Advancement of Photospheric Radius Expansion and Clocked Type-I X-Ray Burst Models with the New $^{22}Mg(\alpha,p)^{25}Al$ Reaction Rate Determined at the Gamow Energy

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We report the first (in)elastic scattering measurement of $^{25}Al + p$ with the capability to select and measure in a broad energy range the proton resonances in ^{26}Si contributing to the $^{22}Mg(\alpha,p)$ reaction at type I x-ray burst energies. We measured spin-parities of four resonances above the α threshold of ^{26}Si that are found to strongly impact the $^{22}Mg(\alpha,p)$ rate. The new rate advances a state-of-the-art model to remarkably reproduce light curves of the GS 1826–24 clocked burster with mean deviation $< 9\%$ and permits us to discover a strong correlation between the He abundance in the accreting envelope of the photospheric radius expansion burster and the dominance of $^{22}Mg(\alpha,p)$ branch.

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Thermonuclear x-ray bursts (XRBs) are the most frequently recorded outbursts that happen in the Galaxy [1–3]. To date, 115 XRB sources have been discovered [4]. More than 62 of the 115 sources are categorized as photospheric radius expansion (PRE) bursters [4] of which their bursting mechanism is still an unresolved puzzle due to their intricate hydrodynamics, e.g., the accretion-powered millisecond pulsar SAX J1808.4–3658 [5,6], which ignited the brightest XRB in recent history [7]. Its first multizone model was recently established [8,9] and is subject to verification; conversely, it offers a first concurrent sensitivity study on reaction rates for the light curves, fluences, and recurrence times, especially the competition between important reactions at a branching point during the onset of an XRB. The GS 1826–24 clocked burster [10–12] is the most investigated due to its nearly consistent accretion rate and light-curve shape. Its XRB serves as a laboratory to probe the rp-process path [13,14], compactness [15], and equation of state of the accreting neutron star [16,17]. Thus, the best model describing the GS 1826–24 light curves is highly desired within the community. The first quantitative comparison of its modeled and observed light curves could only be achieved 19 yr after its discovery [18]; however, up to now, the modeled burst tail does not exactly conform with observation; a similar problem also occurs in other multizone models [15,19,20]. It is crucial to verify whether the incapability of the model is due to astrophysical configurations or some influential nuclear reaction rates.

Two recent sensitivity studies performed by Cyburt *et al.* [21] and by Jacobs *et al.* [22] using GS 1826–24 models [18] reveal that the ^{22}Mg(α, p) rate is the most decisive αp-process reaction in sd-shell nuclei influencing burst light curves, see the Supplemental Material (SM) [23]. The ^{22}Mg(α, p) rate proposed by the compilation reaction library REACLIB v2.2 [37], however, is generated using the Hauser-Feshbach (HF) model [38] assuming a rather high level density of ^{26}Si. This assumption may be invalid and inapplicable considering the selectivity of the (α, p) reaction for natural parity states; moreover, the rate from a high resolution ^{28}Si$(p, t)^{26}$Si measurement [39] was deduced without the experimental information of important resonances within the Gamow window, resulting in a rate up to 6 orders of magnitude lower than the HF-model ^{22}Mg(α, p) rate. Recently, the first direct measurement of the ^{22}Mg(α, p) reaction was performed by Randhawa *et al.* [15]. The evaluated ^{22}Mg(α, p) rate is, however, based on a rather low ^{22}Mg beam intensity of ~900 pps which did not permit a direct measurement of the ^{22}Mg(α, p) reaction in the Gamow window of XRBs. Only protons with a limited range (90°–120°) were analyzed and the PACE4 code [40] had to be used to simulate the total cross section. Consequently, they only obtained cross sections corresponding to 2.6 GK. The reaction rates at XRB temperatures (0.7–1.0 GK) were then extrapolated relying on the TALYS code, without direct experimental information at the relevant temperature. Such an extrapolation could induce a large additional uncertainty that was not presented in Ref. [15]. Thus, confirming the ^{22}Mg(α, p) rate with precisely measured resonance properties within the Gamow window of low uncertainty is crucial to regulate better XRB models to unfold the physics of accreting neutron stars.

In this Letter, we report the first measurement of ^{25}Al + p (in)elastic scattering at x-ray burst energies to deduce the ^{22}Mg$(\alpha, p)^{25}$Al rate. This technique overcomes the difficulties in direct measurement due to the low-cross-section nature of ^{22}Mg(α, p) reaction in the Gamow window. We used the radioactive ion beam separator (CRIB) [41–43] of the University of Tokyo. A primary beam of ^{24}Mg^{8+} at 8.0 MeV/nucleon and 1 eμA bombarded a cryogenic D_2 target [44] to produce a secondary beam of ^{25}Al. The ^{25}Al beam was purified by CRIB using the in-flight method. The ^{25}Al beam, with an energy of 142 ± 1 MeV and an average intensity of 2.0×10^5 pps, was then delivered to the F3 experimental scattering chamber and bombarded a 150-μm-thick CH_2 target, similarly to Ref. [45].

The beam particles were identified event by event and the ^{25}Al beam purity was typically 70%. The impurity was mostly ^{24}Mg, clearly discriminated by the timing information.

The recoiling protons were measured using three sets of silicon detector telescopes at central angles of $\theta_{\mathrm{lab}} = 0°$, 20°, and 23°. Each telescope consisted of a 65-μm-thick and double-sided (16×16 strips) silicon detector and two 1500-μm-thick pad detectors. Protons were clearly identified from other light ions with the ΔE-E method. To identify the inelastic contribution, an array of ten NaI detectors was mounted immediately above the target to detect the γ rays from the decay of excited states of ^{25}Al. Each NaI detector was with a geometry of $50 \times 50 \times 100$ mm, with the array covering 20% of the total solid angle. These detectors had an average energy resolution of 13.5% in full width at half maximum (FWHM) for 662-keV γ rays. In addition, an 80-μm-thick carbon target was used in a separate run for subtracting the carbon background contribution.

The $E_{c.m.}$ resolution of the excitation function was 30–90 keV (FWHM), depending on the energy, for the Si telescope around $\theta_{\mathrm{lab}} = 0°$. The uncertainty was mostly from energy straggling of the particles in the thick target, along with the energy resolution of the silicon detectors. At larger angles, the angular resolution of the recoiling proton produced a larger energy uncertainty and the resulting energy resolution was 75–200 keV at $\theta_{\mathrm{lab}} \sim 20°$. In this Letter, we focus on the forward angle measurement, where we had the highest resolution to determine the resonance parameters.

The excitation function of ^{25}Al + p elastic scattering has been deduced using the standard procedure as described in Refs. [45–48]. The cross section of inelastic scattering, less than 12% of the elastic scattering, was deduced by analyzing gamma-coincident events as plotted in Fig. 1, and its contribution was subtracted from the total excitation function. The excitation function around $\theta_{\mathrm{lab}} = 0°$ is shown in Fig. 1. Several resonances are clearly evident in the spectrum. To determine the parameters of observed resonances, R-matrix calculations have been performed using AZURE2 [49] with a channel radius of $R = 1.4 \times (1 + 25^{1/3})$ fm for the ^{25}Al + p system.

The ground-state spin-parity configurations of ^{25}Al and the proton are $5/2^+$ and $1/2^+$, respectively. Thirteen resonances have been analyzed, and the best fit curve is shown in Fig. 1. The resonance properties are listed in Table I. The lowest five states are in good agreement with the previous ^{25}Al + p resonant scattering measurements [50,51], except the weak 7.379-MeV resonance, where our Γ_{p0} is larger than theirs and the 4^+ assignment by Jung *et al.* [51] cannot reproduce the present data well. The resonances at 8.211 and 8.666 MeV may correspond to the

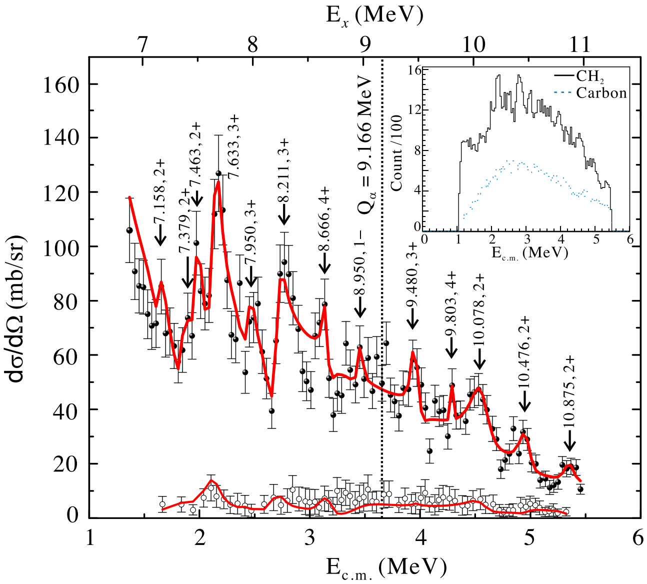

FIG. 1. Excitation function of $^{25}Al + p$ elastic scattering at $\theta_{lab} = 0-8°$. Elastic scattering data (filled circles); inelastic scattering data (open circles); the best R-matrix fit (red curve); the α threshold (dotted line); Inset: the CH_2 spectrum with the normalized carbon background.

ones observed in Ref. [52], and a spin-parity of 1^- was assigned to the 8.211-MeV resonance based on the mirror assignment. Our analysis shows the assignment as 1^- strongly disagrees with our data, however, whereas 3^+ best matches our data. Bohne *et al.* [53] also discovered the 8.666-MeV state via a $^{24}Mg(^3He, n)^{26}Si$ measurement and a tentative J^π assignment (1^- or 2^+) was made based on a distorted wave Born approximation (DWBA) calculation. Our fitting result disagrees with theirs, but supports the 4^+ assignment made by Matic *et al.* [52]. Although higher resonances had been observed by previous studies [39,54,55], no J^π was determined. We observed these resonances in the present work, and assigned their tentative J^π with our best R-matrix fit ($\chi^2/\mathrm{DOF} = 1.08$ for 103 DOF). Our presently assigned J^π generally agree with known states of ^{26}Si. Taking into account all possible assignments for the 9.480-, 9.803-, and 10.078-MeV states, the total $^{22}Mg(\alpha, p)$ rate changes up to a factor of 0.44 for temperature above 0.7 GK. The minimum χ^2 of the R-matrix fit supports the 10.476-MeV state to be assigned as 2^+. This state can also be produced via (p, t) reaction [39] which preferentially excites natural-parity states. The 10.875-MeV state can only be either 2^+, 3^+, or 4^+ due to the selection rule of Gamow-Teller transitions [55]. We assign a 2^+ to the 10.875-MeV state, which gives the minimum χ^2. However, the assignments of 3^+ and 4^+ only produce deviations in χ^2 within the standard deviation σ (0.50σ and 0.62σ, respectively), and thus we also consider its possibility as 3^+ or 4^+ in the analysis below as it determines the rate above 1 GK. Further information of the R-matrix analysis is detailed in the SM [23]. To constrain the level properties of the states contributing the reaction rate, we also performed a simultaneous fit for both elastic and inelastic scattering data. With the limited data quality, we obtained the upper limits of inelastic proton widths, $\Gamma_{p1,\max}$ (Table II).

The ^{26}Si levels above the α threshold are expected to characterize the $^{22}Mg(\alpha, p)$ rates. As the widths are broad for the 10.078-, 10.476-, and 10.875-MeV states, we applied the broad-resonance approximation, in which the reaction rates can be obtained from [56],

$$N_A\langle\sigma v\rangle = \sqrt{2\pi}\frac{N_A\hbar^2}{(\mu kT)^{3/2}}\sum_i \omega_i \int_0^\infty e^{-E/kT} \times \frac{\Gamma_\alpha(E)\Gamma_p(E+Q)}{(E-E_R^i)^2+\Gamma(E)^2/4} dE[\mathrm{cm^3\,s^{-1}\,mol^{-1}}]. \quad (1)$$

TABLE I. The presently determined energy levels of ^{26}Si compared with literature.

	^{26}Si present work			^{26}Si from other works			
No.	E_x (MeV)[a]	J^π	Γ_{p0}[b] (keV)	E_x (MeV)	J^π	Γ_{p0} (keV)	References
1.	7.158(13)	2^+	6(3)	7.162(14)/7.147(27)	2^+	7(4)/2.7(1)	[50]/[51]
2.	7.379(18)	2^+	28(14)	7.402(40)/7.401(28)	$2^+/4^+$	6(4)/1.1(1)	[50]/[51]
3.	7.463(18)	2^+	51(9)	7.484(13)/7.484(28)	2^+	46(11)/15.9(3)	[50]/[51]
4.	7.633(20)	3^+	46(8)	7.704(13)/7.654(29)	$3^+/(2^+,3^+)$	41(6)/(30.1(5), 19.5(3))	[50]/[51]
5.	7.950(22)	3^+	10(5)	8015(14)/7.977(30)	$3^+/(2^+,3^+)$	15(5)/(4.5(3), 3.6(2))	[50]/[51]
6.	8.211(24)	3^+	48(10)	8.222(5)	1^-		[52]
7.	8.666(25)	4^+	8(5)	8.700(30)/8.687(12)	$(1^-,2^+)/(4^+)$		[52]/[53]
8.	8.950(30)	1^-	16(5)	8.952(7)			[54]
9.	9.480(30)	3^+	15(4)	9.433(4)			[55]
10.	9.803(32)	4^+	2(1)	9.802(7)			[54]
11.	10.078(36)[c]	2^+	164(30)	10.070(8)			[54]
12.	10.476(40)	2^+	54(22)	10.436(10)			[39]
13.	10.875(45)	2^+	57(21)	10.827(8)			[55]

[a]Statistical errors due to the R-matrix fit folded with systematic uncertainty of 12–35 keV is given in parentheses.
[b]Elastic scattering proton widths.
[c]An 1^+ assignment is not excluded, but not preferred from the inelastic data and its influence on the final reaction rate is negligible.

TABLE II. Resonance parameters for the ^{22}Mg(α, p) rates.

E_x (MeV)	J^π	Γ_α (eV)	Γ_{p0} (keV)	$\Gamma_{p1,\max}$ (keV)
9.803(32)	4^+	9.69×10^{-13}	2(1)	5.9×10^{-3}
10.078(36)	2^+	1.13×10^{-6}	164(30)	22.6
10.476(40)	2^+	1.80×10^{-3}	54(22)	9.9
10.875(45)	2^+	1.70×10^{-1}	57(21)	1.0

Here, μ is the reduced mass of the target and projectile, T is the temperature, E_R is the energy of the resonance, and the statistical factor $\omega = 2J_i + 1$. The energy dependence of the widths was taken into account by letting the partial widths Γ_α and Γ_p vary as, $\Gamma_x^i(E) = \Gamma_x^i(E_R^i)[P_\ell(E)/P_\ell(E_R^i)]$ where the P_ℓ are the Coulomb penetrabilities for the α and p channels, respectively. The partial width $\Gamma_p(E_R)$ is from our R-matrix fit, and $\Gamma_\alpha(E_R)$ can be inferred from the mirror nucleus ^{26}Mg via the isospin symmetry relation, $\Gamma_\alpha^i = C^2 S_\alpha \Gamma_\alpha^{i,\mathrm{SP}}$, where the $C^2 S_\alpha$ is the α-spectroscopic factor and $\Gamma_\alpha^{\mathrm{SP}}$ is the single-particle α width. We adopted the average $C^2 S_\alpha$ values from Ref. [39]; $C^2 S_\alpha(4^+) = 0.015$ and $C^2 S_\alpha(2^+) = 0.037$, with uncertainties of a factor of 2, as in [57]. Table II shows the adopted resonance parameters in obtaining the ^{22}Mg(α, p) rates, which are shown together with the rates from the HF model (hereinafter NON-SMOKER) [38] and Matic *et al.* [39] in Fig. 2. The resonance $J^\pi(10.875\ \mathrm{MeV}) = 3^+$ does not contribute to the ^{22}Mg(α, p) rate whereas the contribution from assuming it as 4^+ is much lower than assuming it as 2^+. Both possible ^{22}Mg(α, p) rates assuming $J^\pi(10.875\ \mathrm{MeV}) = 3^+$ or 4^+ are similar and the difference in reaction rate is only up to a factor of 0.27. Note that in the critical temperature range for XRB ignition, the NON-SMOKER ^{22}Mg(α, p) rate differs from ours by a factor of ~10 from ~0.4 to ~1 GK, and varies up to a factor of ~160 at 3 GK. Because of the missing resonance data of ^{26}Si above 10 MeV excitation energy in Matic *et al.* [39], there is a discrepancy of about 1 to 5 orders of magnitude between our new rate and the Matic *et al.* rate for $T = 0.7 - 3$ GK (Fig. 2). The ^{22}Mg(α, p) rate by Randhawa *et al.* [15] approximated with the NON-SMOKER ^{22}Mg(α, p) rate divided by 8, is also shown in Fig. 2. Although their evaluated rate does not largely deviate from our present rate at around 1 GK and below, we caution that their evaluation may underestimate the uncertainty due to the theoretical extrapolation without considering each resonance explicitly. Our ^{22}Mg(α, p) rate has a significantly lower uncertainty than theirs (Fig. 2) even if such possible underestimation is ignored, see SM [23] for the further error estimation. Our final rate is merely enhanced by at most 10% when considering the additional $\Gamma_{p1,\max}$.

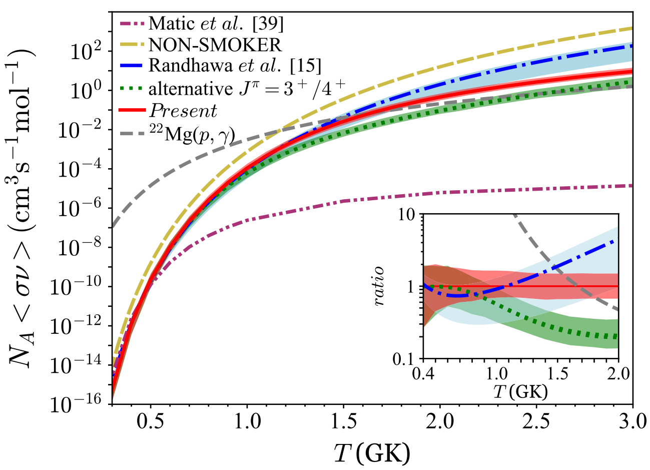

FIG. 2. The ^{22}Mg(α, p) rates. The uncertainty of the present rate (red zone) is estimated via Monte Carlo calculation [58] considering all errors from the present experimental measurement. Both possible rates with $J^\pi(10.875\ \mathrm{MeV}) = 3^+$ or 4^+ are not distinguishable, plotted as a green line and labeled as "alternative $J^\pi = 3^+/4^+$." Randhawa *et al.* [15] rate uncertainty is the blue zone. Inset: the ratios of Randhawa *et al.*, or alternative $J^\pi = 3^+/4^+$ or ^{22}Mg(α, p) [37,59] rate to the present ^{22}Mg(α, p) rate.

GS 1826–24 *clocked burster.*—To quantitatively compare with the GS 1826–24 burster (Fig. 3), we adopt the best fit model from Jacobs *et al.* [22], which has a ratio of accreted ^{1}H to ^{4}He of 2.39, a Carbon-Nitrogen-Oxygen (CNO) metal mass fraction of 0.0075, and an accretion rate of $3.325 \times 10^{-9}\ M_\odot \mathrm{yr}^{-1}$, as our *baseline* model. We update it with the present ^{22}Mg(α, p) rate to represent the *Present* model. The generated burst luminosity, L_x, by the 1D multizone hydrodynamic KEPLER code [18,60] is related to observational flux, F_x by scaling with $[4\pi d^2 \xi_b (1+z)^2]^{-1}$ [61], where d is the distance, ξ_b incorporates the possible burst-emission anisotropy, and the redshift, z, expands the light curve when transforming into an observer's frame. Instead of specifically selecting data close to the burst peak at $t = -10$ to 40 s [15,20], we

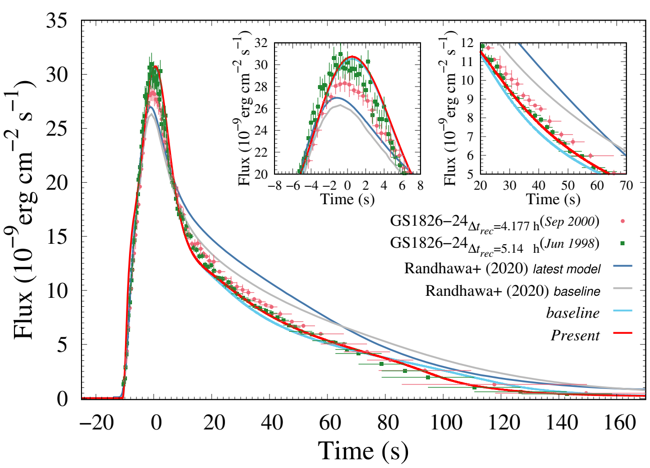

FIG. 3. The best fit *baseline* and *Present* modeled light curves to the observed light curve of epoch *Jun 1998*, and the best fit Randhawa *et al.* [15] light curves to epoch *Sep 2000*. The magnified light curves at the burst peak and $t = 20 - 70$ s are shown in the left and right insets, respectively.

impartially select all observational data of the entire burst time span to fit our modeled bursts. The modeled bursts are averaged and fitted to the averaged light curve of GS 1826–24 epoch *Jun 1998* [62], which were recorded by the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array [4,63,64].

The *baseline* light curve at $t = 16 - 76$ s is enhanced and the discrepancy with observed data becomes only up to 6% due to the present and lower ^{22}Mg(α, p) rate, which at low temperature competes with ^{22}Mg$(\beta\nu)$ decay and overcomes ^{22}Mg(p, γ) at higher temperature $T > 1.67^{+0.15}_{-0.13}$ GK, while the branching temperature is lowered at $T = 1.16$ GK for the NON-SMOKER rate (Fig. 2). The alternative $J^{\pi} = 3^{+}/4^{+}$ rate yields only 3% deviation from the observed data at $t = 16 - 76$ s, which is not discernible in Fig. 3. The matter flow is more siphoned out to ^{22}Mg$(p, \gamma)^{23}$Al$(p, \gamma)^{24}$Si(α, p), enriching more proton-rich nuclei nearer to dripline past the *sd* shell. These nuclei burn hydrogen after the burst peak and enhance the light curve at $t = 16 - 76$ s, depleting hydrogen that is to be burnt by further (p, γ) reactions at later time $t = 80 - 150$ s. Hence, the observed light curve profile at $t = 80 - 150$ s is noticeably reproduced. Therefore, the present work experimentally validates the predicted light curve trend in Ref. [21] and enhances a state-of-the-art model to remarkably reproduce the GS 1826–24 light curve with mean deviation $< 9\%$, as discussed in SM [23]. In the latest model by Randhawa *et al.* [15] (the blue line in Fig. 3), a similar trend is manifested at $t = 8 - 64$ s, however, it deviates their baseline model farther away from observation and affects their fitted redshift distance.

SAX J1808.4–3658 *PRE burster.*—The initial good-fit SAX J1808.4–3658 PRE models constructed by Johnston *et al.* [8] and studied by Goodwin *et al.* [9] are based on the KEPLER code using the NON-SMOKER ^{22}Mg(α, p) rate but these models can still provide us a unique and sensitive study for competition between the ^{22}Mg(α, p) and ^{22}Mg(p, γ) reactions because the temperature of competition between both reactions, T_C (the intersection of ^{22}Mg(α, p) and ^{22}Mg(p, γ) [37,59] rates in inset of Fig. 2), is within the range of accreting-envelope maximum temperature, $1.1 \leqslant T_{\max}/\mathrm{GK} \leqslant 1.6$, during a typical PRE burst, and the He and H abundances are almost equal in the accreting envelope of the SAX J1808.4–3658 PRE burster [8,9]. The present ^{22}Mg(α, p) rate, which has the lowest uncertainty among all available rates, precisely locates the $T_C = 1.67^{+0.15}_{-0.13}$ GK constricting the ^{22}Mg(α, p) branch. With our new rate, the previous model parameters do no longer well reproduce the observation (orange squares in Fig. 4). With only constraining the He abundance in the accreting envelope to be $X_{\mathrm{He}} = 56.7 \pm 0.3\%$, we successfully regulated the ^{22}Mg(α, p) and ^{22}Mg(p, γ) branches and improved the modeled fluences closer to observation (red dots in Fig. 4). The He-abundance constraint reveals a strong correlation with the dominance of the ^{22}Mg(α, p) branch and introduces a striking advancement for the pioneering PRE model. The approximated ^{22}Mg(α, p) rate [15] with large uncertainty, however, estimates a wide range of $T_C = 1.4 - 1.8$ GK; also the propagation of their rate uncertainty yields a less constrained range of He abundance $X_{\mathrm{He}} = 56.1 \pm 1.1\%$ causing large uncertainty in fluences and times (blue triangles in Fig. 4).

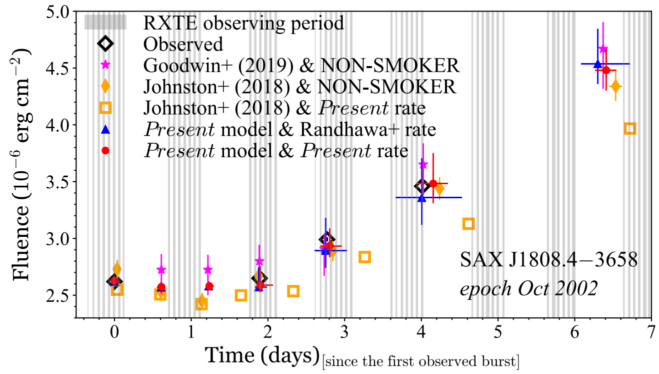

FIG. 4. The bursts' fluences (integration of flux over time) and times for SAX J1808.4–3658 burster, based on the RXTE observation [4], Johnston *et al.* [8] and Goodwin *et al.* [9] models, and present calculations. Johnston *et al.* [8] model is adopted to study the present and Randhawa *et al.* rates.

In summary, we have performed the first (in)elastic scattering measurement of ^{25}Al $+ p$ with the capability to select and measure proton resonances contributing to the ^{22}Mg$(\alpha, p)^{25}$Al reaction at XRB temperature. This provides the spectroscopic information of four resonances above the α threshold of ^{26}Si that strongly influence the ^{22}Mg$(\alpha, p)^{25}$Al reaction rate. We successfully deduced the ^{22}Mg$(\alpha, p)^{25}$Al rate via experiment without implementing a scaling factor on a Hauser-Feshbach statistical model rate as was done in Ref. [15]. The improved nuclear physics input permits us to better reproduce the observed GS 1826–24 light curves than the previous model (see SM [23]) and to further constrain the SAX J1808.4–3658 model.

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