Experimental constraints on the ^{73}Zn(n,γ)^{74}Zn reaction rate

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R. Lewis,[1,2,*] S.N. Liddick,[1,2] A.C. Larsen,[3] A. Spyrou,[1,4,5] D.L. Bleuel,[6] A. Couture,[7] L. Crespo Campo,[3] B.P. Crider,[1,8] A.C. Dombos,[1,4,5] M. Guttormsen,[3] S. Mosby,[7] F. Naqvi,[1] G. Perdikakis,[9,1,5] C.J. Prokop,[1,2] S.J. Quinn,[1,4,5] T. Renstrøm,[3] and S. Siem[3]

[1] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[2] *Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*
[3] *Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[4] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[5] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA*
[6] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[7] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[8] *Department of Physics and Astronomy, Mississippi State University, Mississippi State, MS 39762, USA*
[9] *Central Michigan University, Mount Pleasant, MI 48859, USA*

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Background: The recent observation of a neutron-star merger finally confirmed one astrophysical location of the rapid neutron-capture process (r-process). Evidence of the production of A<140 nuclei was seen, but there is still little detailed information about how those lighter elements are produced in such an environment. Many of the questions surrounding the A≈80 nuclei are likely to be answered only when the nuclear physics involved in the production of r-process nuclei is well understood. Neutron-capture reactions are an important component of the r-process, and neutron-capture cross sections of r-process nuclei, which are very neutron rich, have large uncertainties.

Purpose: Indirectly determine the neutron-capture cross section and reaction rate of ^{73}Zn(n,γ)^{74}Zn.

Methods: The nuclear level density (NLD) and γ-ray strength function (γSF) of ^{74}Zn were determined following a Total Absorption Spectroscopy (TAS) experiment focused on the β decay of ^{74}Cu into ^{74}Zn performed at the National Superconducting Cyclotron Laboratory. The NLD and γSF were used as inputs in a Hauser-Feshbach statistical model to calculate the neutron-capture cross section and reaction rate.

Results: The NLD and γSF of ^{74}Zn were experimentally constrained for the first time using β-delayed γ-rays measured with TAS and the β-Oslo method. The NLD and γSF were then used to constrain the neutron-capture cross section and reaction rate for the ^{73}Zn(n,γ)^{74}Zn reaction.

Conclusions: The uncertainty in the neutron-capture cross section and reaction rate of ^{73}Zn(n,γ)^{74}Zn calculated in TALYS was reduced to under a factor of 2 from a factor of 5 in the cross section and a factor of 11 in the reaction rate using the experimentally obtained NLD and γSF.

I. INTRODUCTION

The production of the elements heavier than iron involves processes that require neutron-capture reactions. The slow neutron-capture process (s-process) and rapid neutron-capture process (r-process) are the most well-known, and are thought to account for the production of the majority of the heavy elements [1, 2]. The r-process in particular is characterized by successive neutron captures on neutron-rich, unstable nuclei, which is possible due to the high neutron flux assumed in such a process. Neutron-star mergers have recently been identified as one site of the r-process through electromagnetic observations of a kilonova afterglow that indicated the presence of r-process nuclei (see *e.g.*, Refs. [3, 4]). Even with this new information, the question of where r-process nuclei are made is not settled. This is partly due to the indication that there may be multiple processes involved in producing r-process nuclei, such as the weak r-process [5, 6] and the intermediate neutron-capture process (i-process) [7]. This is especially important when considering nuclei in the A≈80 region, where the abundance pattern observed in various metal-poor stars is not as robust as it is for heavier elements [8].

Understanding the production of the A≈80 elements requires models of astrophysical processes that combine large-scale astrophysics information with detailed nuclear physics information. Nuclear properties such as β-decay half-lives, masses, fission properties, and neutron-capture rates all impact predicted r-process abundances [9, 10]. Neutron-capture cross sections relevant for r-process nucleosynthesis are particularly difficult to obtain experimentally, due to the short half-lives of the nuclei involved in the neutron-capture reaction and the free neutron. Theoretical neutron-capture cross sections can be obtained using a Hauser-Feshbach model and a knowledge of the optical model potential (OMP), nuclear level density (NLD) and γ-ray strength function (γSF) [11]. The NLD describes the number of levels as a function of excitation energy while the γSF describes the likelihood that a γ ray of a given energy will be emitted from the nucleus. However, the extrapolation of the NLD and γSF are uncertain as a progression is made to short-lived

* lewis@nscl.msu.edu

nuclei [12, 13], leading to a variation of theoretically calculated neutron-capture cross sections that can quickly approach orders of magnitude just a few nucleons away from stable isotopes [14]. The β-Oslo method [15] is one of a few indirect techniques [16–18] used to inform our knowledge of neutron-capture cross sections on short-lived isotopes. The β-Oslo method provides statistical properties of the nucleus—the NLD and γSF—that can be used to calculate a neutron-capture cross section using the Hauser-Feshbach model.

The ^{73}Zn(n,γ)^{74}Zn cross section was identified in a sensitivity study to have an influence on the predicted abundance pattern in the A$\approx$80 region [6]. The astrophysical reaction rate calculated in TALYS [19, 20], a widely used Hauser-Feshbach model code, can be uncertain by a factor of 11 by varying the included NLD and γSF models. The cross section is also uncertain up to a factor of 5. This large uncertainty inherent to model choice has been seen in the A$\approx$70 region to increase quickly just a few neutrons from stability [14]. The neutron-capture cross section and reaction rate of the ^{73}Zn(n,γ)^{74}Zn reaction were constrained by experimentally determining the NLD and γSF of ^{74}Zn following the β decay of ^{74}Cu, reducing the uncertainty in each to under a factor of two.

II. EXPERIMENT

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A beam of ^{86}Kr was accelerated to 140 MeV/nucleon and fragmented on a 376 mg/cm^2 Be target. Ions of ^{74}Cu were separated in the A1900 fragment separator [21] and sent to the experimental end station as part of a cocktail beam of approximately ten nuclei [14, 22, 23]. The experimental setup consisted of the Summing NaI (SuN) detector [24], a Si Double Sided Strip Detector (DSSD), a Si veto detector, and two Si PIN detectors. SuN is cylindrical, 16 inches in height and diameter, with a 1.7inch borehole along the beam axis, and is separated into eight optically isolated segments [15]. The DSSD was placed in the center of the borehole, and was used to stop and detect the ions. The veto detector was placed just downstream of the DSSD, also in the borehole of SuN, for the detection of any light particles that did not stop in the DSSD. The PIN detectors were placed just upstream of SuN.

The DSSD had a set of 16 strips, each 1.2 mm wide, on the front and back face, arranged perpendicular to each other to obtain position information on both the implanted ion and the β-decay electron. The β-decay electrons were correlated to the previously stopped ion based on timing and position information. γ rays following the β decay of implanted ^{74}Cu ions were detected in SuN in coincidence with the β-decay electron in the DSSD within a one second window. The much longer half-life of the daughter, ^{74}Zn (95.6 seconds), compared to the parent, ^{74}Cu (1.63 seconds), allowed for the ^{74}Zn decay to be excluded from the analysis. The half-life of ^{74}Cu was confirmed by fitting the time between the arrival of the ion at the end station and the detection of the β-decay electron, which resulted in a half-life of 1.62(5) seconds that agrees well with the accepted value [25, 26]. The randomly correlated background was obtained by performing the correlation between the ion and β-decay electron backwards in time [27].

The NLD and γSF for ^{74}Zn were extracted from the experimental data using the β-Oslo method, which combines the traditional Oslo analysis [28, 29] with β decay and total absorption spectroscopy. This allows the method to be applied further from stability and at lower beam rates than reaction-based methods, and has been successfully used to constrain the neutron-capture rates of a number of neutron-rich nuclei in the A$\approx$80 region [14, 15, 23]. The β-Oslo method uses the β decay to populate highly excited states in the daughter nucleus, which then de-excites through the emission of γ rays. The application of the β-Oslo technique requires information on both the excitation energy of the nucleus populated in β decay (E_x) and the individual γ-ray energies emitted in the de-excitation to the ground state (E_γ). The excitation energy is obtained from the total energy detected in SuN, while the individual γ-ray energies are obtained from the energy detected in each of the single segments of SuN. There are four main steps to obtain the experimental NLD and γSF used to infer the neutron-capture cross section starting from a raw E_x vs. E_γ matrix: (1) unfolding of the raw γ-ray spectrum for each excitation energy [30], (2) isolation of the primary γ rays [28], (3) extraction of the functional forms of the NLD and γSF [29], and (4) normalization of the NLD and γSF [30, 31].

III. RESULTS AND DISCUSSION

A. β-Oslo analysis

The raw, unfolded, and primary E_x vs. E_γ matrices following the β decay of ^{74}Cu are shown in Fig. 1. The response of SuN was modeled in GEANT4 [32], validated against experimental data, and used to unfold the raw matrix. An iterative subtraction method was used to isolate the primary γ-ray matrix, which contains only the distribution of the first γ rays to leave each excitation energy [28]. This distribution can be used to describe the probability of emitting a γ ray of a given energy as a function of excitation energy using the following proportionality:

$$P(E_x, E_\gamma) \propto \rho(E_x - E_\gamma) \times \mathcal{T}(E_\gamma), \tag{1}$$

where $\rho(E_x - E_\gamma)$ is the NLD at the excitation energy of the nucleus after emission of the γ ray and $\mathcal{T}(E_\gamma)$ is the transmission coefficient of the γ ray. The transmission coefficient can be transformed into the γSF, assuming

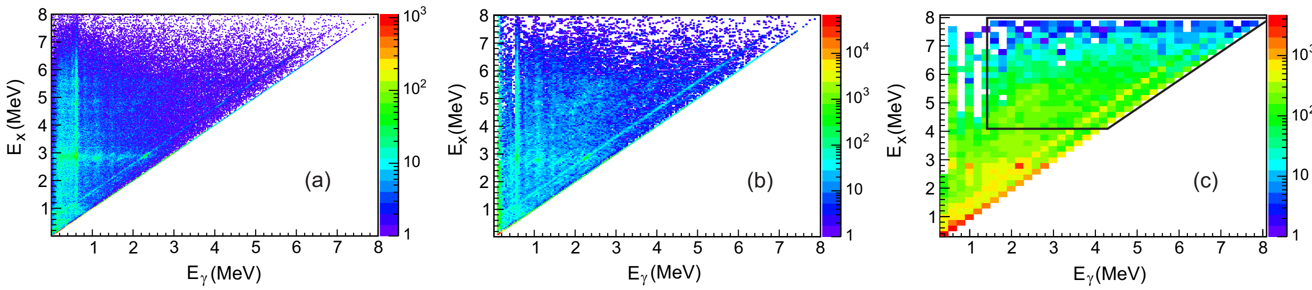


FIG. 1. (a) Raw E_x vs. E_γ matrix from the β decay of ^{74}Cu, with 20 keV/channel binning. (b) Unfolded matrix with 40 keV/channel binning. (c) Primary matrix with 200 keV/channel binning. The black box outlines the E_x, E_γ ranges used in the NLD and γSF extraction.

dipole transitions, using the simple relationship

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

The NLD and $\mathcal{T}(E_\gamma)$ functions were extracted simultaneously from the primary matrix in the range $E_x \in [4.0,8.0]$ MeV and $E_{\gamma,min} = 1.4$ MeV [29]. By an iterative χ^2 minimization procedure, a unique solution of the functional forms of the NLD and $\mathcal{T}(E_\gamma)$ were obtained. Two pieces of information are needed to normalize the NLD: the low-energy level density and the level density at the neutron separation energy ($\rho(S_n)$), which is 8.235 MeV for ^{74}Zn. The low-energy level density was determined using the known levels in ENSDF for ^{74}Zn, and was assumed to be complete up to 3 MeV. There is no experimental data for $\rho(S_n)$, so a tabulated NLD [33] was used and shifted in energy to match the low-energy levels. The energy shift had a value of 0.4 ± 0.2 MeV, resulting in a $\rho(S_n)$ of 5200 MeV^{-1}, with upper and lower values of 6360 and 4230 MeV^{-1}, respectively. Another tabulated level density [34] did not differ significantly from the one used, and the generalized super fluid model (GSM) [35], which has been investigated for other nuclei, does not offer parameters for ^{74}Zn.

β decay populates a narrow spin range in the daughter isotope, which must be taken into account in the normalization. The ground state of ^{74}Cu is 2^- [36] which leads to the range of spins 0-4, of both parities, being populated in the daughter nucleus (^{74}Zn) following an allowed β decay and one dipole photon transition. The spin distribution around $\rho(S_n)$ from the tabulated NLD in Ref. [33] is shown in Fig. 2, with the spins populated following β decay and one dipole photon transition highlighted in blue. This spin range corresponds to 48% of the total level density at the neutron separation energy, leading to reduced $\rho(S_n)$ upper, middle, and lower values of 3070, 2510, and 2040 MeV^{-1}, respectively.

The γSF was normalized to photoabsorption cross section data from the nearby stable nuclei ^{70}Zn and ^{74,76}Ge [37]. Each data set was fit with a Generalized Lorentzian (GLO) function [38], and extrapolated down in energy to 4 MeV. The giant dipole resonance (GDR) parameters obtained from the GLO fits to each nucleus are shown in Table I. The experimental γSF was scaled so as to obtain a χ^2 minimum with the fit of the extrapolated GLO function. The normalized NLD and γSF are shown in Fig. 3.

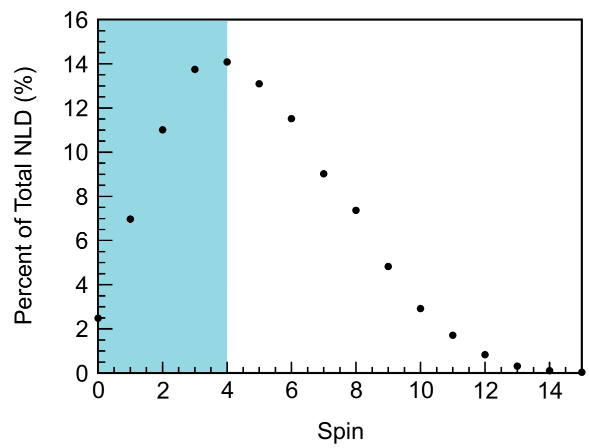
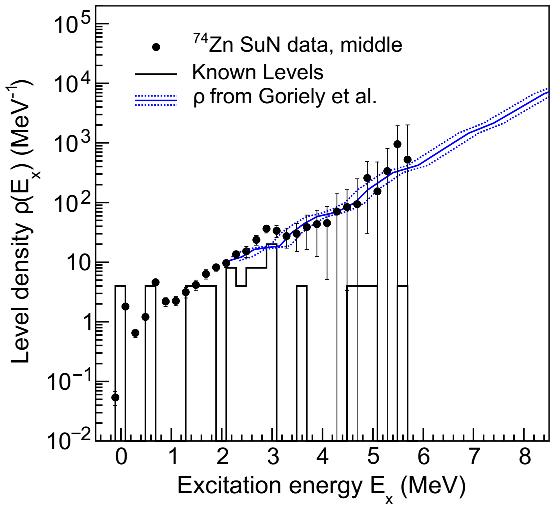


FIG. 2. Distribution of spins for the levels in ^{74}Zn around the neutron separation energy based on tabulated spin-dependent level densities from Ref. [33]. Spins highlighted in blue are populated following the β decay of ^{74}Cu and one dipole photon transition. The ground state of ^{74}Cu is 2^- [36].

TABLE I. GDR parameters from GLO fits to experimental data from Ref. [37]. E_{E1} is the energy of the giant resonance, Γ_{E1} is the width, and σ_{E1} is the strength. A value of 0.7 for T_f in the GLO function was adopted for all three data sets.

Nucleus	E_{E1} (MeV)	σ_{E1} (mb)	Γ_{E1} (MeV)
^{70}Zn	17.64(6)	97(1)	9.9(2)
^{74}Ge	17.86(10)	95(1)	12.4(4)
^{76}Ge	17.64(9)	101(1)	11.2(4)



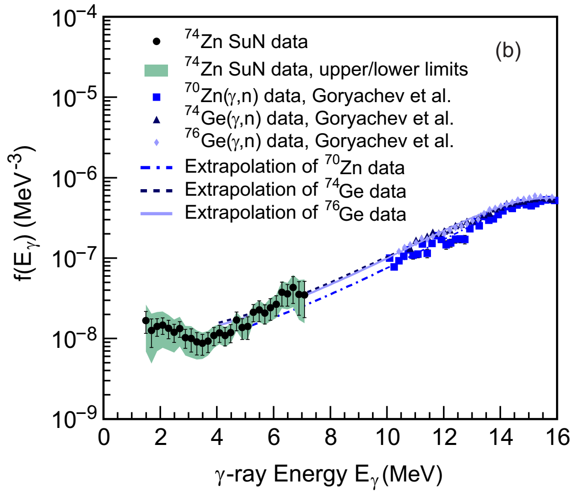


FIG. 3. (a) Nuclear level density for ^{74}Zn showing the experimental data (black circles), known levels from NNDC (solid black line), and level density calculated in Ref. [33] using the Hartree-Fock-Bogoliubov plus combinatorial method (solid blue line, see text for details). Dashed blue lines indicate uncertainties on the shift of the calculated level density. (b) Gamma strength function for ^{74}Zn showing the experimental data (black circles), experimental data for ^{70}Zn and ^{74,76}Ge from Ref. [37] (blue squares, triangles, and diamonds), and the GLO fit to that data and extrapolation to lower energies (blue solid, dashed, and dot-dashed lines). The last 15 points of the experimental γSF were used to minimize the distance between the experimental γSF and the extrapolations of the (γ,n) data sets. The green band indicates the combined statistical and systematic uncertainty.

B. Cross section and reaction rate determination

The normalized NLD and γSF were used as inputs in TALYS to calculate the neutron-capture cross section and reaction rate. The normalized γSF was fit with a GLO function using the GDR parameters from the GLO fits to the photoabsorption data (see Table I) and an exponential function to account for the increase in the γSF at low γ-ray energies [39], with a constant value of $1.02^{+1.24}_{-1.02} \times 10^{-7}$ MeV^{-3} and a slope of 1.6(7) MeV^{-1}.

The neutron-capture cross section and reaction rate are shown in Fig. 4. The lighter, larger bands show the range for both the cross section and reaction rate when using all combinations of NLD and γSF available in TALYS, excluding the temperature-dependent Hartree-Fock-Bogoliubov (HFB) level density [40] and the Brink-Axel single Lorentzian formula for the γSF [41, 42]. Odd-even effects on neutron-capture rates away from stability were enhanced when using the temperature-dependent HFB level density [14], and has been shown to differ from the almost exponential behavior seen in level density experiments [40, 43, 44]. Additionally, the Brink-Axel single Lorentzian γSF formula overestimates experimental neutron-capture cross sections of stable nuclei (for example, Ref. [38, 45]). For all cases the default OMP, from Koning and Delaroche, was used [46]. The Jeukenne-Lejeune-Mahaux (JLM) semi-microscopic OMP [47] was also investigated, and the results were within 5% of the Koning and Delaroche OMP. A reduction of approximately 40% in the uncertainty can be achieved by only using NLD models that fall within the $\rho(S_n)$ normalization point and renormalizing the γSF models using the same procedure as described for the experimental data. A further approximate 30% reduction is obtained in the ^{73}Zn(n,γ)^{74}Zn cross section uncertainty using the experimental data, resulting in an uncertainty of under a factor of 2, as shown with the darker bands.

The uncertainty presented here is specific to a cross section and reaction rate obtained from TALYS using experimental data. However, TALYS is not the only Hauser-Feshbach statistical model code available to determine neutron-capture cross sections. It is not feasible to compare neutron-capture cross sections obtained from different codes for every nucleus where an experimental NLD and γSF has been extracted, so it is important to understand there is a broader uncertainty to these calculations that is extremely difficult to quantify.

For the purpose of comparison, the systematic uncertainty inherent to the choice of Hauser-Feshbach code does not have an impact. Using the β-Oslo method and TALYS to infer neutron-capture cross sections for many nuclei in the A≈80 region will allow for comparisons across neutron and proton numbers of NLDs, γSFs, and cross sections. Having a deeper understanding of the systematic changes to the NLD and γSF, especially, will make predicting neutron-capture cross sections very far from stability more robust.

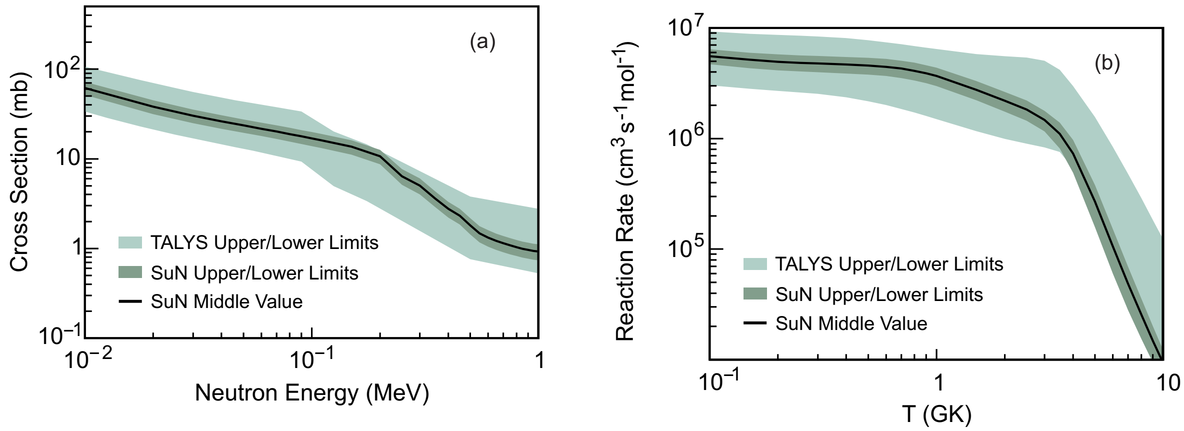


FIG. 4. (a) Cross section for the ^{73}Zn(n,γ)^{74}Zn reaction calculated in TALYS. The lighter band shows the variation in the cross section resulting from combinations of the available NLD and γSF options in TALYS. The darker band shows the uncertainty in the cross section when using the experimental NLD and γSF. (b) Astrophysical reaction rate calculated by TALYS. The lighter and darker bands are the same as for the cross section calculation.

IV. CONCLUSIONS

The cross section and reaction rate for ^{73}Zn(n,γ)^{74}Zn have been experimentally constrained using the β-Oslo method. The NLD and γSF of ^{74}Zn were extracted from the β decay of ^{74}Cu and provide the first experimental measurements of these properties. A reduction in the uncertainty of both the neutron-capture cross section and reaction rate to under a factor of two in TALYS was obtained, which will add to nuclei in the A$\approx$80 region that are used in astrophysical models with small uncertainties.

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