Significantly improved estimates of neutron capture cross sections relevant to the r processA. Couture¹, R. F. Casten^{2,3} and R. B. Cakirli⁴¹*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*²*Wright Lab, Yale University, New Haven, Connecticut 06520, USA*³*Facility for Rare Isotope Beams, Michigan State University (MSU-FRIB), East Lansing, Michigan 48823, USA*⁴*Department of Physics, Istanbul University, Istanbul 34134, Turkey*

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Background: The r process is thought to be a dominant mechanism for the production of medium mass and heavy nuclei. Despite extensive study, neither the process nor its site, and, consequently, the origin of these elements, is well understood. One of the principal reasons is the lack of adequate knowledge of neutron capture cross sections in neutron-rich nuclei, especially up to a few hundred keV. Existing statistical model calculations differ widely and are unreliable more than a few nucleons beyond stability.

Purpose: To provide a new, more reliable empirical method to estimate neutron capture cross sections.

Method: To use an entirely empirical approach by exploiting a newly discovered correlation between two-neutron separation energies and neutron capture cross sections.

Results: It is shown that there is a compact correlation between neutron capture cross sections and S_{2n} for S_{2n} values from 10 to 16 MeV, encompassing nuclei in five mass regions comprising seven classes of nuclei from $A \approx 110$ through the actinides over Maxwellian energy distributions from $kT = 5$ to 100 keV. As a consequence, many unknown cross sections can be predicted by interpolation, with accuracies on the order of $\pm 25\%$. In other cases, the cross sections can still be predicted with greatly improved accuracy compared to current models. Finally, it is shown that, in very neutron-rich nuclei, measurements of S_{2n} can replace more difficult or impossible neutron capture measurements to estimate r -process abundances.

Conclusions: A new approach to estimate neutron capture cross section allows much improved predictions of these key ingredients into r -process calculations, perhaps providing an enhanced ability to model this process and to better define its site(s).

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I. INTRODUCTION

Reactions on atomic nuclei play a key role in understanding environments as diverse as hydrostatic stellar interiors, nuclear reactors, and explosions that occur in the death throes of a massive star. In astrophysics, numerous reactions are critical to answering basic questions concerning stellar environments and the origin of the elements. These questions have engaged nuclear astrophysics since Eddington [1] first suggested that nuclear reactions might be the key mechanism to explain stellar lifetimes and luminosity, and decades later, the modern theory of nucleosynthesis was independently developed by Cameron [2] and Burbidge *et al.* [3].

While major strides have been made since these seminal works, significant uncertainties and open questions remain, particularly for elements heavier than iron. Since fusion reactions above iron are endothermic, they cannot prevent gravitationally induced stellar collapse. Moreover, even if

fusion could contribute energetically, the increased Coulomb barriers with increasing Z of stellar constituents would require much larger energies to allow fusion reactions. The primary mechanism to produce the heavier elements is therefore (exothermic) neutron capture. No Coulomb barrier hindrances are involved and capture reactions can occur at the low kinetic energies typical of stellar interiors. Therefore, critical to understanding the origin of most of the elements beyond iron, and hence the stellar environments in which they are synthesized, is the quantitative understanding of neutron capture cross sections in the energy range (typically keV to a few MeV) relevant to their stellar sites.

Two broad classes of neutron capture reactions are slow neutron capture (the s process) and rapid neutron capture (the r process). The time scales involved are relative to β decay which, when it occurs, arrests subsequent capture on a given element and shifts the nucleosynthetic process to the next higher Z element. The s process centers on stable and near-stable nuclei and competes with β decay, while the r process outruns β decay towards neutron-rich nuclei until special conditions apply. Importantly, therefore, the r process extends to isotopic regions where (n, γ) – (γ, n) equilibrium occurs in hot environments (e.g., core-collapse supernovae) or to the neutron dripline in cold scenarios, such as neutron star mergers.

Recent rediscovery of the so-called intermediate or i process has made this even more challenging [4,5]. This is a neutron capture process predicted during explosive shell burning which, like the s process, operates in β -decay equilibrium, but at orders of magnitude higher neutron density, such that the reactions of interest often take place 5+ neutrons away from stability. For both the i and the r processes, not all nuclides are equally important to final abundances but many contribute, and recent studies have attempted to systematically highlight the specific cross sections to which the nucleosynthetic trajectory is particularly sensitive (see, e.g., Ref. [6]).

The importance of accurate neutron capture cross sections for interpreting r -process abundances and, hopefully, determining the r -process site or sites has been clearly demonstrated. While earlier work argued that neutron capture rates were largely secondary to neutron separation energies, as the burning would take place in nuclear statistical equilibrium (NSE) (see, e.g., [7]), more recent efforts have shown that, even if NSE is reached in an r -process event, during fall-out from NSE, the neutron capture cross sections once again become important [8]. Surman *et al.* demonstrated that uncertainty in neutron capture rates on a multitude of rare-earth isotopes could each have appreciable impact on the predicted final abundances, even in a so-called “hot” r process where NSE is achieved [9]. Further studies by Mumpower *et al.* demonstrated that individual neutron capture rates continue to impact final predicted abundances in a “cold” r process where NSE is not achieved [10]. This type of environment may be more typical in a scenario where a neutron-star merger generates an r process. Liddick *et al.* demonstrated that uncertainties of a factor of 10 or greater in neutron capture cross sections are sufficient to obscure salient details in the predicted rare earth abundances [11]. The data they presented show clear improvements in constraints that can be achieved if the neutron capture cross section uncertainties can be reduced to a factor of 2 from a factor of 10 (for details, see Figure 4 in [11] and the surrounding discussion).

In addition to the importance of neutron capture for element synthesis, terrestrial applications also require reliable neutron capture data on both stable and unstable nuclei. As reactor design has advanced and evolved beyond relatively simple, light-water, thermal reactors with low burn-up, the number of nuclei that participate in both the energy production and the safety envelope have increased, requiring reaction cross sections on a broader range of shorter-lived nuclei. Sensitivity studies have identified needs in the actinides [12,13]. Finally, national security applications require neutron capture cross sections, both for stockpile stewardship and nuclear forensics [14]. Reliable prediction of cross sections for isotopes just off stability continues to be of pressing interest.

Unfortunately, one faces a dual challenge here. First, while capture measurements on stable targets are usually straightforward, those on unstable targets are often either extremely difficult, very time consuming, or impossible with foreseeable technology. The relevant incident neutron energy is quite low, nominally a few to hundreds of keV, requiring detailed resonance spectroscopy of neutron states. Time-of-flight measurements are typically the gold-standard for capture cross section measurements due to their differential information, but

even for s -process studies, orders of magnitude higher neutron densities would be required to complete measurements on all of the necessary branch points [15]. Activation measurements, particularly with accelerator mass spectroscopy for counting, can offer increased sensitivity, but the techniques are limited to those cases with favorable decay branchings and lifetimes [16–18]. Finally, while initial concepts have been floated for how to perform a direct neutron capture experiment with a radioactive ion beam, none are currently under construction [19].

On the theoretical side, prediction of (n, γ) cross sections is daunting since capture produces final nuclei at compound nuclear excitation energies near or above the neutron separation energy, that is, in the multi-MeV range, where the level density is extraordinarily high, the structure of individual levels is largely unknown, and computational challenges of existing nuclear structure models abound.

One thus resorts to statistical nuclear models and computational approaches such as Hauser-Feshbach (H-F) [20,21]. These calculations require a knowledge or estimate of statistical approximations of the structural features including spin-dependent level densities, optical model parameters, and γ -ray de-excitation routes and probabilities. In most cases, the models parameterize these quantities. For stable nuclei, where cross sections are known experimentally, such parametrized calculations, perhaps not surprisingly, generally reproduce the data reasonably well (typically to within 25%). Beyond stability, there are few experimental calibration points, less control or constraints on the H-F variables, and, consequently, different H-F calculations can quickly diverge in their predictions. The problem exacerbates very quickly, leading to rapid disagreements of predictions reaching an order of magnitude within just a few nucleons beyond stability. For decades, extensive work has been done to improve and stabilize the H-F approach, with many added structural degrees of freedom, but adequate convergence is still lacking. Yet, the r process often involves nuclides ten or more neutrons beyond stability where the rapidly growing uncertainty renders it very difficult to distinguish competing models of nucleosynthetic sites and timescales.

We will present below a new approach, introduced in Ref. [22], that obviates these problems for a wide range of nuclei and neutron energies. It can yield much more accurate predictions of neutron capture cross sections, including predictions for many nuclei by a process of interpolation, and hence significantly improve the calculation of r -process abundances and their uncertainties. It further suggests a simple way to estimate these cross sections by easy measurements in currently unknown nuclei.

II. THE NEUTRON CAPTURE CROSS SECTION- S_{2n} CORRELATION

As just noted, the present paper originated in a previous study [22] where we introduced an alternate, purely empirical and parameter-free, correlation of observables that seems to bypass the difficulties discussed above and offers a much easier and more reliable way to estimate many of the needed cross sections, even for nuclei well-off stability. Reference

FIG. 1. (a) Experimental Maxwellian-averaged cross section (MACS) for neutron capture evaluated at $kT = 30 \text{ keV}$ are shown versus atomic mass A for 57 even-even nuclei [23]. (b) The same MACS is shown plotted versus the two-neutron separation energy (S_{2n}) for the nucleus with two more neutrons than the capturing nucleus. The nuclei shown here (33) are even-even deformed nuclei between Nd and W [23–25]. The figure shows a simple best exponential fit function, discussed in the text in Sec. III B, with the lower panel of (b) indicating the deviation of each point from the fit.

[22] focused primarily on one region of even-even deformed rare earth nuclei at one neutron energy, albeit briefly showing some results for other regions. The present paper builds on this by presenting a coherent analysis that combines all the regions considered in Ref. [22], and others, in a unified framework and for a range of relevant temperatures, covering thermal Maxwell-Boltzmann distributions peaked at neutron energies from 5–100 keV.

To give a concrete context to this discussion, it is useful to look at a given region. Figure 1(a) shows the empirically evaluated Maxwellian-averaged cross section (MACS) [23] (hereafter referred to as KADoNiS, which will be discussed further below) at $kT = 30 \text{ keV}$ as a function of atomic mass A . This is a typical neutron energy for the s process where capture cross sections are usually well-measured. Clearly, while there are some trends in Fig. 1(a), the cross sections range

over large factors with little correlation with mass and no clear route to extrapolation.

Figure 1(b) (based on Ref. [22]) shows the new perspective. Instead of plotting the cross sections against a variable that merely identifies the nuclei as in Fig. 1(a), we plot the cross section for each nucleus against another observable pertaining to that nucleus, namely the two-neutron separation energy, S_{2n} .

We note that, for capture on a nucleus with (Z, N) , leading to the nucleus $(Z, N + 1)$, we use the S_{2n} value for the separation of two neutrons from the nucleus $(Z, N + 2)$. In this way, the separation energy focuses on the average binding energy of the $(N + 1)$ th neutron that is actually captured. The choice of S_{2n} instead of S_n was dictated by the desire to avoid issues associated with varying spins and parities of the intermediate odd- N nucleus. The same choice of $(N + 2)$ will apply to odd-even nuclei discussed below. For capture on odd- N nuclei, that is, even-odd and odd-odd species, for the same reason, we will use $S_{2n}(N + 1)$.

The figure exhibits a striking correlation between masses and neutron capture cross sections as discussed in Ref. [22]. The figure also shows a function fitted (see below) to these data which describes the empirical trend very well. The compactness of the correlation provides a new method for predicting unmeasured capture cross sections, at a potentially higher level of accuracy than heretofore available, either by interpolation, where the uncertainty is largely determined by the scatter of the points, or by extrapolation where the accuracy is related to the appropriateness of the fitted function. In both contexts we note that separation energies are among the first observables that can be determined for newly studied nuclei and hence are often known for nuclei quite far from stability. Thus the correlation offers the opportunity to make predictions for neutron capture cross sections that are very difficult or impossible to measure.

The primary purpose of the present paper is to significantly extend this correlation to provide a unified set of results spanning a wide region of the medium mass and heavy elements and the important range of neutron energies from 5–100 keV. We describe this process in the next section. In Sec. IV we show the results. In Sec. V we discuss the results, and methods to predict unknown cross sections. We use these to make a large number of predictions for unknown cross sections, particularly by interpolation. Finally, we comment on the physics reasons behind the success of the correlation. We summarize the conclusions in Sec. VI.

III. METHODS AND RESULTS FOR THE 30 keV DATA

A. Data sources

The primary source for the neutron capture cross sections was the Karlsruhe Astrophysical Database of Nucleosynthesis in Stars (KADoNiS) [23]. This database provides recommended, experimentally based, Maxwellian-averaged neutron-capture cross sections over the range of $kT = 5\text{--}100 \text{ keV}$. While the majority of the data in KADoNiS is experimental, in some cases, where measurements are not available, KADoNiS provides “semiempirical estimates” by

normalizing theoretical calculations to nearby direct measurements. There are also some values provided strictly from theory.

We wanted our approach to be purely data driven, and hence we use only those data that come from direct measurement. We excluded those KADoNiS cross sections that were semiempirical estimates or purely theoretical values. This applies as well to the energy dependence of the cross sections. In some cases, there may be data at a single neutron energy, but the energy dependence in the KADoNiS database may have been derived from scaling theoretical calculations to the measured energy. In these cases, we have only included the measured value at 30 keV, but not those lower and higher energy data based on a model energy dependence.

Finally, note that KADoNiS does not provide neutron capture results above $A = 210$. For the actinides, we have taken values of the MACS at 30 keV obtained with the NucRates tool using the ENDF/B-VII.1 library [26,27]. It is important to note that ENDF is a full evaluation and incorporates both theory and experimental results, which is a deviation from the approach used in KADoNiS. In this work we only show those isotopes for which direct measurements exist and were included in the actinide values. The manner in which uncertainties are assigned in the ENDF framework does not translate well to this study. Instead, for this work, a coarse uncertainty of 10, 15, or 30% was assigned to the actinide cross sections based on the number of measurements and the experimental reliability.

Two-neutron separation energy values (S_{2n}) were all taken from the 2016 Atomic Mass Evaluation (AME2016) [24,25]. As with KADoNiS, the AME2016 mass tabulations also sometimes use estimated or extrapolated values. We did not use them, relying solely on directly measured and evaluated values. Because the mass uncertainties are small relative to S_{2n} values, we do not report them and did not include them in our analysis.

All cross sections, uncertainties, and S_{2n} data used in this work are listed in the Appendix.

B. Exponential fit to the 30 keV rare earth data

To formalize the quality of the correlation and to facilitate later predictions, the data for the 30 keV MACS for the even-even rare earth deformed nuclei in Fig. 1(b) were fit to an exponential function of the form

$$\sigma_{\text{fit}} = p_0 e^{p_1 S_{2n}}. \quad (1)$$

This functional form was chosen because of its close connection to most estimates of the level density and the likely connection between S_{2n} and level densities (see discussion in Sec. V). The least-squares fit of p_0 and p_1 values included weights based on experimental cross section uncertainties. The coefficients $p_{0,1}$ are highly correlated and hence the true uncertainties were obtained by a covariance analysis. Since the system is overconstrained, the fit uncertainties in the predicted cross sections are exceptionally small—typically 1–2%. Of course, the quality of the correlation, in the end, is determined by the empirical scatter of the data. To assess this, we show the residuals from the fit in the bottom panel

FIG. 2. Comparison of the exponential fit function from Fig. 1(b) (solid/blue) and the power law fit function used in Ref. [22] (dashed/green). The choice between the two for low S_{2n} values can be decided by a small number of new neutron capture measurements in the region of $S_{2n} = 8$ –10 MeV.

of Fig. 1(b), most of which are within 25% of the curve. While this is a remarkably small spread, it is much larger than the formal fit function uncertainty; the fit uncertainty does not capture the physics driving the variations. Hence, to reflect the true uncertainty, we use the residuals to assess the uncertainties in predicted cross sections below rather than the formal fit uncertainties.

We note briefly that, in Ref. [22], we used a power law fit function while the present work uses an exponential. The two functions are almost identical over most of the S_{2n} range in the figures but do deviate slightly at the highest and, especially, the lowest S_{2n} ranges. For $A > 100$, these low S_{2n} values correspond to weakly bound, neutron-rich nuclei off stability well into the r -process region. In Fig. 2, we compare the fit functions. The deviation at, say 9 MeV, has grown to approximately a factor of 2. While this is of concern for accurate cross section estimates, even such an uncertainty is small compared to those from statistical model approaches. As noted, in this paper we use the exponential form. We stress that even a few neutron capture measurements for S_{2n} values in the region 8–10 MeV would help distinguish between the two (or other) extrapolations.

IV. EXTENDING THE RESULTS—OTHER REGIONS, EXTENDED NEUTRON ENERGY RANGE

A. Other mass regions—30 keV data

In Ref. [22], we noted briefly that there was a tight correlation between S_{2n} and neutron capture cross sections in four other classes of nuclei (above $A \approx 110$) but the correlations differed from those for the rare earth region. Further study that we report here has revealed that there is a closer correspondence between different regions than heretofore recognized. In particular, to reasonable accuracy, the 30 keV data for these four additional regions can be brought into close correspon-

TABLE I. Table of parameters of the fits. Values fit for a particular class are indicated in bold. The fit uncertainties in p_0 and p_1 are 0.0005 and 0.003, respectively. The reader is reminded that the fit parameters are highly correlated and the fit uncertainties are not representative of the predicted cross section uncertainties. For details, see Sec. III B.

Region	Z - N	p_0 (mb)	p_1	p_2 (MeV)
Rare earth	even-even	1.06×10^{-2}	0.764	—
	even-odd	1.06×10^{-2}	0.764	$+1.04 \pm <.01$
	odd-even	1.06×10^{-2}	0.764	$+1.74 \pm <.01$
Te-Xe-Ba	even-even	1.06×10^{-2}	0.764	$-3.27 \pm <.01$
Ce-Nd-Hg	even-even	1.06×10^{-2}	0.764	-1.92 ± 0.02
Pt-Os	even-even	1.06×10^{-2}	0.764	-0.56 ± 0.03
Actinides	even-even	1.06×10^{-2}	0.764	$+2.96 \pm 0.07$

dence to the even-even rare earth data of Fig. 1, by introducing a single constant shift in S_{2n} for each region. Hence, Eq. (1) was modified to

$$\sigma_{\text{fit}} = p_0 e^{p_1(S_{2n} + p_2)}, \quad (2)$$

where $p_{0,1}$ were kept fixed from the original fit of the even-even rare earth nuclei and only the term p_2 , which shifts the effective S_{2n} , was fit for each region. Moreover, we have now also found that two other important regions can be similarly accommodated. We will discuss the rationale for these shifts below. Here, we treat them as empirical findings.

For each class, the shifts were obtained by a least squares fit to optimize the agreement of the shifted data with the exponential fit function discussed above. Again, each class was an overconstrained system, with shift uncertainties primarily signifying the uncertainties in the cross-section measurements. Typical shift uncertainties were in the range of 20 keV or less, with the actinides being somewhat larger. The impact of these uncertainties on predicted cross sections is again at the $\approx 1\%$ level, which is substantially less than the scatter in the data.

The five classes of nuclei previously considered are the even-even deformed rare earth nuclei, the even-even γ -soft Pt and Os nuclei, the even-even Te-Xe-Ba nuclei that are transitional from spherical to near γ -soft, the even-even spherical Ce, Nd, and Hg nuclei, and the even-odd deformed rare earth nuclei. The new classes comprise the even-even actinide nuclei and the odd-even deformed rare earth nuclei. The shifts for all seven classes are given in Table I. Together these comprise five regions with seven classes of nuclei starting around $A \approx 110$ and ranging to the actinides. The result for a region of odd-Z nuclei is particularly noteworthy for two reasons: it represents the first successful connection between S_{2n} and the capture cross sections for odd-Z nuclei, which is essential for addressing predictions for nuclear astrophysics, and, by giving the first shift for odd-Z nuclei, it expands the reach of an important extension of these results to nuclei with unknown neutron capture cross sections (see below). The resulting correlation for 97 nuclei covering seven classes listed in Table I is shown in Fig. 3. We stress that the fit function shown in Fig. 3 is the same as that used for the even-even rare nuclei in

FIG. 3. Shown above are the same 33 even-even, deformed rare earth nuclei together with six other classes. The fit function is the same as in Fig. 1 determined for the original group of 33 deformed rare earth nuclei. As before, for capture on even- N nuclei, we used $S_{2n}(N + 2)$; for capture on odd- N nuclei we used $S_{2n}(N + 1)$, see text. For each class, a single S_{2n} offset has been introduced to the data, where a negative value ($p_2 < 0$) means the actual S_{2n} was reduced to plot on the figure. The shifts are listed in Table I.

Fig. 1. Thus the data for all these nuclei can be brought into concordance using a single shift constant for each class.

B. Energy dependence

Finally, we now extend the analysis to include a range of neutron energies. From the KADoNiS database we have cross section data for the neutron energies 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, and 100 keV. For each region, the energy dependence of the cross sections was fit by an empirical curve. Using that curve, the data can be normalized to their effective cross section at 30 keV. Not surprisingly the energy dependence found is extremely close to a simple $1/v$ dependence. The dependence differs very slightly from region to region, except for nondeformed nuclei where they deviate somewhat more at neutron energies close to 100 keV. To bring all the data into a single correlation plot we apply a single normalization of the form

$$\sigma_{30} = \sigma_{E_n} c_0 (E_n)^{c_1}, \quad (3)$$

where E_n is the Maxwell-Boltzmann average energy in keV and c_0 and c_1 were fit to the rare-earth even-even data to give $c_0 = 0.154$ and $c_1 = 0.552$. Note that the corresponding exponent c_1 for a $1/v$ dependence would be 0.50.

Figure 4 now combines all the data for the five mass regions, seven classes of nuclei, and 11 neutron energy distributions from 5–100 keV. This represents over 700 cross-section values, from different nuclear structure regions, masses ranging from $A \approx 110$ –240 across the chart of nuclides, exhibiting a simple, analytic connection to nuclear binding energy. There are two remarkable features.

One is simply that the combined data all lie on a reasonably compact trajectory. The other is that the fit function is again

FIG. 4. The figure shows the principal result of this study, the S_{2n} —neutron cross section correlation for all five mass regions, seven classes, and the 11 neutron energy distributions from 5 to 100 keV, about 700 data points in total. The fit function is the same as for the original 33 deformed rare earth nuclei at 30 keV in Fig. 1. The cross section σ_{30} is the energy-corrected, 30 keV equivalent MACS, as defined in Eq. (3). The 30 keV values are in filled, black symbols while the energy-corrected values are in orange, open symbols. In the upper panel, the cross sections are shown on a linear scale while the lower panel shows the same data, over the identical value range, on a logarithmic scale. The two plots give complementary perspectives on the quality of agreement, especially at high and low cross sections and S_{2n} values.

the same exponential as that originally used in Fig. 1. That is, the correlation, with 700 data points, covering 97 nuclei, comprising the energy-and-region-combined data, is closely matched by the same exponential as was used for the 33 data points for the even-even deformed rare earth nuclei at neutron energy of 30 keV in Fig. 1(b).

V. DISCUSSION

A. Physics underpinning the correlation

Although the choice of viewing cross sections versus S_{2n} is simply because it works, it is not without some rationale. That is, why does such a simple ansatz work at all? First, it is well known that the evolution of S_{2n} is well correlated with other properties of nuclei, such as ratios of certain energy

levels or transition rates because it is, in general, correlated with structural changes in nuclei.

More directly relevant to the present subject, elements of the answer recognize that neutron capture in heavy nuclei depends on the overlap of the neutron plus target with the capture state and on the electromagnetic matrix elements connecting the state to lower lying states. Larger S_{2n} values correspond to higher capture state energies, where the level density is higher, thereby increasing both the number of accessible capture states and the decay phase space, and thus the cross sections.

The same perspective makes it easy to provide a qualitative interpretation of the S_{2n} shifts in terms of different level densities at the capture state energy. For example, if the even-even actinide nuclei, for which the level density at the capture state is very high (higher degeneracy of shell model configurations), are plotted at a higher effective S_{2n} they lie close to the rare earth correlation in Fig. 1(b). Likewise, if we also plot the data for the even-odd deformed nuclei (which have higher level density at a given excitation energy due to the absence of one pairing interaction), at a higher effective S_{2n} the correlation again coincides closely with the even-even rare earth nuclei. As a last example, for spherical nuclei with lower level densities at a given S_{2n} than deformed nuclei, a decrease in effective S_{2n} brings these data into better alignment with the deformed rare earth region. This offers an intuitive rationale for the shifts introduced for each region.

B. Predictions of unknown cross sections

There are a number of implications of the extended correlation, some of considerable importance for r -process astrophysics. Some of these were pointed out in the restricted context of Ref. [22] as well but now apply to a much broader set of cross section data. In discussing these we note that reaction networks of neutron capture cross sections usually require input for all Z values including many even-even, even-odd, odd-even, and odd-odd nuclei with unknown cross sections. Even though the data for odd- A nuclei are very limited, we will see that they do allow a wide range of predictions.

1. Predictions by interpolation

Since S_{2n} is determined from the nuclear mass, there is already a wealth of reliable S_{2n} data, extending to N and Z ranges far beyond known capture cross sections. These allow cross section estimates over a wider range of nuclei than can be measured. Especially intriguing is that it often happens that the S_{2n} values for nuclei with unknown neutron cross sections are within the range of known values in Figs. 1(b), 3, and 4. Therefore, new cross section estimates can often be made by the more reliable process of interpolation than extrapolation.

To make this statement concrete and to provide a set of specific predictions we have surveyed all even-even, even-odd, odd-even, and odd-odd nuclei in the five regions comprised in Figs. 1, 3, and 4 for all nuclei whose shifted S_{2n} values fall between 10 MeV and 16 MeV.

For each region we took the empirical S_{2n} values and their shifts as given in Table I. The establishment of shifts for odd- N and odd- Z nuclei (see above) gives at least a plausible approach to regions of nuclei devoid of any cross section data.

Since the shifts for odd- N and for odd- Z nuclei reflect the physics of pairing, we can assume that similar shifts apply to other regions of odd- N or odd- Z relative to the even-even nuclei in each region. For the former, we simply use the shifts established for the rare earth region of 1.04 MeV and for the latter we use a shift of 1.74 MeV found for the odd- Z rare earth region. Finally, for odd-odd nuclei we use the sum of these shifts, namely $1.04 + 1.74 = 2.78$ MeV for odd-odd nuclei. Of course, for unknown regions, the uncertainty in the shifts may be quite large, but, even if one allows uncertainties of several hundred keV, the accuracy in predicted cross sections from the S_{2n} correlation should be superior to existing theoretical methods.

The results are shown in Table II. In all, in this way, we have estimated the cross sections, at a Maxwellian neutron energy distribution of 30 keV, solely by interpolation, for 212 nuclei with currently unknown cross sections. Predictions for other neutron energies can be made by using the energy dependence function discussed in Sec. IV B.

Figure 5 gives an impression of the locus and range of these nuclei with colored boxes for those nuclei given in Table II whose cross sections can be predicted by interpolation using solely the fit function of Fig. 1(b).

It is possible to test these estimated shifts in a few cases. Despite the relative scarcity of neutron capture data on odd- Z nuclei, neutron capture cross sections at 30 keV are known for $^{127,129}\text{I}$ and $^{133,135}\text{Cs}$, which lie in the Te-Xe-Ba region, and ^{154}Eu and ^{176}Lu , which lie in the rare earth region. For I and Cs, for example, we applied the shifts for odd- Z (an effective S_{2n} increase) and for the Te-Xe-Ba region (an effective S_{2n} decrease). As can be seen in Fig. 6, which repeats Fig. 3 with these data superposed with large symbols, the cross sections are in reasonable agreement with the correlation and with the fit function. A similar result is observed in the figure for ^{154}Eu and ^{176}Lu , where both of the shifts effectively increase S_{2n} . This lends confidence to predictions in the region of interpolation.

The nuclei in Table II have already known S_{2n} values with effective S_{2n} lying between 10 and 16 MeV. For some applications involving nuclei further from stability, the S_{2n} values may not be currently known. However, new measurements of S_{2n} values in exotic nuclei are typically far easier than a neutron capture measurement. Indeed, in nuclei very far from stability, new S_{2n} values will often be among the first quantities measured. Whether the masses of new nuclei are measured directly or via the energetics of the reactions used to produce them, the deduced S_{2n} values will often have accuracies <100 keV. This will be more than adequate for estimating neutron capture cross sections using the correlation we have developed.

2. Predictions using extrapolation

Of course, not all S_{2n} values for nuclei of importance with unknown cross sections lie within the interpolation region. In such cases, extrapolation is required. The accuracy then depends not only on the shifts but on the (unknown) quality of the exponential fit function outside the region from 10 to 16 MeV. Indeed, it may happen that a different functional form

TABLE II. For nuclei with effective S_{2n} values between 10 and 16 MeV whose cross sections are unknown, estimated cross sections at $kT = 30$ keV are listed using the fit function in Eq. (2) and the shift values in Table I. An uncertainty of 25% should be assigned to all predictions based on the cross section reproduction for other nuclei with a similar effective S_{2n} .

Isotope	Z	N	σ_{MACS} (Prediction)
Rare earth region			
^{149}Nd	60	89	311
^{151}Nd	60	91	361
^{152}Nd	60	92	89
^{153}Nd	60	93	197
^{154}Nd	60	94	41
^{155}Nd	60	95	90
^{151}Pm	61	90	1133
^{153}Pm	61	92	540
^{154}Pm	61	93	1196
^{155}Pm	61	94	264
^{156}Pm	61	95	585
^{157}Pm	61	96	114
^{158}Pm	61	97	193
^{151}Sm	62	89	934
^{153}Sm	62	91	921
^{155}Sm	62	93	504
^{156}Sm	62	94	105
^{157}Sm	62	95	232
^{158}Sm	62	96	52
^{159}Sm	62	97	116
^{157}Eu	63	94	675
^{158}Eu	63	95	1495
^{159}Eu	63	96	356
^{160}Eu	63	97	789
^{161}Eu	63	98	159
^{162}Eu	63	99	269
^{159}Gd	64	95	657
^{161}Gd	64	97	327
^{161}Tb	65	96	1028
^{158}Dy	66	92	1383
^{165}Dy	66	99	405
^{166}Dy	66	100	112
^{167}Dy	66	101	248
^{167}Ho	67	100	641
^{168}Ho	67	101	1419
^{169}Ho	67	102	349
^{170}Ho	67	103	590
^{169}Er	68	101	593
^{171}Er	68	103	336
^{171}Tm	69	102	960
^{172}Tm	69	103	2127
^{173}Tm	69	104	450
^{174}Tm	69	105	997
^{175}Yb	70	105	383
^{177}Yb	70	107	295
^{177}Lu	71	106	723
^{178}Lu	71	107	1602
^{179}Lu	71	108	354
^{180}Lu	71	109	783
^{181}Lu	71	110	189
^{182}Lu	71	111	418

TABLE II. (*Continued.*)

Isotope	Z	N	σ_{MACS} (Prediction)
¹⁷² Hf	72	100	1583
¹⁷⁵ Hf	72	103	2037
¹⁸¹ Hf	72	109	310
¹⁸³ Hf	72	111	166
¹⁸⁴ Hf	72	112	50
¹⁸⁵ Hf	72	113	111
¹⁷⁹ Ta	73	106	2119
¹⁸¹ Ta	73	108	830
¹⁸² Ta	73	109	1838
¹⁸³ Ta	73	110	467
¹⁸⁴ Ta	73	111	789
¹⁸⁵ Ta	73	112	295
¹⁸⁶ Ta	73	113	499
¹⁷⁶ W	74	102	2027
¹⁷⁸ W	74	104	1345
¹⁸¹ W	74	107	1856
¹⁸⁷ W	74	113	285
¹⁸⁸ W	74	114	92
¹⁸⁹ W	74	115	203
Te-Xe-Ba region			
¹¹⁶ Te	52	64	1272
¹¹⁸ Te	52	66	714
¹¹⁹ Te	52	67	1581
¹²¹ Te	52	69	908
¹²³ Te	52	71	518
¹²⁵ Te	52	73	310
¹²⁷ Te	52	75	194
¹²⁹ Te	52	77	126
¹³¹ Te	52	79	84
¹³² Te	52	80	26
¹²³ I	53	70	1492
¹²⁵ I	53	72	843
¹²⁶ I	53	73	1867
¹²⁷ I	53	74	523
¹²⁸ I	53	75	1159
¹²⁹ I	53	76	334
¹³⁰ I	53	77	740
¹³¹ I	53	78	224
¹³² I	53	79	497
¹³³ I	53	80	154
¹²² Xe	54	68	1160
¹²⁵ Xe	54	71	1372
¹²⁷ Xe	54	73	760
¹²⁹ Xe	54	75	447
¹³¹ Xe	54	77	278
¹³³ Xe	54	79	183
¹²⁷ Cs	55	72	1973
¹²⁹ Cs	55	74	1156
¹³¹ Cs	55	76	761
¹³² Cs	55	77	1685
¹³³ Cs	55	78	518
¹³⁴ Cs	55	79	1148
¹³⁵ Cs	55	80	341
¹²⁶ Ba	56	70	1577

TABLE II. (*Continued.*)

Isotope	Z	N	σ_{MACS} (Prediction)
¹²⁸ Ba	56	72	839
¹²⁹ Ba	56	73	1859
¹³¹ Ba	56	75	1080
¹³³ Ba	56	77	653
¹³⁵ Ba	56	79	420
Ce-Nd-Hg region			
¹⁴³ Ce	58	85	54
¹⁴⁵ Ce	58	87	32
¹⁴³ Pr	59	84	153
¹⁴⁴ Pr	59	85	338
¹⁴⁵ Pr	59	86	87
¹⁴⁶ Pr	59	87	192
¹⁴⁵ Nd	60	85	143
¹⁴⁶ Nd	60	86	38
¹⁴⁷ Nd	60	87	84
¹⁸⁸ Hg	80	108	1367
¹⁹⁰ Hg	80	110	913
¹⁹¹ Hg	80	111	2022
¹⁹² Hg	80	112	638
¹⁹³ Hg	80	113	1414
¹⁹⁴ Hg	80	114	425
¹⁹⁵ Hg	80	115	942
¹⁹⁷ Hg	80	117	636
¹⁹⁹ Hg	80	119	409
²⁰¹ Hg	80	121	238
²⁰³ Hg	80	123	163
Pt-Os region			
¹⁸⁰ Os	76	104	1921
¹⁸² Os	76	106	1207
¹⁸⁵ Os	76	109	1348
¹⁸⁷ Os	76	111	846
¹⁸⁹ Os	76	113	548
¹⁹¹ Os	76	115	405
¹⁹³ Os	76	117	252
¹⁹⁴ Os	76	118	66
¹⁹⁵ Os	76	119	146
¹⁸⁹ Ir	77	112	1587
¹⁹¹ Ir	77	114	1141
¹⁹³ Ir	77	116	683
¹⁹⁴ Ir	77	117	1513
¹⁹⁵ Ir	77	118	437
¹⁹⁶ Ir	77	119	968
¹⁹⁷ Ir	77	120	313
¹⁹⁸ Ir	77	121	693
¹⁸⁶ Pt	78	108	1533
¹⁸⁸ Pt	78	110	1070
¹⁹¹ Pt	78	113	1613
¹⁹² Pt	78	114	493
¹⁹³ Pt	78	115	1092
¹⁹⁴ Pt	78	116	315
¹⁹⁵ Pt	78	117	697
¹⁹⁷ Pt	78	119	432
¹⁹⁹ Pt	78	121	281
²⁰⁰ Pt	78	122	80

TABLE II. (Continued.)

Isotope	Z	N	σ_{MACS} (Prediction)
²⁰¹ Pt	78	123	177
Actinides			
²²⁴ Rn	86	138	188
²²⁵ Rn	86	139	416
²²⁶ Rn	86	140	162
²²⁷ Rn	86	141	359
²²² Ra	88	134	742
²²³ Ra	88	135	1644
²²⁴ Ra	88	136	574
²²⁵ Ra	88	137	1271
²²⁶ Ra	88	138	413
²²⁷ Ra	88	139	915
²²⁸ Ra	88	140	327
²²⁹ Ra	88	141	725
²³⁰ Ra	88	142	240
²³¹ Ra	88	143	532
²³² Ra	88	144	170
²³³ Ra	88	145	377
²²⁹ Ac	89	140	1823
²³¹ Ac	89	142	1270
²³³ Ac	89	144	864
²³⁴ Ac	89	145	1914
²²⁴ Th	90	134	2008
²²⁶ Th	90	136	1514
²²⁸ Th	90	138	1019
²³⁰ Th	90	140	699
²³¹ Th	90	141	1548
²³³ Th	90	143	992
²³⁴ Th	90	144	311
²³⁵ Th	90	145	690
²³⁵ Pa	91	144	1605
²³² U	92	140	1558
²³⁵ U	92	143	1924
²³⁷ U	92	145	1251
²³⁹ U	92	147	825
²³⁹ Np	93	146	2003
²³⁶ Pu	94	142	1921
²³⁸ Pu	94	144	1124
²⁴¹ Pu	94	147	1540
²⁴³ Pu	94	149	1053
²⁴⁵ Pu	94	151	718
²⁴² Cm	96	146	1430
²⁴⁵ Cm	96	149	2133
²⁴⁷ Cm	96	151	1337
²⁴⁸ Cm	96	152	322
²⁴⁹ Cm	96	153	714
²⁴⁹ Bk	97	152	1439
²⁴⁶ Cf	98	148	2096
²⁴⁸ Cf	98	150	1150
²⁵⁰ Cf	98	152	564
²⁵¹ Cf	98	153	1250
²⁵² Cf	98	154	402
²⁵³ Cf	98	155	891
²⁵³ Es	99	154	1814

TABLE II. (Continued.)

Isotope	Z	N	σ_{MACS} (Prediction)
²⁵² Fm	100	152	1022
²⁵⁴ Fm	100	154	699
²⁵⁵ Fm	100	155	1548

will be preferred (such as the power law used in Ref. [22]). However, if only one or two neutron capture measurements can be made for nuclei with low S_{2n} values, it should be possible to better define the entire correlation down to such values. Such measurements, though difficult, might well be worth the effort.

3. Vetting the predictions for new regions

If a particular nucleus in an unstudied or poorly known region is of high significance, but particularly intractable experimentally, the correlation provides an alternate approach to estimating its neutron capture cross section that may be much easier. Less challenging measurements can be performed on a couple of neighboring nuclei to determine the correlation for that region, and the challenging cross section may then be inferred without the need for an extremely difficult or impossible measurement on that particular nucleus. For example, a few key accurate measurements of neutron capture cross sections in odd-even isotopes outside the rare earth region, even at a single neutron energy, would be valuable to refine their correlations and the assumed shifts and allow the prediction of numerous other cross sections.

FIG. 5. Chart of the nuclides from Te to Pb with colored boxes for the nuclei in Table II whose neutron capture cross sections can be estimated from Fig. 4 by interpolation using the fit function of Fig. 1(b). Table II also includes predictions for more than 50 actinide nuclei outside this range that are not shown above.

FIG. 6. Same as Fig. 3 except for the superposition of six nuclei (with large symbols) with known cross sections in regions where a specific shift had not been determined, but was rather extrapolated from the existing shifts. The quality of agreement is comparable to the nuclei fit in the study.

C. Caveat

A limitation of this approach is that the correlations fail below about mass $A \approx 110$. The likely reason is that these lighter nuclei have low level densities such that even Maxwellian averaged neutron capture reactions do not average over a sufficient number of levels (resonances) in the capture state region so that the resulting cross sections are dominated by one or a few resonances and show nonstatistical behavior.

VI. CONCLUSIONS

In the paper we have extended the neutron capture cross section versus S_{2n} correlation to a wider range of medium mass and heavy nuclei and to a range of neutron energies from 5–100 keV, important to the r process and to other applications. We have shown that a single compact correlation (well matched by a simple, physically motivated, exponential function) accommodates this wide array of data, and that the approach provides a way to predict unknown cross sections. In many cases these predictions can be made by interpolation where the expected accuracy is particularly high. In this vein, we provided detailed predictions for over 200 nuclei with currently unknown cross sections. An obvious further step is to use these cross section estimates to refine nucleosynthesis calculations of the r process.

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APPENDIX: DOCUMENTATION OF DATA SOURCES AND VALUES

We report the nuclei with their respective S_{2n} values and cross sections and associated uncertainties for the studies performed as part of this work in Tables III–X. The cross sections and uncertainties are taken from Refs. [23,26,27] while S_{2n} values are taken from Ref. [24].

TABLE III. Data from Refs. [23,24] for Te-Xe-Ba even-even transitional nuclei.

Te-Xe-Ba even-even (transitional $52 \leq Z \leq 56$, $50 \leq N \leq 82$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
^{120}Te	52	70	17089.11	–	–	–	–	–	538 ± 26	–	–	–	–	–
^{122}Te	52	72	16353.50	874	541	427	368	326	295 ± 3	255	230	214	193	180
^{124}Te	52	74	15682.66	477	289	226	195	171	155 ± 2	133	120	112	101	95
^{126}Te	52	76	15071.00	250	152	120	103	90	81.3 ± 1.4	70	62	57	51	48
^{128}Te	52	78	14501.87	91	70	59	52	48	44.4 ± 1.3	39	37	35	32	31
^{130}Te	52	80	13977.87	35	26	21	18	16	14.7 ± 2.8	13	12	11	9.6	9.1
^{124}Xe	54	72	17628.18	–	–	–	–	–	644 ± 83	–	–	–	–	–
^{126}Xe	54	74	16855.97	–	–	–	–	–	359 ± 51	–	–	–	–	–
^{128}Xe	54	76	16162.80	–	–	–	–	–	262.5 ± 3.7	–	–	–	–	–
^{130}Xe	54	78	15541.13	–	–	–	–	–	132 ± 2.1	–	–	–	–	–
^{132}Xe	54	80	14989.49	167	119	95.4	82.5	71.6	64.6 ± 5.3	54.7	49.7	45.7	40.8	37.8
^{134}Xe	54	82	14445.97	–	–	–	–	–	20.2 ± 1.7	–	–	–	–	–
^{130}Ba	56	76	17316.11	–	–	–	–	–	746 ± 34	–	–	–	–	–
^{132}Ba	56	78	16657.47	–	–	–	–	–	397 ± 16	–	–	–	–	–
^{134}Ba	56	80	16079.70	360	283	235	208	190	176 ± 5.6	155	141	131	117	108
^{136}Ba	56	82	15517.35	180	115	90.4	76.9	67.8	61.2 ± 2	52.5	46.2	43.8	39.3	36.7

TABLE IV. Data from Refs. [23,24] for rare-earth, even-even nuclei.

Rare earth even-even (deformed $60 \leq Z \leq 74$, $88 \leq N \leq 112$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹⁴⁸ Nd	60	88	12414.39	414	266	209	177	159	147 ± 2	130	120	113	101	93
¹⁵⁰ Nd	60	90	12612.29	591	353	261	212	181	159 ± 10	143	113	101	86	77
¹⁵⁰ Sm	62	88	13854.10	1176	742	587	505	455	422 ± 4	380	355	337	312	29
¹⁵² Sm	62	90	13835.21	1249	863	687	581	519	473 ± 4	410	365	331	283	25
¹⁵⁴ Sm	62	92	13047.89	561	395	315	265	232	206 ± 9	171	148	131	109	96
¹⁵² Gd	64	88	15141.67	3275	1951	1507	1280	1142	1049 ± 17	933	864	818	756	71
¹⁵⁴ Gd	64	90	14971.59	2801	1863	1477	1258	1124	1028 ± 12	898	810	745	653	59
¹⁵⁶ Gd	64	92	14297.27	1629	1117	892	760	677	615 ± 5	528	468	424	364	32
¹⁵⁸ Gd	64	94	13394.83	842	595	479	408	360	324 ± 3	272	236	209	174	15
¹⁶⁰ Gd	64	96	12481.29	546	310	243	203	175	154 ± 20	126	107	93	80	66
¹⁵⁶ Dy	66	90	16021.02	—	—	—	—	—	1607 ± 92	—	—	—	—	—
¹⁶⁰ Dy	66	94	14651.38	2267	1578	1271	1096	978	890 ± 12	764	677	613	524	46
¹⁶² Dy	66	96	13929.12	1129	796	641	553	492	446 ± 4	379	332	297	250	21
¹⁶⁴ Dy	66	98	12759.46	592	405	320	271	237	212 ± 3	175	151	133	109	93
¹⁶² Er	68	94	15751.00	—	—	—	—	—	1624 ± 124	—	—	—	—	—
¹⁶⁴ Er	68	96	15125.79	—	—	—	—	—	1084 ± 51	—	—	—	—	—
¹⁶⁶ Er	68	98	14207.76	1304	970	802	695	620	563 ± 56	481	426	385	332	29
¹⁶⁸ Er	68	100	13260.14	790	594	490	422	374	338 ± 44	285	250	223	188	16
¹⁷⁰ Er	68	102	12517.57	600	374	280	228	194	170 ± 7	138	117	103	85.4	75
¹⁶⁸ Yb	70	98	15324.65	—	—	—	—	—	1214 ± 49	—	—	—	—	—
¹⁷⁰ Yb	70	100	14634.16	1863	1322	1077	936	840	768 ± 7	665	592	539	464	41
¹⁷² Yb	70	102	13831.70	827	599	488	423	377	341 ± 3	290	254	227	190	16
¹⁷⁴ Yb	70	104	12689.44	374	271	220	190	168	151 ± 1.7	125	108	95	78	67
¹⁷⁶ Yb	70	106	12346.79	295	213	172	147	129	116 ± 2	96	82	72	58	50
¹⁷⁴ Hf	72	102	14874.47	—	—	—	—	—	983 ± 46	—	—	—	—	—
¹⁷⁶ Hf	72	104	14001.55	—	1111	892	769	686	626 ± 11	539	480	471	380	34
¹⁷⁸ Hf	72	106	13486.75	—	556	447	388	348	319 ± 3	276	246	223	191	16
¹⁸⁰ Hf	72	108	12412.79	—	263	218	191	172	157 ± 2	134	118	105	88	76
¹⁸² Hf	72	110	11592.50	—	—	—	—	—	141 ± 8	—	—	—	—	—
¹⁸⁰ W	74	106	14752.58	—	—	—	—	—	660 ± 53	—	—	—	—	—
¹⁸² W	74	108	13601.95	637	459	379	331	298	274 ± 8	239	215	197	173	15
¹⁸⁴ W	74	110	12945.79	—	—	—	—	—	223 ± 5	—	—	—	—	—
¹⁸⁶ W	74	112	12301.92	—	—	—	—	—	235 ± 9	—	—	—	—	—

TABLE V. Data from Refs. [23,24] for rare-earth, even-odd nuclei.

Rare earth even-odd (deformed $60 \leq Z \leq 74$, $88 \leq N \leq 112$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹⁵⁵ Gd	64	91	14971.59	7264	5030	3980	3347	2943	2648 ± 30	2233	1948	1738	1441	1238
¹⁵⁷ Gd	64	93	14297.27	4251	2803	2163	1791	1547	1369 ± 15	1123	959	841	683	580
¹⁶¹ Dy	66	95	14651.38	5710	3891	3051	2554	2214	1964 ± 19	1615	1380	1210	977	825
¹⁶³ Dy	66	97	13929.12	3178	2132	1671	1412	1238	1112 ± 11	936	817	729	606	522
¹⁶⁷ Er	68	99	14207.76	4457	2817	2192	1824	1588	1425 ± 143	1217	1097	1021	933	885
¹⁷¹ Yb	70	101	14634.16	3052	2183	1757	1509	1339	1210 ± 12	1024	893	795	657	565
¹⁷³ Yb	70	103	13831.70	2192	1456	1139	960	841	754 ± 7	633	552	492	410	355
¹⁷⁷ Hf	72	105	14001.55	—	2849	2249	1916	1699	1544 ± 12	1335	1199	1101	965	873
¹⁷⁹ Hf	72	107	13486.75	—	1753	1365	1154	1018	922 ± 8	793	706	642	550	485
¹⁸³ W	74	109	13601.95	1594	1030	797	665	578	515 ± 15	430	374	333	277	242
¹⁸⁵ W	74	111	12945.79	—	—	—	—	—	584 ± 53	—	—	—	—	—

TABLE VI. Data from Refs. [23,24] for rare-earth, odd-even nuclei.

Rare earth odd-even (deformed $60 \leq Z \leq 74$, $88 \leq N \leq 112$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹⁵¹ Eu	63	88	14857.00	11644	7235	5475	4509	3900	3478 ± 77	2933	2593	2354	2035	1806
¹⁵³ Eu	63	90	14593.50	7110	4633	3682	3156	2809	2556 ± 46	2196	1946	1754	1483	1287
¹⁵⁵ Eu	63	92	13783.45	—	—	—	—	—	1320 ± 84	—	—	—	—	—
¹⁵⁹ Tb	65	94	14071.86	4365	2930	2330	2010	1750	1580 ± 150	1340	1185	1070	910	800
¹⁶³ Ho	67	96	14663.30	—	—	—	—	—	2125 ± 95	—	—	—	—	—
¹⁶⁵ Ho	67	98	13524.25	3301	2316	1867	1598	1416	1280 ± 100	1092	967	877	761	692
¹⁶⁹ Tm	69	100	14077.72	3381	2200	1711	1436	1257	1129 ± 56	956	845	769	668	610
¹⁷⁵ Lu	71	104	13360.86	—	2309	1802	1525	1346	1219 ± 10	1043	924	834	701	604
¹⁸¹ Ta	73	108	12997.12	2765	1633	1221	1002	863	766 ± 15	639	557	500	423	374

TABLE VII. Data from Refs. [23,24] for Pt-Os γ -soft, even-even nuclei.

Pt-Os region (γ -soft $76 \leq Z \leq 78$, $104 \leq N \leq 124$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹⁸⁴ Os	76	108	14890.00	—	—	—	—	—	590 ± 39	—	—	—	—	—
¹⁸⁶ Os	76	110	14279.90	1106	683	544	476	437	410 ± 17	374	347	325	292	268
¹⁸⁸ Os	76	112	13713.20	762	462	372	331	308	293 ± 14	272	257	243	221	202.6
¹⁹⁰ Os	76	114	13317.10	—	—	—	—	—	274 ± 12	—	—	—	—	—
¹⁹² Os	76	116	12695.60	—	—	—	—	—	155 ± 7	—	—	—	—	—
¹⁹⁰ Pt	78	112	15124.60	—	—	—	—	—	508 ± 44	—	—	—	—	—
¹⁹⁶ Pt	78	118	13402.10	—	—	—	—	—	183 ± 16	—	—	—	—	—
¹⁹⁸ Pt	78	120	12837.80	—	—	—	—	—	92.2 ± 4.6	—	—	—	—	—

TABLE VIII. Data from Refs. [23,24] for Ce-Nd-Hg spherical, even-even nuclei.

Ce, Nd, Hg even-even (spherical)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹⁴² Ce	58	84	12041.32	—	—	—	—	—	28 ± 1	—	—	—	—	—
¹⁴⁴ Nd	60	84	13320.53	239	147	115	98.9	88.5	81.3 ± 1.5	71.2	64.7	60.3	54.2	50.4
¹⁹⁶ Hg	80	116	15271.00	—	—	—	—	—	204 ± 8	—	—	—	—	—
¹⁹⁸ Hg	80	118	14691.59	588	318	240	205	186	173 ± 15	159	150	145	139	135
²⁰⁰ Hg	80	120	13984.69	324	198	155	135	123	115 ± 12	106	99	94	86	80
²⁰² Hg	80	122	13487.46	—	—	—	—	—	63.2 ± 1.9	—	—	—	—	—
²⁰⁴ Hg	80	124	12398.29	—	—	—	—	—	42 ± 4	—	—	—	—	—

TABLE IX. Data from Refs. [24,26,27] for actinide, even-even nuclei. While energy dependent cross sections can be calculated with ENDF/B-VII.1 and the NucRates, because the evaluation process is different than for KADoNiS, they were not used for comparison and are not reported here.

Actinide even-even (prolate deformed $82 \leq 126$, $126 \leq N$)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
²³² Th	90	142	10976.41	–	–	–	–	–	487 ± 49	–	–	–	–	–
²³⁴ U	92	142	11843.02	–	–	–	–	–	566 ± 170	–	–	–	–	–
²³⁶ U	92	144	11279.50	–	–	–	–	–	551 ± 83	–	–	–	–	–
²³⁸ U	92	146	10734.91	–	–	–	–	–	400 ± 40	–	–	–	–	–
²⁴⁰ Pu	94	146	11551.08	–	–	–	–	–	693 ± 104	–	–	–	–	–
²⁴² Pu	94	148	11053.54	–	–	–	–	–	534 ± 80	–	–	–	–	–
²⁴⁴ Cm	96	148	11977.56	–	–	–	–	–	774 ± 232	–	–	–	–	–
²⁴⁶ Cm	96	150	11366.85	–	–	–	–	–	463 ± 139	–	–	–	–	–

TABLE X. Data from Refs. [23,24] for I, Cs, Eu, and Lu isotopes which were compared to predictions.

Cross sections for predicted isotopes (see Discussion in Sec. V B 1)														
Isotope	Z	N	$S_{2n}(N+2)$	σ_{MACS} (mb)										
			(MeV)	5 keV	10 keV	15 keV	20 keV	25 keV	$kT = 30$ keV	40 keV	50 keV	60 keV	80 keV	100 keV
¹²⁷ I	53	74	15665.85	–	–	–	–	–	635 ± 3	–	–	–	–	–
¹²⁹ I	53	76	15078.22	–	–	–	–	–	441 ± 2	–	–	–	–	–
¹³³ Cs	55	78	15653.35	–	–	–	–	–	509 ± 2	–	–	–	–	–
¹³⁵ Cs	55	80	15106.60	–	–	–	–	–	160 ± 1	–	–	–	–	–
¹⁵⁴ Eu	63	91	14593.50	–	–	–	–	–	4420 ± 670	–	–	–	–	–
¹⁷⁶ Lu	71	105	13360.86	–	–	–	–	–	1639 ± 14	–	–	–	–	–

- [1] A. S. Eddington, *The Observatory* **43**, 341 (1920).
- [2] A. G. W. Cameron, *Annu. Rev. Nucl. Part. Sci.* **8**, 299 (1958).
- [3] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957).
- [4] J. J. Cowan and W. K. Rose, *Astrophys. J.* **212**, 149 (1977).
- [5] 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).
- [6] M. R. Mumpower, R. Surman, G. C. McLaughlin, and A. Aprahamian, *Prog. Part. Nucl. Phys.* **86**, 86 (2016).
- [7] K.-L. Kratz, J.-P. Bitouzet, F.-K. Thielemann, P. Moeller, and B. Pfeiffer, *Astrophys. J.* **403**, 216 (1993).
- [8] K. Farouqi, K. Kratz, B. Pfeiffer, T. Rauscher, F. Thielemann, and J. W. Truran, *Astrophys. J.* **712**, 1359 (2010).
- [9] R. Surman, J. Beun, G. C. McLaughlin, and W. R. Hix, *Phys. Rev. C* **79**, 045809 (2009).
- [10] M. R. Mumpower, G. C. McLaughlin, and R. Surman, *Phys. Rev. C* **86**, 035803 (2012).
- [11] S. N. Liddick, A. Spyrou, B. P. Crider, F. Naqvi, A. C. Larsen, M. Guttormsen, M. Mumpower, R. Surman, G. Perdikakis, D. L. Bleuel *et al.*, *Phys. Rev. Lett.* **116**, 242502 (2016).
- [12] M. Salvatores, G. Aliberti, M. Dunn, A. Hogenbirk, A. Ignatyuk, I. Ishikawa, I. Kodeli, A. J. Koning, R. McKnight, R. W. Mills *et al.*, Technical Report, OECD-NEA (2008), <https://www.oecd-neo.org/science/wpec/volume26/volume26.pdf>.
- [13] G. Aliberti, G. Palmiotti, M. Salvatores, T. K. Kim, T. A. Taiwo, M. Animescu, I. Kodeli, E. Sartori, J. C. Bosq, and J. Tommasi, *Ann. Nucl. Energy* **33**, 700 (2006).
- [14] The Committee on the Assessment of and Outlook for Nuclear Physics; Board on Physics and Astronomy, Division on Engineering and Physical Sciences, National Research Council, *Nuclear Physics: Exploring the Heart of Matter* (The National Academies Press, Washington, DC, 2013).
- [15] A. Couture and R. Reifarh, *At. Data Nucl. Data Tables* **93**, 807 (2007).
- [16] H. Beer and F. Käppeler, *Phys. Rev. C* **21**, 534 (1980).
- [17] E. Überseder, R. Reifarh, D. Schumann, I. Dillmann, C. D. Pardo, J. Görres, M. Heil, F. Käppeler, J. Marganec, J. Neuhausen *et al.*, *Phys. Rev. Lett.* **102**, 151101 (2009).
- [18] M. Heil, F. Käppeler, E. Überseder, R. Gallino, and M. Pignatari, *Phys. Rev. C* **77**, 015808 (2008).
- [19] R. Reifarh and Y. A. Litvinov, *Phys. Rev. ST Accel. Beams* **17**, 014701 (2014).
- [20] W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366 (1952).
- [21] T. Rauscher and F.-K. Thielemann, *At. Data Nucl. Data Tables* **79**, 47 (2001).
- [22] A. Couture, R. F. Casten, and R. B. Cakirli, *Phys. Rev. C* **96**, 061601(R) (2017).

- [23] I. Dillmann, R. Plag, F. Käppeler, and T. Rauscher, in *EFNUDAT Fast Neutrons - Proceedings of the Scientific Workshop on Neutron Measurements, Theory & Applications*, edited by F.-J. Hamsch (European Union, Luxembourg, 2009), <http://www.kadonis.org>.
- [24] M. Wang, G. Audi, F. Kondev, W. Huang, S. Naimi, and X. Xu, *Chin. Phys. C* **41**, 030003 (2017).
- [25] W. J. Huang, G. Audi, M. Wang, F. G. Kondev, S. Naimi, and X. Xu, *Chin. Phys. C* **41**, 030002 (2017).
- [26] M. Chadwick, M. Herman, P. Obložinský, M. Dunn, Y. Danon, A. Kahler, D. Smith, B. Pritychenko, G. Arbanas, R. Arcilla *et al.*, *Nucl. Data Sheets* **112**, 2887 (2011).
- [27] B. Pritychenko, Maxwellian-averaged cross sections and astrophysical reaction rates (2019), <https://www.nndc.bnl.gov/astro/>.