Hydrogen Burning of ^{17}O in Classical Novae

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(Received 22 April 2005; published 14 July 2005)

We report on the observation of a previously unknown resonance at $E_R^{\rm lab} = 194.1 \pm 0.6$ keV in the ^{17}O$(p, \alpha)^{14}$N reaction, with a measured resonance strength $\omega\gamma_{p\alpha} = 1.6 \pm 0.2$ meV. We studied in the same experiment the ^{17}O$(p, \gamma)^{18}$F reaction by an activation method and the resonance-strength ratio was found to be $\omega\gamma_{p\alpha}/\omega\gamma_{p\gamma} = 470 \pm 50$. The corresponding excitation energy in the ^{18}F compound nucleus was determined to be 5789.8 ± 0.3 keV by γ-ray measurements using the ^{14}N$(\alpha, \gamma)^{18}$F reaction. These new resonance properties have important consequences for ^{17}O nucleosynthesis and γ-ray astronomy of classical novae.

DOI: 10.1103/PhysRevLett.95.031101 PACS numbers: 26.30.+k, 25.40.Lw, 25.40.Ny, 27.20.+n

Classical novae are caused by thermonuclear runaways that occur on hydrogen accreting white dwarfs in close binary systems. They are thought to be a major source of the oxygen rarest isotope, ^{17}O [1,2] and to synthesize the radioisotope ^{18}F ($T_{1/2} = 110$ min), whose β^+ decay produces a γ-ray emission that could be detected with the INTEGRAL observatory or with future γ-ray satellites [3,4]. However, both the ^{17}O and ^{18}F productions strongly depend on the ^{17}O$(p, \alpha)^{14}$N and ^{17}O$(p, \gamma)^{18}$F thermonuclear rates, whose precise knowledge is thus required in the range of temperatures attained during nova outbursts [$(1\text{–}4) \times 10^8$ K].

A new resonance at $E_R^{cm} \simeq 180$ keV was recently observed in the ^{17}O$(p, \gamma)^{18}$F reaction [5]. With a measured resonance strength of $(1.2 \pm 0.2) \times 10^{-6}$ eV, the uncertainty of the ^{17}O$(p, \gamma)^{18}$F reaction rate was reduced by orders of magnitude at nova temperatures. This resonance corresponds to a level of spin-parity $J^\pi = 2^-$ in the ^{18}F compound nucleus, which was previously observed at an excitation energy $E_x = 5786 \pm 2.4$ keV via the ^{14}N$(\alpha, \gamma)^{18}$F reaction [6,7]. In the latter experiment, the lifetime of this state was found to be $\tau = 15 \pm 10$ fs from a measurement based on the Doppler-shift attenuation method [6]. This measurement led to the somewhat surprising ratio $\Gamma_\gamma/\Gamma_\alpha \sim 1$, which was used for estimating the (p, α) resonance strength [5,8]. We performed a new experimental study of this state using the ^{14}N$(\alpha, \gamma)^{18}$F reaction, in order to specify both its excitation energy and width. We then measured in a second experiment the strengths of the resonances at $E_R^{cm} \simeq 180$ keV in both the ^{17}O$(p, \gamma)^{18}$F and ^{17}O$(p, \alpha)^{14}$N reactions. For the latter reaction, the resonance was never observed before our measurements.

The first experiment was performed at the 4 MV Van de Graaff accelerator of the CENBG laboratory (Bordeaux), with a ^{4}He beam of energy $E_\alpha = 1775$ keV. Typical beam intensities on target were 20–30 μA with a 3×3 mm spot. We used three TiN targets, which were fabricated by nitration in an atmosphere of purified N of a Ti layer evaporated on a thick Cu backing. The targets were thick enough ($\gtrsim 250$ μg/cm^2) to allow the simultaneous excitation of four levels in ^{18}F between 5.6 and 5.8 MeV. The γ rays were detected with three large volume, high purity Ge detectors placed horizontally at $\sim$9 cm from the target, at the laboratory angles $\theta_{\rm lab} = 0°$, 123°, and 144°. The Ge detector at 0° was actively shielded with bismuth germanate scintillation detectors for Compton suppression. Three radioactive sources of ^{137}Cs, ^{60}Co, and ^{88}Y were permanently placed near the target to measure standard calibration lines together with the beam-induced γ rays. Taking advantage of boron contamination in the target, we also included in the set of calibration lines a ^{13}C, Doppler-unshifted line at 3853.170 ± 0.022 keV, produced by the ^{10}B$(\alpha, p)^{13}$C reaction.

A measured γ-ray spectrum is shown in Fig. 1. The two lines from the decay of the $E_x = 5789.8$ keV state to the lower-lying levels at $E_x = 937.2$ and 1080.54 keV are clearly observed. The excitation energy and lifetime of the level of interest were determined from the measurements at the three detection angles of the energy differences between these two lines and adjacent lines arising from the decay of the lower resonant state in ^{18}F at $E_x = 5671.6 \pm 0.2$ keV [9]. Because the lifetime of the 5671.6 keV level is very short [7], its deexcitation γ rays are affected by a full Doppler shift. The attenuation factor for the Doppler shift of the γ rays produced by the decay of

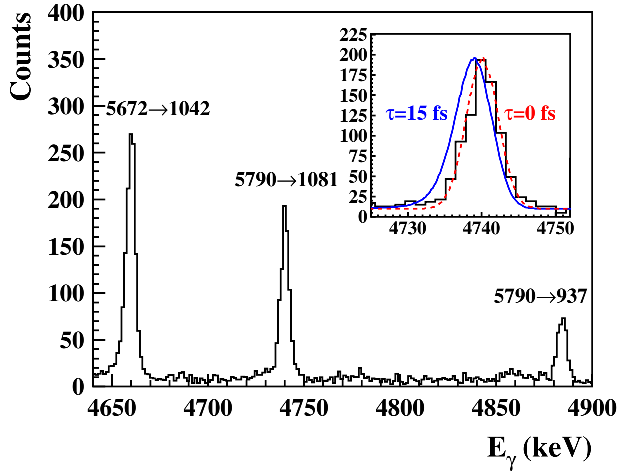

FIG. 1 (color online). Relevant part of a sample γ-ray spectrum obtained in the $^{14}N(\alpha, \gamma)^{18}F$ experiment with the Ge detector at $\theta_{lab} = 0°$. The inset shows a comparison of the observed full-energy peak for the 5789.8 → 1080.54 keV transition in ^{18}F with simulated line emissions calculated for a mean lifetime τ of the 5789.8 keV state equal to 15 fs (solid curve) and 0 fs (dashed curve).

the 5789.8 keV state was found to be $f_a > 0.9925$ (1σ-limit). The corresponding mean lifetime of the decaying level was obtained from detailed Monte Carlo simulations for the slowing down of the recoiling excited ^{18}F nuclei in the target material and the subsequent γ-ray emission and detection with our experimental setup (see as an example the inset of Fig. 1). The result is $\tau < 2.6$ fs, in disagreement with Ref. [6]. The excitation energy was found to be $E_x = 5789.8 \pm 0.3$ keV, in agreement with the very recent result of Ref. [10]. Further details on the data analysis and the Monte Carlo simulations will be given in a forthcoming publication [11].

The search for the previously unknown resonance in the $^{17}O(p, \alpha)^{14}N$ reaction at $E_R^{lab} = 194.1 \pm 0.6$ keV [12] was motivated by the relatively large width found for the corresponding resonant state at $E_x = 5789.8$ keV in ^{18}F: $\Gamma > 250$ meV. This second experiment was carried out at the electrostatic accelerator PAPAP of the CSNSM laboratory (Orsay), which supplies intense proton beams of energies $E_p < 250$ keV. Beam currents of 60–90 μA were typically sustained on the target, which was cooled with deionized water. An annular electrode biased at a voltage of -300 V was mounted in front of the target to suppress the escape of the secondary electrons. The target holder was surrounded with a copper assembly, cooled with liquid nitrogen to limit the carbon buildup during the irradiation.

The outgoing α-particles were detected with 4 passivated implanted planar silicon detectors with active areas of 3 cm^2. They were placed at a distance of 14 cm from the target and at the laboratory angles $\theta_{lab} = 105°$, $120°$, $135°$, and $150°$. Each detector was shielded by a 2 μm thick foil of aluminized Mylar in order to stop the intense flux of elastically scattered protons. The detector solid angle was measured with two calibrated α sources: ^{241}Am and a mixing of ^{239}Pu, ^{241}Am and ^{244}Cm. The average solid angle per detector, Ω_{lab}, was found to be $(1.42 \pm 0.04) \times 10^{-2}$ sr. A sample spectrum is shown in Fig. 2(a).

The strength of the $^{17}O(p, \alpha)^{14}N$ resonance was determined relative to that of the well-known resonance at $E_R^{lab} = 150.9$ keV in the $^{18}O(p, \alpha)^{15}N$ reaction. Targets enriched in ^{17}O or ^{18}O were produced by ion implantation in 0.3 mm thick Ta sheets at the SIDONIE implanter of the CSNSM, using the same experimental procedure. The total irradiation fluence was 1.5×10^{18} atoms cm^{-2}, equally distributed at 30, 10, and 2.5 keV implantation energies. The targets were analyzed by Rutherford backscattering spectrometry measurements performed at the ARAMIS accelerator (CSNSM) with a ^4He beam of 1.2 MeV energy. No difference could be observed between the ^{17}O- and

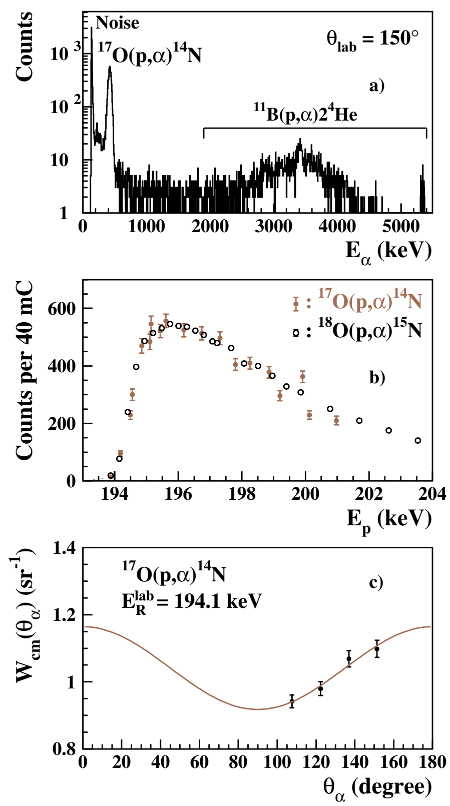

FIG. 2 (color online). (a) Sample α spectrum obtained in the $^{17}O(p, \alpha)^{14}N$ experiment, for $E_p = 196.5$ keV and an accumulated charge of 0.93 C. (b) Yield data for the new resonance at $E_R^{lab} = 194.1$ keV in the $^{17}O(p, \alpha)^{14}N$ reaction (filled symbols) and the well-known $^{18}O(p, \alpha)^{15}N$ resonance at $E_R^{lab} = 150.9$ keV (empty symbols). The data for this latter resonance were appropriately normalized and shifted in energy to be compared with those obtained with the ^{17}O target. (c) α angular distribution (center of mass) for the $^{17}O(p, \alpha)^{14}N$ resonance. The solid line shows a Legendre-polynomial fit to the data, $W_{cm}(\theta_\alpha) = 1 + a_2 P_2(\cos\theta_\alpha)$, which yields $a_2 = 0.16 \pm 0.03$.

^{18}O-implanted targets. In particular, a similar stoichiometry was found for the ^{17}O and ^{18}O targets whatever the depth and surface position, with a maximum ratio $(\mathrm{O/Ta})_{\max} = 3.1 \pm 0.3$. No change in the target stoichiometry could be noted from Rutherford backscattering spectrometry measurements performed after the proton irradiation, where the charge accumulated on each target was typically 1 C.

The similarity of the ^{17}O- and ^{18}O-implanted targets can be seen in Fig. 2(b), which shows a comparison of yield data obtained for the new resonance at $E_R^{\mathrm{lab}} = 194.1$ keV in the $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$ reaction and for the 150.9 keV resonance of $^{18}\mathrm{O}(p, \alpha)^{15}\mathrm{N}$. The observed depth profile is well explained by the implantation procedure. The yield measurements were repeated with three ^{17}O- and two ^{18}O-implanted targets and fully compatible results were obtained.

The strength of the $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$ resonance was deduced from the relation

$$\omega\gamma_{p\alpha} = \omega\gamma_{p\alpha}^{18} \frac{M_{17}}{M_{17} + m_p} \frac{M_{18} + m_p}{M_{18}} \frac{E_R^{17}}{E_R^{18}} \frac{\epsilon_{17}}{\epsilon_{18}} \frac{Y_{p\alpha}^{17}}{Y_{p\alpha}^{18}}. \quad (1)$$

Here, $\omega\gamma_{p\alpha}^{18} = 0.167 \pm 0.012$ eV is the strength of the $^{18}\mathrm{O}(p, \alpha)^{15}\mathrm{N}$ resonance at $E_R^{\mathrm{lab}} = 150.9$ keV [13,14]; m_p, M_{17} and M_{18} are the proton, ^{17}O and ^{18}O masses, respectively; E_R^{17} and E_R^{18} are the laboratory energies of the two resonances; $(\epsilon_{17}/\epsilon_{18}) = 0.95 \pm 0.05$ is the ratio of the effective stopping-powers [15], where the error arises from the uncertainty in the stoichiometry of the ^{17}O and ^{18}O targets; and $(Y_{p\alpha}^{17}/Y_{p\alpha}^{18}) = (7.7 \pm 0.9) \times 10^{-3}$ is the ratio of the measured reaction yields for the two resonances, where the main uncertainties come from the target composition (10%) and the beam current integration (5%). For the determination of $Y_{p\alpha}^{17}$, we took into account the measured α-particle angular distribution shown in Fig. 2(c). Equation (1) gives $\omega\gamma_{p\alpha} = 1.6 \pm 0.2$ meV.

The strength of the $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ resonance at $E_R^{\mathrm{lab}} = 194.1$ keV was obtained from measurements by an activation method of the ^{18}F total production in irradiated ^{17}O targets. The ^{18}F β^+ activity was measured with two large volume Ge detectors positioned opposite one another in a very close geometry, in order to register in time coincidence the two 511 keV photons from positron-electron annihilation. The efficiency for the β^+-activity detection was measured with a calibrated ^{22}Na source to be $\epsilon_{\beta^+} = (2.7 \pm 0.1)\%$. The ^{17}O-implanted targets were bombarded for $\sim$5 hours at $\sim$70 μA beam intensity and then rapidly placed between the two Ge detectors. α-particle yields were continuously recorded during the irradiation.

Apart from ^{18}F ($T_{1/2} = 109.77$ min), only two long-lived positron emitters could be significantly produced during the irradiation phase: ^{11}C ($T_{1/2} = 20.39$ min) by the reaction $^{10}\mathrm{B}(p, \gamma)^{11}\mathrm{C}$ and $^{13}\mathrm{N}(T_{1/2} = 9.965$ min) by the reaction $^{12}\mathrm{C}(p, \gamma)^{13}\mathrm{N}$. The former reaction was found to be negligible, from systematic measurements of the boron contamination in the targets via the $^{11}\mathrm{B}(p, \alpha)2^4\mathrm{He}$ reaction [see Fig. 2(a)]. But a relatively small production of ^{13}N had to be taken into account, because of a carbon buildup on target of about 0.5 μg cm^{-2} per Coulomb of accumulated proton charge. A blank Ta target irradiated in the same experimental conditions showed no activity but the one of ^{13}N.

We used the $^{12}\mathrm{C}(p, \gamma)^{13}\mathrm{N}$ reaction to test the experimental setup. A C target of 20 μg cm^{-2} evaporated on a Ta sheet was irradiated for 30 min at $E_p = 196$ keV. The astrophysical S factor derived from the measured ^{13}N activity is 4.0 ± 0.8 keV b, in good agreement with previous results [16].

Figure 3 compares the measured activities of two ^{17}O targets irradiated at $E_p = 196.5$ and 192.7 keV. The fitted ^{18}F and ^{13}N decay curves were obtained from the maximum of the likelihood function for Poisson-distributed data. The total numbers of ^{18}F nuclei contained in the targets at the end of the proton irradiation were 7160 ± 700 for $E_p = 196.5$ keV (with $T_{1/2} = 105^{+19}_{-14}$ min for the fitted ^{18}F half-life) and 610 ± 260 for $E_p = 192.7$ keV (with $T_{1/2} = 103^{+217}_{-47}$ min). The larger number of ^{18}F nuclei produced at the highest beam energy is clearly due to the excitation of the $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ resonance at $E_R^{\mathrm{lab}} = 194.1$ keV. The ^{18}F production at $E_p = 192.7$ keV results from the direct capture (DC) process interfering with the low-energy tail of the studied resonance. Our measurement agrees within large statistical uncertainties with the DC evaluation of Ref. [17]. To derive the resonance strength, a

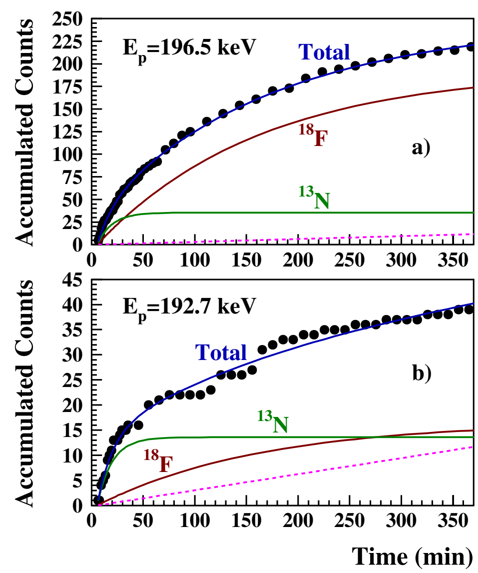

FIG. 3 (color online). Measured β^+ activities of two ^{17}O-implanted targets irradiated at (a) $E_p = 196.5$ keV (on resonance) and (b) $E_p = 192.7$ keV (off resonance). The time origin corresponds to the stopping of the proton irradiation. Also shown are the fitted ^{18}F and ^{13}N decay curves (solid lines) and the measured background radiation (dashed lines).

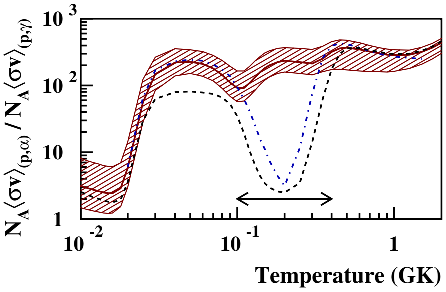

FIG. 4 (color online). Ratio of the $^{17}O(p, \alpha)^{14}N$ and $^{17}O(p, \gamma)^{18}F$ reaction rates (solid line with hatched area reflecting uncertainties), in comparison with the previous results of Angulo *et al.* [8] (dashed line) and Fox *et al.* [5] (dotted-dashed line). The horizontal arrow shows the range of typical novae temperatures.

small contribution of $(6 \pm 3)\%$ for the DC process was subtracted from the ^{18}F total production at $E_p = 196.5$ keV.

We also applied to the measured (p, γ) resonance strength a correction arising from the backscattering of ^{18}F nuclei, which could escape the target at the time of their production. This correction was evaluated to be $(4 \pm 2)\%$ from calculations performed with the program SRIM-2003 [15] for the observed implantation profile of the ^{17}O targets. We finally obtained from the weighted mean of two compatible measurements at $E_p = 196.5$ keV: $\omega\gamma_{p\alpha}/\omega\gamma_{p\gamma} = 470 \pm 50$. Here, the error mainly arises from uncertainties in the measured β^+ activities (7%) and the associated detection efficiency (5%), as well as in the measured α-particle intensities (1%) and detection efficiency (3%). The resulting (p, γ) resonance strength is $\omega\gamma_{p\gamma} = (3.4 \pm 0.6) \times 10^{-6}$ eV, which is significantly larger than the value of Ref. [5]: $\omega\gamma_{p\gamma} = (1.2 \pm 0.2) \times 10^{-6}$ eV (see Ref. [11] for a discussion of the discrepancy).

We calculated the thermonuclear rates of the $^{17}O + p$ reactions by using our experimental results. These calculations will be discussed in detail in Ref. [11]. We show in Fig. 4 the ratio of the (p, α) and (p, γ) reaction rates. The comparison with previous estimates [5,8] essentially illustrates the strong effect of the previously unknown resonance in the $^{17}O(p, \alpha)^{14}N$ reaction, for stellar temperatures of $\sim(1–4) \times 10^8$ K. With the present results, the $^{17}O + p$ rates are now established from measured nuclear data in the whole range of nova temperatures.

The impact of the new $^{17}O + p$ rates has been studied by means of three hydrodynamic simulations of classical nova outbursts. For illustrative purposes, we have adopted a model of $1.15M_\odot$ ONe white dwarf accreting hydrogen-rich material at a rate of $2 \times 10^{-10} M_\odot\,\mathrm{yr}^{-1}$, with three different choices for the $^{17}O + p$ rates: from Refs. [5,8] and this work. With the new $^{17}O + p$ rates, we found the final ^{17}O abundance to be reduced by a factor of 2.4 with respect to Ref. [5] (or 1.4 with Ref. [8] rates). The dramatic increase in the new (p, α) rate reduces the final abundance of ^{18}F by a factor of 2.9 with respect to Ref. [5] (or 7.9 with Ref. [8] rates). This translates into a significant reduction of the detectability distances (assuming that the flux scales with the ^{18}F yield) by a factor of ~ 1.7 with respect to Ref. [5] (or 2.8 with Ref. [8] rates). These new results have also a significant impact in other astrophysical topics (although a deeper study with a larger number of models is required to properly address this issue): this includes the extent of the nova contribution to the Galactic ^{17}O and estimates of oxygen isotopic ratios in the nova ejecta to derive the expected composition of presolar oxide grains.

We wish to thank E. Virassamynaiken and D. Ledu for the preparation of the TiN and O-implanted targets, respectively, as well as the technical staff of the CSNSM for the constant help. This work was supported by the CMEP agreement between France and Algeria under the Project No. 01MDU518 and by AYA2004-06290-C02.

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