Regulated NiCu Cycles with the New ^{57}Cu(p,γ)^{58}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}Cu(p,γ)^{58}Zn reaction 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 ^{58}Zn to deduce the ^{57}Cu(p,γ)^{58}Zn reaction rate. Nevertheless, the order of the 1^+_1 and 2^+_3 resonance states that dominate at $0.2 \lesssim T(\mathrm{GK}) \lesssim 0.8$ is not confirmed. The 1^+_2 resonance state, which dominates at the XRB sensitive temperature regime $0.8 \lesssim T(\mathrm{GK}) \lesssim 2$ was not detected. Using isobaric-multiplet-mass equation (IMME), we estimate the order of the 1^+_1 and 2^+_3 resonance states and estimate the lower limit of the 1^+_2 resonance energy. We then determine the ^{57}Cu(p,γ)^{58}Zn reaction rate using the full *pf*-model space shell 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}Cu(p,γ)^{58}Zn, the latest ^{56}Ni(p,γ)^{57}Cu and ^{55}Ni(p,γ)^{56}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}Cu(p,α)^{56}Ni and ^{59}Cu(p,γ)^{60}Zn reactions suppress the influence of the ^{57}Cu(p,γ)^{58}Zn reaction. They strongly diminish the impact of the nuclear reaction flow that bypasses the ^{56}Ni waiting point induced by the ^{55}Ni(p,γ)^{56}Cu reaction on burst light curve.

The ^{57}Cu(p,γ)^{58}Zn reaction is the fifth most influential (p,γ) 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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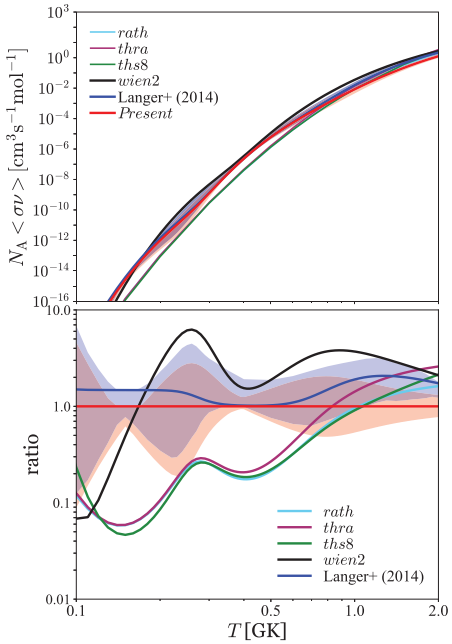

Figure 1. *Top Panel*: The *Present* and Langer *et al*. [2] ^{57}Cu(p,γ)^{58}Zn thermonuclear reaction rates, and available reaction rates compiled in to JINA REACLIB v2.2: *rath*, *thra*, *ths8*, and *wien*2 [3], the rate recommended by JINA REACLIB v2.2. All available rates of REACLIB v2.2 use the ^{58}Zn proton threshold, $S_p(^{58}\mathrm{Zn}) = 2.277$ 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 $S_p(^{58}\mathrm{Zn})$ and nuclear structure. The uncertainty of Langer *et al*. rate is indicated as *blue zone*. The rates of *rath*, *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 *wien*2 rate [3].

[2] experimentally confirmed some low-lying excited states of ^{58}Zn, which are resonance states dominantly contribute to the ^{57}Cu(p,γ)^{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, $0.8 \lesssim T(\mathrm{GK}) \lesssim 2$, 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^+_3 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 ± 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 $0.8 \lesssim T(\mathrm{GK}) \lesssim 2$. 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,γ)^{58}Zn reaction rate for the typical XRB temperature range, in particular, the temperature regime of $0.8 \lesssim T(\mathrm{GK}) \lesssim 1.6$ 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,γ)^{58}Zn, *et al*. Kahl [7] ^{56}Ni(p,γ)^{57}Cu, and Valverde [8] ^{55}Ni(p,γ)^{56}Cu, **(2)** Langer [2] ^{57}Cu(p,γ)^{58}Zn, Kahl [7] ^{56}Ni(p,γ)^{57}Cu, and Valverde [8] ^{55}Ni(p,γ)^{56}Cu, and **(3)** *wien*2 [3] ^{57}Cu(p,γ)^{58}Zn. These **(1)**, **(2)**, and **(3)** combinations are labeled as *Present*§, *Present*$^{\heartsuit}$, 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 *Present*§, *Present*$^{\heartsuit}$, 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

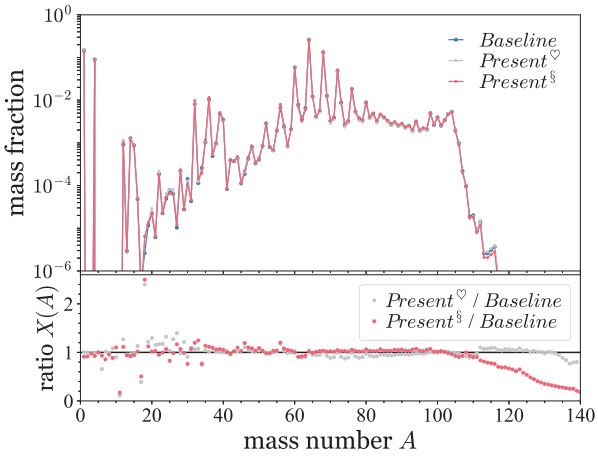

Figure 2. The averaged mass fractions for each mass number at burst tail end when $t \approx 180$ s after the burst peak. The GS 1826−24 model from Jacobs *et al.* [10] is the adjusted to reproduce the recurrence time of *Epoch Jun 1998*. The model uses JINA REACLIB v2.2. and is named as *baseline* model. The *Present*§ (or *Present*$^{\heartsuit}$) model adopts the same astrophysical configurations of *baseline* but implement the *Present* (or Langer *et al.*) ^{57}Cu(p,γ)^{58}Zn, Kahl *et al.* [7] ^{56}Ni(p,γ)^{57}Cu and Valverde *et al.* [8] ^{55}Ni(p,γ)^{56}Cu rates, see text.

the *Present* ^{57}Cu(p,γ)^{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, SCl, 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,γ)^{57}Cu, ^{57}Cu(p,γ)^{58}Zn, and ^{55}Ni(p,γ)^{56}Cu rates. The abundances of nuclei with $A = 64 - 104$ produced by *Present*§ are closer to *baseline* than the ones produced by *Present*$^{\heartsuit}$. 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,γ)^{58}Zn reaction rate produces a different set of burst-ash composition compared to the *Present* ^{57}Cu(p,γ)^{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,γ)^{58}Zn reaction rate.

The impact of *Present* ^{57}Cu(p,γ)^{58}Zn, new ^{56}Ni(p,γ)^{57}Cu and ^{55}Ni(p,γ)^{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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