Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu$(p,\gamma)^{58}$Zn Identified with GRETINA

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An approach is presented to experimentally constrain previously unreachable (p,γ) reaction rates on nuclei far from stability in the astrophysical *rp* process. Energies of all critical resonances in the ^{57}Cu$(p,\gamma)^{58}$Zn reaction are deduced by populating states in ^{58}Zn with a (d, n) reaction in inverse kinematics at 75 MeV/u, and detecting γ-ray-recoil coincidences with the state-of-the-art γ-ray tracking array GRETINA and the S800 spectrograph at the National Superconducting Cyclotron Laboratory. The results reduce the uncertainty in the ^{57}Cu(p,γ) reaction rate by several orders of magnitude. The effective lifetime of ^{56}Ni, an important waiting point in the *rp* process in x-ray bursts, can now be determined entirely from experimentally constrained reaction rates.

The classic doubly magic nucleus ^{56}Ni plays a special role in nuclear physics and astrophysics. It has been identified as one of the potential waiting points in the rapid proton-capture process (*rp* process), a sequence of rapid proton captures and β^+ decays near the proton drip line, that powers type I x-ray bursts. X-ray bursts are frequently observed thermonuclear flashes ignited on the surface of accreting neutron stars with periods of hours to days [1–4]. Once the underlying nuclear physics is understood, comparisons of burst observations with models offer a unique pathway to constrain neutron star properties, such as accretion rate, accreted composition, or stellar radius [5–10].

Waiting points in the *rp* process, such as ^{56}Ni, are nuclei with relatively long decay lifetimes and low proton-capture Q values, where the reaction flow slows down significantly. This affects energy production and therefore observed burst light curves. Of all the waiting points along the *rp*-process path, ^{56}Ni has the longest decay lifetime of $\sim 2.3 \times 10^4$ s under typical x-ray burst conditions [1,2,11]. As this is longer than typical burst time scales of 10–100 s, the delay ^{56}Ni imposes on the *rp* process is entirely determined by

its effective lifetime against proton capture, which needs to be known to reliably model x-ray burst light curves and to interpret observations [5,6,10]. It is also needed to predict the composition of the burst ashes that define the composition of the neutron star crust [12], and that may be partially ejected into the stellar medium to produce observable x-ray spectral features [13,14]. In this context, the effective lifetime of ^{56}Ni determines the amount of $A = 56$ material in the neutron star crust (in systems where the composition is not modified by subsequent reignition of the ashes, such as is observed in the rare superbursts [15]). It has recently been shown that small quantities of $A = 56$ nuclei can trigger significant crust cooling via neutrino Urca processes [16], with cooling rates scaling with the $A = 56$ abundance.

In this Letter, we address the largest remaining nuclear physics uncertainty in the determination of the effective *rp*-process lifetime of ^{56}Ni. The ^{56}Ni proton-capture lifetime is determined by the masses and spins of low-lying levels of ^{56}Ni, ^{57}Cu, and ^{58}Zn, by the β-decay lifetimes of ^{57}Cu and ^{58}Zn, and by the proton-capture rates on ^{56}Ni and ^{57}Cu [2]. All these quantities have been constrained experimentally including the proton-capture rate on ^{56}Ni [17], with the

exception of the $^{57}Cu(p,\gamma)^{58}Zn$ reaction rate. This reaction rate determines the ^{56}Ni lifetime for temperatures in the range of 0.7–1.4 GK [when ^{56}Ni and ^{57}Cu are in (p,γ)-(γ,p) equilibrium, but ^{57}Cu and ^{58}Zn are not], well within the range of typical x-ray burst peak temperatures. Under these circumstances the $^{57}Cu(p,\gamma)^{58}Zn$ reaction drives the breakout from the (p,γ)-(γ,p) equilibrium. This has been confirmed by sensitivity studies that have identified the $^{57}Cu(p,\gamma)^{58}Zn$ reaction rate as important for the prediction of burst light curves and the composition of burst ashes [18,19]. However, no experimental data are available on the states in ^{58}Zn that determine the $^{57}Cu(p,\gamma)^{58}Zn$ rate. The currently recommended astrophysical reaction rate is therefore exclusively based on shell-model predictions [20] and suffers from orders of magnitude uncertainties, mainly due to the unknown excitation energies of states in ^{58}Zn that serve as proton-capture resonances.

The recently developed state-of-the-art γ-ray energy tracking array GRETINA [21], with its significantly enhanced detection efficiency and signal-to-background ratio, opens up the possibility to experimentally constrain many of the rp-process proton-capture rates that were previously out of reach. In this Letter we report first results for $^{57}Cu(p,\gamma)^{58}Zn$ obtained with a novel approach where the $d(^{57}Cu,^{58}Zn)n$ reaction in inverse kinematics was used to preferentially populate the proton single-particle states in ^{58}Zn that may serve as proton-capture resonances. The approach employs a relatively high ^{57}Cu beam energy of 75 MeV/u, enabling the use of a thick target which—together with the large γ-ray detection efficiency of GRETINA—provides the required sensitivity. The populated low-lying ^{58}Zn levels de-excite in-flight mainly by γ-ray emission. Excitation energies E_x are deduced from the measurement of the γ-ray energies with subsequent Doppler correction, and together with the known reaction Q value, the resonance energies $E_r = E_x - Q$ in the $^{57}Cu(p,\gamma)^{58}Zn$ reaction can be obtained.

The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A radioactive ^{57}Cu beam was produced by accelerating stable ^{58}Ni to 160 MeV/u using the NSCL Coupled Cyclotron Facility, and impinging the beam on a 752 mg/cm^2 ^9Be target situated at the entrance of the A1900 fragment separator [22]. Nucleon exchange and pickup reactions produced the secondary ^{57}Cu beam [23]. The radioactive beam was purified with the A1900 fragment separator using the $B\rho - \Delta E - B\rho$ technique in combination with a 300 mg/cm^2 Al wedge installed in the intermediate focal plane. The resulting ^{57}Cu beam had an average intensity of $\sim 3 \times 10^4$ pps, and a beam purity of $\sim 20\%$.

The (d,n) proton-transfer reactions were induced in a CD$_2$ target installed in the center of GRETINA. The recoiled neutron was not measured. Contributions from reactions with the carbon in the CD$_2$ target were determined by separate measurements with a C target. The ^{58}Zn projectile-like residue was identified using energy-loss, position, and time-of-flight detectors situated in the focal plane of the S800 spectrograph [24] located behind GRETINA. For each detected ion, tracking in the S800 focal plane provided kinematic information that was used together with the γ-ray hit position information of GRETINA for an accurate Doppler-shift correction of the measured γ-ray energies emitted in-flight. To achieve the luminosity needed for the detection and identification of $\gamma - \gamma$ coincidences, the CD$_2$ target was chosen to be relatively thick with an areal density of 225 mg/cm^2 (2.8 mm). This target thickness results in a large beam energy loss (which translates into a large velocity spread $\Delta\beta$, with $\beta = v/c$), and, thus, an overall energy resolution of $\sim 2\%$ was achieved after Doppler correction. At γ-ray energies around 2900 keV the resolution is not sufficient for the separation of a transition doublet. In this case, the unique geometrical arrangement of the GRETINA crystals was utilized using a cut around $70°$ in the γ-ray polar detection angle Θ_{Lab} to obtain a nearly target-thickness-independent resolution (see Eq. 5 in Ref. [25] for large $\Delta\beta$). The in-flight γ-ray detection efficiency for the singles mode was extracted by using standard calibration sources with a correction for a beam velocity of $\beta \approx 0.32$. For the strongest γ-ray transition at $E_\gamma = 1356$ keV a singles detection efficiency of $\sim 4.5\%$ was extracted. In order to reconstruct the low-lying level scheme of ^{58}Zn ($T_z = 1$) and tentatively assign spin-parities, $\gamma - \gamma$ coincidences along with experimental information of mirror states from the stable $T_z = -1$ isospin partner ^{58}Ni were used (see, e.g., Refs. [26–29]). We assign the strongest peak in the γ-ray spectrum with an energy of $E_\gamma = 1356(3)$ keV to the transition of the $J^\pi = 2_1^+$ state to the ground state (Fig. 1). Based on the structure of the mirror nucleus we expect this to be a strong line fed by the decay of higher-lying levels, and the energy agrees with the known excitation energy in ^{58}Ni of 1454 keV
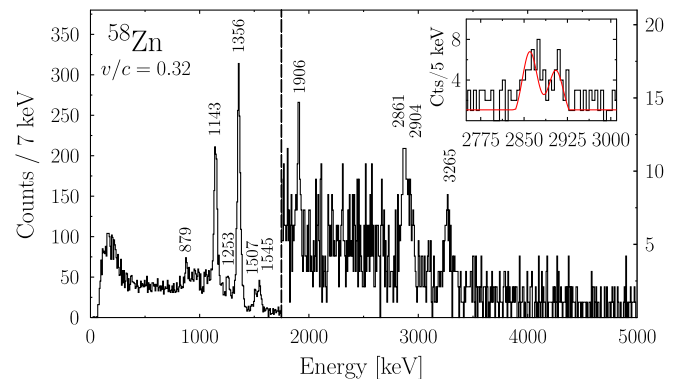

FIG. 1 (color online).   Doppler-corrected γ-ray spectrum measured with GRETINA when gating on ^{58}Zn ions in the S800 focal plane. A simple next-neighbor addback routine has been applied. Inset: Resolving the transition doublet at around 2900 keV by applying a cut in the γ-ray polar detection angle of $\Theta_{lab} \approx 70°$.
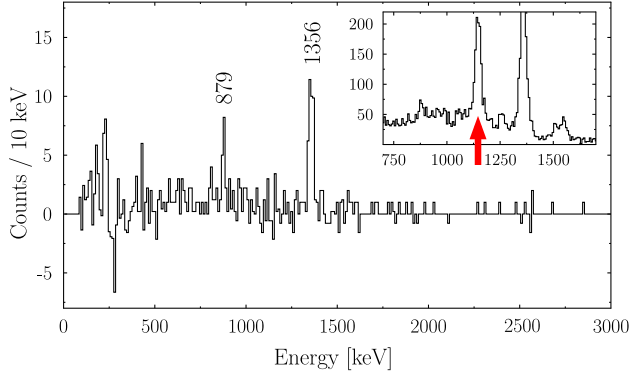
FIG. 2 (color online). The $\gamma - \gamma$ coincidence technique was used to support the extraction of the level scheme. As an example, coincidences are shown when gating on the 1143 keV γ-ray transition (red arrow shown in the inset; same units as in Fig. 1).

within a typical shift of ~ 100 keV. The second strongest transition at $E_\gamma = 1143(3)$ keV is in coincidence with $E_\gamma = 1356(3)$ keV and the weaker $E_\gamma = 879(4)$ keV transition (Fig. 2). Based on the structure of ^{58}Ni we assign $E_\gamma = 1143(3)$ keV to the $4_1^+ \rightarrow 2_1^+$ transition, placing the $J^\pi = 4_1^+$ state at 2499(4) keV, close to the known $J^\pi = 4_1^+$ excitation energy of 2459 keV in the mirror. Based on similar arguments we assign $E_\gamma = 879(4)$ keV to the $3_1^+ \rightarrow 4_1^+$ transition.

We also observe three additional γ-ray transitions at 1507(4) keV, 1545(3) keV, and 1906(4) keV, which differ in energy by 1356 keV from three transitions observed at 2861(4) keV, 2904(5) keV, and 3265(6) keV, respectively. This indicates that decays from energy levels located at the latter three excitation energies feed both the ground and the $J^\pi = 2_1^+$ state. The $E_\gamma = 2861(4)$ keV and 2904(5) keV γ rays form a transition doublet that we resolve by restricting the polar angle Θ_{Lab} to around 70°, achieving high energy resolution (see inset in Fig. 1). There is one more γ ray with

$E_\gamma = 1253(5)$ keV in coincidence with the $2_1^+ \rightarrow 0^+$ transition, indicating a fourth additional state at 2609(6) keV. For this state we do not observe a transition to the ground state.

Two of these four additional states have rather small or no observed ground-state branchings [the 2609 keV and the 2904 keV state with no observed ground-state branching and 19(7)%, respectively], while the remaining two have rather large ground-state branchings [2861 keV and 3265 keV with 47(16)% and 64(25)%, respectively]. In the mirror nucleus, the $J^\pi = 2_2^+$ and $J^\pi = 1_1^+$ states at 2775 keV and 2902 keV are known to have small ground-state branchings (4% and 6%), while the $J^\pi = 2_3^+$ and $J^\pi = 2_4^+$ states are known to have large ground-state branchings (41% and 60%). Based on this, and by requiring reasonable Coulomb shifts, we can tentatively assign these states (Table I and Fig. 3). With these assignments Coulomb shifts span the range from 1 keV to 176 keV, in line with shifts observed for nuclei in the lower and upper pf-shell region (see Ref. [30] and references therein).

The main uncertainty in this assignment is whether the 2904 keV state is the $J^\pi = 1_1^+$ state and the 2861 keV state the $J^\pi = 2_3^+$ state, or vice versa. The states are very close in energy, and while the ground-state branching of the 2904 keV state is smaller [19(7)%] than the one of the 2861 keV state [47(16)%], it is not quite as small as expected from the known branching of the $J^\pi = 1_1^+$ state in the mirror (6%). Nevertheless, a possible reversal of this assignment has no significant effect on the ^{57}Cu$(p, \gamma)^{58}$Zn reaction rate (shaded area in the top panel of Fig. 4).

To provide spectroscopic information needed in addition to the measured excitation energies to calculate the ^{57}Cu$(p, \gamma)^{58}$Zn reaction rate using the narrow-resonance approximation [32], we carried out shell-model calculations with the GXPF1A interaction [31]. For this calculation up to four holes in the $f7/2$ orbitals for protons and/ or neutrons were allowed (Table I). Spectroscopic factors

TABLE I. Extracted levels for ^{58}Zn with observed transition energies and relative intensities I_γ. Tentative spin-parity assignments are shown in parentheses. Spectroscopic factors C^2S are taken from shell-model calculations utilizing the GXPF1A interaction [31], and are used to calculate the partial γ widths Γ_γ and partial proton widths Γ_p.

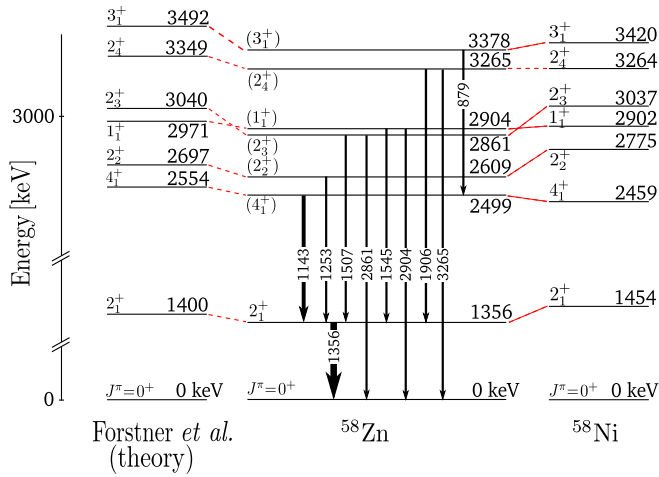|	Experiment			C^2S			
E_x (keV)	E_γ (keV)	I_γ (%)	$J_i^\pi \rightarrow J_f^\pi$	$l = 1$	$l = 3$	Γ_γ (eV)	Γ_p (eV)
1356(3)	1356(3)	100(5)	$2_1^+ \rightarrow 0_{gs}^+$	0.95	0.18	1.4×10^{-3}	
2499(4)	1143(3)	62(6)	$(4_1^+) \rightarrow 2_1^+$		0.69	6.1×10^{-5}	2.1×10^{-17}
2609(6)	1253(5)	7(2)	$(2_2^+) \rightarrow 2_1^+$	0.69	0.011	9.8×10^{-3}	2.5×10^{-10}
2861(4)	1507(4)	8(2)	$(2_3^+) \rightarrow 2_1^+$	0.2	0.025	1.0×10^{-2}	1.4×10^{-5}
	2861(4)	7(2)	$(2_3^+) \rightarrow 0_{gs}^+$				
2904(5)	1545(3)	13(2)	$(1_1^+) \rightarrow 2_1^+$	0.085	0.66	5.8×10^{-3}	2.3×10^{-5}
	2904(5)	3(1)	$(1_1^+) \rightarrow 0_{gs}^+$				
3265(6)	1906(4)	4(2)	$(2_4^+) \rightarrow 2_1^+$	0.11	0.48	5.1×10^{-3}	4.4×10^{-2}
	3265(6)	7(2)	$(2_4^+) \rightarrow 0_{gs}^+$				
3378(5)	879(4)	4(1)	$(3_1^+) \rightarrow (4_1^+)$		0.70	3.4×10^{-3}	1.2×10^{-2}

FIG. 3 (color online). Level scheme of ^{58}Zn in comparison with the results of the shell-model and Coulomb-shift calculation in Ref. [20], and the stable mirror nucleus ^{58}Ni. Tentative assignments are shown in parentheses.

C^2S predicted by this calculation were used to calculate the partial proton and γ widths. Resonance energies $E_r = E_x - Q$ were obtained from measured excitation energies E_x using the AME2012 Q value $Q = 2279(50)$ keV [33]. The direct-capture contribution is calculated using an astrophysical S-factor at the Gamow peak energy E_0 of $S(E_0) = 0.0575$ MeV $\cdot$ b [20]. Due to the structure of the low-lying states, the 2^+ states contribute
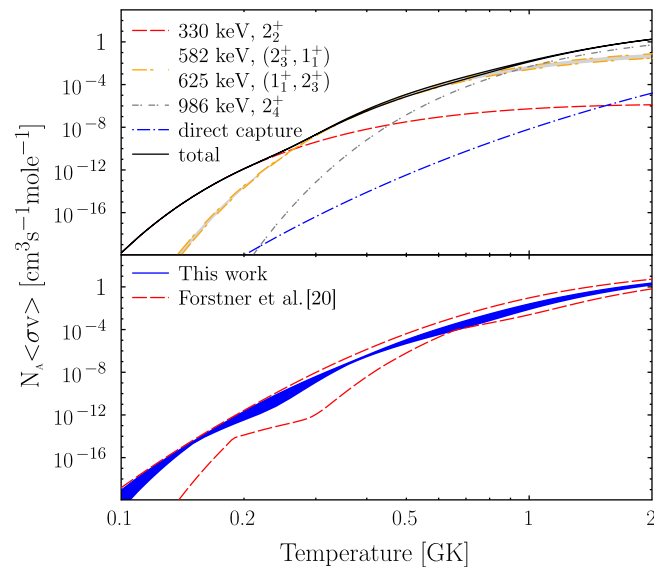
FIG. 4 (color online). Top: Dominant contributions to the ^{57}Cu$(p,\gamma)^{58}$Zn reaction rate. Given are the resonance energies. The shaded area accounts for the uncertain assignment of the $J^\pi = 2_3^+$ and $J^\pi = 1_1^+$ states. Bottom: Upper and lower limits of the ^{57}Cu$(p,\gamma)^{58}$Zn reaction rate prior to our measurement, assuming a 200 keV uncertainty for the ^{58}Zn excitation energies, and from this work.

dominantly to the reaction rate in the typical rp-process temperature range (Fig. 4). Prior to our measurement, the reaction rate was uncertain by up to 4 orders of magnitude for relevant temperatures above 0.3 GK entirely due to the uncertainty of the shell-model predicted energies for the contributing states (Fig. 4). We estimate this uncertainty to be about 200 keV based on a comparison of the measured energy shifts and the predicted shifts in Ref. [20]. This uncertainty reflects the maximum systematic discrepancy found between measured and predicted Coulomb shifts for the few cases known in this region. We note that absolute predictions of excitation energies between various shell-model predictions can differ by up to 300 keV [20,34]. The use of our experimental excitation energies reduces the reaction-rate uncertainty dramatically to at most a factor of 10 (Fig. 4). The remaining uncertainty in the reaction rate is dominated by the 50 keV uncertainty of the Q value [35]. An additional uncertainty of a factor of 2 is estimated to be introduced by uncertainties in partial γ widths based on comparisons of experimental data for the mirror ^{58}Ni and a corresponding shell-model calculation for ^{58}Ni. Uncertainties of spectroscopic factors of $\sim 20\%$ for the dominant states in the reaction rate are negligible.

Preliminary calculations with an x-ray burst model and recommended values for other nuclear physics quantities [36] indicate that a reduction of uncertainty in the ^{57}Cu$(p,\gamma)^{58}$Zn rate from 4 orders of magnitude to a factor of 10 reduces the uncertainty in $A = 56$ nuclei production from just this reaction from a factor of 2 to about 20%. This indicates that our measurement essentially removes the uncertainty contribution of the ^{57}Cu$(p,\gamma)^{58}$Zn reaction in x-ray burst models. However, uncertainties induced by the various nuclear physics quantities that determine the ^{56}Ni lifetime are coupled and also depend on burst model parameters. A comprehensive analysis of the impact these various remaining nuclear physics uncertainties have on x-ray burst observables is beyond the scope of this Letter and will be presented in a forthcoming, longer paper. The major achievement is that this analysis can now be carried out on the basis of experimental data. Our novel experimental approach demonstrated here will enable orders of magnitude reductions of uncertainties in many other rp-process reaction rates, previously out of reach.

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