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Examination of Astrophysical S-Factor and Non-Resonant Rates of the ^{64}Ge(p,γ)^{65}As Reaction

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Abstract

The ^{64}Ge(p,γ)^{65}As reaction rates strongly impact the predictions of the energy generation and isotopic abundance in the *rp*-process in X-ray bursts. However, the rates are ambiguous at present due to the lack of experimental cross section and the uncertainty in the non-resonant reaction rates. To provide informative data for the astrophysical rates of the ^{64}Ge(p,γ)^{65}As reaction, we evaluate the astrophysical S factor and direct capture rates of the ^{64}Ge(p,γ)^{65}As reaction using the cross sections relied on the statistical theory with various mass models. The S factors at 0 energy were found to be $S(0) = 7.2\times10^5$ and 1.1×10^6 MeV.barn for the Finite-Range Droplet Model (FRDM) and the extended Thomas-Fermi (ETFSI) mass models, respectively. These values are about 4 orders of magnitude different from the value obtained in previous study. The empirical parameters for the non-resonant-rate approximations were also deduced for the ^{64}Ge(p,γ)^{65}As reaction and its photodisintegration. By considering the results in this study together with those obtained in the previous work, we confirm that a strong waiting point at the ^{64}Ge nucleus is still a doubt because of large uncertainty of the S factor and non-resonant rates. The results in this study are useful for a better understanding of the X-ray burst properties and reaction flow at ^{64}Ge in the rp-process.

Keywords: Light curves, Proton capture, rp-process, Waiting point, X-ray burst

Introduction

X-ray bursts (XRB) strongly occur under hot condition on the accreting surfaces of massive stars, i.e. neutron star, via *rp*-process (rapid proton capture) consisting of (α,p) reactions, proton captures (p,γ), and β^+ decays [1-3]. Beyond iron group elements, the reaction flows are thought to proceed through the waiting points of ^{64}Ge, ^{68}Se, ^{72}Kr and ^{76}Sr up to the SnSbTe cycles [4,5], as can be seen in **Figure 1**.

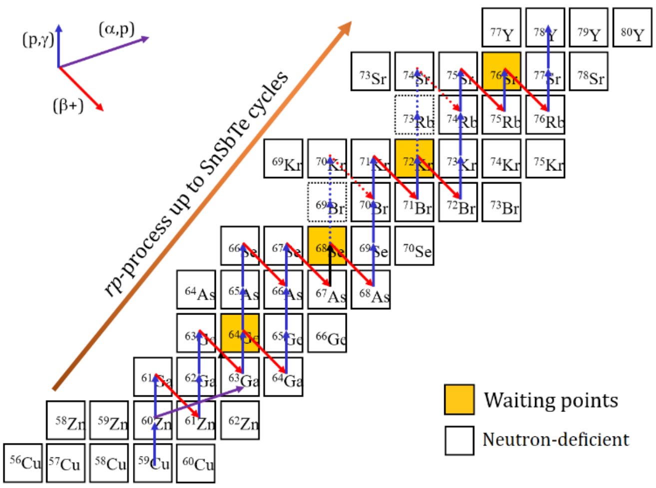

Figure 1 (Color online) Reaction flows proceed through the ^{64}Ge, ^{68}Se, ^{72}Kr, and ^{76}Sr waiting points in the *rp*-process.

It was found that the proton captures of these isotopes, especially for the ^{64}Ge(p,γ)^{65}As reaction, strongly affect the released energy related to XRB light curves [6-8]. For instance, few factors of difference were observed in the energy generation rates and luminosity during the XRBs in 5 - 100 s due to the astrophysical-rate uncertainty of the ^{64}Ge(p,γ)^{65}As reaction [9]. The nucleosynthesis also shift towards the island of stability if the β^+ decay and the photodisintegration ^{65}As(γ,p)^{64}Ge are dominant over the proton capture ^{64}Ge(p,γ)^{65}As. In such scenario, a branching via ^{64}Ge(β^+)^{64}Ga, which can be followed by the beta decay ^{64}Ga(β^+)^{64}Zn or the ^{64}Ga(p,γ)^{65}Ge reaction, at ^{64}Ge may occur to change the reaction flows. Subsequently, the proton capture rates impact on the predictions of not only the luminosity of X-ray burst but also mass fraction of isotopes in the *rp*-process. Since the half life of ^{64}Ge (63.5 s) is compatible with the timescale of the bursts (10 - 100 s), its proton-capture rates are crucial for analysis of the interval in the XRB luminosity [10]. Besides, the mass fraction of isotopes related to the ^{64}Ge(p,γ)^{65}As reaction, such as ^{65,66}As, ^{64}Ga, ^{65}Ge, etc. are varied by the variations in the (p,γ) - (γ,p) equilibrium at ^{64}Ge because the mass fractions depend on the ratios of photodisintegrations to proton captures [11]. For example, the abundance ratio of the A = 64 isotopes to A = 68 nuclei was found to be varied by 1 order of magnitude due to astrophysical rate uncertainty, which are about 2 orders of magnitude, of the ^{64}Ge(p,γ)^{65}As reaction [9].

Although the astrophysical rates of the ^{64}Ge(p,γ)^{65}As reaction are very important for the understanding of properties of X-ray bursts and modification of theoretical models, they still have large uncertainty due to both lack of experimental data and reliable calculations. The uncertainties of the rates can be identified by some reasons, such as exciation energies of the compound nucleus, nuclear mass uncertainty of isotopes in the reactions, astrophysical S factor for non-resonant rates, and so on. Because the exciation energies above the proton emission threshold (S_p = 90 keV with nuclear mass in Ref. [12]) are unknown for the ^{65}As nucleus, the methods for calculations of the non-resonant rates (or direct capture rates) are still questions. In principle, there are 2 approaches for the calculations of the non-resonant rates, which are based on the statistical model [13-15] and transitions of individual states. The 1st approach is considered if the compound nucleus has continuum states, while the second one is referred to the dispersive levels. Both of the non-resonant rate calculations can be proceeded in terms of the astrophysical S factor [11,16,17]. Therefore, the S factor, especially at 0 energy, plays a key role in estimation of the non-resonant rates. Similarly to the reaction rates, the S factor is still very uncertain and its results strongly depend on calculation approaches. To reduce the uncertainty of non-resonant rates, evaluations of the astrophysical S factor are highly demanded.

Notice that the S factor of the ^{64}Ge(p,γ)^{65}As reaction was determined based on the Wood-Saxon nuclear potential and Coulomb potential of uniform-charge distribution method [18] by Lam *et al.* [9] with assumption of the individual excited states in the ^{65}As nucleus. This assumption has not been confirmed by experiments or other realiable calculations yet. However, the compound nucleus may have continuum states, specially for the energy range just 1.0 MeV above the proton threshold (90 keV) because the rates of the concerned reaction in the high energy (or temperature) range (i.e. T_9 > 2.0 GK) were found to match to the statistical model calculations [9]. Therefore, in this study we calculate the S factor by using the statistical model, instead of the method proposed by Bertulani [18] which was employed in the previous study. In this calculation the effects of the mass models on the S factor (and nonresonant rates) are also considered. Later we estimate the non-resonant rates of the ^{64}Ge(p,γ)^{65}As reaction using the calculated S factor in low temperature range of T_9 = 0.1 - 3 GK. Subsequently, the difference between the non-resonant rates deduced by statistital model in this study and those obtained in the previous work [9] is evaluated. The evaluation approaches and results are described in the next sections.

Materials and methods

Theoretical framework

The astrophysical S factor, S(E), is defined in terms of the reaction cross section, σ(E), and sommerfeld factor, η, as [17].

$$S(E) = E\sigma(E)\exp(2\pi\eta) \qquad \text{(MeV.barn)}, \tag{1}$$

where the sommerfeld factor can be expressed in terms of the Coulomb factor, Z_1Z_2, as

$$2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2} \tag{2}$$

with Z_1, Z_2, E (in keV), and μ (in amu) being the atomic numbers of projectile and target, energy in center-of-mass frame, and reduced mass of the projectile-target system of the concenred reaction, respectively.

The astrophysical S factor can be approximated by the Taylor transformation, which is a polynomial function in terms of energy E, as [17].

$$\begin{aligned} S(E) &= S(0) + \dot{S}(0)E + \frac{1}{2!}\ddot{S}(0)E^2 + ... \\ &= s_0 + s_1 E + s_2 E^2 + ... \end{aligned} \quad \text{(MeV.barn)}, \tag{3}$$

where s_0 = S(0) is the S factor at 0 energy and s_i (i = 1, 2, 3,…) denote the coefficients in the Taylor transformation, which are deduced by chi-square fitting the values of the S factor, which are determined by using the cross section as described in Eq. (1), with a polynomial function. Notice that the S factor at 0 energy, S(0), is extremely important for calculating the non-resonant rates. In this study, the direct capture cross sections of the (p,γ) reaction calculated based on the statistical model by using NON-SMOKER code [13,19].

For the non-resonant reaction rate, if the energy levels are totally identified (low density), the rate is determined based on the S factor as [16,17].

$$N_A \langle \sigma v \rangle_{nr} = 7.83 \times 10^9 \left(\frac{Z_1 Z_2}{\mu T_9^2} \right)^{1/3} \times S(E) \times \exp\left(-4.2487 \left(\frac{\mu Z_1^2 Z_2^2}{T_9} \right)^{1/3} \right), \tag{4}$$

with T_9 in the unit of GK. In this case, the S(E) factor is also estimated by [16,17,20]

$$S(E) = S(0)\left(1 + \frac{5}{12\tau}\right) \quad \text{(MeV.barn)}, \tag{5}$$

with τ being the dimensionless parameter, which is calculated by

$$\tau = -4.2487 \left(\frac{\mu Z_1^2 Z_2^2}{T_9} \right)^{1/3}. \tag{6}$$

For convenience in numerical calculation, the rates can be approximated as [11, 13, 16]

$$N_A \langle \sigma v \rangle_{nr} = \exp\left(a_0 + a_1 T_9^{-1} + a_2 T_9^{-1/3} + a_3 T_9^{1/3} + a_4 T_9 + a_5 T_9^{5/3} + a_6 \ln T_9 \right), \tag{7}$$

where a_i (i = 0, 1, 2, …6) are the fitting parameters, which are determined in this study. Notice that the photodisintegration, (γ,p) reaction, rates can also be estimated by using this parameterization with a set of b_i parameters, which are deduced by using the a_i values as [13].

$$\begin{cases} b_0 = a_0, \quad b_1 = a_1 - 11.6045Q, \quad b_2 = a_2, \\ b_3 = a_3, \quad b_4 = a_4, \quad b_5 = a_5, \quad b_6 = a_6 + 1.5 \end{cases} \tag{8}$$

with Q being the Q-value of the (p,γ) reaction. The Q-value is deduced by the nuclear mass of the ^{64}Ge and ^{65}As isotopes, which can be obtained from Ref. [12]

Methods

To determine the S factor and non-resonant rates of the ^{64}Ge(p,γ)^{65}As reaction, we calculated the reaction cross sections σ(E) in a wide range of energy, up to 5 MeV, which are suitable for the statistical model. The cross sections were estimated using 2 mass models (Finite-Range Droplet Mass (FRDM) [21,22] and Thomas-Fermi (ETFSI) [23,24]) to examine the uncertainty in theoretical predictions due to the difference in the nuclear mass of the isotopes in the reaction. In the next step, the S factor determined using Eq. (1) were fitted to Eq. (3) to deduce the S factor at 0 energy, S(0). Subsequently, the non-resonant rates of the reaction were estimated using the deduced S(0) and relation in Eq. (4). For convenient calculations of the proton capture ^{64}Ge(p,γ)^{65}As and its reverse reactions, the determined non-resonant rates were fitted to Eq. (7) to obtain the reaction-rate parameters in Eq. (8). Finally, the results based on the 2 models were compared to each other and to those obtained in a previous study [9].

Results and discussion

The cross sections of the ^{64}Ge(p,γ)^{65}As reaction in the energy range of $E_{cm.}$ = 0.1 - 5 MeV corresponding to the Gamov window [17] range of T_9 = 0.1 - 5 GK were calculated based on the statistical model because of the lack of excited states of ^{65}As in the energy range of interest. Additionally, the statistical model is consistent with measured data for many reactions in other previous studies (e.g., Ref. [25]). The results with the Finite-Range Droplet Mass (FRDM) [21,22] and Thomas-Fermi (ETFSI) [23,24] mass models are shown in **Figure 2**. Notice that the mentioned energy (or temperature) range was considered because it is relevant to the condition of XRBs. It was found that the cross section is rapidly (slightly) increased by reaction energies in the range of $E_{cm.}$ < 1.5 MeV ($E_{cm.}$ > 1.5 MeV). The cross sections are less than 1 μb for $E_{cm.}$ < 1.5 MeV and about 1 - 100 μb for $E_{cm.}$ > 1.5 MeV. These results indicate that the proton capture of ^{64}Ge(p,γ)^{65}As more easily occur under hot condition, T_9 > 1.0 GK, rather than in low temperature environment of XRBs.

On the other hand, the cross sections based on the 2 models are comparable to each other at an energy of about 1.0 MeV while the results based on the ETFSI model are about 1 order of magnitude higher than those relied on the FRDM method in the energy range of $E_{cm.}$ > 1.5 MeV. This discrepancy is understood by the difference of the mass predicted by FRDM and ETFSI models. This mass difference results in the pairing and shell corrections [13-15] and subsequently impacts on the estimated level density in the statistical model calculations for the cross sections.

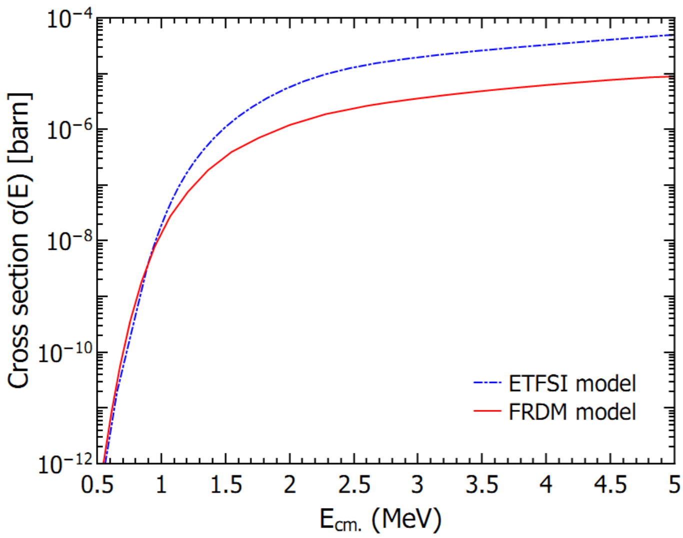

Figure 2 (Color online) Cross sections of the ^{64}Ge(p,γ)^{65}As reaction are calculated based on statistical model with different mass models, FRDM (solid curve) and ETFSI (dashed-dotted curve) using the NON-SMOKER code.

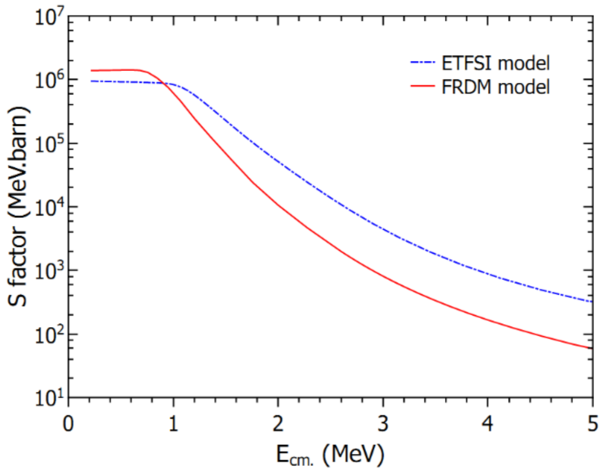

Figure 3 (Color online) Calculated astrophysical S factor of the ^{64}Ge(p,γ)^{65}As reaction based on the cross sections which are deduced by using different mass models, FRDM (solid curve) and ETFSI (dashed-dotted curve).

The astrophysical S factor were determined by using Eq. (1) in which the cross sections, *σ(E)*, were calculated with the statistical model by using NON-SMOKER code [13,19]. The results show that the S factors are decreased by increasing reaction energies, as can be seen in **Figure 3**. This phenomenon can be understood by the exponential dependence of the S factor on the square-root of energy, $E^{-1/2}$. The uncertainty of the estimated S factors was found to be a few factors in the range of $E_{cm.} > 1.5$ MeV. This deviation can be explained by the cross-section uncertainty due to the difference in the FRDM and ETFSI mass models. Notice that the deviation in the astrophysical S-factors observed in the present study is in a good agreement with the general uncertainty in theoretical calculations, as can be found in Refs. [25,26]. The results obviously reflect that the mass uncertainty impacts on the prediction of the cross section and, subsequently, on the astrophysical S factors.

Since the astrophysical S factor can be transformed into the Taylor series in a form of the polynomial function, in which the S factor at 0 energy, S(0), is assigned to the 1st parameter, as described in Eq. (3). Therefore, a polynomial fitting with low energies was performed to determine the value of S(0) factor. The best fitting results are shown in **Figure 4**. The values of S(0) were found to be 7.2×10^5 and 1.1×10^6 MeV.barn for the cases of the FRDM and ETFSI models, respectively. Notice that this factor was predicted to be 3.5×10^1 MeV.barn by Lam *et al.* [9]. This discrepancy can be understood by the difference of the approaches for the cross-section calculations. The average transmission coefficients are considered in the statistical model [13-15], which was utilized in the present study, whilst individual transitions were taken into the Bertulani approach [18] used in the previous work [9].

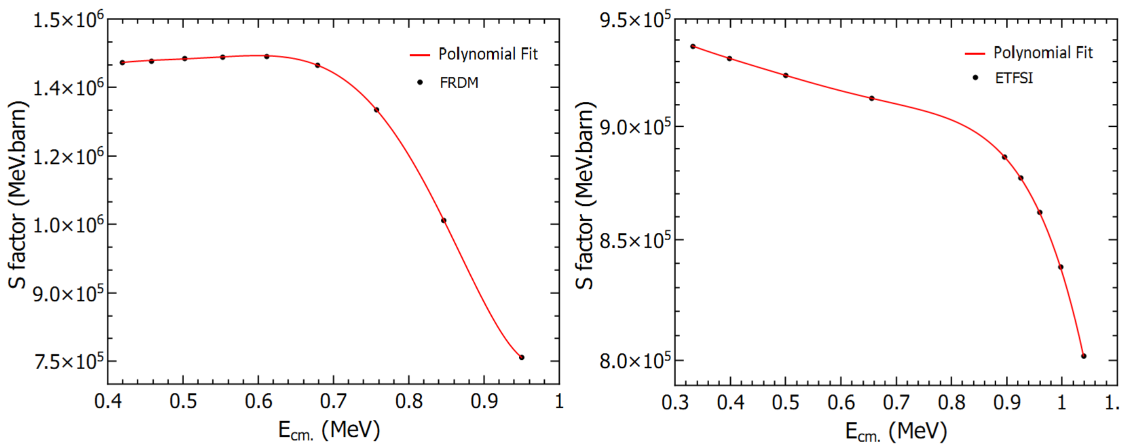

Figure 4 (Color online) Polynomial fitting curves for extrapolating S factor at 0 energy, S(0), based on cross sections which are deduced by using FRDM (left panel) and ETFSI (right panel) mass models.

Taking the calculated values of S(0) in the present study and those obtained from Ref. [9], the non-resonant rates of the proton capture were determined by using Eqs. (4) and (5). Notice that the energies were converted into temperatures, T_9, by using the definition of the Gamov peak [17]. As shown in Fig. 5, the direct capture rates are dominant over the β^+ decay, whose rate is about 10^{-2} (s^{-1}), under condition of $T_9 > 1.0$ GK and vice versa for $T_9 < 1.0$ GK. At the typical XRB temperature of $T_9 = 1.0$ GK, the β^+ decay is compatibale with the captures. In other words, the proton capture can proceed faster than the β^+ decay in the hot evironment of XRBs if its photodisintegration rates are underestimated. On the other hand, a factor of about 1.5 was found for the non-resonant rate uncertainty due to the difference of S(0). Hence, the difference between the estimated values of S(0) based on the FRDM and ETFSI mass models can be negligible in the considered temperature (or energy) range. Still in **Figure 5**, we found that the rates calculated based on the value S(0) = 35 MeV.barn, which was deduced by Lam *et al.* [9] in the previous study, are about 4 orders of magnitude underestimated in comparison to the statistical model results in the present work. The lower rates can be explained by the propagation of the smaller S factor at 0 energy. The results indicate that there is a large discrepancy between the S(0) factors (and non-resonant rates) which were deduced by the statistical model and Bertulani approach. To reduce this uncertainty, measurements and/or realiable calculations for excited states of the ^{65}As nucleus and/or its mirror (^{65}Ge) are strongly suggested.

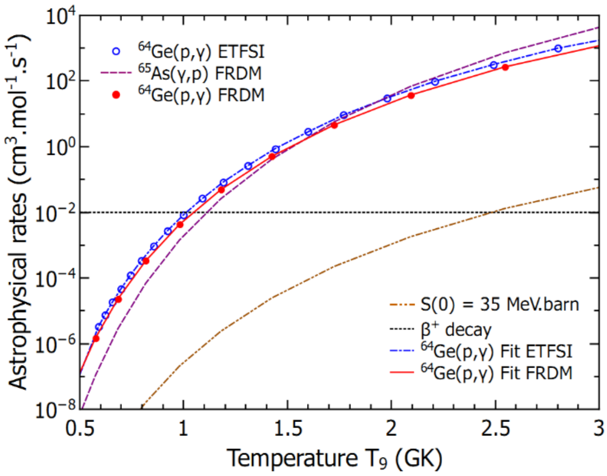

Figure 5 (Color online) Astrophysical rates of the ^{64}Ge(p,γ)^{65}As reaction, which are estimated based on the S factor. The red solid and blue dashed-dotted curves are the results of chi-square fitting for the a_i parameters in Eq. (7), which are compared to the rates (orange dashed-dotted-dotted curve) calculated using S(0) deduced by Lam *et al.* [9]. The dashed line is the β^+-decay rate of the ^{64}Ge nucleus. The dashed curve presents the photodisintegration rates.

Table 1 Fitting parameters for non-resonant rates, which were approximated by Eq. (7), of the ^{64}Ge(p,γ)^{65}As reaction and its photodisintegration in the temperature range of T_9 = 0.5 - 3 GK.

Parameters	**FRDM**	**ETFSI**
S(0) (MeV.barn)	$7.2\times10^5 \pm 5.5\times10^4$	$1.1\times10^6 \pm 7.2\times10^4$
$a_0 = b_0$	41.991 ± 1.085	38.268 ± 0.172
a_1	1.997 ± 0.474	0.189 ± 0.085
$a_2 = b_2$	–85.287 ± 10.124	–46.609 ± 1.837
$a_3 = b_3$	37.666 ± 8.936	3.513 ± 1.650
$a_4 = b_4$	–1.628 ± 0.386	–0.152 ± 0.073
$a_5 = b_5$	0.085 ± 0.020	0.008 ± 0.004
a_6	–23.975 ± 5.528	–2.848 ± 1.012
b_1	0.952 ± 0.474	–0.855 ± 0.085
b_6	–22.475 ± 5.528	–1.348 ± 0.172

By using the rates calculated based on the astrophysical S factor, the parameters a_i for the approximation in Eq. (7) were determined by chi-square fitting. The results related to the 2 mass models are presented in **Table 1**. The best fits are shown in **Figure 5**. These results show that the model in Eq. (7) is convenient to be employed for the astrophysical rates. With the present parameters, the non-resonant rates of the ^{64}Ge(p,γ)^{65}As reaction in XRB environments is easily to be estimated.

The parameters b_i for the photodisintegration rates were also determined by using the a_i parameter set. The results are presented in **Table 1**. To evaluate the competition between the proton capture and its photodisintegration at the waiting point ^{64}Ge, the photodisintegration rates were calculated based on the b_i parameters, which were deduced from the a_i values by using Eq. (8). Notice that only the capture rates based on the FRDM mass model were considered because this model is widely used for charge-particle induced reactions [27]. The Q-value of the ^{64}Ge(p,γ)^{65}As reaction was computed to be Q = 0.09 MeV. **Figure 5** shows the competition of the direct capture, photodisintegration, and β^+-decay rates. The direct capture is observed to be dominant over the photodisintegration under condition of T_9 < 1.5 GK, and vice versa for T_9 > 1.5 GK. Obviously, the photodisintegration becomes the impedance of the proton capture at high temperature. As a result, the nucleosynthesis awaits the β^+ decay of the ^{64}Ge waiting-point. Subsequently, a branching can appear at ^{64}Ge via ^{64}Ge(β^+)^{64}Ga path and the reaction flow shift towards the island of stability. Since the photodisintegration prevents the reaction flow to proceed via (p,γ) reaction, the enrichment of ^{64}Ge and reduction of ^{65}As at T_9 > 1.5 GK can occur in the timescale of the ^{64}Ge lifetime. Because the photodisintegration and beta decay cannot compete with the proton capture at the typical temperature T_9 = 1.0 - 1.5 GK of XRBs, the nucleosynthesis strongly proceed via the (p,γ) reaction under such condition. Therefore, the waiting-point feature of the ^{64}Ge is weakly exhibited in this temperature range. The aforementioned results are varied by the non-resonant rates deduced by the calculation of the S factor based on the Bertulani approach, which was estimated to be 35 MeV.barn. It can be seen that the proton capture cannot compete with the β^+ decay in the temperature range of T_9 < 2.5 GK. Therefore, the ^{64}Ge nucleus becomes a strong waiting point in this case. Together with the total rates (resonant + non-resonant rates) obtained by Lam *et al.* [9], the non-resonant rates in this study gives a conclusion that a strong waiting point of ^{64}Ge cannot be confirmed at present.

Conclusions

In this study, the direct capture cross sections of the ^{64}Ge(p,γ)^{65}As reaction were calculated based on the statistical approach by using the NON-SMOKER code with the FRDM and ETFSI mass models. The discrepancy between these cross sections was found to be about 1 order of magnitude, which subsequently results in the uncertainty of the astrophysical S factor. The astrophysical S factors at 0 energy, S(0), were also determined for the non-resonant rates of the reaction. The results show that the S(0) values originated from the 2 mass models are just slightly different from each other. Subsequently, the variations in non-resonant rates due to the mass-model dependence of the S(0) factor can be negligible. On other hand, the fitting parameters were deduced for the temperature-dependent function of the rates. By using these parameters, the rates can be easily approximated for evaluating the (p,γ)-(γ,p) competition. Moreover, we also found that there is a large difference, about 4 orders of magnitude, between the values of S(0) which were determined by using the statistical model and Bertulani approach. This difference leads to a large uncertainty of the ^{64}Ge(p,γ)^{65}As reaction rates. Subsequently, a strong waiting point at ^{64}Ge is still questionable. Therefore, the results in this study recommend that more measurements and reliable calculations for this reaction are still necessary. The results in this work are useful for further studies on the luminosity of the X-ray burst light curves and the rp-process isotopic abundance. It should be noted that the cross-section calculation in the present study is limited by the theoretical level density. Hence, excited states of ^{65}As are strongly suggested to be measured to improve the accuracy of the ^{64}Ge(p,γ)^{65}As reaction rates.

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