Constraints on the Neutron Star Compactness: Extraction of the Important ^{23}Al(p,γ) Reaction Rate for the rp-Process

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The ^{23}Al$(p,\gamma)^{24}$Si reaction is among the most important reactions driving the energy generation in Type-I X-ray bursts. However, the present reaction-rate uncertainty limits constraints on neutron star properties that can be achieved with burst model-observation comparisons. Here, we present a novel technique for constraining this important reaction by combining the GRETINA array with the neutron detector LENDA coupled to the S800 spectrograph at the National Superconducting Cyclotron Laboratory. The ^{23}Al(d,n) reaction was used to populate the astrophysically important states in ^{24}Si. This enables a measurement in complete kinematics for extracting all relevant inputs necessary to calculate the reaction rate. For the first time, a predicted close-lying doublet of a 2_2^+ and $(4_1^+,0_2^+)$ state in ^{24}Si was disentangled, finally resolving conflicting results from two previous measurements. Moreover, it was possible to extract spectroscopic factors using GRETINA and LENDA simultaneously. This new technique may be used to constrain other important reaction rates for various astrophysical scenarios.

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Introduction.– Type-I X-ray bursts (XRBs), thermonuclear explosions powered by hydrogen and helium burning on the surface of accreting neutron stars, provide unique insights into the nature of matter at near and above nuclear densities [1–4]. Advances in modeling XRBs have created an opportunity to constrain the properties of the system and the underlying neutron star, such as the mass, radius, and composition and rate of accreted material. These models are sensitive to the underlying nuclear physics inputs, in particular, the nuclear reactions involved in the thermonuclear runaway.

Systematic surveys have identified the ^{23}Al$(p,\gamma)^{24}$Si reaction rate as having one of the most significant impacts on the XRB light curve [5, 6]. In principle, this reaction can siphon material from the ^{22}Mg waiting-point, which is already in $(p,\gamma)-(\gamma,p)$ equilibrium with ^{23}Al in the early part of the rapid proton-capture (rp)-process [7]. However, the extent to which such a bypass is possible is highly uncertain owing to the current ^{23}Al$(p,\gamma)^{24}$Si reaction-rate uncertainty. Cyburt *et al.* [6] found that a scale-down factor of 30, determined from the existing experimental uncertainty, with respect to the *recommended* value from REACLIB [8], is sufficient to essentially remove this bypass, resulting in a significant increase of the light-curve rise time and a decrease of its convexity [9]. Even more importantly, it has been shown recently that such a reduction of the reaction rate has a strong impact on the inferred neutron star compactness [9]. By comparing the observed light curve to simulations, it is possible to constrain the distance $d\xi_b^{1/2}$ and the surface gravitational redshift $1+z$ [10–13]. This, in turn, can be used to extract the mass-to-radius ratio M_{NS}/R_{NS}, since they are directly related [14]. This technique offers a complementary approach to the method described in e.g. [15, 16] for sources where the Eddington limit is not reached. Meisel *et al.* investigated the sensitivity of the distance and the gravitational redshift of the *textbook* GS 1826-24 XRB source to uncertainties in several important nuclear reaction rates. Interestingly, they found that scaling the ^{23}Al$(p,\gamma)^{24}$Si reaction rate down by a factor of 30 [6] results in a drastic reduction of the surface gravitational redshift. Therefore, it is critical to

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reduce the ^{23}Al$(p,\gamma)^{24}$Si rate uncertainty in order to investigate the neutron-star compactness from simulation-observation comparisons.

For the ∼0.4 GK temperature where the ^{22}Mg waiting-point bypass may be possible, ^{23}Al$(p,\gamma)^{24}$Si is mostly governed by resonant capture from the $5/2^+$ ground state of ^{23}Al into the first proton-unbound 2_2^+ state of ^{24}Si, with moderate contributions from direct capture into the ground and first excited (bound) 2_1^+ state. At present, the main source of uncertainty for this reaction rate is in the excitation energy of the resonant 2_2^+ state $E(2_2^+)$, which defines the resonance energy $E_r = E(2_2^+) - Q$. Whereas the Q-value is known with 19 keV uncertainty [17], only two measurements of $E(2_2^+)$ exist, with conflicting results. In particular, the 3441(10) keV and 3410(16) keV values measured by Schatz *et al.* [18] and Yoneda *et al.* [19], respectively, differ by more than one standard deviation (1-σ). Since $E(2_2^+)$ enters exponentially in the calculation of the rate, this conflict leads to drastically different outcomes. As for the direct component of the reaction, the only existing experimental study was performed by Banu *et al.* [20] to extract an asymptotic normalization coefficient (ANC) for the ground state of ^{24}Si using one-proton breakup reactions. An experimental extraction of the spectroscopic factor of the 2_1^+ state is still necessary.

In the present work we aimed at measuring all the relevant sources of uncertainty in the ^{23}Al$(p,\gamma)^{24}$Si reaction rate using a novel technique based on the complete kinematics measurement of the ^{23}Al$(d,n)^{24}$Si transfer reaction. As the (d,n) reaction preferentially populates the states that might be of astrophysical interest at intermediate beam energies of 30 - 80 MeV/u [21–23], it can be used to measure excitation energies, partial population cross sections from which spectroscopic factors C^2S can be inferred, spins and γ-ray decay cascades. A recent (d,n) experiment at intermediate beam energies has been successfully employed to that effect to study the reaction ^{26}Al$(p,\gamma)^{27}$Si by measuring the γ-rays emitted in the de-excitation of populated states and their corresponding "angle-integrated" cross section [24]. Using that approach, the authors determined the C^2S of these populated states. Similarly, the ^{30}S$(p,\gamma)^{31}$S reaction, which is a key reaction during novae nucleosynthesis, was constrained using this method [25]. In this Letter, we demonstrate a novel (d,n)-based technique that takes the final step by measuring the full kinematics: γ-rays, projectile-like heavy recoils, and low-energy ejectile neutrons. This new approach opens up the possibility for complete measurements in a single experiment for astrophysically important reaction rates far from stability.

Experiment.– The ^{23}Al$(d,n)^{24}$Si experiment was carried out at the National Superconducting Cyclotron Laboratory at Michigan State University. To produce the secondary ^{23}Al beam, a stable ^{24}Mg beam with an intensity of 60 pnA at an energy of 170 MeV/u impinged on a 1904 mg/cm^2 thick ^{9}Be production target located at the entrance of the A1900 fragment separator [26]. Since multi-nucleon transfer and pickup reactions produced a mix of several isotopes [21, 27], the resulting beam was subsequently purified using the standard $B\rho - \Delta E - B\rho$ separation technique (with a 1050 mg/cm^2 Al wedge) in the A1900 fragment separator. Only isotopes within a 2% momentum spread acceptance were transmitted. A beam with an average intensity of roughly 8×10^3 pps of ^{23}Al with a purity of 13% (other isotonic admixtures from mainly ^{22}Mg and ^{21}Na) was subsequently delivered to the target position of the S800 magnetic spectrograph [28] where the (d,n) reaction took place. The high-resolution GRETINA γ-ray tracking device [29, 30] with eight detector modules mounted in one of the hemispheres was used to detect in-flight ^{24}Si γ-ray de-excitations, while the other hemisphere was removed to provide space for the neutron detection. The thickness of 110(5) mg/cm^2 for the CD_2 reaction target and the ^{23}Al beam energy of 48 MeV/u were intended to maximize the reaction yield. A pure C target of 78(4) mg/cm^2 was also used in dedicated background runs; the extracted data taken with the C target were scaled and subtracted from the data taken with the CD_2 target in the analysis. The detection efficiency of GRETINA in singles mode was calibrated using standard sources and is about 4% at an energy of 1800 keV.

For detection of the neutrons, the low-energy neutron detector array (LENDA) [31, 32] was used. In this experiment, LENDA consisted of 24 plastic-scintillation detector bars ($300\times45\times25$ mm each) which were installed in two vertical rows located at 1 m and 1.1 m distance from the S800 target covering scattering angles between $110 \leq \theta_{\rm lab} \leq 175$ degrees with no gaps between the bars.

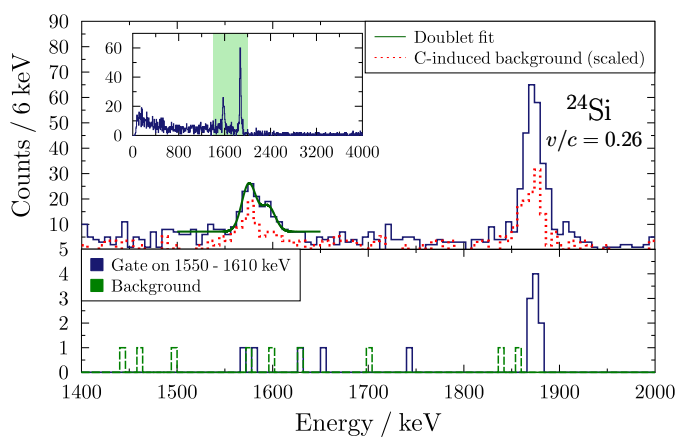

FIG. 1. Top: Doppler-corrected γ-ray spectrum of decays in ^{24}Si in the $1400-2000$ keV range measured with GRETINA when gating on ^{24}Si ions in the S800 focal plane. The dotted histogram displays the scaled background induced by reactions on the carbon atoms in the target. A fit consisting of two Gaussian functions resolves the doublet structure at $E_\gamma \simeq 1600$ keV. The inset shows the full spectrum. Bottom: The γ-ray coincidence spectrum gated on the E_γ region between 1550 to 1610 keV. The coincidence with the γ-rays at 1874 keV can be clearly identified.

The neutron time-of-flight (TOF) (used to determine the neutron kinetic energy) was derived from the difference between the neutron timing signal from LENDA and the recoil time signal from the S800 focal plane scintillator. The TOF resolution, as determined from the prompt-coincidence events in which a photon was emitted, was 744(9) ps (FWHM) [27].

The ^{24}Si recoil was separated and identified using its energy-loss, tracked positions, and time-of-flight measured with the S800 focal-plane detectors [28]. Because of the beam velocity of $\beta = v/c \approx 0.26$, a Doppler correction of the deposited γ-ray energy in GRETINA was performed event-by-event after tracking the angle and the velocity of the residual nucleus ^{24}Si through the S800 magnetic spectrograph with an ion-dynamical calculation using the COSY code [33]. Excitation energies (E_x) were deduced from the measurement of the γ-ray energies after Doppler correction. Together with the known reaction Q-value of 3293(20) keV [17], resonance energies $E_r = E_x - Q$ in the ^{23}Al$(p,\gamma)^{24}$Si reaction were obtained. Due to the relatively thick CD_2 target combined with the 2% momentum uncertainty of the incoming ^{23}Al beam, the neutron energy resolution was ∼1.1 MeV which does not allow to resolve individual states [27]. Nevertheless, the detection of neutrons allowed for extraction of valuable spectroscopic information as shown in the next section.

Results.– Figure 1 shows the Doppler-corrected γ-ray spectrum measured with GRETINA when gating on incoming ^{23}Al and on ^{24}Si in the outgoing channel. A nearest-neighbor add-back algorithm [30] was applied to improve the peak-to-background ratio. Optimum parameters for the Doppler reconstruction were determined using known energy transitions from nuclei transmitted to the S800 focal plane in this experiment, like ^{18}Ne (1489 keV and 1887 keV), ^{23}Mg (1599 keV), ^{20}Ne (1633 keV). The normalized contribution measured with a pure carbon target for background subtraction is also shown in Fig. 1 (dashed line).

In order to extract the low-lying level scheme of ^{24}Si ($T_z = +2$), experimental information from the isobaric $T_z = -2$ mirror nucleus ^{24}Ne was compared to our observations. The strongest transition at $E_\gamma = 1874(3)$ keV can be assigned to the de-excitation of the bound 2_1^+ state, similarly observed in previous experiments at energies of $E_\gamma = 1879(11)$ keV [18] and $E_\gamma = 1860(10)$ keV [19], respectively. This assignment is supported by the first excited 2^+ state in the mirror nucleus ^{24}Ne at an energy of $E_x = 1982(1)$ keV resulting in a Coulomb shift of 108 keV between the isobaric partners.

A broad structure is observed at an energy of about 1590 keV. Based on this peak width (∼1.9% FWHM) compared to the peak widths measured for other nuclei in the same experiment (1.1 - 1.4% FWHM), it can be identified as two partially overlapping γ-ray transitions. Using a fit consisting of two Gaussian functions on top of a background contribution, two γ-ray energies of 1575(3) keV and 1597(5) keV were extracted. Both of these γ-rays are in coincidence with the $2_1^+ \rightarrow$ g.s. transition ($E_\gamma = 1874(3)$ keV) as shown in the bottom panel of Fig. 1. Consequently, this yields excitation energies of $E_x = 3449(5)$ keV and $E_x = 3471(6)$ keV, respectively.

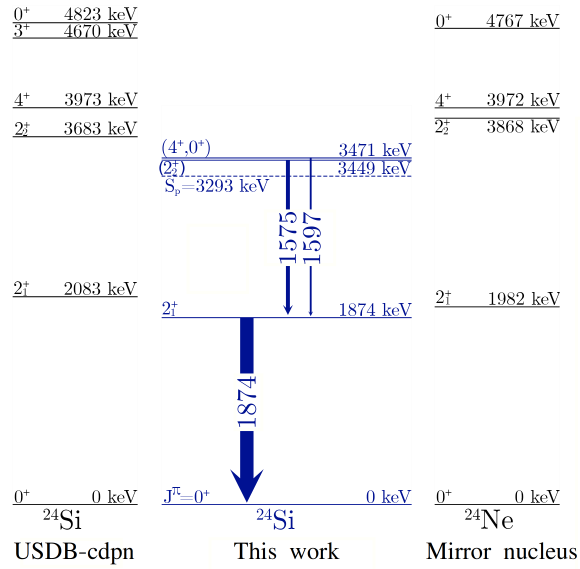

FIG. 2. The extracted level scheme of ^{24}Si in this experiment in comparison with a shell-model calculation using the USDB-cdpn interaction and the mirror nucleus ^{24}Ne.

In the two previous experiments on ^{24}Si, only one state was identified at excitation energies of $E_x = 3441(10)$ keV [18] and $E_x = 3410(16)$ keV [19], respectively. However, in the mirror as well as in the shell-model calculations of [19], two states separated by just a few keV were expected (Fig. 2).

Detailed ^{24}Si shell-model calculations using the USDB-cdpn interaction [34] were combined with information from the mirror nucleus ^{24}Ne and compared to the experimentally observed γ-ray transitions. Using these additional information, it was possible to tentatively assign spin-parities to the observed $E_x = 3449(5)$ keV and $E_x = 3471(6)$ keV states.

The energy of the state at $E_x = 3449(5)$ keV agrees very well with the already measured and assigned 2_2^+ state in [18] at $E_x = 3441(10)$ keV. Moreover, in the mirror as well as in the shell-model calculation, the 2_2^+ state is lower in energy than the other states. Compared to the mirror, for which a roughly 10% ground state decay branching is observed, no decay branching for this state is detected in this experiment for ^{24}Si. Based on these arguments, we tentatively assign the state at $E_x = 3449(5)$ keV to be $J^\pi = 2_2^+$. This results in a Coulomb shift of 419 keV compared to the isobaric 2_2^+ state in ^{24}Ne at $E_x = 3868$ keV. In principle, our new technique allows for assigning spin-parities based on the simultaneously measured angular distribution of the neutrons when requiring a γ-neutron coincidence. In this experiment, the statistics were too low to make use of this additional information.

TABLE I. Extracted level energies (E_x) and corresponding decay γ-ray energies (E_γ) in ^{24}Si measured in this experiment. The (tentative) assignments are indicated. Different l and j values are presented for each state. Calculated cross sections within the ADWA theory ($\sigma_{\rm theo}$) are compared to the measured partial cross sections ($\sigma_{\rm exp}$) in this experiment. Theoretical spectroscopic factors ($C^2S_{\rm theo}$), proton width (Γ_p), the γ-width (Γ_γ) and the spectroscopic strength ($\omega\gamma$) were calculated using the UDSB-cdpn shell model with the adapted $C^2S_{\rm exp}$. For determination of $C^2S_{\rm exp}$ see text and Eq. 1. No final assignment of the 3471 keV state is possible within this work; possible assignments are listed. The total (d,n) cross section is 563(67) μb.

E_x (keV)	E_γ (keV)	$J_i^\pi \to J_f^\pi$	l	j	$\sigma_{\rm theo}$ (μb)	$C^2S_{\rm theo}$	$\sigma_{\rm exp}$ (μb)	$C^2S_{\rm exp}$	Γ_p (eV)	Γ_γ (eV)	$\omega\gamma$ (eV)
0			2	5/2	98	3.44	$\leq$ 271	$\leq$ 2.8			
1874(3)	1874(3)	$2_1^+ \to 0_{\rm gs.}^+$	0	1/2	139	0.27	263(83)	0.6(2)			
			2	3/2	473	0.03		0.07(2)			
			2	5/2	411	0.17		0.4(1)			
3449(5)	1575(3)	$(2_2^+) \to 2_1^+$	0	1/2	86	0.45	78(41)	0.7(4)	1.0×10^{-4}	1.9×10^{-2}	4.2×10^{-5}
			2	3/2	402	0.001		0.002(1)			
			2	5/2	349	0.176		0.3(2)			
3471(6)	1597(5)	$(4_1^+) \to 2_1^+$	2	3/2	722	0.016	54(30)	0.07(4)	7.0×10^{-7}	5.0×10^{-4}	5.2×10^{-7}
			2	5/2	629	0.001		0.004(3)			
		$(0^+) \to 2_1^+$	2	5/2	69	0.24	54(30)	0.8(4)	6.2×10^{-5}	1.6×10^{-3}	5.0×10^{-6}

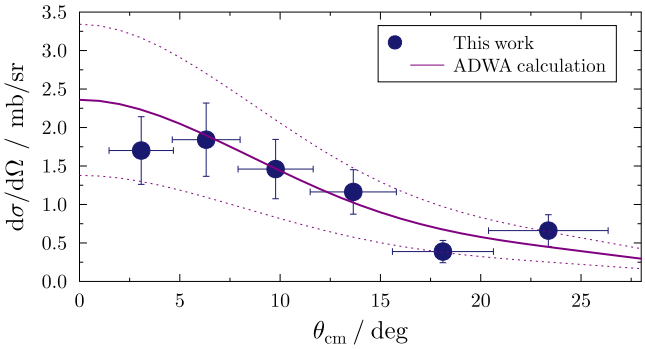

FIG. 3. Differential cross section in the center-of-mass system measured with the LENDA detector. Shown is the sum of all different populated states. The purple line represents the result of a detailed ADWA calculation adding all single contributions weighted by our derived spectroscopic factors. Error bands (dotted lines) are due to the uncertainty in the experimental spectroscopic factors.

The next higher-lying state in the mirror and in the shell-model calculation is a 4_1^+ state at an energy of E_x = 3972 keV and E_x = 3973 keV, respectively. It decays exclusively through a γ-ray cascade to the 2_1^+ state (observed at E_x = 3471(6) keV). The shell-model calculation, however, predicts a rather small spectroscopic factor for this 4_1^+ state, whereas the calculated single-particle cross section $\sigma_{\rm theo}$ is large (see Tab. I). The next possible state in the mirror nucleus is the second 0^+ state at an energy of E_x = 4767 keV, which also decays predominantly via the first 2^+ state followed by a transition to the ground state. If the state at E_x = 3471(6) keV in ^{24}Si corresponds to this second 0^+, the Coulomb shift would be $\approx$ 1300 keV, which is rather large: in [35] also downward shifts in excited states of ^{25}Si relative to those in the mirror nucleus ^{25}Na and from the USDB-cdpn calculation were observed. This was interpreted as a Thomas-Ehrman shift for levels that are near and above the proton-decay threshold (S_p = 3.29 MeV), and that have a relative large occupancy of the $s_{1/2}$ proton orbital. For ^{24}Si the $s_{1/2}$ proton orbital occupancies increase with excitation energy: 0.52 (g.s.), 0.72 (2_1^+), 0.97 (2_2^+), 0.49 (4_1^+) and 1.54 (0_2^+). Thus, the Thomas-Ehrman shift is likely responsible for the lowering of excited state energies. It is therefore most likely that the experimental state at E_x = 3.471(6) MeV is the 4_1^+ shifted down from ^{24}Ne by about 500 keV. If it were 0_2^+, the shift from ^{24}Ne would be the largest Thomas-Ehrman shift ever observed. This shift is difficult to calculate, since one should take into account the two-proton decay channel ($S_{(2p)}$ = 3.43 MeV). However, therefore, based on our data no clear conclusion can be drawn. We list both possibilities in Tab. I. The proposed level scheme is shown in Fig. 2.

Similar to the method described in [24, 25], the γ-ray transition intensities can be used to extract the integral and partial population cross sections after correcting for feeding. An integral ^{23}Al$(d,n)^{24}$Si cross section of 563(67) μb at $E_{\rm beam}$ = 48 MeV/u was extracted after subtracting the ^{24}Si production due to carbon-induced reactions on the target using the pure C target runs and after correcting for the S800 momentum acceptance. Table I summarizes the measured partial cross sections for states directly populated by the ^{23}Al$(d,n)^{24}$Si reaction. The partial cross section to the ground state was obtained by subtracting the sum of all excited states partial cross sections measured in GRETINA from the total cross section measured in the S800.

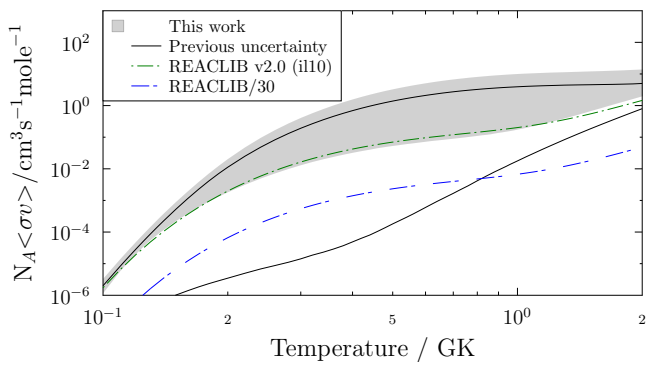

FIG. 4. Upper and lower 1-σ uncertainty of the current rate (black lines) due to the conflicting results of [18] and [19]. Also shown is the 1-σ rate uncertainty calculated within this work (gray band); the reduction in uncertainty is clearly visible. The calculations include the Q-value uncertainty of about 20 keV, which is now the dominant error source. Moreover, the recommended REACLIB (green) and REACLIB/30 (blue) rates are shown.

Partial single-particle cross sections for the (d, n) transfer reactions were calculated using the FRESCO code [36] in the adiabatic wave approximation (ADWA) [37] which explicitly incorporates deuteron breakup. The potentials and procedures used were the same as those implemented for [24] (shown in Tab. I as σ_{theo}). Using the inferred ground-state partial cross section and the single-particle cross section, we obtain an upper limit of ≤ 2.8 for the ground-state spectroscopic factor. This is in excellent agreement with the value of 2.7(2) obtained in [20].
Theoretical spectroscopic factors, C^2S_{theo}, were calculated with the shell model using the USDB-cdpn interaction. Table I shows the shell-model theoretical spectroscopic factors and experimentally inferred C^2S_{exp} that have been extracted for individual quantum numbers i using the following relation:

$$C^2S^i_{\text{exp}} = \frac{C^2S^i_{\text{theo}} \times \sigma^i_{\text{theo}}}{\sum_{i'} \left(C^2S^{i'}_{\text{theo}} \times \sigma^{i'}_{\text{theo}}\right)} \times \frac{\sigma_{\text{exp}}}{\sigma^i_{\text{theo}}} \qquad (1)$$

The neutron differential angular cross section in the center-of-mass frame measured with the LENDA detector is shown in Fig. 3. Due to the low yield of the reaction roughly 100 counts can be identified at energies between 6 and 16 MeV for the measured angles. The relatively large thickness of the CD_2 reaction target, the low statistics, and the momentum spread of 2% of the incoming beam make it impossible to distinguish individual states in the neutron spectra by requiring a γ-neutron coincidence. Nevertheless, the total differential cross section in the center-of-mass frame can be used to independently verify the derived partial cross sections weighted by the experimentally extracted C^2S values from GRETINA (see Tab. I). For each state and every single l-transfer, a specific angular distribution was calculated with the FRESCO code and weighted by our derived C^2S values. Eventually, all single contributions were added, which is shown as the solid line in Fig. 3. The dotted lines represent the uncertainty given by the uncertainty in the experimentally derived C^2S values. Using this method, a remarkable agreement is achieved (see Fig. 3). This confirms the possibility to perform these studies in complete kinematics and to extract all required information for the astrophysical reaction rate within one experiment (except for the equally important reaction Q-value).

Astrophysical results.– Using the newly derived spectroscopic factors and the highly constrained excitation energies of the resonant states (with the $J^\pi = 4^+_1$ assignment for the state at $E_x = 3471(6)$ keV), a new reaction rate was calculated. Therefore, the narrow resonance approximation [38] was used with the excitation energies and the resonance strengths as input for each state above the proton separation energy (see Tab. I). The direct-capture component was adapted from the most recent extraction in [20] with a value of $S(E_0) = 3.0812 \times 10^{-3}$ MeV b. The main uncertainty contribution stems from the resonance energy of the 2^+_2 state which is due to the Q-value uncertainty of 19 keV. In Fig. 4, the upper and the lower 1-σ error band of the new rate is shown (gray band) including all uncertainties in combination with the Q-value uncertainty. Moreover, the 1-σ rate uncertainty obtained by combining the experimental information available prior to the present work [18, 19] is included (solid black lines). As can be seen, the results presented here reduce the previous rate uncertainty by as much as 3-4 orders of magnitude in the temperature region of interest for XRBs. It is also worth emphasizing that, whereas the new rate is somewhat compatible with the values taken from the REACLIB database (green line), it clearly rules out the 30 scale-down factor determined by Cyburt *et al.* on the basis of previously available experimental information [6] (blue line). With the results presented here, a major step forward is taken to better constrain the neutron-star compactness of the GS 1826-24 XRB source by matching the observed and simulated light curves.

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