

Lawrence Berkeley National Laboratory

LBL Publications

Title

Constraining the astrophysical i process: The $\text{Kr}87(n,\gamma)\text{Kr}88$ reaction rate

Permalink

<https://escholarship.org/uc/item/98z635cj>

Journal

Physical Review C, 113(6)

ISSN

2469-9985

Authors

Uthayakumaar, S

Spyrou, A

Harris, C

et al.

Publication Date

2026-06-01

DOI

10.1103/x665-sgt7

Peer reviewed

Constraining the Astrophysical i process: The $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ Reaction Rate

S. Uthayakumaar,¹ A. Spyrou,^{1,2} C. Harris,^{1,2} P. A. Denissenkov,^{3,4} D. Mcher,⁵ H. C. Berg,^{1,2} J. A. Clark,⁶ P. A. DeYoung,⁷ A. C. Dombos,¹ B. Greaves,⁸ M. Guttormsen,⁹ F. Herwig,^{3,4} A. C. Larsen,⁹ S. N. Liddick,^{1,10} S. Lyons,¹¹ J. Owens-Fryar,^{1,2} A. Palmisano-Kyle,¹² G. Perdikakis,¹³ A. L. Richard,^{1,14} D. Santiago-Gonzalez,⁶ G. Savard,⁶ S. Siem,⁹ M. K. Smith,¹ W. W. von Seeger,¹⁵ and M. Wiedeking¹⁶

¹*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*

²*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

³*Astronomy Research Centre and Department of Physics and Astronomy,
University of Victoria, Victoria, British Columbia V8W 2Y2, Canada*

⁴*NuGrid Collaboration, <http://nugridstars.org>*

⁵*Institut fr Kernphysik der Universitt zu Kln, Zlpicher Strasse 77, D-50937 Kln, Germany*

⁶*Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*

⁷*Department of Physics, Hope College, Holland, Michigan 49423, USA*

⁸*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

⁹*Department of Physics, University of Oslo, NO-0316 Oslo, Norway*

¹⁰*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*

¹¹*Pacific Northwest National Laboratory, Richland, Washington, 99354, USA*

¹²*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*

¹³*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*

¹⁴*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*

¹⁵*Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556, USA*

¹⁶*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

Recent astronomical observations indicate that additional nucleosynthesis pathways are required to understand some atypical elemental abundance patterns revealed by new observations. One such process that can help to explain these observations is the intermediate neutron-capture process (i process). The nuclear properties of isotopes involved in this nucleosynthesis pathway are experimentally well constrained with the exception of the neutron-capture reaction rates, which are provided almost entirely by theory. In this paper, the first experimentally constrained reaction rate on the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction is provided by employing the β -Oslo method. The impact of this reaction on the abundance of rubidium within the i process is investigated.

I. INTRODUCTION

The distribution of observed elemental abundances across the universe provides insight into the various nucleosynthesis pathways taken since the inception of the Big Bang. One of the most critical open scientific questions is how nucleosynthesis of elements heavier than iron takes place. Since the ground-breaking work from Burbidge *et al.* [1] and Cameron *et al.* [2], it was shown that heavy elements are produced through three processes: the slow (s) [3] and rapid (r) [4–6] neutron-capture processes, which occur through a combination of neutron captures and β decays, and the p process [7–9], which is dominated by photo-disintegration reactions in the neutron-deficient region of the valley of stability.

Although this was considered to be the complete picture to explain the observed abundances of elements in various stars, recent observations from Carbon-Enhanced Metal-Poor (CEMP) stars [10, 11], and some post Asymptotic Giant Branch (AGB) stars such as Sakurai’s object [12], have shown that abundance patterns cannot be replicated by using the s and r processes alone or by the combination of the two processes [13, 14]. Hence, this requires additional nucleosynthesis pathways to explain how heavier elements are produced. One such process, proposed by Cowan and Rose [15], is the intermediate (i)

neutron-capture process, which occurs at neutron densities between $N_n = 10^{13-16}$ n/cm³, between the s process ($N_n < 10^{12}$ n/cm³) and the r process ($N_n > 10^{20}$ n/cm³). The nuclei involved are 2-8 mass units away from the valley of stability and are mostly accessible by current radioactive beam facilities.

The exact site where the i process occurs is still debated, requiring collaborative research at the intersection of experimental nuclear physics, modeling and observational astronomy [16]. This process requires a neutron source that produces intermediate neutron densities from $N_n = 10^{13-16}$ n/cm³, for which the presence of hydrogen and helium-burning shells is required. This condition allows for an interplay of reactions to occur within the same convective helium-burning zone due to proton ingestion. To produce such neutron intensities, a two-step process is undertaken. The first step involves the replenishment of ^{13}C production through the proton capture of ^{12}C via the $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reaction. This occurs during a helium flash where ^{12}C mixes with the outermost hydrogen shell. After the subsequent β decay of ^{13}N , neutrons are produced in the helium layer through the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction, increasing the neutron density through convective mixing. Possible sites where this process can occur are in thermally pulsing AGB, post-AGB and super-AGB stars [12, 17–23], rapidly accreting white

dwarf stars (RAWDs) [24–28], core-He flash in stars with low masses [29–31], or in massive stars in their last stages of life [32, 33].

To understand the production of heavier nuclei through the i process, models that incorporate details of the astrophysical conditions with the relevant nuclear properties are required [34]. For nuclei involved along the i process pathway, nuclear properties such as β -decay half-lives and masses are relatively well constrained. The main inputs with limited experimental constraints are the neutron-capture reaction rates, which are provided almost entirely by theoretical calculations, typically with unknown systematic uncertainties. Due to the short half-lives of the nuclei involved, the direct measurements of neutron-capture reaction rates of i -process nuclei are particularly challenging.

Theoretical estimates of the reaction rates and cross sections are typically obtained using the Hauser-Feshbach statistical model [35], where the nuclear level density (NLD), γ strength function (γ SF) and the optical model potential (OMP) are essential input parameters. The NLD describes the number of levels within an excitation bin as a function of excitation energy, while the γ SF details the probability of emission of a γ ray with a particular energy and multipolarity from the nucleus. The OMP describes the interaction between the nucleus and the neutron. In this work, the NLD and γ SF were the two key input parameters that were constrained. Different theoretical models are used to predict these two properties. These models are well constrained along the valley of stability. However, the calculations of the neutron-capture reaction rates vary up to a few orders of magnitude when moving away from stability [36, 37]. In order to constrain and inform the neutron-capture reaction rates for exotic neutron-rich isotopes, a variety of different indirect techniques can be applied [38]. Such examples include the surrogate reaction technique [39, 40], the γ SF technique [41], the Oslo method [42–44], and the Shape method [45, 46]. A variation of the Oslo method, namely the β -Oslo method [36, 47], is employed in this work to extract the NLD and γ SF for short-lived isotopes.

In recent sensitivity studies from Martinet *et al.* and Denissenkov *et al.* [48, 49], the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate was identified as having significant influence on the production of Rb isotopes. There are challenges in observing spectral lines for Rb abundances. However, some observations do exist (e.g. Ref. [12]), and astrophysical model calculations aim to reproduce stellar observations. For this reason, it is paramount to have a good constraint of the nuclear physics input.

In the present work, the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate was constrained by using the β decay of ^{88}Br to populate the compound nucleus ^{88}Kr and to experimentally constrain the NLD, and hence its γ SF. Previous work from Mcher *et al.* [46] successfully extracted the NLD of the ^{88}Kr nucleus through the Shape method [45]. Here, we combine the two results to provide an experimentally constrained reaction rate, and also present i -process cal-

culations using our new reaction rate.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at the CARIBU facility at Argonne National Laboratory. A ^{88}Br beam was utilized and delivered to the center of the Summing NaI(Tl) (SuN) detector [50, 51], a γ -ray total absorption spectrometer that was developed by Michigan State University. The beam was implanted into the SuN Transport system for Active Nuclei (SuNTAN) attached at the center of SuN [52]. The subsequent γ rays following the decay of ^{88}Br to ^{88}Kr , were detected in SuN in coincidence with detected β particles using a plastic scintillator barrel (SuNSPOT) surrounding the implantation area located at the center of SuN [52]. The light produced by the plastic scintillator barrel was collected by 32 wavelength-shifting fiber optics that were connected to the scintillator. The collected light output was transported to two photomultiplier tubes located outside SuN.

Typically, beams provided by the CARIBU facility include isobaric contamination. In the present work, the contaminants were the β decay products from ^{88}Se ($T_{1/2} = 1.53$ s) and ^{88}Kr ($T_{1/2} = 169.5$ min). The half life of the isotope of interest, ^{88}Br , is 16.3 s. For this reason, two different tape cycle settings were used in SuNTAN: (1) beam on for 5 seconds, beam off for 1 second, and (2) beam on for 120 seconds, beam off for 1 second. The former tape cycle setting was chosen to enhance the decay of ^{88}Se to ^{88}Br . The latter setting includes contributions from the decays of ^{88}Se and ^{88}Br . Since the half-lives of the contaminants are notably different, the two settings for the tape cycles were chosen to distinguish the different components, allowing for the ^{88}Se component from setting (1) to be subtracted from setting (2) to isolate the decay of ^{88}Br to ^{88}Kr . In this case, SuN was counting events during the beam-on portion of the tape cycle as the half life of ^{88}Kr is long lived. Therefore, the longer beam-off tape cycles were not needed.

SuN is a cylindrical detector that has dimensions of 16 inches in diameter and length with a 1.8 inch diameter borehole along the beam axis [50]. The detector is separated into 8 optically isolated segments, allowing for the extraction of individual γ -ray energies (E_γ) emitted by the compound nucleus of interest, being ^{88}Kr in this case. Summing the deposited energy across all of the segments on an event-by-event basis provides information of the excitation energies in the nucleus (E_x) through total absorption spectroscopy (TAS). Fig. 1 shows the contributions of the contaminants using the different tape settings detailed above in coincidence with SuN. The TAS obtained from the decay of ^{88}Se using the short tape cycle setting is shown by the black line in Fig. 1, where the strong presence of the peak at $E_x=1903$ keV is observed for this decay. The TAS spectrum for the longer tape cycle, consisting of decays of ^{88}Se and ^{88}Br contaminants, is denoted by the red line. Through the subtraction pro-

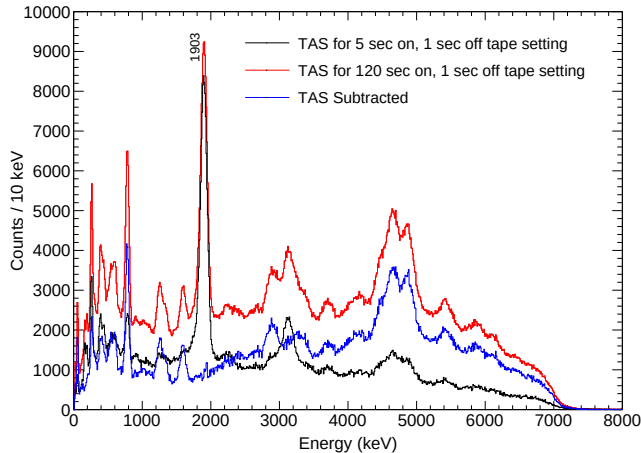


FIG. 1. The measured total absorption spectra (TAS) for the two settings used for the tape cycles. The black line shows the measured E_x for the 5 second beam on, 1 second beam-off setting, where the contribution from the decay of ^{88}Se was enhanced. The red line represents the E_x for the 120 second beam on, 1 second beam-off setting, where this setting consisted of ^{88}Se and ^{88}Br components. The blue line represents the E_x obtained when the ^{88}Se component (black) was subtracted from the second tape setting (red) to isolate the ^{88}Kr contribution.

cess between the two settings, the decay of ^{88}Br to ^{88}Kr becomes optimized, as shown by the blue line in Fig. 1, where it can be observed that the 1903 keV peak from the ^{88}Se contaminant is fully removed.

Following this optimization procedure, the combination of the measured E_γ and E_x into a two-dimensional matrix allows for the NLD and γSF of ^{88}Kr to be extracted from the experimental data using the β -Oslo method [47]. The raw matrix, following the subtraction of the contaminants resulting from the β decay of ^{88}Se and ^{88}Kr , is shown in Fig. 2(a), consisting of ~ 2 million counts.

III. RESULTS

A. β -Oslo Analysis

The β -Oslo method implements the traditional Oslo method [42–44] in cases where the nucleus of interest is produced via β decay. Highly excited states in the nucleus of interest are populated in the β decay, which de-excite through the emission of γ rays. An advantage of this approach is that it can be applied to nuclei far away from stability at lower implantation rates of ~ 1 -10 pps.

There are four main steps that are taken to extract the experimental NLD and γSF from the raw two-dimensional E_x vs E_γ matrix: (1) unfolding the γ -ray spectrum for each corresponding initial excitation energy

by taking into account the detector response [43], (2) isolating the primary γ -rays by applying an iterative subtraction process to obtain the distribution of the first γ rays emitted from each cascade for each initial excitation energy [44], (3) extraction of the functional form of the NLD and γ -ray transmission coefficient since the primary γ -ray matrix is proportional to the product of the NLD and γSF [42], and (4) applying external normalizations to determine the amplitude of the NLD and γSF , where the combination of these two statistical quantities are used to give the constrained neutron-capture reaction rate [43, 53].

The extraction of the NLD for ^{88}Kr has previously been performed by Mcher *et al.* using the Shape method as detailed in Ref. [46]. The main focus of the present work was to extract the γSF of ^{88}Kr , using the β -Oslo technique, and to combine the two experimental results to infer the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate.

The raw, unfolded, and primary γ -ray matrices for ^{88}Kr are plotted in Fig. 2(a), Fig. 2(b), and Fig. 2(c), respectively, with E_x as a function of E_γ . For the first step in the analysis, the unfolding procedure of the raw $^{88}\text{Kr}(E_\gamma, E_x)$ matrix takes into account the detector response of SuN as shown in Fig. 2(b). An iterative subtraction process, as detailed in Ref. [44], was used to produce the primary γ -ray matrix. This corresponds to the distribution of the first γ ray emitted from each E_x as shown in Fig. 2(c).

The distribution of the first γ ray observed from each E_x describes the probability of obtaining a γ ray of a given energy from its corresponding excitation energy, as shown by [42]:

$$P(E_x, E_\gamma) \sim \rho(E_x - E_\gamma) \cdot T(E_\gamma), \quad (1)$$

where $\rho(E_x - E_\gamma)$ is the NLD at the excitation energy after γ -ray emission of energy E_γ , and $T(E_\gamma)$ is the γ -ray transmission coefficient. The γ -ray transmission coefficient is related to the γSF , while assuming dipole transitions, by:

$$f(E_\gamma) = \frac{T(E_\gamma)}{2\pi E_\gamma^3}. \quad (2)$$

While the NLD has been previously extracted by Mcher *et al.* [46], this analysis focuses on the extraction of the experimental γSF , where bin widths, E_γ and E_x limits were considered from the primary γ -ray matrix. The corresponding region utilized to obtain the experimental γSF for ^{88}Kr is shown by the black solid lines in Fig. 2(c), where limits of $E_x=5.5$ -6.5 MeV and $E_\gamma=1.8$ MeV were applied. These limits were applied to avoid contributions from discrete levels.

B. Extraction of the γSF

The previously extracted upper and lower limits of the partial NLD for ^{88}Kr by Mcher *et al.* [46] is represented

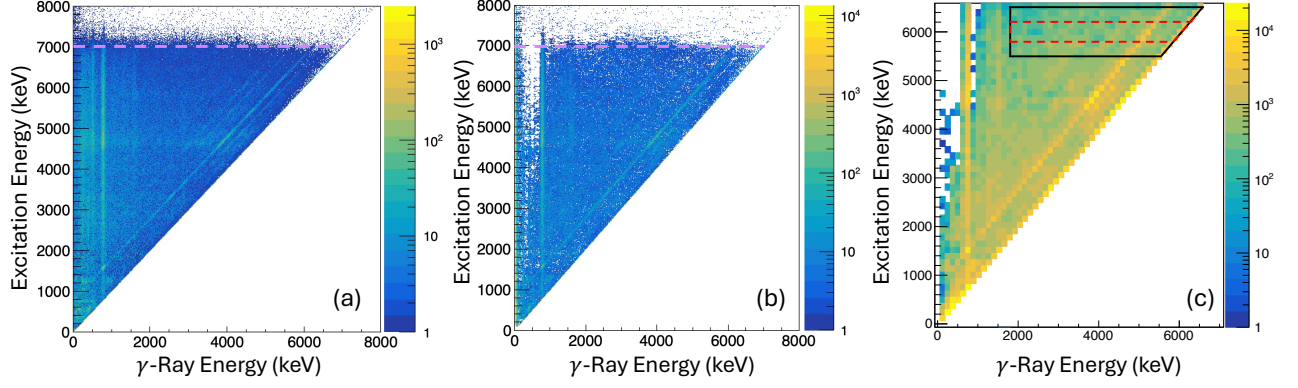


FIG. 2. The experimental matrices showing (a) the raw E_x vs. E_γ matrix from the β decay of ^{88}Br , with 8 keV/channel binning. The β -decay Q-value of ^{88}Br is 8.97 MeV. (b) shows the unfolded matrix with 8 keV/channel binning. In both (a) and (b), the dashed purple line represents the neutron separation energy, $S_n=7.053$ MeV. (c) shows the primary γ -ray matrix for ^{88}Kr obtained from the β - γ coincidences following the ^{88}Br decay. The bin width on both axes of the primary matrix is 128 keV/channel. The black trapezoid shown in (c) indicates the γ -ray and excitation energy limits applied to determine the experimental γSF . The region defined by the dashed red lines shows an example of a region considered for the evaluation of the systematic uncertainty.

by the yellow band in Fig. 3. The red points show the NLD extracted from the present work compared to the discrete levels as shown by the purple bars. The red points presented in Fig. 3 were extracted to reproduce the results obtained from Ref. [46]. In both cases, the NLD includes a spin range that assumes allowed β -decay transitions from the ground state of ^{88}Br (1^-), followed by a dipole γ -ray emission. The discrepancy observed between the extracted NLD from the present work and the upper and lower limits from Ref. [46] below 2.4 MeV is due to the nature of the theoretical models, which are meant to predict the NLD in a statistical regime. Below 2.4 MeV, the NLD becomes dominated by discrete levels. The more elaborate analysis by Mcher *et al.* [46], using the same dataset, was used to constrain the cross section.

The primary goal of the present analysis was to obtain the absolute γSF for ^{88}Kr . The β -Oslo method alone can extract the functional form of the NLD and $T(E_\gamma)$, where absolute quantities can be extracted by using external normalizations from equations 3 and 4:

$$\rho'(E_x - E_\gamma) = A e^{\alpha'(E_x - E_\gamma)} \rho(E_x - E_\gamma) \quad (3)$$

$$T'(E_\gamma) = B e^{\alpha'(E_\gamma)} T(E_\gamma) \quad (4)$$

where A and B are scaling factors and α' represents the slope parameter. The A and α' parameters are typically determined from the following normalization data: (1) discrete states at low excitation energies, and (2) the level density at the neutron separation energy, $\rho(S_n)$ found by using average level spacing data for s-wave neutrons (D_0) at S_n , if available. The third parameter, B , represents the magnitude of the γSF , which is determined using the average radiative width ($\langle\Gamma_\gamma\rangle$) at S_n . Due to the short half-lives of the exotic nuclei explored in this

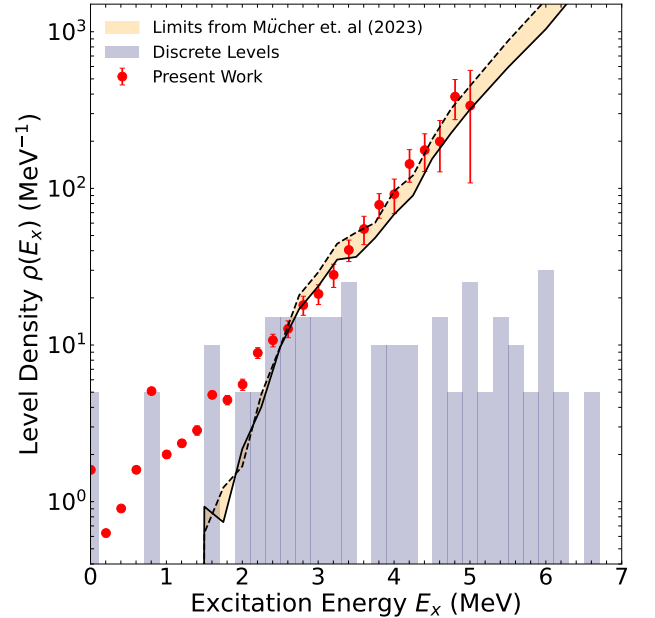


FIG. 3. The partial NLD extracted from present work (red circles). The discrete levels are shown by the purple bars by taking into account the states populated in ^{88}Kr following allowed β -decay and one dipole γ -ray transition. The upper and lower limits of the NLD extracted from the Shape method by Mcher *et al.* [46] are shown by the yellow band.

work, these normalization parameters were not available. As detailed in Ref. [46], this issue was addressed by determining the slope of the γSF , and consequently the NLD, using the Shape method. Here, the slope of the γSF from the β -Oslo method was fixed to that from the Shape method [46].

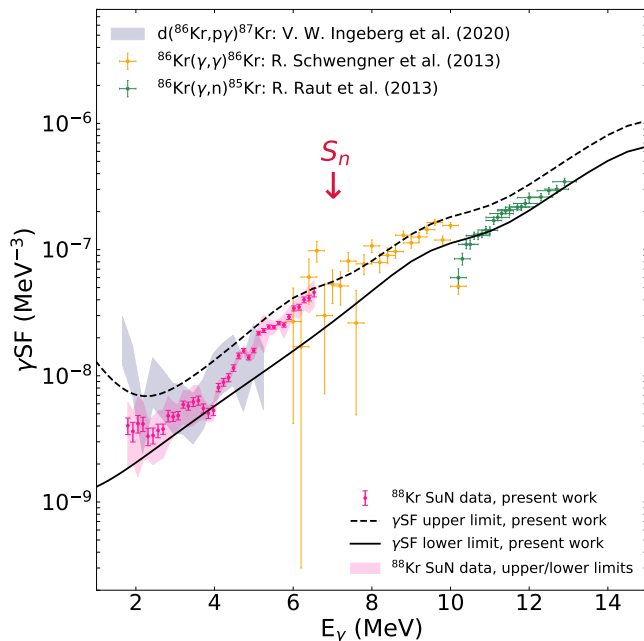


FIG. 4. The γ SF for ^{88}Kr where the experimental data extracted from the present work is shown by the pink points. The γ SF was normalized to the γ SF from Ingeberg *et al.* [54] at $E_\gamma=4.35$ MeV. The pink band shows the systematic uncertainty resulting from variations in matrix binning and choice of limits applied for the statistical region. Experimental data for ^{85}Kr and ^{86}Kr from Refs. [55, 56] are shown by the green and orange points, respectively. Experimentally extracted upper and lower limits for the ^{88}Kr γ SF, shown by the black dashed and solid lines, respectively, were normalized to data from Ingeberg *et al.* [54], presented by the purple band. The Skyrme-Hartree-Fock BCS model with QRPA [57] was applied in TALYS to fit the upper and lower limits of the extracted γ SF.

The absolute experimental γ SF extracted from the current work, denoted by the pink points in Fig. 4, was normalized to the data of Ingeberg *et al.* [54] for the $d(^{86}\text{Kr}, p\gamma)^{87}\text{Kr}$ reaction, shown by the purple band. Photoabsorption data from the nearby ^{85}Kr (green points) and ^{86}Kr isotopes (yellow points) [55, 56] were also applied for comparison. The upper and lower limits taken from the β -Oslo analysis were fit using the shape of the Skyrme-Hartree-Fock BCS model [57], as shown by the black dashed and solid lines in Fig. 4, respectively.

In addition to uncertainties due to the normalization process, systematic uncertainties due to the analysis were also taken into account. The limits for statistical decay in the primary γ -ray matrix were varied to determine the γ SF. An example of one of the statistical regions explored in this analysis is defined by the dashed red lines in Fig. 2(c). The regions explored in this work were chosen such that the strong contributions from the 775 keV and 1577 keV γ rays along the E_γ axis were not included in the analysis since these respective γ rays result from the decays of the discrete 2_1^+ and 2_2^+ states. Based on

these criteria, the limit of $E_\gamma=1.8$ MeV was applied to the defined statistical regions in Fig. 2(c). The excitation energy limits were applied such that the absolute γ SF exclude possible contributions from discrete states, contamination effects in the beam and neutron-induced background within the region defined by the black lines in Fig. 2(c).

By varying the bin widths and the limits of E_x in the primary matrix, it was observed that the structural features, such as the upbend [58–60] and the pygmy dipole resonance (PDR) [61–64], and the overall shape of the extracted γ SF were found to be consistent. This was found to be true as long as the lower limit of E_x in the primary matrix is placed within the statistical region, and that the lower limit of E_γ was placed above the region where γ -ray emission from discrete levels become prevalent.

The contribution of the systematic uncertainties for the extracted experimental γ SF is denoted by the pink band in Fig. 4. This was calculated by determining the square root of the sum of the residuals of the γ SFs obtained from the variation of the statistical limits applied in the matrix in correspondence with the absolute experimental values of γ SF at each E_γ . This approach allows for the systematic uncertainties to be folded into the statistical uncertainties, indicating the limits where the γ SF can vary within. The uncertainty band is quite narrow in the region $E_\gamma=4\text{--}5.5$ MeV due to this being the E_γ region corresponding to the center-of-mass for primary γ spectra.

C. Determining the Constrained Reaction Rate

The corresponding upper and lower limits of the NLD from M ucher *et al.* [46] and γ SF were used as inputs to TALYS [65] to calculate the experimentally constrained reaction rate of the $^{87}\text{Kr}(n, \gamma)^{88}\text{Kr}$ reaction.

The black dashed line in Fig. 4 is the fit extracted for the upper limit of the γ SF. This fit includes a small enhancement between 5–6.5 MeV to better reproduce the data, and was considered to contribute to the uncertainty in the extracted reaction rate. An exponential function, known as the upbend [58–60], was also applied to the upper and lower limits of the normalized experimental γ SF within the TALYS framework to account for the increase in the γ SF at low γ -ray energies. The black solid line in Fig. 4 represents the fit to the lower limit of the γ SF, shown by the pink data points. The enhancement seen at $E_\gamma=5\text{--}6.5$ MeV was not included in the fit of the lower limit of the γ SF to account for all sources of systematic uncertainties that could contribute to the overall constrained reaction rate. For the lower limit, a shallow upbend was applied to encapsulate the lower limit of the uncertainties at $E_\gamma < 4$ MeV. In both cases, it is important to note that the upper and lower fits of the extracted absolute γ SF is a generous estimate to account for the maximum uncertainties resulting from systematic tests.

The reaction rate of the $^{87}\text{Kr}(n, \gamma)^{88}\text{Kr}$ reaction, cal-

culated from the combination of the extracted upper and lower limits of the NLD from Ref. [46] and the γ SF (see Fig. 4), is shown in Fig. 5. The lighter and wider blue band shows the range of reaction rates taking into account all possible combinations of the NLD and γ SF models available in TALYS 1.96 [65]. For the NLD, all six available models were utilized [66–71]. All nine models for the E1 component [57, 72–79] and two models for the M1 component of the γ SF [80] have been considered to determine the maximum and minimum rates. The default model from Koning and Delaroche was applied [81] for the optical model potential (OMP) for all the models considered for the NLD and γ SF.

By utilizing the limits of the extracted experimental NLD and γ SF shown in Figs. 3 and 4, it can be seen that the range of the predicted reaction rate uncertainty is greatly reduced for the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction (shown by the orange band in Fig. 5). The constrained reaction rate was also compared to the default reaction rate from JINA REACLIB v2.2 [82] (dashed black line), which is used for astrophysical calculations.

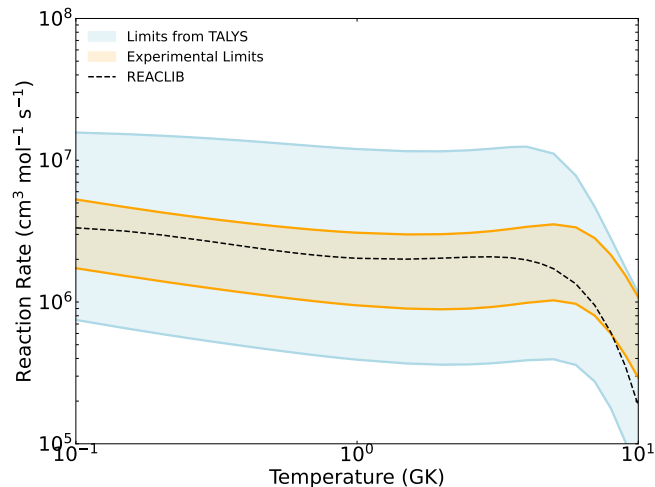


FIG. 5. The reaction rate of the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction. The light blue band represents the range of the predicted reaction rates from TALYS 1.96 [65] for all available models for the NLD and γ SF. The orange band shows the experimentally constrained reaction rate obtained from the current analysis, resulting from the corresponding upper and lower limits of the NLD and γ SF. The dashed black line represents the theoretical reaction rate taken from JINA REACLIB v2.2 [82].

IV. ASTROPHYSICAL CALCULATIONS

The experimentally constrained reaction rate was applied in astrophysical i -process calculations to understand the impact of the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction on the final Rb abundance patterns. The NuGrid sppn code in its constant neutron density configuration as described in Ref. [83] was utilized, with neutron density parameters typical for the i process. To study the impact of

the deduced constrained reaction rate on the observed Rb abundance patterns, the investigation of particular neutron densities that are within the range of where the i -process occurs is required. In this work, two constant neutron densities were considered: $N_n=3.16\times 10^{13}\text{ cm}^{-3}$ and $N_n=3.16\times 10^{14}\text{ cm}^{-3}$, which are within the proposed i -process range.

One-zone Monte-Carlo (MC) simulations, similar to those done in Refs. [26, 49], but with random variations of neutron-capture rates for all relevant unstable species in the i -process pathway were run for these two neutron densities. The MC simulations require estimates for maximum variation factors, v_i^{max} , and lower and upper limits for random multiplication factors, f_i , applied to selected reaction rates. The choice of sets of v_i^{max} values used in our work for MC simulations is based on a comparison of maximum and minimum reaction rates computed with 20 different Hauser-Feshbach input model combinations, as explained in Refs. [26, 49]. Possible rate correlations were not taken into account. Compared to the v_i^{max} values proposed in Ref. [48], the differences between the factors utilized are not significant, where the identification of impactful reactions is not affected.

The MC simulations produces sets of elemental and isotopic abundances, X_k , predicted by a given astrophysical nucleosynthesis model for the same number of different sets of reaction rate multiplication factors, f_i . A statistical analysis of these data can reveal reactions whose rate variations have the strongest impact on the abundance of a given species. Such reactions have simultaneously the largest (by absolute magnitude) correlation coefficients between X_k and f_i and logarithmic slopes, s_i^1 , with $X_k \propto f_i^{s_i}$. For Rb, such a reaction is $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ with correlation coefficients and slopes equal to -0.77 and -0.36 for $N_n=3.16\times 10^{13}\text{ cm}^{-3}$ and -0.59 and -0.57 for $N_n=3.16\times 10^{14}\text{ cm}^{-3}$, indicating that such a reaction would dominate the Rb distribution.

Uncertainties of predicted abundances are determined by v_i^{max} values for reactions having the strongest impact on these abundances. As estimated values of v_i^{max} depend on the Hauser-Feshbach model setup, the absolute abundance uncertainties still remain poorly constrained. Therefore, the MC simulations can be used to identify the most impactful reactions, where the application of experimentally constrained rates of such reactions can reduce variations in the predictions of elemental abundances.

Bifurcation plots in Fig. 6 present distributions of the $[\text{Rb}/\text{Zr}]$ abundance ratio, logarithmic and with respect to the solar one, obtained in 4 sets of our 10,000 MC runs. The split of the $[\text{Rb}/\text{Zr}]$ distributions into two peaks is caused by a bifurcation of the i -process path at the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction. The blue and yellow peaks

¹ The logarithmic slopes, s_i , are calculated with the NumPy's polyfit function using linear fits of elemental abundances X_k obtained in Monte Carlo simulations as functions of reaction rate multiplication factors f_i

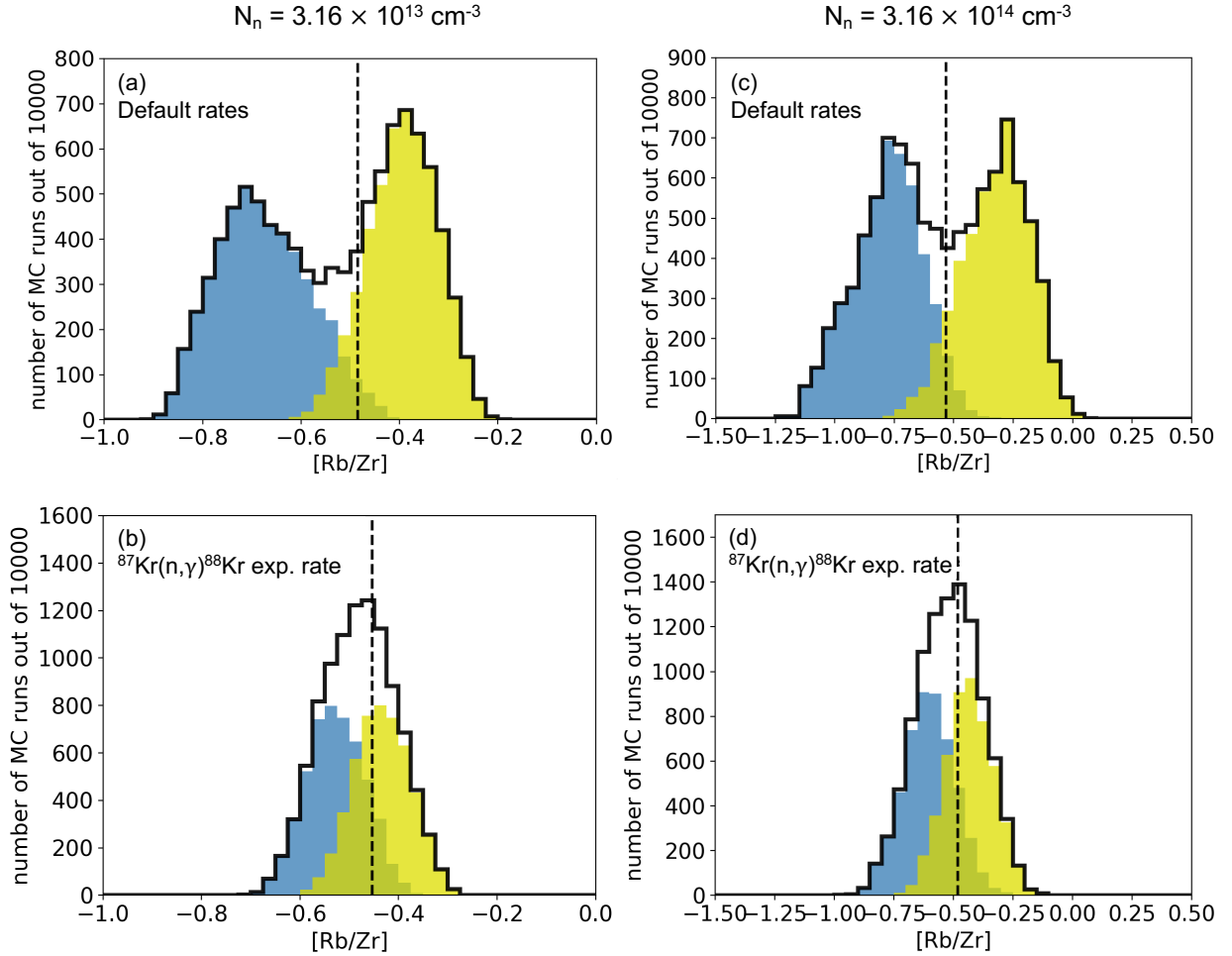


FIG. 6. The bifurcation plots comparing the distributions of $[Rb/Zr]$ abundance ratio when (a) the default reaction rates were implemented to the Monte Carlo (MC) simulations, and (b) when the constrained $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate was added, respectively. For both plots, the neutron density of $N_n=3.16\times 10^{13} \text{ cm}^{-3}$ was utilized. Figure (c) shows the default bifurcation plots, and (d) when the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate is included. For both plots, a neutron density of $N_n=3.16\times 10^{14} \text{ cm}^{-3}$ was applied. The constrained results are shown by the thick black line in all plots and the vertical dashed lines show the results of calculations in which default rates ($f_i = 1$) were used for all other reactions. The single-peak distributions, shown by the blue and yellow peaks, contain multiplication factors of $f_i > 1$ and $f_i < 1$ for all figures.

represent the $[Rb/Zr]$ ratios obtained with the multiplication factors $f_i > 1$ and $f_i < 1$ applied to the default rate of this reaction, respectively. Fig. 6(a) shows the bifurcation plot with the inclusion of the experimentally constrained $^{90,92}\text{Sr}(n,\gamma)^{91,93}\text{Sr}$ reaction rates [83, 84] at the neutron density (N_n) of $3.16\times 10^{13} \text{ cm}^{-3}$. These reactions were included in the calculations to constrain the abundances in Zr. Fig. 6(c) shows the bifurcation plot with the experimentally constrained $^{90,92}\text{Sr}(n,\gamma)^{91,93}\text{Sr}$ reaction rates at $N_n=3.16\times 10^{14} \text{ cm}^{-3}$. This reduces variations of the Zr abundance that correlate with these reaction rates. In both cases, we highlight the use of the $^{90,92}\text{Sr}(n,\gamma)^{91,93}\text{Sr}$ reactions as these new measurements

have not been included in previous reaction networks. Hence, these reactions were added to the default reaction set to ensure the use of the most up-to-date experimental constraints. For comparison, it is important to note that with the maximum variation factors estimated for the TALYS set B Hauser-Feshbach model from Ref. [48], the blue and yellow peaks in Fig. 6(c) would be located between the values of $[Rb/Zr]=-1$ and $[Rb/Zr]=-0.05$.

The upper and lower limits of the experimentally constrained rate for the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction (see orange band in Fig. 5) were used in the astrophysical i -process calculations. These limits were applied to deduce the impact of the reduced uncertainty of this reaction rate

on the Rb abundances, seen in Figs. 6(b) and 6(d) for $N_n = 3.16 \times 10^{13} \text{ cm}^{-3}$ and $N_n = 3.16 \times 10^{14} \text{ cm}^{-3}$, respectively. It is important to note that the application of this constrained reaction rate shows a significant relative reduction in the resulting uncertainty shown by the narrowing of the blue and yellow peaks.

From Figs. 6(b) and 6(d), the source of the remaining separation seen between the two peaks is in question. From the MC correlation plots in the sensitivity study from Ref. [49], the $^{85}\text{Br}(n,\gamma)^{86}\text{Br}$ reaction also has a negative correlation with the predicted abundance of Rb, although with a reduced coefficient compared to the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction. Furthermore, additional reactions that contribute to the Zr predicted abundances can also play a role to reduce this uncertainty, where the correlation coefficient of the currently studied reaction was found to be strongly positive.

V. CONCLUSIONS

From the present work, the first experimental constraint of the $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$ reaction rate has been determined by utilizing previous results from the Shape method by Mcher *et al.* [46] to extract the NLD, and through the β -Oslo method in the current work to determine the γ SF. Both quantities were required to constrain the resulting experimental rate for this reaction. The resulting rate has been applied in astrophysical *i*-process calculations to explore the impact of this reaction on the Rb abundance patterns, where it was found that the scatter in the predicted [Rb/Zr] abundance ratio has been greatly reduced. This emphasizes that even a single experimentally constrained neutron-capture reaction rate with a reduced uncertainty can have a large effect on a comparison of theoretically predicted elemental abundance patterns with those observed in stars containing products of *i*-process nucleosynthesis. Furthermore, it is highlighted that the uncertainty of an astronomical observable that involves Rb, such as the [Rb/Zr] abundance ratio, is now well constrained experimentally. It can be further noted that other neutron-capture reactions that impact the [Rb/Zr] abundance ratio should also be ex-

plored, in particular the $^{85}\text{Br}(n,\gamma)^{86}\text{Br}$ reaction. We also recommend that future stellar observations of Rb abundances, possibly also in pre-solar grains, would benefit our understanding of Rb production within the *i* process.

VI. ACKNOWLEDGMENTS

Contributions from F. Zeiser are gratefully acknowledged. This research utilized resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility. This material is based upon work supported by the Department of Energy National Nuclear Security Administration through the Nuclear Science and Security Consortium under Award Numbers DE-NA0003996 and DE-NA0003180, the Stewardship Science Academic Alliances program through DOE Award Number DE-NA0003906. This project was also supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-SC0023633. This material is also based upon work supported by the National Science Foundation under grants PHY-2209429 and 1913554. P.A. Denissenkov and F.H. acknowledges support from the Natural Sciences and Engineering Research Council of Canada (NSERC) award SAPPJ-797 2021-00032 and a Discovery Grant. S.S., A.C.L. and M.G. acknowledge funding by the Research Council of Norway through its grant to the Norwegian Nuclear Research Centre (Project No. 341985). A.C.L. also gratefully acknowledges funding from the Research Council of Norway (Project Grant No. 316116). G.P. acknowledges support from the College of Science and Engineering of Central Michigan University. W.W.S. acknowledges support from the National Science Foundation through grant number NSF PHY-2310059. P.A. DeYoung acknowledges support from the National Science Foundation through grant number NSF PHY-2209138. S.L. acknowledges support from the Laboratory Directed Research and Development Program at Pacific Northwest National Laboratory operated by Battelle for the U.S. Department of Energy. M.W. acknowledges support by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-AC02-05CH11231 (LBNL).

-
- [1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957).
 - [2] A. G. W. Cameron, *Publications of the Astronomical Society of the Pacific* **69**, 201 (1957).
 - [3] F. Kppeler, R. Gallino, S. Bisterzo, and W. Aoki, *Rev. Mod. Phys.* **83**, 157 (2011).
 - [4] M. Arnould, S. Goriely, and K. Takahashi, *Physics Reports* **450**, 97 (2007).
 - [5] C. Sneden, J. J. Cowan, and R. Gallino, *Annual Review of Astronomy and Astrophysics* **46**, 241 (2008).
 - [6] J. J. Cowan, C. Sneden, J. E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martnez-Pinedo, and F.-K. Thielemann, *Rev. Mod. Phys.* **93**, 015002 (2021).
 - [7] M. Arnould and S. Goriely, *Physics Reports* **384**, 1 (2003).
 - [8] N. Nishimura, T. Rauscher, R. Hirschi, A. S. J. Murphy, G. Cescutti, and C. Travaglio, *Monthly Notices of the Royal Astronomical Society* **474**, 3133 (2017).
 - [9] C. Travaglio, T. Rauscher, A. Heger, M. Pignatari, and C. West, *The Astrophysical Journal* **854**, 18 (2018).
 - [10] M. Asplund, D. L. Lambert, T. Kipper, D. Pollacco, and M. D. Shetrone, *Astron. Astrophys.* **343**, 507 (1999).
 - [11] I. U. Roederer, A. I. Karakas, M. Pignatari, and F. Herwig, *The Astrophysical Journal* **821**, 37 (2016).

- [12] F. Herwig, M. Pignatari, P. R. Woodward, D. H. Porter, G. Rockefeller, C. L. Fryer, M. Bennett, and R. Hirschi, *Astrophys. J.* **727**, 89 (2011).
- [13] L. Dardelet, C. Ritter, P. Prado, E. Heringer, C. Higgs, S. Sandalski, S. Jones, P. Denisenkov, K. Venn, M. Bertolli, *et al.*, in *XIII Nuclei in the Cosmos (NIC XIII)* (2014) p. 145.
- [14] M. Hampel, R. J. Stancliffe, M. Lugaro, and B. S. Meyer, *The Astrophysical Journal* **831**, 171 (2016).
- [15] J. J. Cowan and W. K. Rose, *Astrophys. J.* **212**, 149 (1977).
- [16] M. Wiedeking, S. Goriely, M. Guttormsen, F. Herwig, A. C. Larsen, S. N. Liddick, D. Mcher, A. L. Richard, S. Siem, and A. Spyrou, *Nat. Rev. Phys.* **7**, 696–712 (2025).
- [17] M. M. Bertolami and L. G. Althaus, *Astronomy & Astrophysics* **454**, 845 (2006).
- [18] R. A. Malaney, *Monthly Notices of the Royal Astronomical Society* **223**, 683 (1986).
- [19] S. Cristallo, L. Piersanti, O. Straniero, R. Gallino, I. Domnguez, and F. Kppeler, *Publications of the Astronomical Society of Australia* **26**, 139–144 (2009).
- [20] S. Cristallo, D. Karinkuzhi, A. Goswami, L. Piersanti, and D. Gobrecht, *The Astrophysical Journal* **833**, 181 (2016).
- [21] A. Choplin, L. Siess, and S. Goriely, *Astronomy & astrophysics* **648**, A119 (2021).
- [22] H. H. B. Lau, R. J. Stancliffe, and C. A. Tout, *Monthly Notices of the Royal Astronomical Society* **396**, 1046 (2009).
- [23] S. Jones, C. Ritter, F. Herwig, C. Fryer, M. Pignatari, M. G. Bertolli, and B. Paxton, *Monthly Notices of the Royal Astronomical Society* **455**, 3848 (2015).
- [24] P. A. Denissenkov, F. Herwig, U. Battino, C. Ritter, M. Pignatari, S. Jones, and B. Paxton, *The Astrophysical Journal Letters* **834**, L10 (2017).
- [25] P. A. Denissenkov, F. Herwig, P. Woodward, R. Andrassy, M. Pignatari, and S. Jones, *Monthly Notices of the Royal Astronomical Society* **488**, 4258 (2019).
- [26] P. A. Denissenkov, F. Herwig, G. Perdikakis, and H. Schatz, *Monthly Notices of the Royal Astronomical Society* **503**, 3913 (2021).
- [27] L. Piersanti, L. R. Yungelson, S. Cristallo, and A. Tornamb, *Monthly Notices of the Royal Astronomical Society* **484**, 950 (2019).
- [28] D. Stephens, F. Herwig, P. Woodward, P. Denissenkov, R. Andrassy, and H. Mao, *Monthly Notices of the Royal Astronomical Society* **504**, 744 (2021).
- [29] S. W. Campbell, M. Lugaro, and A. I. Karakas, *Astronomy & Astrophysics* **522**, L6 (2010).
- [30] M. Cruz, A. Serenelli, and A. Weiss, *Astronomy & Astrophysics* **559**, A4 (2013).
- [31] T. Battich, M. M. Bertolami, A. Serenelli, S. Justham, and A. Weiss, *Astronomy & Astrophysics* **680**, L13 (2023).
- [32] O. Clarkson, F. Herwig, and M. Pignatari, *Monthly Notices of the Royal Astronomical Society: Letters* **474**, L37 (2017).
- [33] P. Banerjee, Y.-Z. Qian, and A. Heger, *The Astrophysical Journal* **865**, 120 (2018).
- [34] S. Goriely, L. Siess, and A. Choplin, *Astronomy & Astrophysics* **654**, A129 (2021).
- [35] W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366 (1952).
- [36] S. N. Liddick, A. Spyrou, B. P. Crider, F. Naqvi, A. C. Larsen, M. Guttormsen, M. Mumpower, R. Surman, G. Perdikakis, D. L. Bleuel, A. Couture, L. Crespo Campo, A. C. Dombos, R. Lewis, S. Mosby, S. Nikas, C. J. Prokop, T. Renstrom, B. Rubio, S. Siem, and S. J. Quinn, *Phys. Rev. Lett.* **116**, 242502 (2016).
- [37] M. Wiedeking and S. Goriely, *Philosophical Transactions A* **382**, 20230125 (2024).
- [38] A. Larsen, A. Spyrou, S. Liddick, and M. Guttormsen, *Progress in Particle and Nuclear Physics* **107**, 69 (2019).
- [39] J. E. Escher, J. T. Harke, F. S. Dietrich, N. D. Scielzo, I. J. Thompson, and W. Younes, *Rev. Mod. Phys.* **84**, 353 (2012).
- [40] J. Cizewski, R. Hatarik, K. Jones, S. Pain, J. Thomas, M. Johnson, D. Bardayan, J. Blackmon, M. Smith, and R. Kozub, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **261**, 938 (2007).
- [41] H. Utsunomiya, S. Goriely, H. Akimune, H. Harada, F. Kitatani, S. Goko, H. Toyokawa, K. Yamada, T. Kondo, O. Itoh, M. Kamata, T. Yamagata, Y.-W. Lui, I. Daoutidis, D. P. Arteaga, S. Hilaire, and A. J. Koning, *Phys. Rev. C* **82**, 064610 (2010).
- [42] A. Schiller, L. Bergholt, M. Guttormsen, E. Melby, J. Rekstad, and S. Siem, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **447**, 498 (2000).
- [43] M. Guttormsen, T. Tveter, L. Bergholt, F. Ingebretsen, and J. Rekstad, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **374**, 371 (1996).
- [44] M. Guttormsen, T. Ramsy, and J. Rekstad, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **255**, 518 (1987).
- [45] M. Wiedeking, M. Guttormsen, A. C. Larsen, F. Zeiser, A. Grgen, S. N. Liddick, D. Mcher, S. Siem, and A. Spyrou, *Phys. Rev. C* **104**, 014311 (2021).
- [46] D. Mcher, A. Spyrou, M. Wiedeking, M. Guttormsen, A. C. Larsen, F. Zeiser, C. Harris, A. L. Richard, M. K. Smith, A. Grgen, S. N. Liddick, S. Siem, H. C. Berg, J. A. Clark, P. A. DeYoung, A. C. Dombos, B. Greaves, L. Hicks, R. Kelmar, S. Lyons, *et al.*, *Phys. Rev. C* **107**, L011602 (2023).
- [47] A. Spyrou, S. N. Liddick, A. C. Larsen, M. Guttormsen, K. Cooper, A. C. Dombos, D. J. Morrissey, F. Naqvi, G. Perdikakis, S. J. Quinn, T. Renstrm, J. A. Rodriguez, A. Simon, C. S. Sumithrarachchi, and R. G. T. Zegers, *Phys. Rev. Lett.* **113**, 232502 (2014).
- [48] S. Martinet, A. Choplin, S. Goriely, and L. Siess, *Astronomy & astrophysics* **684**, A8 (2024).
- [49] P. Denissenkov, G. Perdikakis, F. Herwig, H. Schatz, C. Ritter, M. Pignatari, S. Jones, S. Nikas, and A. Spyrou, *Journal of Physics G: Nuclear and Particle Physics* **45**, 055203 (2018).
- [50] A. Simon, S. Quinn, A. Spyrou, A. Battaglia, I. Beskin, A. Best, B. Bucher, M. Couder, P. DeYoung, X. Fang, J. Grres, A. Kontos, Q. Li, S. Liddick, A. Long, S. Lyons, K. Padmanabhan, J. Peace, A. Roberts, D. Robertson, *et al.*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **703**, 16 (2013).

- [51] 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, F. Naqvi, C. S. Sumithrarachchi, and R. G. T. Zegers, *Phys. Rev. C* **93**, 064317 (2016).
- [52] C. M. Harris, M. K. Smith, A. Spyrou, P. DeYoung, J. Clark, H. Berg, A. Dombos, J. Gombas, B. Greaves, R. Lewis, S. Liddick, S. Lyons, F. Naqvi, G. Owens-Fryar, A. Palmisano-Kyle, A. Richard, G. Savard, D. Santiago-Gonzalez, C. Sumithrarachchi, A. Torode, and W. von Seeger, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1084**, 171185 (2026).
- [53] A. C. Larsen, M. Guttormsen, M. Krťicka, E. Bťatak, A. Břrger, A. Gřrgen, H. T. Nyhus, J. Rekstad, A. Schiller, S. Siem, H. K. Toft, G. M. Tveten, A. V. Voinov, and K. Wikan, *Phys. Rev. C* **83**, 034315 (2011).
- [54] V. W. Ingeberg, S. Siem, M. Wiedeking, K. Sieja, D. L. Bleuel, C. P. Brits, T. Bucher, T. S. Dinoko, J. L. Easton, A. Gřrgen, M. Guttormsen, P. Jones, B. V. Kheswa, N. A. Khumalo, A. C. Larsen, E. A. Lawrie, J. J. Lawrie, S. N. T. Majola, K. L. Malatji, L. Makhathini, *et al.*, *The European Physical Journal A* **56**, 68 (2020).
- [55] R. Raut, A. P. Tonchev, G. Rusev, W. Tornow, C. Iliadis, M. Lugaro, J. Buntain, S. Goriely, J. H. Kelley, R. Schwengner, A. Banu, and N. Tsoneva, *Phys. Rev. Lett.* **111**, 112501 (2013).
- [56] R. Schwengner, R. Massarczyk, G. Rusev, N. Tsoneva, D. Bemmerer, R. Beyer, R. Hannaske, A. R. Junghans, J. H. Kelley, E. Kwan, H. Lenske, M. Marta, R. Raut, K. D. Schilling, A. Tonchev, W. Tornow, and A. Wagner, *Phys. Rev. C* **87**, 024306 (2013).
- [57] S. Goriely and E. Khan, *Nuclear Physics A* **706**, 217 (2002).
- [58] A. Voinov, E. Algin, U. Agvaanluvsan, T. Belgia, R. Chankova, M. Guttormsen, G. E. Mitchell, J. Rekstad, A. Schiller, and S. Siem, *Phys. Rev. Lett.* **93**, 142504 (2004).
- [59] A. Simon, M. Guttormsen, A. C. Larsen, C. W. Beausang, P. Humby, J. T. Harke, R. J. Casperson, R. O. Hughes, T. J. Ross, J. M. Allmond, R. Chyzh, M. Dag, J. Koglin, E. McCleskey, M. McCleskey, S. Ota, and A. Saastamoinen, *Phys. Rev. C* **93**, 034303 (2016).
- [60] A. C. Larsen, N. Blasi, A. Bracco, F. Camera, T. K. Eriksen, A. Gřrgen, M. Guttormsen, T. W. Hagen, S. Leoni, B. Million, H. T. Nyhus, T. Renstrřm, S. J. Rose, I. E. Ruud, S. Siem, T. Torny, G. M. Tveten, A. V. Voinov, and M. Wiedeking, *Phys. Rev. Lett.* **111**, 242504 (2013).
- [61] N. Paar, D. Vretenar, E. Khan, and G. Colř, *Reports on Progress in Physics* **70**, R02 (2007).
- [62] D. Savran, T. Aumann, and A. Zilges, *Progress in Particle and Nuclear Physics* **70**, 210 (2013).
- [63] A. Bracco, E. Lanza, and A. Tamii, *Progress in Particle and Nuclear Physics* **106**, 360 (2019).
- [64] E. Lanza, L. Pellegri, A. Vitturi, and M. Andrřs, *Progress in Particle and Nuclear Physics* **129**, 104006 (2023).
- [65] A. J. Koning, S. Hilaire, and M. C. Duijvestijn, in *International Conference on Nuclear Data for Science and Technology* (EDP Sciences, 2007) pp. 211–214.
- [66] A. Gilbert and A. G. W. Cameron, *Canadian Journal of Physics* **43**, 1446 (1965).
- [67] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, *Nuclear Physics A* **217**, 269 (1973).
- [68] A. V. Ignatyuk, J. L. Weil, S. Raman, and S. Kahane, *Phys. Rev. C* **47**, 1504 (1993).
- [69] S. Goriely, F. Tondeur, and J. Pearson, *Atomic Data and Nuclear Data Tables* **77**, 311 (2001).
- [70] S. Goriely, S. Hilaire, and A. J. Koning, *Phys. Rev. C* **78**, 064307 (2008).
- [71] S. Hilaire, M. Girod, S. Goriely, and A. J. Koning, *Phys. Rev. C* **86**, 064317 (2012).
- [72] J. Kopecky and M. Uhl, *Phys. Rev. C* **41**, 1941 (1990).
- [73] D. M. Brink, *Nuclear Physics* **4**, 215 (1957).
- [74] P. Axel, *Phys. Rev.* **126**, 671 (1962).
- [75] S. Goriely, E. Khan, and M. Samyn, *Nuclear Physics A* **739**, 331 (2004).
- [76] S. Goriely, *Physics Letters B* **436**, 10 (1998).
- [77] I. Daoutidis and S. Goriely, *Phys. Rev. C* **86**, 034328 (2012).
- [78] S. Goriely, S. Hilaire, S. Pėru, and K. Sieja, *Phys. Rev. C* **98**, 014327 (2018).
- [79] V. Plujko, O. Gorbachenko, R. Capote, and P. Dimitriou, *Atomic Data and Nuclear Data Tables* **123–124**, 1 (2018).
- [80] R. Capote, M. Herman, P. Oblořinský, P. Young, S. Goriely, T. Belgia, A. Ignatyuk, A. Koning, S. Hilaire, V. Plujko, M. Avrigeanu, O. Bersillon, M. Chadwick, T. Fukahori, Z. Ge, Y. Han, S. Kailas, J. Kopecky, V. Maslov, G. Reffo, *et al.*, *Nuclear Data Sheets* **110**, 3107 (2009), special Issue on Nuclear Reaction Data.
- [81] A. Koning and J. Delaroche, *Nuclear Physics A* **713**, 231 (2003).
- [82] R. H. Cyburt, A. M. Amthor, R. Ferguson, Z. Meisel, K. Smith, S. Warren, A. Heger, R. Hoffman, T. Rauscher, A. Sakharuk, *et al.*, *The Astrophysical Journal Supplement Series* **189**, 240 (2010).
- [83] B. Greaves, D. Mřcher, A. Spyrou, P. Denissenkov, C. M. Harris, M. K. Smith, A. Sweet, D. L. Bleuel, P. A. DeYoung, A. C. Dombos, J. Gombas, E. Good, R. Lewis, S. N. Liddick, S. M. Lyons, F. Naqvi, A. Palmisano-Kyle, C. F. Persch, A. L. Richard, E. K. Ronning, N. D. Scielzo, C. E. Svensson, A. Torode, W. W. von Seeger, M. Wiedeking, and Y. Xiao, *Phys. Rev. C* **112**, 065803 (2025).
- [84] A. Sweet, D. L. Bleuel, N. D. Scielzo, L. A. Bernstein, A. C. Dombos, B. L. Goldblum, C. M. Harris, T. A. Laplace, A. C. Larsen, R. Lewis, S. N. Liddick, S. M. Lyons, F. Naqvi, A. Palmisano-Kyle, A. L. Richard, M. K. Smith, A. Spyrou, J. Vujic, and M. Wiedeking, *Phys. Rev. C* **109**, 054305 (2024).