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

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(Received 30 April 2004; published 18 August 2004)

We report on the observation of a new resonance at $E_R^{\mathrm{lab}} = 190$ keV in the $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ reaction. The measured resonance strength amounts to $\omega\gamma_{p\gamma} = (1.2 \pm 0.2) \times 10^{-6}$ eV. With this new value, the uncertainties in the $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ and $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$ thermonuclear reaction rates are reduced by orders of magnitude at nova temperatures. Our significantly improved reaction rates have major implications for the galactic synthesis of ^{17}O, the stellar production of the radioisotope ^{18}F, and the predicted oxygen isotopic ratios in nova ejecta.

DOI: 10.1103/PhysRevLett.93.081102 PACS numbers: 26.30.+k, 24.30.Gd, 25.40.Lw, 26.50.+x

Classical novae are remarkable phenomena at the intersection of stellar physics, nuclear physics, and cosmochemistry. They are caused by the thermonuclear explosion of hydrogen-rich matter on the surface of a white dwarf in a close binary star system [1]. The study of classical novae is of considerable interest for several reasons. Spectroscopic studies of nova ejecta reveal the nature of the underlying white dwarf. The observed elemental abundances also reflect the evolution of the thermonuclear runaway, such as peak temperatures and expansion time scales, and thus provide constraints for models of stellar explosions. Classical novae clearly contribute to the chemical evolution of the Galaxy. In fact, they have been proposed [2–4] as the most significant source of the isotopes ^{13}C, ^{15}N, and ^{17}O in the Universe. Novae are also likely to synthesize the short-lived radioisotope ^{18}F ($T_{1/2} = 110$ min) whose decay produces γ radiation at a time when the expanding envelope becomes transparent. A detection of these γ rays would significantly constrain current nova models [5] and thus is one of the goals of the INTEGRAL mission. Finally, there is evidence that certain presolar grains in primitive meteorites with anomalous C and N isotopic ratios originate from nova explosions [6]. The future observation of O isotopic ratios in nova grains would provide crucial constraints on the nova type (CO versus ONe), the underlying white dwarf mass, and the mixing process during the thermonuclear explosion [7].

The $^{17}\mathrm{O}(p, \gamma)^{18}\mathrm{F}$ and $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$ reactions have an impact on all of these issues since they govern the destruction of ^{17}O and the formation of ^{18}F. Of particular interest is the branching ratio at ^{17}O, i.e., the probability that this nucleus is destroyed during thermonuclear burning via the (p, α) reaction as opposed to the (p, γ) reaction. The thermonuclear reaction rates, which represent a quantitative measure for the nuclear reaction probabilities in the stellar plasma, are displayed in Fig. 1 for both reactions. For a better comparison, we show the reaction rate ratio (top and middle panel) of the currently accepted upper (or lower) limit and the recommended rate [8]. It can be seen that the rates of both reactions at temperatures important for nova explosions (with peak temperatures of about $T = 0.1$–0.4 GK, depending on the details of the adopted nova model) are uncertain by several orders of magnitude. The branching ratio for the (p, α) and (p, γ) reactions is shown in the bottom panel. The dashed line corresponds to the ratio of the recommended rates, while the solid lines represent the current uncertainty [8]. It can be seen that the branching ratio varies by almost 5 orders of magnitude at $T \approx 0.2$ GK. Consequently, ^{17}O and ^{18}F abundance predictions based on the current $^{17}\mathrm{O} + p$ reaction rates are highly uncertain. The impact of these uncertainties on the nucleosynthesis in novae has been investigated previously [9,10].

The errors shown in Fig. 1 are mainly caused by an unobserved narrow resonance. This case represents a prime example in nuclear astrophysics of the fact that a single resonance can entirely dominate the reaction rates. The resonance corresponds to a known state at $E_x = 5786 \pm 2$ keV [11] in the ^{18}F compound nucleus. Its expected location is $E_R^{\mathrm{lab}} \approx 190$ keV, as calculated from the excitation energy and the proton separation energy in ^{18}F ($S_p = 5606.5 \pm 0.5$ keV [12]). We measured this previously unobserved resonance at the Laboratory for Experimental Nuclear Astrophysics, located at the Triangle Universities Nuclear Laboratory. A 1 MV Van de Graaff accelerator provided proton beams at laboratory energies between 180 and 210 keV, with beam currents of up to 100 μA on target. The beam entered the target chamber through a liquid-nitrogen cooled copper tube that was biased to -300 V in order to suppress the emission of secondary electrons from the target and the beam collimator. The target was directly water cooled using deionized water. The target backing consisted of a 0.5 mm

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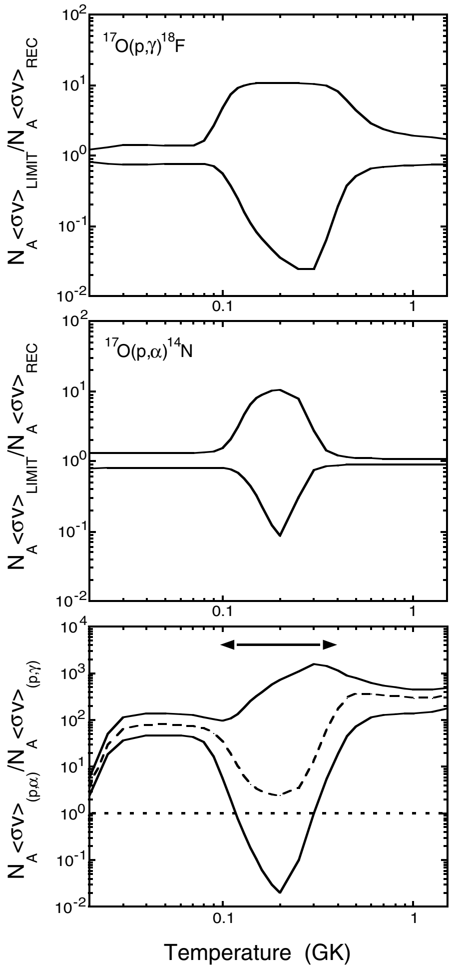

FIG. 1. Reaction rates [8] for the (p, γ) and (p, α) reaction on ^{17}O prior to the present work. The first two panels show ratios of the lower or upper rate limit and the recommended rate for the (p, γ) and (p, α) reactions (top and middle panel, respectively). The lower panel shows the ratio of (p, α) and (p, γ) reaction rates (dashed line: ratio of recommended rates; solid lines: corresponding uncertainties). In all panels, the area between the solid lines represents the uncertainty in the reaction rate ratios. The horizontal arrow in the lower panel indicates the temperature range of interest in novae.

thick tantalum sheet. Prior to target preparation, the surface of the tantalum backing was etched [13] in order to remove some of the impurities that are a source of beam-induced background radiation. The target itself was prepared by anodization of the tantalum backing in ^{17}O-enriched (83.8% according to the supplier) water. Such targets have been found [14] to be of well-defined stoichiometry (Ta_2O_5) with a target thickness that is precisely determined by the anodizing voltage. Prompt γ rays from the $^{17}O(p, \gamma)^{18}F$ reaction were detected using a large-volume (582 cm^3) HPGe detector placed at an angle of 0° and at a distance of 16 mm from the target. Energy and efficiency calibrations were established using radioactive sources and the decays from well-known resonances in the $^{14}N(p, \gamma)^{15}O$ and $^{27}Al(p, \gamma)^{28}Si$ reactions. The full-energy peak efficiency was about 5% at a γ-ray energy of 1.33 MeV. Since the γ-ray detector was placed in very close geometry to the target, coincident summing corrections had to be considered carefully in all of our measured γ-ray spectra. The corrections were performed with a computer code that is based on the matrix formalism of Ref. [15].

Some of our experimental results are shown in Fig. 2. The top panel displays the excitation function (i.e., γ-ray yield versus energy) of the well-known $^{17}O(p, \gamma)^{18}F$ resonance at $E_R^{lab} = 519$ keV for the primary transition to the

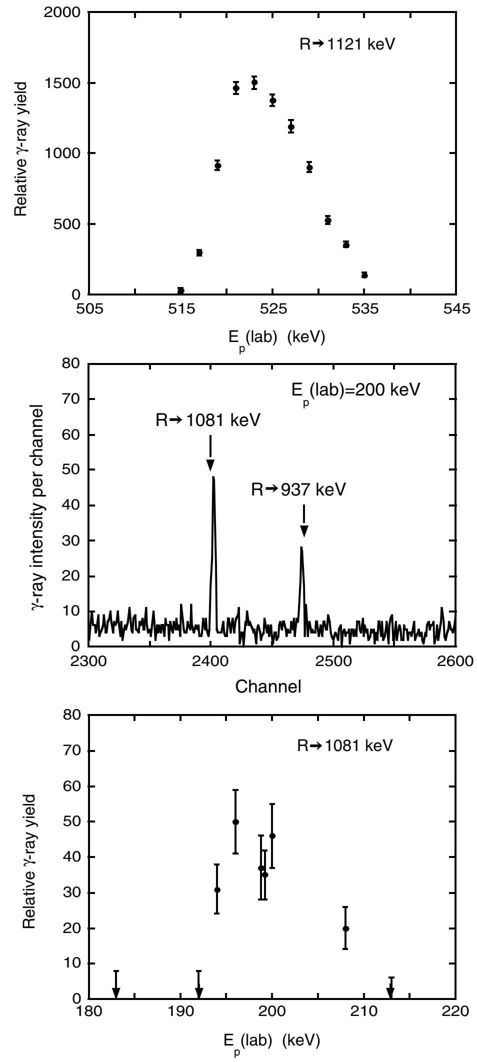

FIG. 2. (Top panel) Excitation function of the primary $R \rightarrow$ 1121 keV transition for the well-known $^{17}O(p, \gamma)^{18}F$ resonance at $E_R^{lab} = 519$ keV; (middle panel) relevant part of the on-resonance γ-ray spectrum, measured at $E_R^{lab} = 200$ keV. The two primary γ-ray decays of the previously unobserved $E_R^{lab} = 190$ keV resonance to the ^{18}F levels at 937 and 1081 keV are clearly observed; (bottom panel) excitation function of the primary $R \rightarrow 1081$ keV transition for the new $E_R^{lab} = 190$ keV resonance. All uncertainties shown represent 1σ errors.

$E_x = 1121$ keV level ($R \to 1121$ keV). It can be seen that the target thickness at this bombarding proton energy amounts to about ≈ 11 keV. The resonance strength can be calculated from the measured maximum yield [16] and the derived value agrees within errors with previous results [8]. Using this resonance, the target was checked frequently, and no degradation in yield or target thickness has been observed during the course of the experiment. As an additional test, we have also measured the well-known ^{18}O$(p, \gamma)^{19}$F resonance at $E_R^{\rm lab} = 151$ keV. Our measured resonance strength again agrees within errors with previous results [8]. The middle panel displays the relevant part of a γ-ray spectrum measured in the ^{17}O$(p, \gamma)^{18}$F reaction at a bombarding energy of $E_p^{\rm lab} = 200$ keV. Two primary γ-ray decays of the $E_x = 5786$ keV state in ^{18}F to the lower-lying levels at $E_x = 937$ and 1081 keV [11] are clearly observed ($R \to 937$ and 1081 keV, respectively). The γ-ray intensities of the primary transitions agree, after correction for detection efficiencies, with those of the secondary decays to the ^{18}F ground state that are also observed in the same spectrum (but not shown in Fig. 2). The ^{17}O$(p, \gamma)^{18}$F excitation function of the primary $R \to 1081$ keV transition at bombarding energies around ≈ 200 keV is shown in the bottom panel. No yield is observed below and above the excitation function ("off-resonance"), while the width of the measured yield curve agrees, after correction for stopping powers, with the one displayed in the top panel. These arguments clearly demonstrate that the previously unobserved $E_R^{\rm lab} = 190$ keV resonance has indeed been detected. From the measured maximum yield we obtain a resonance strength of $\omega\gamma_{p\gamma} = (1.2 \pm 0.2) \times 10^{-6}$ eV. The error is mainly determined by uncertainties in the measured γ-ray intensities (10%), the γ-ray detection efficiency (5%), and the coincident summing corrections (5%), and by the adopted [17] stopping powers (10%). The first three contributions can be regarded as random errors, while the last one represents a systematic error. We have combined all errors quadratically. Although we measured the γ-ray yield at one angle only, the solid angle subtended by the detector was sufficiently large for angular correlation effects to be negligible. We estimated these corrections with the aid of Monte Carlo simulations and found them to contribute less than 2% to the total error. Our procedure and analysis will be discussed in detail in a forthcoming publication [18].

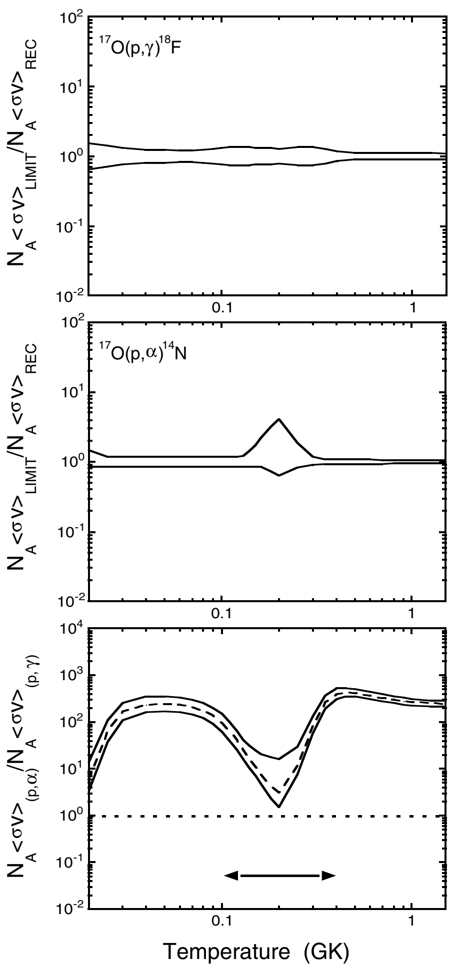

FIG. 3. Same as Fig. 1, but with ^{17}O + p reaction rates from the present work. Comparison to Fig. 1 reveals the dramatic reduction in reaction rate uncertainties due to the observation of the $E_R^{\rm lab} = 190$ keV resonance in the (p, γ) reaction.

We reevaluated the ^{17}O + p reaction rates by using the measured (p, γ) strength of the $E_R^{\rm lab} = 190$ keV resonance. Note that the corresponding ^{18}F state at $E_x = 5786$ keV was previously observed as a resonance in the ^{14}N$(\alpha, \gamma)^{18}$F reaction, while its mean lifetime was also reported [11]. With our measured (p, γ) resonance strength and the previously determined values for the (α, γ) strength and the mean lifetime, we also obtain an improved estimate for the (p, α) resonance strength ($6 \times 10^{-8} \leq \omega\gamma_{p\alpha} \leq 3 \times 10^{-5}$ eV; for details, see Ref. [18]). The new reaction rate ratios are displayed in Fig. 3. The dramatic improvement in accuracy compared to Fig. 1 is evident. At a temperature of 0.2 GK, the uncertainty in the ^{17}O$(p, \gamma)^{18}$F reaction rates is reduced from a few orders of magnitude to $\approx 30\%$ (top panel). The uncertainty in the ^{17}O$(p, \alpha)^{14}$N rates is reduced from an order of magnitude to a factor of ≈ 2.5 (middle panel). Finally, the branching ratio for the (p, α) and (p, γ) reactions varies by a factor of ≈ 10 (bottom panel) compared to almost 5 orders of magnitude in Fig. 1.

Hydrodynamic nova simulations have been performed in order to demonstrate clearly the astrophysical implications of our new measurement. For this purpose, a specific nova model is chosen in the present work. The model assumes a $1.15 M_\odot$ white dwarf of ONe composition, a mass accretion rate of $(2 \times 10^{-10}) M_\odot$/yr and 50% mixing between accreted and white dwarf matter prior to

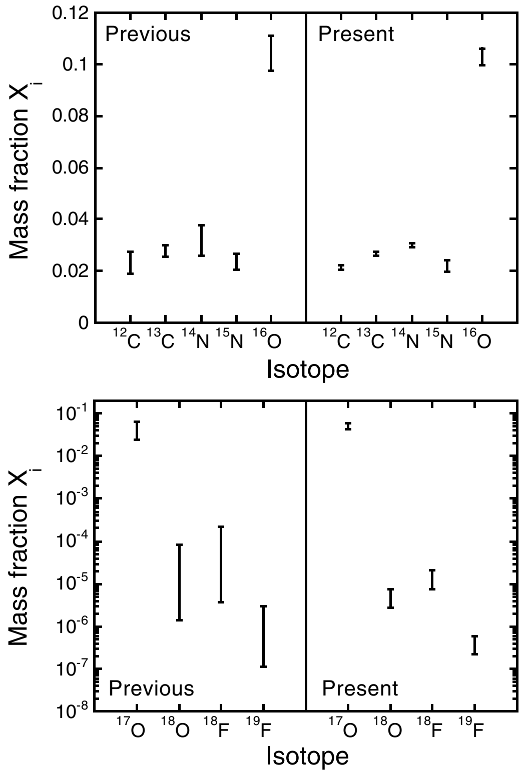

FIG. 4. Final abundances (mass fractions) of CNOF isotopes at the end of hydrodynamic nova model computations, i.e., when the expanding envelope has reached a radius of 10^{12} cm. The abundance of radioactive ^{18}F is presented at a time of 1 h after peak temperature has been reached. The vertical bars represent the range of values that result from $^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reaction rate uncertainties. The left and right hand sides of the figure are obtained by using the previous [8] and present $^{17}O + p$ reaction rates, respectively.

the outburst (⊙ denotes the solar value). This nova model achieves a peak temperature of $T_{peak} = 0.231$ GK [19]. The only changes in the different nova model calculations concerned the choices of $^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reaction rates. All possible combinations of upper and lower limits on the $^{17}O + p$ reaction rates have been taken into account. The variations of final isotopic abundances obtained in the CNOF mass range are shown in Fig. 4 as vertical bars. The left and right hand sides of the figure display results obtained with the previously accepted [8] and the present $^{17}O + p$ rates, respectively. The improvement in the predicted values of final isotopic abundances is evident. The most significant changes occur for oxygen and fluorine isotopes (bottom panel). While the final abundances of ^{18}O, ^{18}F, and ^{19}F vary by 1–2 orders of-magnitude using the previous $^{17}O + p$ reaction rates, the variation amounts to less than a factor of 3 when our new reaction rates are used. The uncertainty in the final ^{17}O abundance is reduced from 46% to 17%. Smaller, but still substantial, improvements occur for the isotopes ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O (top panel). Note that varying the present or previous $^{17}O + p$ reaction rates has only a small, though noticeable, effect on the energetics of the explosion (e.g., the mean kinetic energy of the ejecta or the ejected mass). We emphasize that for illustrative purposes only a single nova model is explored in the present work. A more detailed account and results of additional hydrodynamic model calculations will be given elsewhere [18]. In summary, the present detection of the $E_R^{lab} = 190$ keV resonance in the $^{17}O(p,\gamma)^{18}F$ reaction reduces significantly the uncertainties in the predictions for the galactic synthesis of ^{17}O, the stellar production of the radioisotope ^{18}F, and the oxygen isotopic ratios in nova ejecta.

This work was supported in part by the U.S. Department of Energy under Contract No. DE-FG02-97ER41041, the Spanish MCYT Grant No. AYA2002-0494-C03-01, and the Catalan AGAUR.

[1] S. Starrfield, J.W. Truran, W. M. Sparks, and G. S. Kutter, Astrophys. J. **176**, 169 (1972).
[2] A. Kovetz and D. Prialnik, Astrophys. J. **477**, 356 (1997).
[3] J. José and M. Hernanz, Astrophys. J. **494**, 680 (1998).
[4] S. Starrfield, J.W. Truran, M. Wiescher, and W. M. Sparks, Mon. Not. R. Astron. Soc. **296**, 502 (1998).
[5] M. Hernanz, J. José, A. Coc, and J. Isern, Astrophys. J. Lett. **465**, 27 (1999).
[6] S. Amari, X. Gao, L. R. Nittler, E. Zinner, J. José, M. Hernanz, and R. S. Lewis, Astrophys. J. **551**, 1065 (2001).
[7] J. José *et al.* (to be published).
[8] C. Angulo *et al.*, Nucl. Phys. **A656**, 3 (1999).
[9] A. Coc, M. Hernanz, J. José, and J.-P. Thibaud, Astron. Astrophys. **357**, 561 (2000).
[10] C. Iliadis, A. E. Champagne, J. José, S. Starrfield, and P. Tupper, Astrophys. J. Suppl. Ser. **142**, 105 (2002).
[11] D. R. Tilley, H. R. Weller, C. M. Cheves, and R. M. Chasteler, Nucl. Phys. **A595**, 1 (1995).
[12] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).
[13] D. A. Vermilyea, Acta Metall. **1**, 282 (1953).
[14] D. Phillips and J. P. S. Pringle, Nucl. Instrum. Methods **135**, 389 (1976).
[15] T. Semkow, G. Mehmood, P. Parekh, and M. Virgil, Nucl. Instrum. Methods Phys. Res., Sect. A **290**, 437 (1990).
[16] H. E. Gove, in *Nuclear Reactions I*, edited by P. M. Endt and M. Demeur (North-Holland, Amsterdam, 1959).
[17] J. F. Ziegler and J. P. Biersack, Program SRIM (unpublished).
[18] C. Fox *et al.* (to be published).
[19] J. José, A. Coc, and M. Hernanz, Astrophys. J. **520**, 347 (1999).