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New thermonuclear reaction rates of ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se for type-I x-ray bursts

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Abstract. We present a new set of ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se reaction rates based on recently evaluated proton separation energies $S_p(^{65}\text{As})$ and $S_p(^{66}\text{Se})$, and nuclear structure data from large-scale shell model calculations. Our new 64Ge(p,g) rate differs from those available in REACLIB by up to two orders of magnitude at temperatures encountered within type I X-ray bursts. We used one-zone post-processing type-I x-ray burst model to test our new rates, and present the astrophysical impact of these rates.

1 Introduction

Type I x-ray burst (XRB) is generated in the accreted envelope of a neutron star in a close binary star system during thermonuclear explosion. Presently, about 100 bursters have been discovered. Based on the characteristics of discovered bursters, their light curves have typical peak luminosities of roughly $10^4 - -10^5 L_\odot$, timescales of 10–100 s, and recurrence time of one to several hours, see Ref. [1] and references therein.

Several models estimated that an accreted envelope rich in H/He develops to be intensely enriched in heavier mass nuclei through the α-particle-induced (αp) and rapid-proton-capture (rp) reactions on stable and radioactive nuclei during an XRB [2, 3]. In addition, β-decays may occasionally occur based on the properties of the created nuclear species during the abundance flow. When the rp-process advances to the proton dripline, capture of subsequent protons by nuclei is hindered by photodisintegration, (γ, p), which has an almost equal reaction rate as the respective rp-process. Hence, abundances accumulate at these particular proton-rich nuclei, namely "waiting points". In XRBs, beta decay of these waiting point nuclei may compete with the rate of proton capture. Such competitions play their role in extending nucleosynthesis to heavier nuclei up to mass $A \approx 100$ during XRB.

Some pivotal waiting points, e.g., ^{64}Ge, ^{68}Se, ^{72}Kr, were predicted by Schatz *et al.* [3] and the importance of long-lived ^{64}Ge was reassured by Woosley *et al.* [4] in a simulation of 15 sequential bursts. Various models based on multiple factors, like the accretion rate, the composition of the accreted material, the mass and equation of state assumed for the neutron star, and the nuclear masses and reaction rates, predict ^{65}Ar(p,γ) is one of the important reactions in XRB nucleosynthesis. These models varying the ^{65}As(p,γ)^{66}Se rate by a factor of 10 at the respective temperature range cause the end-stage abundances of $65 \lesssim A \lesssim 100$ to vary by factors as large as ∼5 [5]. A recent review of Parikh *et al.* [6] also showed the importance of ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se reactions with respect to uncertainty of rates and their impact on nucleosynthesis during XRBs. However, up to now, there is no direct measurement of these reactions at the respective energies in XRBs. Secondly, the mass of ^{66}Se is unmeasured. Thirdly, the energy levels of both ^{65}As and ^{66}Se nuclei up to $1 \lesssim E_x \lesssim 2$ MeV are also unmeasured. In such missing important nuclear physics input, most of the XRB simulations use ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se reaction rates derived from statistical-model.

Recently, the previously unknown proton separation energy of ^{65}As, S_p(^{65}As) was measured to be −90 ± 85 keV [7] at the HIRFL-CSR (Cooler-Storage Ring at the Heavy Ion Research Facility in Lanzhou) [8] in an IMS (Isochronous Mass Spectrometry) mode. With the new S_p(^{65}As) value, the X-ray burst model employed in Ref. [7] proposed that ^{64}Ge is not a significant rp-process waiting point. This suggestion is different from the previous expectations [3, 4, 9–11].

This present work investigates the above controversy with a new set of thermonuclear ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se reaction rates based on the updated S_p(^{65}As), newly evaluated S_p(^{66}Se), see Atomic Mass Evaluation (AME2012) [12], and the nuclear structure information from large-scale shell-model calculations. The astrophysical impact of our new rates and other available rates, e.g. rates from Van Wormer *et al.* [13], from statistical-model (Hauser-Feshbach formalism) NON-SMOKER code [14], and from JINA REACLIB [15][1], has been checked using the post-processing one-zone XRB model.

2 Reaction rates

2.1 The formalism

The total reaction rate includes the resonant and direct-capture rates of proton capture on ground state and all thermally excited states in the target nucleus weighted with their individual population factors [16, 17]. We calculated the direct-capture rates for the ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se reactions by using the Woods-Saxon nuclear potential and a Coulomb potential of uniform-charge distribution embedded in RADCAP code [18]. We found that the ratio of direct-capture contributions to resonant contributions are less than about 0.01 for $T \leq 0.05$ GK, and for $T \geq 0.05$ GK, the total rates are dictated by resonant contributions for both reactions. Therefore, we only assume the resonant contributions to be the total reaction rates for both *rp* processes.

We employed the narrow resonance formalism [17, 19],

$$N_A\langle\sigma v\rangle_r = 1.54 \times 10^{11} (\mu T_9)^{-3/2} \omega\gamma \exp\left(-\frac{11.605 E_r}{T_9}\right),$$

to obtain the resonant rate. The reduced mass μ is defined as $A_T/(1{+}A_T)$, with A_T the target mass, and resonant strength $\omega\gamma$ and the resonant energy E_r are in units of MeV. The resonant strength $\omega\gamma$ is defined by

$$\omega\gamma = \frac{2J+1}{2(2J_T+1)} \frac{\Gamma_p \times \Gamma_\gamma}{\Gamma_{\rm tot}}, \tag{1}$$

of which the J_T and J are the spins of the target and resonant state, respectively. Γ_p is the proton width for the entrance channel, and Γ_γ is the gamma (γ) width for the exit channel, and other decay

[1] http://groups.nscl.msu.edu/jina/reaclib/db

channels are closed [20] thus the total width $\Gamma_{\rm tot} \approx \Gamma_p + \Gamma_\gamma$. The proton width is defined as

$$\Gamma_p = \sum_{nlj} \theta^2(nlj)\,\Gamma_{sp}(nlj)\,, \tag{2}$$

of which $\theta^2(nlj)$ is proton-transfer spectroscopic factors, and Γ_{sp} is single-proton widths [21]. The Γ_{sp} are obtained from proton scattering cross sections calculated with Woods-Saxon potential well [22]. The other alternative to compute the proton partial widths is,

$$\Gamma_p = \frac{3\hbar^2}{\mu R^2} P_\ell(E)\theta^2. \tag{3}$$

of which $R = r_0 \times (1 + A_T)^{1/3}$ fm (with $r_0 = 1.25$ fm) is the nuclear channel radius, see Refs [13, 23] for definition of notations. Both methods (i.e., by Eq. 2 and Eq. 3) obtained the proton widths in a maximum difference of about 35%.

The main constituents needed to obtain the resonant ^{64}Ge(p,γ) and ^{65}As(p,γ) rates are energy levels of ^{65}As and ^{66}Se, proton transfer spectroscopic factors, and proton and γ-ray partial widths. However, only has a single level been observed at $E_x = 187(3)$ keV [24] for ^{65}As; whereas one level has been confirmed at $E_x = 929$ keV, and two other levels were tentatively assigned at 2064 keV (4^+) and 3520 keV (6^+) for ^{66}Se [24, 25]. We obtained other levels up to Gamow energy window, spectroscopic factors and γ widths with the large-scale shell model using NuShellX@MSU [26]. The nuclear wave functions have been computed from numerical diagonalization of isospin-conserving Hamiltonian of pf-shell nuclei, namely GXPF1a [27, 28], without truncation. The total γ width [17, 23] for every considered level consists of $B(E2)$ and $B(M1)$ matrix elements. Both matrix elements of every electromagnetic transition have been obtained based on the empirical effective charges and empirical quenching factors defined in Ref. [27]. For the ^{65}As(p,γ)^{66}Se reaction rates, we have also considered proton captures on the first few excited states of ^{65}As. The first set of the properties of every resonance of both reactions were shown in Tables 1 and 2 of Ref. [29].

Recent hydrodynamic XRB models have approached maximum temperatures in the range of $1.5 \lesssim T[\mathrm{GK}] \lesssim 2$ [4, 11]. Resonant rates of the ^{64}Ge(p,γ) and ^{65}As(p,γ) reactions at this temperature range tend to be dominated by levels below ≈ 2.5 MeV of the respective proton thresholds. There are some high-spin levels below this thresholds referring to the mirror nuclei of ^{64}Ge and ^{65}As, i.e. ^{65}Ge and ^{66}Ge, respectively. However, the total contribution from these high-spin states to the total resonant rates is negligible because of the small proton partial widths.

2.2 The *Present* ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se reaction rates

Both thermonuclear ^{64}Ge(p,γ) and ^{65}As(p,γ) reaction rates were first computed by Van Wormer *et al.* [13] by referring to the properties of the mirror nuclei ^{65}Ge and ^{66}Ge, including the S_p values. Then, both rates have been revisited by Rauscher and Thielemann [30] with a statistical-model (Hauser-Feshbach formalism) [14] using the masses of ^{65}As and ^{66}Se estimated by the finite-range droplet macroscopic model (FRDM) [31] and ETSFIQ mass model [32]. The other set of theoretical rates are recently compiled and available online, i.e. JINA REACLIB [15]. However, the estimated rates above differ from one another by up to several orders of magnitude over the respective XRB temperature range mainly due to the selected proton separation energies. Also, the level densities of excited states in both mirrors ^{65}Ge and ^{66}Ge are not high, and thus such low-density properties are also expected in ^{65}As and ^{66}Se near their proton thresholds. Hence, the reliability of the statistical-model calculations for both reactions may be questionable.

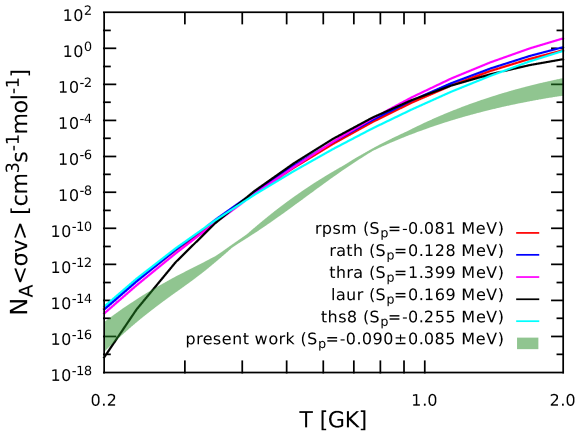

Figure 1. ^{64}Ge(p,γ)^{65}As reaction rates. The *Present* rate is shown as a green band with the upper and lower limits. See details in the text.

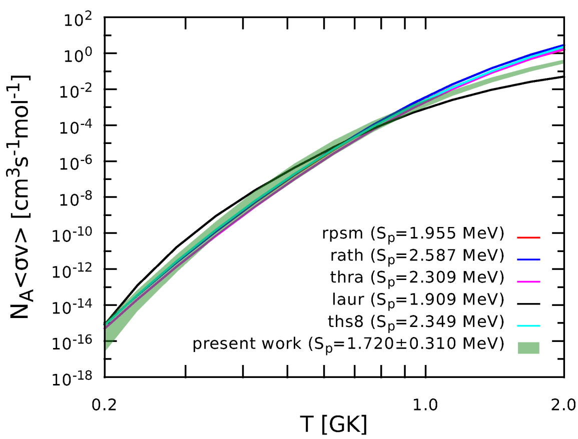

Figure 2. ^{65}As(p,γ)^{66}Se reaction rates. See details in the text.

The uncertainty in the *Present* ^{64}Ge(p,γ) rate arises from the uncertainty in S_p(^{65}As) along with an uncertainty of +/-100 keV for every ^{65}As energy level calculated with the shell model. The uncertainty in the *Present* ^{65}As(p,γ) rate arises simply from the large uncertainty of +/-310 keV in S_p(^{66}Se).

2.3 The comparison of *rp*-reaction rates

In the following discussion, we use the nomenclature mentioned in JINA REACLIB database: the *laur* rate – the rate estimated by Van Wormer [13]; the *rath* rate – the rate calculated by Raucher and Thielemann [30]; the *rath, thra, rpsm* rates – the statistical-model calculations with FRDM, ETSFIQ, and estimated masses from Audi and Wapstra [33], respectively; and the *ths8* rate – the recent theoretical rate from Rauscher [15].

The comparison of the *Present* ^{64}Ge(p,γ)^{65}As rate with others compiled in JINA REACLIB – *rpsm*, *rath*, *thra*, *laur*, and *ths8*, is shown in Fig. 1. Significantly, the *Present* rate deviates from others in the temperature range of interest in XRBs. Although the S_p value adopted in *rpsm* is almost within 1σ error of the value that we used for the *Present* rate based on the recent measurement [7], the *rpsm* is not close to our *Present* rate. This deviation manifests the weakness of statistical-model in describing reaction that has low-density of excited states, particularly ^{65}As.

A similar comparison of the *Present* ^{65}As(p,γ)^{66}Se rate with other rates from JINA REACLIB is presented in Fig. 2. The S_p values adopted in *rath*, *thra*, and *ths8* are beyond 1σ error of the data compiled in AME2012, except those adopted in *laur* and *rpsm*. In the temperature regime beyond 1 GK, the *Present* rate deviates significantly from others, whereas *laur* is the lowest rate because only were three excited states taken into account [13].

3 Astrophysical implication

We used the one-zone K04 model [5, 10] to check the astrophysical impact of our *Present* ^{64}Ge(p,γ) and ^{65}As(p,γ) rates, especially the final abundances (as mass fractions X) and the nuclear energy generation rate, E_{gen}, during an XRB. In this proceeding, we compare the final abundances and E_{gen} produced from *Present* rates to results obtained from rates available in JINA REACLIB: *laur, rath, rpsm, thra, ths8*, c.f. Figs. 3(c) and 4(c) of Ref. [29], respectively.

Fluxes of reactions are rather similar before the ^{64}Ge waiting point, but tremendous increments happen on net fluxes toward higher masses for rates of JINA REACLIB. The model using both *Present* ^{64}Ge(p,γ) and ^{65}As(p,γ) rates predicts a very remarkable lowest final abundances at the highest masses, c.f. Fig. 3(c) of Ref. [29]. Comparing to predictions using rates from JINA REACLIB, the differences are as large as a factor of ≈ 7 at individual values of mass A. Consequently, the estimated E_{gen} using both *Present* rates is among the lowest at late times, c.f. Fig. 4(c) of Ref. [29].

Furthermore, the model predicted a large depletions of $A = 64$ using other rates, except using the *Present* or the *ths8* rates. The underlying reason is because using the *Present* rates predicts $A = 64$ to be the largest mass fraction of all XRB nucleosynthesis products. José *et al.* also predicted an almost similar outcome using 1-D hydrodynamic XRB models, and the largest predicted mass fractions are $A = 60$ and 64 [11].

4 Summary and perspectives

We have obtained new thermonuclear rates for the ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se reactions based on large-scale shell model calculations and proton separation energies, S_p(^{65}As) and S_p(^{66}Se) derived from a recent mass measurement of the ^{65}As [7] and AME2012 [12]. The ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se rates are lower than other rates up to a factor of ≈ 6 and differs by up to a factor of ≈ 3 from other rates presented in the literature, respectively.

Secondly, we have used an one-zone type-I X-ray burst model to check the impact of the *Present* rates and to compare the end-stage abundances and E_{gen} with results from different available rates. Our new rates strongly quench the production of nuclide toward $A \approx 100$, which reverses the recent claim that ^{64}Ge is not a significant *rp*-process waiting point in Ref. [7], but agrees with the previous predictions [3, 4, 9–11].

In the following improvement of the new rates, we will fold the uncertainty of S_p values with the root-mean-square deviation value of the employed shell-model Hamiltonian and will also check with other possibly dominant uncertainties which may alter the upper and lower limits of the *Present* rates. Moreover, we will also examine the new rates with more type-I X-ray burst models.

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