae (e.g. Nova Aql 1982 [And94, Sni87]), and equilibrium condensation calculations predict the incorporation of sulfides into SiC grains [Lod95]; however, no sulfur isotopic ratios have been determined yet. Sulfur measurements are complicated by how H_2SO_4 is used in the separation of SiC, introducing strong contamination; nevertheless, these data are hoped for in the near future. (The analysis of some graphite grains showed solar S isotopic ratios, but these results are suspected to suffer from contamination [Jos04].)

The most important destruction mechanism for ^{33}S in nova explosions is the $^{33}S(p,\gamma)^{34}Cl$ reaction (Q = 5143 keV). (Nova explosions are thought to occur with peak temperatures T = 0.1 – 0.4 GK, but the creation of elements above silicon in these proton-rich environments require T > 0.3 GK due to the large Coulomb barriers involved [Jos01].) This rate has been calculated using both the Hauser-Feshbach statistical model [Ili01] and the available experimental data [Jos01]. (Note that ^{34}Cl has an isomeric state located at E_x = 146 keV; we will denote the ground state (0+; $t_{1/2}$ = 1.53 s) as ^{34g}Cl and the isomeric state (3+; $t_{1/2}$ = 32 m) as ^{34m}Cl. The general nucleus will be written simply as ^{34}Cl.) Iliadis et al. (2002) explore the effect of varying the $^{33}S(p,\gamma)^{34}Cl$ rate (as found using Hauser-Feshbach calculations) in various ONe nova models. They find decreases in the ^{33}S nova abundance by factors of ~ 1000 when the rate is multiplied by 100, and increases by factors of ~3 when this rate is divided by 100 [Ili02]. Jose et al. (2001) calculate the $^{33}S(p,\gamma)$ rate using experimental data for the resonance energies, along with calculated strengths for the threshold states (as no experimental measurements of these strengths exist, see below) [Jos01]. They determine both the $^{33}S(p,\gamma)^{34g}Cl$ and $^{33}S(p,\gamma)^{34m}Cl$ rates at nova temperatures using information about the gamma-decay branching ratios for the important resonances [End90]. To reflect the uncertainty in their calculated strengths, they include an arbitrary factor f = 0 – 1 in their rates. If f = 1, their rate for the $^{33}S(p,\gamma)^{34}Cl$ reaction agrees with that of Iliadis et al. (2001) to a factor of ~3 over nova temperatures. As the resonance strengths of Jose et al. (2001) were found by scaling calculated upper limits by 0.1, a more conservative range for f might be 0 – 10. This would imply that the

$^{33}S(p,\gamma)^{34}Cl$ rate calculated using currently available *experimental* information leads to variations by factors of at least ~0.1 – 3 (i.e. $X_{33}/X_{33_{\odot}}$ ~ 15 - 450) in the amount of ^{33}S produced in nova explosions, given the sensitivity study of Iliadis et al. (2002). The existence and impact of new resonances must also be explored.

As ^{33}S measurements in presolar grains are expected, and given the typical uncertainty of ~ 5% in isotopic ratio determinations [e.g. Ama01], experimental information on proton-threshold resonances in $^{33}S(p,\gamma)^{34}Cl$ is desired to reduce the nuclear physics uncertainty in the amount of ^{33}S produced in nova explosions.

1.2. Observing ^{34m}Cl β-delayed gamma-rays

The observation of gamma-rays emitted following the β+ decay of ^{34m}Cl (E_γ = 1.177, 2.218, 3.304 MeV, as well as from pair-annihilation – see fig. 1) has been proposed as a possible signature of a classical nova [Lei87, Coc99]. The short half-life (32 m) of ^{34m}Cl (55.4% β+ to excited states of ^{34}S, 44.6% γ-decay to ^{34g}Cl) requires the ambient medium about an astrophysical event to clear rapidly enough following the nucleosynthesis of ^{34m}Cl to permit the escape of gamma-rays; it is thought that novae may provide a suitable environment [Lei87]. Coc et al. (1999) consider thermally-induced transitions between ^{34m}Cl and ^{34g}Cl in an astrophysical plasma, and find the effective half-life of ^{34m}Cl drops from the laboratory value of 32 m down to ~ 1 s over T = 0.1 – 0.4 GK [Coc99]. Jose et al. (2001) adopt this effective lifetime in their model of a nova explosion on a 1.35 $M_\odot$ white dwarf, and find a mean mass fraction $X(^{34m}Cl) = 7 \times 10^{-7}$ in the ejecta, 30 minutes after the peak temperature T = 0.33 GK [Jos01] (at which most of the ^{34}Cl was produced). This might be compared to the amount of the β-delayed γ-emitter ^{22}Na ($t_{1/2}$ = 2.6 y; E_γ = 1.275 MeV, and from pair-annihilation) expected in the ejecta from a nova explosion on a 1.35 $M_\odot$ white dwarf: $X(^{22}Na) \sim 10^{-3}$ [Jos99]. Given the fact that gamma-rays from the decay of ^{22}Na have not yet been observed, the intensity of gamma-rays from the decay of ^{34m}Cl would seem to be too low for current telescopes.

In nova explosions, ^{34m}Cl is formed only through the $^{33}S(p,\gamma)^{34m}Cl$ reaction since ^{34}Ar does not populate the isomer in its β-decay [End90]. A dramatic increase in the $^{33}S(p,\gamma)$ rate, through actual measurements of the important resonance strengths and/or the discovery of new resonances, may once again show gamma-rays from the decay of ^{34m}Cl to be viable nova observables.

1.3 Spectroscopy of ^{34}Cl

Figure 2 shows the level structure of ^{34}Cl, with the rough energy regions of interest (i.e. the Gamow peaks) for the $^{33}S(p,\gamma)$ reaction at T = 0.2, 0.3, and 0.4 GK indicated. The most recent direct studies of resonances in the $^{33}S(p,\gamma)^{34}Cl$ reaction were made by Dassie et al. (1977) (who examined resonances from E_x = 6.13 – 7.08 MeV [Das77]) and Waanders et al. (1983) (who examined resonances from E_x = 5.58 – 6.32 MeV [Waa83]). Resonance energies, strengths, J^π values and γ-decay schemes were found in both studies. Based on the gamma-ray spectra, these two groups also deduced three states in ^{34}Cl between

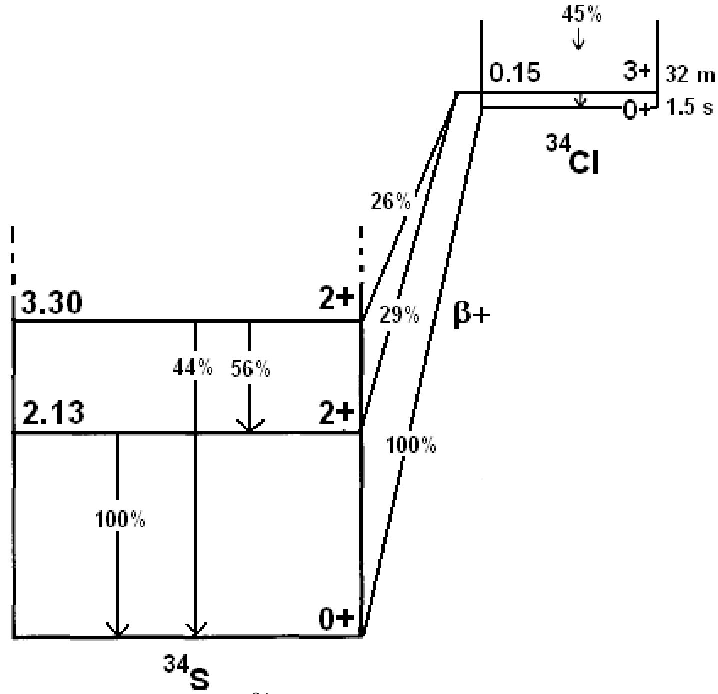

Fig. 1: Decays of the ground and metastable states of ^{34}Cl. Excitation energies are in MeV. Not shown here are β+ decays of ^{34m}Cl to the 4.11, 4.69, and 4.88 MeV states of ^{34}S (0.5, 0.03, 0.04%, respectively). Figure is after [End90].

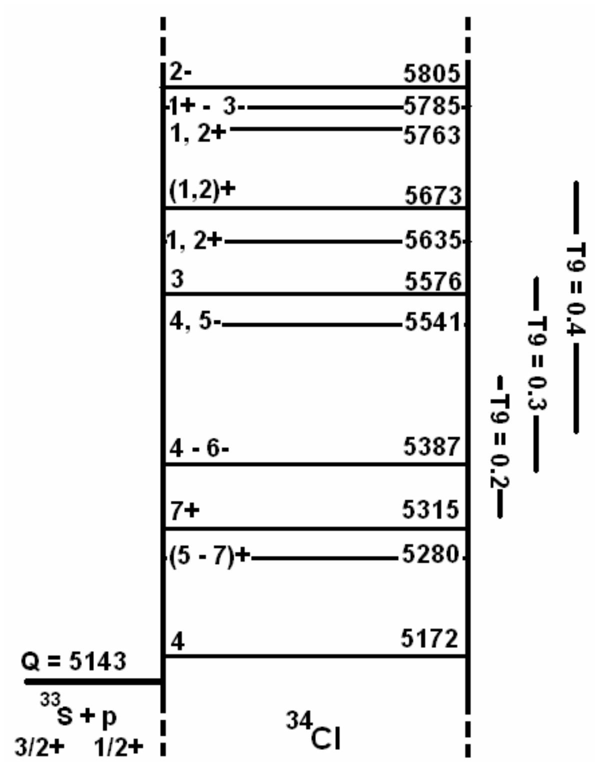

Fig. 2: The level structure of ^{34}Cl above the ^{33}S+p threshold. All energies are in keV. The energy regions of importance at nova temperatures are indicated. The Q-value of the ^{33}S(p,γ) reaction is from [Aud03]; J^{π} values and excitation energies are from [End90] (converted from E_p when possible). Note that [End90] considers the state at E_x = 5.28 MeV as identical to the state at E_x = 5.315 MeV – but see [Nan77].

the ^{33}S+p threshold and E_x = 5.576 MeV (the lowest-energy resonance that has been directly observed), at E_x = 5.17, 5.39 and 5.54 MeV. Studies of the (α,d) and (^{3}He,p) reactions indicated the existence of another state close to the proton threshold at E_x = 5.28 MeV [Del76, Nan77]. Finally, Baumann et al. (1978) and van der Poel et al. (1982) observed a level at E_x = 5.315 MeV through measurements of the (^{12}C, $\alpha n\gamma$) and (^{12}C,pnγ) reactions, respectively [Bau78, Van82]. This information is summarized in tables 1 and 2.

As is seen in table 2, experimental information on the strengths of the states just above the ^{33}S+p threshold in ^{34}Cl (and below E_x = 5.576 MeV) is not known. The J^π values of table 2 indicate that these states would not be s or p-wave resonances. Proton and/or gamma partial widths Γ_p, Γ_γ have not been measured for these states; the spectroscopic factors are also unknown. As ^{34}Cl has an equal number of protons and neutrons, no additional information can be obtained by appealing to the characteristics of a mirror nucleus.

Jose et al. (2001) calculated the strengths $\omega\gamma$ of four of the threshold states by assuming $\Gamma_p << \Gamma_\gamma$ so that

$$\omega\gamma \equiv \frac{(2J+1)}{(2J_1+1)(2J_2+1)} \times \frac{\Gamma_\gamma \Gamma_p}{\Gamma} \approx \omega\Gamma_p ,$$

where J, J_1 and J_2 are the spins of the state in ^{34}Cl, the projectile and the target, respectively. They then found Γ_p by estimating upper limits based on single-particle calculations, and then scaling these by 0.1 [Jos01]: see table 2.

1.4 Current rate

In a stellar environment, the resonant component of the nuclear reaction rate is calculated as (in $cm^3s^{-1}mol^{-1}$)

$$N_A < \sigma v > = 1.540 \times 10^{11} (\mu T_9)^{-3/2} \sum_i (\omega\gamma)_i \exp(-11.605 E_{R,i}^{CM} / T_9) \tag{1}$$

where T_9 is the temperature in GK, μ is the reduced mass in amu, the $E_{R,i}^{CM}$ are the center-of-mass resonance energies in MeV, and the $(\omega\gamma)_i$ are the strengths in MeV. The sum allows for the contributions of all the resonant states through which the reaction may proceed at the temperature of interest. Note that eq. (1) is valid only if these states are narrow ($\Gamma << E_R^{CM}$) and isolated ($E_{R,i} - E_{R,j} >> \Gamma_i$).

Since the proton-capture rates to both ^{34g}Cl and ^{34m}Cl are desired, eq. (1) must be multiplied by a factor G_i (or $1-G_i$) to account for the population of the ground and/or isomeric states in the gamma-decay of the compound nucleus. Gamma-ray branching ratios for the resonances in Table 1, as well as the possible resonances at E_R^{CM} = 244 and 398 keV have been measured by Waanders et al. (1983). In addition, Dassie at al. (1977) and Van der Poel et al. (1982) measured the gamma-decay schemes of the possible resonances at E_R^{CM} = 29 and 172 keV, respectively [Das77, Van82]. In the calculations below, we will simply discuss the overall ^{33}S(p,γ)^{34}Cl rate.

Table 1: Experimental information for $E_R^{CM} < 1$ MeV resonances in $^{33}S(p,\gamma)$, from direct measurements [End90]. Proton energies have been converted to E_R^{CM} and E_x using masses in [Aud03].

E_R^{CM} (keV)	E_x (keV)	J^π	$\omega\gamma$ (meV)
434(1)	5576(1)	3	50(13)
492.5(2)	5635.3(2)	(1,2+)	88(25)
530(1)	5673(1)	(1,2+)	88(38)
620(1)	5763(1)	(1,2+)	8(4)
642(1)	5785(1)	(1+ - 3-)	50(25)
663(1)	5805(1)	2-	50(25)
709.7(3)	5852.5(3)	(2,3)-	63(25)
754(1)	5897(1)	2	63(25)
798(1)	5940(1)	2+	100(25)
887(2)	6030(2)	(1,2)+	50(25)
945.9(2)	6088.7(2)	(1,2+)	125(38)
993(1)	6135(1)	(1+ - 3+)	88(25)
998(1)	6141(1)	(1,2+)	138(38)

Table 2: Possible low-energy resonances in $^{33}S(p,\gamma)$ [End90]. Excitation energies have been deduced from gamma-ray cascades or indirect measurements (see text); these have been converted to E_R^{CM} using Q = 5142.75 keV [Aud03]. Resonance strengths are 10% of calculated upper limits [Jos01]. Note that both [End90] and [Jos01] consider the E_x = 5280 keV state to be identical to the E_x = 5315 keV state; for the strength of this possible resonance, we use 10% of the E_x = 5315 keV strength.

E_R^{CM} (keV)	E_x (keV)	J^π	$\omega\gamma^{calc}$ (meV)
28.8(3)	5171.6(3)	4	2.4×10^{-26}
137(10)	5280(10)	(5-7)+	1.5×10^{-11}
172.2(3)	5315.0(3)	7+	1.5×10^{-10}
244.0(15)	5386.8(15)	4 – 6-	0.024
398.0(11)	5540.8(11)	4, 5-	1.0

Figure 3 shows contributions to the $^{33}S(p,\gamma)$ resonant rate for T = 0.25 – 0.45 GK. The calculations of Jose et al. (2001) (see table 2) are used for the strengths of the possible resonances below E_x = 5576 keV. We see that over this temperature range, the three lowest-energy observed resonances (E_R^{CM} = 434, 492, 530 keV) and two of the possible lower-energy resonances (E_R^{CM} = 244, 398 keV) are most important. The possible resonances at E_R^{CM} = 29, 137 and 172 keV seem to be completely negligible (the contribution of the possible resonance at E_R^{CM} = 29 keV is at $N_A<\sigma v> \sim 10^{-23}$ $cm^3s^{-1}mol^{-1}$, and is off the scale of fig. 3). As well, more resonances may be present.

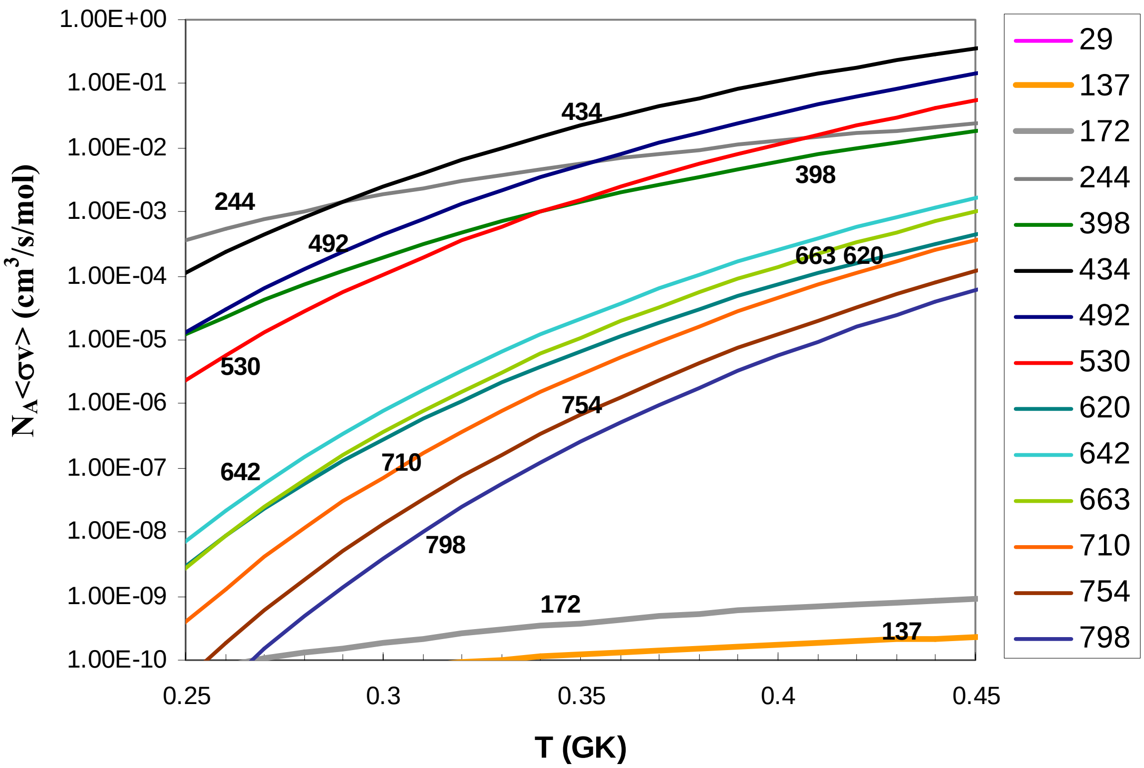

Figure 3: Contributions to the $^{33}S(p,\gamma)$ resonant rate for T = 0.25 – 0.45 GK. The calculations of Jose et al. (2001) (see table 2) are used for the strengths of the possible resonances below E_x = 5576 keV; the measurements of Waanders et al. (1983) are used for the strengths of observed resonances (see table 1). Labels are center-of mass resonance energies, in keV. The possible resonance at E_R^{CM} = 29 keV is at $N_A<\sigma v> \sim 10^{-23}$ $cm^3s^{-1}mol^{-1}$, and is off the scale of the graph.

2 Description of experiment

We propose to improve the $^{33}S(p,\gamma)^{34}Cl$ rate at relevant nova temperatures (T = 0.3 – 0.4 GK) by confirming the strengths of the known resonances at E_R^{CM} = 434, 492 and 530 keV, directly measuring the strengths of the possible $^{33}S+p$ resonances at E_R^{CM} = 244 and 398 keV, and scanning for new resonances between E_R^{CM} ~ 220 keV (the low energy end of the Gamow interval – see fig. 2) and the lowest previously-observed resonance (E_R^{CM} = 434 keV). With sufficient beam intensity (see below), we would scan to lower energies.

The $^{33}S(p,\gamma)^{34}Cl$ reaction will be measured in inverse kinematics using the DRAGON facility. The thick target reaction yield Y is given by

$$Y = \frac{\lambda^2}{2\varepsilon}\frac{M_{beam}+m_{tgt}}{m_{tgt}}(\omega\gamma) \qquad (2)$$

where λ is the center-of-mass de Broglie wavelength, ε is the stopping cross-section per target atom in the lab frame, M_{beam} and m_{tgt} are the atomic masses of the beam and target, respectively, and ωγ is the resonance strength. The strength of a resonance is therefore directly determined through measurement of the reaction yield.

Table 3 lists expected yields for the possible and previously-measured resonances that should be the largest contributors to the $^{33}S(p,\gamma)$ rate at T = 0.3 – 0.4 GK. With I_{beam} = 1 particle-nA, all of these strengths could be efficiently measured. As well, re-measuring even higher-energy resonances would be quick, should our measurements disagree with those of Waanders et al. (1983) for the resonances at E_R^{CM} = 434, 492 and 530 keV.

Table 4 gives expected count rates (for I_{beam} = 1 particle-nA) for the scan for new "important" resonances between E_R^{CM} ~ 220 keV and E_R^{CM} ~ 430 keV in ~10 keV steps (the DRAGON gas target spans ΔE ~ 15 keV with a pressure of 6 torr). The strengths for the calculations of Table 4 were chosen such that a resonance at the given energy would contribute as much as the E_R^{CM} = 434 keV resonance (see fig. 3) to the $^{33}S(p,\gamma)$ rate, at T = 0.33 GK. Again, these measurements should proceed rapidly at 1 particle-nA.

With somewhat more beam we would continue the scan for new resonances to lower energies. For example, with the calculated strength of Table 2, the possible resonance at E_R^{CM} = 172 keV would have a count rate of 7×10^{-9} per particle-nA-hour. For a resonance at this energy to contribute as much to the $^{33}S(p,\gamma)$ rate as the E_R^{CM} = 434 keV resonance (at T = 0.33 GK), its strength would need to increase by a factor of at least 3×10^{7}, giving a count rate of 0.2 per particle-nA-hour. Excluding the contribution of this possible resonance to the $^{33}S(p,\gamma)$ rate at T = 0.3 – 0.4 GK, then, would best be done with $I_{beam} \geq 10$ particle-nA.

3 Experimental details

The ^{33}S beam will be provided by the off-line ion source (OLIS) and sent to the DRAGON experimental area. DRAGON consists of a windowless gas target surrounded by an array of BGO gamma-ray detectors, an electromagnetic separator to discriminate against unreacted beam while transmitting actual reaction products (or 'recoils'), and end detectors. More details can be found in facility papers [Hut03,Eng05] and papers from previous DRAGON experiments [Bis03, DAu04, Rui06].

Table 3: Yields for possible and previously-known resonances in $^{33}S(p,\gamma)^{34}Cl$, with the strengths in tables 1 and 2, and stopping cross-sections from SRIM. The final column assumes $\eta_{sep} = \eta_{DSSSD}$ = 100% and $\eta_{BGO} = \eta_{CSD}$ = 50% (see eq. (3)).

E_R^{CM} (keV)	E_x (keV)	E_{beam}(keV/u)	Yield (per ion)	Cts/hr @ 1 pnA
244.0(15)	5386.8(15)	250	1.1 x10^{-13}	0.6
398.0(11)	5540.8(11)	407	2.3 x10^{-12}	13
434(1)	5576(1)	444	1.0 x10^{-10}	570
492.5(2)	5635.3(2)	504	1.5 x10^{-10}	860
530(1)	5673(1)	542	1.4 x10^{-10}	790

Table 4: Yields for new, "important" resonances for the $^{33}S(p,\gamma)^{34}Cl$ rate at T = 0.3 – 0.4 GK. The strengths were chosen such that a resonance at the given energy would contribute as much as the E_R^{CM} = 434 keV resonance (see fig. 3) to the $^{33}S(p,\gamma)$ rate, at T = 0.33 GK. Stopping cross-sections are from SRIM, and the final column assumes $\eta_{sep} = \eta_{DSSSD}$ = 100% and $\eta_{BGO} = \eta_{CSD}$ = 50% (see eq. (3)).

E_R^{CM} (keV)	E_{beam}(keV/u)	$\omega\gamma$ (meV) to be an "imp. res."	Cts/hr @ 1 pnA
224	229	0.031	0.93
234	239	0.044	1.2
254	260	0.090	2.2
264	270	0.13	2.9
274	280	0.18	3.9
284	290	0.26	5.2
294	301	0.37	7.1
304	311	0.52	9.6
314	321	0.74	13
324	331	1.1	18
334	342	1.5	24
344	352	2.1	33
354	362	3.0	45
364	372	4.3	61
374	382	6.1	84
384	393	8.7	115
404	413	18	218
414	423	25	300
424	434	35	415

The strengths $\omega\gamma$ of $^{33}S(p,\gamma)$ resonances will be found through measurement of the reaction yield (see eq. (2)). This yield Y can be further expressed as follows:

$$Y = \frac{n_{recoils}}{n_{beam}\eta_{sep}\eta_{BGO}\eta_{CSD}\eta_{DSSSD}}, \quad (3)$$

where $n_{recoils}$ is the number of reaction products (i.e. ^{34}Cl ions) observed for the number of ^{33}S ions (n_{beam}) received by the gas target. As the ^{34}Cl recoils will be identified, in part, through the requirement of coincidence between measurement of a prompt gamma-ray in the BGO detector array and measurement of a particle in a double-sided silicon strip detector (DSSSD) at the end of DRAGON, the efficiencies of these detectors (η_{BGO} and η_{DSSSD}) are required. Since the electromagnetic separator requires selection of a charge state, we must also know the fraction η_{CSD} of ^{34}Cl recoils in the selected charge state. Finally, the fraction of recoils η_{sep} created in the gas target that actually reaches the DSSSD at the end of DRAGON must be considered.

The requirement of coincidence between the BGO array and the DSSSD is often not sufficient to obtain $n_{recoils}$ because of accidental coincidences between 'leaky' beam transmitted through to the DSSSD (at a level of ~ 10^{-10}) and room background in the BGO array (~50 Hz with a 1.5 MeV trigger threshold). Therefore, we will require good events to also have the correct timing; time-of-flights for ^{34}Cl recoils will vary by less than ± 2% (± 60 ns at the lowest energies of the scan). The number of accidental coincidences (which will have a random TOF distribution) within this TOF window will be ~ 0.03 cts/hour, at 1 particle-nA.

The number of beam particles n_{beam} received by DRAGON will be found by measuring the number of protons Rutherford-scattered by beam, using a surface-barrier detector already mounted within the target. These measurements are then normalized to readings with Faraday cups.

The efficiency of the BGO array η_{BGO} is found through Monte-Carlo simulation and comparison with results from calibrated sources. The gamma-decay schemes of the known states in Table 3 have been measured [Waa83]; for unknown resonances, the decay schemes can be deduced from the BGO data. The efficiency of the entire array should be > 50% if only a single gamma-ray from a cascade is above the trigger threshold. The efficiency of the DSSSD η_{DSSSD} can easily be measured with an alpha source.

The maximum recoil cones for ^{34}Cl vary from 5 – 9 mrad for possible resonances at the proposed energies. Given the ~ 17 mrad full acceptance of DRAGON, the transmission of the separator η_{sep} will not be of concern. A Cl beam will be required to determine the charge-state distribution η_{CSD} of ^{34}Cl recoils at energies where ^{33}S+p resonances are observed.

During the experiment, the beam energy will be measured using the first dipole magnet of DRAGON. Stopping cross-sections ε will be determined by measuring the beam energy with and without gas in the target. For the energy scan, the range in resonance energy spanned by the target will depend on the gas pressure. At a pressure of 6 torr, the target will span ~ 15 keV in E_R^{CM}; steps of 10 keV in the scan would ensure thorough coverage. As in E989, the energy of a resonance can be determined using the distribution of BGO detectors triggered by gamma-rays from reactions in the target [Rui06].

Measurement of the known $^{33}S(p,\gamma)$ resonances at E_R^{CM} = 434, 492 and 530 keV should allow for checkout of the DRAGON facility, calibration of detector gains and TOF offsets. In case of disagreements, we could also examine a strong, low-energy $^{32}S(p,\gamma)$ resonance carefully measured by Iliadis et al. (1992) (E_R^{CM} = 589 ± 1 keV, $\omega\gamma$ = 130 ± 30 meV [Ili92]).

4 Readiness

The DRAGON facility is ready.

A ^{33}S beam of (at least) charge state +2 will be required from the off-line ion source (OLIS) to allow acceleration through the RFQ (designed for $6 < A/q < 30$). This should be possible following installation of the recently-purchased ECR source in early 2007.

5 Beam Time required

We request 18 shifts of ^{33}S beam time. This time will be distributed as follows:
6 shifts to measure resonance strengths for known levels at E_R^{CM} = 244, 398, 434, 492, 530 keV (see table 3)
10 shifts for energy scan (see table 4)
2 shifts for tuning, calibration and contingency

Minimum usable intensity is 1 particle-nA; optimum intensity is > 10 particle-nA.

An additional 3 shifts of ^{35}Cl or ^{37}Cl beam time (> 100 enA at DRAGON) are requested to measure charge-state distributions.

6 Data Analysis

Standard DRAGON data analysis methods, such as those developed and used for E989, will be sufficient for this experiment.

References:

[Ama01] S. Amari et al., Astrophys. J. 551 (2001) 1065.

[And94] J. Andrea et al., Astron. Astrophys. 291 (1994) 869.

[Aud03] G. Audi et al., Nucl. Phys. A729 (2003) 337.

[Bau78] P. Baumann et al., Phys. Rev. C 18 (1978) 247.

[Bis03] S. Bishop et al., Phys. Rev. Lett. 90 (2003) 162501.

[Cla75] D. D. Clayton, Nature 257 (1975) 36.

[Coc99] A.Coc et al., Phys. Rev. C 61 (1999) 015801.

[Das77] D. Dassie et al., Nucl. Phys. A276 (1977) 260;
D. Dassie et al., Nucl. Phys. A276 (1977) 279.

[DAu04] J. M. D'Auria et al., Phys. Rev. C 69 (2004) 065803.

[Del76] R. M. Del Vecchio et al., Nucl. Phys. A265 (1976) 220.

[End90] P. M. Endt, Nucl. Phys. A521 (1990) 1.

[Eng05] S. Engel et al., Nucl. Inst. Meth. A553 (2005) 491.

[Hut03] D.A. Hutcheon et al., Nucl. Inst. Meth. A498 (2003)190.

[Ili92] C. Iliadis et al., Nucl. Phys. A539 (1992) 97.

[Ili01] C. Iliadis et al., Astrophys. J. Suppl. 134 (2001) 151.

[Ili02] C. Iliadis et al., Astrophys. J. Suppl. 142 (2002) 105.

[Jos99] J. Jose et al., Astrophys. J. 520 (1999) 347.

[Jos01] J. Jose et al., Astrophys. J. 560 (2001) 897.

[Jos04] J. Jose et al., Astrophys. J. 612 (2004) 414.

[Lei87] M. D. Leising and D. D. Clayton, Astrophys. J. 323 (1987) 159.

[Lod95] K. Lodders and B. Fegley Jr., Meteoritics 30 (1995) 661.

[Nan77] H. Nann et al., Phys. Rev. C 15 (1977) 1959.

[Rui06] C. Ruiz et al., Phys. Rev. Lett. 96 (2006) 252501.

[Sni87] M. A. J. Snijders et al., Mon. Not. Roy. Astron. Soc. 228 (1987) 329.

[Van82] C. J. Van der Poel et al., Nucl. Phys. A373 (1982) 81.

[Waa83] F. B. Waanders et al., Nucl. Phys. A411 (1983) 81.

PUBLICATION LIST OF SPOKESPERSON(S) (2001-2006)

C. Ruiz, A. Parikh, J. Jose, L. Buchmann, J. Caggiano, A. A. Chen, J. Clark, H. Crawford, B. Davids, J. M. D'Auria, C. Davis, C. Deibel, L. Erikson, L. Fogarty, D. Frekers, U. Greife, D. A. Hutcheon, C. Jewett, R. Lewis, A. Olin, D. F. Ottewell, C. V. Ouellet, P. Parker, J. Pearson, G. Ruprecht, M. Trinczek, C. Vockenhuber and C. Wrede, *Measurement of the* E_{CM} *= 184 keV resonance strength in the* $^{26g}Al(p,\gamma)^{27}Si$ *reaction*, Phys. Rev. Lett. 96, 252501 (2006).

A. Parikh, J. A. Caggiano, C. Deibel, J. P. Greene, R. Lewis, P. D. Parker and C. Wrede, *Mass measurements of* ^{22}Mg *and* ^{26}Si *via the* $^{24}Mg(p,t)^{22}Mg$ *and* $^{28}Si(p,t)^{26}Si$ *reactions*, Phys. Rev. C 71, 055804 (2005).

R. Lewis, J. Caggiano, A. Parikh, C. Deibel, D. Visser, K. Fear, P. Parker and W. R. Hix, $^{26}Al^{g,m}$ *+ p resonances studied via proton decays of* ^{27}Si, Nucl. Phys. A758, 84c (2005).

J. P. Schiffer, S. J. Freeman, J. A. Caggiano, C. Deibel, A. Heinz, C.-L. Jiang, R. Lewis, A. Parikh, P. D. Parker, K. E. Rehm, S. Sinha and J. S. Thomas, *Is the nuclear spin-orbit interaction changing with neutron excess?*, Phys. Rev. Lett. 92, 162501 (2004).

D. W. Visser, J. A. Caggiano, R. Lewis, W. B. Handler, A. Parikh and P. D. Parker, *Particle decay branching ratios for states of astrophysical importance in* ^{19}Ne, Phys. Rev. C 69, 048801 (2004).