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On the Nature of Low-Energy Electromagnetic Radiation in Atomic Nuclei

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Abstract

The emission and absorption of electromagnetic radiation are phenomena we all encounter on a daily basis¹⁻⁵. In nuclear science, photons are emitted as the atomic nucleus transitions from an excited state to a state of lower energy. The likelihood of photon emission is a function of the photon energy and properties of the initial and final nuclear states, and is known as the photon (or γ -ray) strength function (γ SF)^{6,7}. Of the features present in the γ SF, an enhancement in the low-energy region has been observed in some nuclei^{8,9}. Despite two decades of research, the electromagnetic nature of this enhancement remains an open question. This low energy enhancement in the γ SF significantly impacts our understanding of how elements are created in stars and the structure of the nucleus^{10,11}. In this work, we present the results from an experiment on the γ SF of ⁷⁰Zn which show for the first time that the

enhancement in the γ SF of this nucleus is of magnetic nature. This insight answers a long-open question about atomic nuclei and directly impacts our predictive capabilities in nuclear science.

Introduction

The way matter emits and absorbs light across the electromagnetic spectrum underpins much of modern science, including our communication with the rest of the world, the diagnosis and treatment of diseases, and observations of the Universe around us. The electromagnetic radiation (photons) that originates from nuclear processes is called gamma (γ) radiation¹². The first description of the nature of γ rays emitted during a radioactive decay came in 1904 by Ernest Rutherford¹². Three decades later, it was again Rutherford who confirmed that γ rays were also emitted during nuclear reactions¹³. Today, γ rays are considered the fingerprints of atomic nuclei and are used in many applications, from basic research in nuclear structure and astrophysics to food sterilization, medicine, and national security¹⁻⁵.

Gamma rays are emitted when nuclei transition from higher-energy quantum states to lower-energy ones. At low excitation energies, the emitted γ rays are individually resolvable with discrete and characteristic energies. At high excitation energies, however, the number of available quantum levels per unit energy (Nuclear Level Density, or NLD) is large, the transitions between these levels are complex, and our ability to resolve individual γ rays diminishes. The resulting measured γ -ray energy emission is no longer discrete but instead follows a largely continuous distribution as a function of energy, known as the radiative strength function or γ -ray strength function (γ SF)^{6,7}.

Electromagnetic transitions are defined as either electric or magnetic in nature. In electric transitions, the average distribution of nuclear charge (spatial redistribution of protons) changes between the initial and final states. Magnetic transitions involve changes in how the charge and magnetic moments are moving (redistribution of currents, orbital angular momenta, and spin orientations). Both types of transitions represent different ways the nucleus can rearrange itself and release γ radiation. The most probable electromagnetic transitions in the γ SF, especially at high γ -ray energies are of electric dipole (E1) character, where change in the angular momentum (I) and parity (π) of the initial and final states involved in the transition are both equal to one. Magnetic dipole (M1) transitions do not have a parity change ($\Delta\pi = 0$) but do have a change in angular momentum ($\Delta I = 1$) and are generally weaker than E1 transitions.

The γ SF is a measure of the average electromagnetic decay of a nucleus and has been studied since the mid-20th century, predominantly in stable isotopes. It was found to be characterized by a broad “giant resonance” structure which peaks around 12-20 MeV¹⁴. Over the last 40 years, explorations of the γ SF have revealed additional, smaller, resonance-like structures which have been attributed to certain electromagnetic behavior. In deformed nuclei, a decay resonance at $E_\gamma = 1 - 4$ MeV (now known as the “scissors mode”) was first observed in ¹⁶¹Dy by Guttormsen *et al.*¹⁵ and in ¹⁵⁶Gd by Bohle *et al.*¹⁶. This resonance is thought to be the result of the orbital part of the M1 operator causing protons and neutrons to oscillate with opposite phase around the nuclear core^{17,18}. Additionally, a resonance occurring from 5-10 MeV, known as the pygmy dipole resonance (PDR), is thought to arise from the collective oscillations of a neutron-skin around a proton-neutron core, though the understanding of the origin and properties of the PDR is still a work in progress^{19,20,21}.

In this work, we focus on the most poorly understood feature of the γ SF: the Low Energy Enhancement (LEE). The LEE appears as an enhancement in the low-energy ($E_\gamma < 3$ MeV) portion of the γ SF, and was first discovered in ^{56,57}Fe by Voinov *et al.*⁸ and confirmed in ⁹⁵Mo by Wiedeking *et al.*⁹. Following these initial measurements, the LEE has been observed in many (though not all) light and medium-mass nuclei close to stability²², as well as in some radioactive^{23,24} and higher mass²⁵⁻²⁷ nuclei. The presence of the LEE has a significant impact on predictions of nuclear reaction rates; it increases radiative neutron-capture reaction cross sections compared to theoretical expectations, and a better predictive power regarding which nuclei contain the LEE is imperative to modeling astrophysical nucleosynthesis^{10,11}. Since its discovery, the LEE has been investigated

extensively. After over two decades of research, it still remains unclear what the electromagnetic nature of the LEE is, and how its amplitude and shape might depend on nuclear structure effects²⁴. Many theoretical studies^{22,28-34} predict the LEE to result from M1 transitions (with some exceptions³⁰), but these results have yet to be confirmed experimentally. In 2013 Larsen *et al.*³⁵ showed that the LEE is of dipole nature, but despite significant efforts³⁶, no clear conclusion has been drawn on whether the LEE is of electric or magnetic character (E1 or M1).

Here we present results from an experiment conducted at the Facility for Rare Isotope Beams at Michigan State University, where we studied the electromagnetic behavior of the LEE in the γ SF of ^{70}Zn using a novel combination of experimental β decay and γ -ray spectroscopy techniques and analytical methods. With our measurement we are able to show for the first time that the LEE is of magnetic nature, providing a solution to a decades-long unanswered question in the nuclear physics community.

Results

In this experiment, the γ SF of the nucleus ^{70}Zn was extracted following the population of excited states using the β -decaying nucleus ^{70}Cu . Details regarding this experiment and analysis using the Shape method^{37,38} and the β -Oslo method³⁹ are presented in the Methods section. Here, we use a novel technique to extract the γ SF by feeding the nucleus of interest (^{70}Zn) using the β decay from two states in the same nucleus (^{70}Cu). Specifically, the γ SF of ^{70}Zn was extracted both from the second isomer ($^{70}\text{Cu}^{\text{m2}}$, $J^\pi=1^+$) and the ground state ($^{70}\text{Cu}^{\text{gs}}$, $J^\pi=6^-$) β decays of ^{70}Cu . Beta decay is a very selective process for populating states in the nucleus of interest. Assuming allowed β -decay transitions, β decay will populate states with a spin range of 0 or ± 1 from the spin of the parent state and retain the same parity. The spins of the low-energy decaying states in ^{70}Cu have been confirmed using laser spectroscopy and are firm assignments⁴⁰. Thus, the β decay of the 6^- $^{70}\text{Cu}^{\text{gs}}$ is expected to directly populate $5^-, 6^-, 7^-$ states in ^{70}Zn . The β decay of the 1^+ $^{70}\text{Cu}^{\text{m2}}$ is expected to directly populate $0^+, 1^+, 2^+$ states in ^{70}Zn , resulting in two ^{70}Zn γ -ray strength functions that can be compared. The total energy released in the β decay (Q_β value) of $^{70}\text{Cu}^{\text{gs}}$ is 6.58 MeV⁴¹. The relative population of different excitation energies within the Q_β window following the decay of either parent state can be obtained from total absorption spectroscopy, which was measured in the present data set (see the Methods section, where the total absorption spectra are inset into Figure 4 or in a previous publication⁴²). In general, the β decay from $^{70}\text{Cu}^{\text{m2}}$ favors decays to lower-energy positive parity states in ^{70}Zn , whereas the β decay from $^{70}\text{Cu}^{\text{gs}}$ favors decays to higher energy negative parity states in ^{70}Zn , though experimentally observed feeding is present up until around Q_β in both cases. Following β decay, the excited states decay through the emission of photons until the ground state is reached.

The two strength functions extracted from $^{70}\text{Cu}^{\text{m2}}$ and $^{70}\text{Cu}^{\text{gs}}$ β decay are plotted in Figure 1, where the blue data are associated with $^{70}\text{Cu}^{\text{gs}}$ and the orange data are associated with $^{70}\text{Cu}^{\text{m2}}$ (see Methods section for details). In Figure 1, the high energy portion (9-25 MeV) of the γ SF in the region of the Giant Dipole Resonance (GDR) is comprised of data from $^{70}\text{Zn}(\gamma, n)^{69}\text{Zn}$ and $^{68}\text{Zn}(\gamma, n)^{67}\text{Zn}$ reactions⁴³.

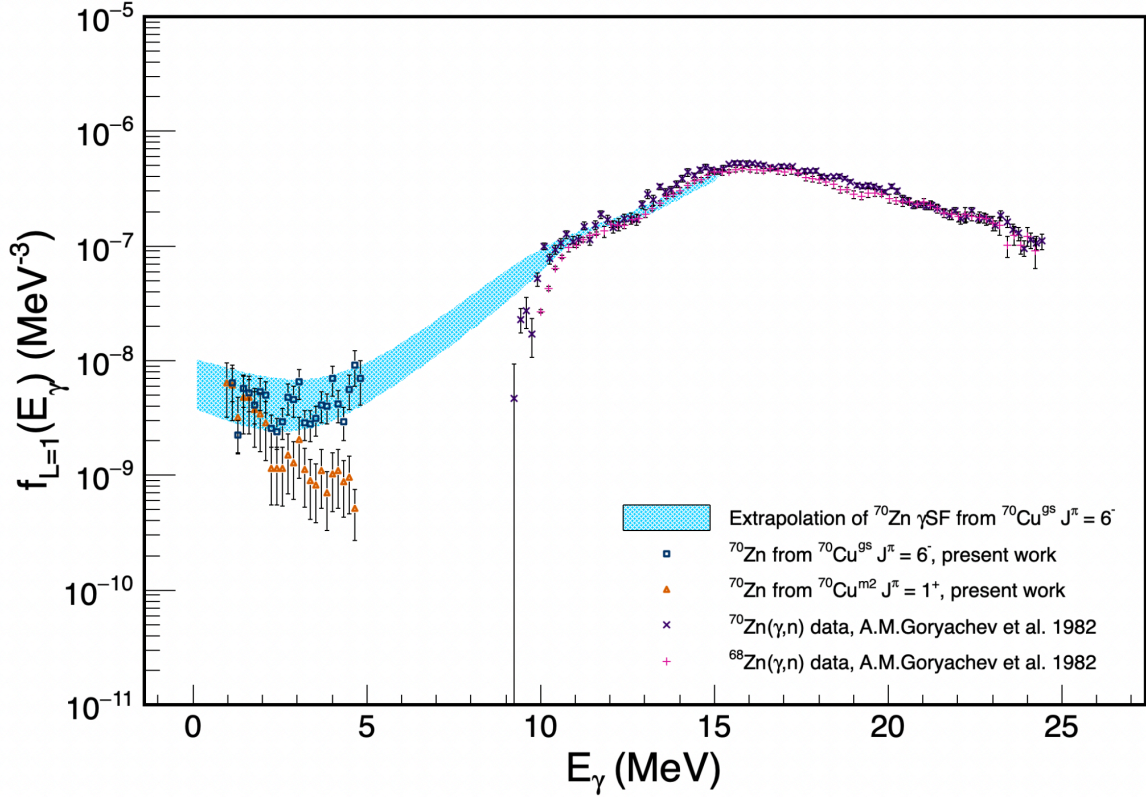


Figure 1: The γ -ray strength functions of ^{70}Zn extracted from the β decays of $^{70}\text{Cu}^{m2}$ (orange triangles) and $^{70}\text{Cu}^{gs}$ (blue squares). The data from the β decay of $^{70}\text{Cu}^{gs}$ are normalized in magnitude and extrapolated to GDR data from $^{70}\text{Zn}(\gamma, n)$ and $^{68}\text{Zn}(\gamma, n)$ measurements by Goryachev *et al.*⁴³, shown in the blue band. The absolute normalization of the data following the β decay of $^{70}\text{Cu}^{m2}$ is relative to the blue band.

In the low-energy region ($E_\gamma < 3$ MeV) of the γ SFs presented in Figure 1, there is a significant difference in the shape between the γ SF extracted from the β decay of 6^- $^{70}\text{Cu}^{gs}$ state compared to one extracted from the 1^+ $^{70}\text{Cu}^{m2}$ state. The difference between the shapes of the two γ SFs can be explained by the different starting distribution of states in ^{70}Zn populated by the two respective β decays and the distribution of positive and negative parity states in ^{70}Zn . The high-energy γ rays of the two strength functions shown in Figure 1 connect the states at high excitation energy with states at low excitation energy in ^{70}Zn . At low excitation energy in ^{70}Zn below 3 MeV there are almost exclusively positive parity states. The 1^+ $^{70}\text{Cu}^{m2}$ parent state populates 0^+ , 1^+ , 2^+ states at high excitation energy in ^{70}Zn . There are few available negative parity states at low excitation energy in ^{70}Zn and as a result, the E1 γ SF inferred following the decay of the 1^+ $^{70}\text{Cu}^{m2}$ is significantly suppressed. In this interpretation of selective suppression of the E1 γ SF, the difference in the two γ SF from $^{70}\text{Cu}^{m2}$ and $^{70}\text{Cu}^{gs}$ β decay does not appear, in our interpretation, to violate the generalized Brink-Axel hypothesis,^{44,45} but instead reflects a different availability of states.

The discrepancy in the parity of states is illustrated by the low-energy level scheme of ^{70}Zn , reproduced in Figures 2a and 2b⁴¹. Below approximately 3 MeV there are only two negative parity states. We use Gogny+Hartree-Fock-Bogoliubov (HFB) calculations⁴⁶ of the NLD contained in the Hauser-Feshbach code TALYS⁴⁷ to describe the ratio of the negative and positive parity states in ^{70}Zn , shown in Figure 2c. The ratio is zero at low energy, matching the expectation based on discrete levels where there are few negative parity states in the nucleus, and approaches 1 toward higher excitation energies where there should be an equal number of positive and negative parity states. The two lines in Figure 2c are to distinguish the parity asymmetry for the two different spin

ranges $J=0-3$ (orange, $^{70}\text{Cu}^{m2}$) and $J=4-8$ (blue, $^{70}\text{Cu}^{gs}$). Shell model calculations using the `jun45`⁴⁸ and `jj44b`⁴⁹ Hamiltonians produce qualitatively similar ratios for the parity asymmetry as a function of excitation energy. Experimental levels with firmly assigned spin-parity exhibit similar behavior, where above 3 MeV the ratio of negative parity states to positive parity states is higher for spins $J=4-8$ than it is for spins $J=0-3$.

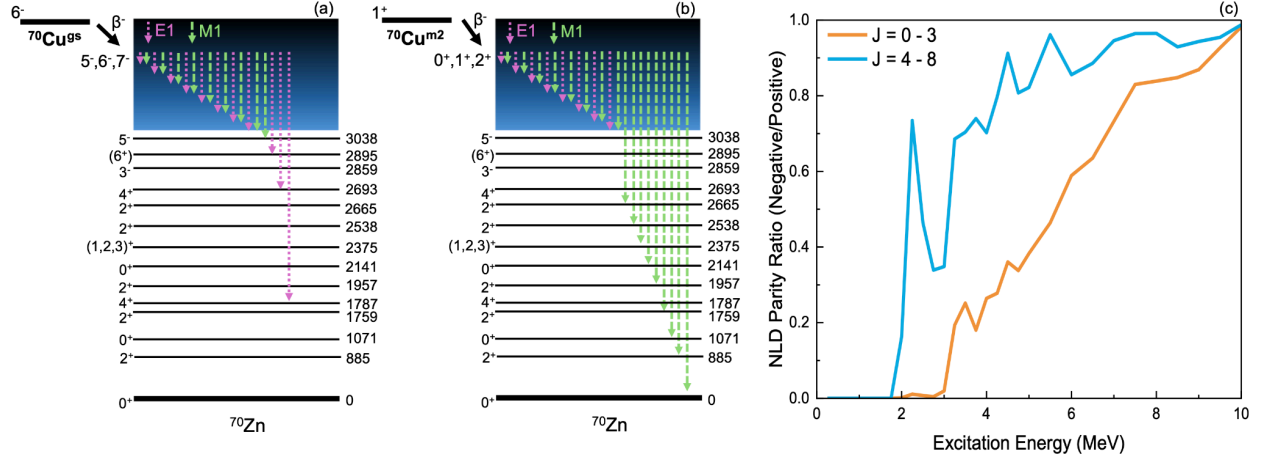


Figure 2: Panels (a) and (b) show a schematic level scheme of ^{70}Zn with known levels and their associated energies in keV, spins, and parities up to 3 MeV populated from $^{70}\text{Cu}^{gs}$ and $^{70}\text{Cu}^{m2}$ β decays respectively⁴¹. Here transitions of M1 character are shown in green, and transitions of E1 character are shown in purple. In the level scheme of $^{70}\text{Cu}^{m2}$ the decay of high energy positive parity states to low energy positive parity states heavily favors dipole transitions of magnetic nature, which is not the case from $^{70}\text{Cu}^{gs}$ where E1 are favored. Panel (c) shows the parity distribution of ^{70}Zn (represented by the ratio of negative parity states to positive parity states) up to 10 MeV for two different spin ranges: the spins populated following β decay of the 6^- $^{70}\text{Cu}^{gs}$ state and one dipole transitions (spins 4-8, blue) and the spins populated following the β decay of the 1^+ $^{70}\text{Cu}^{m2}$ state and one dipole transition (spins 0-3, orange).

To qualitatively demonstrate the suppression of the E1 strength function we first model the experimental γSF extracted following the β decay of the 6^- $^{70}\text{Cu}^{gs}$ state (blue squares in Figure 1). Here, the shape of the E1 strength was based on the Gogny+HFB with QRPA model (using the D1M version of the Gogny force) by Goriely *et al.*⁵⁰¹ and the shape of the M1 strength is modeled by a generalized Lorentzian⁵¹. An additional exponential component was added to account for the M1 LEE, as the LEE is expected to have an energy dependence that can be modeled by an exponential function^{20,28-34}. The three components, E1, M1, and the M1 exponential LEE were fit to the γSF extracted from the 6^- $^{70}\text{Cu}^{gs}$ decay. The amplitude of the E1 and M1 exponential LEE components were allowed to freely vary and the non-exponential M1 component was fixed at approximately an order of magnitude weaker than the E1 strength. This order of magnitude difference between E1 and M1 strengths is expected based on other nuclei within this mass region¹⁴. The total γSF obtained by summing the contributions from E1, M1, and M1 exponential LEE is presented as the solid black line in Figure 3. This line falls within the blue band in Figure 1.

The asymmetric parity distribution illustrated in Figure 2c significantly alters the γSF inferred from the decay of the 1^+ $^{70}\text{Cu}^{m2}$ state. Low-spin positive-parity states populated in ^{70}Zn from $^{70}\text{Cu}^{m2}$ β decay will transition to the ground state through cascades of γ rays. The lack of negative parity states at low energy in ^{70}Zn suppresses the presence of E1 transitions in the γSF because those states are not allowed to decay to the positive parity final states. The suppression of E1 strength is present at all γ -ray energies but is the strongest for the high-energy transitions. The M1 transitions are unaffected.

To account for and quantify the impact of the parity asymmetry on the extracted γSF we determined an E1 reduction factor for each γ -ray energy. For a given primary γ -ray energy (E_γ) we first identify all excitation energies

(E_x) where it is energetically possible to emit a primary E_γ . Then we determine the reduction factor based on the parity asymmetry at the energy of $E_x - E_\gamma$ to account for the lack of negative parity levels at the destination excitation energy. Above $E_\gamma \approx 3.5$ MeV the multiplicative E1 reduction factor is 0, as there are no available negative parity states in the nucleus to accommodate the emission of a primary E1 γ -ray at these energies. The reduction factor at each E_x is weighted by the population of that specific E_x in β decay, taken from total absorption spectroscopy results⁴¹. The final reduction factor for each E_γ was applied to the E1 strength function, leading to the dashed blue line in Figure 3. The M1 and M1 exponential LEE are unaffected by the parity asymmetry and the total reduced strength function is provided in Figure 3 as the dashed black line. The dashed black line matches the shape of the experimentally measured γ SF from the 1^+ β decays of $^{70}\text{Cu}^{m2}$; it should be noted that this behavior holds if the M1 LEE exponential is allowed to vary in slope within the error of experimental data at low energies. Further, the difference in shape between the ^{70}Zn γ SF extracted from the $^{70}\text{Cu}^{m2}$ β decays and $^{70}\text{Cu}^{gs}$ β decays is attributable to the suppression of the E1 strength and the existence of the M1 exponential LEE. Therefore the experimental data confirms that the LEE is M1 in nature.

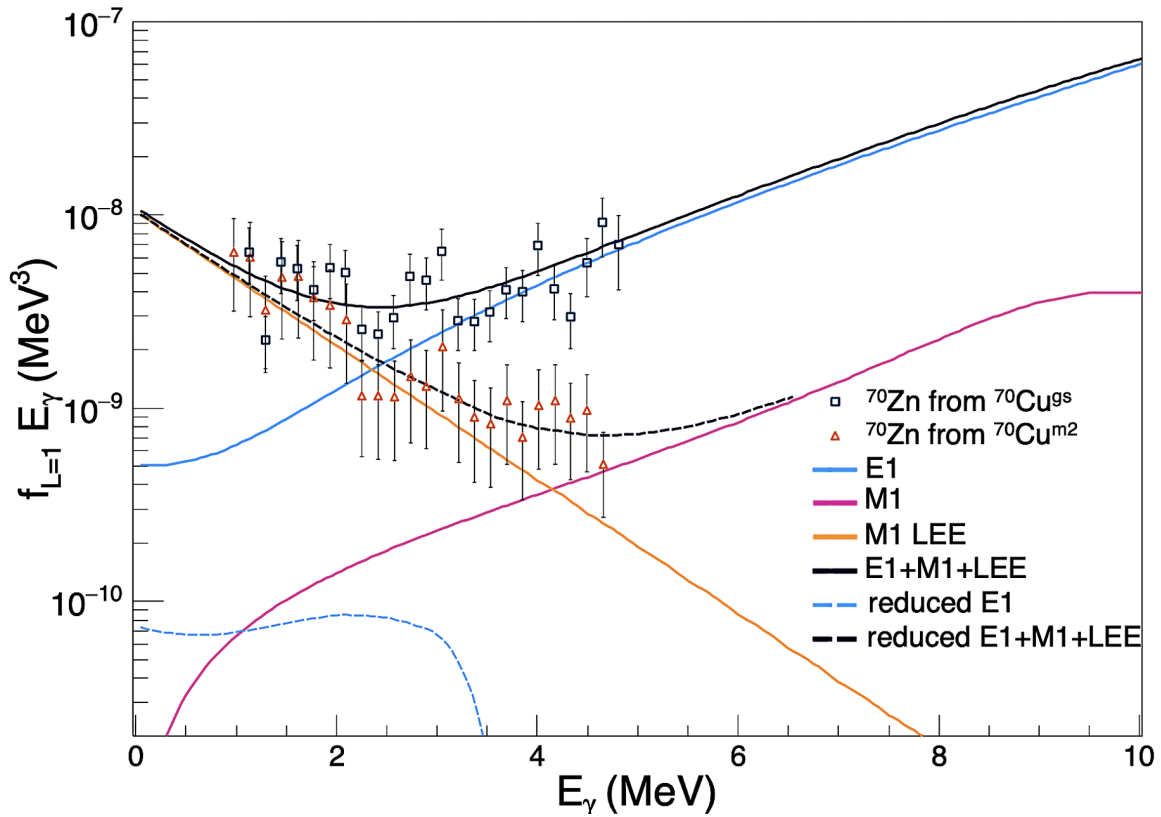


Figure 3: Figure illustrating the components of the γ -ray strength function of ^{70}Zn . Here the E1+M1+LEE γ SF from Gogny+Hartree-Fock-Bogoliubov (HFB) calculation in TALYS 1.96⁴⁶ is shown as the solid black line. The individual components of this γ SF are as follows: the E1 component is shown in the solid blue line, the M1 component is shown as the solid pink line, and the M1 LEE is shown as the solid orange line. The γ SF with the applied E1 suppression factor is shown as the dashed black line, where the reduced E1 component is shown as the dashed blue line and the two M1 components remain the same. The hollow blue squares represent the ^{70}Zn γ SF extracted from $^{70}\text{Cu}^{gs}$ and the hollow orange triangles represent the ^{70}Zn γ SF extracted from $^{70}\text{Cu}^{m2}$. We see good agreement between the data from $^{70}\text{Cu}^{gs}$ and the standard E1+M1+LEE γ SF, and good agreement between the data from $^{70}\text{Cu}^{m2}$ and the suppressed E1+M1+LEE γ SF.

The determination that the LEE is M1 in nature sheds light on a long-standing open question regarding the nature of γ -ray radiation in nuclei. With the nature of the LEE finally fully established for the case of ^{70}Zn , we can focus our efforts into addressing remaining questions regarding the γSF , such as how the amplitude and shape of the LEE might depend on nuclear structure, how we can predict this behavior⁵², and how it might be related to the generalized Brink-Axel hypothesis. Understanding the nature of the LEE will improve our ability to predict neutron and proton capture reaction rates in astrophysical environments, help us begin to disentangle the complex picture of stellar nucleosynthesis, and understand the complex interplay of nucleons in atomic nuclei.

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Methods

This experiment was conducted at the Facility for Rare Isotope Beams (FRIB) at Michigan State University, in the area behind the Low Energy Beam and Ion Trap (LEBIT) 9.4 T Penning trap mass spectrometer⁵³. A 215 MeV/u primary beam of ^{82}Se was impinged on a ^{12}C target with a thickness of 4.88 mm. The Advanced Rare Isotope Separator (ARIS)⁵⁴ was used to purify and select ions of ^{70}Cu , which were then passed through a gas cell where they were thermalized⁵⁵. Using a dipole mass separator with a resolution power of ~ 1500 , the ^{70}Cu ions were further isolated and transmitted to LEBIT. The percentage of ground ($J^\pi = 6^-$) and two isomeric ($J^\pi = 3^-, 1^+$) states in the ^{70}Cu beam were quantified via time-of-flight ion-cyclotron-resonance (ToF-ICR) mass spectrometry^{56,57} (see Figure 4).

To isolate the individual β -decaying states within LEBIT, the undesired two spin-parity states were selectively driven to large radial amplitudes via targeted dipole excitation and removed⁵⁸. In this way, the decays of $^{70}\text{Cu}^{m2}$ and $^{70}\text{Cu}^{gs}$ were isolated. The isolated ^{70}Cu ions were transmitted to a double sided silicon strip detector (DSSD) at the center of the SuN++ total absorption spectrometer⁵⁹. The DSSD is composed of 32 strips (16 horizontal and 16 vertical) each with a width of 1.2 mm. The DSSD detects electrons from the implanted β -decaying ^{70}Cu ions, and the subsequent β -delayed γ rays were detected by the SuN++ total absorption spectrometer. Successful isomeric separation of the isolated $^{70}\text{Cu}^{m2}$ and $^{70}\text{Cu}^{gs}$ ions were confirmed using data from Van Roosbroeck *et al.*⁶⁰ and Ronning⁴², seen in Figure 4.

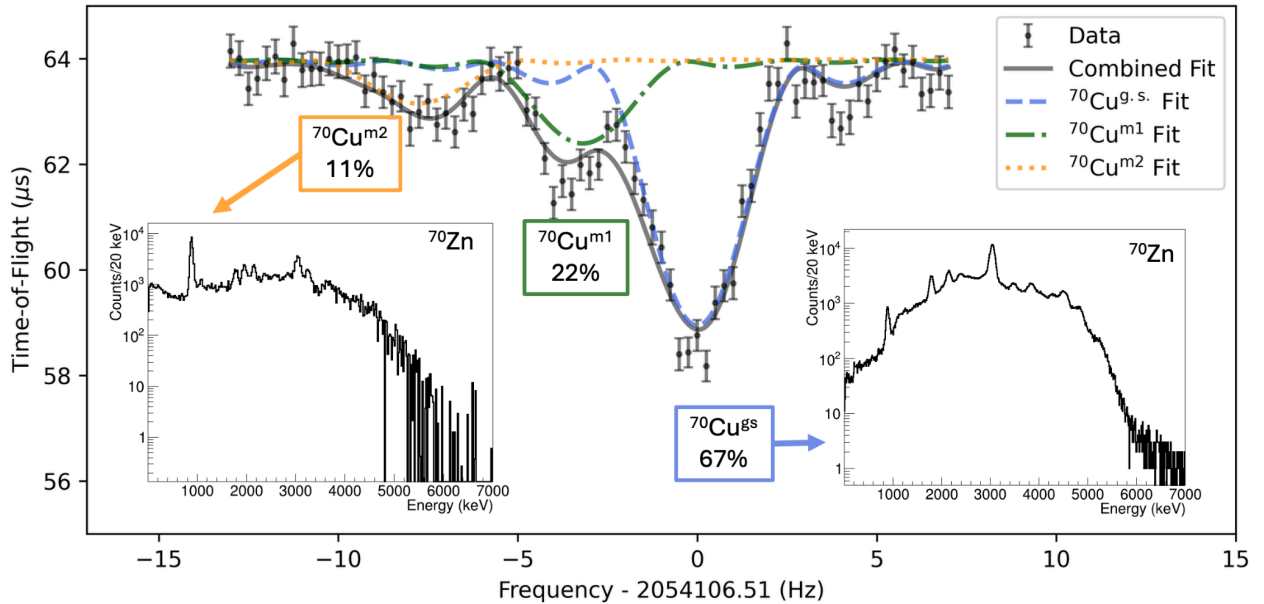


Figure 4: The ToF-ICR curve from LEBIT showing ^{70}Cu data in black data points, fits to $^{70}\text{Cu}^{\text{gs}}$ (blue dashed), $^{70}\text{Cu}^{\text{m1}}$ (green dot-dashed), and $^{70}\text{Cu}^{\text{m2}}$ (orange dotted), and a total fit in gray. The total absorption spectra of ^{70}Zn measured in SuN++ from the isolated β decay of the $^{70}\text{Cu}^{\text{m2}}$ (orange, 1^+) isomer and $^{70}\text{Cu}^{\text{gs}}$ (blue, 6^-) ground state are inset on the ToF-ICR curve.

Here, we use two methods to extract the γ -ray strength functions of ^{70}Zn from the β decay of $^{70}\text{Cu}^{\text{gs,m2}}$: the Shape method^{37,38} and the β -Oslo method³⁹. The Shape method is a model independent way of extracting the shape (energy dependence) of the γ SF, without the necessity of external normalization parameters. The β -Oslo method is a variation of the standard Oslo method⁶¹⁻⁶³, where states in the nucleus of interest are populated via β decay and measured with a segmented total absorption spectrometer. Using the β -Oslo method produces a γ SF with a broader E_γ range than the Shape method, but it requires external normalization points to determine the slope of the γ SF, which leads to a large uncertainty in its shape. In cases where it is possible to apply both the Shape method and β -Oslo method to the same data set, the data from the β -Oslo method can be normalized with the model independent slope extracted via the Shape method, resulting in a larger E_γ range without the need of external normalization factors, save for a scaling parameter applied to the γ SF.

For this experiment, the segmented total absorption spectrometer SuN++⁵⁹ was used to measure individual β -delayed γ rays, and when these γ rays are measured within the same β -decay event they can be summed together to create the total absorption spectrum, which is related to the excitation energy of the state populated from β decay. The information from SuN++ is used to produce a matrix of excitation energy-tagged γ rays (E_x vs E_γ matrix). The two raw ^{70}Zn E_x vs E_γ matrices from $^{70}\text{Cu}^{\text{m2}}$ and $^{70}\text{Cu}^{\text{gs}}$ are shown in Figure 5 (a) and (d), where we see strong diagonals that allow us to perform the Shape method and β -Oslo method on the same data set.

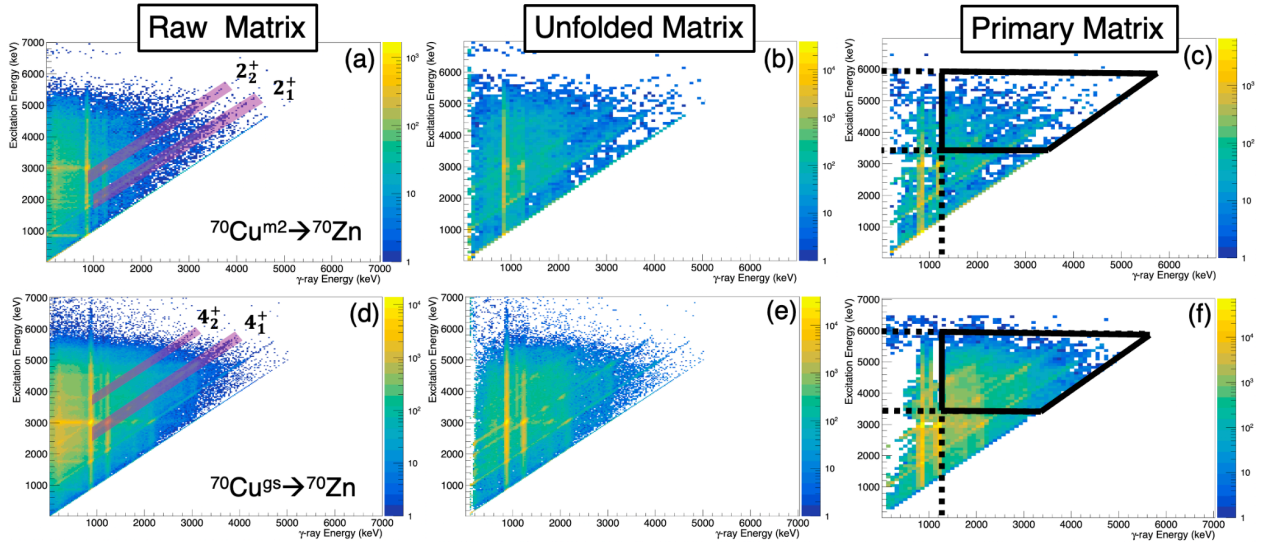


Figure 5: The raw, unfolded, and primary E_x vs E_γ matrices for ^{70}Zn , populated via the β decay of $^{70}\text{Cu}^{\text{m2}}$ in panels (a)-(c) and $^{70}\text{Cu}^{\text{gs}}$ in panels (d)-(f). The binning of panel (a) is 20 keV/bin and of panels (d) and (e) is 10 keV/bin. Panels (b) and (c) have binning of 80 keV/bin and panel (f) has binning of 60 keV/bin. The presence of diagonals corresponding to a strong population of certain levels in ^{70}Zn is highlighted in each raw matrix in purple and these diagonals were used for the Shape method. The $2^+_{1,2}$ states are highlighted in the raw matrix populated from $^{70}\text{Cu}^{\text{m2}}$ (a), and the $4^+_{1,2}$ states are highlighted in the raw matrix populated from $^{70}\text{Cu}^{\text{gs}}$ (d). Panels (b) and (e) correspond to the detector response-corrected “unfolded” matrices. The region outlined in black in panels (c) and (f) represent the regions in the primary matrix from which the γ SF was extracted with the β -Oslo method.

The two E_x vs E_γ matrices from Figure 5 were first unfolded using the technique from Guttormsen *et al.*⁶¹ to account for the detector response of SuN++. The response function for SuN++ was developed using GEANT4^{59,64}. These unfolded spectra are also seen in Figure 5 (b) and (e). The primary γ -ray matrix, which contains the

distribution of the first γ rays emitted in the γ -ray cascades, was isolated using an iterative subtraction procedure⁶². The primary ^{70}Zn E_x vs E_γ matrices from $^{70}\text{Cu}^{m2}$ and $^{70}\text{Cu}^{gs}$ are shown in Figure 5 (c) and (f). For the matrix (f) populated by the $^{70}\text{Cu}^{gs}$ β decay, a diagonal cut of 450 keV was used to remove incomplete summing features from lower-lying cascades.

From the primary matrix $P(E_\gamma, E_x)$, the functional forms of the NLD, $\rho(E_x - E_\gamma)$, and γ -ray transmission coefficient, $\mathcal{A}(E_\gamma)$ can be obtained⁶³. The NLD and $\mathcal{A}(E_\gamma)$ in this case can be extracted from a region with E_x limits of $E_{\min} < E_x < Q_\beta$, where $E_{\min}$ is the minimum energy at which the γ -decay and population of daughter nucleus is statistical, and Q_β is the β -decay Q-value. The statistical region is also constrained by the lower γ ray energy bound ($E_{\gamma, \min}$) to avoid strong contributions from discrete γ ray transitions. For ^{70}Zn , ($E_{\gamma, \min}$) = 1100 keV, $E_{\min}$ = 3300 keV, and the maximum E_x bound was chosen to be 6100 keV due to lack of statistics (these bounds are represented by the black traced bounds in Figure 5). These limits were varied to check for consistency. The ^{70}Zn level densities extracted from $^{70}\text{Cu}^{m2}$ and $^{70}\text{Cu}^{gs}$ β decay are partial level densities, assumed to result from spins associated with allowed Gamow-Teller decay and one dipole transition ($J = 0 - 3$ for $^{70}\text{Cu}^{m2}$ and $J = 4 - 8$ for $^{70}\text{Cu}^{gs}$). We assume allowed Gamow-Teller β decay because forbidden decays are roughly 3 to 4 times slower than allowed decays and therefore much less probable to occur in the quasi-continuum region. Each partial NLD is normalized to low-lying discrete levels.

In Figure 5, strong diagonal features are present and are labeled. These diagonals correspond to statistical γ -ray decays from the quasicontinuum to specific discrete low-lying levels (L_j). In these cases, the Shape Method can be used to extract the energy-dependence or "shape" of the γ -ray strength function independent from potentially unknown normalization parameters³⁷. We assume, as we do with the standard Oslo method, that the primary γ -decays into L_j are dipole transitions, as dipole transitions are known to dominate decay in the quasi-continuum⁶⁵. For the matrix populated from the β decay of $^{70}\text{Cu}^{m2}$ (Figure 5 (a)), we restrict our analysis to two discrete states: E_{L1} = 885 keV and E_{L2} = 1759 keV, where both states have identical spin $L_{1,2} = 2_{1,2}^+$. For the matrix populated from the β decay of $^{70}\text{Cu}^{gs}$ (Figure 5 (d)), our analysis is restricted to two different discrete states: E_{L3} = 1786 keV and E_{L4} = 2693 keV, where in this case the two states have spin $L_{3,4} = 4_{1,2}^+$.

Using the ShapeIt program and methodology³⁸, projections along the diagonals for different excitation energies were used to extract the γ -ray intensities into the states of interest. These intensities (N_{Lj}) were determined from Gaussian fits with a linear background, corrected for the detector response, and then related to the ratio of the γ SFs. The Shape method is applied within the same energy region used to extract the NLD and γ SF using the Oslo method, where the behavior of the daughter nucleus is considered to be statistical.

To extract information about the relative γ -ray strengths of $L_{1,2}$, five E_x bins of 300 keV, ranging from 3300 keV < E_x < 4800 keV were used. To extract information about states $L_{3,4}$, five E_x bins of 300 keV were also used, however the range was restricted to 4200 keV < E_x < 5700 keV, as the energy of L_4 is too high to extract the γ SF at lower E_x values. The γ SF from $L_{1,2}$ and $L_{3,4}$ were obtained with a "sewing" approach, where pairs of data points from each E_x bin were normalized to one another via linear interpolation³⁷. In our case we use the "symmetric sewing" from M ucher *et al.*³⁸. Using varying bin positions of 50 keV, the strength function weighted average energy was determined and the values for $f(E_\gamma)$ were calculated. The resulting γ SFs from $L_j = (2_1^+, 2_2^+)$ and $L_j = (4_1^+, 4_2^+)$ were scaled in magnitude via χ^2 minimization to the respective results from the β -Oslo method, and the final displayed strength functions have fixed energy bins of 250 keV.

The γ -ray strength functions from the β -Oslo method were then transformed using a change in the slope parameter α ($\Delta\alpha$) to best match the slope of the γ SF of the shape method. Following the methodology from M ucher *et al.*³⁸ a Monte Carlo approach is used to determine a χ^2 fit of the $\Delta\alpha$ parameter within a randomized γ -ray energy range, resulting in a near-Gaussian distribution where the centroid is the $\Delta\alpha$.

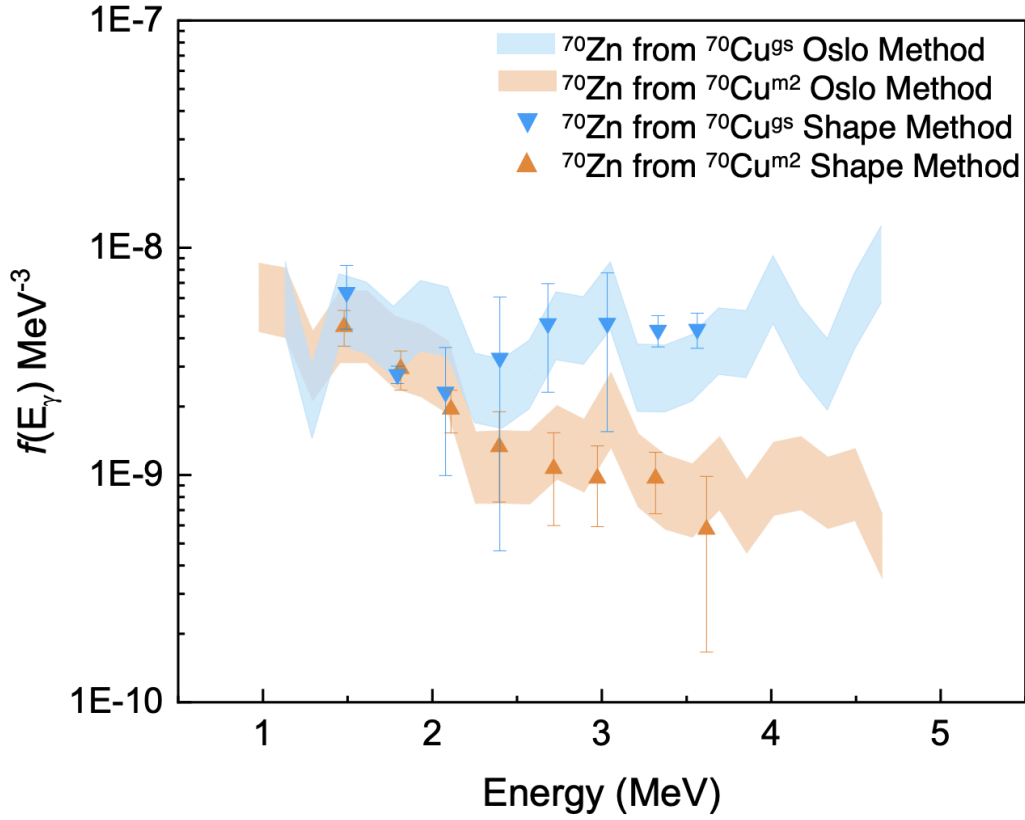


Figure 6: The comparison between the extracted γ -ray strength functions via the β -Oslo (bands) and Shape methods (triangles). The data from $^{70}\text{Cu}^{m2}$ β decay are shown in orange, and the data from $^{70}\text{Cu}^{gs}$ β decay are shown in blue.

The ^{70}Zn γ SF extracted following the β decay of $^{70}\text{Cu}^{gs}$ was normalized in absolute magnitude to GDR data from $^{70}\text{Zn}(\gamma, n)^{69}\text{Zn}$ and $^{68}\text{Zn}(\gamma, n)^{67}\text{Zn}$ measurements by Goryachev *et al.*⁴³ and the ^{70}Zn γ SF extracted from the β decay of $^{70}\text{Cu}^{m2}$ was normalized relative to the data from the β decay of $^{70}\text{Cu}^{gs}$, to maintain consistency with the interpretation that this γ SF has a suppressed E1 component. The resulting γ SFs from the β decay of $^{70}\text{Cu}^{gs}$ and $^{70}\text{Cu}^{m2}$ extracted with the Oslo and Shape methods are shown in Figure 6. Here, the data in orange correspond to the $^{70}\text{Cu}^{m2}$ β decay and the data in blue correspond to $^{70}\text{Cu}^{gs}$ β decay. The blue inverted triangles and orange upright triangles show the results from the Shape method, where the γ SF was extracted for γ -ray energies between 1.5 and 3.5 MeV. The orange and blue bands represent the γ SF results from the Oslo method, where the slopes of these strength functions have been shifted to the $\Delta\alpha$ values from above. The uncertainties associated with the $\Delta\alpha$ from the slope-shift are included in these error bands. The data from the Oslo method extend beyond the Shape method results, from approximately 1 MeV to 5 MeV and are reported above in Figures 1 and 3.

Data Availability: The data sets generated during and/or analyzed during the current study are available from the corresponding author on request.

Code Availability: The codes used for the analysis of the present data are publicly available on github: <https://github.com/oslocyclotronlab/oslo-method-software>, <https://github.com/dennismuecher/ShapeIt>. The last commit to the Oslo codes at the time of download by the authors was commit 21e45ce. The last commit to ShapeIt at the time it was downloaded by the authors was commit b7666a8. It should be noted that the response functions for SuN++ were created for this analysis and are not present in the referenced commit here.

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