Hydrogen Burning of $^{17}$O in Classical Novae


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We report on the observation of a previously unknown resonance at $E_{\gamma}\text{lab}=194.1\pm0.6$ keV in the $^{17}$O$(p,\gamma)^{18}$F reaction, with a measured resonance strength $\omega_{\gamma p}=1.6\pm0.2$ meV. We studied in the same experiment the $^{17}$O$(p,\gamma)^{18}$F reaction by an activation method and the resonance-strength ratio $\omega_{\gamma p}/\omega_{\gamma p}=470\pm50$. The corresponding excitation energy in the $^{18}$F compound nucleus was determined to be $5789.8\pm0.3$ keV by $\gamma$-ray measurements using the $^{14}$N$(\alpha,\gamma)^{18}$F reaction. These new resonance properties have important consequences for $^{17}$O nucleosynthesis and $\gamma$-ray astronomy of classical novae.

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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. We studied the radioisotope $^{18}$F ($T_{1/2}=110$ min), whose $\beta^+$-decay produces a $\gamma$-ray emission that could be detected with the INTEGRAL observatory or with future $\gamma$-ray observatories by orders of magnitude at nova temperatures. This resonance was clearly observed. The excitation energy and lifetime of the lower resonant state in $^{18}$F were determined to be $5789.8\pm0.3$ keV by $\gamma$-ray measurements using the $^{14}$N$(\alpha,\gamma)^{18}$F reaction. These new resonance properties have important consequences for $^{17}$O nucleosynthesis and $\gamma$-ray astronomy of classical novae.

The first experiment was performed at the 4 MV Van de Graaff accelerator of the CENBG laboratory (Bordeaux), with an $^4$He beam of energy $E_\alpha=1775$ keV. Typical beam intensities on target were $20-30$ $\mu$A with a $3$-mm$\times$3-mm spot. We used three TiN targets, which were fabricated by nitration in an atmosphere of purified N of a Ti layer evaporated on a thick Cu backing. The targets were thick enough ($\gtrsim 250$ $\mu$g/cm$^2$) to allow the simultaneous excitation of four levels in $^{18}$F between 5.6 and 5.8 MeV. The $\gamma$-rays were detected with three large volume, high purity Ge detectors placed horizontally at $\sim 9$ cm from the target, at the laboratory angles $\theta_{\text{lab}}=0^\circ$, $123^\circ$ and $144^\circ$. The Ge detector at $0^\circ$ was actively shielded with BGO 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 $\gamma$-rays. Taking advantage of boron contamination in the target, we also included in the set of calibration lines a $^{13}$C, Doppler-reshifted line at $3853.170\pm0.022$ keV, produced by the $^{10}$B$(\alpha,\gamma)^{13}$C reaction.

A measured $\gamma$-ray spectrum is shown in Fig. 1. The two lines from the decay of the $E_\gamma=5789.8$ keV state to the lower-lying levels at $E_\gamma=937.2$ 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 $E_\gamma=5671.6\pm0.2$ keV. Because the lifetime of the $5671.6$ keV level is very short, its deexcitation $\gamma$-rays are affected by a full Doppler shift. The attenuation factor for the Doppler shift of the $\gamma$-rays produced by the decay of the $5789.8$ keV state was found to be $f_\alpha>0.9925$.

The strength of the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ resonance was determined relative to that of the well-known resonance at $E_R^{15}=150.9$ keV in the $^{18}\text{O}(p,\alpha)^{15}\text{N}$ reaction. Targets enriched in $^{17}\text{O}$ or $^{18}\text{O}$ 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 $1.5 \times 10^{18}$ atoms cm$^{-2}$, equally distributed at 30, 10 and 2.5 keV implantation energies. The targets were analyzed by Rutherford backscattering spectrometry (RBS) measurements performed at the ARAMIS accelerator (CSNSM) with a $^4\text{He}$ beam of 1.2 MeV energy. No difference could be observed between the $^{17}\text{O}$- and $^{18}\text{O}$-implanted targets. In particular, a similar stoichiometry was found for the $^{17}\text{O}$ and $^{18}\text{O}$ targets whatever the depth and surface position, with a maximum ratio (O/Ta)$_{\text{max}}$=3.1±0.3. No change in the target stoichiometry could be noted from RBS measurements performed after the proton irradiation, where the charge accumulated on each target was typically $1\text{C}$.

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

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

$$\omega_{\gamma p\alpha} = \omega_{\gamma p\alpha}^{18} M_{17} E_R^{17} \epsilon_{17} Y_{p\alpha}^{17} M_{18} E_R^{18} \epsilon_{18} Y_{p\alpha}^{18},$$

Here, $\omega_{\gamma p\alpha}^{18}=0.167\pm0.012$ eV is the strength of the $^{18}\text{O}(p,\alpha)^{14}\text{N}$ resonance at $E_R^{15}=150.9$ keV [10, 17]; $m_p$, $M_{17}$ and $M_{18}$ are the proton, $^{17}\text{O}$ and $^{18}\text{O}$ masses, respectively; $E_R^{17}$ and $E_R^{18}$ are the laboratory energies of the two resonances; $(\epsilon_{17}/\epsilon_{18})=0.95\pm0.05$ is the ratio of the effective stopping-powers [12], where the error arises from the uncertainty in the stoichiometry of the $^{17}\text{O}$ and $^{18}\text{O}$ targets; and $(Y_{p\alpha}^{17}/Y_{p\alpha}^{18})=(7.7\pm0.9)\times10^{-3}$ 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 $\alpha$-particle angular distribution shown in Fig. 2c. Equation 1 gives $\omega_{\gamma p\alpha}=1.62\pm0.2$ meV.

The strength of the $^{17}\text{O}(p,\gamma)^{18}\text{F}$ resonance at $E_R^{18}=194.1$ keV was obtained from measurements by an...
onance were appropriately normalized and shifted in energy.

FIG. 2: (a) Sample α spectrum obtained in the
$^{17}$O(p,α)$^{14}$N experiment, for $E_p=196.5$ keV and an accumulated charge of 0.93 C. (b) Yield data for the new resonance at $E_{194.1}$ keV in the $^{17}$O(p,α)$^{14}$N reaction (filled symbols) and the well-known $^{18}$O(p,α)$^{15}$N resonance at $E_{150.9}$ 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,α)$^{14}$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 $a_2=0.16\pm0.03$.

activation method of the $^{18}$F total production in irradiated $^{17}$O targets. The $^{18}$F $\beta^+$-activity was measured with two large volume Ge detectors positioned opposite to 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 $\beta^+$-activity detection was measured with a calibrated $^{22}$Na source to be $\epsilon_{\beta^+}=(2.7\pm0.1)\%$. The $^{17}$O-implanted targets were bombarded for ~5 hours at ~70 $\mu$A 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 $^{10}$B(p,α)$^{11}$C and $^{13}$N ($T_{1/2}=9.965$ min) by the reaction $^{12}$C(p,α)$^{13}$N. The former reaction was found to be negligible, from systematic measurements of the boron contamination in the targets via the $^{11}$B(p,α)$^2$He reaction (see Fig. 2a). 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 $\mu$g 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 $^{12}$C(p,γ)$^{13}$N reaction to test the experimental setup. A C target of 20 $\mu$g 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 $4.0\pm0.8$ keV b, in good agreement with previous results [10].

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 $T_{1/2}=105_{-14}^{+19}$ min for the fitted $^{18}$F half-life) and 610±260 for $E_p=192.7$ keV (with $T_{1/2}=103_{-21}^{+27}$ min). The larger number of $^{18}$F nuclei produced at the highest beam energy is clearly due to the excitation of the $^{17}$O(p,γ)$^{18}$F resonance at $E_{194.1}=194.1$ 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 res-
FIG. 4: Ratio of the $^{17}\text{O}(p,\alpha)^{14}\text{N}$ and $^{17}\text{O}(p,\gamma)^{18}\text{F}$ 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. [9] (dotted-dashed line). The horizontal arrow shows the range of typical novae temperatures.

The dramatic increase in the new $(p,\alpha)$ rate reduces the final abundance of $^{18}\text{F}$ by a factor of 2.9 with respect to Ref. [8] (or 7.9 with Ref. [5] rates). This translates into a significant reduction of the detectability distances (assuming that the flux scales with the $^{18}\text{F}$ yield) by a factor of $\sim 1.7$ with respect to Ref. [8] (or 2.8 with Ref. [5] 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 $^{17}\text{O}$ and estimates of oxygen isotopic ratios in the nova ejecta to derive the expected composition of presolar oxide grains.

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