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Reexamining the β decay of ^{53,54}Ni, ^{52,53}Co, ^{51}Fe, and ^{50}Mn

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The β decay of ^{53,54}Ni, ^{52,53}Co, ^{51}Fe, and ^{50}Mn was investigated via the fragmentation of a ^{58}Ni primary beam with an energy of 68.6 MeV/u. The proton-γ coincidences of ^{53}Ni β-delayed proton emission were observed. Based on the analysis of the proton-γ coincidence events, it was inferred that the previous assignment of the excitation energy for the isobaric analog state in ^{53}Co may be problematic. The half-lives of these nuclei were obtained, in which the uncertainty of ^{52}Co half-life was reduced by a factor of 3. The half-lives were evaluated and used as inputs of nucleosynthesis calculations of the rapid proton-capture process in an x-ray burst.

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I. INTRODUCTION

The decay half-lives ($T_{1/2}$) of proton-rich nuclei together with (p,γ) reaction rates are the essential inputs into reaction network calculations to determine the nucleosynthesis pathways in the rapid proton-capture (rp) process [1]. It is also important to measure the isobaric analog states (IAS) via β-delayed proton emission because the masses of parent nuclei can be precisely determined based on the isobaric multiplet mass equation (IMME) which has been tested for the nuclei close to stability [2]. In addition, the decay branching ratios of proton-rich nuclei help us determine the evolution of shell structure for the nuclei off stability. For example, we can constrain Gamow-Teller (GT) quenching factors through comparison between the experimental and shell model transition strengths B(GT) [3].

While the β decay of proton-rich nuclei has been well studied in the mass region of $A < 100$, there are some remaining discrepancies that could influence the rp-process pathway. Some of the existing experiments were limited to single-proton inclusive detection, which may result in ambiguities of excitation energy assignments of the β-decay daughter nuclei due to possible proton emission to the excited states in the βp daughter nuclei, subsequently leading to possible uncertainties of IMME parameters. Moreover, the β-delayed γ branching ratios, the necessary data for determining B(GT) distributions and quenching factors, were not presented in many previous works. More measurements with full detection of protons, β, and γ rays are desirable to ameliorate this situation.

In particular, ^{53}Ni has a well determined half-life [4,5], but there is insufficient information on the decay branching ratios and the IAS excitation energy in ^{53}Co. The lack of p-γ coincidence data in previous works [4,5] means that the excitation energy of the IAS assigned therein needs to be confirmed. This in turn makes it premature to draw firm conclusions regarding the IMME applicability in the fp shell region.

In this work, the β and βp decays in some fp shell nuclei were measured with a focus on the p-γ coincidence of the ^{53}Ni decay. Our new data were evaluated together with those from previous works and used for discussing the excitation energy of ^{53}Co IAS and the nucleosynthesis in x-ray bursts.

II. EXPERIMENT

The experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL). The K450 separate sector cyclotron (SSC) provided a primary beam of ^{58}Ni with an intensity of 20 enA and an energy of 68.6 MeV/u. The ^{53,54}Ni, ^{52,53}Co, ^{51}Fe, ^{50}Mn, and other nuclides were produced via the fragmentation reaction of ^{58}Ni in a natural nickel target of thickness 147 μm at the Radioactive Ion Beam

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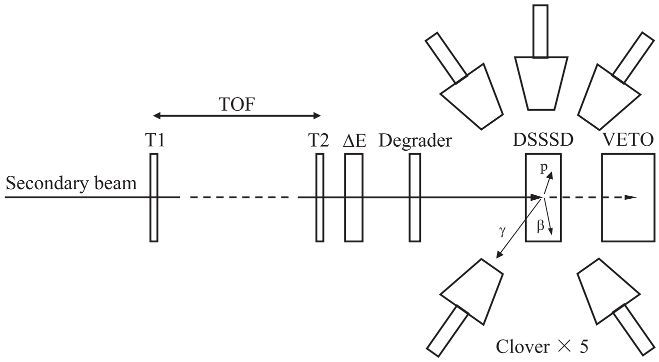

FIG. 1. Schematic layout of the detection setup.

Line in Lanzhou (RIBLL) [6]. The momentum acceptance of RIBLL was set to be 0.49%. During the experiment, the typical intensity of the secondary ^{53}Ni beam was 14 particles per hour, a factor of 10 lower than that estimated with the LISE++ code [7]. The lower than calculated intensity could be due to the overestimation of LISE++ for multineutron stripping cross sections. Although the available secondary beam intensity was relatively low, it still allowed us to carry out the decay measurement, owing to the high efficiencies of our charged-particle and γ-ray detection systems.

The schematic layout of the detection setup is shown in Fig. 1. Two plastic scintillator films (T1 and T2) were used to provide the time-of-flight (TOF) information. The mean flight distance between T1 and T2 is 17 m, and the TOF resolution is 140 ps [8]. The energy loss (ΔE) of the secondary beam was measured by a 280 μm thick silicon detector. The ions in the secondary beam were identified by using the ΔE-TOF information. At the beginning of the experiment, the ΔE-TOF detectors were calibrated via measurements with a low intensity primary beam at various energies obtained by using degraders.

A double-sided silicon strip detector (DSSSD) of thickness 500 μm served as both implantation stopper and as $\beta/\beta p$ detector. A 132 μm thick aluminum degrader was placed upstream to ensure that the desirable ions can be stopped within the DSSSD. The DSSSD position information was used to determine the coincidences of the ion implantation with the $\beta/\beta p$-decay events. A veto detector of thickness 1500 μm was installed downstream to suppress a possible disturbance from the penetrating light particles. Before and after the experiment, the DSSSD and the veto detectors were calibrated with ^{241}Am (α) and ^{207}Bi (β) sources. A logarithmic preamplifier was utilized to accommodate the large dynamic range of heavy ions, protons, and β rays. Moreover, we put a time tag on each decay event with an 11 kHz clock generator to generate a decay-time spectrum.

Outside the DSSSD chamber, five segmented clover detectors were installed to measure the γ rays associated with the decay of proton-rich nuclei. The clover detector array was calibrated with a ^{152}Eu source. The absolute efficiency and energy resolution were measured to be (4.3 ± 0.3)% and 4 keV, respectively, for the 778.9 keV γ ray.

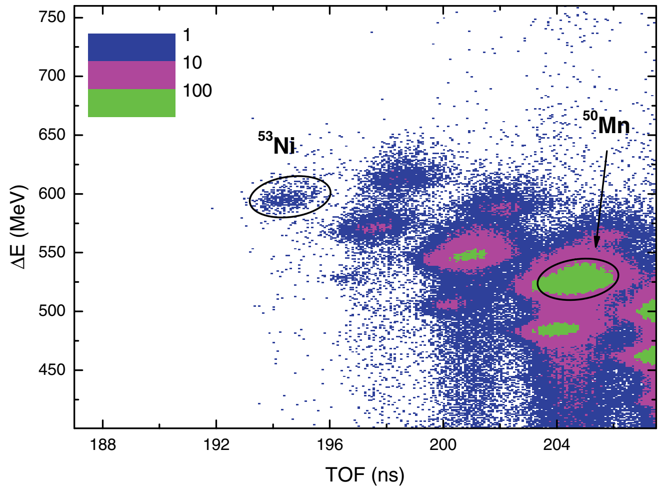

FIG. 2. (Color online) Two-dimensional identification plot of ΔE and TOF. The gates of ^{53}Ni and ^{50}Mn ions are indicated.

III. HALF-LIFE ANALYSIS

The gates of implanted nuclei were applied to the ΔE-TOF two-dimensional particle identification spectrum according to the simulation with LISE++ and the calibration with the ^{58}Ni primary beam, as shown in Fig. 2. The widths of the ΔE and TOF gates were set to be $\pm 2\sigma$ (σ being the measured standard deviation).

To calibrate our system and estimate systematic uncertainties, we examined the decay of ^{50}Mn^m. Figure 3 shows the measured γ-ray spectrum gated by β rays. The labeled peaks are the known γ rays from the decay of the ^{50}Mn isomeric state at 5^+ 229 keV. Based on the γ windows and the ΔE-TOF gate, the half-life of ^{50}Mn^m was determined to be 1.74 ± 0.1 min. The relative γ intensities of ^{50}Mn^m were also obtained, as listed in Table I. The above results are in good agreement with the previous measurements [9,10].

The decay signals were associated with implantation events through their position and time information. Whenever a desired implantation event occurs, a time window of 10 s

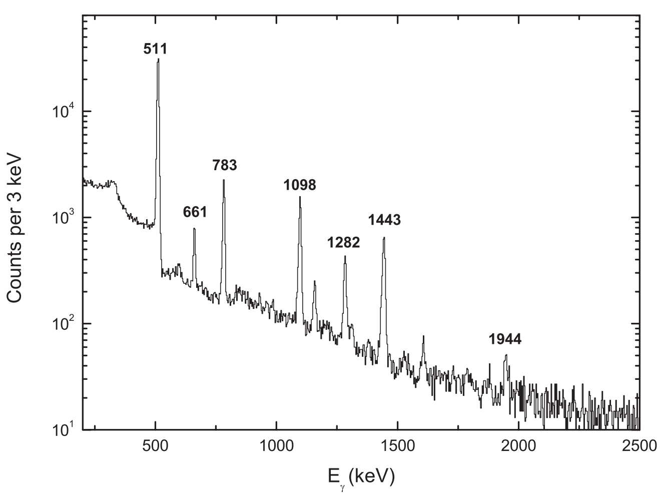

FIG. 3. γ-ray spectrum in coincidence with β rays; the peaks marked are the known γ rays from the ^{50}Mn^m decay.

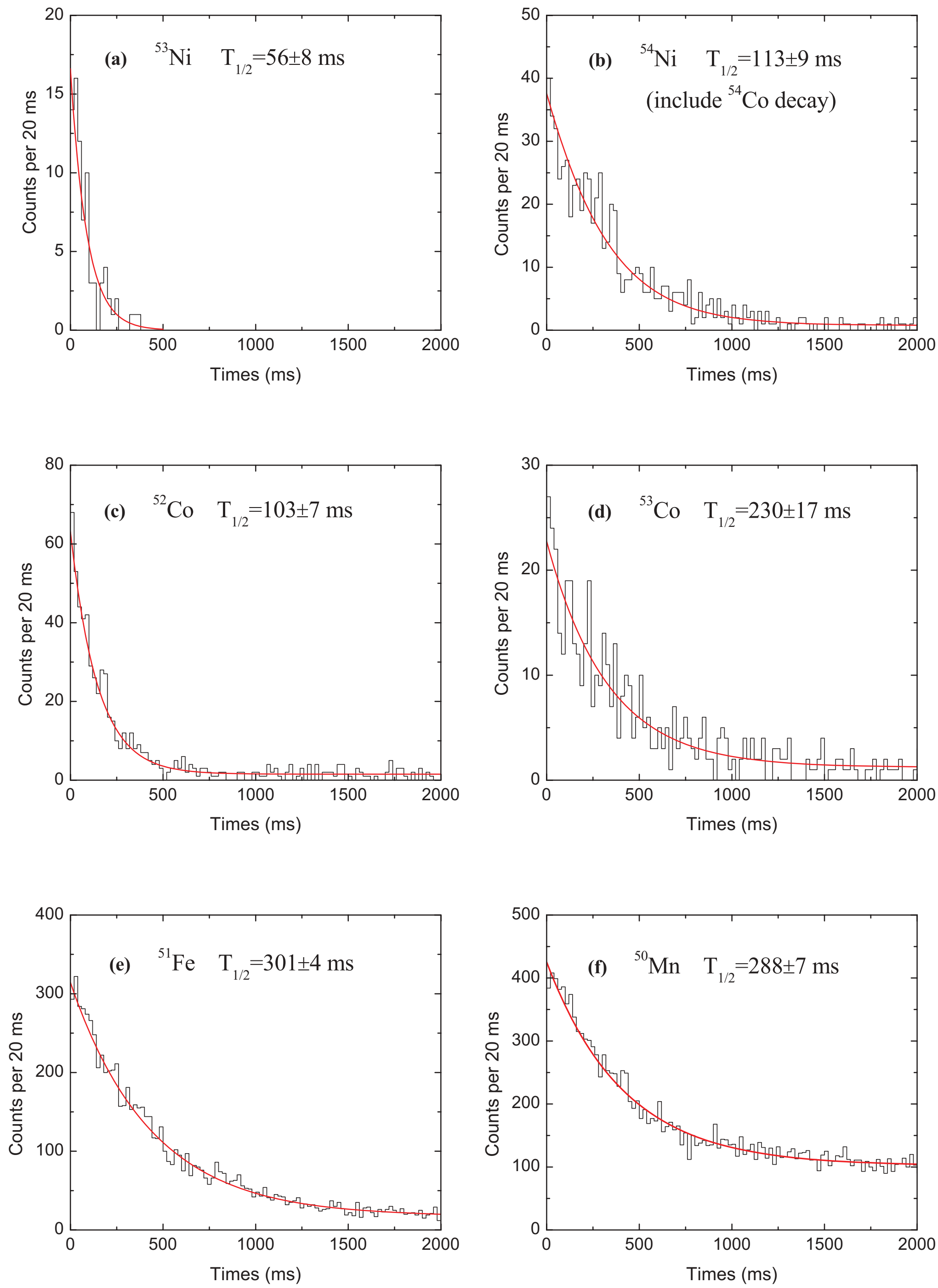

FIG. 4. (Color online) Decay-time spectra of ^{53,54}Ni, ^{52,53}Co, ^{51}Fe, and ^{50}Mn together with the exponential fitted curves.

was opened, in which the subsequent βp or β events in the same pixel were recorded. The time differences between ion implantations and decay events were used to construct decay-time spectra. Figure 4 shows the obtained decay-time spectra of ^{53,54}Ni, ^{52,53}Co, ^{51}Fe, and ^{50}Mn, in which the decay-time spectrum of ^{53}Ni was derived with the gate of the βp events. Since ^{53}Ni is the only nuclide with a sizable βp-decay branch [5] in the secondary beam, the disturbance from any other nuclei was negligible and the decay-time spectrum of ^{53}Ni was basically free of background. For the remaining nuclei, the decay-time spectra were gated by the β events, hence the presence of other long-lived nuclei in the secondary beam produced a nearly constant background in the corresponding decay-time spectra.

The decay-time spectra of ^{53}Ni, ^{52,53}Co, ^{51}Fe, and ^{50}Mn were fitted to extract their half-lives with a formula composed of an exponential decay and a constant background. The decay-time spectrum of ^{54}Ni was analyzed with the successive decay

TABLE I. Relative intensities of γ rays associated with $^{50}Mn^m$ decay compared with the previous works.

γ energy (keV)	Relative intensity (%)		
	Present work	Sutton [9]	Raman [10]
661	27 ± 2	20 ± 7	25 ± 1
783	100 ± 5	100 ± 12	100 ± 2
1098	97 ± 5	98 ± 11	103 ± 4
1282	31 ± 2	27 ± 5	33 ± 2
1443	61 ± 3	62 ± 12	69 ± 5
1944	3.8 ± 0.6		3.8 ± 0.5

equation because the ^{54}Ni and its daughter nucleus ^{54}Co have comparable half-lives. Our results are in good agreement with the half-lives from previous works, with the uncertainty of the ^{52}Co half-life being reduced by a factor of 3. The present half-lives of the above nuclei are listed in Table II together with the previous data. Our recommended values were given by the weighted average of all the data therein, and were inputted to the rp-process network calculation.

IV. ANALYSIS OF THE ^{53}NI DECAY

The energy spectrum of ^{53}Ni β-delayed protons measured in the present work is shown in Fig. 5. The main peaks are marked according to those given by Dossat *et al.* [5]. In their work [5], the peak at 1929 keV was assigned to the proton emission from the IAS in ^{53}Co. They assumed that this emission goes to the first excited state (2^+) in ^{52}Fe, which deexcites to the ground state (0^+) via emitting an 849 keV γ ray. The excitation energy of the ^{53}Co IAS was then conjectured to be 4380 keV.

It is worth noting that the previous works have not measured the p-γ coincidence of the ^{53}Ni decay [4,5], and thus the above assignment of the excitation energy for the ^{53}Co IAS lacked the sufficient experimental basis. In order to verify this assignment, we analyzed the p-γ coincidence data by adding the proton gates to the γ-ray spectrum, as shown in Fig. 6. Figure 6(a) shows the γ spectrum gated with the ^{53}Ni decay, in which there is a clear peak at 511 keV and a visible peak with four events at 849 keV. Figure 6(b) displays the γ spectrum gated with the ^{53}Ni decay and tagged with the proton peak at 1929 keV, where no events appear at 849 keV. Figure 6(c) is the γ spectrum gated with the ^{53}Ni decay and tagged with the proton peak at 2399 keV, where three events appear at 849 keV. Figure 6(d) is the γ spectrum gated with the random events, and no events at 849 keV were observed.

TABLE II. Summary of the half-lives obtained in the present and previous works, and our recommended values.

Nucleus	Half-life (ms)		
	Present work	Previous work	Recommended data
^{53}Ni	56 ± 8	55.2 ± 0.7 [5]	55.2 ± 0.7
^{54}Ni	113 ± 9	104 ± 7 [11][a]	107 ± 6
^{52}Co	103 ± 7	115 ± 23 [12]	104 ± 7
^{53}Co	230 ± 17	240 ± 9 [13]	238 ± 8
^{51}Fe	301 ± 4	305 ± 5 [14]	303 ± 3
^{50}Mn	288 ± 7	283.19 ± 0.10 [15][b]	283.19 ± 0.10

[a]Weighted average of 106 ± 12 ms [16] and 103 ± 9 ms [13].
[b]Weighted average of 283.10 ± 0.14 ms [17], 283.29 ± 0.08 ms [18], 282.72 ± 0.26 ms [19], and 282.8 ± 0.3 ms [20].

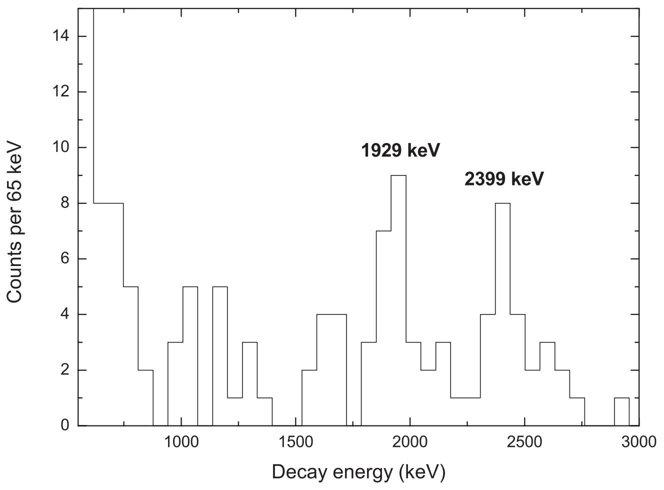

FIG. 5. Energy spectrum of the ^{53}Ni β-delayed protons.

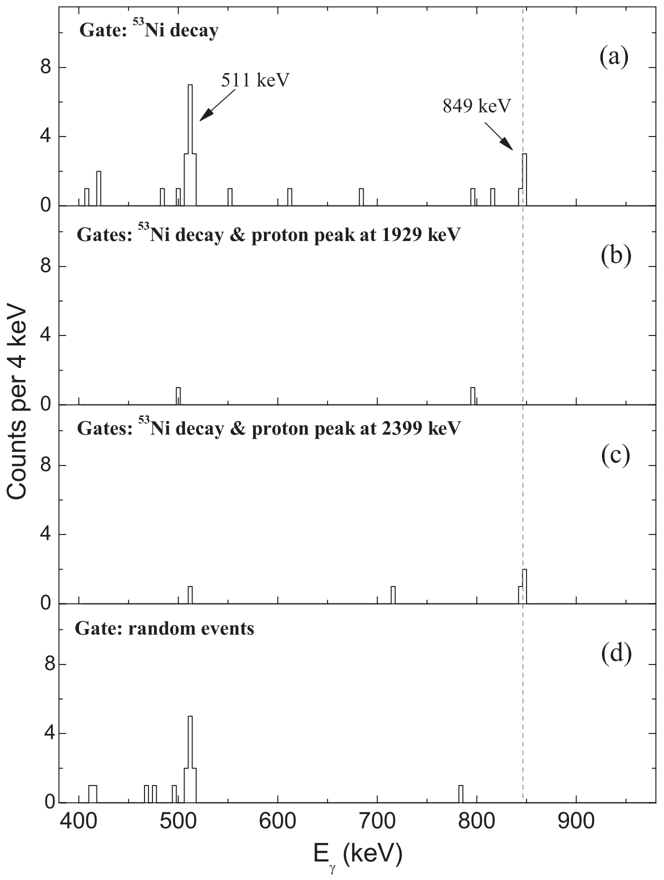

FIG. 6. γ-ray spectra measured in this work: (a) gated with the ^{53}Ni decay, (b) gated with the ^{53}Ni decay and tagged with the proton peak at 1929 keV, (c) same as (b), but tagged with the proton peak at 2399 keV, and (d) gated with random events. See text for further details.

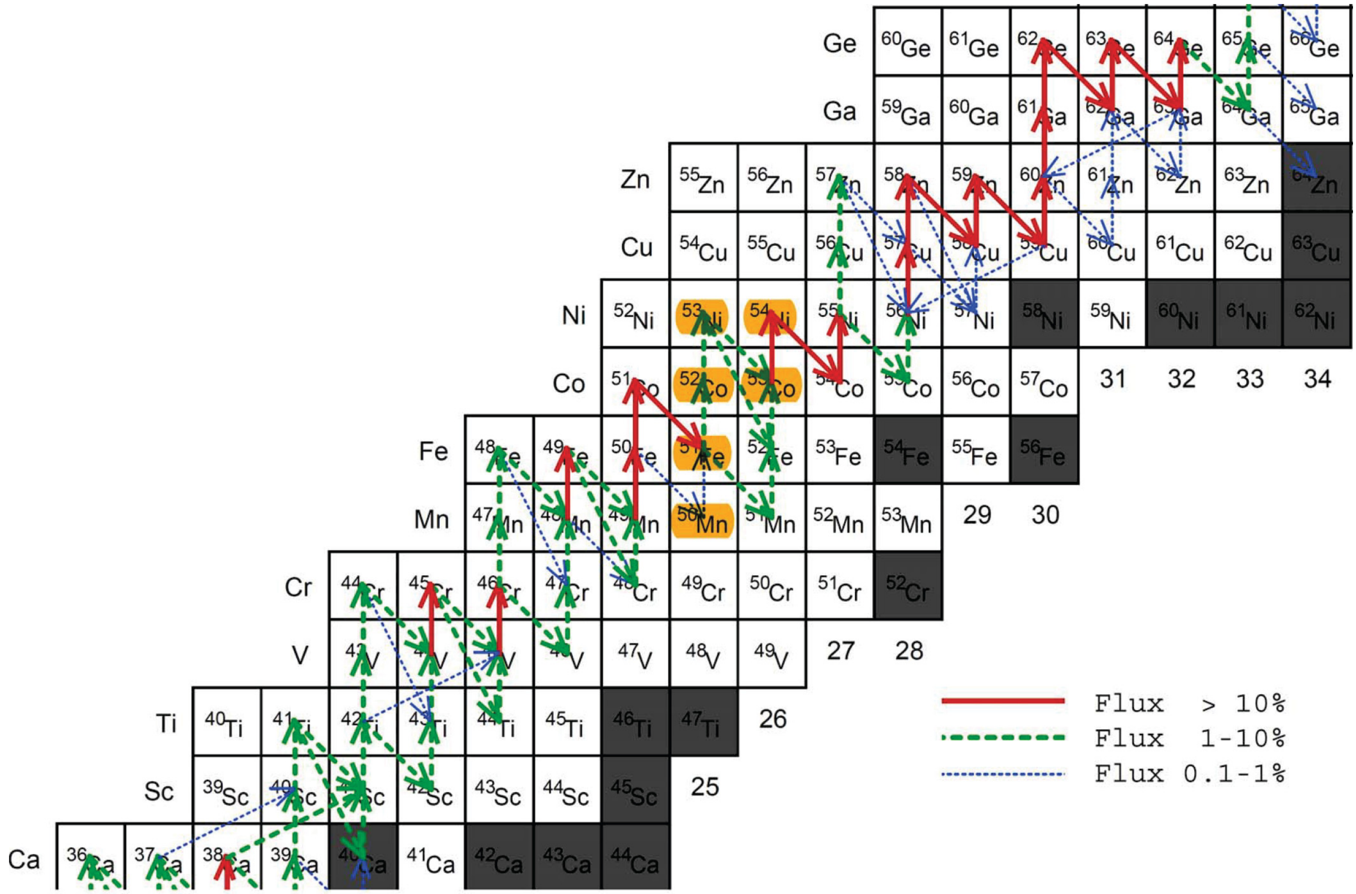

FIG. 7. (Color online) Results of a rp-process network calculation showing the mass flow in the $Z = 20$ to $Z = 32$ region at ∼500 s after the peak temperature phase of the x-ray burst. Stable nuclei are marked in gray. The half-lives of highlighted isotopes were determined in the present experiment.

Based on the decay mode of ^{53}Ni given in Refs. [4,5], each 1929 keV proton emitted from the ^{53}Co IAS should be associated with an 849 keV γ ray. According to the γ-ray detection efficiency and the number of protons detected in our experiment, the probability of missing corresponding events in Fig. 6(b) would be 37.5%. Contrarily, if ^{53}Co emits a proton from the IAS directly to the ground state in ^{52}Fe, instead of to its first excited state, then the absence of 849 keV γ-ray events in Fig. 6(b) is reasonable. The latter possibility means that the ^{53}Co IAS excitation energy should be reduced from 4380 to 3531 keV, which significantly deviates from the IMME prediction.

V. IMPLICATION FOR *rp*-PROCESS NETWORK

To study the possible impact of the present recommended half-lives on the rp-process pathway, a reaction network calculation for a one-zone x-ray burst was carried out by using the code described in Ref. [21] which is based upon the equations in Ref. [22]. The simulation used the REACLIB [23] database for the main reaction rates, the x-ray burst model previously described in Ref. [24], and the time-dependent temperature and density profile given in Ref. [25]. The initial abundances were taken from Ref. [26]. Figure 7 displays the main reaction flow in the region from Ca ($Z = 20$) to Ge ($Z = 32$), which shows little change from the standard reaction flow path.

VI. CONCLUSION AND DISCUSSION

We have measured the decay properties of six rp-process nuclei at the Lanzhou unstable beam line RIBLL. A more accurate half-life of ^{52}Co was extracted. Proton-γ coincidences were obtained for the β-delayed proton emission of ^{53}Ni. If the 1929-849 keV proton-γ coincidence mentioned in Sec. IV still cannot be observed in further experiments, the ^{53}Co IAS excitation energy should be reduced from 4380 to 3531 keV, and the applicability of IMME for the $A = 53$ ($T = 3/2$) quartet would be problematic. This is of especial interest since Zhang *et al.* have measured the ^{53}Ni mass at the HIRFL-CSR facility recently [27], where they found a breakdown of the quadratic form of IMME for the $A = 53$ ($T = 3/2$) quartet. Otherwise the IAS excitation energy given by Dossat *et al.* [5] should be reduced by 78 keV. Indeed, a new experiment with better statistics and proton energy resolution is highly desirable to pin down the possible deviation of the ^{53}Co IAS excitation energy.

We also studied the astrophysical implication of the new half-lives by simulating an x-ray burst center zone. The result shows little change from the standard reaction flow path.

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[1] M. S. Smith and K. E. Rehm, Annu. Rev. Nucl. Part. Sci. **51**, 91 (2001).
[2] J. Britz, A. Pape, and M. S. Antony, At. Data Nucl. Data Tables **69**, 125 (1998).
[3] W. Liu *et al.*, Phys. Rev. C **58**, 2677 (1998).
[4] D. J. Vieira *et al.*, Phys. Lett. B **60**, 261 (1976).
[5] C. Dossat *et al.*, Nucl. Phys. A **792**, 18 (2007).
[6] Z. Sun *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **503**, 496 (2003).
[7] O. B. Tarasov and D. Bazin, Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 4657 (2008).
[8] J. X. Li *et al.*, High Energy Phys. Nucl. Phys. **23**, 231 (1999).
[9] D. C. Sutton, Ph.D. thesis, Princeton University, 1962 (unpublished).
[10] S. Raman *et al.*, Nucl. Phys. A **184**, 138 (1972).
[11] J. D. Huo and S. Huo, Nucl. Data Sheets **107**, 1393 (2006).
[12] E. Hagberg *et al.*, Nucl. Phys. A **613**, 183 (1997).
[13] M. J. López Jiménez *et al.*, Phys. Rev. C **66**, 025803 (2002).
[14] H. Hama *et al.*, Cyclotron Rad. Center, Tohoku Univ., Ann. Rept. 1987, 43 (1988).
[15] E. Zoltan, T. Janos, and S. Balraj, Nucl. Data Sheets **112**, 1 (2011).
[16] I. Reusen *et al.*, Phys. Rev. C **59**, 2416 (1999).
[17] P. H. Barker and A. P. Byrne, Phys. Rev. C **73**, 064306 (2006).
[18] V. T. Koslowsky *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **401**, 289 (1997).
[19] D. H. Wilkinson and D. E. Alburger, Phys. Rev. C **13**, 2517 (1976).
[20] J. M. Freeman *et al.*, Phys. Lett. B **53**, 439 (1975).
[21] N. C. Shu *et al.*, Nucl. Phys. A **758**, 419 (2005).
[22] L. Van Wormer *et al.*, Astrophys. J. **432**, 326 (1994).
[23] R. H. Cyburt *et al.*, Astrophys. J. Suppl. **189**, 240 (2010).
[24] A. Heger *et al.*, Astrophys. J. **671**, L141 (2007).
[25] M. S. Smith *et al.*, http://www.nucastrodata.org
[26] E. Anders and N. Grevesse, Geochim. Cosmochim. Acta **53**, 197 (1989).
[27] Y. H. Zhang *et al.*, Phys. Rev. Lett. **109**, 102501 (2012).