TRIUMF — RESEARCH PROPOSAL

Experiment no. **1076**

Title of proposed experiment:

The $^{17}O(p,\gamma)^{18}F$ Reaction and ^{18}F Abundance in Novae

Name of group: DRAGON

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

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Start of preparations: November 2005

Date ready: December 2005

Completion date: 2006

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
30	ISAC-HE	No

The observation of γ-rays from nova outbursts will provide theorists with a unique opportunity to test the predictions of current nova models. Assuming that the nuclear reaction rates are sufficiently well-known, such observational data would allow the underlying hydrodynamics of these models to be tested. The recent launch of the INTEGRAL satellite, and future proposed missions such as EXIST, which are aimed at making these observations, emphasize the current need for improved information on the relevant nuclear reaction rates.

The decay of ^{18}F is the major source of γ-rays of 511 keV and below from novae. Consequently, knowledge of the final abundance of ^{18}F synthesized during such an event is important to constrain nova models. Moreover, the distance from which these γ-rays could be detected, and thus the number of nova events which could be observed in this fashion, also relies on such information.

The abundance of the rarest stable oxygen isotope ^{17}O and the radioisotope ^{18}F strongly depend on the ^{17}O(p,γ)^{18}F and ^{17}O(p,α)^{14}N thermonuclear reaction rates. Knowledge of these rates in the astrophysically important temperature region of 1–4 $\times$ 10^8 K is crucial in determining the abundances of ^{18}F and ^{17}O, and the likelihood of seeing novae using ^{18}F decay.

We propose to use high-intensity stable beams from the TRIUMF ISAC facility and the DRAGON experimental apparatus to resolve discrepancies in measurements of the resonance strength, $\omega\gamma_{p\gamma}$, for the ^{17}O(p,γ)^{18}F reaction in the region of the astrophysically important $E_R^{cm} =$ 183 keV resonance, with an ^{17}O beam of 197 keV/u energy.

Experimental area

ISAC high-energy DRAGON beamline.

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

^{17}O, 197 keV/u.
Desired intensity of 3×10^{11} pps at DRAGON.
Minimum intensity of 1×10^{11} pps at DRAGON.
^{19}F, 182 keV/u for charge-state studies.

Secondary channel None.

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

None.

TRIUMF SUPPORT:

^{17}O bunched beam production.
Operational support.

NON-TRIUMF SUPPORT

NSERC project grant (J. D'Auria) approved by NSERC in 2003 for 3-year support.
NSERC project grant (A. Chen) approved by NSERC in 2003 for 4-year support.

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 Justification

The β^+-decay of ^{18}F is thought to be the main contributor to the γ-ray flux, at and below 511 keV, during the first few hours after a nova explosion. This γ-ray emission is directly related to the abundance of ^{18}F in the nova ejecta synthesized during the outburst. Observation of this emission is one of the goals of the INTEGRAL satellite, and measured fluxes would provide strong observational constraints on the final abundances of certain nuclides and thus on the underlying nova models, if the relevant reaction rates are sufficiently well-known [Her99,Her04].

Assuming that the nuclear inputs to the models are accurate, in terms of reaction rates for the production and destruction of ^{18}F, such an observation would provide unique information on the physical conditions during a nova outburst, including isotopic abundances and mixing of core and accreted material, allowing better predictions of parameters such as the ejected mass. The observation of ^{22}Na, which via its decay to an excited state in ^{22}Ne is responsible for a characteristic γ-ray of 1.275 MeV, could be used in this context as could ^{18}F. A relatively high abundance of ^{18}F is produced in novae and its half-life of 109.8 minutes is such that the decay positrons are emitted after the expanding ejecta becomes transparent to γ-rays.

During a nova outburst, the production of ^{18}F arises from the hot CNO cycles (see Figure 1). Depending on the relative rates of the ^{17}O(p,γ)^{18}F and the ^{17}O(p,α)^{14}N reactions, the amount of ^{18}F can vary significantly [Ili02]. The ^{17}O(p,γ)^{18}F reaction suffers from large uncertainties in the astrophysical temperature range of $T = 1$–4×10^8 K (see Figure 2), when an accuracy of 20 % is required for consistent astrophysical modeling. Most of the inaccuracy comes from the rate contribution of a level at $E_x = 5789$ keV in ^{18}F. This resonance is thought to be particularly important to astrophysics as it lies within the temperature range of the Gamow window relevant to nuclear burning in novae, as shown in Figure 3, and has only recently been observed in the ^{17}O(p,α)^{14}N reaction [Cha05].

A previous observation found this resonance at an excitation energy of $E_x = 5786 \pm 2.4$ keV through a measurement of the ^{14}N(α,γ)^{18}F reaction [Rol73]. This experiment employed the Doppler-shift attenuation method and obtained a lifetime for this level of $\tau = 10 \pm 7$ fs. However, this implies that $\Gamma_\gamma/\Gamma_\alpha \sim 1$ which is surprisingly high for this energy and hence prompted a remeasurement of the level parameters. Level parameters for resonances just above the ^{17}O+p threshold (at 5.6065 ± 0.0006 MeV) important to nuclear astrophysics are shown in Table 1.

E_R^{cm} (keV)	E_x(^{18}F) (keV)	J^π (keV)	$\omega\gamma_{p\gamma}$ (eV)
66.0 ± 0.3	5672.6 ± 0.3	1^-	$(5.9^{+1.9}_{-1.1}) \times 10^{-11}$
179.5 ± 2.4	5786 ± 2.4	2^-	$< 0.6 \times 10^{-3}$
489.9 ± 1.1	6096.4 ± 1.1	4^-	$(9 \pm 1.6) \times 10^{-3}$
501.5 ± 3.0	6108 ± 3	1^+	< 0.21
529.97 ± 0.33	6136.5 ± 0.33	0^+	$(75 \pm 16) \times 10^{-3}$
556.7 ± 0.9	6163.2 ± 0.9	3^+	$(22 \pm 5) \times 10^{-2}$
633.9 ± 0.8	6.2404 ± 0.8	3^-	$(10.6 \pm 1.9) \times 10^{-2}$

Table 1: Adopted values of resonance parameters for the ^{17}O(p,γ)^{18}F reaction, taken from the current NACRE compilation [Ang99]. The values given are those prior to recent measurements by [Cha05,Fox05].

Most of the parameters are reasonably well-known, the exception being the contribution to the reaction rate from the $E_x = 5786 \pm 2.4$ keV level. This level had never been observed with the ^{17}O(p,γ)^{18}F reaction, and so prompted several recent attempts to measure its contribution to the reaction rate. The first of these, performed at TUNL, involved a proton beam with an ^{17}O anodized tantalum target [Fox05]. Beams of up to 100 μA intensity from a Van de Graaff accelerator were used with energies from 140–540 keV. The 0.5 mm thick tantalum targets were etched and anodized using 90 % ^{17}O-enriched water. A ~ 6 mm beam spot was focused on to the water cooled anodized target and prompt γ-rays from the ^{17}O(p,γ)^{18}F reaction were detected in a large volume HPGe detector at 0°, 16 mm from the target (γ-ray branching ratios for the level of interest are given in Figure 3).

From the measured yield curve, a resonance energy was obtained and a value of $E_R^{lab} = 193.2 \pm 0.9$ keV was adopted, corresponding to a ^{18}F excitation energy of $E_x = 5788.8 \pm 1.0$ keV. The resonance strength was measured to be 1.2 ± 0.2 μeV. Data for all resonances were evaluated and the uncertainty in the stellar reaction rate was greatly reduced: for example, at 0.2 GK the uncertainty in the rate has decreased from more than 2 orders of magnitude to less than 30 %. Two other resonance strengths also were measured as a check of the experimental setup: an ^{17}O(p,γ)^{18}F resonance at $E_R^{lab} = 518.9 \pm 1.0$ keV (corresponding to $E_R^{cm} = 489.9$ keV) and an ^{18}O(p,γ)^{19}F resonance at $E_R^{lab} = 150.82 \pm 0.09$ keV. In both cases, the measured values agree well with those previously published, adding confidence that the result of the measurement of ^{17}O(p,γ)^{18}F resonance at $E_R^{lab} = 193.2 \pm 0.9$ keV is reliable.

More recently, however, a series of experiments were performed at the CENBG and CSNSM laboratories in France, investigating the same ^{17}O(p,γ)^{18}F $E_R^{lab} \approx 194$ keV resonance [Cha05]. First, the resonance energy and lifetime of this state were measured using the ^{14}N(α,γ)^{18}F reaction. A Van de Graaff accelerator was used to provide a ^{4}He beam with an energy of 1775 keV at an intensity of 20–30 μA. The 3 mm beam spot was directed on to TiN targets, which were formed with N and Ti evaporated on to a thick Cu backing. Three HPGe detectors were used to detect the γ-rays at 0°, 123° and 144°, at a distance of ~ 9 cm from the target. The energy of the ^{18}F level was found to be $E_x = 5789.8 \pm 0.3$ keV in good agreement the value of $E_x = 5788.8 \pm 1.0$ keV from Reference [Fox05]. The mean lifetime of this $E_R^{lab} = 194.1 \pm 0.6$ keV state was found to be < 2.6 fs, in disagreement with the currently tabulated value of 15 ± 10 fs [Til95].

The same group then undertook a set of measurements using a proton beam of 60–90 μA and a water-cooled target, investigating the strength of the ^{17}O(p,α)^{14}N $E_R^{lab} \approx 194$ MeV resonance. Targets were made from 0.3 mm thick Ta sheets which were ion implanted with ^{17}O and ^{18}O beams. Reaction products were detected in four silicon detectors with active areas of 3 cm^2 at 105°, 120°, 135° and 150°, at a distance of 14 cm from the target. A 2 μm aluminized Mylar foil was placed in front of the detectors to protect them from an intense flux of elastically scattered protons. The resonance strength was found to be $\omega\gamma_{p\alpha} = 1.6 \pm 0.2$ meV.

Finally, the French team measured the ^{17}O(p,γ)^{18}F $E_R^{lab} \approx 194$ keV resonance strength by using the activation technique on the total ^{18}F production in irradiated ^{17}O targets. The ^{17}O implanted targets were bombarded for ~ 5 hr with a ~ 70 μA proton beam. The ^{18}F β^+-decay activity was measured with two large-volume Ge detectors positioned opposite one another in a very close geometry. In this configuration it is possible to register, in time coincidence, the two 511 keV photons from electron-positron annihilation. Using the measurement of the ^{17}O(p,α)^{18}F reaction (described in the previous paragraph), the resonance strength ratio was found to be $\omega\gamma_{p\alpha}/\omega\gamma_{p\gamma} = 470 \pm 50$. The strength of the $E_R^{lab} \approx 194$ keV resonance was deduced to be $\omega\gamma_{p\gamma} = 3.4 \pm 0.6$ μeV, which is significantly larger than the value from Reference [Fox05] with $\omega\gamma_{p\gamma} = 1.2 \pm 0.2$ μeV.

As a check of the experimental setup and procedure, the ^{12}C(p,γ)^{13}N reaction was used. A 20 μg/cm^2 C target was evaporated on a Ta sheet and irradiated with a proton beam with energy E_p = 196 keV. The astrophysical S-factor from the ^{13}N activity was measured to be 4.0 ± 0.8 keV b in good agreement with a previous measurement [Rol74]. To illustrate of the effect of the new measurement of $\omega\gamma_{p\gamma}$, hydrodynamic simulations for a nova outburst using the new ^{17}O+p rates were performed and a reduction in the abundances of ^{17}O by a factor of 2.4 and ^{18}F by a factor of 2.9 were found with respect to Reference [Fox05].

A comparison of the ^{17}O(p,α)^{14}N/^{17}O(p,γ)^{18}F reaction rate ratio from the two recent measurements, and the previous accepted ^{17}O(p,γ)^{18}F rate, show a difference of a factor of ~ 100 between the maximum and minimum rates (see Figure 4). Owing to the factor of three discrepancy between the two measurements of $\omega\gamma_{p\gamma}$ (1.2 ± 0.2 μeV from Fox *et al.* [Fox05] and 3.4 ± 0.6 μeV from Chafa *et al.* [Cha05]) and the importance of knowing this reaction rate, the need for additional experimental information was expressed and is clearly needed. DRAGON can be used to provide an entirely independent measurement of the resonance strength and should resolve the factor $\times 3$ discrepancy between existing measurements. This will avoid uncertainties due to implanted-target stoichiometry, effective energy loss of the beam in the target and avoids corrections for ^{18}F backscattering out of the target. Also, coincident summing corrections do not have to be applied as in [Fox05] although γ-ray detection efficiency corrections will have to be made.

2 Experiment Description

It is proposed to determine the $E_R^{cm} = 183$ keV ^{17}O(p,γ)^{18}F resonance strength with an ^{17}O beam in inverse kinematics using the DRAGON facility. A diagram of the DRAGON apparatus is shown in Figure 5; for a detailed description of the facility the reader is referred to [Hut03].

The oxygen beam can be produced using a 90 % enriched ^{17}O water target with the offline ion-source (OLIS) at ISAC. The desired beam intensity to perform this study is 3×10^{11} pps at DRAGON, but a higher intensity will be required from OLIS due to loss from charge-state selection after the beam has passed through a carbon stripper-foil (boosting the charge-state from 1^+ to 3^+ to give $A/q < 6$ for acceptance into the drift-tube-linac (DTL)). Stripping foils last approximately 200 pnA h for oxygen beams, so for example, a foil will last only 3 hours with a beam intensity of 4×10^{11} pps (without including considerable OH beam contamination). Therefore, to perform this study with the desired ^{17}O intensity, either the use of an ECR ion source for OLIS or the development of an $^{17}O^{3+}$ or $H_2{}^{17}O^{1+}$ beam will be required. If the ECR ion source is used, $^{17}O^{3+}$ beam intensities of several hundred microamps can be produced without the OH contamination [Bri05], and therefore a rate of 3×10^{11} pps or more can be readily achieved.

The beam will be accelerated using the DTL to 197 keV/u and delivered to the DRAGON experimental area, where it will be centred through the windowless gas-target. The beam current will be measured with a Faraday cup upstream of the target, with additional monitoring by two elastic-scattering surface-barrier detectors located within the gas cell. The target will be filled with H_2 gas at a pressure of 4.5 Torr, providing a beam energy-loss of 42 keV/Torr. The energy spread of the beam will be larger than the width of the resonance but smaller than the beam energy-loss in the target, making the thick-target-yield method applicable. The separator will be tuned to transmit the most intense charge-state of the recoils through to the detector at the tail of the separator. A double-sided-silicon-strip-detector (DSSSD) will be used in conjunction with a micro-channel-plate detector (MCP) to identify these recoils and provide E–T discrimination. A bismuth-germanate-oxide (BGO) detector array surrounding the gas target will be used to detect γ-rays in coincidence with the detected recoils.

From the thick target yield, Y, the resonance strength, $\omega\gamma_{p\gamma}$, can be obtained. The two quantities are related in the following way:

$$Y = \frac{\lambda^2}{2\varepsilon}\frac{m_{17}+m_p}{m_p}\omega\gamma_{p\gamma} \tag{1}$$

In this equation λ is the de Broglie wavelength, m_{17} the mass of the projectile ^{17}O, m_p the mass of the target proton and ε the stopping power of the projectile in the target in the laboratory system. For a resonant capture reaction, the resonance strength is defined as:

$$\omega\gamma_{p\gamma} = \frac{2J_R}{(2J_{17}+1)(2J_p+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma} \tag{2}$$

Here J_R, J_{17} and J_p are the spins of the ^{18}F resonance, ground-state of the projectile ^{17}O and target proton respectively, and Γ_p, Γ_γ and Γ are the entrance-channel width, the γ-width and the total width respectively ($\Gamma = \Gamma_\alpha + \Gamma_p + \Gamma_\gamma$ if no other channel is open). Therefore, with a measurement of the thick target yield, and knowledge of the stopping power of the projectile in the target (which can be measured in the experiment), the resonance strength can be found, which in turn is directly proportional to the stellar reaction rate.

To test the experimental apparatus, the $E_R^{cm} = 489$ keV resonance will be used and the measured $\omega\gamma_{p\gamma}$ compared to previous results [Fox05,Rol73]. The charge-state distribution of recoils and detection efficiency of the BGO array will also need to be taken into account for this measurement. As this resonance is relatively strong, charge-state distributions will be measured directly by detecting the yield of ^{18}F for each charge state in the end detector. The BGO efficiency depends on the energy of the detected γ-ray and varies from 40–60 % for γ-rays of 1–10 MeV respectively. Taking the BGO efficiency as 45 % for 5 MeV prompt γ-rays, and assuming a fraction of 0.45 for the most populous charge-state, a counting rate of $\sim$ 7500 recoils/hour can be expected if the desired beam intensity of $\sim$ 50 pnA can be obtained. A summary of the resonances to be measured is shown in Table 2.

E_R^{cm} (keV)	E_x (keV)	E_{beam} (keV/u)	$\omega\gamma_{p\gamma}$ (eV)	θ_{max} (mrad)	Y (per ion)
183	5789	197	$(1.2 \pm 0.2) \times 10^{-6}$	18	8.5×10^{-15}
489.9 ± 1.1	6096.4 ± 1.1	520	$(1.3 \pm 0.3) \times 10^{-2}$	11.6	3.4×10^{-11}

Table 2: Summary of parameters for resonances to be measured in the experiment. The resonance strength for the 490 keV resonance is taken from [Fox05], and is the correctly normalized value from [Til95].

For the resonance of interest at $E_R^{cm} \sim 183$ keV, a yield of 1.7×10^{-15} per incoming beam particle is expected if recoil charge-state distributions and BGO efficiencies are taken into account. With a separator suppression of $\sim 10^{-9}$, time-of-flight window of 100 ns and a background rate of 50 Hz in the BGO array, a background yield of $\sim 5 \times 10^{-15}$ per incoming beam particle is expected. However, by applying software cuts to the data, it should be possible to suppress background counts by another order of magnitude. Examples of such cuts would be on end-detector energy, on BGO-detector energy and on the γ-ray-RF timing spectrum. With the above parameters and a beam of 3×10^{11} pps, a coincidence rate of $\sim$ 2 counts/hr is expected. Charge-state distributions will be measured using a ^{19}F beam at an energy of 182 keV/u with a H_2 gas target. The current due to each charge state will be measured in a Faraday cup after the MD1 bending magnet (see Figure 5), with the assumption that the distribution for the ^{19}F recoils is the same as that of the ^{18}F beam if their E/m ratios are equal. It will not be necessary to scan the resonance as the height of the plateau in the experimental yield curve is measured (giving the resonance strength), and position information taken from the BGO-detector array hit-pattern is used to ensure the resonance is located entirely within the gas-target cell. To assess the background contribution to the rate, measurements off-resonance, at a slightly higher beam energy of 215 keV/u, will be made.

The largest uncertainty in the measurement is likely to come from the separator acceptance. The maximum cone angle for this particular resonance is $\theta_{max} = \pm 18$ mrad, greater than the separator acceptance of ± 15 mrad for 100 % transmission. For this particular reaction, a precise measurement requires good knowledge of the acceptance. One way to obtain the separator acceptance is by using GEANT, a calculation which yields an efficiency of 86 % for detecting recoils for the $E_R^{cm} \sim 183$ keV resonance centred in the gas target. As a test of the GEANT simulation, a measurement of the acceptance could also be made by using Rutherford scattering from a thin solid target. This would involve setting the DRAGON separator to accept recoils from $\theta_{cm} = 180^\circ$ Rutherford scattering. At this angle the cross-section for Rutherford scattering is essentially constant and scattered particles can be assumed to be distributed isotropically over the region of the separator entrance. Comparing the total number of ions detected at the tail of DRAGON to the expected yield from Rutherford scattering will give an experimental handle on the acceptance.

3 Beam Time Request

The beam time requested will enable the resonance strength of interest to be measured with a statistical accuracy of 10 %. Shifts are given for both the desired beam intensity and the minimum acceptable intensity shown in brackets (3×10^{11} and 1×10^{11} pps at DRAGON respectively). If, however, the ECR ion source is used for beam production of $\sim 10^{12}$ pps, the total required shifts would be halved to 15.

Measurement	Shifts	
$p(^{17}\mathrm{O},\gamma)^{18}\mathrm{F}$ $E_R^{cm} = 183$ keV on resonance	10	(16)
$p(^{17}\mathrm{O},\gamma)^{18}\mathrm{F}$ $E_R^{cm} = 200$ keV off resonance	10	(16)
$p(^{17}\mathrm{O},\gamma)^{18}\mathrm{F}$ $E_R^{cm} = 489$ keV on resonance	5	(5)
$p(^{19}\mathrm{F})$ charge-state distribution	1	(1)
Contingency	4	(4)
Total	30	(42)

4 Readiness

DRAGON is ready to accept beam for this experiment.

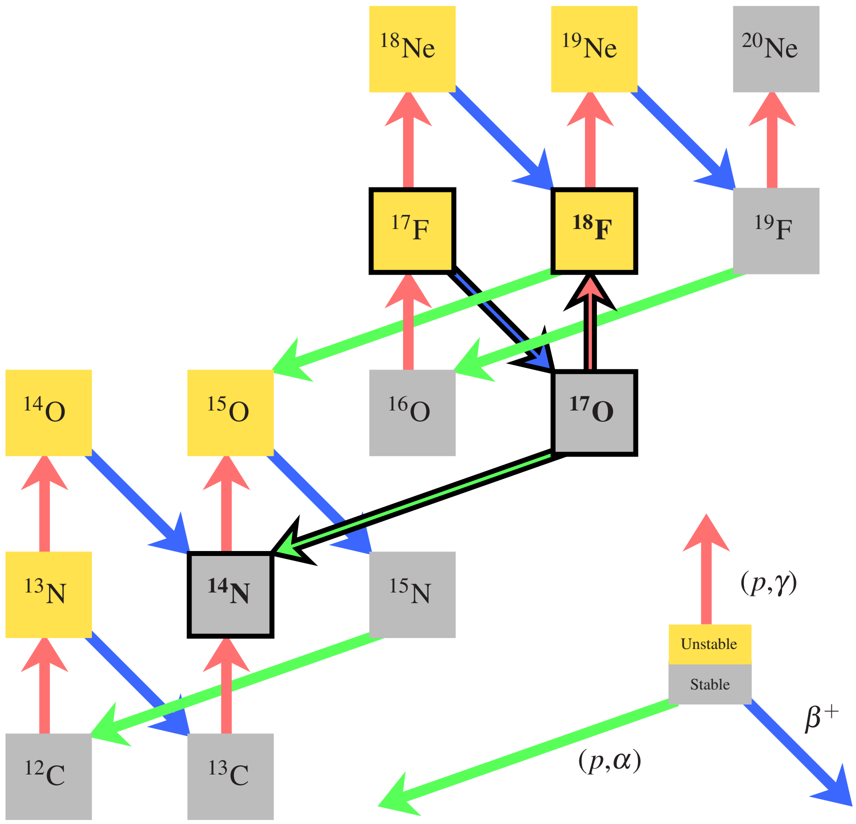

Fig. 1: The hot CNO cycle. The reactions relevant to this proposal (outlined in bold) that contribute to the production of ^{18}F are the ^{17}O$(p,\gamma)^{18}$F and ^{17}O$(p,\alpha)^{14}$N reactions and the β^+-decay of ^{17}F.

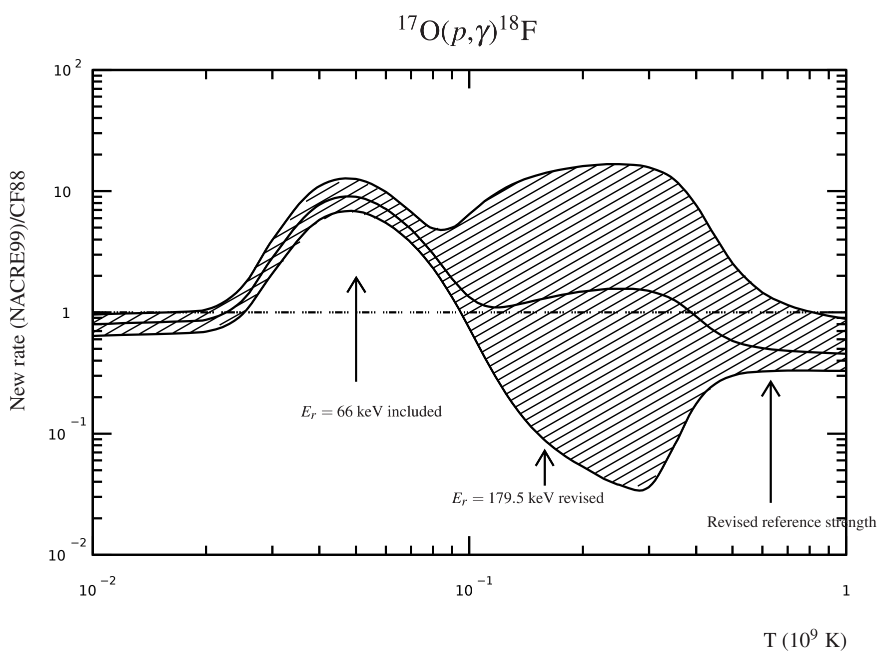

Fig. 2: Uncertainty in the ^{17}O$(p,\gamma)^{18}$F rate [Coc00] prior to recent results. This plot shows the ratio between the low, recommended and high NACRE and [Cau88] rates. The largest uncertainty occurs at an energy corresponding to the poorly-known contribution to the rate from the $E_R^{cm} = 183$ keV level.

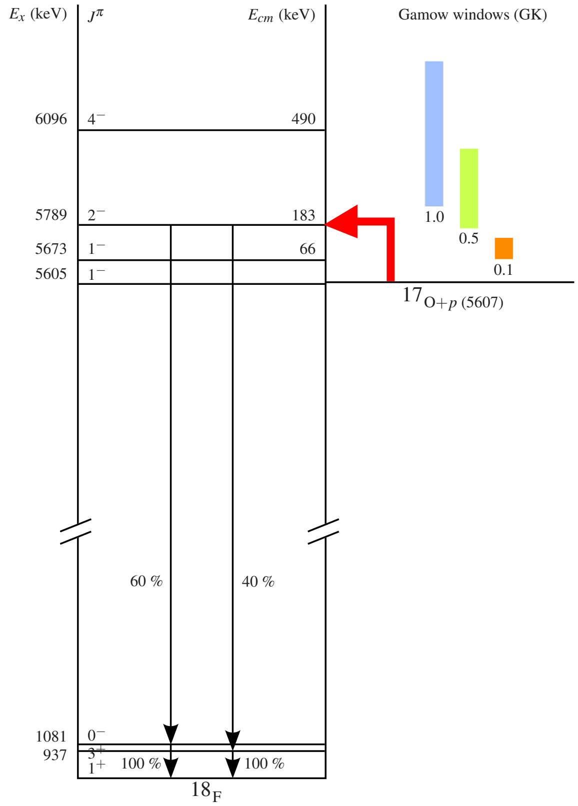

Fig. 3: Energy level diagram for ^{18}F. The Gamow window is shown for three different temperatures (0.1, 0.5 and 1.0 GK); temperatures between 0.1 to 0.4 GK are relevant to novae. The branching ratios for the γ-ray decay from the level of interest are also given.

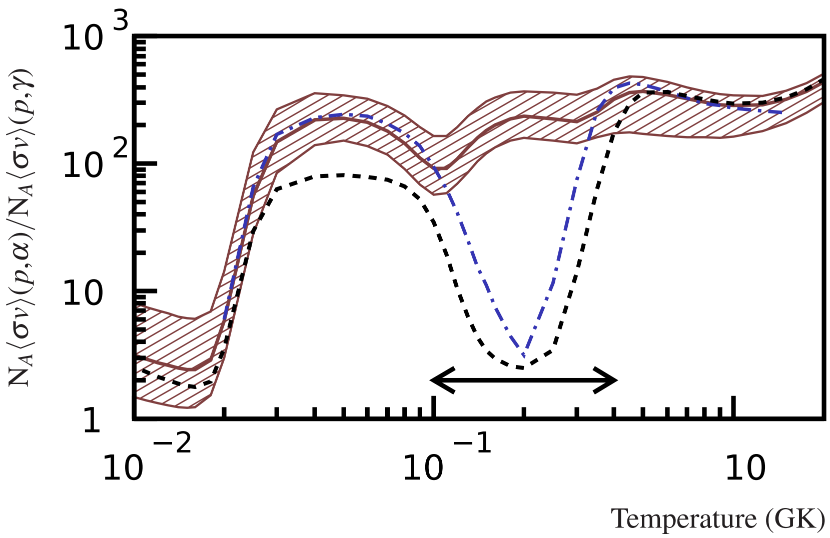

Fig. 4: The ratio of the ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F reaction rates [Cha05]. Ratios are taken from three different compilations: [Cha05] (solid line), [Ang99] (dashed line) and [Fox05] (dotted-dashed line). The rate from [Cha05] includes their new measurement of the $\omega\gamma_{p\alpha}$ resonance strength.

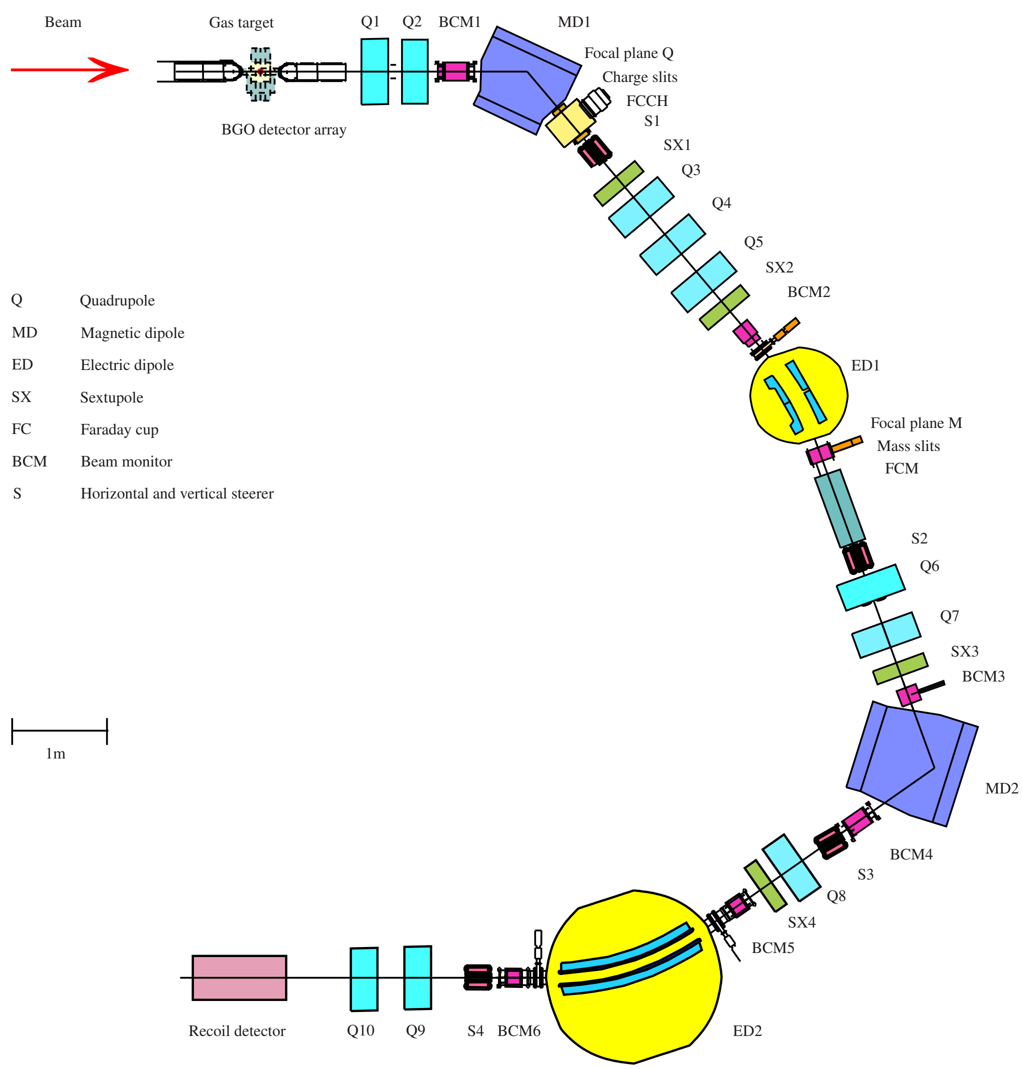

Fig. 5: A schematic diagram of the DRAGON separator [Hut03]. The four important components of the setup are i) the windowless gas-target, ii) the γ-ray BGO-detector array, iii) the mass and charge separation components and iv) the recoil detector at the end of the separator.

References

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