Regulated NiCu Cycles with the New $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ Reaction Rate and the Influence on Type-I X-Ray Bursts: GS 1826–24 Clocked Burster

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Abstract. In Type-I X-ray bursts (XRBs), the rapid-proton capture (rp-) process passes through the NiCu and ZnGa cycles before reaching the region above Ge and Se isotopes that hydrogen burning actively powers the XRBs. The sensitivity study performed by Cyburt et al. [1] shows that the $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ reaction rate in the NiCu cycles is the fifth most important rp-reaction influencing the burst light curves. Langer et al. [2] precisely measured some low-lying energy levels of $^{59}\text{Zn}$ to deduce the $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ reaction rate. Nevertheless, the order of the $1^+_1$ and $2^+_1$ resonance states that dominate at $0.2 \lesssim T'(\text{GK}) \lesssim 0.8$ is not confirmed. We then determine the $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ reaction rate using the full $pf$-model space model calculations. The new rate is up to a factor of four lower than the Forstner et al. [3] rate recommended by JINA REACLIBv2.2. Using the present $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$, the latest $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ and $^{55}\text{Ni}(p,\gamma)^{56}\text{Cu}$ reaction rates, and 1D implicit hydrodynamic Kepler code, we model the thermonuclear XRBs of the clocked burster GS 1826–24. We find that the new rates regulate the reaction flow in the NiCu cycles and strongly influence the burst-ash composition. The $^{59}\text{Cu}(p,\alpha)^{56}\text{Ni}$ and $^{59}\text{Cu}(p,\gamma)^{60}\text{Zn}$ reactions suppress the influence of the $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ reaction. They strongly diminish the impact of the nuclear reaction flow that bypasses the $^{56}\text{Ni}$ waiting point induced by the $^{55}\text{Ni}(p,\gamma)^{56}\text{Cu}$ reaction on burst light curve.

The $^{57}\text{Cu}(p,\gamma)^{58}\text{Zn}$ reaction is the fifth most influential $(p,\gamma)$ reaction that affects the light curve of GS 1826–24, the clocked burster [4], as found by Cyburt et al. [1]. Langer et al.

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Figure 1. Top Panel: The Present and Langer et al. [2] $^{57}$Cu(p,$\gamma$)$^{58}$Zn thermonuclear reaction rates, and available reaction rates compiled in to JINA REACLIB v2.2: $r_{\text{ath}}$, $thra$, $ths8$, and $\text{wien2}$ [3], the rate recommended by JINA REACLIB v2.2. All available rates of REACLIB v2.2 use the $^{58}$Zn proton threshold, $S_{\text{p}}(^{58}\text{Zn}) = 2.277$ MeV.

Bottom Panel: The comparison of the Present rate with Langer et al. and all available reaction rates of REACLIB v2.2. The uncertainty of the Present rate (red zone) folds the uncertainties from the $S_{\text{p}}(^{58}\text{Zn})$ and nuclear structure. The uncertainty of Langer et al. rate is indicated as blue zone. The rates of $r_{\text{ath}}$, $thra$, and $ths8$ based on the Hauser-Feshbach statistical model are very close to one another from 0.1 to 2.0 GK, and they are lower than the Present rate up to one order of magnitude at temperature $T \lesssim 0.9$ GK. The Present rate is up to a factor of two lower than Langer et al. rate from 0.8 to 2 GK covering the typical maximum temperature of accreted envelope of the GS 1826−24 burster, and up to a factor of four lower than the $\text{wien2}$ rate [3].

[2] experimentally confirmed some low-lying excited states of $^{58}$Zn, which are resonance states dominantly contribute to the $^{57}$Cu(p,$\gamma$)$^{58}$Zn reaction rate. The order of the dominant resonance states, $1^+_1$ and $2^+_3$, that they precisely measured was, however, unconfirmed. The $1^+_2$ resonance state, one of the dominant resonances sensitive to the clocked burst temperature regime, $0.8 \leq T(\text{GK}) \leq 2$, was not detected.

In the present study, we first compare the theoretical and experimental IMME $c$ coefficients for the $A = 58$, isospin $I = 1$ multiplets to obtain the root-mean-square (rms) deviation value 22 keV as the theoretical uncertainty. Then, we study and propose the most plausible order of the $2^+_1$ and $1^+_1$ states based on the $A = 58$, $I = 1$ multiplets of $^{58}$Zn, $^{58}$Cu, and $^{58}$Ni. We then use IMME to estimate the lowest limit energy of the $1^+_2$ state ($3.664 \pm 0.022$ MeV). The corresponding resonance energy is 1.384 MeV. This is 329 keV higher than the direct estimation of shell-model calculation by Langer et al. [2]. The contribution of the $1^+_2$ resonance state reduces by about one order of magnitude, reducing the total reaction rate in the temperature regime $0.8 \leq T(\text{GK}) \leq 2$. With the presently deduced nuclear structure information, we use the full $pf$-model space shell model calculations with GXPF1A interaction [5] to construct the Present $^{57}$Cu(p,$\gamma$)$^{58}$Zn reaction rate for the typical XRB temperature range, in particular, the temperature regime of $0.8 \leq T(\text{GK}) \leq 1.6$ relevant to the GS 1826−24 burster. The comparison of the Present rate with Langer et al. rate and with other reaction rates compiled into JINA REACLIB v2.2 [6] is shown in Fig. 1.

Using the GS 1826−24 model obtained from Kepler, we construct three XRB models based on each combination of reaction rates: (1) the Present $^{57}$Cu(p,$\gamma$)$^{58}$Zn, et al. Kahl [7] $^{56}$Ni(p,$\gamma$)$^{57}$Cu, and Valverde [8] $^{55}$Ni(p,$\gamma$)$^{56}$Cu, (2) Langer [2] $^{57}$Cu(p,$\gamma$)$^{58}$Zn, Kahl [7] $^{56}$Ni(p,$\gamma$)$^{57}$Cu, and Valverde [8] $^{55}$Ni(p,$\gamma$)$^{56}$Cu, and (3) $\text{wien2}$ [3] $^{57}$Cu(p,$\gamma$)$^{58}$Zn. These (1), (2), and (3) combinations are labeled as Present8, Present7, and baseline models, respectively.

We remark that the observed burst tail end of Epoch Jun 1998 of the GS 1826–24 burster is closely reproduced by the Present8, Present7, and baseline models (Fig. 5 of Ref. [9]). Figure 2 shows the burst-ash composition at the burst tail end produced by three models. Using
Figure 2. The averaged mass fractions for each mass number at burst tail end when $t \approx 180$ s after the burst peak. The GS 1826–24 model from Jacobs et al. [10] is adjusted to reproduce the recurrence time of Epoch Jun 1998. The model uses JINA REACLIB v2.2 and is named as baseline model. The Present\(^5\) (or Present\(^6\)) model adopts the same astrophysical configurations of baseline but implement the Present (or Langer et al.) \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn, Kahl et al. [7] \(^{56}\)Ni(p,\(\gamma\))\(^{57}\)Cu, and Valverde et al. [8] \(^{55}\)Ni(p,\(\gamma\))\(^{56}\)Cu rates, see text.

the Present \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn rate, the productions of \(^{12}\)C is reduced by a factor of 0.2, the nuclei with $A = 17$ and 18 breaking out from the hot CNO cycle are affected up to about a factor of 0.5 and 2.5, respectively. The abundances of the daughters of SiP, SCI, and ArK cycles are reduced up to a factor of 0.7. The overall production of \(^{56}\)Ni and its remnant increases up to a factor of 1.2 due to the correlated influence between the new \(^{56}\)Ni(p,\(\gamma\))\(^{57}\)Cu, \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn, and \(^{55}\)Ni(p,\(\gamma\))\(^{56}\)Cu rates. The abundances of nuclei with $A = 64 – 104$ produced by Present\(^5\) are closer to baseline than the ones produced by Present\(^6\). Furthermore, the abundances of the nuclei with $A = 105 – 140$ are decreased by up to a factor of 0.2 (red dots in the bottom panel of Fig. 2). Notably, the Langer et al. \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn reaction rate produces a different set of burst-ash composition compared to the Present \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn rate, especially the nuclei with $A = 20 – 34$; the abundance of the nuclei with $A = 65 – 84$, is reduced by up to a factor of 0.9; and the abundance of the nuclei with $A = 100 – 134$ is closer to baseline than the impact suggested by the change to the Present \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn reaction rate.

The impact of Present \(^{57}\)Cu(p,\(\gamma\))\(^{58}\)Zn, new \(^{56}\)Ni(p,\(\gamma\))\(^{57}\)Cu and \(^{55}\)Ni(p,\(\gamma\))\(^{56}\)Cu rates on burst ash composition is due to the cumulative effect of redistributing and reassembling of reaction flows in the NiCu cycles that eventually affects the nucleosyntheses of \(^{56}\)Ni, \(^{57}\)Cu, \(^{58}\)Zn, and nuclei in the ZnGa cycles. A detail analysis of the evolution of the episode of clocked bursts is presented in Ref. [9].

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