

Improved direct measurement of low-energy resonances in the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction

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(Received 31 May 2025; accepted 27 August 2025; published 3 November 2025)

In the nova temperature range, $0.1 \text{ GK} < T < 0.4 \text{ GK}$, several low-energy resonances dominate the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction rate, which is currently affected by large uncertainties. We present a high-precision study of the resonances at $E_r^{\text{lab}} = 127.3, 271.4, 272.3, 291.5$, and 352.6 keV , measured directly at the Laboratory for Underground Nuclear Astrophysics in Italy. The strengths of the 127.3-, 271.4-, and 291.5-keV resonances are consistent with previous measurements within 1σ . However, for the 272.3- and 352.6-keV resonances, we report strength values of $(129.9 \pm 5.8) \text{ meV}$ and $(14.9 \pm 0.8) \text{ meV}$, respectively, more than a factor of 1.5 higher than literature values. In addition, we report on new branching ratios for the 127.3-, 272.3-, and 352.6-keV resonances, leading to updated decay schemes. Finally, we present a revised thermonuclear reaction rate and investigate its impact on the NeNa nucleosynthesis.

DOI: [10.1103/vqt1-jxpw](https://doi.org/10.1103/vqt1-jxpw)

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Introduction. The neon-sodium (NeNa) cycle in hydrogen burning allows the conversion of four protons into helium, using neon and sodium isotopes as catalysts [1,2]. Although it contributes minimally to stellar energy generation due to the high Coulomb barriers involved, the NeNa cycle plays a key role in the synthesis of isotopes ranging from ^{20}Ne to ^{24}Mg . Furthermore, the NeNa cycle can bridge light-element nucleosynthesis towards heavier elements [3]. In recent years, significant progress has been made in reducing the uncertainties of many nuclear reactions in the NeNa cycle and in understanding their impact on the resulting abundances, thanks to the efforts of several research groups [4–10]. However, the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ and $^{23}\text{Na}(p, \alpha)^{20}\text{Ne}$ reaction rates are still affected by large uncertainties. Therefore, high-precision experimental data are needed to improve our understanding of the production of Ne-Na isotopes in both asymptotic giant branch (AGB) stars and explosive stellar environments such as novae and supernovae. In AGB stars, the NeNa cycle is activated at the base of the convective envelope during hot bottom burning (HBB) at $T \leq 0.1$ GK, when the stellar mass is $\geq 4 M_{\odot}$. In explosive environments, the radioactive ^{22}Na (with a half-life of 2.6 yr) plays a particularly significant role. It offers a direct probe of nucleosynthesis in novae events [11,12], i.e., thermonuclear explosions on the surface of a white dwarf in a binary system with a less evolved companion. Its production is strongly associated with oxygen-neon (ONe) white dwarfs, the descendants of stars with initial masses in the range of 8–10 $M_{\odot}$. The ^{22}Na decay emits a 1.275-MeV photon [13], whose detection would allow one to estimate the amount of ^{22}Na produced in an ONe nova. Detecting the 1.275-MeV γ -rays requires a nearby nova explosion, within a distance of a few kpc (1 kpc = 3262 light years) [14]. Although no ^{22}Na γ -rays have been observed, this may be achieved by future satellite missions with advanced detector technology and unprecedented line sensitivity [15]. To fully harness their potential, especially in the event of a nearby nova, accurate nuclear physics inputs must be established.

Another astrophysical scenario where ^{22}Na plays a crucial role is supernovae. In core-collapse supernovae, even though the 1.275-MeV line from ^{22}Na [16,17] is much weaker than the 1.238-MeV [18] γ -ray line from the decay of ^{56}Co , ^{22}Na production can be traced through the signature of its decay into ^{22}Ne , observed as a strong excess in meteoritic stardust grains [19,20]. This excess likely originates from ^{22}Na trapped in grains formed during supernovae explosions [21]. A precise determination of the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction rate can help to identify the paternity of presolar meteoritic grains, through better estimates of a number of Ne isotopic ratios [22].

In the temperature range relevant to novae, from 0.1 to 0.4 GK, the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction rate is dominated by two low-energy resonances at $E_r^{\text{lab}} = 127.3$ and 272.3 keV. At higher temperatures, $T > 0.4$ GK, relevant to explosive nucleosynthesis during supernovae, also the $E_r^{\text{lab}} = 291.5$ and 352.6 keV resonances contribute significantly to the reaction rate [23]. The strengths of all these low-energy resonances have been previously measured by Görres *et al.* [23], Berg *et al.* [24], Görres *et al.* [25], and Becker *et al.* [26] with a typical reported uncertainty of 15%–20% [23,26]. In this work,

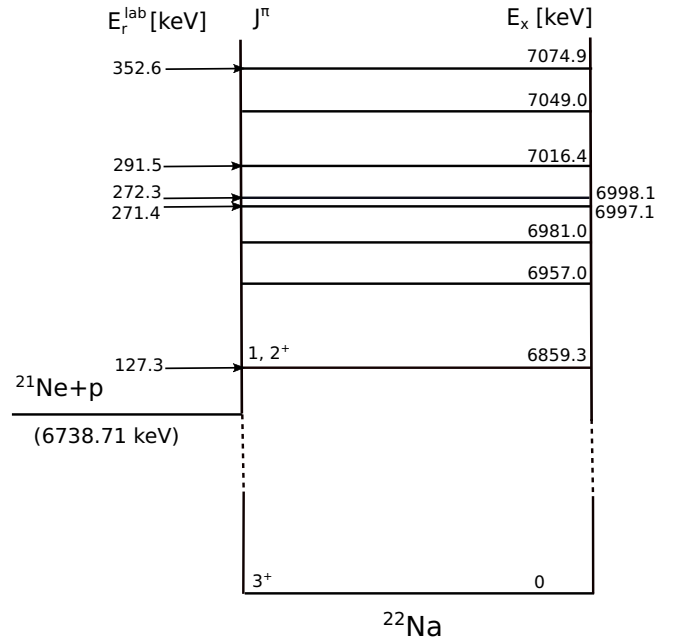


FIG. 1. Partial level scheme of ^{22}Na up to the energy $E_x = 7074.9$ keV. The excited states and corresponding resonance energies E_r^{lab} investigated in the present experiment are indicated.

we report on new direct and precise measurements of the resonances at $E_r^{\text{lab}} = 127.3$, 271.4, 272.3, 291.5, and 352.6 keV.

Experiment. The $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction (Q value = 6738.71 keV [13]) was studied at the Laboratory for Underground Nuclear Astrophysics (LUNA) [27,28], taking advantage of the low environmental background levels [29,30] at the Gran Sasso National Laboratory (LNGS), Italy. The experiment was performed using the high-intensity proton beam (beam current up to 300 μA) provided by the LUNA 400-kV accelerator [31]. The beam entered a parallelepiped-shaped windowless reaction chamber filled with 2-mbar pressure of either natural neon ($^{20}\text{Ne} = 90.48\%$, $^{21}\text{Ne} = 0.27\%$, and $^{22}\text{Ne} = 9.25\%$) or ^{21}Ne -enriched neon ($^{20}\text{Ne} = 5.53\%$, $^{21}\text{Ne} = 59.1\%$, and $^{22}\text{Ne} = 35.37\%$) gas, both used in the recirculation mode [32]. The beam was stopped on a Cu calorimeter that measured its beam current [33]. The γ -rays emitted by the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction were detected using two large high-purity germanium (HPGe) detectors with relative detection efficiencies of 90% and 130%, mounted at two different positions along the beam path. The entire setup was surrounded by a 20-cm lead shielding to further reduce the environmental background.

The γ -detection efficiency of the detectors was characterized using calibrated radioactive sources (^{133}Ba , ^{137}Cs , and ^{60}Co) for the low-energy region (up to 1.3 MeV) and the well-known $^{14}\text{N}(p, \gamma)^{15}\text{O}$ resonance at $E_r^{\text{lab}} = 278$ keV [34] to extend the efficiency determination up to 7 MeV. The adopted experimental setup was implemented in the LUNA giant4 [35] framework `simluna` and was fine-tuned using experimental data. A description of the setup and Monte Carlo simulations can be found in Ref. [36].

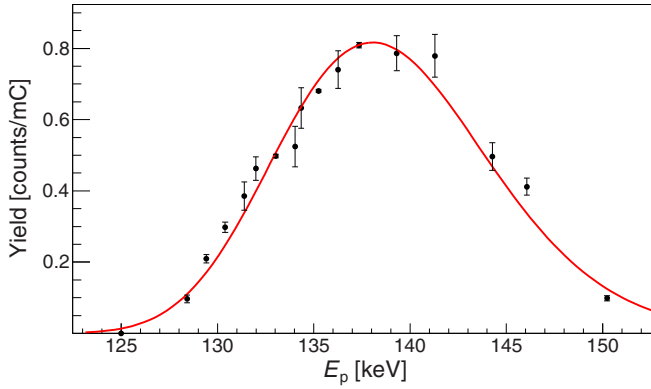


FIG. 2. Experimental scan of the $E_r^{\text{lab}} = 127.3$ keV resonance as a function of the proton beam energy, measured with the HPGe 130% detector. A fit to the experimental data is also shown.

Data taking and analysis. Figure 1 shows the level scheme of ^{22}Na in the energy range accessible with the LUNA 400-kV accelerator. For each measured resonance, as a first step, a run was performed at the beam energy where the maximum yield was expected according to the literature resonance energy, taking into account the beam energy loss and the efficiency profile of the detectors. A resonance scan was then performed by varying the beam energy in steps of 1–2 keV and measuring the yield of one of the most intense primary γ transitions (i.e., transitions from the resonance under study to a given state in ^{22}Na). Figure 2 shows the scan of the resonance at $E_r^{\text{lab}} = 127.3$ keV, measured with the HPGe 130% detector. Scans for the remaining resonances are provided in the Supplemental Material [37]. Using these excitation functions, the resonance energies for the five resonances were determined. The details of the adopted method and the results are reported in Ref. [36].

To measure the resonance strengths, long runs (up to 50 C of accumulated beam charge) were performed at beam energies where the maximum yield was observed, corresponding to the resonance being populated in front of the two HPGe detectors. For the $E_r^{\text{lab}} = 127.3$, 272.3, and 291.5 keV resonances, new primary γ transitions were discovered in addition to those already reported in the literature [13]. Figures 3 and 4 display the experimental spectra obtained for the resonances at 127.3 and 272.3 keV, respectively. Primary γ transitions are marked; the corresponding branching ratios (BRs) are provided in Table I. The experimental spectrum and the BRs of the $E_r^{\text{lab}} = 291.5$ keV resonance are reported in Ref. [36]. For the 352.6-keV resonance, the intensity of the observed primary γ transitions (Table I) is in agreement with the values reported in the literature [13].

The intrinsic widths Γ of all the resonances investigated in this work are significantly smaller (less than a few eV) than the beam energy loss inside the target ($\Gamma \ll \Delta E_{\text{c.m.}}$) [26] and, hence, the thick-target condition [38] is valid to calculate the resonance strength $\omega\gamma$. Under this assumption, $\omega\gamma$ is determined as [39]

$$\omega\gamma = \frac{2}{\lambda_r^2} Y \epsilon_r \frac{M}{m + M}, \quad (1)$$

where λ_r is the de Broglie wavelength at the resonance energy, ϵ_r is the effective stopping power in the laboratory system, and m and M are projectile and target masses, respectively. The total yield Y is obtained as

$$Y = \frac{1}{Q} \sum_i \frac{N_i}{\eta_i}, \quad (2)$$

where Q is the integrated beam charge, N_i is the number of net counts measured for each primary transition i (determined following Ref. [40], see Ref. [37]), and η_i is the corresponding full energy detection efficiency, calculated from `simluna`. By

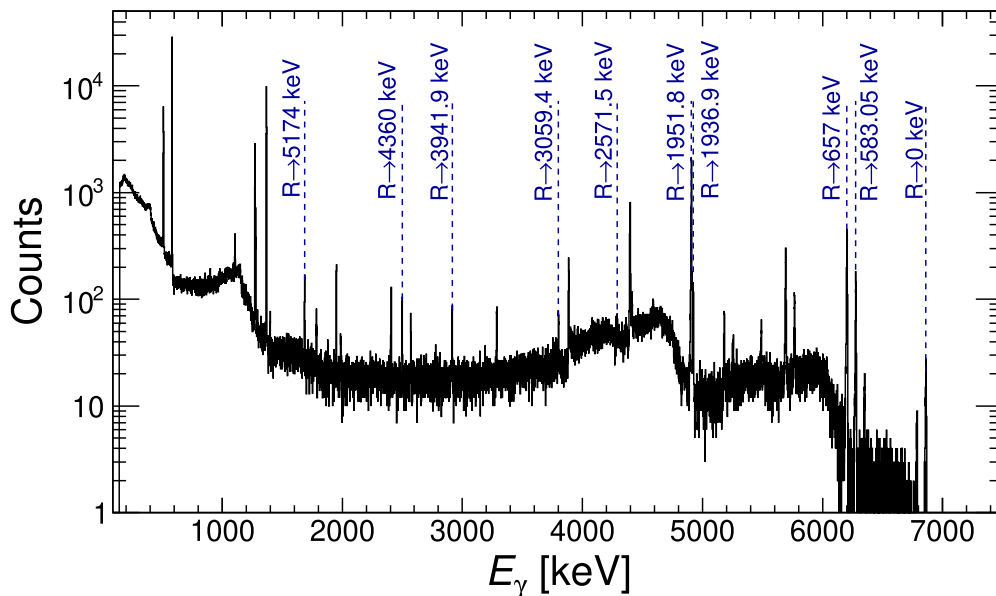


FIG. 3. Experimental spectrum measured with the HPGe 130% detector at the maximum detection yield for the $E_r^{\text{lab}} = 127.3$ keV resonance. Primary transitions from the $E_x = 6859.3$ keV excited state (R) are labeled.

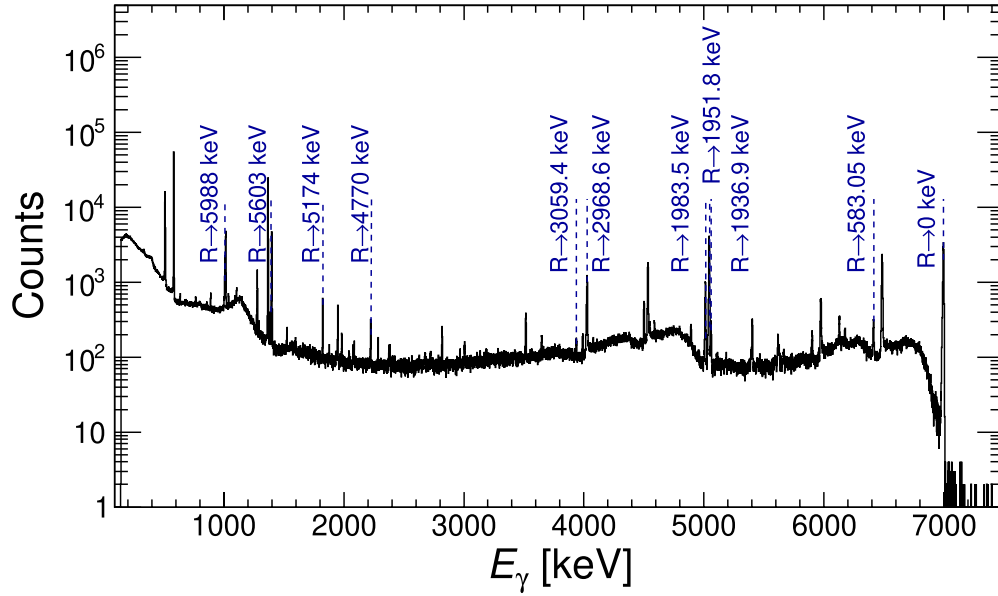


FIG. 4. Experimental spectrum measured with the HPGe 130% detector at the maximum detection yield of the $E_r^{\text{lab}} = 272.3$ keV resonance. Primary transitions from the excited state (R) at $E_x = 6998.1$ keV are labeled.

TABLE I. Branching ratios (BRs) for the primary γ -rays from the levels at $E_x = 7074.9$, 6998.1 , and 6859.3 keV corresponding to the resonances at $E_r^{\text{lab}} = 352.6$, 272.3 , and 127.3 keV, respectively. The format of BRs evaluated in this work is value $\pm$ total uncertainty ($=\sqrt{\text{statistical uncertainty}^2 + \text{systematic uncertainty}^2}$), both in %. For comparison, the branching ratios from the literature [13], along with their total uncertainties, are also provided.

E_x (keV)	7074.9		6998.1		6859.3	
	LUNA	Lit. value	LUNA	Lit. value	LUNA	Lit. value
5995	5.4 ± 0.3	3.64 ± 0.38				
5988			2.4 ± 0.2	—		
5959	12.6 ± 0.7	9.71 ± 0.64				
5739	0.58 ± 0.04	0.61 ± 0.17				
5725	0.41 ± 0.04	0.36 ± 0.08				
5700	2.7 ± 0.2	14.71 ± 1.74				
5603			0.5 ± 0.2	—		
5174	4.6 ± 0.3	3.64 ± 0.28	0.98 ± 0.06	0.96 ± 0.22	1.25 ± 0.09	—
5062.5	0.75 ± 0.05	0.53 ± 0.17				
4770			0.66 ± 0.04	—		
4622	0.57 ± 0.05	0.53 ± 0.17				
4583	0.67 ± 0.05	0.61 ± 0.17				
4360	0.56 ± 0.05	0.61 ± 0.17			1.16 ± 0.09	—
4296.2	0.50 ± 0.05	0.69 ± 0.17				
3941.9	0.90 ± 0.06	0.69 ± 0.25			0.98 ± 0.08	—
3519.1	1.31 ± 0.09	1.30 ± 0.17				
3059.4	3.1 ± 0.2	2.16 ± 0.26	0.38 ± 0.05	—	1.1 ± 0.1	—
2968.6			6.0 ± 0.4	4.48 ± 0.97		
2571.5					0.6 ± 0.1	—
1983.5			6.8 ± 0.4	6.30 ± 0.57		
1951.8	5.7 ± 0.4	5.83 ± 1.40	33.2 ± 1.9	30.95 ± 2.37	64.2 ± 3.8	80 ± 13
1936.9			1.5 ± 0.1	2.03 ± 0.54	3.2 ± 0.2	—
657	27.7 ± 1.6	27.75 ± 1.90			19.6 ± 1.2	20 ± 9
583.05	31.9 ± 1.8	26.09 ± 1.88	2.2 ± 0.2	1.92 ± 0.43	6.8 ± 0.4	—
0	—	0.53 ± 0.17	45.3 ± 2.6	53.36 ± 2.76	1.16 ± 0.09	—

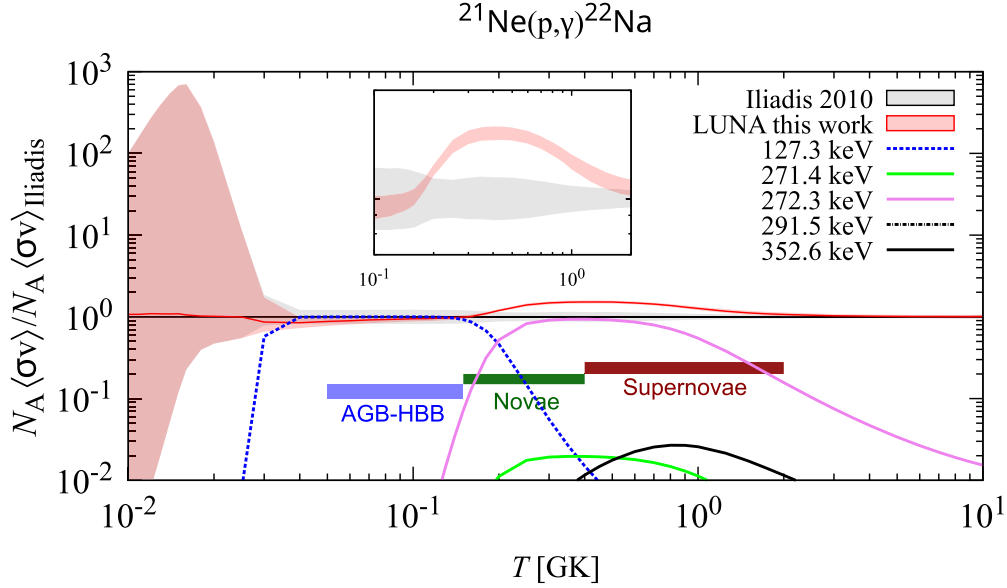


FIG. 5. LUNA thermonuclear reaction rate for the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction (red) compared with Iliadis *et al.* [46] (gray). The shaded area shows the 1σ uncertainty. The rates are normalized to Iliadis *et al.* [46]. The AGB, novae, and supernovae temperature regions of interest are also shown.

summing over all primary γ transitions, the total resonance strength is determined. The effect of true coincidence summing on γ -ray cascades and the influence of beam energy straggling are included in the simulation [36,41].

For the $E_r^{\text{lab}} = 271.4$ keV resonance ($E_x = 6997.1$ keV, see Fig. 4 in Ref. [37]), it was not possible to calculate the resonance strength from the total yield Y , as the 5013.4- and 6995.9-keV primary γ -rays were mixed with those from the $E_r^{\text{lab}} = 272.3$ keV resonance ($E_x = 6998.1$ keV) just 1-keV apart. In addition, according to the literature, the 5468.7-keV primary γ -ray is weak ($\text{BR} = 4.9 \pm 1.0\%$ [13]), and its signal was not observed in the present experimental data. Therefore, the resonance strength was determined using the 2287-keV primary γ -ray, normalized to its BR. Further details are provided in Ref. [37].

For the $E_r^{\text{lab}} = 352.6$ keV resonance, all primary γ -ray transitions, except the 7075.4-keV primary γ -ray (which is mixed with a broad energy bump, see Fig. 5 in Ref. [37]), were used to determine Y . This primary γ -ray should have very low intensity ($\text{BR} = (0.53 \pm 0.17)\%$ [13]) according to the literature, and its contribution is thus included in the error budget.

For the $E_r^{\text{lab}} = 127.3$, 271.4, and 291.5 keV resonances, the $\omega\gamma$ values agree with the measurements reported in Görres *et al.* [23] and Becker *et al.* [26] within 1σ uncertainty. Instead, for the $E_r^{\text{lab}} = 272.3$ and 352.6 keV resonances, the measured $\omega\gamma$ values show a 3.4σ and 4.3σ deviation, respectively, from the $\omega\gamma$ values reported in Görres *et al.* [23].

For each resonance, we calculated the electron screening correction factor f in the adiabatic approximation [42]; the results are reported in the last column of Table II. We underline that, except for the $E_r^{\text{lab}} = 127.3$ keV resonance, the correction is smaller than the quoted uncertainties on the strength. In addition, according to a recent paper from Iliadis

[43], the electron screening correction for narrow resonances should always be neglected.

Thermonuclear reaction rates and implications. We have updated the thermonuclear reaction rates for the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction using the resonance strengths reported in this work. The rate is calculated using the Monte Carlo code *ratesmc* [44]. For the five low-energy resonances at $E_r^{\text{lab}} = 127.3$, 271.4, 272.3, 291.5, and 352.6 keV, we adopted our new measured values. For all other resonances, we used the data from Iliadis *et al.* [45]. The total reaction rate in the temperature range from 0.01 to 10 GK is provided in Table I in the Supplemental Material [37].

A comparison between the updated LUNA rate and the rate from Iliadis *et al.* [46] is shown in Fig. 5. The new rate is in agreement with the previous one [46], except in the temperature range relevant for classical novae (0.1–0.4 GK), where the rate is dominated by the $E_r^{\text{lab}} = 272.3$ keV resonance. In this range, the LUNA rate is approximately 23% higher than the

TABLE II. Resonance strengths measured in this work (not corrected for electron screening) and literature values [23,26]. The format of LUNA data is value $\pm$ statistical uncertainty $\pm$ systematic uncertainty. In the last column, the electron screening factor f is reported.

E_r^{lab} (keV)	$\omega\gamma_{\text{literature}}^a$ (meV)	$\omega\gamma_{\text{LUNA}}$ (meV)	f
127.3	0.0375 ± 0.0075 [26]	$0.0375 \pm 0.0002 \pm 0.0017$	1.10
271.4	2.125 ± 0.375 [23]	$2.7 \pm 0.3 \pm 0.4$	1.03
272.3	82.5 ± 12.5 [23]	$129.9 \pm 0.4 \pm 5.8$	1.03
291.5	2.00 ± 0.37 [23]	$1.99 \pm 0.01 \pm 0.09$	1.03
352.6	8.125 ± 1.375 [23]	$14.9 \pm 0.4 \pm 0.7$	1.02

^aValues taken from Table 1 of Ref. [23], except for the resonance strength of $E_r^{\text{lab}} = 127.3$ keV taken from Table 1 of Ref. [26].

one reported in Iliadis *et al.* [46]. At lower temperatures ($T < 0.1$ GK), relevant for AGB stars, the new rate is compatible with the previous one, but more precise.

To evaluate the astrophysical impact of the updated rate, we used different stellar evolution codes according to the astrophysical scenario. We performed hydrodynamic simulations of ONe novae using the *shiva* code [47,48], which is widely applied in modeling stellar explosions such as classical novae, x-ray bursts, and Type Ia supernovae. Simulations were performed for three different white dwarf masses: 1.05, 1.15, and $1.25 M_{\odot}$. For each case, two models were computed, using the new LUNA recommended $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction rate and the Iliadis *et al.* reaction rate [46]. Further calculations were performed using the LUNA $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ high and low rates (1σ uncertainty). For both tests, the results show that the mass-averaged abundances of isotopes sensitive to the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction, including ^{22}Ne , ^{22}Na , and ^{25}Mg , remain essentially unchanged, due to the well-constrained reaction rate in the LUNA energy range.

For the AGB scenario, we considered a $5 M_{\odot}$ star with solar metallicity ($Z = 0.014$), representative of HBB conditions. Nucleosynthesis calculations using both the LUNA and Iliadis *et al.* [46] rates showed no significant differences in the final elemental abundances. This confirms the limited sensitivity of the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction rate in AGB stars and further supports the robustness of the thermonuclear reaction rate.

Conclusions. We have presented new high-precision direct measurements of five low-energy resonances in the $^{21}\text{Ne}(p, \gamma)^{22}\text{Na}$ reaction performed at the LUNA underground laboratory. The resonance strengths at $E_r^{\text{lab}} = 127.3$, 272.3, and 291.5 keV were determined with uncertainties as low as 4%, while those at 271.4 and 352.6 keV were measured with uncertainties of 19% and 5%, respectively. In particular, the strength of the 272.3-keV resonance, which affects the nova energy range, shows a 3.4σ increase compared to previous measurements. New branching ratios were determined for three resonances ($E_r^{\text{lab}} = 127.3$, 272.3, and 352.6 keV), providing updated decay schemes. The improved resonance strengths were used to determine a new thermonuclear reaction rate using Monte Carlo techniques and to investigate

the impact on the NeNa nucleosynthesis. The new rate is about 23% higher than previous evaluations for temperatures near peak values for novae, mainly due to the new data for the 272.3-keV resonance. Nevertheless, the hydrodynamic models of the classical novae show no variation on ^{22}Na production in novae, when this new rate is used. In AGB stars, the impact of the revised rate is negligible, confirming the limited sensitivity of that scenario.

Acknowledgments. D.C. and the technical staff of the LNGS are gratefully acknowledged for their support. We acknowledge funding from the following: INFN, the European Union (ERC-CoG STARKEY, Grant No. 615604; ERC-StG SHADES, Grant No. 852016; and ChETEC-INFRA, Grant No. 101008324), the Deutsche Forschungsgemeinschaft (DFG, Grant No. BE 4100-4/1), the Helmholtz Association (Grant No. ERC-RA-0016), the Hungarian National Research, Development, and Innovation Office (Grant No. NKFIH K134197), and the European Collaboration for Science and Technology (COST Action ChETEC, Grant No. CA16117). E.M. acknowledges an Alexander von Humboldt postdoctoral fellowship. M.A., C.G.B., T.D., and R.S.S. acknowledge funding from STFC (Grant No. ST/P004008/1). J.J. acknowledges support from the Spanish MINECO under Grant No. PID2023-148661NB-I00, the E.U. FEDER funds, and the AGAUR/Generalitat de Catalunya under Grant No. SGR-386/2021. We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for Tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union—NextGenerationEU—Projects Title CaBS, CUP E53D230023, and Title SOCIAL, CUP I53D23000840006—Grant Assignment Decree No. 974 adopted on 30/06/2023 by MUR, the Lendület Program LP2023-10 of the Hungarian Academy of Sciences and STFC ST/V001051/1.

Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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