Novae are the third most energetic stellar explosions in the universe, after gamma-ray bursts and supernovae. These outbursts occur in binary systems consisting of a white dwarf and a less evolved companion star. Accretion of hydrogen-rich material from the outer envelope of the companion star onto the surface of the white dwarf leads to thermonuclear runaway outbursts occur in binary systems consisting of a white dwarf and a less evolved companion star. Accretion of hydrogen-rich material from the outer envelope of the companion star onto the surface of the white dwarf leads to thermonuclear runaway (TNR) driven by the CNO cycle [1]. At higher temperatures, the nuclear processing and energy generation proceed via the hot-CNO cycles. In the first few hours, before the optical light curve is observed, γ-ray emission is thought to be dominated by annihilation photons from the β decay of 18F, and so understanding its production can provide important constraints on the conditions during the outburst when compared with observations. Results are presented from the lowest-energy direct measurement to date, performed at the Isotope Separator and Accelerator radioactive beam facility at the TRIUMF laboratory, Canada. Cross section measurements at center-of-mass energies of 250, 330, 453, and 673 keV are obtained and the results compared to previous data and R-matrix calculations. The implications for the overall reaction rate in the context of nova explosions have been discussed.

The 18F(p, α)15O reaction rate is crucial for understanding the final abundance of 18F predicted by nova models. The γ-ray emission in the first few hours after a nova outburst is expected to be dominated by 511 keV annihilation photons from the decay of 18F, and so understanding its production can provide important constraints on the conditions during the outburst when compared with observations. Results are presented from the lowest-energy direct measurement to date, performed at the Isotope Separator and Accelerator radioactive beam facility at the TRIUMF laboratory, Canada. Cross section measurements at center-of-mass energies of 250, 330, 453, and 673 keV are obtained and the results compared to previous data and R-matrix calculations. The implications for the overall reaction rate in the context of nova explosions have been discussed.

The 18F(p, α)15O reaction was undertaken at effective center-of-mass energies of 250, 330, 453, and 673 keV. The 665 keV resonance has been well studied (see Refs. [10,11] and references therein), and so a measurement in this region allowed the validity of the technique to be confirmed. The 453 keV energy was chosen because it falls between two previous measurements by de Séréville et al. [12], at 402 and 486 keV, and would allow the presence of a possible 3/2+ resonance at 430(30) keV to be determined. The third energy measurement allowed an independent measurement of the 330 keV resonance, previously studied directly by Bardayan et al. [4]. However, the main aim of the present work was to measure the cross section below the 330 keV resonance to constrain the contribution from interference, between the 3/2+ states, in the Gamow window for nova events. We report here a direct measurement of the 18F(p, α)15O cross section at 250 keV, the lowest energy to date.

The measurement was performed at the Isotope Separator and Accelerator (ISAC) radioactive beam facility, TRIUMF, Canada, utilizing a high-intensity (average 5 x 10^6 pps) 18F(p, α)15O beam. The 18O contamination in the beam, which was monitored throughout the experiment, dropped from an initial 70% (during 673 keV runs) to less than 5% during the 250 keV data runs. The 18F beam was focused onto a (CH2)n target located within the TRIUMF UK Detector Array (TUDA) scattering chamber. The beam intensity was monitored in real time with a Faraday cup and the beam constituents were determined by using monitor detectors positioned downstream of the

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A monolithic silicon detector [13] provided \(\Delta E/E\) information to separate \(^{18}\text{O}\) and \(^{18}\text{F}\). These data were complemented by direct beam data, using an attenuated beam between runs, from a Hamamatsu photodiode, located behind a 2-\(\mu\)m aluminum foil and mounted on the target ladder. This foil provided sufficient differential stopping such that \(^{18}\text{F}\) and \(^{18}\text{O}\) could be distinguished. The hydrogen content of the target was monitored by measuring the ratio of hydrogen to carbon recoils scattered, at a given angle, by the beam. When the ratio dropped significantly, the target was replaced. Two targets were used during the experiment, with thicknesses of \(32 \pm 2\) and \(34 \pm 2\) \(\mu\)g/cm\(^2\), respectively.

Coincident \(\alpha\)-particle and heavy-ion products were detected by highly segmented silicon strip detector arrays, providing particle energy, time-of-flight, and scattering angle information. One MSL YY1 LEDA (LEDA-2) [14] silicon strip detector was positioned upstream covering downstream laboratory angles of \(4^\circ\)–\(146^\circ\) and three further silicon strip detector arrays, one LEDA (LEDA-1) and two S2s (S2-1 and S2-2) [15], covered downstream laboratory angles of \(4^\circ\)–\(69^\circ\). Energy calibration of the silicon detectors was accomplished by using a standard \(^{238}\text{Pu}-^{241}\text{Am}-^{243}\text{Cm}\) \(\alpha\)-source. Figure 1 shows the raw energy-energy spectrum for coincident events at \(E_{\text{c.m.}} = 673\) keV \((E_{\text{beam}} = 12.96\) MeV\). The kinematic loci of \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) \((Q = 2.882\) MeV\) and \(^{18}\text{O}(p,\alpha)^{15}\text{N}\) events \((Q = 3.981\) MeV\) can be clearly seen, and are well separated, above the broad feature due to elastically scattered \(^{18}\text{F}\) and \(^{18}\text{O}\).

The presence of the \(^{18}\text{O}\) contamination allowed normalization of the measured \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) yield to the known \(^{18}\text{O}(p,\alpha)^{15}\text{N}\) cross sections (average of Refs. [16] and [17]) at the two highest energies. At the lower two energies, there were insufficient \(^{18}\text{O}(p,\alpha)^{15}\text{N}\) events to allow this technique to be used and here the yield was normalized by comparison to Rutherford scattering from the \(^{12}\text{C}\) in the target. The consistency of the two techniques was confirmed by using the 673 keV data.

Coincidence events of interest were then identified by selecting on summed energy, coplanarity, and opening angle, the latter of which was particularly effective. Figure 2 shows for these events, the \(Q\) value (uncorrected for energy loss), at each beam energy, calculated from the \(\alpha\) particle’s energy and angle, assuming the reaction to be \(^{18}\text{F}(p,\alpha)^{15}\text{O}\). At \(E_{\text{c.m.}} = 250\) keV, there are two events of interest that are well separated from elastic scattering events at lower \(Q\) values.

For all energies except 330 keV (which is assumed to be an \(\ell = 1\) transfer), the angular distributions were assumed to be isotropic, and the total reaction cross sections were obtained by multiplying the differential cross sections by \(4\pi\). For the 330 keV data, the measured angular distribution was fitted with an \(\ell = 1\) Legendre polynomial and the integral over this polynomial was calculated to give the total cross section. The total cross sections for the present data are given in Table I and the calculated astrophysical \(S\) factors are shown in Fig. 3 with previous data sets for comparison. Error bars include statistical and systematic contributions. The uncertainty for the data point at 250 keV is entirely dominated by the low statistics and was calculated according to the Feldman-Cousins approach [18], based on two events with no background. The error bars indicate 68%, 90%, and 95% confidence levels. The assumption of zero background in the region of interest (2500–3500 keV in Fig. 2) was validated by using a time-of-flight gate on the data. The events at lower \(Q\) values

![FIG. 1. (Color online) Energy in LEDA-1 vs energy in S2-2. The \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) (lower) and \(^{18}\text{O}(p,\alpha)^{15}\text{N}\) (upper) loci are highlighted, clearly separated from the broad elastic scattering feature. No cuts have been applied, apart from a 1 MeV threshold on all energies.](image1)

![FIG. 2. Reaction \(Q\) values calculated from \(\alpha\)-particle energy (uncorrected for energy loss in the target and detector dead layer) and angle, for all four energies, for coincident events in LEDA-1 vs S2-2. Gates applied to each energy are coplanarity, sum energy, and angle, for all four energies, for coincident events in LEDA-1 vs S2-2. The vertical dotted lines indicate the \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) and \(^{18}\text{O}(p,\alpha)^{15}\text{N}\) \(Q\) values.](image2)
(below 2000 keV) had time-of-flight values consistent with carbon recoils from elastic scattering. The cross section data point from the present work at 673 keV agrees well with existing data. The point at 453 keV neither indicates nor excludes the presence of the possible resonance at 430 keV, and further measurements with improved statistics are needed. The 330 keV data point agrees with the work of Bardayan et al. [4] within errors.

Multichannel R-matrix calculations were performed using the DREAM code [20] to calculate the astrophysical S factor from the 10 above-threshold resonances given in Table II. The level information used is taken from Ref. [3] with the addition of a 3/2+ state at 1347 keV observed by Murphy et al. [7]. The R-matrix channel radius parameter used was 5 fm, and an energy resolution of 15 keV (full width at half maximum) was assumed.

Interference between resonances of the same spin-parity results in significant differences in the S factor in the interresonance regions. For the five 3/2+ resonances included, 16 phases are possible. Within the energy region of interest, interference between the 8-, 38-, and 665 keV resonances causes the greatest variation. This results in four groupings of S factors, with the width of each group reflecting the effects of the interference between the remaining two resonances (827 and 1347 keV). The upper and lower S factor curves for each group are shown in Fig. 3. As can be seen, the lowest-lying group of S-factor curves is strongly disfavored (>95%) by the data point at 250 keV, whereas the second-lowest group is weakly disfavored.

Neither of the two 1/2+ resonances (−0.41 and 1.49 MeV) predicted by Dufour and Descouvemont [6] are included in the present R-matrix calculations but their predicted contribution is shown in Fig. 3 for comparison. The interference between the two states is negligible [6] and their contribution may be approximated by the sum of these two isolated states. The 1.49 MeV resonance was observed via inelastic scattering of 18Ne by Dalouzy et al. [8] but was not seen in elastic scattering by Murphy et al. [7]. The 1.49 MeV state, if it is present, does not make a significant contribution at nova temperatures, contrary to the conclusions of Dalouzy et al. [8], but its observation (or lack thereof) would indicate the existence (or not) of the −0.41 MeV resonance which, due to the predicted width of around 230 keV, does make a significant contribution in the relevant region. Further experiments to clarify the existence of both states are therefore important. There is a known state in 19Ne at 6.013 MeV (Er = −0.398 MeV), but this state is considered to be either 3/2− or 1/2− [21] and is not broad enough [22] to be the predicted −0.41 MeV resonance.

The picture is further complicated by recent indications that the 8 keV resonance may be a 3/2− and that there is a significant contribution from a subthreshold ℓ = 0 state at −121 keV [9]. However, recent data obtained by Josephides et al. [23], using 18O(α, α) scattering, suggests that a state in this energy region, which may be the same state, is most consistent with a 5/2+ assignment. The recent compilation by Iliadis et al. [5] assumed the −121 keV state to be 1/2+ and the 8 keV state to be 3/2−. The S factor calculated with these assumptions (all other parameters held as before and not including the 1089- and 1347 keV resonances, as per Ref. [5]) is shown in Fig. 4. The

![Graph](image-url)
upper curves now indicate a slightly lower $S$ factor in the region relevant to nova temperatures, whereas below 0.05 keV the $S$ factor is more than an order of magnitude lower. The curves agree well with previous low-energy data (Refs. [4,12]) as well as the present work. It can be seen from Fig. 4 that the change in parity of the 8 keV state and resultant lack of interference with the 38- and 665 keV states has a significant effect on the uncertainty in the $S$ factor in the region relevant to novae, reducing it from over a factor of 10 to around a factor of 2. However, this still results in up to a factor-of-10 uncertainty in the reaction rate [5]. An improved measurement at 250 keV could reduce this uncertainty by distinguishing between the upper and lower curves.

The preceding analysis is based on the assignments assumed in Ref. [5], and the resulting reaction rates are used by current nova models. However, the other assignments for the $-121$ keV resonance have not been excluded. Thus, for completeness, also shown in Fig. 4 are four curves corresponding to upper and lower limits on the $S$ factor, assuming the $-121$ keV resonance to be either $5/2^+$ [23] or $3/2^+$ [9]. Now the range of possible $S$ factors is significantly larger, particularly in the $3/2^+$ case due to interference with the 38- and 665 keV resonances. In both these cases, the experimental data favor the higher $S$-factor curves; however, confirmation of the spin of this state is required.

In conclusion, the lowest energy measurement to date of the astrophysically important $^{18}$F($p,\alpha$)$^{15}$O reaction was performed using a $^{18}$F beam delivered by the ISAC radioactive beam facility at the TRIUMF laboratory, Canada. Measurements of the reaction cross section were made at four different energies and the calculated cross sections were used to constrain the $R$-matrix $S$-factor calculations at nova temperatures. It is clear that current knowledge of the level scheme of $^{19}$Ne above the $\alpha$ threshold is incomplete and some of the accepted parameters may yet be shown to be inaccurate. Thus, there is a resultant uncertainty in $R$-matrix calculations based on incomplete data. Moreover, even if the state information on $^{19}$Ne were complete, direct measurements of the cross section would still be needed to distinguish between the different interference possibilities. The present work is the first nonresonant measurement in the Gamow window for this reaction and thus the first to put significant constraints on the interference in the region relevant to novae. These data suggest that the cross section in the region of most importance to novae is either characterized by constructive interference between $3/2^+$ resonances at 38 and 665 keV and/or that there is a strong contribution from $1/2^+$ subthreshold states. This constraint on the cross section implies that stronger rates of destruction of $^{18}$F in novae are preferred. Consequently, a lower abundance of $^{18}$F, and thus a reduced detectability distance, is predicted. There remains, however, significant uncertainty in the nuclear physics, and further measurements, both direct and indirect, are needed.

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