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Indirect Measurement of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ Reaction Cross Section and the Implications on Astrophysical Zr Production

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The intermediate neutron-capture process (*i* process) has gained notable traction within the past decade as a way to describe stellar abundance observations which cannot be explained by the slow and rapid neutron-capture processes. Despite the general success of *i*-process models, many open questions remain. Among the observations, Zr stands out, as its elemental abundance is difficult to replicate with available *i*-process models, while the reactions that affect its production through the *i* process are close enough to stability to study experimentally. Here, we present the experimental constraint of the nuclear level density (NLD) and γ -strength function (γ SF) of ^{91}Sr using the β -Oslo method, which were then input into the TALYS Hauser-Feshbach code to produce the first experimental constraint of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ capture reaction. This constraint was used alongside that of $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ for a reduction in the uncertainty of $[\text{Y}/\text{Zr}]$ production in the *i*-process relevant environmental neutron density of $10^{13.5}$ neutrons/cm³ and $10^{14.5}$ neutrons/cm³.

PACS numbers:

I. INTRODUCTION

The slow (*s*) and rapid (*r*) neutron-capture processes have long been considered to produce nearly the entirety of elements above iron [1]. The *s* process produces heavy isotopes over the course of thousands of years in asymptotic giant branch and massive stars through slow neutron-capture reactions followed by β decays [2]. In contrast, the *r* process occurs in neutron-rich environments, such as neutron star mergers and core-collapse supernovae, creating extremely neutron-rich isotopes in a matter of seconds that then decay to heavy stable isotopes [3].

When comparing predicted *s*-process and *r*-process yields with spectroscopic data, inconsistencies in abundances arise [4–6]. These discrepancies are attributed to additional nucleosynthesis processes, such as the weak *r* process [7], *rp* process [8], *n* process [9], and *i* pro-

cess [10], among others. Here we focus on the intermediate (*i*) neutron-capture process, which operates at environmental neutron densities ranging from $10^{13} - 10^{15}$ neutrons/cm³ [11], between the operational densities of the *s* and *r* processes [12–14]. This process was originally theorized in the late 1970s [10], but has recently gained significant traction in resolving differences between models and observations [4, 15].

Based on the neutron densities characteristic of the *i* process [4], the most prominent sites in which the *i* process is predicted to occur are the He-flash driven convective shells of rapidly-accreting white dwarfs (RAWDs) activated by hydrogen ingestion [16], low-mass metal-poor asymptotic giant branch (AGB) stars [17, 18], and post-AGB stars, such as Sakurai’s object (V4334 Sagittarii) [5, 13].

The stellar models of these *i*-process sites predict abundances of the first (Rb, Sr, Y, and Zr) and sec-

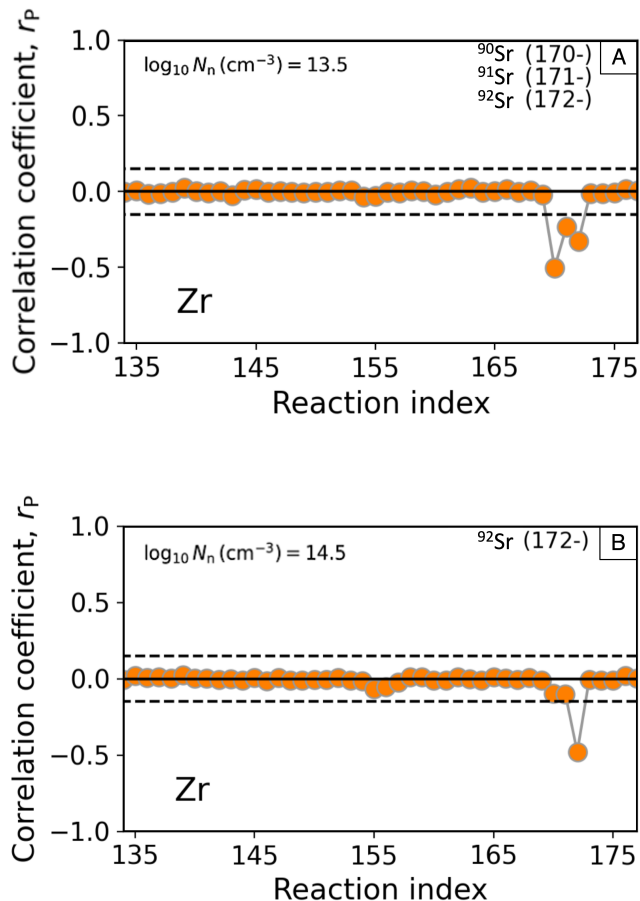


Figure 1: A notable negative correlation coefficient for Zr production is observed in relation to the neutron-capture rates of (A) ^{90}Sr , ^{91}Sr , and ^{92}Sr at a neutron density of $10^{13.5}$ neutrons/cm³ and (B) ^{92}Sr at a neutron density of $10^{14.5}$ neutrons/cm³. The Reaction Index is a sequential number of 1256 unstable isotopes, from ^{60}Co to ^{240}Pb , with neutron-capture reaction rate variations included in our Monte Carlo simulations. Isotopes with the Pearson product-moment correlation coefficients $|r_P| > 0.15$ are listed at the top-right corners of the panels with their reaction indices and signs of r_P .

ond (La, Ba, Eu, and others) peak elements in a reasonably good agreement with the abundances of the same elements measured in carbon-enhanced metal-poor (CEMP)-*i* stars and Sakurai’s object [12, 13, 16]. These models provide a strong pathway to better characterize *i*-process pathways and abundances, but rely on uncertain nuclear inputs [13, 19]. Here, we focus our investigation on the production of Zr through the *i* process.

Through the spectroscopic observations of Sakurai’s object, a notable disagreement between Monte Carlo (MC) predicted abundance distributions and observations can be seen specifically in the abundance of Zr, where a clear over-prediction by the theoretical models is observed [13]. These discrepancies are largely attributed

to uncertainties in the neutron-capture reaction rates of exotic nuclei along the path of the *i* process. Many of these capture reaction cross sections lack experimental measurements due to the inherent difficulty in performing direct-capture measurements on unstable nuclei [20]. To overcome this challenge, indirect methods are used to probe the structure of the reaction product, and in this way, constrain the neutron-capture cross section. Prominent analytic techniques used to constrain the relevant neutron-capture rates are the surrogate [21], Oslo [22], inverse-Oslo [23], and β -Oslo methods [24].

Typically, (n, γ) reaction rates used in nucleosynthesis models are calculated using the Hauser-Feshbach statistical model [25]. The main inputs required are the nuclear level density (NLD), γ -ray strength function (γSF), and neutron optical model potential (n-OMP). In practical terms, the NLD can be described as the number of levels per unit of excitation energy, whereas the γSF is the probability of γ -ray emission as a function of the emitted γ -ray energy. The n-OMP is the interaction potential for the target nucleus and the neutron, and is characterized theoretically [26]. For exotic capture reactions, the NLD and γSF also rely on theoretical models [20], which contribute the majority of the uncertainty in reaction-rate calculations. Indirect measurements of these two functions provide an opportunity to limit this uncertainty and overall reliance on theoretical models. The experimentally constrained NLD and γSF can then be applied in the Hauser-Feshbach reaction-rate calculation using TALYS [27] to minimize previous theoretical uncertainties.

To visualize the impact of the reaction-rate variation for a given reaction on resultant stellar nucleosynthesis abundances, a Pearson product-moment correlation coefficient can be used [13]. This quantity compares the variation of the predicted abundance for a given observable element with the multiplication factor for a specific neutron-capture rate, where the multiplication factor can be practically defined as the uncertainty range for this reaction rate. To determine which reactions have the greatest impact on a given observable element, sensitivity studies can be completed using nucleosynthesis models. In the present work, a one-zone nucleosynthesis simulation with constant neutron density was used [13]. Although lacking the details of the astrophysical environment, this type of sensitivity study helps to identify specific reactions that impact the prediction of each element [13]. The results of such one-zone studies were shown to be comparable to more realistic multi-zone models [13].

In the case of Zr, uncertainties in the neutron-capture rates of Sr isotopes ^{90}Sr , ^{91}Sr , and ^{92}Sr were shown to impact the Zr abundance uncertainty, as seen by significant negative Pearson product-moment correlation coefficients in Fig. 1. This implies that the production of Zr in *i*-process environments changes inversely with the neutron-capture reaction rates of these three Sr isotopes.

Constraining the neutron-capture of these Sr isotopes

can act as a useful tool in resolving Zr abundance expectations with theoretical models. Here we focus on two reactions: $^{90,92}\text{Sr}(n,\gamma)^{91,93}\text{Sr}$. The experimental investigation of $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ was presented in a previous publication [28]. Here we present the experimental details of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ reaction-rate constraint using the β -Oslo method, where the ^{91}Sr compound nucleus was populated via β decay from ^{91}Rb . The impact of the experimental constraints of both reactions on the modeled i -process Zr abundance is discussed.

II. EXPERIMENTAL DETAILS

This measurement was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A beam of ^{96}Zr at 120 MeV/u was impinged on a ^9Be target producing a secondary cocktail beam, from which a beam containing ^{91}Rb was selected using the A1900 fragment separator [29]. The secondary beam was then transferred to the N4 gas stopping cell [30] where the ^{91}Rb ions were further separated from contaminants and thermalized, and delivered to the Summing NaI(Tl) (SuN) experimental station with an intensity of 245 pps.

SuN [31] is a high-efficiency total absorption spectrometer composed of 8 optically isolated NaI(Tl) scintillating crystals, each with 3 photomultiplier tubes (PMTs). The SuN spectrometer was positioned concentrically around a mylar tape transport system, known as the SuN Tape Station for Radioactive Nuclei (SuNTAN) [32], onto which the beam was implanted and decays were measured in 30 minute intervals. Following each implantation interval, the tape was moved approximately 20 cm, relocating the previously implanted nuclei outside of SuN and providing a clean implantation site for a new cycle. For differentiation of β -decay events, the SuN Scintillating Plastic Optical Transport (SuNSPOT) β detector [32], composed of 8 panels of 3 mm thick BC408 organic scintillating plastic, was positioned in an octagonal barrel along the beam axis between SuNTAN and SuN. Each panel was embedded with four optical fibers, which transported the light to two PMTs located outside of SuN.

III. ANALYSIS

The individual segments of SuN were used to measure the emitted γ rays of a β -decay event in coincidence with signals from the two PMTs of the scintillating β -detector. Single events detected in different SuN segments within a 1 μs time window were summed together, providing sensitivity to the initial excitation energy for the observed γ -ray cascade. A matrix of γ -ray energy (E_γ) versus excitation energy (E_x) was then produced. This is the so-called raw matrix for the case of the ^{91}Rb decay into excited states of ^{91}Sr , shown in Fig. 2(A). The Q_{β^-} value of ^{91}Rb at 5907 keV allowed for ^{91}Sr to be populated from

its ground state to excitation energies approaching its neutron separation energy at $S_n = 5772$ keV. Based on the 30 minute tape cycle and the half lives of ^{91}Rb and ^{91}Sr , 58 seconds and 9.68 hours respectively, less than 2% contamination was expected from β decays of ^{91}Sr into ^{91}Y , however no distinct γ decays from ^{91}Y were observed in the matrix.

A. β -Oslo Analysis

Initially developed in the mid-1990s [22, 33], the Oslo method can be used to extract the functional forms of the NLD and γSF from an experimental matrix of the γ -ray energy (E_γ) versus excitation energy (E_x). The β -Oslo method [34] is an alteration where the isotope of interest, and resulting matrix, is populated through β decay.

To isolate these two functions, the experimental matrix was first deconvoluted from the detector response using an unfolding method [33], the result is shown in Fig. 2(B). Following this, the matrix consisting of only the first γ ray emitted from a specific excitation energy, i.e. the primary γ ray, was extracted by iteratively subtracting secondary γ rays with increasing excitation energy [35]. This analysis has been used several times in the past with the SuN detector [6, 36, 37].

Prior to the extraction of the γSF and NLD, the primary γ -ray energy vs. excitation energy matrix was compressed to reduce statistical fluctuations. The range of data used for further analysis was limited to the statistical region, which in this case was within the excitation energy range of 3.3 MeV to 4.5 MeV, with a lower limit of γ -ray energy at 1.1 MeV. This region was fixed by adjusting each energy limit independently and comparing the extracted NLD and γSF functional forms. Within the statistical range, little variation is found in the extracted functional forms, however the shape of the extracted functions changes when the boundary is extended to include weakly populated areas in the matrix or those containing discrete structure. Consequently, each boundary was set to include only data producing consistent results for the NLD and γSF , while maximizing the included statistics to reduce the uncertainty associated with the extracted functions. This range can be seen outlined in Fig. 2(C).

B. Extraction of γSF & NLD

Through the Oslo method, only the functional form of the NLD and γSF can be extracted. Absolute values can be estimated through the use of external normalizations. This normalization process utilizes Eqs. 1 and 2 [38]

$$\tilde{\rho}(E - E_\gamma) = Ae^{\alpha(E - E_\gamma)}\rho(E - E_\gamma) \quad (1)$$

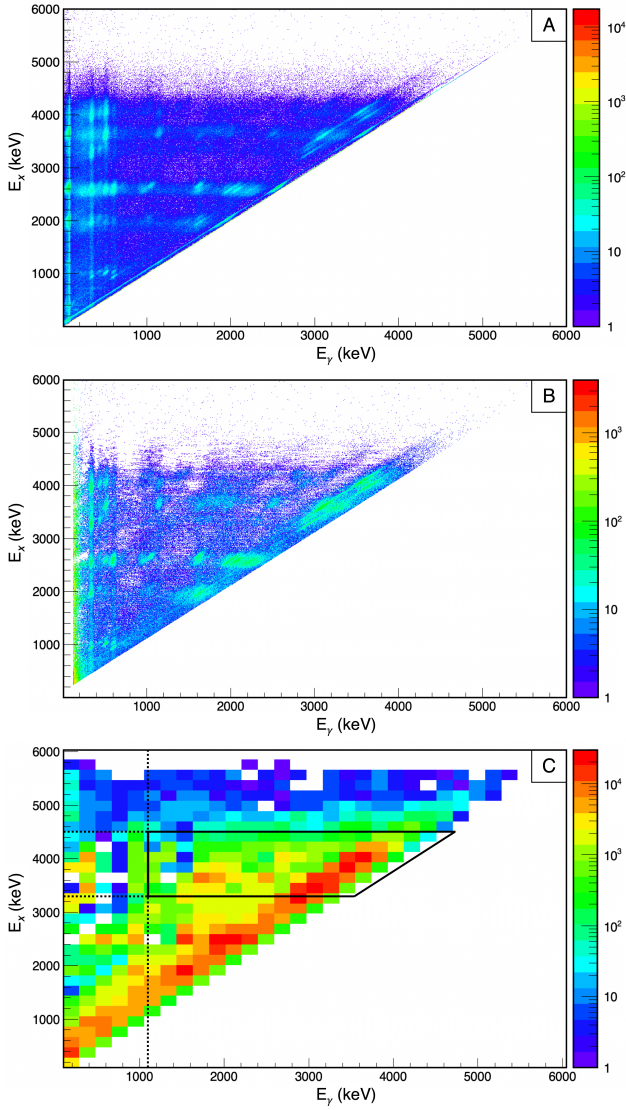


Figure 2: Shown above are the (A) uncompressed, raw matrix containing the β -gated γ -energy vs. excitation-energy coincidences, (B) the unfolded matrix, corrected for detector response, and (C) the primary matrix, having undergone the iterative subtraction of fed states such that only the primary γ -ray vs. excitation energy events remain. This final matrix was compressed to reduce statistical fluctuations, and the statistical region used for the extraction of the γ SF and NLD is outlined.

$$\tilde{T}(E_\gamma) = B e^{\alpha E_\gamma} T(E_\gamma) \quad (2)$$

where ρ and T are the NLD and transmission coefficient, respectively, and their shifted iterations are denoted by $\tilde{\rho}$ and $\tilde{T}$. The transformation parameter α acts on the energy dependent exponential term and was applied to both ρ and T , affecting their slope. In addition, the ρ and T each have an independent linear shift, A and B , respectively. These normalization parameters allow for the adjustment of the NLD and γ SF, the latter of which is directly proportional to the transmission coefficient given

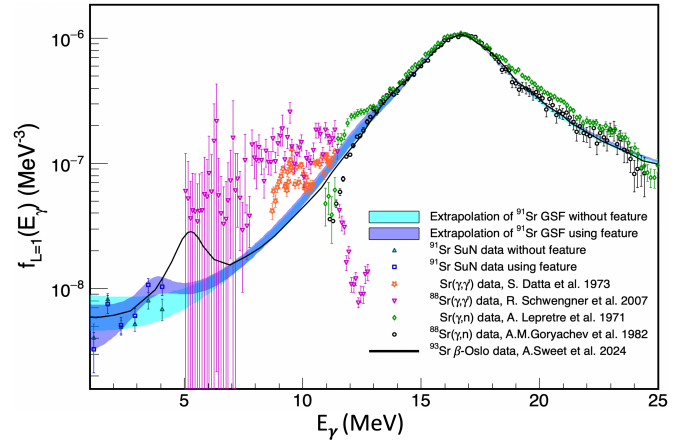


Figure 3: Constrained γ SF bounds used for TALYS calculation of the ^{90}Sr neutron-capture cross section, with and without the inclusion of the ^{93}Sr PDR [28] in the normalization data, in blue and cyan, respectively. Previous γ SF measurements acquired through photon-scattering by Datta *et al.* [45] and Schwengner *et al.* [46] on natural Sr and ^{88}Sr , respectively, are shown in the orange and magenta markers. Photoabsorption GDR measurements of natural Sr and ^{88}Sr made by Lepretre *et al.* [47] and Goryachev *et al.* [43], respectively, are shown in the green and black markers.

in Eq. 2.

Due to the exotic nature of the ^{91}Sr compound nucleus, the absolute normalization of the γ SF needs to be guided by either theoretical calculations, which are affected with rather large model and parameter uncertainties, or by data from neighboring nuclei. In the present work, the slope α was fixed using the experimental γ SF of ^{93}Sr [28], determined using the Shape method [39, 40]. Since the ^{93}Sr data exhibit a feature at approximately 5 MeV, two normalizations were completed, with and without including a potential feature. Nuclear structure studies suggest near-spherical and rather constant deformations for Sr nuclei with neutron numbers between $N=48$ and $N=56$ [41, 42]. Thus, we do not expect major changes in the overall shape of the γ SFs in this region, justifying the here proposed normalization procedure.

The first γ SF output was fixed to the underlying trend of the ^{93}Sr γ SF [28] approaching the Giant Dipole Resonance (GDR) experimentally measured for ^{88}Sr [43]. Here, the assumption was made that there was no strong enhancement in the γ SF from 3 - 5 MeV. In the second case, the ^{91}Sr γ SF was minimized to the slope of the ^{93}Sr γ SF approaching the Pygmy Dipole Resonance (PDR) found in that work [28]. The end result for these two γ SF constraints and their associated uncertainties [44] can be seen in Fig. 3, as the cyan triangles and blue squares, respectively.

In order to use the ^{91}Sr γ SF for the $^{90}\text{Sr}(n, \gamma)^{91}\text{Sr}$ cross section calculation in TALYS, the γ SF was extrapolated towards higher energies. $^{88}\text{Sr}(\gamma, n)$ photoabsorption data [43] was fit with a combination of two generalized Lorentzians. Upper and lower bounds were fit for

each of the two γ SF bands using an exponential term for the low energy upbend and a generalized Lorentzian to model contributions below 6 MeV. The resulting sets of constrained γ SFs of ^{91}Sr can be seen by the uncertainty bands in Fig. 3, compared to the γ SF for ^{93}Sr by Sweet *et al.* [28] and the ^{88}Sr GDR measurement by Goryachev [43] used for extrapolation. Previous literature data of the photoabsorption measurement of natural Sr [47] and the photo-scattering measurements taken on natural Sr [45] and ^{88}Sr [46] that were not used in the γ SF extrapolation of ^{91}Sr are also presented within this plot. The photon-scattering measurements were excluded from the extrapolation due to the large associated uncertainties and inconsistencies between these measurements. The photoabsorption measurement of ^{88}Sr [43] was preferred over that of natural Sr [47] due to its isotopic purity as the closest stable Sr isotope to the ^{91}Sr measured.

Each shifted γ SF resulted in a corresponding NLD with a matching slope (α) shift. The shift was applied to the upper and lower bounds calculated through the Oslo analysis package, then the total NLD was shifted with the independent linear A parameter, such that it was in agreement with evaluated discrete levels below 2 MeV.

The NLD required similar care in the extrapolation for use in the TALYS Hauser-Feshbach calculation. For the two sets of shifted NLD produced, the semi-microscopic level density model with Skyrme force (TALYS LD4) [48] was used for extrapolation beyond the output of the β -Oslo data, as this model showed good agreement with the experimentally constrained slopes. This semi-microscopic model has two free parameters, one adjusting the slope in an exponential term and the second adjusting linearly. Only the linear shift was used to follow the trend of each upper and lower bound. The resulting NLDs which correspond to the two γ SF sets can be seen in Fig. 4.

IV. RESULTS

A. Cross Section & Reaction Rate

Each pair of NLD and γ SF, with and without the feature, was used to calculate the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ cross section and reaction rate. The results from all combinations of constrained NLDs and γ SFs were used to produce the cyan uncertainty bands seen in Fig. 5. In the same figure, the predicted uncertainty using the combination of all default NLDs and γ SFs in TALYS 1.96, without experimental constraints, is shown in grey. The experimental constraint is in agreement with the lower bound of TALYS expectations, reducing the uncertainty by approximately a factor of two. The default JINA REACLIB [49] reaction rate lies above the uncertainty of the experimentally constrained $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ reaction rate.

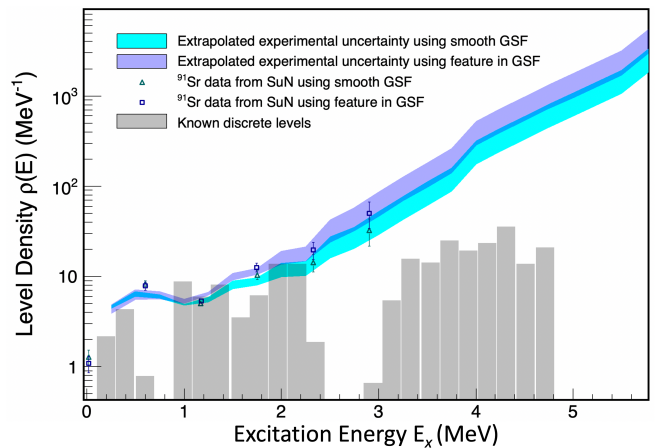


Figure 4: Constrained NLD bounds used for TALYS calculation of the ^{90}Sr neutron-capture cross section, with and without the inclusion of the weak feature in blue and cyan respectively, with high energy extrapolation done using the linearly shifted microscopic NLD with Skyrme force (TALYS LD4) [48].

B. Impact on i -process Abundances

The experimentally constrained reaction rates of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ reactions were used to calculate the effect on the $[Y/Zr]$ through i -process capture channels operating at neutron densities of $10^{13.5}$ to $10^{14.5}$ neutrons/cm³. To isolate discrepancies between the predicted and observed abundances caused by stellar models and (n,γ) reaction-rate uncertainties, we ran a stellar model-independent one-zone model of i -process nucleosynthesis at constant neutron density. The simulation ran until an equilibrium state was reached, after which the elemental abundance ratios stop changing. Here, we make the assumption that in the CEMP- i stars, we see abundances of heavy elements produced in an i -process environment that had reached equilibrium. This is supported by the relatively high abundance values of these elements, even after the i -process abundances were substantially diluted in convective envelopes of the CEMP- i stars, which is a signature of a long neutron exposure. For each neutron density, a one-zone simulation was run using the default JINA REACLIB (n,γ) rates. After this, 10^4 MC one-zone simulations with a constant neutron density were run, in which the default rates of neutron captures by 1256 unstable isotopes were multiplied by randomly selected factors, uniformly distributed between the default rates divided and multiplied by their corresponding maximum variation factors, estimated using a method similar to that described by Denissenkov *et al.* [11].

From the results of the MC simulations, we calculated the Pearson product-moment correlation coefficients that compare the variations of predicted abundances, or their ratios, with the variations of the reaction-rate multiplication factors. For each abundance or abundance ra-

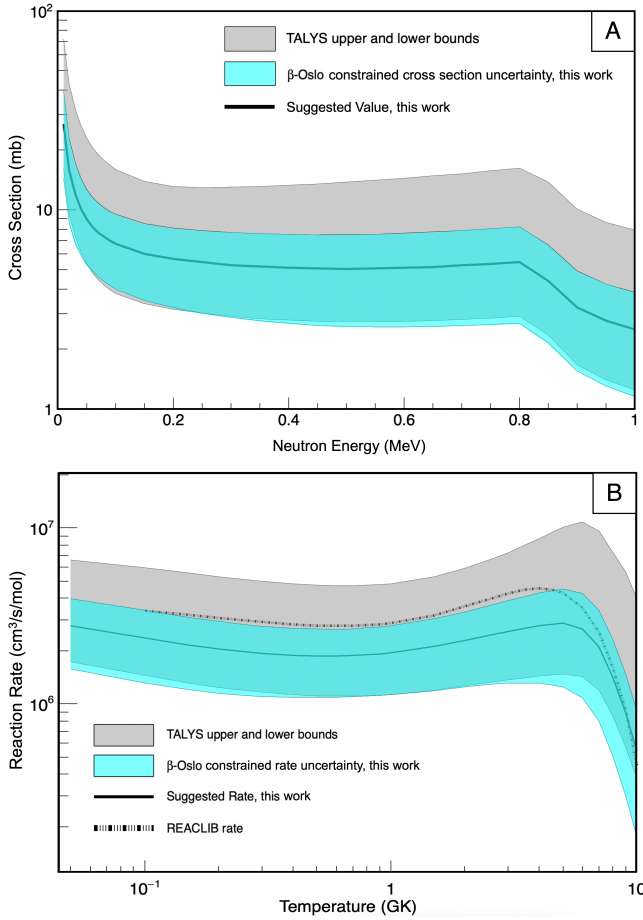


Figure 5: The resulting constrained (A) cross section and (B) reaction rate of $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ are shown in cyan, compared to the uncertainty range calculated using unconstrained TALYS models in grey. In addition, the expected REACLIB reaction rate [49] is overlaid in comparison to the experimental reaction-rate uncertainty.

tio, the (n,γ) reactions with the largest correlation coefficients are assumed to be the reactions that will have the strongest impact on the abundance ratio. For correlation coefficients with an absolute magnitude exceeding ~ 0.5 , a double-peaked distribution of abundances is typically obtained in the MC simulations, an example of which can be seen in Figs. 6A and 7A. The two peaks correspond to MC sub-samples with multiplication factors above and below one, and are represented as the blue and yellow histograms. These double-peaked distributions are called bifurcations (of i -process paths) occurring at the (n,γ) reactions of particular identified unstable isotopes.

Figs. 6 and 7 show the bifurcation of $[\text{Y}/\text{Zr}]$, using the default (panels A) and experimentally constrained (panels B) rates of $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ in the environmental neutron densities $10^{13.5}$ neutrons/cm³ and $10^{14.5}$ neutrons/cm³, respectively. The thick solid black lines show the total distribution of predicted abundances from the MC simulations, summing both yellow and blue sub-samples. The thick dashed vertical lines dis-

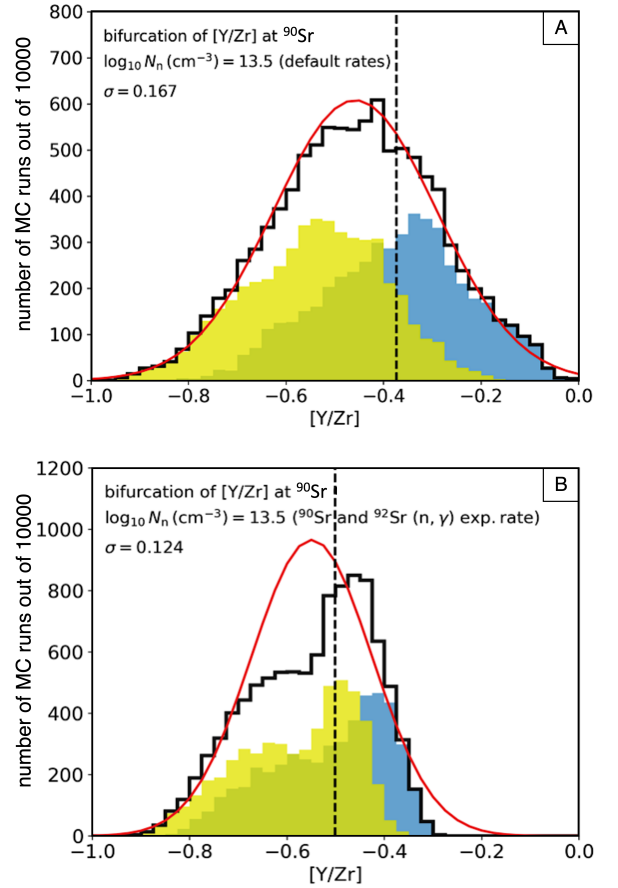


Figure 6: Bifurcation plots of $[\text{Y}/\text{Zr}]$ (A) before and (B) after including the newly constrained ^{90}Sr and ^{92}Sr neutron-capture cross sections at a neutron density of $10^{13.5}$ neutrons/cm³. The yellow and blue peaks correspond to sub-samples calculated using the minimum and maximum rate uncertainties, and their summed total is shown in black. Each summed total is fit with a Gaussian in red, with the corresponding σ listed on each plot showing the reduction in the abundance-ratio uncertainty.

play $[\text{Y}/\text{Zr}]$ ratios obtained using the default (Figs. 6(A) and 7(A)) and experimental (Figs. 6(B) and 7(B)) reaction rates.

The ratio $[\text{Y}/\text{Zr}]$ along with $[\text{Sr}/\text{Y}]$, $[\text{Ba}/\text{La}]$, $[\text{La}/\text{Eu}]$ and some others are used to compare predicted and observed elemental abundances in the CEMP- i stars [6]. By comparing Figs. 6 and 7, it is evident that at the lower neutron density, the bifurcation of the $[\text{Y}/\text{Zr}]$ distribution was mainly caused by the variation of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ reaction rate, while at the higher neutron density the bifurcation of $[\text{Y}/\text{Zr}]$ primarily occurs at the reaction $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$.

In the MC simulation results presented in these figures, we used the maximum variation factors 4.2 for the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and 8.7 for the $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ reaction rates estimated from Hauser-Feshbach computations [13]. Their default (JINA REACLIB [49]) values at 300 MK are $2.9 \times 10^6 \text{ cm}^3/(\text{mole s})$ and $2.1 \times 10^6 \text{ cm}^3/(\text{mole s})$,

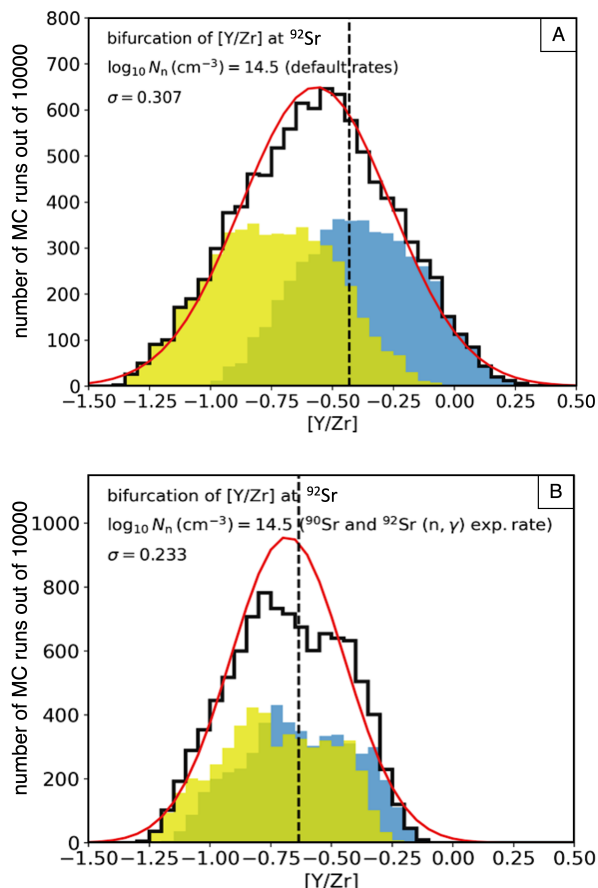


Figure 7: Bifurcation plots of $[Y/Zr]$ (A) before and (B) after including the newly constrained ^{90}Sr and ^{92}Sr neutron-capture cross sections at a neutron density of $10^{14.5}$ neutrons/cm³. Plots are presented with the same details as in Fig 6.

respectively. The experimentally constrained maximum variation factors for these reactions have the same value of 1.6, with their average rates reduced to 1.5×10^6 cm³/(mole s) and 7.1×10^5 cm³/(mole s).

Figs. 6 and 7 show how the distributions of $[Y/Zr]$ have changed at the neutron densities $10^{13.5}$ neutrons/cm³ and $10^{14.5}$ neutrons/cm³ after these experimental data were applied in the MC one-zone simulations. As anticipated, the reduction of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ reaction rates result in the default $[Y/Zr]$ ratios shifting to lower values, while reducing the spread of each distribution. The residual double-peak morphologies of the $[Y/Zr]$ histograms seen in the bottom panels of Figs. 6 and 7 are expected to be caused by the strong sensitivity ($|r_P| > 0.5$) of the Y abundance to variations of the $^{89}\text{Rb}(n,\gamma)^{90}\text{Rb}$ reaction rate [13].

Fig. 8 shows the shift of the abundances of $[\text{Rb}/\text{Zr}]$, $[\text{Sr}/\text{Zr}]$, and $[Y/Zr]$ predicted with a one-zone model using the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$ rate constraints. A notable reduction in the overall one-zone uncertainties is visible in the adjusted predicted abundance ratios of

$[\text{Rb}/\text{Zr}]$, $[\text{Sr}/\text{Zr}]$, and $[Y/Zr]$ using the new experimental constraint, given by the solid stars with associated bright uncertainty bands (on the left of each pair), as compared to the hollow stars with dull bands representing the default abundances (on the right of each pair). While $[\text{Sr}/\text{Zr}]$ ratios are systematically underpredicted at $10^{13.5}$ neutrons/cm³, when comparing to CEMP-*i* stars with $-0.1 \leq [\text{Sr}/\text{Y}] \leq 0.2$ from the JINAbase [50], better agreement is seen with the $10^{14.5}$ neutrons/cm³ environment. Simultaneously, the agreement with the $[Y/Zr]$ was also improved.

V. CONCLUSION

The first experimental constraint of the $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ has been performed through the indirect population of ^{91}Sr via β decay of ^{91}Rb , measured with the SuN spectrometer and analyzed using the β -Oslo method. The γSF and NLD were constrained using systematics from surrounding nuclei, notably the γSF of ^{93}Sr .

The resultant constrained cross-section and reaction-rate uncertainty bands are lower in magnitude than current JINA REACLIB defaults. When incorporated into our one-zone MC simulations of the *i*-process nucleosynthesis, the centroid of $[Y/Zr]$ was shifted to lower values and the width of the distribution was reduced. Similar results were observed in the ratios of $[\text{Rb}/\text{Zr}]$ and $[\text{Sr}/\text{Zr}]$ at both $10^{13.5}$ neutrons/cm³ and $10^{14.5}$ neutrons/cm³. With these two reactions constrained, new impactful reactions on *i*-process observables can be identified. Three such reactions are $^{87}\text{Kr}(n,\gamma)^{88}\text{Kr}$, $^{88}\text{Kr}(n,\gamma)^{89}\text{Kr}$, and $^{89}\text{Rb}(n,\gamma)^{90}\text{Rb}$ [13], which are expected to have major impacts on the production of Rb, Sr, and, Y, respectively.

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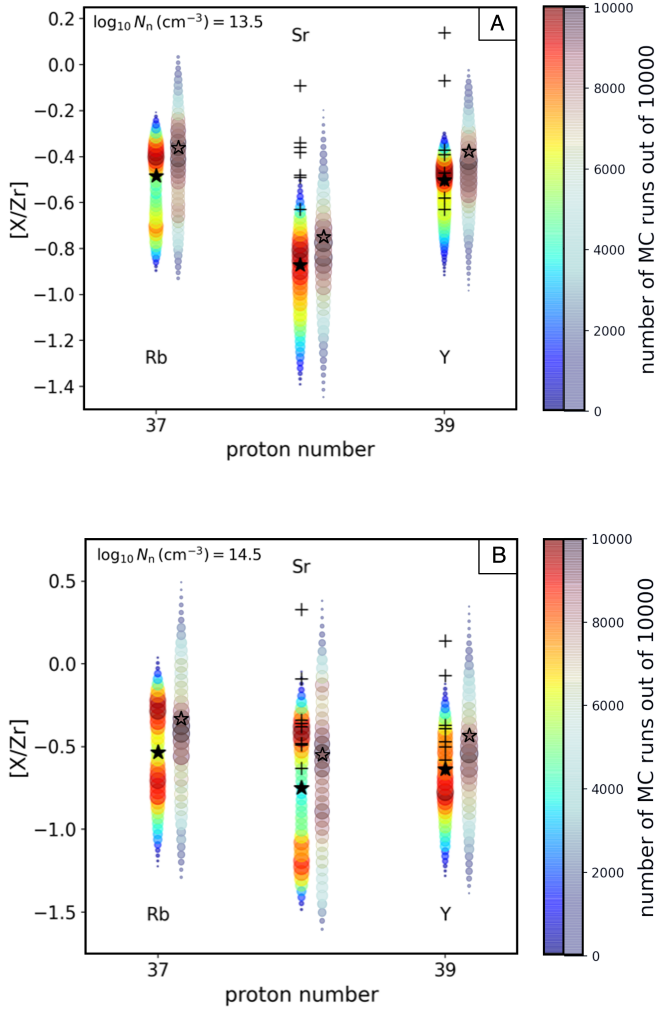


Figure 8: Results of one-zone Monte Carlo simulations of the *i*-process nucleosynthesis, demonstrating the shift in predicted abundances for $[Rb/Zr]$, $[Sr/Zr]$, and $[Y/Zr]$ using the new experimentally constrained rates of the reactions $^{90}\text{Sr}(n,\gamma)^{91}\text{Sr}$ and $^{92}\text{Sr}(n,\gamma)^{93}\text{Sr}$. The default abundances and their associated uncertainties are denoted by the hollow stars and dull bands, compared to the reduced uncertainty of the updated abundances, seen above denoted by the solid stars, for both (A) $10^{13.5}$ neutrons/cm³ and (B) $10^{14.5}$ neutrons/cm³. In both plots, the $[Sr/Zr]$ and $[Y/Zr]$ values for 8 CEMP-*i* stars with $-0.1 \leq [Sr/Y] \leq 0.2$ from the JINAbase are shown as black crosses for comparison [50].

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