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Experimentally well-constrained masses of ^{27}P and ^{27}S: Implications for studies of explosive binary systems

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A B S T R A C T

The mass of ^{27}P is expected to impact the X-ray burst (XRB) model predictions of burst light curves and the composition of the burst ashes, but large uncertainties and inconsistencies still exist in the reported ^{27}P masses. We have used the β-decay spectroscopy of ^{27}S to determine the most precise mass excess of

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^{27}P to date to be −659(9) keV, which is 63 keV (2.3σ) higher and a factor of 3 more precise than the value recommended in the 2016 Atomic Mass Evaluation. Based on the new ^{27}P mass, the ^{26}Si$(p,\gamma)^{27}$P reaction rate and its uncertainty were recalculated using Monte Carlo techniques. We also estimated the previously unknown mass excess of ^{27}S to be 17678(77) keV, based on the measured β-delayed two-proton energy and the Coulomb displacement energy relations. The impact of these well-constrained masses and reaction rates on the modeling of the explosive astrophysical scenarios has been investigated by post-processing XRB and hydrodynamic nova models. Compared to the model calculations based on the masses and rates from databases, the abundance of $A = 26$ in the burst ashes is increased by a factor of 2.4, while no substantial change was found in the XRB energy generation rate or the light curve. Our calculation also suggests that ^{27}S is not a significant waiting point in the rapid proton capture process, and the change of the ^{26}Si$(p,\gamma)^{27}$P reaction rate is not sufficiently large to affect the conclusion previously drawn on the nova contribution to the synthesis of galactic ^{26}Al.

1. Introduction

Type I X-ray bursts (XRB) and classical novae are the two most frequent types of thermonuclear stellar explosions in the Galaxy. They are powered by thermonuclear runaways occurring in the accreted envelopes of compact objects in stellar binary systems. In the case of XRBs, hydrogen- or helium-rich material is transferred from a low mass main sequence or red giant star onto the surface of a neutron star, while nova explosions occur in a similar system with a white dwarf in place of the neutron star. As they are driven by a suite of nuclear processes, accurate nuclear physics inputs such as β-decay rates, masses, and nuclear reaction rates of proton-rich isotopes are needed to model the energy production and nucleosynthesis in these explosions. Our understanding of these systems has greatly improved with time, but despite decades of work, many open questions remain [1–6].

A recent systematic investigation of the impact of nuclear mass uncertainties on XRB models found that the mass uncertainties of ^{27}P can strongly affect the model predictions of the burst light curve and the composition of the burst ashes in a typical mixed H/He burst [7]. This study was carried out based on the mass excess of $\Delta(^{27}\mathrm{P}) = -722(26)$ keV reported by the 2012 Atomic Mass Evaluation (AME2012) [8], and the latest AME2016 still adopted the same value [9]. Since then, a ^{27}S β-decay measurement using an optical time projection chamber [10] reported a mass excess of $\Delta(^{27}\mathrm{P}) = -640(30)$ keV, which was inconsistent with the AME value. A more recent $\Delta(^{27}\mathrm{P}) = -685(42)$ measured via isochronous mass spectrometry in the Cooler Storage Ring [11] was not sufficiently precise to resolve the existing discrepancies. Additionally, ^{27}S was considered to be a waiting-point nucleus in the thermonuclear reaction network, and its mass uncertainty could impact the nucleosynthesis in some XRB model calculations [12,13] based on the mass excess of $\Delta(^{27}\mathrm{S}) = 17540(200)$ keV in AME2003 [14]. Nevertheless, the ^{27}S mass is unknown experimentally and both AME2012 and AME2016 roughly estimated the mass to be $\Delta(^{27}\mathrm{S}) = 17030(400)$ keV [8,9]. Hence, experimental efforts should be made to better quantify the mass excesses of ^{27}P and ^{27}S.

Furthermore, the origin of large amounts of ^{26}Al in the interstellar medium of the galaxy has been a focus of interdisciplinary investigations in astronomy, astrophysics, and nuclear physics [15]. The nova nucleosynthesis of ^{26}Al is dominated by a reaction sequence of ^{24}Mg$(p,\gamma)^{25}$Al$(\beta^+)^{25}$Mg$(p,\gamma)^{26}$Al$(p,\gamma)^{27}$Si, but this sequence may be bypassed through ^{25}Al$(p,\gamma)^{26}$Si$(p,\gamma)^{27}$P [16,17]. Under a wide temperature range of 0.1-2 GK, the ^{26}Si$(p,\gamma)^{27}$P reaction rate was found to be dominated only by a single resonant proton capture on the ^{26}Si ground state to the $3/2^+$ first excited state in ^{27}P. According to previous nova nucleosynthesis calculations [18], the ^{26}Si$(p,\gamma)^{27}$P rate was not expected to play a critical role, but it should be noted that a complete experimental constraint on the thermonuclear ^{26}Si$(p,\gamma)^{27}$P rate had never been set. Estimates of those key resonance strengths have relied on limited experimental information on the structure of ^{27}P, supplemented by shell model calculations or the mirror nucleus information [19–29]. A reevaluation of the role of the ^{26}Si$(p,\gamma)^{27}$P reaction with more accurate ^{27}P mass and resonance properties may benefit the long-standing study of the galactic ^{26}Al origin.

Recently, we reported the highest-statistics β-decay spectroscopy of ^{27}S to date [30]. The charged particles and γ rays emitted in the β decay of ^{27}S were measured simultaneously for the first time, allowing us to determine an accurate ^{27}P mass excess and to place a constraint on the ^{27}S mass excess based on experimental results. In this Letter, we further investigate the astrophysical impact of the newly determined masses using the XRB and nova models.

2. Mass evaluation

The present data set and analysis procedures have been detailed in Ref. [30]. The main nuclear structure information relevant to the astrophysics topic is summarized in Fig. 1 and are briefly discussed here for completeness. The mass excess of the ^{27}P is determined to be −659(9) keV by combining the measured excitation energy of 1125(2) keV and the proton-decay energy of 318(8) keV of the first excited state in ^{27}P with the well-known mass excesses of ^{26}Si and ^{1}H from AME2016 [9]. The γ-ray energy of 1125(2) keV has been confirmed by a recent in-beam γ-ray spectroscopy [31], which reported two γ-ray energies of 1125(6) keV and 1119(8) keV. Previously, the AME2003 value of $\Delta(^{27}\mathrm{P}) = -717(26)$ keV [14] was the weighted average of $\Delta(^{27}\mathrm{P}) = -753(35)$ keV measured using the ^{32}S$(^{3}\mathrm{He},{}^{8}\mathrm{Li})^{27}$P reaction [32] and $\Delta(^{27}\mathrm{P}) = -670(41)$ keV measured using the ^{28}Si$(^{7}\mathrm{Li},{}^{8}\mathrm{He})^{27}$P reaction [19]. The AME2012 reevaluated the latter value to be $\Delta(^{27}\mathrm{P}) = -683(41)$ keV based on a new ^{8}He mass measured by Penning trap mass spectrometry [33] and updated the weighted average mass to be $\Delta(^{27}\mathrm{P}) = -722(26)$ keV [8]. This evaluation remained unchanged in the AME2016 [9]. As shown in Fig. 2, the mass excess of ^{27}P determined in our work represents the most precise ^{27}P mass measurement to date. Our value deviates from the AME2016 value by 63 keV (2.3σ) while improving the precision by a factor of 3. Since the release of AME2016, all three independent measurements [10,11,30] are in good agreement, indicating a need for the reevaluation of the ^{27}P mass in the next version of AME. Theoretical ^{27}P mass values show even large discrepancies than experimental values, such as, $\Delta(^{27}\mathrm{P}) = -716(7)$ keV calculated using the isobaric mass multiplet equation [7], $\Delta(^{27}\mathrm{P}) = -779(289)$ keV [34], −565(44) keV [35], −551(87) keV [35], and −731 keV [36] calculated using mirror nuclei relations. Hence, our result provides

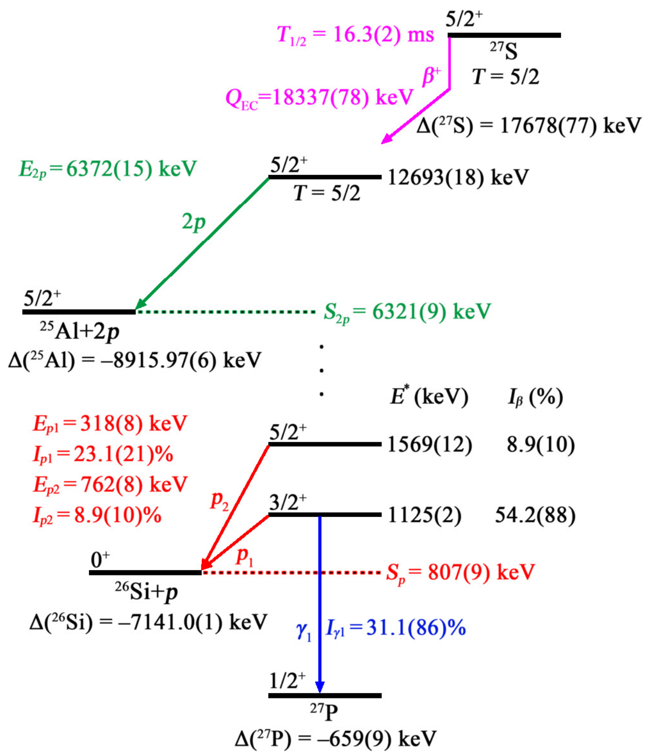

Fig. 1. Simplified decay scheme of ^{27}S. The drawing is not to scale. All the energies, mass excesses, and intensities labeled in the scheme are deduced from our work [30], except for the well-known mass excesses of ^{25}Al and ^{26}Si from AME2016 [9]. See text for details.

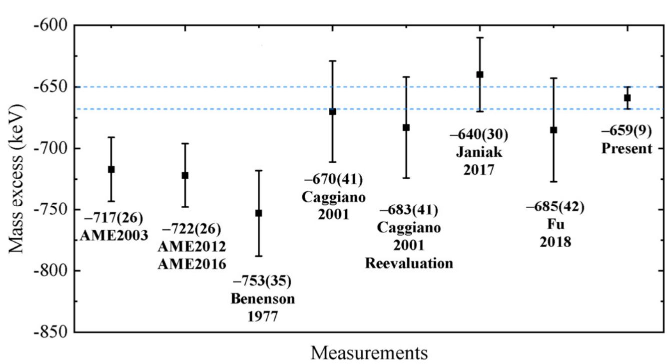

Fig. 2. Mass excesses of ^{27}P measured in our work compared with the recommended value from AME [14,8,9] and values previously measured by Beneson et al. [32], Caggiano et al. [19], Janiak et al. [10], and Fu et al. [11], with our uncertainty indicated by the dashed lines. All mass values have been rounded to the closest integer for simplicity.

an important benchmark against which local nuclear mass models can be tested and constrained, thereby improving the accuracy and predictive power of models.

The two-proton emission from the $T = 5/2$ isobaric analog state (IAS) in ^{27}P to the ^{25}Al ground state was identified in previous ^{27}S decay studies [37,38], whereas the two measured center-of-mass energies, $E_{2p} = 6410(45)$ keV [37] and $E_{2p} = 6270(50)$ keV [38], were mutually inconsistent by 2.1σ. This two-proton energy was measured to be 6372(15) keV in our work [30], which falls between these two previous results [37,38]. It is worth mentioning that we further investigate the relationship between the energy loss, position, and path length of the escaping particles in different silicon detectors to verify that this is indeed two-proton emission rather than one-proton emission at the same energy [39]. Combining the energy of two-proton emission $E_{2p} = 6372(15)$ keV with the well-known mass excesses of $\Delta(^{25}\text{Al}) = -8915.97(6)$ keV and $\Delta(^{1}\text{H}) = 7288.97061(9)$ keV from AME2016 [9], the mass excess of the $T = 5/2$ IAS in ^{27}P is determined to be 12034(15) keV using the relation $\Delta(^{27}\text{P IAS}) = \Delta(^{25}\text{Al}) + 2\Delta(^{1}\text{H}) + E_{2p}$. Combined with the aforementioned mass excess of the ^{27}P ground state, the excitation energy of the ^{27}P IAS is determined to be 12693(18) keV. The mass excess of ^{27}S is estimated to be $\Delta(^{27}\text{S}) = 17678(77)$ keV using the relation $\Delta(^{27}\text{S}) = \Delta(^{27}\text{P IAS}) + \Delta E_C - \Delta_{nH}$, where $\Delta_{nH} = 782.3465(5)$ keV [9] is the mass difference between the neutron and hydrogen atom. $\Delta E_C = 6426(76)$ keV is the Coulomb displacement energy calculated by using the semiempirical relation given by Ref. [40] with the corresponding isospin of $T = 5/2$, mean atomic number of $\overline{Z} = 15.5$, and mass number of $A = 27$ in this case. The present $\Delta(^{27}\text{S})$ is 648 keV (1.6σ) higher than the $\Delta(^{27}\text{S}) = 17030(400)$ keV estimated by AME2016 [9] and correspondingly reduces the $S_p(^{27}\text{S}) = 581(215)$ keV compared with the AME2016 value of $S_p(^{27}\text{S}) = 1230(450)$ keV [9].

3. Thermonuclear ^{26}Si$(p,\gamma)^{27}$P reaction rate

The Gamow window for the ^{26}Si$(p,\gamma)^{27}$P reaction is calculated from a numerical study of the relevant energy ranges for astrophysical reaction rates [41]. The second and third resonances ($5/2_1^+$ and $5/2_2^+$) enter the Gamow window at temperatures above 1.2 GK and 2.0 GK, respectively, and their contributions have proven to be negligible compared to the first resonance ($3/2_1^+$) at 318(8) keV [22,23,30]. At any given temperatures below 2.0 GK, the first resonance is always the closest one to Gamow peaks. Its proton partial width is calculated to be $\Gamma_p = 2.55(74)$ meV using the relation $\Gamma_\gamma = \Gamma_p \times I_\gamma / I_p$, with the γ-ray partial width $\Gamma_\gamma = 3.43(170)$ meV adopted in the compilation [42]. Here, the ratio of the γ-ray branch to the proton branch of $I_\gamma / I_p = 1.35(39)$ has been determined experimentally for the first time in our work [30]. Thus, a resonance strength of $\omega\gamma = 2.92(191)$ meV can be derived by taking into account the partial widths and the known spins of the resonance, proton, and the ground state of ^{26}Si. By combining these values with the existing parameters for the two trivial $5/2^+$ resonances and the direct-capture component evaluated by Iliadis et al. [42], the total rate is determined based on Monte Carlo techniques [43], where uncertainties are rigorously defined. This result agrees with the rate computed using a simple numerical integration [30].

Currently, the ^{26}Si$(p,\gamma)^{27}$P reaction rate evaluated by Iliadis et al. [42,44] is recommended in both REACLIB [45] and STARLIB [46] and universally adopted in various astrophysical model calculations. As shown in Fig. 3, the present rate is up to two orders of magnitude lower than the recommended rate in the temperature range $0.06 < T < 0.3$ GK (typical for nova nucleosynthesis). Our rate is higher than the recommended rate by up to a factor of 4 around 2.0 GK (typical for XRB nucleosynthesis). The deviation is due to the larger resonance energy and strength for the $3/2^+$ resonance derived from our experiment. It can be seen that the present rate has much smaller uncertainties than the recommended one almost over the entire temperature range, except that the present reaction rate follows the trend of the recommended one below 0.06 GK where the direct-capture uncertainty dominates.

4. Astrophysical implications for XRB model

We have investigated the impact of the present mass excesses of ^{27}P and ^{27}S and the ^{26}Si$(p,\gamma)^{27}$P reaction rate on the composition of XRB nucleosynthesis zone using the one-zone post-processing nucleosynthesis code, a branch of the NuGrid framework [47], together with a trajectory K04 from Ref. [48]. The

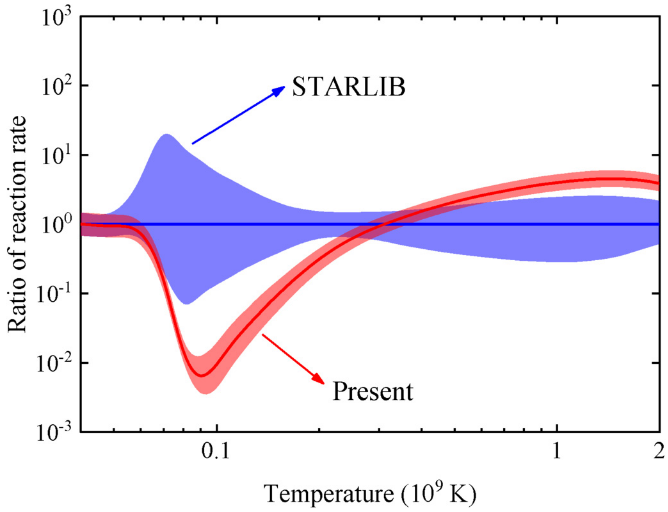

Fig. 3. Ratio of the ^{26}Si$(p,\gamma)^{27}$P reaction rate determined in the present work to that from STARLIB [44]. The relative uncertainties of these two rates are computed using the same Monte Carlo method and shown in shaded areas.

comparison to the calculation using the rates and masses from databases [9,44] are shown in Fig. 4. No visible change is found in the two nuclear energy generation rates during the burst, but the mass fractions of ^{26}Al and ^{26}Si, therefore the $A = 26$ abundance, are clearly increased. This change is mainly attributed to the reverse ^{27}P$(\gamma,p)^{26}$Si rate, which exponentially depends on the reaction Q-value. The higher mass excess of ^{27}P results in a significant increase in ^{27}P$(\gamma,p)^{26}$Si rate, which will impede the proton capture process and leaves more ^{26}Si and its corresponding β-decay daughter ^{26}Al. Due to the neutron star gravitational potential, most of the burst ashes remain on the neutron star surface and replace the crust of the neutron star, and thus, they will have an impact on the accreted crusts thermal and compositional structure [49]. A proper understanding of the ashes produced by XRBs is also important for the modeling of the crust evolution of accreting neutron stars [50].

Similarly, the higher ^{27}S mass value obtained in our work would also result in a much stronger reverse ^{27}S$(\gamma,p)^{26}$P rate which can effectively impact the final yield of ^{27}S. Our XRB model calculation shows that the final abundance ratio ^{27}S/^{26}P is 3.8 and 3500 using the ^{27}S mass value from AME2003 [14] and AME2012 (or 2016) [8,9], respectively, compared to the ^{27}S/^{26}P ratio of 0.4 using our ^{27}S mass value. Previously, ^{27}S was considered to be a waiting-point nucleus in the rapid proton capture process [12,13]. However, the present significant abundance change strongly implies that ^{27}S should not be regarded as a waiting-point nucleus.

5. Astrophysical implications for nova model

The impact of the aforementioned nuclear physics input on nova nucleosynthesis, and in particular on the synthesis of ^{26}Al, has been examined through a series of hydrodynamic simulations. To this end, a suite of evolutionary sequences of nova outbursts hosting ONe white dwarfs of 1.15, 1.25, and 1.35 $M_\odot$ have been computed with the spherically symmetric, Lagrangian, hydrodynamic code SHIVA, extensively used in the modeling of novae and XRBs (see Refs. [1,6] for details). Results have been compared with those obtained in three additional hydrodynamic simulations for the same white dwarf masses described above and the same physics inputs except for the ^{26}Si$(p,\gamma)^{27}$P reaction rate, which was taken from the evaluation [44]. As confirmed by these simulations, the dominant destruction channel for ^{26}Si in nova outbursts occurs via its β^+ decay to the isomeric state of ^{26}Al, which subsequently

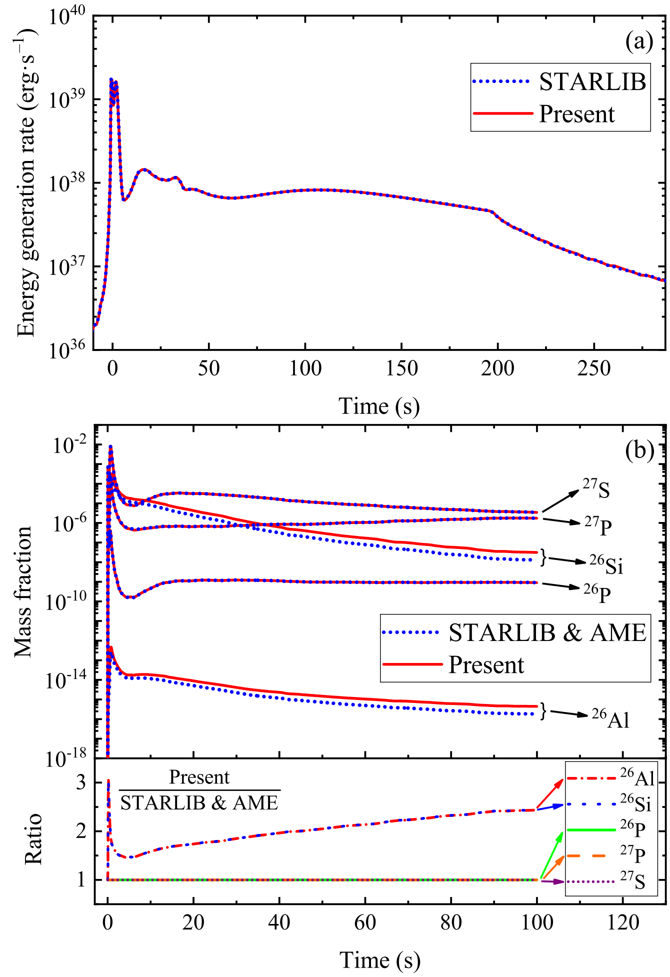

Fig. 4. Comparison of the calculated (a) nuclear energy generation rates and (b) abundances for nuclei with $A = 26, 27$ during an XRB as functions of time using the masses and rates determined in our work (solid lines) to that using values from AME2016 [9] and STARLIB [9] (dotted lines). The ratios of present abundances to database abundances are shown in the bottom of panel (b).

decays to the ground state of ^{26}Mg. No significant change in the element production in the Mg-P mass region was found when using the ^{26}Si$(p,\gamma)^{27}$P reaction rate from Iliadis et al. [44] or from the present work. Moreover, no significant changes were found when variations in this rate within uncertainties were used [51]. The dominant destruction mode of ^{26}Si under nova temperatures is confirmed to be β^+ decay rather than the ^{26}Si$(p,\gamma)^{27}$P reaction. Compared to the result using the recommended Iliadis et al. [44] rate, the contribution of classical nova outbursts to the galactic ^{26}Al mass is only marginally increased by about 0.5%. This verifies previous predictions of the nova contribution to the synthesis of galactic ^{26}Al [6,52,53] and places the expected ^{26}Al/^{27}Al ratios in presolar grains of a inferred nova origin on a more solid experimental ground [54].

6. Conclusion

Based on the β-decay spectroscopy of ^{27}S, we have determined the mass excess of ^{27}P, constrained the mass excess of ^{27}S, and computed the ^{26}Si$(p,\gamma)^{27}$P reaction rate using the Monte Carlo method. A series of astrophysical model calculations incorporating these quantities have been performed. Although the mass value determined in this work has no significant effects on the energy production in XRB, the mass fractions of ^{26}Al and ^{26}Si at the end of the burst are found to be increased by a factor of 2.4. The XRB model calculations using our ^{27}S mass value also indicate that ^{27}S is not a significant waiting point, contrary to the previous expectation [13]. The nova model calculations confirm the previous predictions of the nova contribution to the synthesis of galactic ^{26}Al.

The 9-keV uncertainty in the present mass excess of ^{27}P is dominated by the uncertainty in the β-delayed proton energy measured by silicon detectors. To further improve the precision of the ^{27}P mass, a direct measurement using Penning trap mass spectrometry facilities would be desirable [55].

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