First Direct Measurement of the ^{17}O$(p, \gamma)^{18}$F Reaction Cross Section at Gamow Energies for Classical Novae

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Classical novae are important contributors to the abundances of key isotopes, such as the radioactive ^{18}F, whose observation by satellite missions could provide constraints on nucleosynthesis models in novae. The ^{17}O$(p, \gamma)^{18}$F reaction plays a critical role in the synthesis of both oxygen and fluorine isotopes, but its reaction rate is not well determined because of the lack of experimental data at energies relevant to novae explosions. In this study, the reaction cross section has been measured directly for the first time in a wide energy range $E_{c.m.} \simeq 200$–370 keV appropriate to hydrogen burning in classical novae. In addition, the $E_{c.m.} = 183$ keV resonance strength, $\omega\gamma = 1.67 \pm 0.12$ μeV, has been measured with the highest precision to date. The uncertainty on the ^{17}O$(p, \gamma)^{18}$F reaction rate has been reduced by a factor of 4, thus leading to firmer constraints on accurate models of novae nucleosynthesis.

Classical novae, a frequent phenomenon in our Galaxy, are explained as thermonuclear explosions on the surface of white dwarf stars accreting hydrogen-rich material from less evolved companions in binary star systems [1] and have been proposed as a key source of ^{13}C, ^{15}N, ^{17,18}O, and ^{18,19}F isotopes in the Universe [2]. In particular, the short-lived radioisotope ^{18}F ($t_{1/2} = 110$ min) may provide a signature of novae outbursts through the detection of 511 keV γ-ray emission from positron-electron annihilation following its β^+ decay. Indeed, the observation of these γ rays by satellite missions could put constraints on current nova models [3]. Hydrogen burning of ^{17}O is believed to play a key role in the destruction of ^{17}O and in the formation of ^{18}F, mainly through the competing reactions ^{17}O$(p, \gamma)^{18}$F and ^{17}O$(p, \alpha)^{14}$N. Thus, the thermonuclear rates of both reactions should be determined

with a high degree of accuracy directly in the energy region of hydrogen burning in classical novae. In this Letter, we report on a fourfold improvement in the ^{17}O$(p, \gamma)^{18}$F reaction rate determination. We have measured the ^{17}O$(p, \gamma)^{18}$F reaction cross section down to the lowest energies to date and within the Gamow window [4] for peak temperatures $T = 0.1$–0.4 GK [2].

At nova temperatures, the ^{17}O$(p, \gamma)^{18}$F reaction rate is dominated by a direct-capture (DC) reaction mechanism despite the presence of two narrow resonances at $E = 66$ and 183 keV above the proton threshold in ^{18}F [5,6] (all energies are in the center-of-mass system unless otherwise stated). In addition, nonresonant contributions arise from the low-energy tails of two broad resonances at $E = 556.7$ and 676.7 keV. A reliable determination of the total ^{17}O$(p, \gamma)^{18}$F reaction rate thus requires the accurate

knowledge of the individual energy dependence of both resonant and nonresonant contributions.

Early investigations by Rolfs [7] reported a constant DC contribution to the S factor (S_{DC}) [4,8] in agreement with the four lowest data points measured at energies $E = 280$–425 keV by prompt γ-ray detection [7]. It was later questioned by Fox *et al.* [5] whether these data points were dominated by the DC process or affected by the presence of the two broad resonance tails. Thus, in Ref. [5], the S_{DC} was calculated using measured spectroscopic factors and a realistic Woods-Saxon potential and found to be up to a factor of ~ 2.5 lower than that reported in Ref. [7]. A subsequent measurement [6] at $E \simeq 257$–470 keV led to an S_{DC} in agreement with the predictions by Fox *et al.* [5] and still about a factor of 2 lower than in Ref. [7]. More recently, the total (i.e., DC plus broad-resonance contributions) S factor was measured at $E = 260$–470 keV using the DRAGON recoil separator at TRIUMF [9] and found to be in fairly good agreement with values by Ref. [6], but consistently higher than the total S factor reported in Ref. [5]. As for the $E = 183$ keV resonance strength, only two values exist to date: $\omega\gamma = (1.2 \pm 0.2) \times 10^{-6}$ eV, as determined by a prompt γ-ray measurement [5,10], and $\omega\gamma = (2.2 \pm 0.4) \times 10^{-6}$ eV, as determined by the activation technique [11]. These disagree at the 95% confidence level. The origin of this discrepancy is not understood at present, but may be due in part to unobserved gamma transitions in Refs. [5,10] and/or to an inappropriate subtraction of the DC component in either Refs. [5,10] or Ref. [11]. Thus, the lack of experimental data at low energies and the largely unconstrained S_{DC} factor have so far precluded the accurate determination of the thermonuclear rate for this important reaction.

Here, we report on the results of a new and improved investigation of the $^{17}O(p, \gamma)^{18}F$ reaction using both activation and prompt γ-ray detection techniques to address a key source of discrepancy in existing results. Measurements were carried out at the 400 kV LUNA accelerator [12] of the Laboratory for Underground Nuclear Astrophysics (LUNA) facility, which offers significant improvements in sensitivity thanks to its low-background environment [13]. A proton beam, with currents up to 200 μA on target, entered the target chamber through a liquid-nitrogen cooled copper pipe biased to -300 V for secondary electron suppression. The target was directly water cooled with deionized water. Targets were prepared by anodization of Ta backings (0.3 mm thick disks) in isotopically enriched water (66% in ^{17}O and 4% in ^{18}O). Full details on target preparation and characterization have been reported in [14]. The target thickness was closely monitored for signs of degradation during intense proton-beam bombardment by regularly measuring the thick-target yield profile [4] of the narrow isolated resonance at $E = 143$ keV in $^{18}O(p, \gamma)^{19}F$ [14]. Prompt γ rays from the $^{17}O(p, \gamma)^{18}F$ reaction ($Q = 5606.5 \pm 0.5$ keV)

were detected using a large volume (115% relative efficiency) high-purity germanium detector placed at 1.5 cm from the target and surrounded by 5 cm lead. Both detector and target were at an angle of 55° with respect to the beam axis, with the detector's front face parallel to the target surface. Energy calibration, full-energy peak efficiency, and total efficiency were determined taking into account corrections for true-coincidence summing as described in Ref. [15]. Further details on the data analysis not reported here will be presented in a forthcoming publication [16].

The $^{17}O(p, \gamma)^{18}F$ reaction proceeds by populating several states in ^{18}F, leading to a complex decay scheme. Measurements were taken at the 183 keV resonance and at several off-resonance energies. At LUNA it was possible to observe and identify a large number of the γ-ray transitions from the entrance channel to ^{18}F intermediate or ground state (the *primaries*) and subsequent direct or multistep decay of excited states to the ^{18}F ground state (the *secondaries*). A sample γ-ray spectrum showing the quality of our data is given in Fig. 1. Independent determinations of the total S factor were carried out for all primary and secondary transitions. The main primary transitions to ^{18}F states at $E_x = 937$, 1121, 3061, 3791, 3839, and 4116 keV were analyzed using the peak-shape approach described in Ref. [17]. The resulting total astrophysical S factor, obtained from the sum of all primary contributions, is shown in Fig. 2. In total, 14 secondaries were also observed and analyzed, leading to an S factor (not shown in the figure) in agreement with that from the primaries. Summing corrections amounted on average to about 30% and were properly taken into account. In addition to the statistical errors shown, the primary total S-factor data carry a systematic uncertainty due to summing effects (1.5%), relative (1.5%), and absolute (3.5%) efficiency uncertainties, and an additional contribution of 7.6% (in common with the activation data) obtained as a sum in quadrature of uncertainties on collected charge (3%), stopping power (4%), stoichiometry (3%), target thickness (3.8%), and ^{17}O abundance (3%).

The $E = 183$ keV resonance strength $\omega\gamma$ was determined using the thick-target yield approach [4]. Prior to our investigation the $E = 183$ keV resonance had been observed to decay to only two states at $E_x = 1080$ and 937 keV in ^{18}F, with branching ratios of 60% and 40%, respectively [18]. However, several additional transitions were identified in our study, as shown in Fig. 1. Both the resonance strength and the branching ratios of all observed transitions were treated as free parameters in a global χ^2 fit to the experimental counts as in Ref. [17]. For the three most dominant transitions, $R \rightarrow 1080$, $R \rightarrow 937$, and $R \rightarrow 2101$ keV, the branching ratios were determined as $41 \pm 3\%$, $25 \pm 2\%$ and $12 \pm 2\%$, respectively. The branching ratios for a remaining six observed transitions were less than 6% each. Nonresonant contributions were subtracted for each transition individually. The measured
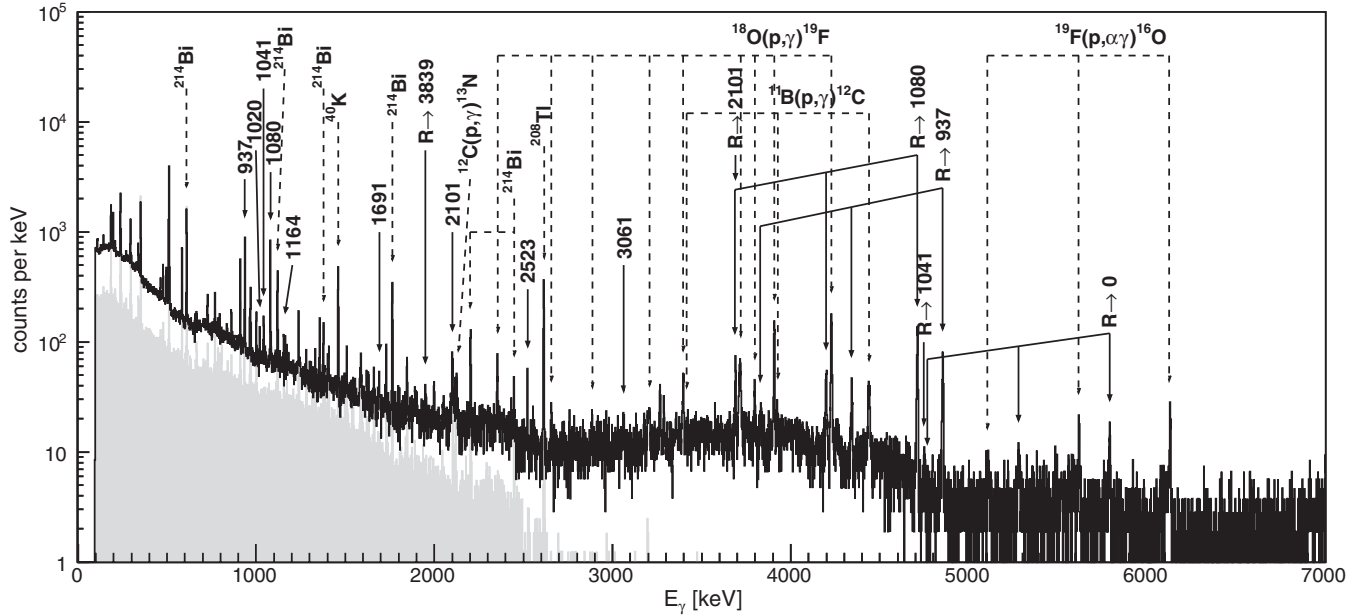
FIG. 1.   Sample spectrum from prompt γ-ray measurements of the ^{17}O$(p, \gamma)^{18}$F reaction at the $E = 183$ keV resonance. Primary transitions are labeled as $R \rightarrow E_x$, while secondary transitions are labeled by their energies. Some of the most prominent background transitions (dashed arrows) are also shown for comparison, together with a time-normalized background spectrum (gray area).

$E = 183$ keV resonance strength was $\omega\gamma = 1.70 \pm 3\%(\text{stat}) \pm 7.7\%(\text{syst})\ \mu$eV. (Note that for measurements at the resonance, the target thickness uncertainty is only relevant for the DC subtraction and the common uncertainties reduce to 6.6%.)

An independent determination of both resonant and nonresonant contributions to the ^{17}O$(p, \gamma)^{18}$F total cross section was also obtained with the activation technique,

FIG. 2 (color online).   Total astrophysical S factor as a function of center-of-mass energy for the ^{17}O$(p, \gamma)^{18}$F reaction. Filled symbols refer to the activation (circles) and the prompt γ-ray (squares) measurements in the present study. The solid line is the best fit to our data, while the dotted line labeled "Newton" is calculated using the DC contribution from Ref. [6] and the resonance parameters from Ref. [5] as used in Ref. [20] (see text for further details).

i.e., by detecting the 511 keV γ rays from the positron annihilation following the β^+ decay of ^{18}F. Targets were irradiated for several hours to saturate the ^{18}F activity, using the same setup described earlier but without lead shielding. Loss of ^{18}F from the target during irradiation was estimated to be below 1% at all bombarding energies according to GEANT4 Monte Carlo simulations. Activation spectra were recorded every 20 min over a period of several hours using the low-background facility, Subterranean Low Level Assay (STELLA) [19]. The absolute efficiency of the detector was measured with a calibrated ^{85}Sr source which emits a single γ-ray line at 514 keV allowing for a direct determination of the efficiency at the required energy, free from summing corrections. The laboratory background was negligible compared to the count rate of the activated targets. The irradiated targets were placed on top of the detector crystal and a Ta absorber, in direct contact with the activated target, was used to fully stop the emitted positrons. Our best value of $t_{1/2} = 109.6 \pm 0.4$ min for the ^{18}F half-life was obtained as an average of several fits to experimental data at different energies and found to be in excellent agreement with the literature value $t_{1/2} = 109.77 \pm 0.05$ min. The only contaminant to the spectra was found to be the short-lived ^{13}N β^+ emitter. No longer-lived positron emitters were observed after several half-lives. From the number of observed disintegrations at off-resonance energies, the total S factor was determined following a standard procedure described in Ref. [4]. Results from the activation analysis are shown in Fig. 2. In addition to the statistical errors shown, data are affected by an independent systematic uncertainty of 2.9% [sum in quadrature of uncertainties from backscattering losses
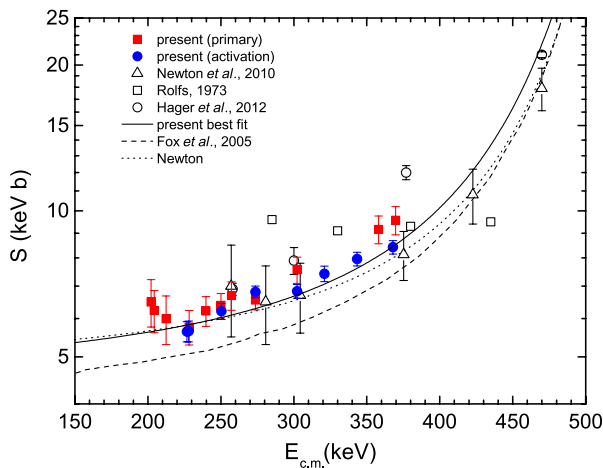
TABLE I.   Reaction rate for the $^{17}O(p, \gamma)^{18}F_{gs}$ reaction as a function of temperature.

Temperature T (GK)	Lower limit	Recommended value $N_A\langle\sigma v\rangle$ (cm^3 mol^{-1} s^{-1})	Upper limit
0.040	2.15×10^{-12}	2.50×10^{-12}	2.90×10^{-12}
0.050	6.62×10^{-11}	7.71×10^{-11}	8.96×10^{-11}
0.060	6.66×10^{-10}	7.69×10^{-10}	8.87×10^{-10}
0.070	3.63×10^{-09}	4.13×10^{-09}	4.71×10^{-09}
0.080	1.40×10^{-08}	1.57×10^{-08}	1.76×10^{-08}
0.090	4.47×10^{-08}	4.91×10^{-08}	5.40×10^{-08}
0.100	1.27×10^{-07}	1.38×10^{-07}	1.50×10^{-07}
0.110	3.40×10^{-07}	3.67×10^{-07}	3.96×10^{-07}
0.120	8.57×10^{-07}	9.22×10^{-07}	9.92×10^{-07}
0.130	2.05×10^{-06}	2.20×10^{-06}	2.36×10^{-06}
0.140	4.60×10^{-06}	4.92×10^{-06}	5.26×10^{-06}
0.150	9.67×10^{-06}	1.03×10^{-05}	1.10×10^{-05}
0.160	1.91×10^{-05}	2.03×10^{-05}	2.17×10^{-05}
0.180	6.22×10^{-05}	6.62×10^{-05}	7.05×10^{-05}
0.200	1.67×10^{-04}	1.78×10^{-04}	1.89×10^{-04}
0.250	1.10×10^{-03}	1.17×10^{-03}	1.25×10^{-03}
0.300	4.70×10^{-03}	5.04×10^{-03}	5.41×10^{-03}
0.350	1.88×10^{-02}	2.04×10^{-02}	2.21×10^{-02}
0.400	7.65×10^{-02}	8.44×10^{-02}	9.29×10^{-02}
0.450	2.83×10^{-01}	3.16×10^{-01}	3.51×10^{-01}
0.500	8.80×10^{-01}	9.88×10^{-01}	$1.10 \times 10^{+00}$
0.600	$5.18 \times 10^{+00}$	$5.82 \times 10^{+00}$	$6.51 \times 10^{+00}$
0.700	$1.87 \times 10^{+01}$	$2.09 \times 10^{+01}$	$2.34 \times 10^{+01}$
0.800	$4.87 \times 10^{+01}$	$5.44 \times 10^{+01}$	$6.06 \times 10^{+01}$
0.900	$1.02 \times 10^{+02}$	$1.13 \times 10^{+02}$	$1.26 \times 10^{+02}$
1.000	$1.82 \times 10^{+02}$	$2.02 \times 10^{+02}$	$2.24 \times 10^{+02}$

(1%), ^{13}N contamination (1%), detector efficiency (2.5%)], and by a 7.6% uncertainty in common with the prompt γ-ray data (see above). The $E = 183$ keV resonance strength was derived from measurements at energies on the plateau of the thick-target yield after subtraction of a DC contribution of about 18%, which results in a 3% DC-correction uncertainty on $\omega\gamma$. The obtained resonance strength, $\omega\gamma = 1.65 \pm 1.8\%(\text{stat}) \pm 7.8\%(\text{syst})$ μeV, is in excellent agreement with the result of the prompt γ-ray measurements. The weighted average of the resonance strength values from both measurements gives $\omega\gamma = 1.67 \pm 0.12(\text{stat} + \text{syst})$ μeV.

To obtain an overall total S factor, the activation and the prompt γ-ray data sets were analyzed in a common fit procedure. Unfortunately, inclusion of other data sets (e.g., from Ref [9]) in our fit was not possible since these seem to be affected by a mixture of systematic and point-to-point uncertainties that prevent a common and self-consistent analysis of all data sets. Following the phenomenological approach of Refs. [5,20], the fitting function included contributions from the two broad resonances at $E = 557$ and 667 keV, with energy dependence of the involved partial widths described by the broad-resonance formalism [4], as well as a constant DC term. The weak energy dependence of the DC component was neglected in the present analysis, as in previous works

[5,20], since its effect is beyond the precision of our data. Finally, preliminary calculations [16] indicate that interference effects between resonant and DC contributions are negligible and have not been included. A proper treatment of the systematic uncertainties [21] required the introduction of three scaling factors, one for each data set to account for noncommon systematic uncertainties, and one for the common uncertainties. Their values were then obtained simultaneously in a modified χ^2 fit (for a similar approach see Ref. [22]). Additional free parameters in the fit were the DC contribution and the partial Γ_γ width of the 557 keV resonance. The former parameter was left unconstrained while the latter was treated as a free parameter weighed by a Gaussian probability distribution with expectation value and standard deviation given by the literature value $\Gamma_{\gamma,557} = 0.57 \pm 0.13$ eV [23]. The influence of the second broad resonance on the fit quality was extremely small and, thus, $\Gamma_{\gamma,677}$ was fixed to the literature value [23]. The best fit ($\chi^2 = 13.9$ for 19 data points and five fit parameters) was obtained for $\Gamma_{\gamma,557} = 0.70$ eV and a DC component of $S_{DC} = 4.4 \pm 0.4$ keV b with scaling factors of $c_{act} = 1.008$, $c_{prim} = 0.972$, and $c_{com} = 0.963$. These factors are in good agreement with their expectation value of 1, within the corresponding systematic uncertainties they represent.
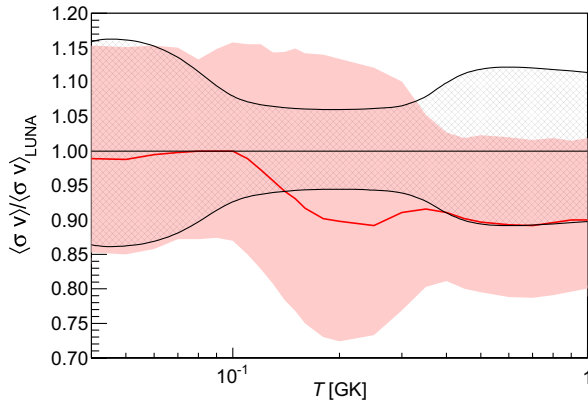
FIG. 3 (color online). $^{17}O(p, \gamma)^{18}F$ reaction rate ratio as a function of temperature. The [gray (red)] solid line is the ratio between the rate from a recent compilation rate (Ref. [20]) and the present value. Hatched and shaded areas represent a 1σ uncertainty on the present and previous rate, respectively. In the relevant nova temperatures $T = 0.1$–0.4 GK, the rate uncertainty is reduced by a factor of 4 in the present study.

The astrophysical $^{17}O(p, \gamma)^{18}F$ reaction rate was calculated using the formalism described in Ref. [24] as an incoherent sum of contributions from two narrow resonances (the $E = 183$ keV one from the present work, the $E = 66$ keV one from the literature [23]) and the combined contribution of the broad resonances and the direct capture, this latter obtained as numerical integration of the present S-factor best fit (solid curve in Fig. 2). The resulting reaction rate is tabulated in Table I with lower and upper limits given by the 68% confidence level. A comparison between our rate and that from a recent compilation [20] (Fig. 3) shows an improvement of a factor of 4 in the present rate uncertainty.

On the basis of our improved rate, we have explored preliminary implications on the abundances of key isotopes produced by classical novae. For example, according to Ref. [25] a 25% (1σ) uncertainty in the $^{17}O(p, \gamma)^{18}F$ reaction rate leads to a 40%-50% variation on the calculated yields of ^{18}O, ^{18}F, and ^{19}F at $T = 0.1$–0.4 GK. With the present rate being determined at the 5% level (see Fig. 3), the uncertainty on the ^{18}O, ^{18}F, and ^{19}F abundances reduces to less than 10% and puts firmer constraints towards more accurate nucleosynthesis calculations in novae events. The effects of our revised rate on the computation of detailed nova models will be discussed in a forthcoming paper.

In summary, the $^{17}O(p, \gamma)^{18}F$ reaction cross section has been measured for the first time in the relevant energy region of hydrogen burning in classical novae. The astrophysical S factor has been determined both by means of prompt γ-ray and activation measurements, and results from the two approaches were found to be in excellent agreement. In addition, we have obtained the most accurate determination of the $E = 183$ keV resonance strength to date as $\omega\gamma = 1.67 \pm 0.12$ μeV. The reaction rate uncertainty was reduced by a factor of 4 leading to improved constraints on classical novae nucleosynthesis.

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