TRIUMF — RESEARCH PROPOSAL	Experiment no. 946	Sheet 1 of 16

Title of proposed experiment:

Energy Generation and Nucleosynthesis in the HotCNO Cycles: Measurement of the $^{17}F(p,\gamma)^{18}Ne$ Reaction Rate

Name of group: DRAGON

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

Name	Institution	Status	Time
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L. Buchmann	TRIUMF	Research Scientist	20%
J.M. D'Auria	Simon Fraser University	Professor	60%
S. Engel	Ruhr-Universität Bochum	Graduate Student	60%
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J. Rogers	TRIUMF	Research Scientist	80%
C. Wrede	Simon Fraser University	Graduate Student	50%

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Start of preparations:	2003
Date ready:	Fall 2003
Completion date:	2004

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
40 (^{17}F)	2A / ISAC	No
9 (stable)	na / ISAC	na

SUMMARY

In the high temperature environments found in novae and X-ray bursts, one of the main energy sources consists of reaction sequences in the Hot-CNO cycles. Within these cycles, the $^{17}F(p,\gamma)^{18}Ne$ reaction is an important link, since in novae both the $^{17}O/^{18}O$ ratio and the rate of emission of 511 keV annihilation gamma-rays from the decay of ^{18}F, depend sensitively on uncertainties in its rate. Furthermore, in X-ray bursts, the $^{17}F(p,\gamma)^{18}Ne$ reaction is one of the steps leading to breakout from the Hot-CNO cycles through the $^{18}Ne(\alpha, p)^{21}Na$ reaction. At nova temperatures (T = 0.2-0.3 GK), the $^{17}F(p,\gamma)^{18}Ne$ reaction rate is determined by the direct capture contribution, while for X-ray bursts (T > 0.5 GK), contributions from resonances dominate. No direct measurements have been performed to date. We propose to use high-intensity beams from the TRIUMF-ISAC facility and the DRAGON facility to measure an excitation function for the $^{17}F(p,\gamma)^{18}Ne$ reaction, thereby constraining the direct capture component and determining the resonant contribution to the reaction rate.

Experimental area

DRAGON facility in the ISAC experimental hall.

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

500 MeV proton beam from the TRIUMF cyclotron.

Secondary channel ISAC - HE

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

The secondary beam required is ^{17}F with intensities $> 10^9$ ions per second and with energies from 400 to 800 keV/u. In addition, stable beams of ^{17}O will be needed to calibrate the DRAGON facility.

TRIUMF SUPPORT:

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

NON-TRIUMF SUPPORT

NSERC DRAGON Project Grant (J.M. D'Auria et al.), approved by NSERC in 2001 for 3-year support.

SAFETY

This experiment does not introduce any additional safety hazards beyond those covered under the normal operation of the DRAGON and ISAC facilities. Safety procedures for the operation of DRAGON have been developed and approved.

1 Scientific Motivation

At the high temperatures and densities (10^{8-9} K, 10^{3-6} gm/cm^3) found in novae and X-ray bursts, the energy trigger for the thermonuclear runaway is provided through the Hot-CNO cycles [1]. These cycles are an extension of the classic, quiescent CNO cycle, and involve hydrogen and helium burning on radioactive isotopes, since the respective reaction rates become faster than the corresponding beta decays under these extreme ambient conditions. In addition to increasing the energy generation toward the explosion, the Hot-CNO cycles also have important implications to the nucleosynthesis, both in the CNO mass region and beyond. In some cases, the resulting abundances and abundance ratios can be used as observational markers that provide constraints on the viability of present models of explosive nucleosynthesis, and clues about the conditions in the explosion. The model predictions for these observable quantities often depend sensitively on the rates of the thermonuclear reactions involved; hence, in these cases, a solid knowledge of these rates is essential for progress in a quantitative understanding of these astrophysical events. The focus of this proposal is on the destruction of ^{17}F in novae and x-ray bursts via the ^{17}F(p,γ)^{18}Ne reaction.

1.1 ^{17}F(p,γ)^{18}Ne in Novae

Based on our present picture of explosive nucleosynthesis, the range of peak temperatures in different classes of novae lead to different roles for the ^{17}F(p,γ)^{18}Ne reaction, depending on whether or not its rate is faster or slower than the beta decay of ^{17}F ($T_{1/2}$ = 64 seconds) in the nova burning shell. In the former case, likely to be found in a class of novae known as CO novae, the beta decay of ^{17}F initiates the reaction sequence ^{17}F($e^+\nu_e$)^{17}O(p,α)^{14}N(p,γ)^{15}O. Since ^{15}O is relatively long-lived and its destruction through the ^{15}O(α,γ)^{19}Ne reaction at these temperatures is slow, the ^{15}O isotopes eventually decay to stable ^{15}N after being mixed into the surface of the burning envelope. The production site of ^{15}N in the universe remains unknown, and although recent observations favor production in massive stars [2], a significant contribution from novae cannot be discounted at present.

If the ^{17}F(p,γ)^{18}Ne is faster than the ^{17}F beta decay, then a substantial amount of ^{18}F can be produced through the beta decay of ^{18}Ne. The ^{18}F is relatively long-lived, and is therefore brought to the surface of the burning envelope through convection. Upon decaying to stable ^{18}O, the final isotopic ratio of ^{17}O to ^{18}O, which serves as an important observable for constraining nova models, is determined. Furthermore, the amount of ^{18}F produced is important since the energy from its beta-decay can have an impact on the overall luminosity and ejection dynamics, and also since recent simulations have pointed to the potential detection of the 511 keV annihilation photons in the nova ejecta, by present or future instruments [3]. These effects depend sensitively on the ^{17}F(p,γ)^{18}Ne rate, as well as on the rates of the reactions that destroy the ^{18}F before it reaches the cooler surface. The latter reactions have been recently studied extensively at Oak Ridge National Laboratory [4], and earlier studies were performed at Louvain-la-Neuve [5] and at Argonne National Laboratory [6].

A recent study that investigated the effect of variations in reaction rates on the nucleosynthesis in a variety of nova simulations was performed by Iliadis et al. [7]. For the case of the ^{15}N variations in a number of reaction rates in the CNO region, including the ^{17}F(p,γ)^{18}Ne reaction resulted in changes of less than 50% in the ^{15}N abundance. The authors conclude that the present reaction rates are adequate for reasonable predictions of ^{15}N abundances in nova ejecta. However, the abundances of ^{18}O, ^{18}F and ^{17}O were found to depend very strongly on variations in the ^{17}F(p,γ)^{18}Ne reaction rate over its present range of uncertainty. For ^{17}O, the abundance changes by factors of up to 500, depending on the nova model tested, while for ^{18}F and ^{18}O, the changes reach up to a factor of 600.

1.2 ^{17}F(p,γ)^{18}Ne in X-ray Bursts

In X-ray bursts where the temperature is higher than that in novae, the Hot-CNO cycles function as the trigger for the burst, while specific reactions that bridge the CNO mass region to the $A > 20$ region enable the star to substantially enhance its energy generation and produce elements up to mass $A = 100$ (via the αp-process and the rp-process) [8]. The breakout reactions consist of helium burning on nuclei produced in the Hot-CNO cycles, whose abundances in the cycles are high due to their relatively long half-lives. Thus, the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ and $^{18}\mathrm{Ne}(\alpha,\mathrm{p})^{21}\mathrm{Na}$ reactions have been identified in the models as the two key breakout reactions. These reactions are poorly understood in their own right, and many efforts have been carried out and are planned to measure them. Another important piece of information is the amount of seed ^{15}O and ^{18}Ne produced in the Hot-CNO cycles [1]. With regards to the latter, the ^{17}F(p,γ)^{18}Ne is important in that the ^{18}Ne abundance at X-ray burst temperatures is largely produced through the $^{14}\mathrm{O}(\alpha,\mathrm{p})^{17}\mathrm{F}(\mathrm{p},\gamma)^{18}\mathrm{Ne}$ reaction sequence.

1.3 Previous work related to the ^{17}F(p,γ)^{18}Ne reaction

The resonant contribution to the ^{17}F(p,γ)^{18}Ne reaction rate depends on the properties of levels in ^{18}Ne. The first theoretical calculations indicated that the analog to the 3^+ state in ^{18}O ($E_X(^{18}\mathrm{O}) = 5.38$ MeV) in ^{18}Ne would provide a strong ^{17}F+p s-wave resonance [9]. Since then, the level energies needed to determine the resonant contribution to the reaction rate under conditions explosive hydrogen burning have been determined through a number of transfer reaction studies with stable beams, such as (^{3}He, n) [10], (^{12}C,^{6}He) [11] and (p, t) [11][12], as well as through a recent measurement of the p(^{17}F, p)^{17}F at Oak Ridge National Laboratory (ORNL) [13][14]. This elastic scattering measurement determined not only the energy of the dominant resonance ($E_X(^{18}\mathrm{Ne}) = 4.524$ keV), but also the proton width which corresponds roughly to the total width of the state. However, the resonant reaction rate depends primarily on the gamma-width of these resonances, and these quantities have not been determined experimentally. The three resonances that contribute to the rate for the relevant temperature range ($T < 2$ GK) are listed below, along with their spectroscopic properties:

- **E_x = 4.519 MeV** (E_r = 595 keV): the energy is known to ±5 keV, while the spin and parity have been determined to be 1^-. The gamma-width Γ_γ has been estimated to be $(1.5\pm0.3)\times10^{-5}$ keV, based on the analogous reduced transition strength in ^{18}O. The proton width Γ_p has been assigned an upper limit of 0.1 keV, inferred from spectroscopic factors in ^{18}O and single particle widths calculated with an optical model [10].

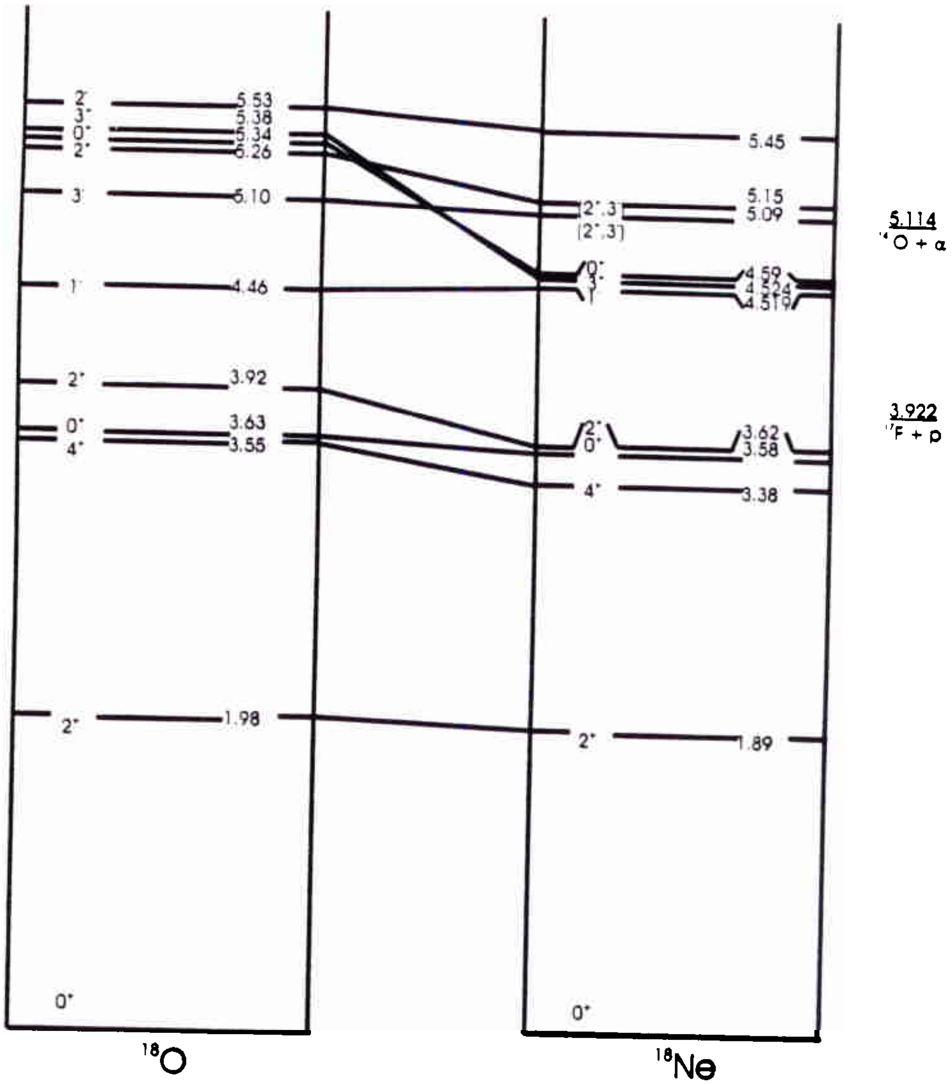

Fig. 1 Level structure of ^{18}Ne close to the ^{17}F+p threshold and the analog state region in ^{18}O.

- **E_x = 4.524 MeV** (E_r = 600 keV): for this state, $J^\pi = 3^+$ and the energy uncertainty is ±2 keV. This is a broad state, with a proton width of 18 keV in the CMS, as determined by Bardayan et al. [14]. The gamma-width has been estimated with shell model calculations as described in Garcia et al. [10], and has a value of $(2.5 \pm 1.6) \times 10^{-5}$ keV.

- **E_x = 4.590 MeV** (E_r = 666 keV): this level has $J^\pi = 0^+$ and an energy uncertainty of ±5 keV. The proton and gamma widths are estimated in the same manner as for the E_x = 4.519 MeV state, with resulting values of 1.0 keV and $(1.0 \pm 0.2) \times 10^{-6}$ keV, respectively, which were used in the reaction rate calculation by Bardayan et al. [14].

Our present understanding of levels in ^{18}Ne is shown in Figure 1, while a summary of the published spectroscopic information for the three important levels is displayed in Table 1. Based on the most recent published calculation of the ^{17}F(p,γ)^{18}Ne reaction rate [14], the two dominant contributions to the reaction rate over the temperature range of interest come from the resonance strength of the E_r = 600 keV level for $T \geq 0.5$ GK, and from the direct capture contribution for $T < 0.5$ GK.

Table 1 Resonance parameters adopted for the ^{17}F(p,γ)^{18}Ne reaction, Q-value = 3924 keV (see text for details).

E_x(^{18}Ne) (keV)	E_r (keV)	J^π	Γ_p (keV)	Γ_γ [a] (eV)	$\omega\gamma$ [b] (eV)
4519(5)	595(5)	1^-	0.1 [a]	0.015	3.7×10^{-3}
4524(2)	600(2)	3^+	18(2)	0.025	1.5×10^{-2}
4590(5)	666(5)	0^+	1.0 [a]	0.001	8.3×10^{-5}

[a] From Garcia et al. (Ref. [10]).

[b] With $\omega\gamma=(2J_r+1)\Gamma_p\Gamma_\gamma/12\Gamma$

The S-factor for the ^{17}F(p,γ)^{18}Ne reaction is shown in Figure 2. The CMS ^{17}F+p energy corresponding to peak nova temperatures (typically, T = 0.28-0.35 GK) is about 250 keV, where the reaction rate is dominated by the direct capture (DC) contribution. The DC component was estimated by Garcia et al. using spectroscopic information from levels in ^{18}O [10]. More recently, Iliadis et al. adopted an uncertainty of a factor of 10 in the reaction rate due to the lack of direct experimental information in the region of interest to nova simulations [7] [15]. At ORNL, a recent measurement of the ^{14}N(^{17}F,^{18}Ne)^{13}C was performed to constrain the direct capture component through a measurement of the asymptotic normalization coefficient. The results from this measurement are still forthcoming. We note that a direct measurement of the resonant component is planned at ORNL, and is contingent on the achievement of higher beam currents than have been available to date [16]. Direct measurements of the ^{17}F(p,γ)^{18}Ne reaction over the energy region of interest would provide additional constraints on the determination of the DC component and a measurement of the resonant contribution, thereby improving our understanding of the impact of this important reaction in explosive nucleosynthesis. The present proposal focuses on performing such measurements.

2 Description of the Experiment

We propose to determine the ^{17}F(p,γ)^{18}Ne reaction rate with ^{17}F beams in inverse kinematics with the DRAGON facility. For a detailed description of the DRAGON facility, the reader is referred to Ref. [18]. A schematic of the DRAGON facility is shown in Figure 2. An excitation function will be measured over the E_{cm} = 400 – 800 keV, which will determine both the resonant contributions and constrain the direct capture component. The projected ^{17}F beam intensity at ISAC with a SiC target and a 1 μA primary proton beam is on the order of 10^{10} particles per second [19]. Beam development efforts will be required to optimize the beam intensity for higher primary beam currents.

The beam current will be measured with a Faraday cup located upstream of the H_2

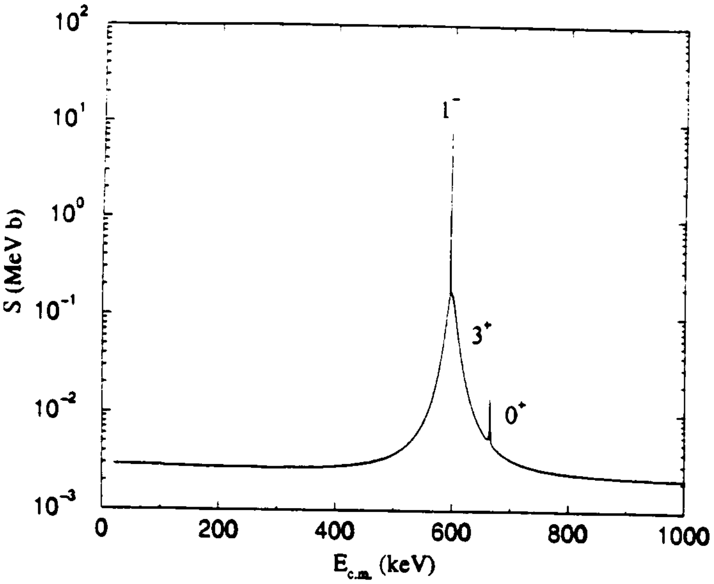

Fig. 2 The astrophysical S-factor for the $^{17}F(p,\gamma)^{18}Ne$ reaction (figure from Ref. [17].)

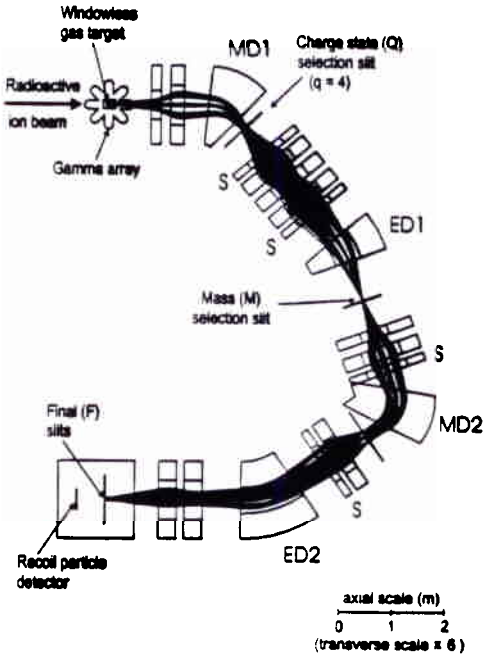

Fig. 3 A schematic of the DRAGON facility. The four major components are shown: the windowless gas target, the gamma detector array, the EMS (composed of two magnetic dipoles and two electrostatic benders) and the recoil end-detector station. (Note that the q = 4 charge state selection need not correspond to the selected charge state for the $^{17}F(p,\gamma)^{18}Ne$ reaction.)

Energy (keV)	Resonant + DC Yield (hr^{-1})
500	0.6
550	2
575	8
590	33
595	3125
600	74
625	11
666	154
700	3

Table 2 Estimated total yield for the $^{17}F(p,\gamma)^{18}Ne$ reaction.

gas target, and subsequently monitored by measuring the elastic scattering of the beam in the gas target, as well as by counting the decay activity at the slits where most of the beam is dumped, after the first stage of mass separation. The separator will be tuned to transmit the most intense charge state of the beam and recoils through to the detector at the end of the separator. Except for beam energies below about 500 keV, an ionization chamber should be able to provide $E - \Delta E$ discrimination. However, the BGO gamma array surrounding the gas target will be used to detect gamma rays from the direct capture process, thereby allowing for a cleaner identification of true events. Based on gamma branching ratios for the analog states in ^{18}O, all three of the resonances under consideration decay through a cascade of two gamma rays with energies between about 1 – 3 MeV. The BGO array efficiency under these conditions is estimated to be about 30%. The overall setup and calibration of the DRAGON facility will be carried out with stable beams of ^{17}O and the $^{17}O(p,\gamma)^{18}F$ reaction through known resonances. These will include measurements of charge state distributions.

The resonant contribution will be determined by measuring an excitation function over the $E_{cm} = 500 - 700$ keV range. Assuming cross sections derived from the resonance parameters and the direct capture calculation of Garcia et al., with a ^{17}F beam intensity of 1 pnA, a gas target thickness of 10^{18}atoms/cm^2, corresponding to a H_2 pressure of 1 Torr and an energy thickness of 5 keV in the CMS, the estimated total yield at the selected energies are listed in the Table 2. Assuming a DRAGON detection efficiency of 10%, the estimated yield at 500 keV during 4 shifts would be about three counts, while at 550 keV and 700 keV, the yield in 4 shifts would be 10-15 counts. For the other energies, 2 shifts will provide reasonable statistics.

In order to constrain the direct capture component, we propose to measure three additional points away from the region of the resonances discussed above. For the following energies, listed in Table 3, the yield is dominated by the DC contribution. Below 400 keV, the cross-section becomes prohibitively small. At 400 keV, the estimated yield is less than one count for four shifts, but we will aim to at least set an upper limit to the direct capture rate at this energy. We note that the time required will be significantly reduced if the actual beam intensity is higher than the one used in these yield estimates.

By unfolding the target profile from the measured excitation function, the astrophysical S-factor for the $^{17}F(p,\gamma)^{18}Ne$ reaction at the energies above will be calculated. The S-

Energy (keV)	Resonant + DC Yield (hr^{-1})
400	0.14
450	0.3
800	4

Table 3 Estimated total yield for the $^{17}F(p,\gamma)^{18}Ne$ reaction.

factor will then be fit with contributions from two narrow resonances, one broad resonance, and a polynomial function for the direct capture component.

3 Beam Time Request

Measurement	**Shifts Required**
• DRAGON calibration with 17O stable beam:	9
• Excitation function for the p(^{17}F,γ)^{18}Ne reaction:	
Beam energy:	
400 keV	4
450 keV	4
500 keV	4
550 keV	4
575 keV	2
590 keV	2
595 keV	2
600 keV	2
625 keV	2
666 keV	2
700 keV	4
800 keV	4
• Beam energy changes and contingency:	4
TOTAL:	49 shifts

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PUBLICATION LIST OF SPOKESPERSON(S)	Expt # 946	Sheet 15 of 16

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

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