

# Total absorption spectroscopy of two isomers in $^{70}\text{Cu}$ influencing nucleosynthesis signatures

E. K. Ronning<sup>1,2,\*</sup>, A. L. Richard<sup>1,3,‡</sup>, S. N. Liddick<sup>1,2</sup>, A. Spyrou<sup>1,4</sup>, I. Yandow<sup>1,4</sup>, R. Ringle<sup>1</sup>, G. W. Misch<sup>5</sup>, M. R. Mumpower<sup>1,5,6,7,8</sup>, B. A. Brown<sup>1,4</sup>, A. Chester<sup>1</sup>, K. Childers<sup>9</sup>, S. Cupp<sup>5,6</sup>, P. DeYoung<sup>10</sup>, G. Owens-Fryar<sup>1,4</sup>, A. Gross<sup>5,6</sup>, A. Hamaker<sup>1,4</sup>, C. Harris<sup>1,4</sup>, R. Lewis<sup>1,2</sup>, R. S. Lubna<sup>1</sup>, S. Lyons<sup>11</sup>, M. J. Mogannam<sup>1,2</sup>, A. Palmisano-Kyle<sup>12</sup>, D. Puentes<sup>1,4</sup>, T. M. Sprouse<sup>5,6</sup>, C. S. Sumithrarachchi<sup>1</sup>, M. Wiedeking<sup>13,14,15</sup> and Y. Xiao<sup>16</sup>

<sup>1</sup>*Facility for Rare Isotope Beams, East Lansing, Michigan 48824, USA*

<sup>2</sup>*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*

<sup>3</sup>*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*

<sup>4</sup>*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

<sup>5</sup>*Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*

<sup>6</sup>*Center for Theoretical Astrophysics, Los Alamos, New Mexico 87544, USA*

<sup>7</sup>*Obsidian Research, Fort Wayne, Indiana 46835, USA*

<sup>8</sup>*Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46656, USA*

<sup>9</sup>*Remote Sensing Laboratory, Nevada National Security Site, North Las Vegas, Nevada 89030, USA*

<sup>10</sup>*Hope College, Holland, Michigan 49423, USA*

<sup>11</sup>*Pacific Northwest National Laboratory, Richland, Washington 99354, USA*

<sup>12</sup>*Department of Nuclear Engineering, University of Tennessee Knoxville, Knoxville, Tennessee 37996, USA*

<sup>13</sup>*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

<sup>14</sup>*SSC Laboratory, iThemba LABS, P.O. Box 722, Somerset West, 7129, South Africa*

<sup>15</sup>*School of Physics, University of the Witwatersrand, 2050 Johannesburg, South Africa*

<sup>16</sup>*University of Kentucky, Lexington, Kentucky 40506, USA*



(Received 12 September 2024; revised 14 January 2026; accepted 14 April 2026; published 4 May 2026)

Isomers have long been known to be important for astrophysical nucleosynthesis processes, yet they are often neglected in network calculations due to computational limitations or lack of data. "Astomers" are astrophysically metastable nuclear states that can greatly impact nucleosynthesis pathways. In this work we show that astomers further impact the time-dependent electromagnetic signal during heavy element nucleosynthesis. In an experiment performed at the National Superconducting Cyclotron Laboratory, three  $\beta$ -decaying states of  $^{70}\text{Cu}$  ( $6^-$  ground state, and two isomeric states:  $3^-$  and  $1^+$ ) were produced.  $\beta$ -feeding values were extracted from experimental spectra and compared to shell-model and QRPA + PVC calculations. Average  $\gamma$ -ray energies from the  $\beta$ -decay events were incorporated into simulations of heavy element nucleosynthesis and were found to exhibit different energy release profiles over time, which may impact, in aggregate, time-dependent observable signals.

DOI: [10.1103/sy2b-3pbr](https://doi.org/10.1103/sy2b-3pbr)

## I. INTRODUCTION

The important role played by nuclear isomers (long-lived excited nuclear states) in nuclear astrophysics is well known but often neglected [1–3].  $^{26m}\text{Al}$  is a common example of the impact that isomers have in astrophysical environments; the half-life of the  $J^\pi = 5^+$  ground state ( $7.17 \times 10^5$  years) is much longer than the half-life of the  $J^\pi = 0^+$  isomer (6.346 sec), which in the hot astrophysical environments typical of nucleosynthesis processes can impact production. As a result of the difference in lifetimes, it is well documented that the

ground state and isomeric state of  $^{26}\text{Al}$  must be treated as separate species in network calculations [4].

Astrophysically metastable isomers such as  $^{26m}\text{Al}$  are called "astomers," and they play a particularly important role in the rapid neutron-capture process ( $r$  process), where nuclear isomers are dynamically populated along the path of nucleosynthesis [5]. The  $r$  process accounts for the production of over half of the existing nuclei heavier than iron. The astrophysical site of the  $r$  process (core-collapse supernova, neutron star mergers, etc.) has been the subject of extensive debate in the astrophysics community [6–8]. This process has been recently associated with observed kilonovae, which are thought to arise from the energy release of radioactively decaying species after the merger of compact objects [9].

Predictions of nucleosynthesis in possible  $r$  process sites require nuclear physics data input. Detailed nuclear

\*Present address: Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, I-35131 Italy.

†Contact author: [ronning@pd.infn.it](mailto:ronning@pd.infn.it)

‡Contact author: [richardal@ohio.edu](mailto:richardal@ohio.edu)

structure and decay information are required to determine if a nuclear isomer is indeed an astromer in a particular environment (see the formalism developed in Refs. [10,11]). When data are available, astromers have been shown to impact nucleosynthesis pathways and the heat emitted as nuclei radioactively decay [5]. Nuclear data are often lacking, and measurements of nuclear properties can help resolve present ambiguities, as was illustrated with the recent mass measurement of  $^{128m}\text{Sb}$  [12].

Here, we identify and study the  $\beta$  decay of a nucleus produced in the  $r$  process that has not one but two astromers:  $^{70}\text{Cu}$ . There are three  $\beta$ -decaying states in  $^{70}\text{Cu}$ , the ground state ( $J^\pi = 6^-$ ,  $^{70}\text{Cu}^{\text{gs}}$ ) and two isomeric states: a 101.3-keV ( $J^\pi = 3^-$ ,  $^{70}\text{Cu}^{m1}$ ) state and a 242.6-keV ( $J^\pi = 1^+$ ,  $^{70}\text{Cu}^{m2}$ ) state [13,14]. The ground state has a half-life of 44.5(2) s, the 101-keV isomer has a half-life of 33(2) s, and the 242-keV isomer has a half-life of 6.6(2) s [13,15]. The difference in the spin parity and half-lives of the two isomeric states in  $^{70}\text{Cu}$  leads to astromeric behavior in the  $r$  process. Here, we illustrate the potential impact of incorporating experimental radioactive decay information on astromers into  $r$  process simulations. We measure experimental average  $\gamma$ -ray energies from the  $\beta$  decay of two astromers in  $^{70}\text{Cu}$  using the method of total absorption spectroscopy (TAS) and incorporate the experimentally determined average  $\gamma$ -ray energy into energy-generation simulations to assess their impact on energy release over time. We present the first isomer-separated TAS study of the three  $\beta$ -decaying states in  $^{70}\text{Cu}$  to stable  $^{70}\text{Zn}$ . We extract the average energy release into electrons and photons, and show that while  $^{70}\text{Cu}$  alone will not drastically impact the  $r$  process, the energy generation in the  $r$  process can depend on the presence of isomers.

## II. EXPERIMENTAL DETAILS

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University.  $^{70}\text{Cu}$  ions were produced from a  $^{76}\text{Ge}$  primary beam of 140 MeV/nucleon impinging on a 470 mg/cm $^2$   $^9\text{Be}$  target. The resulting fragmentation reaction products were separated by the A1900 fragment separator [16] and passed through a momentum compression beamline where an Al wedge was used to degrade the beam energy before entering the gas stopper [17,18].  $^{70}\text{Cu}$  ions were thermalized in the gas stopper.

Following extraction from the gas cell,  $^{70}\text{Cu}$  ions were selected in a mass analyzer and transmitted to the Low Energy Beam and Ion Trap (LEBIT) facility at rate of 4 kHz. LEBIT is a 9.4-T Penning trap mass spectrometer [19]. The ground and isomeric states of  $^{70}\text{Cu}$  ions were detected via the time-of-flight ion-cyclotron-resonance (ToF-ICR) technique [20,21]. LEBIT was used to quantify the percentage of each spin-parity state in the beam: 8(7)%  $^{70}\text{Cu}^{m2}$ , 23(4)%  $^{70}\text{Cu}^{m1}$ , and 69(4)%  $^{70}\text{Cu}^{\text{gs}}$ ; the three spin-parity states can be seen in the ToF-ICR spectrum of Fig. 1.

The  $^{70}\text{Cu}$  ions were then transmitted to the summing NaI(Tl) (SuN) total absorption spectrometer. In this experiment, LEBIT sits on a high-voltage platform biased at 30 kV, and SuN is at ground potential. Ions are ejected out of the Penning trap by switching the potential applied to the

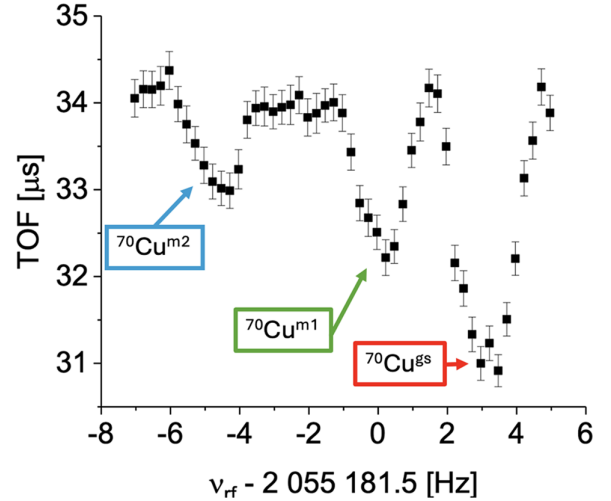


FIG. 1. Time-of-flight scans from LEBIT when  $^{70}\text{Cu}$  was delivered to the LEBIT facility. Time of flight in  $\mu\text{s}$  is on the y-axis, and  $\nu_{rf}$  centered around  $\nu_c$  for the  $3^-$  state is on the x-axis. The highest energy isomer ( $1^+$ ,  $^{70}\text{Cu}^{m2}$ ) on the left, the  $3^-$  ( $^{70}\text{Cu}^{m1}$ ) isomer is in the middle, and the  $6^-$  ( $^{70}\text{Cu}^{\text{gs}}$ ) ground state is on the right. Percentages of each spin-parity state correspond to the depths of each well in the ToF-ICR spectrum.

electrodes and accelerating them to about 10 eV. They travel through a series of focusing electrodes and are accelerated up to about 2 keV before being accelerated up to 30 keV (across a high-voltage break) for delivery to SuN.

SuN is a 16-inch-width by 16-inch-radius cylindrical NaI(Tl) scintillating detector, with a 45-mm radius borehole at the center [22]. SuN consists of two hemicylindrical halves, each comprised of four optically isolated segments. Each of the eight segments are attached to three photomultiplier tubes (PMTs). Total absorption spectroscopy has been performed using the SuN detector in various mass regions [23–25] and on other Cu isotopes such as  $^{64,65}\text{Cu}$  [26]. A total absorption spectrum, which is sensitive to the energy of the populated level, is created by summing signals from the segments together. Additionally, because SuN has eight segments, spectra from the isolated segments give individual  $\gamma$ -ray energies. A multiplicity spectrum provides additional information about the number of individual segments that register an event, which is related but not equivalent to the number of  $\gamma$ -rays involved in a cascade.

The  $^{70}\text{Cu}$  isotopes were implanted in a 1-mm-thick double-sided silicon strip detector (DSSD) located at the geometric center of SuN. The DSSD consists of 16, 1.2-mm-wide vertical and horizontal strips. The  $^{70}\text{Cu}$  ions selected in the gas cell passed through LEBIT and thus background contributions were negligible in the  $\beta$ -coincidence gated  $\gamma$  spectra; negligible background in  $\beta$ -gated- $\gamma$  spectra is similar to what is shown in previous total absorption spectroscopy studies using SuN [25,27]. The  $^{70}\text{Cu}$  beam was implanted for 600 sec, followed by a 600-sec period of beam-off time to measure the decay. This process created time-dependent activity profiles that could be used to isolate  $\beta$ -decay spectra from  $^{70}\text{Cu}^{m2}$ ,  $^{70}\text{Cu}^{m1}$ , and  $^{70}\text{Cu}^{\text{gs}}$  based on their half-lives.

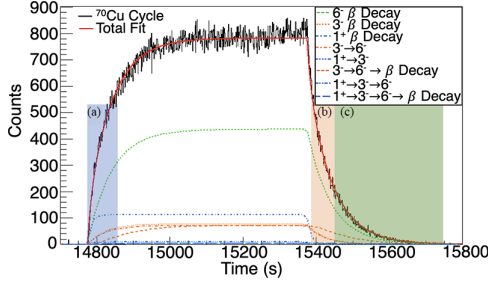


FIG. 2. An example of a grow-in/decay curve fit to Bateman equations. The gate in (c) was used to isolate the  $^{70}\text{Cu}^{gs}$   $\beta$  decays, (b) was used to isolate  $^{70}\text{Cu}^{m1}$   $\beta$  decays, and (a) was used to isolate  $^{70}\text{Cu}^{m2}$   $\beta$  decays through a series of subtractions.

### III. ANALYSIS

Time-dependent activity profiles created from cycling the beam were fit to Bateman equations modeling the  $^{70}\text{Cu}^{gs}$ ,  $^{70}\text{Cu}^{m1}$ , and  $^{70}\text{Cu}^{m2}$   $\beta$  decay using decay and internal conversion branching ratios determined by Ref. [13], and the beam composition determined from the LEBIT ToF-ICR spectra. An example of the fit between the Bateman equations and the time-dependent activity profile from this experiment is shown in Fig. 2. In these fits, the  $\beta$ -decay half-lives of each state were fixed to their literature values but allowed to vary within their literature uncertainty. These uncertainties were propagated through future analysis steps.

Gates were placed on the time-dependent activity profiles to isolate total absorption spectra resulting from the decay of different compositions of spin-parity states in the  $^{70}\text{Cu}$  ion beam. The three selected time gates were applied to the TAS, individual  $\gamma$  sum of segments and multiplicity spectra. Gate (c) begins after the decays from the  $^{70}\text{Cu}^{m2}$  and  $^{70}\text{Cu}^{m1}$  states of  $^{70}\text{Cu}$  are negligible according to the Bateman fits, effectively isolating a total absorption spectrum associated with  $\beta$  decay from the  $6^-$  ground state. Gate (b) begins after the  $^{70}\text{Cu}^{m2}$  has fully decayed away, isolating a spectrum that contains decays from only  $^{70}\text{Cu}^{m1}$  and  $^{70}\text{Cu}^{gs}$ ; from this the  $^{70}\text{Cu}^{m1}$   $\beta$ -decay spectra were isolated. Gate (a) begins right as the beam is turned on in the cycle, where the amount of  $^{70}\text{Cu}^{m2}$   $\beta$  decays is the largest within the cycle;  $^{70}\text{Cu}^{m2}$   $\beta$ -decay spectra were isolated from this gate. To confirm the isolation of the  $\gamma$  rays from each  $\beta$ -decaying state, lower-lying excitation energies and  $\gamma$  rays were identified to match the known  $^{70}\text{Zn}$  level schemes published by Refs. [13,28].

Known levels in  $^{70}\text{Zn}$  populated from the  $\beta$  decays of  $^{70}\text{Cu}$  from each spin-parity state from Ref. [14] were simulated in *geant4* to account for detector response. The development and characterization of this *geant4* simulation for the SuN detector is outlined in Ref. [22] with modifications for use in  $\beta$ -decay experiments [26]. The deexcitation of known levels up to 5.06 MeV for  $^{70}\text{Cu}^{gs}$   $\beta$  decay, 3.246 MeV for the  $\beta$  decays from the  $^{70}\text{Cu}^{m1}$ , and 3.635 MeV for  $\beta$  decays from  $^{70}\text{Cu}^{m2}$  were simulated. The  $\beta$ -decay Q values ( $Q_\beta$ ) for each spin-parity state are 6.588(3) MeV, 6.689(3) MeV, and 6.831(3) MeV, respectively [14], and thus to accurately fit the

experimental data, pseudolevels were constructed using the statistical Monte Carlo simulation code *rainier* [29].

*rainier* relies on select models for the nuclear level density,  $\gamma$ -ray strength function, and spin distribution and is used to simulate  $\gamma$ -ray cascades from decays from a given excitation energy level in the nucleus of interest. In our case, the nuclear level density was modeled with the constant temperature model [30], and the  $\gamma$ -ray strength function was modeled with a generalized Lorentzian [31] function. The spins and parities of the entry state in the daughter nucleus are  $J^\pi = 5^-, 6^-$ , and  $7^-$  for  $^{70}\text{Cu}^{gs}$ ,  $2^-, 3^-$ , and  $4^-$  for  $^{70}\text{Cu}^{m1}$ , and  $0^+, 1^+$ , and  $2^+$  for  $^{70}\text{Cu}^{m2}$ , assuming allowed Gamow-Teller  $\beta$ -decay transitions. The pseudolevels simulated in *rainier* do not represent an actual level energy but rather an energy bin that is equivalent to the energy resolution of SuN. Pseudolevels are simulated in *rainier* from above the highest known excitation energy to the  $Q_\beta$  value. The size of the energy bins up to  $Q_\beta$  are not constant but increase with the resolution of SuN; thus the bins were 100 keV from 3–4 MeV, 150 keV from 4–6 MeV, and 200 keV from 6 MeV up to  $Q_\beta$ .

The resulting *rainier* simulations are fed through the SuN *geant4* simulation to account for the detector response. A  $\chi^2$  minimization procedure is employed to simultaneously fit the simulated total absorption, sum of segments, and multiplicity spectra from various excitation energies to experimental data, where the amplitude of each level is allowed to vary. The  $\chi^2$  value is then calculated between the magnitudes for each bin for an experimental spectrum compared to the corresponding simulated spectrum. The resulting amplitudes are used to calculate the  $\beta$ -feeding intensity distribution resulting from the  $\beta$  decays of the ground and isomeric states of  $^{70}\text{Cu}$ .

### IV. RESULTS

The total absorption spectra produced via the  $\beta$  decay of the  $^{70}\text{Cu}^{m2}$ ,  $^{70}\text{Cu}^{m1}$ , and  $^{70}\text{Cu}^{gs}$  are overlaid in Fig. 3 with their corresponding  $\chi^2$  minimization results. The  $^{70}\text{Zn}$  total absorption spectrum populated via  $^{70}\text{Cu}^{gs}$   $\beta$  decay shows very good agreement between the fits and the experimental data. In the  $^{70}\text{Zn}$  total absorption spectrum populated via  $^{70}\text{Cu}^{m1}$   $\beta$  decay, the simulated fits do not account for some feeding below 800 keV. This missing feeding amounts to 0.3% of the total feeding and thus does not make a large impact on the extracted  $\beta$ -feeding values reported below.

Isolation of the  $^{70}\text{Zn}$  total absorption spectrum from  $^{70}\text{Cu}^{m2}$   $\beta$  decay revealed the presence of unobserved TAS peaks at excitation energies between 2.2 and 3.4 MeV. In order to characterize these peaks, individual segment spectra of SuN were used. Using each identified and previously unobserved TAS peak as a gate (with 200-keV width),  $\gamma$ - $\gamma$  coincidence spectra were produced using individual segment spectra of SuN. These  $\gamma$ - $\gamma$  coincidence plots revealed that some of the  $\beta$ -delayed  $\gamma$ -rays measured previously in Ref. [13] and assigned based on half-life to the  $^{70}\text{Cu}^{m1}$   $\beta$  decay only, were also present after  $^{70}\text{Cu}^{m2}$   $\beta$  decay. These peaks are listed in Table I.

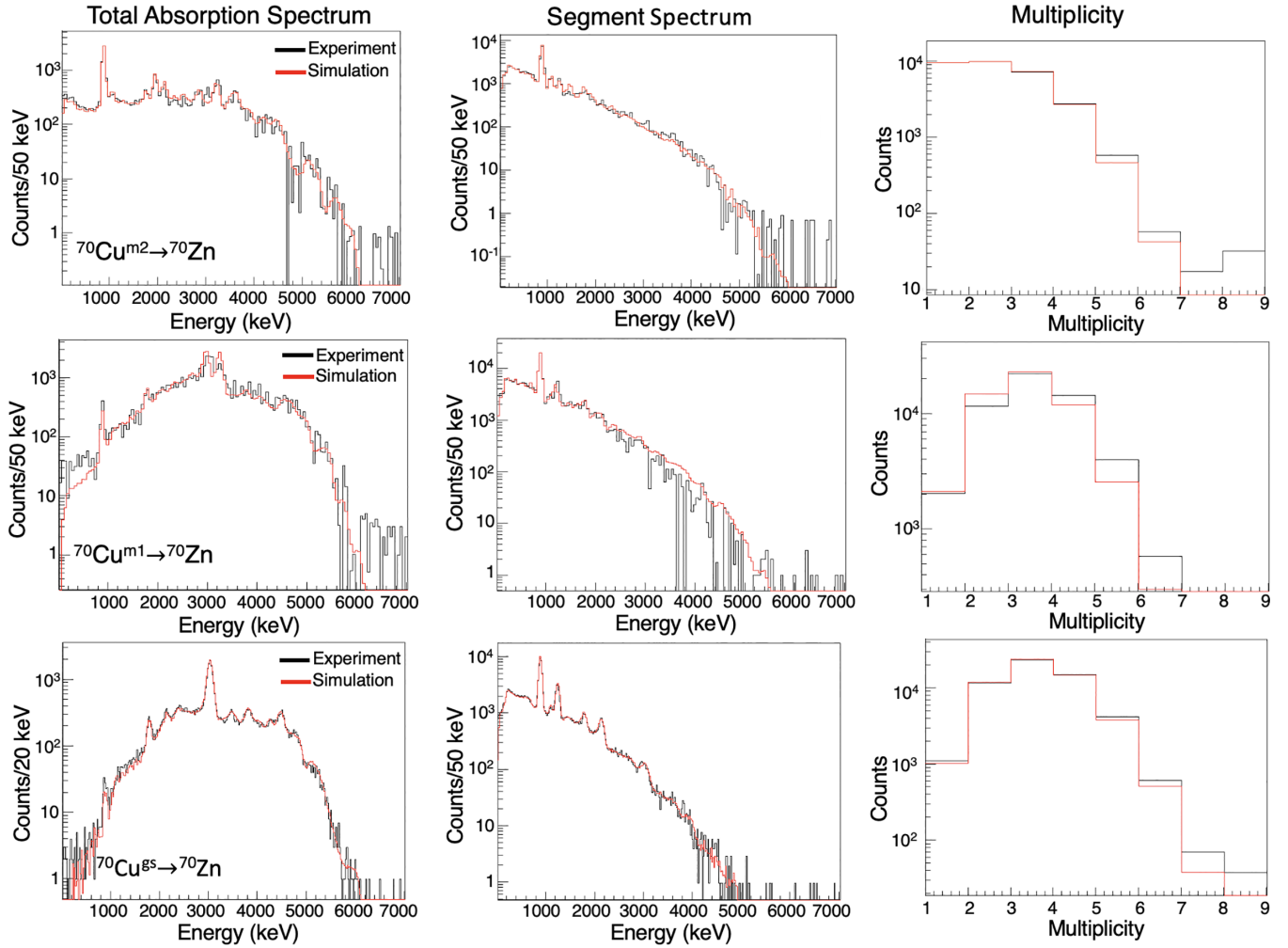


FIG. 3. The  $^{70}\text{Zn}$  total absorption (left), segments (middle), and multiplicity (right) spectra populated from the  $^{70}\text{Cu}^{m2}$  (top),  $^{70}\text{Cu}^{m1}$  (middle), and  $^{70}\text{Cu}^{gs}$   $\beta$  decays. Experimental spectra are in black and the  $\chi^2$  fits are shown in red.

To accurately reproduce the low-energy portion of the TAS spectrum from the  $\beta$  decay of  $^{70}\text{Cu}^{m2}$ , a ground-state branch was added into the geant4 simulations. This ground-state branch is not included in the nuclear data evaluation by Ref. [14]. Previous work by Ref. [13] stated that this

TABLE I. The excitation energies and  $\gamma$ -rays added into the geant4 simulations for the  $\beta$  decay of  $^{70}\text{Cu}^{m2}$ . These peaks were determined from observed  $\gamma$ -rays in Ref. [13] and the  $\gamma$ - $\gamma$  spectra from SuN.

| Excitation energy (MeV) | $\gamma$ -rays in each cascade (keV) |
|-------------------------|--------------------------------------|
| 2.348                   | 208, 1255, 885                       |
| 2.312                   | 553, 874, 885                        |
| 2.529                   | 389, 1255, 885                       |
| 2.860                   | 1101, 874, 885                       |
| 2.839                   | 1954, 885                            |
| 3.219                   | 1460, 874, 885                       |

branch is 0% based on the work of Ref. [32], where it was assumed that no ground-state feeding occurred in the decay of  $^{70}\text{Cu}$ . However, a ground state-to-ground state transition of 46(10)% from  $^{70}\text{Cu}^{m2}$  ( $J^\pi = 1^+$ )  $\beta$  decay to the  $0^+$  ground state of the  $^{70}\text{Zn}$  daughter was previously observed by the researchers of Ref. [33]. Furthermore shell-model calculations indicate the feeding should be 49.19%. Inclusion of this ground-state branch in the  $\chi^2$  minimization results in a 29(6)% ground-state feeding from  $^{70}\text{Cu}^{m2}$ . With contribution of the ground-state branch and the additional peaks from Table I, the subtracted spectra from  $^{70}\text{Cu}^{m2}$   $\beta$  decay were fit with good agreement to the geant4 simulations.

From the best fits for each of the spin-parity states, the  $\beta$ -decay feeding intensities were extracted and the results are shown in Fig. 4. The uncertainties were determined by combining the statistical uncertainties from counts and various subtractions of the spectra with the uncertainties from the  $\chi^2$  fitting procedure. The  $\beta$ -feeding intensities ( $I_\beta$ ) from the different spin-parity states in Fig. 4 follow the expected allowed Gamow-Teller transitions. The  $\beta$  decay of  $^{70}\text{Cu}^{m2}$

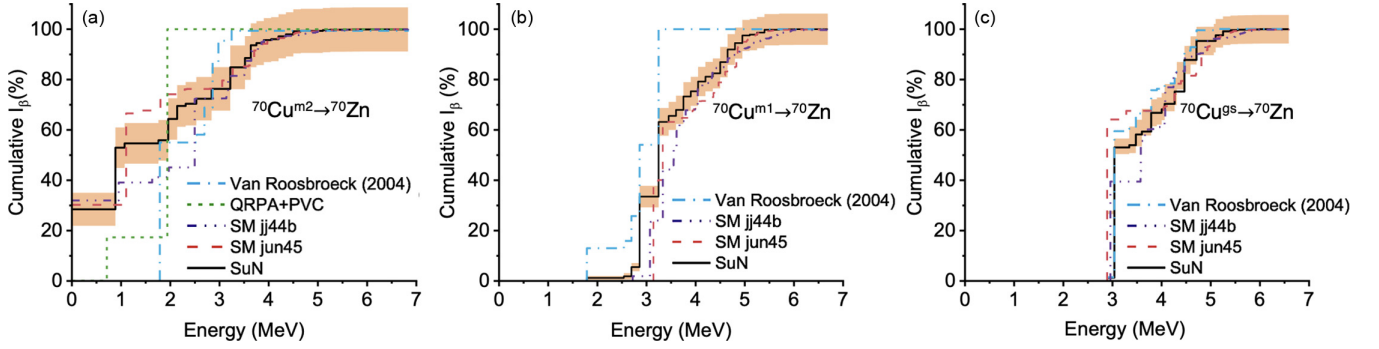


FIG. 4. The calculated cumulative  $I_\beta$  values from  $^{70}\text{Cu}^{m2}$  (a),  $^{70}\text{Cu}^{m1}$  (b), and  $^{70}\text{Cu}^{gs}$  (c)  $\beta$  decays compared to previous literature values from Van Roosbroeck *et al.* [13], and two shell-model Hamiltonians: SM jun45 [35] and SM jj44b [36]. Data from the decay of  $^{70}\text{Cu}^{m2}$  are also compared to QRPA + PVC calculations [37,38].

feeds lower energies with lower spin states,  $^{70}\text{Cu}^{gs}$  primarily feeds higher energy levels in  $^{70}\text{Zn}$  (the lowest being 2.895 MeV), and  $^{70}\text{Cu}^{m1}$  is in the middle but has a similar feeding distribution to  $^{70}\text{Cu}^{gs}$ .

The experimentally extracted feeding distribution from  $^{70}\text{Cu}^{gs}$   $\beta$  decay matches well with the previously reported feeding intensities by Ref. [13]. For the  $\beta$  decay of  $^{70}\text{Cu}^{m1}$  and  $^{70}\text{Cu}^{m2}$ , however, the feeding distributions from Ref. [13] do not match as well. The previously reported  $\beta$ -decay feeding from  $^{70}\text{Cu}^{m1}$  assumes that the last known fed level is at 3.2 MeV, whereas the experimental feeding we see here is far more fragmented above these energies. For the  $\beta$  decay of  $^{70}\text{Cu}^{m2}$ , the feeding is dispersed over a broader energy range than is reported by Ref. [13].

From the experimental  $\beta$ -feeding values, the average  $\gamma$ -ray energy per  $\beta$ -decay event was calculated for the ground state and the two isomers following the methodology reported in Ref. [34]. The average  $\gamma$ -ray energies from the  $\beta$  decay of  $^{70}\text{Cu}^{gs}$ ,  $^{70}\text{Cu}^{m1}$ , and  $^{70}\text{Cu}^{m2}$  are 3.62(21) MeV, 3.48(75) MeV, and 1.57(36) MeV, respectively.

## V. DISCUSSION

### A. Shell-model and QRPA calculations

Experimental measurements of  $\beta$ -decay properties such as half-lives,  $\beta$ -delayed neutron emission probabilities,  $\beta$ -feeding values can all impact  $r$  process simulations [39–42]. When experimental  $\beta$ -decay information is unavailable, theoretical calculations are used across the nuclear landscape to predict  $\beta$ -decay properties in these astrophysical simulations [43–45]. Theoretical calculations are typically bench-marked against known half-lives and  $\beta$ -delayed neutron emission probabilities instead of comparing against the full distribution of  $\beta$ -decay feeding ( $I_\beta$ ) values as a function of excitation energy. A more direct comparison to theory is to then compare experimental  $I_\beta$  values with  $I_\beta$  values used in theoretical calculations. Here, we compare experimental  $I_\beta$  values for the  $\beta$  decay of ground and isomeric states in  $^{70}\text{Cu}$  with QRPA (quasiparticle random phase approximation) and shell-model (SM) calculations.

Comparisons of experimental  $\beta$ -decay feeding intensities to both shell-model calculations and quasirandom phase approximation with particle-vibration coupling calculations are shown in Fig. 4. The shell-model calculations were carried out in the jj44 model space consisting of the  $0f_{5/2}$ ,  $1p_{3/2}$ ,  $1p_{1/2}$ ,  $0g_{9/2}$  set of orbitals for protons and neutrons using the NUSHELLX code [46].

Two empirical Hamiltonians have been developed for this model space: jun45 [35] and jj44b [36]. These Hamiltonians are in isospin formalism with the  $T = 1$  set of two-body matrix elements being the same for protons and neutrons. The Coulomb interaction is added in terms of a constant  $Z$ -dependent shift. The methods used to obtain these Hamiltonians from fits to experimental binding energy and excitation energy data for nuclei in the region of  $28 \leq Z < 50$  and  $32 \leq N \leq 50$  are summarized in the Appendix of [36].

Both shell-model Hamiltonians have some defects with regard to the experimental energy levels; however, the jj44b model matches the experimental data better than jun45, particularly at energies below 3 MeV. In particular, the  $0_1^+$  state is too high in energy with the jj44b model space. The  $4_1^+$  and  $6_1^+$  states are too high energy with jun45, as seen in Fig. 5. Given

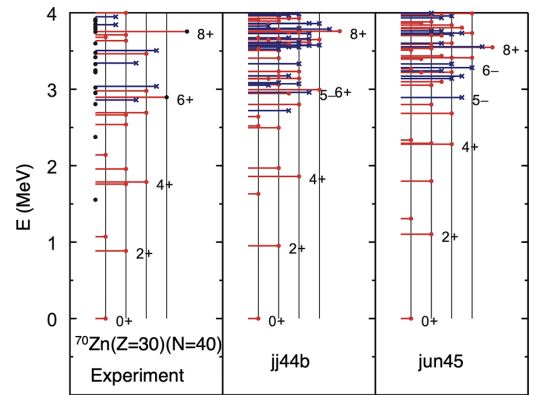


FIG. 5. Comparison of experimental and calculated energy levels for  $^{70}\text{Zn}$  with the SM Hamiltonians jj44b [36] and jun45 [35]. The length of the horizontal lines is proportional to the  $J$  value. Positive-parity levels are shown by red lines, and negative-parity levels are shown by blue lines. The black dots on the experimental side indicate the level does not have a definitive spin-parity assignment.

the uncertainty associated with the differences between jun45 and jj44b Hamiltonians for the cumulative  $I_\beta$  shown in Fig. 2, the shell-model calculations are in excellent agreement with the data.

The relativistic quasiparticle random phase approximation (RQRPA) calculations have been done using the NL3 parametrization of the meson-exchange interaction [47] for the particle-hole channel. The isovector pairing interaction is a simple monopole force and the isoscalar pairing is not included. More details can be found in Refs. [48,49]. The odd-odd nucleus  $^{70}\text{Cu}$  is treated in the same way as even-even nuclei, with a constraint on the number of particles, and is also considered to be spherical.

In order to capture correlations beyond the relativistic QRPA (RQRPA), (quasi)particle-vibration coupling (PVC) effects are included, which take into account the interplay between single (quasi)nucleons and collective vibrations of the nucleus. Such coupling typically constitutes the leading correlation mechanism in midmass and heavy nuclei and is known to largely improve Gamow-Teller strength and  $\beta$ -decay half-lives of several nuclei in the  $\beta^-$  channel. In particular, PVC provides spreading width of Gamow-Teller resonances, as well as fragmentation of the low-energy strength [37,38]. Included in Fig. 4 are the QRPA + PVC calculations, because with the NL3 functional considered here and in the absence of static isoscalar pairing force, RQRPA predicts no states below the decay  $Q$  value and thus an infinite lifetime. On the other hand, the PVC correlations bring fragmentation of the strength distribution and states appear in the decay energy window. The QRPA-PVC calculations compare best to the feeding from the  $1^+$  isomer, which is consistent with assumed physics in the calculation and thus we only compare the calculations to the  $1^+$  isomer in Fig. 4. The QRPA + PVC calculations are only in very qualitative agreement with the data.

The above QRPA + PVC calculations are representative of calculations typically used in astrophysical simulations. However, these calculations cannot predict spin-dependent behavior, and in the case of the ground and isomeric  $\beta$ -decaying states of  $^{70}\text{Cu}$ , the QRPA + PVC calculations are in poor agreement with experimental data. The shell-model calculations presented in Fig. 4 can predict spin-dependent behavior and thus are in better agreement with experimental data, particularly for the ground state and  $3^-$  isomer, but these calculations are not standard input into astrophysical simulations.

### B. Impact on time-dependent energy generation in the $r$ process

We find the behavior of  $^{70}\text{Cu}$  and its two potential astromers to be sensitive to the thermodynamic evolution of explosive nucleosynthesis. Here we report on a temperature and density profile found in one of the 460,000 trajectories of a black hole accretion disk by Ref. [50]. This particular trajectory was chosen as it is representative of the mass-weighted average conditions found in the disk. Using the computational methods of Refs. [10,11,51], we simulate  $r$ -process nucleosynthesis with (colored lines) and without (black line) the two nuclear isomers in  $^{70}\text{Cu}$  (Fig. 6).

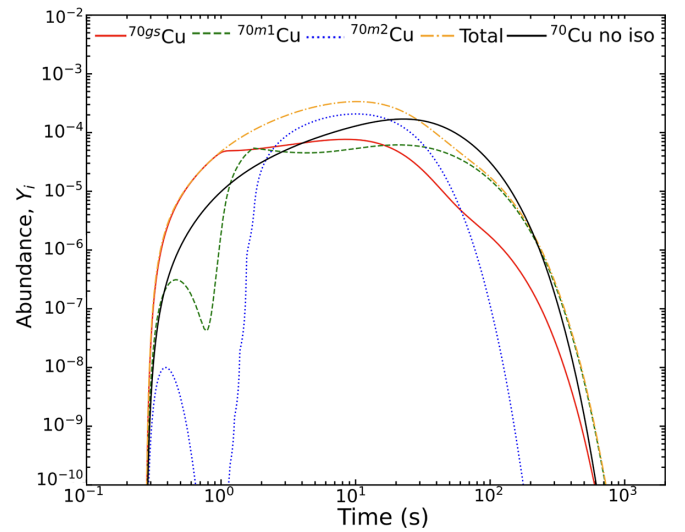


FIG. 6. Time evolution of  $^{70}\text{Cu}$  abundances assuming individual states are populated (colored lines) vs the ground state only (“no iso,” solid black line). After thermal equilibrium breaks (roughly 1 sec),  $^{70}\text{Cu}$  contains two astromers.

The initial population of the states in  $^{70}\text{Cu}$  come from two sources: the  $\beta$  decay of  $^{70}\text{Ni}$  and neutron capture from  $^{69}\text{Cu}$ . At these early times in the simulation ( $< 1$  sec), the environment is hot and thermal equilibrium quickly reorders the state populations; the individual states of  $^{70}\text{Cu}$  are populated according to a Boltzmann distribution. At high temperatures, the relative population of the states in  $^{70}\text{Cu}$  only depend on the spin and excitation energy of the state, which is reflected in the relative population fraction with  $gs > m1 > m2$ . The sum of the population of all three states of  $^{70}\text{Cu}$  is indicated by the “Total” curve (orange dash dot). The ground-state population (red curve) is higher than in the case of the “ $^{70}\text{Cu}$  no iso” (black curve) where no isomers are considered in the simulation. This observation highlights the intricate influence neighboring isomers can have on each other. In the simulation with isomers, the population of  $^{69}\text{Cu}$  is high at early times owing to the fast  $\beta$ -decaying isomer in  $^{69}\text{Ni}$ . Since no isomers are present in the “ $^{70}\text{Cu}$  no iso” simulation, this effect is not present and the black curve is lower than the red curve.

As the environment expands and cools, the thermal equilibrium breaks down, and the excited-state population decreases as these states can no longer be populated by thermal transitions. A new population fraction arises at around 1 sec. At this time most of the free neutrons have been consumed, so the population of the states are now primarily populated via  $\beta$  decay from  $^{70}\text{Ni}$ . Between one and 100 sec, we also observe that these states are indeed astromers, which is evident from the ordering of their population (now the excited states are on par, or more populated than the ground state). At 10 sec, the first astromeric state (dotted blue line) is most populated followed by the second astromeric state (green dashed line), and then the ground state (red line). At the end of the simulation, a small amount of residual neutron capture on  $^{69}\text{Cu}$ , which predominantly populates the ground state and first excited states of  $^{70}\text{Cu}$ , lengthens the effective half-lives of these two states. This behavior demonstrates the importance of understanding

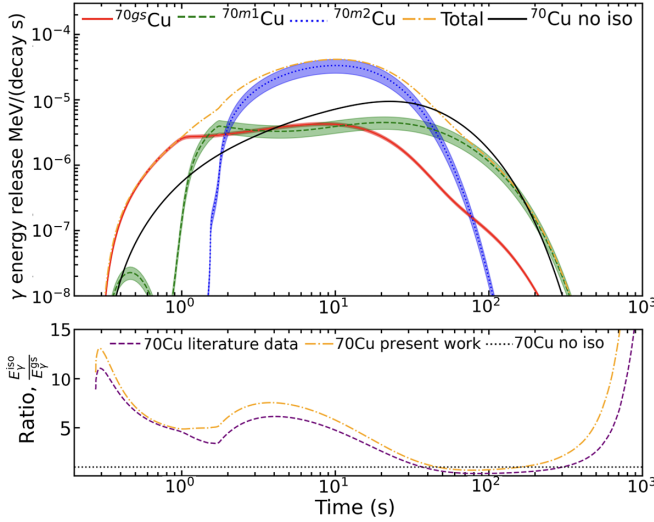


FIG. 7. The top panel shows the  $\gamma$ -ray energy release from the population of  $^{70}\text{Cu}$  using the experimental data of this work, where the bands surrounding the colored lines indicate experimental uncertainties. The energy release is substantially altered from the ground-state-only calculation (“no iso,” black) when excited states are included (colors). The bottom panel shows the ratio of the  $\gamma$ -ray energy release in the simulation with isomers relative to the simulation with no isomers (“ $^{70}\text{Cu}$  no iso,” black) where the ratio is 1. The orange line represents the present work and the purple line represents previous data from Ref. [13].

not only the decay of isomers in astrophysical environments but also the role they may play in nuclear reactions.

The average  $\gamma$ -ray energy released in the  $\beta$  decay of each spin-parity state from our experiment was directly incorporated into the nucleosynthesis simulation to estimate the time-dependent  $\gamma$ -ray energy release. The population of the two astromers substantially impacts the energy release in comparison to the treatment of  $^{70}\text{Cu}$  as a single species, as shown in Fig. 7.

The top panel of Fig. 7 shows the  $\gamma$ -ray energy release from  $^{70}\text{Cu}$  when considering isomers (colored lines) versus the no-isomer case (black line). In the top panel, the bands surrounding the colored lines indicate the experimental uncertainties associated with the present experimental work. The total energy release when considering isomers (orange dash dot curve) is substantially different than in the case of the ground state only (black). This can be seen more quantitatively by taking the ratio of the  $\gamma$ -ray energy release in the simulation with isomers relative to the simulation with no isomers (ground states only), see bottom panel of Fig. 7. During the time in which  $^{70}\text{Cu}$  is significantly populated, the ratio of the energy release is on average 6 times higher when considering isomers than when considering the case of no isomers. In the bottom panel we also plot a line assuming use of experimental data from Ref. [13] (purple). A significant deviation in the average  $\gamma$ -ray energy of the first excited state causes this difference, indicating the importance of continued measurements, even where data may presently exist.

Our finding provides the first indications of how the populations of astromers will impact time-dependent energy release in the synthesis of heavy elements. While  $^{70}\text{Cu}$  alone may not drastically impact the  $r$  process, the culmination of many of these effects in various nuclei will have a strong influence on the time-dependent  $\gamma$ -ray spectra, and this change in energy release may subsequently alter the observable kilonova signal and heating. Such a calculation is presently out of reach due to the lack of nuclear data on excited states. Our results therefore may be taken as further impetus for experimental exploration of the properties of short-lived nuclei.

## VI. CONCLUSION

Here we identified the presence of two astromers in  $^{70}\text{Cu}$  and performed the first isomer-separated total absorption spectroscopy experiment to study the impact of its  $\beta$  decay using the SuN total absorption spectrometer and LEBIT at the NSCL.  $\beta$ -feeding values for the  $\beta$  decays of the  $^{70}\text{Cu}^{gs}$ ,  $^{70}\text{Cu}^{m1}$ ,  $^{70}\text{Cu}^{m2}$  have been isolated and are reported, which are compared to shell-model and QRPA + PVC calculations. We show that the inclusion of astromers can impact the  $\gamma$ -ray spectra of  $r$ -process nucleosynthesis, and our results are indicative of the importance of including detailed microphysics to understand heavy element formation.

## ACKNOWLEDGMENTS

The authors would like to thank Caroline Robin for her contribution of QRPA + PVC calculations to this work. This material is based upon work supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-SC0023633. B.A.B. and P.A.DeY. acknowledge support from the U.S. National Science Foundation (NSF) under Grants No. PHY-2110365 and No. 1911418, respectively. This work is also made possible by U.S. NSF Grants No. 1913554 and No. 2209429. M.R.M. acknowledges support from the Directed Asymmetric Network Graphs for Research (DANGR) initiative at Los Alamos National Laboratory (LANL). LANL is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy (Contract No. 89233218CNA000001). The research was also sponsored by the U.S. Department of Energy, National Nuclear Security Administration, under Award No. DE-NA0003180 and the Stewardship Science Academic Alliances program through DOE Award No. DOE-DE-NA0003906. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. This work is based on research supported in part by the National Research Foundation of South Africa (Grant No. 118846). This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-AC02-05CH11231 (LBNL). S.L. was supported by the

Laboratory Directed Research and Development Program at Pacific Northwest National Laboratory (PNNL). PNNL is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830

## DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

- [1] A. Aprahamian, K. Langanke, and M. Wiescher, Nuclear structure aspects in nuclear astrophysics, *Prog. Part. Nucl. Phys.* **54**, 535 (2005).
- [2] G. D. Dracoulis, P. M. Walker, and F. G. Kondev, Review of metastable states in heavy nuclei, *Rep. Prog. Phys.* **79**, 076301 (2016).
- [3] S.-I. Fujimoto and M.-A. Hashimoto, The impact of isomers on a kilonova associated with neutron star mergers, *Mon. Not. R. Astron. Soc. Lett.* **493**, L103 (2020).
- [4] R. A. Ward and W. A. Folwer, Thermalization of long-lived nuclear isomeric states under stellar conditions, *Astrophys. J.* **238**, 266 (1980).
- [5] G. W. Misch, T. M. Sprouse, and M. R. Mumpower, Astromers in the Radioactive Decay of *r*-process nuclei, *Astrophys. J. Lett.* **913**, L2 (2021).
- [6] S. E. Woosley, J. R. Wilson, G. J. Mathews, R. D. Hoffman, and B. S. Meyer, The *r*-process and neutrino-heated supernova ejecta, *Astrophys. J.* **433**, 229 (1994).
- [7] T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer, Protoneutron star evolution and the neutrino-driven wind in general relativistic neutrino radiation hydrodynamics simulations, *Astron. Astrophys.* **517**, A80 (2010).
- [8] D. Kasen, N. R. Badnell, and J. Barnes, Opacities and spectra of the *r*-process ejecta from neutron star mergers, *Astrophys. J.* **774**, 25 (2013).
- [9] D. Kasen, B. Metzger, J. Barnes, E. Quataert, and E. Ramirez-Ruiz, Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event, *Nature (London)* **551**, 80 (2017).
- [10] G. W. Misch, S. K. Ghorui, P. Banerjee, Y. Sun, and M. R. Mumpower, Astromers: Nuclear isomers in astrophysics, *Astrophys. J. Suppl. Ser.* **252**, 2 (2021).
- [11] G. W. Misch, T. M. Sprouse, M. R. Mumpower, A. J. Couture, C. L. Fryer, B. S. Meyers, and Y. Sun, Sensitivity of neutron-rich nuclear isomer behavior to uncertainties in direct transitions, *Symmetry* **13**, 1831 (2021).
- [12] D. E. M. Hoff, K. Kolos, G. W. Misch, B. Liu, A. A. Valverde, M. Brodeur, D. P. Burdette, N. Callahan, J. A. Clark, F. G. Kondev, *et al.*, Direct mass measurements to inform the behavior of  $^{128m}\text{Sb}$  in nucleosynthetic environments, *Phys. Rev. Lett.* **131**, 262701 (2023).
- [13] J. Van Roosbroeck, H. De Witte, M. Gorska, M. Huyse, K. Kruglov, K. Van de Vel, P. Van Duppen, S. Franchoo, J. Cederkall, V. N. Fedoseyev, *et al.*, Coupling a proton and a neutron to the semidoubly magic nucleus  $^{68}\text{Ni}$ : A study of  $^{70}\text{Cu}$  via the  $\beta$  decay of  $^{70}\text{Ni}$  and  $^{70}\text{Cu}$ , *Phys. Rev. C* **69**, 034313 (2004).
- [14] G. Gürdal and E. A. Mccutchan, Nuclear data sheets for  $A = 70$ , *Nucl. Data Sheets* **136**, 1 (2016).
- [15] J. Van Roosbroeck, C. Guenaut, G. Audi, D. Beck, K. Blaum, G. Bollen, J. Cederkall, P. Delahaye, A. De Maesschalck, H. De Witte, D. Fedorov, *et al.*, Unambiguous identification of three  $\beta$ -decaying isomers in  $^{70}\text{Cu}$ , *Phys. Rev. Lett.* **92**, 112501 (2004).
- [16] D. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, Commissioning the A1900 projectile fragment separator, *Nucl. Instrum. Methods Phys. Res. Sect. B* **204**, 90 (2003).
- [17] K. Cooper, C. Sumithrarachchi, D. Morrissey, A. Levand, J. Rodriguez, G. Savard, S. Schwarz, and B. Zabransky, Extraction of thermalized projectile fragments from a large volume gas cell, *Nucl. Instrum. Methods Phys. Res. Sect. A* **763**, 543 (2014).
- [18] C. Sumithrarachchi, D. Morrissey, S. Schwarz, K. Lund, G. Bollen, R. Ringle, G. Savard, and A. Villari, Beam thermalization in a large gas catcher, *Nucl. Instrum. Methods Phys. Res. Sect. B* **463**, 305 (2020).
- [19] R. Ringle, S. Schwartz, and G. Bollen, Penning trap mass spectrometry of rare isotopes produced via projectile fragmentation at the LEBIT facility, *Int. J. Mass Spectrom.* **349-350**, 87 (2013).
- [20] G. Bollen, R. B. Moore, G. Savard, and H. Stolzenberg, The accuracy of heavy-ion mass measurements using time of flight-ion cyclotron resonance in a Penning trap, *Appl. Phys.* **68**, 4355 (1990).
- [21] M. König, G. Bollen, H.-J. Kluge, T. Otto, and J. Szerypo, Quadrupole excitation of stored ion motion at the true cyclotron frequency, *Int. J. Mass Spectrom. Ion Processes* **142**, 95 (1995).
- [22] A. Simon, S. J. Quinn, A. Spyrou, A. Battaglia, I. Beskin, A. Best, B. Bucher, M. Couder, P. A. DeYoung, X. Fang, J. Gorres, *et al.*, SuN: Summing NaI(Tl) gamma-ray detector for capture reaction measurements, *Nucl. Instrum. Methods Phys. Res. Sect. A* **703**, 16 (2013).
- [23] A. C. Dombos, A. Spyrou, F. Naqvi, S. J. Quinn, S. N. Liddick, A. Algara, T. Baumann, J. Brett, B. P. Crider, P. A. DeYoung, *et al.*, Total absorption spectroscopy of the  $\beta$  decay of  $^{101,102}\text{Zr}$  and  $^{109}\text{Tc}$ , *Phys. Rev. C* **103**, 025810 (2021).
- [24] A. Spyrou, S. N. Liddick, F. Naqvi, B. P. Crider, A. C. Dombos, D. L. Bleuel, B. A. Brown, A. Couture, L. Crespo Campo, M. Guttormsen, *et al.*, Strong neutron- $\gamma$  Competition above the neutron threshold in the decay of  $^{70}\text{Co}$ , *Phys. Rev. Lett.* **117**, 142701 (2016).
- [25] S. Lyons, A. Spyrou, S. N. Liddick, F. Naqvi, B. P. Crider, A. C. Dombos, D. L. Bleuel, B. A. Brown, A. Couture, L. Crespo Campo, *et al.*,  $^{69,71}\text{Co}$   $\beta$ -decay strength distributions from total absorption spectroscopy, *Phys. Rev. C* **100**, 025806 (2019).
- [26] F. Naqvi, S. Karampagia, A. Spyrou, S. N. Liddick, A. C. Dombos, D. L. Bleuel, B. A. Brown, L. Crespo Campo, A. Couture, B. Crider, *et al.*, Total absorption spectroscopy measurement on neutron-rich  $^{74,75}\text{Cu}$  isotopes, *Nucl. Phys. A* **1018**, 122359 (2022).
- [27] A. C. Dombos, D. L. Fang, A. Spyrou, S. J. Quinn, A. Simon, B. A. Brown, K. Cooper, A. E. Gehring, S. N. Liddick, D. J. Morrissey, *et al.*, Total absorption spectroscopy of the  $\beta$  decay of  $^{76}\text{Ga}$ , *Phys. Rev. C* **93**, 064317 (2016).
- [28] P. Vingerhoets, K. T. Flanagan, M. Avgoulea, J. Billowes, M. L. Bissell, K. Blaum, B. A. Brown, B. Cheal, M. De Rydt, D. H. Forest, *et al.*, Nuclear spins, magnetic moments, and quadrupole

- moments of Cu isotopes from  $N = 28$  to  $N = 46$ : Probes for core polarization effects, *Phys. Rev. C* **82**, 064311 (2010).
- [29] L. Kirsch and L. Bernstein, RAINIER: A simulation tool for distributions of excited nuclear states and cascade fluctuations, *Nucl. Instrum. Methods Phys. Res. Sect. A* **892**, 30 (2018).
- [30] T. Ericson, A statistical analysis of excited nuclear states, *Nucl. Phys.* **11**, 481 (1959).
- [31] J. Kopecky, M. Uhl, and R. E. Chrien, Radiative strength in the compound nucleus  $^{157}\text{Gd}$ , *Phys. Rev. C* **47**, 312 (1993).
- [32] S. Franchoo, M. Huyse, K. Kruglov, Y. Kudryavtsev, W. F. Mueller, R. Raabe, I. Reusen, P. Van Duppen, J. Van Roosbroeck, L. Vermeeren, *et al.*, Beta decay of  $^{68-74}\text{Ni}$  and level structure of neutron-rich Cu isotopes, *Phys. Rev. Lett.* **81**, 3100 (1998).
- [33] W. L. Reiter, W. H. Breunlich, and P. Hille, Short-lived activities produced in  $^{70}\text{Zn}$  with 14 MeV neutrons, *Nucl. Phys. A* **249**, 166 (1975).
- [34] B. C. Rasco, K. P. Rykaczewski, A. Fijałkowska, M. Karny, M. Wolińska-Cichocka, R. K. Grzywacz, D. W. Stracener, E. F. Zganjar, J. C. Batchelder, J. C. Blackmon, *et al.*, Deciphering  $^{98}\text{Nb}$   $\beta$  decay with the modular total absorption spectrometer at ORNL, *Phys. Rev. C* **105**, 064301 (2022).
- [35] M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, New effective interaction for  $f_5^9\text{Pg}$  -shell nuclei, *Phys. Rev. C* **80**, 064323 (2009).
- [36] S. Mukhopadhyay, B. P. Crider, B. A. Brown, S. F. Ashley, A. Chakraborty, A. Kumar, M. T. McEllistrem, E. E. Peters, F. M. Prados-Estevez, and S. W. Yates, Nuclear structure of  $^{76}\text{Ge}$  from inelastic neutron scattering measurements and shell model calculations, *Phys. Rev. C* **95**, 014327 (2017).
- [37] C. Robin and E. Litvinova, Nuclear response theory for spin-isospin excitations in a relativistic quasiparticle-phonon coupling framework, *Eur. Phys. J. A* **52**, 205 (2016).
- [38] C. Robin and E. Litvinova, Coupling charge-exchange vibrations to nucleons in a relativistic framework: Effect on Gamow-Teller transitions and  $\beta$ -decay half-lives, *Phys. Rev. C* **98**, 051301(R) (2018).
- [39] P. Hosmer, H. Schatz, A. Aprahamian, O. Arndt, R. R. C. Clement, A. Estrade, K. Farqi, K. L. Kratz, S. N. Liddick, A. F. Lisetskiy, *et al.*, Half-lives and branchings for  $\beta$ -delayed neutron emission for neutron-rich Co–Cu isotopes in the  $r$ -process, *Phys. Rev. C* **82**, 025806 (2010).
- [40] T. Kajino, W. Aoki, A. B. Balantekin, R. Diehl, M. A. Famiano, and G. J. Mathews, Current status of  $r$ -process nucleosynthesis, *Prog. Part. Nucl. Phys.* **107**, 109 (2019).
- [41] P. Sarriguren and J. Pereira,  $\beta$ -decay properties of neutron-rich Zr and Mo isotopes, *Phys. Rev. C* **81**, 064314 (2010).
- [42] P. Sarriguren, A. Algara, and J. Pereira, Gamow-Teller response in deformed even and odd neutron-rich Zr and Mo isotopes, *Phys. Rev. C* **89**, 034311 (2014).
- [43] P. Möller, J. R. Nix, W. D. Meyers, and W. J. Swiatecki, Nuclear ground-state masses and deformations, *At. Data Nucl. Data Tables* **59**, 185 (1995).
- [44] P. Möller, J. R. Nix, and K. L. Krtaz, Nuclear properties for astrophysical and radioactive-ion-beam applications, *At. Data Nucl. Data Tables* **66**, 131 (1997).
- [45] M. T. Mustonen and J. Engel, Global description of  $\beta^-$  decay in even-even nuclei with the axially-deformed Skyrme finite-amplitude method, *Phys. Rev. C* **93**, 014304 (2016).
- [46] B. A. Brown and W. D. M. Rae, The shell-model code NuShellX@MSU, *Nucl. Data Sheets* **120**, 115 (2014).
- [47] G. A. Lalazissis, J. König, and P. Ring, New parametrization for the Lagrangian density of relativistic mean field theory, *Phys. Rev. C* **55**, 540 (1997).
- [48] C. Robin, E. Litvinova, and G. Martínez-Pinedo, Beyond-mean-field calculations of allowed and first-forbidden  $\beta^-$  decays of  $r$ -process waiting-point nuclei, *EPJ Web Conf.* **260**, 03002 (2022).
- [49] C. Robin and G. Martínez-Pinedo, Competition between allowed and first-forbidden  $\beta$  decay in  $r$ -process waiting-point nuclei within a relativistic beyond-mean-field approach, *Phys. Rev. C* **110**, 065803 (2024).
- [50] T. M. Sprouse, K. A. Lund, J. M. Miller, G. C. McLaughlin, and M. R. Mumpower, Emergent nucleosynthesis from a 1.2 s long simulation of a black hole accretion disk, *Astrophys. J.* **962**, 79 (2024).
- [51] T. M. Sprouse, G. W. Misch, and M. R. Mumpower, Isochronic evolution and the radioactive decay of  $r$ -process nuclei, *Astrophys. J.* **929**, 22 (2022).