Strength of the $^{18}F(p,\alpha)^{15}O$ Resonance at $E_{c.m.} = 330$ keV

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Production of the radioisotope ^{18}F in novae is severely constrained by the rate of the $^{18}F(p,\alpha)^{15}O$ reaction. A resonance at $E_{c.m.} = 330$ keV may strongly enhance the $^{18}F(p,\alpha)^{15}O$ reaction rate, but its strength has been very uncertain. We have determined the strength of this important resonance by measuring the $^{18}F(p,\alpha)^{15}O$ cross section on and off resonance using a radioactive ^{18}F beam at the ORNL Holifield Radioactive Ion Beam Facility. We find that its resonance strength is 1.48 ± 0.46 eV, and that it dominates the $^{18}F(p,\alpha)^{15}O$ reaction rate over a significant range of temperatures characteristic of ONeMg novae.

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Nova explosions are some of the most violent events in the universe, exceeded in energy release only by supernovae and gamma-ray bursts [1]. Despite intensive efforts to understand the nova mechanism, significant discrepancies exist between the results of nova models and observations for many global properties such as the ejected envelope mass [1,2]. A further constraint on nova models could come from observations of the gamma rays emitted from nova ejecta [3,4]. Missions, such as the recently launched INTEGRAL observatory and the planned Advanced Compton Telescope, promise to provide us with the most detailed pictures of the gamma-ray emission from novae ever available. To interpret these observations, however, we must know the relevant thermonuclear reaction rates that affect radioisotope production.

Novae emit gamma rays during the first several hours after the explosion predominantly at energies of 511 keV and below [5]. This emission is produced by electron-positron annihilation in the expanding envelope and the subsequent Compton scattering of the resulting gamma-ray photons. Of the possible positron sources, the decay of ^{18}F is the most important because of the relatively large ^{18}F abundance, and because the relatively long length of the ^{18}F half-life ($t_{1/2} = 109.8$ m) enables positrons to be emitted after the expanding envelope becomes transparent to gamma-ray radiation [5]. Of particular interest for ^{18}F observations are ONeMg novae which have more massive white dwarf progenitors, are hotter ($T_{peak} =$ 0.2–0.4 GK), eject more ^{18}F, and are thus easier to detect than the cooler CO novae [6]. The amount of ^{18}F produced (and thus the flux of emitted gamma rays) is severely constrained by its destruction rate via the $^{18}F(p,\alpha)^{15}O$ reaction in the burning shells. Recent studies have found that the uncertainties in the $^{18}F(p,\alpha)^{15}O$ reaction rate result in a factor of $\sim$300 variation in the amount of ^{18}F produced in models [7]. It is difficult to say whether gamma-ray observations of ^{18}F in novae are feasible without a more precise value of the $^{18}F(p,\alpha)^{15}O$ reaction rate.

The $^{18}F(p,\alpha)^{15}O$ reaction rate is composed of contributions from several resonances [8]. Since the 1982 study by Wiescher and Kettner of the $^{18}F(p,\alpha)^{15}O$ reaction [9], however, it has generally been believed that the $^{18}F(p,\alpha)^{15}O$ reaction rate is dominated over a wide range of nova temperatures by a resonance at $E_{c.m.} = 330 \pm 6$ keV that arises from a $J^\pi = \frac{3}{2}^-$ level in ^{19}Ne at $E_x = 6.741$ MeV [7–11]. This belief has been further reinforced by recent studies of the $^{18}F(d,p)^{19}F$ reaction [12,13] that constrain the contributions of lower-energy resonances. These studies indicate that a 38-keV resonance provides the largest contribution below $T \lesssim$ 0.25 GK while the 330-keV contribution is the largest from 0.25 GK $\lesssim T \lesssim$ 0.4 GK. All of the $^{18}F(p,\alpha)^{15}O$ reaction rate calculations since the publication of Ref. [9], however, have relied on estimates for the single-particle reduced width (θ_p^2) of the 330-keV resonance, upon which the rate depends linearly. Such estimates may be incorrect by an order of magnitude or more [7]. An indication of this resonance may have been seen in Ref. [11], but the statistics in that study were too poor and the background subtraction too uncertain to reliably extract a resonance strength. We have considerably improved upon the measurement in Ref. [11] by using a coincidence technique along with kinematic reconstruction to produce an essentially background-free measurement of the strength of this important resonance. Because the resonance energy is known well from previous studies and because the resonance is rather narrow ($\Gamma \simeq 3$ keV), we have chosen to measure the thick-target yield of the ^{1}H(^{18}F, α)^{15}O reaction by covering the energy range $\Delta E_{\mathrm{c.m.}} =$ 305–350 keV within the target energy loss. In such a study, a measurement of the step height of the yield on resonance is directly related to the resonance strength of the state.

We measured the ^{18}F(p, α)^{15}O cross section at $E_{\mathrm{c.m.}} =$ 330 keV using a radioactive ^{18}F beam at the ORNL Holifield Radioactive Ion Beam Facility (HRIBF). The ^{18}F beam (2×10^5 ^{18}F/s, ^{18}F/^{18}O ~ 0.2) bombarded a thin (57 μg/cm^2) polypropylene (CH_2) target, and recoil alpha particles and ^{15}O ions were detected in coincidence in the SIDAR Silicon Detector Array (an annular array of silicon strip detectors) [14]. The experimental configuration is the same as the one described in Ref. [10] with the exception that the SIDAR covered laboratory angles 18°–48° ($101° < \theta_{\mathrm{c.m.}} < 150°$) in 2° segments in this measurement. The beam purity was monitored downstream of the target location by an isobutane-filled gas ionization counter, which provided energy loss information that enabled the proton number of the detected ion to be determined.

The ^{1}H(^{18}F, α)^{15}O events were identified by reconstructing the total energy of the reaction products detected in coincidence, as described in Ref. [10]. As a result of the positive Q value of the ^{18}F(p, α)^{15}O reaction, the events of interest were readily distinguished from elastic scattering which was the major source of background coincident events. The ^{1}H(^{18}F, α)^{15}O events were then further distinguished from ^{1}H(^{18}O, α)^{15}N events by plotting (Fig. 1) the lab angles of the detected α particles versus their energies. Through this procedure, the yield of the ^{1}H(^{18}F, α)^{15}O reaction was measured on resonance [$E(^{18}\mathrm{F}) = 6.6$ MeV] and off resonance [$E(^{18}\mathrm{F}) =$ 7.5 MeV]. The data collected during these measurements are shown in Fig. 1, where the off-resonance plot was compiled with only $\sim$60% of the incident beam flux used to produce the on-resonance spectrum.

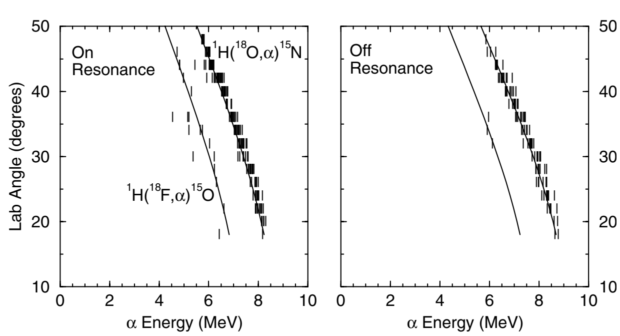

FIG. 1. The angle of detection of the emitted α particles is plotted as a function of their energies. Owing to the different Q values of the reactions, the ^{1}H(^{18}F, α)^{15}O events are cleanly distinguished from ^{1}H(^{18}O, α)^{15}N events. Curves have been drawn at the expected energies.

The observed yield is related to the differential cross section for the ^{1}H(^{18}F, α)^{15}O reaction by

$$Y(E) = IN \sum_s \Delta\Omega_s \varepsilon_s \left(\frac{d\sigma}{d\Omega}\right)_s, \tag{1}$$

where I was the number of ^{18}F ions incident on target, N was the number of target atoms (^{1}H) per unit area, $\Delta\Omega_s$ was the solid angle covered by a SIDAR strip in the center-of-mass system, ε_s was the coincidence efficiency for detecting an α particle in strip s and an ^{15}O ion in another strip, and $(d\sigma/d\Omega)_s$ was the differential cross section in the center of mass for detecting an α particle in strip s. The sum is over all SIDAR strips with $\theta_{\mathrm{lab}} > 21°$, since only α particles detected in these strips could physically have a recoil ^{15}O ion detected in coincidence. The number of ^{18}F ions incident on target was determined from the measured amount of beam that was elastically scattered into the SIDAR from carbon in the target and using the ratio of ^{18}F to ^{18}O in the beam which was continuously monitored downstream of the target by the ion counter. The calibrations of the target thickness, solid angle coverage, and coincidence efficiency were determined using the same procedure as in Ref. [10]. The total ^{18}F(p, α)^{15}O cross section was calculated by integrating the differential cross section obtained from Eq. (1) assuming an angular distribution characteristic of populating a $J^\pi = \frac{3}{2}^-$ resonance. This angular distribution was calculated using the R-matrix codes MULTI [15] and SAMMY [16]. The total cross sections extracted using the angular distributions calculated with the two codes agreed within 1% of each other and differed by $\leq 10\%$ from that obtained assuming isotropy.

The cross sections measured on and off resonance are plotted in Fig. 2 along with the previously measured data for the 665-keV resonance [10]. The uncertainties in the low-energy cross section measurements are dominated by statistical uncertainties, but other sources of uncertainty were also considered. Since the integrated beam current was determined from the amount of elastic scattering observed from carbon in the target, our extracted cross sections do not directly depend on the absolute target thickness but instead on the ratio of hydrogen to carbon in the target. We recently measured this ratio for these targets to be H/C $= 1.8 \pm 0.1$ and to not change significantly after bombardment by low-intensity radioactive beams [14]. As a further check of our measured cross sections, we extracted the ^{18}O(p, α)^{15}N cross sections from our data using the same procedure. We found the ^{18}O(p, α)^{15}N cross section at $\theta_{\mathrm{c.m.}} \simeq 125°$ to be 63 ± 9 μb/sr and 199 ± 30 μb/sr at $E_{\mathrm{c.m.}} = 330$ and 378 keV, respectively. These values are within uncertainties of those published previously [17,18] differing, on average, by $<$10% from the mean of the previously measured values. Combining these possible sources of uncertainty

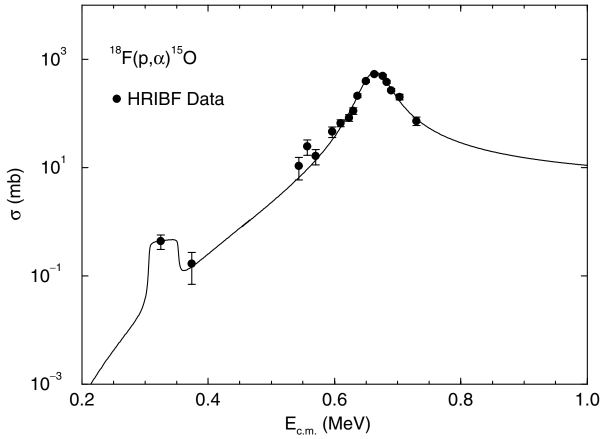

FIG. 2. The measured $^{1}H(^{18}F, \alpha)^{15}O$ cross section is shown along with a fit to the data. The 330-keV data are from this work while the 665-keV data are from Ref. [10]. The plotted curve is the calculated cross section which has been averaged over the energy loss in the target for direct comparison with the data. Since the width of the 330-keV resonance is much less than the target energy loss, the curve appears "flat-topped" at these energies.

in quadrature with the statistical uncertainties, we find the $^{18}F(p, \alpha)^{15}O$ cross section on- and off-resonance to be 0.44 ± 0.13 mb and 0.17 ± 0.10 mb, respectively.

We also show in Fig. 2 a fit to our data assuming two resonances: a $J^{\pi} = \frac{3}{2}^{-}$ resonance at 330 keV and a $\frac{3}{2}^{+}$ resonance at 665 keV. The parameters of the 665-keV resonance were fixed to those reported in Ref. [10]. The calculated cross section was averaged over the energy loss in the target for direct comparison with the data. Since the resonance energies and target energy loss are well known, the only fit parameter that was allowed to vary was the proton width of the 330-keV resonance (i.e., the only free parameter in the cross section calculation was the step height which is directly related to the proton width since, for this resonance, the proton width is much smaller than the α width). The best fit was obtained for a proton width of the 330-keV resonance of $\Gamma_p = 2.22 \pm 0.69$ eV where the uncertainty includes contributions from the cross section and the target energy loss. This value of the proton width is smaller by a factor of ~ 2 than the estimates of Refs. [8,11], but agrees well with the calculated proton widths in Refs. [9,19] which assumed $\theta_p^2 = 0.01$ for negative parity states. Using our new value of the proton width, we calculate the strength of this important $^{18}F(p, \alpha)^{15}O$ resonance to be 1.48 ± 0.46 eV. Additionally, we extracted a resonance energy from the α-particle angle-energy relationship shown in Fig. 1. Since the emitted α particles lose very little energy in the thin target, simultaneous measurements of their energies and recoil angles can be directly related to the center of mass energy at which the reaction occurred. A fit to the data in Fig. 1 yields a resonance energy of 332 ± 17 keV, in good agreement with 330 ± 6 keV reported previously by Utku *et al.* [8].

Using our resonance parameters, we have calculated the 330-keV contribution to the $^{18}F(p, \alpha)^{15}O$ reaction rate at nova temperatures. A total reaction rate requires the addition of the contributions from the other known resonances at $E_{c.m.} = 8$, 26, 38, 287, and 665 keV. The energy dependence of the widths of these levels was obtained by scaling the on-resonance widths with the Coulomb penetrability calculated using Coulomb wave functions. The resonance energies, spins, and alpha widths were taken from Ref. [8] except for the 665-keV resonance parameters which were taken from Ref. [10]. A combined single-particle reduced width of $\theta_p^2 \simeq 0.22$ was extracted for the $\frac{3}{2}^{+}$ doublet at 8 and 38 keV in Refs. [12,13]. We, therefore, use $\theta_p^2 = 0.11 \pm 0.11$ for the 8- and 38-keV resonances resulting in $\Gamma_p = (3.9 \pm 3.9) \times 10^{-37}$ keV and $(2.4 \pm 2.4) \times 10^{-14}$ keV, respectively. The proton width of the 26-keV resonance was corrected from Ref. [8] as suggested by Ref. [7] and a factor of 3 uncertainty was assumed in its strength. An upper limit of $\theta_p^2 < 0.03$ was obtained in Ref. [13] for the 287-keV resonance. We, therefore, take $\theta_p^2 = 0.015 \pm 0.015$ for this level, resulting in $\Gamma_p = (3.8 \pm 3.8) \times 10^{-5}$ keV. The proton width of the 330-keV resonance is taken from the present work. The astrophysical S factor was numerically integrated using the resonance parameters given in Table I to produce the rates shown in Fig. 3. A mistake in Ref. [10] for the 665-keV contribution at low temperatures has been corrected. The uncertainty in the rate at each temperature was calculated by varying each resonance's contribution within its uncertainty and then combining the resulting rate variations in quadrature. We find that in the temperature range 0.27 GK $\lesssim T \lesssim$ 0.41 GK, the 330-keV resonance provides the largest contribution. As a result of our measurement of the strength of the 330-keV resonance, we find its contribution to be a factor of ~ 2 lower than reported in Ref. [11]. We find, furthermore, that the total $^{18}F(p, \alpha)^{15}O$ reaction rate (i.e., the sum of the contributions in Fig. 3) is reduced a factor of 1.5–2 from the rate in Ref. [7] at nova temperatures.

We have investigated the effects of our improved $^{18}F(p, \alpha)^{15}O$ rate on the calculated nova nucleosynthesis of ^{18}F by running multizone postprocessing calculations

TABLE I. Resonance parameters used to calculate the $^{18}F(p, \alpha)^{15}O$ reaction rate.

E_r (keV)	J^{π}	Γ_p (keV)	Γ_α (keV)[a]	Ref.
8	3/2+	$(3.9 \pm 3.9) \times 10^{-37}$	0.5	[8,12,13]
26	1/2−	$(2.8^{+5.6}_{-1.9}) \times 10^{-20}$	220	[7,8]
38	3/2+	$(2.4 \pm 2.4) \times 10^{-14}$	4.0	[8,12,13]
287	5/2+	$(3.8 \pm 3.8) \times 10^{-5}$	1.2	[8,13]
330	3/2−	$(2.22 \pm 0.69) \times 10^{-3}$	2.7	This work
665	3/2+	15.2 ± 1.0	23.8	[10]

[a]Uncertainties in the α widths are not quoted because (except for the 665-keV resonance) $\Gamma_\alpha \gg \Gamma_p$, and thus the uncertainties in the α widths do not affect the calculated $^{18}F(p, \alpha)^{15}O$ rate.

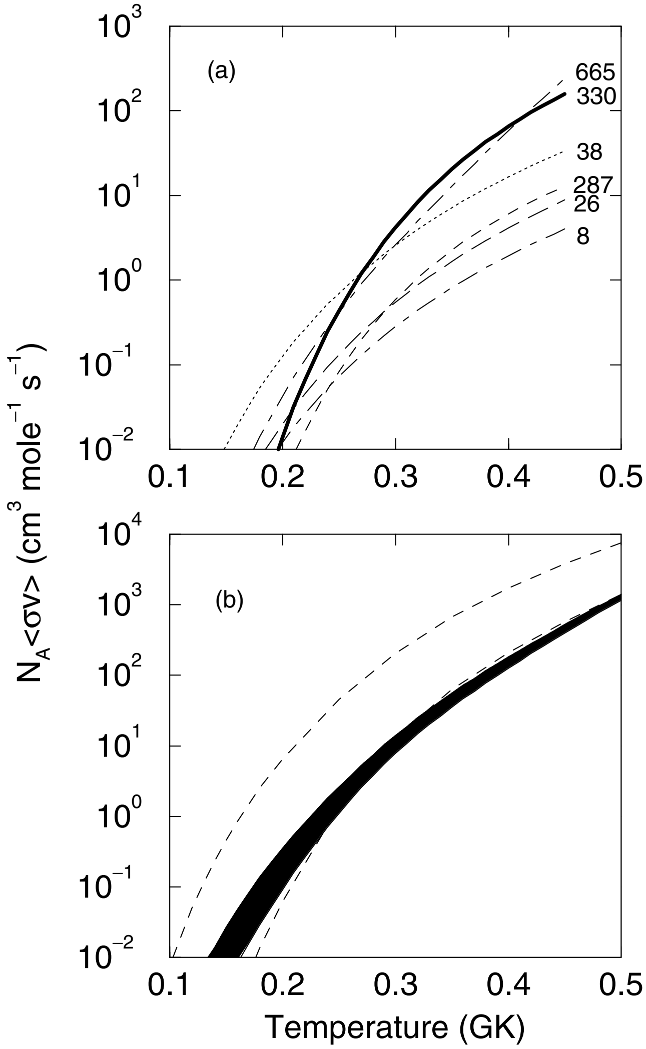

FIG. 3. (a) The astrophysical ^{18}F$(p, \alpha)^{15}$O reaction rate at nova temperatures labeled with the energies in keV of the contributing resonances. (b) The total ^{18}F$(p, \alpha)^{15}$O reaction rate from this work is shown as a shaded band. The dashed lines are from Ref. [7].

[20] with hydrodynamic trajectories (the temperature and density as a function of time) from Ref. [21]. The largest effect observed was in the hottest zone of a $1.35 M_\odot$ ONeMg white dwarf model ($T_{\rm peak} \simeq 0.43$ GK) where the final ^{18}F abundance is determined as the temperature drops from $T_{\rm peak}$ to 0.23 GK. Approximately twice as much ^{18}F was produced using our new rate than when using the Coc *et al.* rate [7]. Significant changes were also observed for the synthesized abundances of ^{18}O and ^{19}F. This increase implies that the 511-keV line should be observable by the SPI instrument on INTEGRAL for novae at distances out to ~6 kpc [6].

In conclusion, the astrophysical rate of the ^{18}F$(p, \alpha)^{15}$O reaction at nova temperatures is critical to understanding production of the radioisotope ^{18}F, which may be used to constrain nova models via observations with the coming generation of satellite-based γ-ray telescopes. For the past 20 years, this reaction was thought to be dominated by an important but unmeasured $\frac{3}{2}^-$ resonance at $E_{\rm c.m.} =$ 330 keV. We have made the first significant measurement of the strength of this resonance using a radioactive ^{18}F beam at the HRIBF. The results of the present work indicate that the ^{18}F$(p, \alpha)^{15}$O reaction rate is lower than previous estimates by a factor of ~2. Nucleosynthesis network calculations indicate that this results in more ^{18}F being produced than previously thought, where the amount of the enhancement depends on the particular nova model used.

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