TRIUMF — RESEARCH PROPOSAL	Experiment no. 805 Supplement	Sheet 1 of 10

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Title of proposed experiment:

A Study of the ^{13}N$(p,\gamma)^{14}$O Reaction with a ^{13}N Beam

Name of group: HOT/RP

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Start of preparations:

Date ready: When ECR source is on line

Completion date:

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
≈ 34	ISAC/DRAGON	No

SUMMARY

In July of 1997 the EEC approved the proposed measurement of the $^{13}N(p,\gamma)^{14}O$ cross section as a commissioning experiment. The experimental information on this reaction has not changed since that time but there have been some developments on the importance of this reaction as a possible source of γ rays in the early stages of a nova explosion. A brief review of this new work is given in this report and the original proposal is attached as an appendix, as the estimated cross section and count rates remain unchanged. The major uncertainty at this time is the ^{13}N beam intensity that can be delivered to the DRAGON facility. This requires development work on the target/ECR ion source that will produce such a beam.

BEAM REQUIREMENTS	Expt # 805 Supplement	Sheet 3 of 10

Experimental area

DRAGON experimental area

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

500 MeV protons of $\approx 10\ \mu$A intensity, CW

Unpolarized

Suitable primary target needs to be developed; ECR ion source

Secondary channel ISAC

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

^{13}N; 60 keV; $\approx 10^9 - 10^{10}$ s^{-1}; accelerated beam range: 400-1000 keV/u

SUPPORT REQUIREMENTS

TRIUMF SUPPORT:

Operation of the ISAC and DRAGON facilities and the gas target

Pool electronics (shared with other DRAGON experiments)

Mechanical and electrical engineering (shared with other ISAC experiments)

NON-TRIUMF SUPPORT

NSERC Project Grants, DOE grants

Normal procedures for the operation of ISAC/DRAGON and the gas target, as set out by the TRIUMF Safety Group, will be followed. Short-lived isotopes will be mass-separated and transported to the DRAGON experimental area where they will be monitored. Standard radioactive sources for calibration will be used.

1 Scientific Justification

1.1 Introduction

The importance of the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction in the hot CNO cycle has been detailed in the E805 proposal of 1997, which is attached to this updated proposal. There has been little change[1] in the experimental information for this reaction since 1997, but there have been recent developments on the role that this reaction might play in classical nova outbursts (including prompt γ-ray emission, identification of nova grain candidates, and the overall contribution of novae to the galactic chemical abundances [1,2]). As pointed out by Starrfield *et al.* [3], the mechanism for mass ejection during nova outbursts relies on the efficient convective transport that carries a fraction of the short-lived, β-unstable $^{13}\mathrm{N}$, $^{14}\mathrm{O}$, $^{15}\mathrm{O}$ and $^{17}\mathrm{F}$ towards the outer cooler layers of the envelope. In these lower-temperature layers proton-capture reactions are inhibited by the Coulomb barriers and these species survive to eventually decay. It is the sudden release of energy from the decay of such isotopes that powers the ejection of the envelope, first by the decay of $^{17}\mathrm{F}$ ($T_{\frac{1}{2}}$=1.075 m), and then by $^{14}\mathrm{O}$ ($T_{\frac{1}{2}}$=1.177 m), $^{15}\mathrm{O}$ ($T_{\frac{1}{2}}$=2.037 m) and, partially, by $^{13}\mathrm{N}$ ($T_{\frac{1}{2}}$=9.965 m). The $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction in competition with $^{13}\mathrm{N} \to \beta + ^{13}\mathrm{C}$ determines the amount of $^{14}\mathrm{O}$ that is synthesized during the explosion, thereby having implications on the overall energy released during the explosion, on the dynamics of the explosion itself, and on the amount of matter ejected during the outburst. This reaction also determines the amount of $^{13}\mathrm{N}$ remaining in nova ejecta.

One of the strongest predictions of the thermonuclear runaway model of classical novae is the potential emission of γ rays at various stages of the explosion [4–6]. Two main phases of γ-ray emission have to be distinguished. Firstly, there is a prompt emission, a few hours after the peak temperature is achieved, that is associated with the β decay of $^{13}\mathrm{N}$ and $^{18}\mathrm{F}$ ($T_{\frac{1}{2}}$=1.829 h). These positron emitters produce only a 511 keV annihilation γ ray (slightly blue-shifted and broadened due to emission from an envelope expanding at high velocity) and a continuum at lower energy with a cut-off at 20 – 30 keV due to photoelectric absorption. The continuum is composed of Compton-scattered 511 keV photons and photons from the decay of triplet-state positronium. Later, as the envelope expands and becomes transparent to higher-energy photons, γ rays due to longer-lived nuclei, such as $^{22}\mathrm{Na}$ ($T_{\frac{1}{2}}$=2.603 y), begin to appear.

The prompt emission is, by far, the most intense γ-ray signal predicted for novae. However, it has a very short duration (only a few hours) and appears before the maximum in visual luminosity, which makes observation difficult. Accurate predictions of this prompt emission depend on knowing the amount of $^{13}\mathrm{N}$ and $^{18}\mathrm{F}$ in the expanding ejecta (which determines the number of decay photons) and understanding the physical properties of the expanding envelope (density and velocity profiles and chemical composition) which determine the number of photons that escape. Peaks in the γ-ray intensity emission are expected at about one hour, due to $^{13}\mathrm{N}$ decay, and at about 6 hours, due to $^{18}\mathrm{F}$ decay, with the first being more prominent [7].

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[1] A new Coulomb dissociation result for Γ_γ of the dominant 1^- resonance was given in an abstract to the joint meeting of the Divisions of Nuclear Physics of the APS and JPS in Maui in October, 2001, but the paper was not given.

Several isotopes from the CNO cycles (mainly ^{13}C, ^{15}N and ^{17}O) have been suggested as fingerprints of classical nova outbursts in the galactic chemical pattern [8]. In order to evaluate the overall contribution of nova outbursts to the abundances of these "fingerprint" nuclei, it is necessary to have well-determined cross sections for the reactions involved in their production and in their destruction.

As the material ejected during a nova explosion expands and cools condensation of ejecta material into grains takes place. Quite recently, a number of presolar grains with a likely nova origin have been discovered [9]. The low ^{12}C/^{13}C and ^{14}N/^{15}N ratios measured in these grains strongly support a nova origin. Predictions for these ratios rely on a good knowledge of the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ rate.

2 Description of the Experiment

2.1 Target and beam development

At TISOL we used a zeolite target to produce ^{16}N. However, zeolite is not likely to withstand more than about 2 μA of proton beam before failing. Marik Dombsky has suggested that a heavy oxide is probably required for efficient production and release of ^{13}N. An estimated 6 shifts are required for target development.

As explained in Sect. 2.3 of the 1997 proposal, there will be ^{13}C contamination in the ^{13}N beam. Recently, the ISAC mass separator successfully separated ^{75}Ga from ^{75}Rb with a mass difference of 1 part in 6200 [10]. Also, if there is no carbon in the target selected for ^{13}N production, it is expected that the ^{13}C contamination in the extracted beam may be comparable in intensity to the ^{13}N in the beam [10]. Once a suitable target has been found, we shall have to determine which extracted mass and separator resolution setting will provide the lowest ^{13}C to ^{13}N ratio in the beam to the gas target at the highest intensity. An estimated 6 shifts are required for beam development.

2.2 Estimated rates

Rates for the $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction were estimated in the proposal presented in 1997. These estimates are still valid and are reproduced in Table 1 for easy reference. The cross section for the reaction is > 1 μb over the range from 400 to 1000 keV and the projected yield is reasonably high over this range. With a thin, windowless, gas target of 10^{18} atoms/cm^2, a ^{13}N beam of 10^{10} s^{-1}, and an estimated peak cross section of 330 μb, the yields shown in column three of Table 1 would be obtained. The gas target developed for DRAGON has about 5×10^{18} atoms/cm^2 so that the rates shown in the table could be obtained with a beam of 2×10^9 s^{-1}.

2.3 Detection of reaction products

The $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ reaction has a broad $J^\pi = 1^-$ resonance at 526 keV (cm) populating a state at 5.155 MeV in ^{14}O which can decay only to the ground state. The $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$

Table 1 Expected thin target yield

E (keV)	$\sigma(E)$ (μb)	Resonance + DC Y (hr^{-1})	Resonance only Y (hr^{-1})
200	0.014	0.6	0.3
300	0.26	10	7
350	0.87	31	25
400	2.9	100	70
450	12	430	390
500	111	4.0×10^3	3.8×10^3
526	330	1.1×10^4	1.1×10^4
550	115	4.1×10^3	4.2×10^3
575	45	1.6×10^3	1.7×10^3
600	24	870	970
650	11	390	460
700	6.5	230	300
750	4.4	160	230
800	3.2	120	190
850	2.5	89	150
900	2.0	71	130
950	1.6	58	110
1000	1.3	48	100

reaction has a broad state at 517.5 keV (cm) populating a state in ^{14}N at 8.068 MeV which decays 80% of the time to the ground state. Therefore, γ rays from capture of ^{13}N in the gas target might be obscured by the Compton tail of 8 MeV γ rays if there is an appreciable ^{13}C content in the beam. Thus, it may be difficult to separate $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$ from $^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}$ events via delayed coincidences between γ rays in the BGO detector and recoil detection in the DRAGON end station detector. It may be possible to separate ^{14}O recoils from ^{14}N recoils in the detector at higher beam energies (i.e. above the resonance). This needs to be studied when a ^{13}N beam becomes available.

The ^{14}O recoil nucleus is unstable with a β^+ half-life of 1.177 m while the ^{14}N recoil is stable. Therefore, the possibility exists of counting the ^{14}O recoils by observing their decay. Two scenarios exist.

1. If the rejection of ^{13}N from the primary beam by the DRAGON system is high enough, the ^{14}O recoils could be collected on a tape at the end of the system and a Ge counter could be stationed just outside the vacuum system to count 511 keV γ's from the decay and/or the 2.313 MeV γ's that are produced in each decay.
2. If the presence of ^{13}N with a half-life of 9.965 m causes too high a background at the end station, the recoils could be collected on a foil that could be periodically rotated to a position between a pair of Ge detectors where coincidences between 511 and 2824 (511+2313) γ's would be counted. Since the β^+ decay of ^{13}N is to the ground state of ^{13}C this would effectively discriminate against the ^{13}N background.

Either of these methods would require careful calibration of the efficiency of the Ge detector(s). This could be accomplished with an ^{14}O beam of as little as 10 particles per second. This should be available from the the target chosen for ^{13}N production.

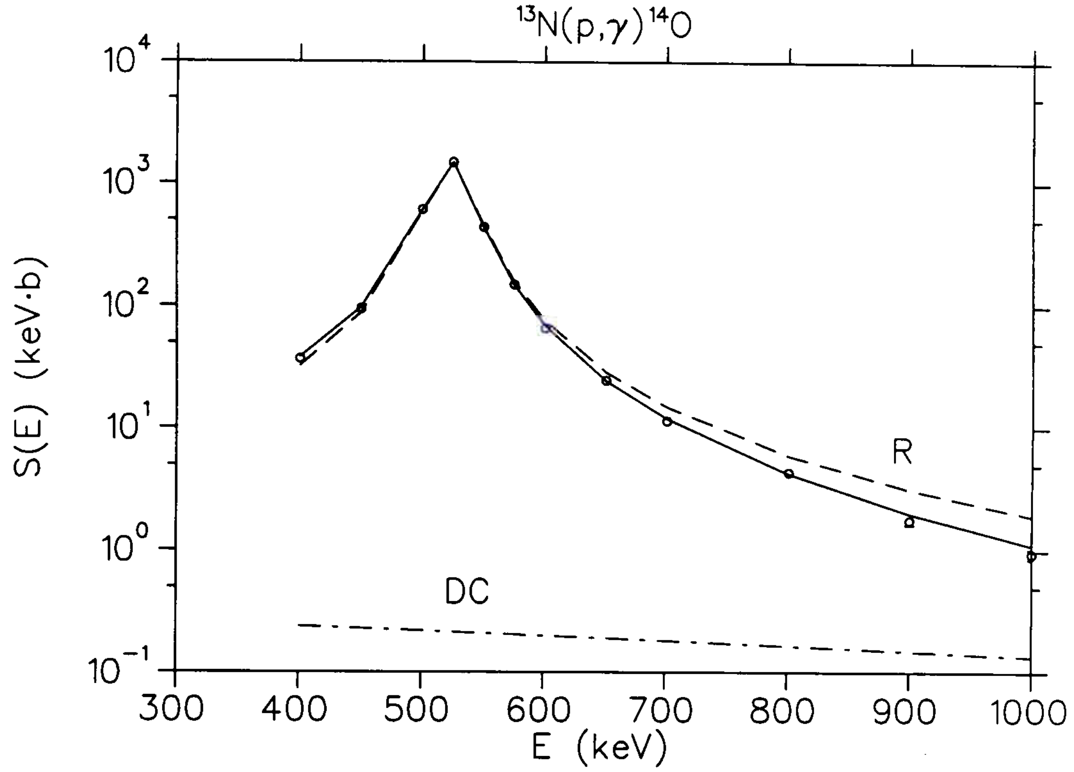

Fig. 1 Fit to the 12-point randomized yield curve. See 1997 proposal for details.

2.4 Shifts required

It is difficult to update the number of shifts required to measure the yield curve. In the 1997 proposal we estimated 24 shifts to acquire the 12-point yield curve shown in Fig. 1. This was calculated under the assumption of a 10^{10} s^{-1} ^{13}N beam on the gas target and a detection efficiency of 10% for the ^{14}O recoils. Target and beam development is required to improve the assumption of beam intensity, and tests of transmission through DRAGON with a ^{13}N beam on target are required to improve the assumption about detection efficiency. For example, we might be able to detect ^{14}O separately from ^{14}N via ΔE-E measurements; or by gamma-recoil delayed coincidences; or by detection of ^{14}O activity at the end station with or without moving the collector foil. Each of these would have a different efficiency for detection and would have to be determined if, or when, required. Under these conditions it seems appropriate at this time to propose the following request for beam shifts.

1. Target development:	6 shifts
2. Beam development:	6 shifts

After demonstration of the production of a ^{13}N beam of sufficient intensity and quality:

3. ^{13}C beam from off-line source for set-up: 6 shifts
4. ^{14}O beam for γ-ray detector efficiency tests, if necessary: 4 shifts
5. ^{13}N beam for detector tests: 6 shifts

References

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