Examination of the role of the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction rate in type I x-ray bursts

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Type I x-ray bursts (XRBs) are characterized by sudden dramatic increases in luminosity of roughly 10–100 s in duration, with peak luminosities of roughly $10^{38}$ erg/s. These recurrent phenomena (on timescales of hours to days) have been the subject of many observational, theoretical and experimental studies (for reviews see e.g., [1–3]). The bursts have been interpreted as being generated by thermonuclear runaway on the surface of a neutron star that accretes H- and He-rich material from a less evolved companion star in a close binary system [4,5]. The accreted material burns stably through the hot, β-limited carbon-nitrogen-oxygen (HCNO) cycles, giving rise to the persistent flux. Once critical temperatures and densities are achieved, breakout from this region toward higher masses can occur through alpha-induced reactions. Subsequently, the rapid-proton capture (rp) process drives nucleosynthesis toward the proton drip-line [2,3]. This eventually results in a rapid increase in energy generation (ultimately leading to the XRB) and nucleosynthesis up to A~100 mass region [10,11].

It has long been known that helium burning on HCNO seeds (e.g., $^{14}\text{O}$ and $^{17}\text{O}$) drives the thermonuclear runaway and that the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction initiates one of the reaction sequences leading to breakout from the HCNO cycles [6,8,12,13]. The astrophysical impact of different calculated $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rates (as well as associated uncertainties) has not, however, been carefully assessed. The precise rate of this reaction has previously been suspected to be of only secondary importance [10,11] yet the need for improved determinations...
was nonetheless repeatedly stressed [3, 6, 18, 22]. In addition, variations of an adopted rate by constant factors in different one-zone XRB models has had possibly inconsistent effects on predicted energy generation rates [22, 23]. As such, it is of interest not only to resolve discrepancies in recent $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate calculations through new measurements but also to evaluate the astrophysical impact of recent rates using a consistent set of XRB model calculations.

Contributions from $^{14}\text{O}+\alpha$ resonances in $^{18}\text{Ne}$ ($Q_a=5.115$ MeV [24]) dominate the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate at $T$ relevant to XRBs ($\approx 0.2$–$2$ GK). Although our understanding of this rate has been improved by indirect studies [20, 25, 31], direct study [32], as well as time-reversal studies [33, 35], most of the required resonance parameters (such as, $J^\pi$ and $\Gamma_0$) have still not been sufficiently well determined.

In the temperature region below $\sim 1$ GK, a state at $E_x=6.15$ MeV (tentatively assigned as $1^-$, see below) was thought to dominate the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate [25]. About twenty-five years ago, Wiescher et al. [19] predicted a $J^\pi=1^-$ state at $E_x=6.125$ MeV in $^{18}\text{Ne}$ with a width of $\Gamma=51$ keV based on a Thomas-Ehrman shift calculation. Later on, Hahn et al. [23] observed a state at $E_x=6.15\pm0.01$ MeV through studies of the $^{16}\text{O}(^{3}\text{He},n)^{18}\text{Ne}$ and $^{12}\text{C}(^{3}\text{He},n)^{18}\text{Ne}$ reactions. The transferred angular momentum was restricted to $\ell\leq2$ from the $(^{3}\text{He},n)$ angular distribution measured. Based on the Coulomb-shift calculation and prediction of Wiescher et al., a $J^\pi=1^-$ was tentatively assigned to this state. Gómez et al. [28] studied the resonances in $^{18}\text{Ne}$ by using the elastic scattering of $^{17}\text{F}+p$ and fitted the $6.15$-MeV state with $1^-$ by an $R$-matrix code. However, their $1^-$ assignment was questioned in a later $R$-matrix reanalysis [30]. He et al. [36] thought that this $1^-$ resonance should behave as a dip-like structure (rather than the peak observed in Ref. [28]) in the excitation function due to the interference. Unfortunately, our previous low-statistics measurement could not resolve this state [31]. Recently, Bardayan et al. [37] reanalyzed the unpublished elastic-scattering data in Ref. [28] and identified the expected dip-like structure, however, the statistics were not sufficient to constrain the parameters of such a resonance. Therefore, three possibilities arise regarding the results of Ref. [28] on the $J^\pi$ of the $6.15$ MeV state: (i) their analysis procedure may be questionable as they reconstructed the excitation functions (above $2.1$ MeV) with some technical treatment since the high-energy protons escaped from two thin Si detectors; (ii) the peak observed in Ref. [28] may be due to the inelastic scattering contribution [37, 38], or the carbon-induced background (from CH$_2$ target itself) which was not measured and subtracted accordingly; (iii) the $1^-$ assignment for the $6.15$-MeV state was wrong in Ref. [28]. If their data were correct, the results [30] show that the $6.15$-MeV state most probably has a $3^-$ or $2^-$ assignment, while the $6.30$-MeV state becomes the key $1^-$ state. In addition, the inelastic branches of $^{17}\text{F}(p,p')^{17}\text{F}^*$ (not measured in Ref. [28]) can contribute to the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction rate considerably. Constraining the proton-decay branches to the ground and first excited ($E_x=495$ keV, $J^\pi=1/2^+$) states of $^{17}\text{F}$ is therefore of critical importance. Such inelastic channels were observed for several $^{18}\text{Ne}$ levels [20, 29, 32, 37, 39], however, there are still some controversies [40].

In this work, we first address outstanding uncertainties of relevant $^{14}\text{O}+\alpha$ resonances in $^{18}\text{Ne}$ through a new $^{17}\text{F}+p$ resonant elastic scattering measurement in inverse kinematics, with a $^{17}\text{F}$ radioactive ion beam. The thick target method [41–45], proven to be successful in our previous studies [46, 49, 50], was used in this experiment. In particular, we have unambiguously determined the $1^-$ character of the important $6.15$ MeV resonance. We then use all available experimental input to calculate a new $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate at temperatures involved in XRBs. Finally, we have examined the impact of multiple recent $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rates within the framework of one-zone XRB postprocessing calculations.

The experiment was performed using the CNS Radioactive Ion Beam separator (CRIB) [50, 51], installed by the Center for Nuclear Study (CNS), the University of Tokyo, in the RI Beam Factory of RIKEN Nishina Center. A primary beam of $^{16}\text{O}(^{6}\text{Li},p)^{16}\text{O}$ was accelerated up to $6.6$ MeV/nucleon by an AVF cyclotron ($K=80$) with an average intensity of $560$ enA. The primary beam delivered to CRIB bombarded a liquid-nitrogen-cooled D$_2$ gas target ($\sim 90$ K) [52] where $^{17}$F RI beam was produced via the $^{16}\text{O}(d,n)^{17}\text{F}$ reaction in inverse kinematics. The D$_2$ gas at $120$ Torr pressure was confined in a $80$-mm long cell with two $2.5$ mm thick Havar foils. The $^{17}\text{F}$ beam, with a mean energy of $61.9\pm0.5$ MeV (measured by a silicon detector) and an average intensity of $2.5\times10^5$ pps, bombarded a thick H$_2$ gas target in a scattering chamber located at the final focal plane (F3); the beam was stopped completely in this target.

The experimental setup at the F3 chamber is shown in Fig. 1 which is quite similar to that used in Ref. [49]. The beam purity was about $98\%$ after the Wien filter. Two PPACs (Parallel Plate Avalanche Counters) [53] provided the timing and two-dimensional position information of the beam particles. The beam profile on the secondary target was monitored by the PPACs during the data acquisition. The beam particles were identified event-by-

FIG. 1: Schematic diagram of the experimental setup at the scattering chamber, similar to that used in Ref. [49].
event by the time of flight (TOF) between PPACa (see Fig. 1) and the production target using the RF signal provided by the cyclotron. Figure 2(a) shows the particle identification at PPACa. The H$_2$ gas target at a pressure of 600 Torr was housed in a 300-mm-radius semicircular chamber sealed with a 2.5-μm-thick Havar foil as an entrance window and a 25-μm-thick aluminized Mylar foil as an exit window. Comparing to the previously used solid CH$_2$ target [20, 28, 29, 31, 34, 35], the gas target is free from intrinsic background from carbon.

The recoiling light particles were measured by three ΔE–E Si telescopes at average angles of $\theta_{lab}$≈3°, 10° and 18°, respectively. In the c.m. frame of elastic scattering, the corresponding scattering angles are $\theta_{c.m.}$≈155°±18°, 138°±22° and 120°±22°, respectively. At $\theta_{lab}$≈3°, the telescope consisted of a 65-μm-thick double-sided-strap (16×16 strips) silicon detector and two 1500-μm-thick pad detectors. The last pad detector was used to veto any energetic light ions produced in the production target and satisfying the $B_P$ selection, but not rejected by the Wien filter because of scattering in the inner wall of the beam line. The configuration of the other two telescopes is similar to that at $\theta_{lab}$≈3°, except for the absence of the third veto layer. The position sensitive ΔE detectors measured the energy, position and timing signals of the particles, and the pad E detectors measured their residual energies. The recoiling particles were clearly identified by using a Δ$E - E$ method as shown in Fig. 2(b). The energy calibration for the silicon detectors was performed by using a standard triple α source and secondary proton beams at several energy points produced with CRIB during calibration runs. The contribution of background was evaluated through a separate run with Ar gas at 120 Torr (chosen to achieve the equivalent stopping power as in the H$_2$ gas).

The excitation functions of $^{17}$F+p elastic scattering have been reconstructed using the procedure described previously [31, 42, 47]. The excitation functions at two scattering angles are shown in Fig. 3 data from the third telescope (at $\theta_{lab}$≈18°) were not included in the analysis due to its considerably poorer resolution. The normalized Ar-gas background spectra shown was subtracted accordingly. Our results demonstrate that the pure H$_2$ gas target allows us to minimize the background protons. It can be regarded as a strong merit compared to the generally used CH$_2$ solid target which contributes significantly more background from C atoms. The length of the gas target (300 mm) led to an uncertainty of about 3% in the solid angle, as determined in event-by-event mode. Such uncertainty in the cross-section is comparable to the statistical one (≈1%).

Several resonant structures were clearly observed in the spectra. In order to determine the resonant parameters of observed resonances, multichannel R-matrix calculations [54, 56] (see examples [30, 57]) have been performed in the present work. A channel radius of $R$=1.25×(1+1.75)$^2$≈4.16 fm appropriate for the $^{17}$F+p system [19, 23, 28, 31, 36, 58] has been utilized in the calculation. The choice of radius only has minor effect on the large uncertainties quoted both for the excitation energies and widths (see Table 1).

The ground-state spin-parity configurations of $^{17}$F and proton are 5/2$^+$ and 1/2$^+$, respectively. Thus, there are two channel spins in the elastic channel, i.e., $\alpha$=2 and 3. In the present R-matrix calculation, the $\alpha$ partial

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**FIG. 3:** (Color online) The center-of-mass differential cross-selections for elastically scattered protons of $^{17}$F+p at angles of (a)$\theta_{c.m.}$≈155°±18°, and (b)$\theta_{c.m.}$≈138°±22°. The red lines represent the best overall R-matrix fits. The locations of inelastic scattering events for the 6.15-MeV state are indicated as the asterisks. The indicated background spectra (from the Ar gas run) was subtracted accordingly. Additional R-matrix fits for the 6.15- and 6.85-MeV states are shown in (c) and (d), respectively. See text for details.

**FIG. 2:** (Color online) (a) Identification plot for the beam particles before H$_2$ target via time-of-flight (TOF) technique. Two groups of particles appear for a single beam, since the data for two extraction cycles of the cyclotron are plotted together. (b) Identification plot for the recoiled particles via ΔE – E technique. See text for details.
widths ($\Gamma_\alpha$) are negligible relative to the proton widths ($\Gamma_\alpha/\Gamma_p$) $\gtrsim 20$. Five resonances, at $E_x=6.15, \ 6.28, \ 6.35, 6.85$, and $7.05$ MeV, have been analyzed, and the best overall fitting curves are shown in Fig. 3(a) & (b). The resonant parameters obtained are listed in Tab. I. In order to fit the data around $E_{c.m.}=3.2$ MeV, it was necessary to include an additional known resonance $(E_x\approx 7.40$ MeV, $J^p=2^+$, $\Gamma=40$ keV) $\gtrsim 20$. The resonant parameters from the work of Hahn et al., as well as $E_x=3.2$ MeV, was not observed in the previous experiments [25, 27].

If this state was not involved in their $\ell=2$ excitation, which has been a long standing problem [28].

The 6.35-MeV state is fitted well with parameters of $\Gamma_p/\Gamma_p=0.2$, and total $\Gamma=60$ keV, where $\Gamma_p$ and $\Gamma_p$ are the proton-branching widths for populating the ground and first excited states, respectively. He et al. [29] detected decay $\gamma$ rays in coincidence with $^{17}$F+p protons looking at the 495-keV $\gamma$ rays, and yielded a ratio of $\Gamma_p/\Gamma_p=\gamma$. By reanalyzing the data in Ref. [29], Bardayan et al. [30] derived a new ratio of $\Gamma_p/\Gamma_p=0.42\pm 0.03$, and $\Gamma=53.7\pm 2.0$ keV. Most recently, Almaraz-Calderon et al. [31] populated the 6.15-MeV state through the $^{19}$F+$^1$He $\rightarrow ^{18}$O reaction, where inclusion of a small non-zero $\Gamma_p$ has no effect on the conclusion regarding $J^p=1^+$ discussed above.

A shell-model calculation for $\Lambda=17$ and 18 nuclides has been performed with a shell-model code OXBASH [61]. The calculation was carried out in a full model space (spsdpf) using an isospin-conserving WBB interaction of Warburton and Brown [62]. The energy of the second $1^-$ state was predicted to be $E_x=6.652$ MeV for $^{18}$O. According to the knowledge of the mirror $^{19}$O, this $1^-$ state originates mainly from the valence hole of $1p_{3/2}$. The spectroscopic factors are calculated to be about $S_{1p_{3/2}}=0.01$ for both proton decays to the ground and the first excited states in $^{17}$F. The calculated value of $S$ is about three times smaller than the experimental one $\gtrsim 20$. The spectroscopic factor ratio between the ground and first excited state should be reliable. The calculated branching ratio is $\Gamma_\gamma/\Gamma_p=0.66$ with a partial proton width relation of $\Gamma_p=\frac{m_p}{\mu} P_1 C^2 S_{1p}$. The calculated proton width is about 20 keV with $C^2 S_{1p}=0.01$. These results are reasonable given the reanalysis by Bardayan et al. [30].

(a) States between 6.1–6.4 MeV

According to the $R$-matrix analysis, a dip-like structure around $E_{c.m.}=2.21$ MeV, corresponding to the 6.15-MeV state in $^{18}$Ne, is best fit as a natural-parity $1^-$ state as shown in Fig. 3(c). The fitted parameters are $\ell=1$, $s=2$, and $\Gamma=50 \pm 15$ keV (see Table I), where the measured total width $\Gamma$ is consistent with $\Gamma=53.7 \pm 2.6$ keV reported before [37]. The resonance shape of this state varies with that of a previous low-statistics experiment [20] reanalyzed by Bardayan et al. [30]. The natural-parity character of this state was verified by the previous direct $^{14}$O($\alpha$,p)$^{17}$F measurement [32]. Thus, the unnatural-parity $2^-$ assignment can be excluded, and such assignment is also unlikely based on the discussions of the 2p-emission from this state [29, 34]. In addition, the $3^-$ assignment is very unlikely as shown in Fig. 3(c), and such assignment can also be ruled out because of the large inelastic branch observed for this state. Therefore, we confirmed the $1^-$ assignment of the important 6.15-MeV state. Our resonance shape is entirely different from the bump-like shape observed in Ref. [28]. This may be due to issues in the data of Ref. [28] as well as their $R$-matrix analysis (see the lower panel of Fig. 2 in Ref. [28]). As a result, other $J^\pi$ assignments suggested in Ref. [35] are also questionable.

A structure at $E_x=6.28$ MeV was observed in the excitation function, and its shape is reproduced with those resonant parameters from the work of Hahn et al., i.e., $E_{c.m.}=2.36$ MeV, $J^\pi=3^-$, and $\Gamma=20$ keV. In Ref. [28], this state was not involved in their $R$-matrix fit. This natural-parity state was clearly observed in the direct $^{14}$O($\alpha$,p)$^{17}$F experiment [32].

The 6.35-MeV state is fitted well with parameters of $J^\pi=2^-$, and $\Gamma=10 \pm 5$ keV. This $J^\pi$ assignment is consistent with that speculated by Hahn et al. It was only weakly populated in the transfer reactions of $^{14}$He(n) and (p,t), and unobserved in the direct $^{14}$O($\alpha$,p)$^{17}$F experiment [32]. With an unnatural-parity $2^-$ assignment, this state does not contribute to the rate [25, 35].

In summary up to this point, we have made confirmation of the three states between 6.1 and 6.4 MeV for the first time, which has been a long standing problem [25, 27]. Because of nuclear structure considerations (4$p$-2h configuration of $h$ (hole) being in 1p3/2 and $p$ (particle) in 2s1/2 or 1d3/2 orbits), $1^-$ has very small (p,t) cross section, and that is why the 6.15-MeV state was not observed in the previous experiments [25, 27]. On the other hand, the $2^-$ state can be expected to have appreciable amplitude with a simple $p$-$h$ component, since there is always (p,t) multistep component even for an unnatural-parity state [25]. That is why the 6.35-MeV state could be observed even by the (p,t) reactions [25, 27]: but this $2^-$ amplitude is significantly smaller than that of $3^-$ natural-parity state at 6.286-MeV.

The first study to observe inelastic scattering from the 6.15-MeV state was reported by Blackmon et al. They yielded a branching ratio of $\Gamma_p/\Gamma_p=2.4$, and total $\Gamma\sim 58$ keV, where $\Gamma_p$ and $\Gamma_p$ are the proton-branching widths for populating the ground and first excited states, respectively. He et al. [29] detected decay $\gamma$ rays in coincidence with $^{17}$F+p protons looking at the 495-keV $\gamma$ rays, and yielded a ratio of $\Gamma_p/\Gamma_p=\gamma$. By reanalyzing the data in Ref. [29], Bardayan et al. [30] derived a new ratio of $\Gamma_p/\Gamma_p=0.42\pm 0.03$, and $\Gamma=53.7\pm 2.0$ keV. Most recently, Almaraz-Calderon et al. [31] populated the 6.15-MeV state through the $^{19}$F+$^1$He $\rightarrow ^{18}$O reaction, where inclusion of a small non-zero $\Gamma_p$ has no effect on the conclusion regarding $J^p=1^+$ discussed above.

A shell-model calculation for $\Lambda=17$ and 18 nuclides has been performed with a shell-model code OXBASH [61]. The calculation was carried out in a full model space (spsdpf) using an isospin-conserving WBB interaction of Warburton and Brown [62]. The energy of the second $1^-$ state was predicted to be $E_x=6.652$ MeV for $^{18}$O. According to the knowledge of the mirror $^{18}$O, this $1^-$ state originates mainly from the valence hole of $1p_{3/2}$. The spectroscopic factors are calculated to be about $S_{1p_{3/2}}=0.01$ for both proton decays to the ground and the first excited states in $^{17}$F. The calculated value of $S$ is about three times smaller than the experimental one $\gtrsim 20$. Due the complicated configuration mixing, the theoretical value may fail to reproduce the absolute experimental $S$ value, but the spectroscopic factor ratio between the ground and first excited state should be reliable. The calculated branching ratio is $\Gamma_\gamma/\Gamma_p=0.66$ with a partial proton width relation of $\Gamma_p=\frac{m_p}{\mu} P_1 C^2 S_{1p}$. The calculated proton width is about 20 keV with $C^2 S_{1p}=0.01$. These results are reasonable given the reanalysis by Bardayan et al. [30].

(b) State at 6.85 MeV

It is very interesting that a shoulder-like structure around $E_{c.m.}=2.93$ MeV was observed by both telescopes as shown in Fig. 3(a) & (b). This is possibly a new state at $E_x=6.85\pm 0.10$ MeV. Both $J^\pi=0^+$ or $0^+$ resonances can reproduce the observed shape as shown in Fig. 3(d). Because of the small energy shift for the negative-parity
states in this excitation energy region 59, such a state is possibly the analog state of 18O at E\textsubscript{x}=6.880 MeV (0\textsuperscript{+}). In fact, Wiescher et al. 19 predicted a J\textsuperscript{π}=0\textsuperscript{+} state in 18Ne, analog to the 6.88 MeV state in 18O, at 6.85 MeV with a proton spectroscopic factor of C\textsuperscript{2}\textsubscript{sp}=0.01. However, another possibility still exists.

A strong proton resonance from a state at E\textsubscript{x}~6.6 MeV was observed in an earlier direct 14O(α,p)17F experiment 32. Because no such state was previously observed in 18Ne, Notani et al. speculated that it might be due to a state at E\textsubscript{x}~7.1 MeV decaying to the first excited state of 17F. Later on, a careful 17F+p scattering experiment 30 was performed, but no evidence of inelastic 17F+p scattering was observed in this energy region, and the decay branching ratio to the first excited state (Γ\textsubscript{p}/Γ\textsubscript{ν}) was constrained to be <0.03. Almaraz-Calderon et al. recently reported a ratio of 0.19±0.08 for the 7.05 MeV state. Later on, this large ratio was questioned by Fortune 40 who estimated a ratio less than about 2×10\textsuperscript{-3}, in agreement with an earlier limit of <1/90 from Harss et al. 35. Based on the suggestion of Fortune, Almaraz-Calderon et al. thought that their large number might be attributed to an unknown state at E\textsubscript{x}=6.7 MeV in 18Ne. In fact, there is a hint of a weak state observed at E\textsubscript{x}=6.8 MeV state (see Figure 6 in Ref. 32). As discussed above, such a state at E\textsubscript{x}=6.85±0.10 MeV was also observed in the present work. Therefore, we conclude that very likely a new state around 6.8 MeV exists in 18Ne. Since this state was populated in the direct 14O(α,p)17F reaction, it should have a natural parity. Thus, it is also possible a candidate for the J\textsuperscript{π}=0\textsuperscript{+} state, a bandhead state of the six-particle four-hole (6p-4h) band 65,66. If this 6.85-MeV state were 0\textsuperscript{+}, its spin width would be roughly 149 eV, as estimated with the expression of Γ\textsubscript{α}=\frac{\hbar^2}{2\pi} P\textsubscript{α}(E)C\textsuperscript{2}\textsubscript{sp} 19. Here, a spectroscopic factor of 0.01 was assumed in the calculation. As such, if the state is 0\textsuperscript{+} (ω\textsubscript{γ}=149 eV), its contribution to the 14O(α,p)17F rate would be larger than that of the 7.05-MeV state (ω\textsubscript{γ}=203 eV) but still much smaller than that of the 6.15 MeV state below ~2.5 GK. Of course, if it is, in fact, 0\textsuperscript{-}, it would not contribute to the rate at all. The exact J\textsuperscript{π} for this 6.85 MeV state still needs to be determined by additional experiments (though we prefer 0\textsuperscript{+}).

(c) States at 7.05 and 7.35 MeV

In this work, a state at E\textsubscript{x}=(7.05±0.03) MeV (4\textsuperscript{+}, Γ=95 keV) 32 was observed at E\textsubscript{cm}=3.13 MeV. However, the doublet structure around E\textsubscript{x}=7.05 and 7.12 MeV suggested in Refs. 25,31 could not be resolved within the present energy resolution (~80 keV in FWHM in this region). A single peak is adequate for the fit to our data, with similar χ\textsuperscript{2} value to a fit using two peaks.

One state at (7.35±0.02) MeV was observed in the (3He,n) and (12C,4He) reactions 23 and showed (1\textsuperscript{−}, 2\textsuperscript{+}) characteristics in the (3He,n) angular distribution. Hahn et al. 23 suggested a 1\textsuperscript{−} for this state based on a very simple mirror argument. Later on, following the arguments of Fortune and Sherr 52, Harss et al. 53 speculated it, i.e., at (7.37±0.06) MeV, as a 2\textsuperscript{+} state based on a Coulomb-shift discussion. Our present and previous results 31 all support the 2\textsuperscript{+} assignment. However, its mirror partner is still uncertain 65. Combining with the discussion of Fortune and Sherr 66, we speculate that a new 7.796-MeV state recently observed 67 in 18O may be the mirror of the 7.35 MeV state in 18Ne. This would imply that the bandhead (0\textsuperscript{+}) of the six-particle four-hole (6p-4h) band in 18O is still missing.

By evaluating all the available data, the resonance parameters adopted for the 14O(α,p)17F resonant rate calculations are summarized in Table I. Here, the excitation and resonance energies are adopted from the work of Hahn et al. 23. Similar to the method utilized by Hahn et al. and Bardayan et al. 60, the 14O(α,p)17F total rate has been numerically calculated using the resonance parameters listed in Table I and the direct reaction S-factors calculated by Funck & Langanke 70. Here, the interference between the direct-reaction t=1 partial wave and the 6.15-MeV (1\textsuperscript{−}) excited state was included in the calculations; the inelastic branches (listed in Table II) were also included in the integration. Two different 14O(α,p)17F rates were calculated by assuming the constructive (“Present+”) and destructive (“Present−”) interferences between the direct and resonant captures (for the 6.15-MeV state). These two rates differ by a factor of ≈5 at 0.35 GK and less than 10% at 1 GK. In the temperature region of 0.3–3 GK, our “Present+” and “Present−” rates are about 1.1–2.2 times larger than the corresponding rates from Hahn et al. Our adopted parameters are more reliable than the older ones determined by Hahn et al. about twenty years ago. It is worth noting that our rates are orders of magnitude greater than those of Harss et al. 32 and Almaraz-Calderon et al. 39 below 0.3 GK, because they did not consider the interference effects, and only utilized a simple narrow-resonance formalism to calculate the resonant rate of the 6.15-MeV state. The comparison between our rates and the previous ones are shown in Fig. III. The 1σ uncertainties (lower and upper limits as utilized below) of the present rates were estimated to be about 10–30% (for “Present+”) and 20–50% (for “Present−”) over 0.1–3 GK, using a Monte-Carlo method with parameter errors adopted in Table I. We found that the contribution from the 6.15 MeV state dominates the total rate over temperatures of interest in XRBs. The present (+/−) recommended rates for T\textsubscript{9}≤3 GK can be analytically expressed by N\textsubscript{A}(σ\textsubscript{v})\textsuperscript{+}=\exp\left[1.896×10^{-2}-0.179T\textsubscript{9}^{-1/3}-4.872T\textsubscript{9}^{-1/3}-2.358T\textsubscript{9}^{-1/3}+1.145T\textsubscript{9}^{-1/3}ight]+18.51T\textsubscript{9}^{-2/3}+22.61T\textsubscript{9}^{-1/3}+52.71T\textsubscript{9}^{-1/3}+38.83\lnT\textsubscript{9}]×10^{-2}+11.843T\textsubscript{9}^{-1}-9.492T\textsubscript{9}^{-1/3}-1.166×10^{2}T\textsubscript{9}^{-1/3}-0.994×10^{2}T\textsubscript{9}^{-1/3}-49.47×10^{2}\lnT\textsubscript{9}].

The impact of the present new 14O(α,p)17F rates has been examined using one-zone XRB models. With the representative K04 temperature-density-time thermodynamic history (T\textsubscript{peak}=1.4 GK 23), the nuclear energy generation rate (E\textsubscript{gen}) during an XRB has
be studied by performing separate post-processing calculations with different rates: the present rates (“Present+” & “Present-“) and their lower and upper limits, as well as previous rates from Wiescher et al. [19] (“W87”), Hahn et al. [22] (“Hahn+” & “Hahn-“), Harss et al. [25], and Alamaraz-Calderon et al. [35]. Table I shows $E_{\text{gen}}$ at early times of the burst calculated using the upper limit of the “Present+” rate and the lower limit of the “Present-“ rate. $E_{\text{gen}}$ curves calculated using the lower limit of the “Present+” rate and the upper limit of the “Present-“ rate lie between these two curves. The spread between the solid curves in Fig. 5 reflects the impact of the uncertainties of the present rates. Here only the result with the “Hahn-“ rate is shown for comparison since the curve calculated using the “Hahn+” rate is similar to that shown for the “Present- (LL)” rate. Clearly, the sign of the interference has only a very marginal effect on the predicted $E_{\text{gen}}$. The predicted $E_{\text{gen}}$ profiles using the rates of Harss et al. and Alamaraz-Calderon et al. are not shown in Fig. 5 as these profiles differ from that of the “Present- (LL)” curve only between $\approx 0.30-0.32$ s, where they lie between the two solid curves. The $E_{\text{gen}}$ profile calculated using the rate of Wiescher et al. (“W87”) shows the largest differences from the $E_{\text{gen}}$ calculated using the present rates. For example, at $\approx 0.31$ s, $E_{\text{gen}}$ calculated using the present rates is a factor of $\approx 3$ less than that determined using “W87”.

Given the role of the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction in the break-out from the HCNO cycle during an XRB, it is not surprising that different rates affect $E_{\text{gen}}$ at early times. Nonetheless, the impact is decidedly modest: the largest shift in the initial peaks observed for the different $E_{\text{gen}}$ curves is only $\approx 0.01$ s; this could be compared to the length of typical bursts ($\approx 10-100$ s). Observing such a shift is certainly beyond the capabilities of current telescopes. As such, for the adopted model, our results imply that the precise rate of this reaction has limited impact on the predicted nuclear energy generation during the burst.

Through a new $^{17}\text{F}+\text{p}$ resonant elastic scattering experiment, we have determined the energies, $J^\pi$ values and widths of three $^{14}\text{O}+\alpha$ resonances between $6.1$ and $6.4$ MeV in $^{18}\text{Ne}$. We have firmly assigned $J^\pi=1^+$ to the $6.15$ MeV state, resolving a dispute in the literature. This state dominates the thermonuclear rate of the $^{14}\text{O}(\alpha,p)^{17}\text{F}$ reaction below $\approx 2$ GK. As well, we have found the evidence for a new state at $E_x=6.85$ MeV and discussed the possible structure origin. Using all available experimental input, we have determined a new thermonuclear $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate and provided the quantitative tests with an XRB model of the impact of multiple recent $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rates. Contrary to many previous expectations in the literature on the critical nature of this reaction rate, we find only minor variations in the predicted nuclear energy generation rates when using reaction rates that differ by up to two orders of magnitude at the relevant temperatures. Indeed, the present rate and uncertainties seem to be sufficient for calculations with

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**TABLE I: Resonant parameters derived from the present $R$-matrix analysis.** The excitation energies are the average values derived from our data sets, and uncertainties are estimated by a Monte-Carlo simulation. The widths available in the literature are listed for comparison.

| $E_x$ (MeV) | $J^\pi$ | $\Gamma$ (keV) | $T_{\text{gen}}$ (s) | $T_{\text{gen}}$ at $E_x=6.4$ MeV |
|------------|------|-------------|-------------------|-------------------|
| 6.15(0.03) | 1$^-$1 | 50(15)      | $\leq 40$ [25]; $53.7\pm 2.0$ [37] |
| 6.28(0.03) | 3$^-$1 | 20(15)      | $\leq 20$ [25]; $8\pm 7$ [26] |
| 6.35(0.03) | 2$^-$1 | 10(5)       | $45\pm 10$ [25]; $18\pm 9$ [26] |
| 6.85(0.11) | 0$^+$3 | 50(30)      | $<120$ [25]; $90\pm 40$ [35] |
| 7.05(0.03) | 4$^+$2 | 95(20)      | $<120$ [25]; $90\pm 40$ [35] |

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**FIG. 4:** (Color online) Ratios between the present reaction rates and previous calculations [10, 22, 32, 39]. See text for details.

**FIG. 5:** (Color online) Nuclear energy generation rates during one-zone XRB calculations using the K04 thermodynamic history [22]. Results using the “Present” rates (black line for the lower limit (LL) of “Present-“, grey line for the upper limit (UL) of “Present+“) and the “Hahn-“ rates [22] (red dotted line) are indicated. The result with Wiescher et al. [19] rate is also shown for comparison (labeled as “W87”). See text for details.
the XRB model employed. Further tests using hydrodynamic XRB models are encouraged to confirm these results and examine the impact of different $^{14}$O($\alpha,p$)$^{17}$F rates.

Acknowledgments

We would like to thank the RIKEN and CNS staff for their kind operation of the AVF cyclotron. This work is financially supported by the NNSF of China (Nos. 11135005, 11205212, 11321064), the 973 Program of China (2013CB834406), as well as supported by JSPS KAKENHI (No. 25800125). AP was supported by the Spanish MICINN (Nos. AYA2010-15685, EU12009-04167), by the E.U. FEDER funds as well as by the ESF EUROCORES Program EuroGENESIS. A.A.C and D.I were supported by the National Science and Engineering Research Council of Canada. K.IH was supported by the NRF grant funded by the Korea government (MSIP) (No. NRF-2012M7A1A2055625) and J.Y.M. H.S.J. and C.S.L by the Priority Centers Research Program in Korea (2009-0093817).

TABLE II: Resonance parameters adopted in the calculation of the $^{14}$O($\alpha,p$)$^{17}$F reaction rate.

| $E_r$ (MeV) | $E_{res}$ (MeV) | $J^p$ | $\Gamma$ (eV) | $T_p$ (keV) | $T_{pp}$ (keV) | $T$ (keV) | $\omega^*$ (MeV) |
|------------|---------------|------|--------------|------------|--------------|---------|----------------|
| 5.153±0.01 | 0.039         | $^a$ 3 | 4.3×10$^{-6}$ | 1.7        | $<15^*$      | 3.0×10$^{-7}$ |
| 6.150±0.01 | 1.036         | 1$^-$ | 3.9±1.0$^b$  | 37.8±1.9$^c$ | 15.9±0.7$^d$ | 53.7±2.0$^e$ | 1.2×10$^{-5}$ |
| 6.280±0.01 | 1.172         | 3$^-$ | 0.34$^*$     | 20±15$^*$  | 15.9±0.7$^d$ | 2.4×10$^{-6}$ |
| 7.05±0.03  | 1.396         | 4$^+$ | 22.6±3.2$^b$ | 90±40$^c$  | 90±40$^d$    | 2.0×10$^{-4}$ |
| 7.35±0.02  | 2.236         | 2$^+$ | 40±30$^d$    | 70±60$^e$  | 70±60$^f$    | 2.0×10$^{-4}$ |
| 7.62±0.02  | 2.506         | 1$^-$ | 1000±120$^f$ | 72±20$^f$  | 75±20$^f$    | 3.0×10$^{-3}$ |
| 7.94±0.01  | 2.826         | 3$^+$ | (11±6.6)×10$^{10}$ | 35±15$^f$ | 9.0±5.6$^d$ | 55±20$^d$ | 6.2×10$^{-2}$ |
| 8.11±0.01  | 2.996         | 3$^+$ | (6.3±3.9)×10$^{14}$ | 20±4$^g$  | 43±9$^d$     | 30$^d$  | 3.5×10$^{-2}$ |

$^a$ From Hahn et al. [23]; $^b$ From Fortune [40]; $^c$ From Bardayan et al. [51].

\[ \text{From present work; From Fortune [40]; From Hars et al. [52]; From Almaraz-Calderon et al. [53].} \]
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