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New reaction rates of ^{64}Ge$(p,\gamma)^{65}$As$(p,\gamma)^{66}$Se and the impact on type-I X-ray bursts

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The nucleosynthesis occurring in type-I X-ray bursts (XRBs) and the respective energy released in these thermonuclear explosions are sensitive to nuclear masses and reaction rates around the ^{64}Ge waiting point. Based on the recently measured masses of ^{64}Ge and ^{65}As, the deduced proton separation energies $S_p(^{65}\mathrm{As})$ and $S_p(^{66}\mathrm{Se})$, and nuclear structure information from large-scale shell model calculations, we have obtained new reaction rates of ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se with reliable uncertainties. Our new thermonuclear reaction rate of ^{64}Ge$(p,\gamma)^{65}$As differs from those available in REACLIB by up to two orders of magnitude at temperature range associated with type-I X-ray bursts. We evaluated the impact of these new rates, particularly the energy generation and the burst light curve, with self-consistent one-zone model [Schatz *et al.* Phys. Rev. Lett. 86 (2001) 3471]. Also, we identified the nuclear physics uncertainties determining the role of the ^{64}Ge to be a waiting point in XRBs, and strongly affecting XRB model predictions of the synthesis of ^{64}Zn and the synthesis of nuclei $A \geq 64$.

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1. Introduction

Since the discovery of type-I X-ray bursts (XRBs) independently by Grindlay *et al.* and Belian *et al.* in 1975 [1, 2], more than 100 sources of XRB had been observed, see a list of known Galactic XRB sources presented by in 't Zand [3]. A type-I XRB arises from an unstable ignition of the accreted envelope of the neutron star in a low-mass X-ray binary system (LMXB) [4, 5, 6, 7, 8]). Different XRB sources may have light curves of peak luminosities in the range of $10^4 \lesssim L_{\text{peak}}/L_{\odot} \lesssim 10^5$ and recurrence times may be in the range from one to several hours [8], and even up to 1.5 year for superbursts [9]. In the onset of an XRB, models predict that a mixture of accreted H/He-rich envelope may be ignited in temperatures reaching the thermal instability, and nuclei more heavier than iron group are produced through αp-processes and a series of successive rapid-proton capture (rp)-processes and β decays [5, 10, 11, 12, 13, 14, 15]. The first two processes involve α-particle-induced and proton-capture reactions on stable and radioactive nuclei, respectively. When the rp-process path reaches the proton dripline, the following proton captures by exotic nuclei are blocked by a strong reverse . Then, at that so-called "waiting points", for example, ^{60}Zn, ^{64}Ge, and ^{68}Se, the competition between the respective proton capture and the β-decay of a waiting point governs the flow of materials and determines the abundances of following heavier nuclei [5], and may eventually affect the end light curve of the burst. During the thermonuclear runaway of that XRB, peak temperatures may be close to or exceed 1 GK, causing nucleosynthesis of nuclei up to $A \approx 100$ nuclei [15, 16]. A few decisive factors like accretion rate, the composition of accreted materials, the neutron star radius and surface gravity, nuclear masses and reaction rates are the essential input data for XRB models. Up to now, only can the last two factors be directly measured, provided that advancement of experimental technique must be available; whereas the rests can only be conjectured from observations or model predictions. In order to pin down the vast uncertainties of XRB models, one of the crucial steps is to decrease the error bars of reaction rates related to significant waiting points.

In recent reviews of XRB models [5, 6, 17, 18, 19], including post-processing model [18], one-zone model [15, 17], and multizone 1D hydrodynamic model [20], the reactions of ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se are identified to have a critical impact on nucleosynthesis during XRBs. The last two models are fully self-consistent that consider the mutual influence of changes between nuclear energy generation and astrophysical condition [20]. However, there is no direct measurement of these two reactions at the respective energy range in XRBs. Secondly, the mass of ^{66}Se is not measured. Also, the scarce information of nuclear states within $\approx$ 1–2 MeV thresholds of the ^{64}Ge+p and the ^{65}As+p in ^{65}As and ^{66}Se, respectively, prevent us from estimating rates for these reactions solely based on experimental data. Hence, previous XRB models could only use ^{64}Ge$(p,\gamma)^{65}$As and ^{65}As$(p,\gamma)^{66}$Se thermonuclear rates calculated from statistical model. Some post-processing models varied the ^{65}As$(p,\gamma)^{66}$Se rate by a factor of ten at the relevant temperatures affecting the abundances of nuclei between $A \approx 65$–100 by factors as large as about 5 [21]. Furthermore, Schatz [22] found that for a given temperature and proton density, $S_p(^{65}\text{As})$, $S_p(^{66}\text{Se})$, and ^{65}As(p,γ), dictate the effective lifetime of ^{64}Ge.

In this contribution, we used the recently measured $S_p(^{65}\text{As}) = -90 \pm 85$ keV [23, 24] and newly extrapolated $S_p(^{66}\text{Se}) = 1720 \pm 310$ keV from Atomic Mass Evaluation 2012 (AME2012) [25] together with nuclear structure information estimated from large-scale shell-model calculations to deduce a new set of thermonuclear reaction rates of ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se with identified uncertainties [26]. We compared our reaction rates with rates available in the JINA REACLIB database [27], i.e. *laur* [28], *ths8* [27], *rath* [29], *thra*, and *rpsm* rates. The last three rates are deduced from the statistical Hauser-Feshbach formalism (NON-SMOKER [30]) using masses estimated from the finite-range droplet model (FRDM) [31], ETSFIQ model [32], and AME1995 [33], respectively.

Using these new reaction rates of ^{64}Ge(p,γ)^{65}As(p,γ)^{66}Se with known nuclear physics uncertainties that affect the rp-process through ^{64}Ge, we rechecked the question of ^{64}Ge as the important waiting point, which was predicted by various XRB models in Refs. [5, 6, 17, 18, 19], though Tu *et al.* [24] showed that the waiting point may be weak and less important.

2. Reaction rates of ^{64}Ge(p,γ)^{65}As and ^{65}As(p,γ)^{66}Se

The total thermonuclear proton capture reaction rate,

$$N_A\langle\sigma v\rangle = \sum_i (N_A\langle\sigma v\rangle^i_{\mathrm{DC}} + N_A\langle\sigma v\rangle^i_{\mathrm{R}})\frac{(2J_i+1)e^{-E_i/kT}}{\sum_n (2J_n+1)e^{-E_n/kT}}\,, \tag{2.1}$$

is a sum of direct-capture (DC) and resonant- (R) on ground state and thermally excited states in the target nucleus. Each capture with given initial and final states is weighted with individual population factor [34, 35].

We found that even estimated upper limits have been taken into account, the total DC rates of ^{64}Ge(p,γ)^{65}As and of ^{65}As(p,γ)^{66}Se are only about 0.3% and 0.1% of the resonant rates at 0.06 GK and 0.05 GK, respectively. Therefore, the contributions from the direct-capture rates can be neglected from the total rates of both reactions. Within the range of a Gamow energy window, the resonant reaction rate for capture on a nucleus in an initial state i, $N_A\langle\sigma v\rangle^i_{\mathrm{R}}$, is a sum over all relevant compound nucleus states j above the proton threshold [35, 36, 37],

$$N_A\langle\sigma v\rangle^i_{\mathrm{R}} = \ 1.54\times 10^{11}(\mu T_9)^{-3/2}\times\sum_j \omega\gamma_{ij}\mathrm{exp}\left(-\frac{11.605E_{ij}}{T_9}\right)[\mathrm{cm^3s^{-1}mol^{-1}}], \tag{2.2}$$

where the resonance energy in the center-of-mass system, $E_{ij}[\mathrm{MeV}] = E_j - S_p - E_i$, is a composition of excitation energies of the initial E_i and compound nucleus E_j state; whereas the resonance energy of the ground-state capture is $E^i_{\mathrm{R}}[\mathrm{MeV}] = E^j_x - S_p$. The temperature, T_9, is defined in Giga Kelvin (GK) and the reduced mass, μ, of the entrance channel in atomic mass units is defined as ($\mu = A_T/(1+A_T)$, with A_T the target mass number). The resonance strength $\omega\gamma$ [MeV] is defined by

$$\omega\gamma_{ij} = \frac{2J_j+1}{2(2J_i+1)}\frac{\Gamma^{ij}_p\times\Gamma^j_\gamma}{\Gamma^j_{\mathrm{total}}}. \tag{2.3}$$

where J_i is the target spin and J_j, Γ^{ij}_p, Γ^j_γ, and $\Gamma^j_{\mathrm{total}}$ are spin, proton-decay width, γ-decay width, and total width of the compound nucleus state j, respectively. We assumed other decay channels are closed [25] in the excitation energy range considered in this work, hence the total width is only given by $\Gamma^j_{\text{total}} = \Gamma^j_\gamma + \sum_i \Gamma^{ij}_p$. The proton width is,

$$\Gamma_p = \sum_{nlj} C^2 S(nlj)\,\Gamma_{sp}(nlj)\,, \tag{2.4}$$

where $C^2S(nlj)$ denotes a proton-transfer spectroscopic factor, while Γ_{sp} is a single-proton width for capture of a proton on an (nlj) quantum orbital. The Γ_{sp} are obtained from proton scattering cross sections calculated with a Woods-Saxon potential [38, 39], or can be deduced by using Coulomb penetrability method [28, 40],

$$\Gamma_p = \frac{3\hbar^2}{\mu R^2} P_\ell(E) C^2 S\,, \tag{2.5}$$

where R is the nuclear channel radius, and P_ℓ is the Coulomb penetration factor. We found that the proton widths given by these two methods (i.e., by Eqs. 2.4 and 2.5) agree well with each other, and the maximum difference is only about 35%. Such difference does not change our conclusion in this contribution.

In fact, there are not many available experimental level schemes for ^{65}As [41] and ^{66}Se [41, 42], we had supplemented those missing but important experimental data with theoretical ones, e.g. energy levels, spectroscopic factors, and gamma widths using large-scale shell model calculations, without truncation, with the aid from the shell-model code NuShellX@MSU [43]. The effective interaction GXPF1a [44, 45] had been used for obtaining those theoretical data of these pf-shell nuclei. We obtained the γ widths, Γ_γ, in Eq.(2.3) only based on transitions of $M1$ and $E2$ types, of which we used a set of empirical g-factors, i.e. $g^s_p = 5.586$, $g^s_n = -3.826$ and $g^l_p = 1$, $g^l_n = 0$ to get the $B(M1)$ values, and the empirical effective charges, i.e. $e_p = 1.5e$, $e_n = 0.5e$ to deduce $B(E2)$ values [44]. The new reaction rates of ^{64}Ge$(p,\gamma)^{65}$As$(p,\gamma)^{66}$Se are depicted in Figs. 1 and 2. Those considered resonances of these reactions within their respective Gamow energies can be found in Ref. [26]. We compared other reaction rates from JINA REACLIB [27] in both plots. Both grey bands in these Figs. 1 and 2 show the upper and lower limits deduced from known experimental and theoretical uncertainties. The uncertainties of both reaction rates are basically due to the uncertainties in both masses of ^{65}As and ^{66}Se. Besides, uncertainties in the resonance energies of ^{65}As$(p,\gamma)^{66}$Se also contribute to the rate of ^{65}As(p,γ). The present ^{64}Ge(p,γ) rate (red line in Fig.1) deviating from others is basically due to the newly defined $S_p(^{65}$As) and the low

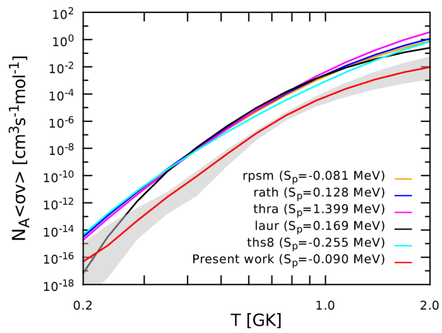

Figure 1: ^{64}Ge$(p,\gamma)^{65}$As reaction rates.

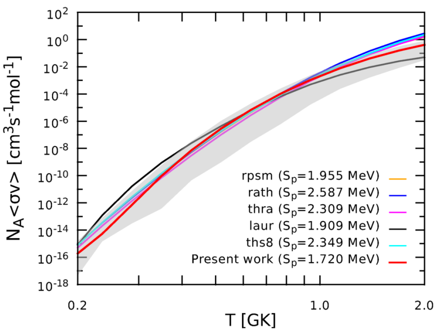

Figure 2: ^{65}As$(p,\gamma)^{66}$Se reaction rates.

compound nucleus level densities of ^{64}Ge(p,γ). Although the S_p(^{66}Se) we used for deducing the present ^{65}As(p,γ) rate is the lowest one, the present ^{65}As(p,γ) rate (red line in Fig.2) is not the lowest rate due to the high density of compound nucleus level. Furthermore, the statistical model calculations for these two rates may overestimate the densities of the compound nucleus level, especially for ^{64}Ge(p,γ).

3. Astrophysical implication

We used the self-consistent one-zone model [15] to check the impact of the presently deduced ^{64}Ge(p,γ) and ^{65}As(p,γ) rates. The model, which is different from K04 [13], defines very hydrogen rich ignitions at high accretion rates and very low accreted metallicity in order to get a maximum extent burst throughout the rp-process path towards elements far heavier than iron group. This model helped us to identify the influences of uncertainties on the end light curves. Two extreme calculations taking the upper (lower) limits of the ^{64}Ge(p,γ) and ^{65}As(p,γ) reaction rates, and of $S_{\rm p}$(^{65}As) and $S_{\rm p}$(^{66}Se), were performed to investigate the affected abundances of isotopes after rp-process passing through the ^{64}Ge waiting point, see Figs. 3 and 4 for the impact of the nuclear physics uncertainties on burst light curve and final composition. The blip at ∼140 s of the upper limit curve in Fig. 3 is due to the change of using opacity table to using analytical approximation.

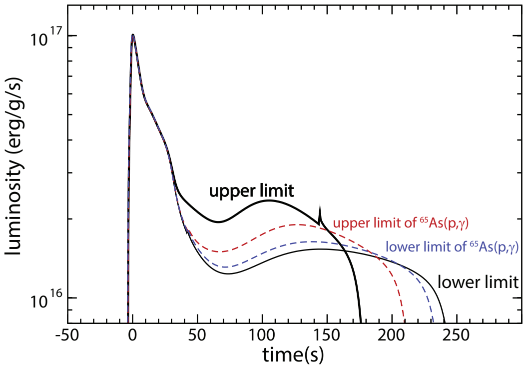

Figure 3: End light curves produced from various sets of upper and lower limits.

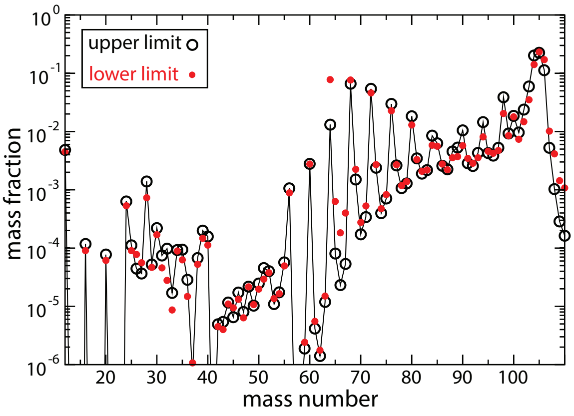

Figure 4: Final mass composition.

The abundance ratio of $A = 64$ to $A = 68$ can be used as a measure to evaluate whether the ^{64}Ge is a significant waiting point. We found that the ratio is in the range of 1.1 to 0.2 when taking into account all nuclear physics uncertainties. Such range indicates that with the lower limit setting, a strong ^{64}Ge waiting point with maximum ratio of 1.1 cannot be ruled out as the flow of material almost accumulated at $A = 64$, and vice versa. Nevertheless, the minimum ratio of 0.2 signifies that ^{64}Ge is a weak waiting point, which is consistent with Tu *et al.* [24].

Furthermore, if we separately used the upper or lower limit of each $S_{\rm p}$(^{65}As) and/or $S_{\rm p}$(^{65}As), which is due to the uncertainty of the respective masses, these settings produce almost similar light curves. However, if we varied the ^{65}As(p,γ) reaction rate with maximum and minimum of uncertainties, and fixed $S_{\mathrm{p}}(^{65}\mathrm{As})$ and $S_{\mathrm{p}}(^{66}\mathrm{Se})$ at existing values, a significant changes of light curve are resulted, and the ratio of $A = 64$ to $A = 68$ becomes in the range of 1 to 0.7. The red (blue)-dashed line in Fig. 3 depicts the light curve of upper (lower) limit of ^{65}As(p,γ) reaction rate while fixing the ^{64}Ge(p,γ) rate, $S_{\mathrm{p}}(^{65}\mathrm{As})$, and $S_{\mathrm{p}}(^{66}\mathrm{Se})$. This illustrates that the uncertainties of resonance energies of the ^{65}As(p,γ) reaction rate have roles in determining whether ^{64}Ge is a strong waiting point.

In conclusion, we had deduced new reaction rates of ^{64}Ge$(p,\gamma)^{65}$As$(p,\gamma)^{66}$Se with identified uncertainties based on recently measured mass of ^{65}As, extrapolated mass of ^{66}Se, and large-scale shell model calculations. Both new rates are different from commonly used rates in the JINA REACLIB [27]. We found that the remaining uncertainties in $S_{\mathrm{p}}(^{65}\mathrm{As})$, $S_{\mathrm{p}}(^{66}\mathrm{Se})$, and the ^{65}As$(p,\gamma)$ reaction rate play decisive role in determining the possibility of ^{64}Ge as a significant waiting point in the rp-process path. Also, these rates determine the productions of nuclei $A > 64$ and $A = 64$ material in the burst ashes which will eventually decay to ^{64}Zn, and the end light curve. We propose future experiments to focus on more precise measurements of the ^{65}As and ^{66}Se masses, and level scheme of ^{66}Se, which determines the ^{65}As$(p,\gamma)^{66}$Se reaction rate.

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