Bulg. J. Phys. **44** (2017) 357–361

A Simple Way to Correlate and Predict Neutron Capture Cross Sections Relevant to Astrophysics and to Nuclear Science Applications

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Received *30 October 2017*

Abstract. Neutron capture cross sections in the keV range are critical for understanding nucleosynthesis in several important astrophysical environments. Certain key cross sections are also of relevance to reactor performance and design and for nuclear forensics. For decades. considerable effort has gone into measuring these cross sections where possible and modeling them where not. Theoretical estimates of unknown cross sections (usually using various statistical models combined with specific structural and reaction input) are often quite uncertain especially when they involve extrapolation to unknown cases. These limitations contribute to ambiguities in understanding various nucleosynthetic processes and delineating the sites where they occur. It is therefore of considerable importance to develop an improved method to correlate known cross sections and to predict new ones with higher accuracy and confidence. Here we present such a method, newly developed, that is simple, empirical, robust, model independent, and based on readily available empirical information. It can provide estimates of unknown cross sections often with accuracies of 20-40%, often for nuclei even quite far from stability, and often converts the estimation process from extrapolation to interpolation.

1 Introduction

Neutron capture cross sections in the keV range are critical to understanding the nucleosynthesis of medium mass and heavy nuclei and in identifying and understanding the stellar sites and events where they occur. This has been well documented in recent studies which also highlight those cross sections with the most sensitivity and impact [1, 2]. Often these cross sections are for capture on unstable nuclei where experimental measurements are difficult. Neutron capture cross sections are also of importance in nuclear reactor physics where capture can produce poisons, and in a variety of nuclear medicine and nuclear forensics applications.

For decades, extensive theoretical effort [3–5] has gone into modeling such cross sections. These approaches usually use Hauser-Feshbach statistical approaches and incorporate numerous ingredients, such as the excitation energy of the capture state, level densities, spin distributions, coupling to single particle and collective modes, including M1 and E1 degrees of freedom, the associated gamma strength functions, and so on, and often require normalization to existing data. Despite this, such approaches often differ from each other by large amounts, depend on detailed model assumptions, and, especially for nuclei several isotopes removed from stability, can differ by factors of ten or more.

These problems have hindered a reliable understanding of nucleosynthesis and of the sites where this occurs and therefore present a significant gap in our understanding of cosmic evolution. There is therefore a critical need for a more accurate and more reliable approach.

It is the purpose of this paper to present such an approach. It is purely empirical, model independent, and easily extrapolated to unknown isotopes with expected accuracies in the 20-40% range. Its success also raises questions about how to approach future modeling.

2 The Neutron Capture – S_{2n} Correlation

Figure 1 presents the main result of this work. It shows Maxwellian average cross sections (taken from Ref. [6]) centered on 30 keV neutron energy on the deformed and transitional rare earth nuclei from Nd to W, plotted against the two neutron separation energy S_{2n}(N+2). As is immediately evident there is an extremely tight, compact, correlation, the implications of which extend well

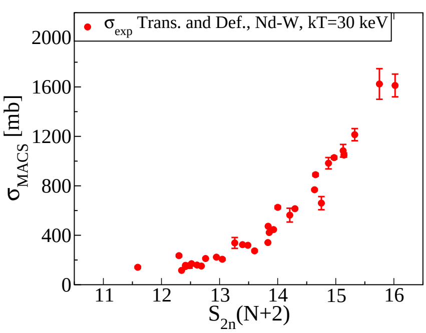

Figure 1. (color online) Maxwellian averaged neutron capture cross sections (MACS) at 30 keV plotted versus S_{2n}(N+2) as discussed in the text.

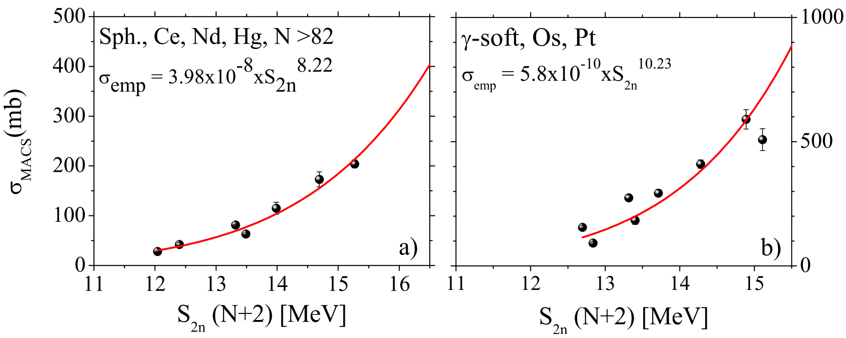

Figure 2. (color online) Similar to Figure 1 for different sets of nuclei. The nuclei shown are summarized in each panel.

beyond this one plot. That is, it is also robust, with correlations occurring in many other regions (see below) and to other neutron energies. We note in passing that we use S_{2n} at neutron number N + 2 (for a target with N neutrons, for example, for neutron capture on ^{166}Er we use S_{2n} for ^{168}Er) so as to reflect the actual excitation energy for the deposited $(N+1)^{th}$ neutron.

The high level of correlation with S_{2n}(N+2), though surprising, immediately allows the estimation of unknown cross sections in this region with significantly higher accuracy (again, see below).

As just noted, the correlation is not limited to this region, although the detailed trends are region and structure dependent. This is illustrated in Figure 2 which shows the correlation for two other regions, spherical Ce,Nd and Hg nuclei, and axially asymmetric nuclei in the Os-Pt region. Again, though the data are fewer, the correlation is comparably tight. A similar correlation also occurs for capture on odd-A targets in the rare earth region.

In lighter nuclei (e.g., for $Z<50$) and magic nuclei, the correlations break down completely. This may be correlated with large s-wave neutron capture state energy spacings.

We have shown the results for a MACS at 30 keV. The MACS cross sections at other energies from 5 to at least 100 keV behave almost identically except for overall scale and hence the present method works for a broad range of stellar neutron energy scenarios.

3 Predictive Power

The tightness of the correlations allows one to make predictions for unknown cross sections. To do this we have fit the data in Figure 1 with a power law function in S_{2n}(N+2). The results are shown in Figure 3, which includes the parameters of the fit function. The uncertainties in the scale coefficient and the

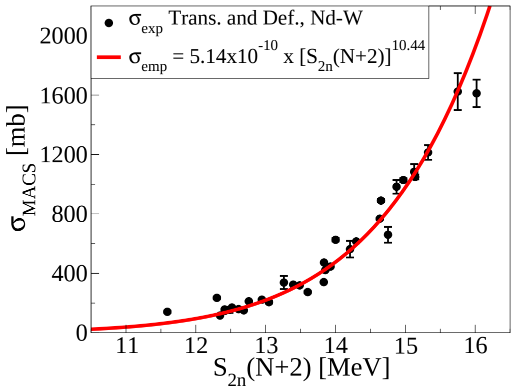

Figure 3. (color online) Same as Figure 1 but including the fit function as specified in the legend.

power exponent are highly correlated but a covariance matrix analysis yields total uncertainties that are typically in the 20-40% range even for nuclei up to 10 nucleons beyond the last measurement.

Table 1. Predictions of 30 keV MACS neutron capture cross section (with uncertainties) for selected nuclei including high-impact cases for r- process scenarios using the fit function given in Figure 3. NON-SMOKER values are laboratory cross-sections calculated in Ref. [5].

Nucleus (^{A}Z)	S_{2n}(N+2) (MeV)	σ_{emp} (mb)	Δ_{emp} (fit)	Δ_{emp} (S_{2n})	NON-SMOKER (mb)
^{162}Nd	7.149 (160)	0.43 (13)	(8)	(11)	1.75
^{166}Sm	7.286 (160)	0.52 (16)	(9)	(13)	2.62
^{168}Sm	6.325 (200)	0.12 (5)	(2)	(5)	1.47
^{168}Gd	8.849 (160)	3.97 (99)	(56)	(82)	9.09
^{178}W	15.372 (32)	1270 (133)	(130)	(30)	921.57

One advantage of the S_{2n} correlation is that S_{2n} values are known for many nuclei far from stability. Moreover, when not known, S_{2n} values can be accurately extrapolated because, except at magic numbers and shape transition regions, they behave almost linearly with neutron number. When S_{2n} values for new nuclei lie within the range of S_{2n} values already covered in Figure 3 the accuracy of the predicted cross sections are given solely by the scatter of points in the correlation.

We illustrate predictions for a few nuclei in Table 1 chosen for their importance in nucleosynthetic scenarios (from Refs. [1, 2]), or their distance from stability, or their importance in nuclear forensics. We compare these to NON-SMOKER results [5] using an FRDM mass model [7]. We note that, even within this small group of nuclei that there are significant differences in the predictions.

4 Conclusions and Implications

We have shown that neutron capture cross sections in the keV range are highly correlated with values of the 2-neutron separation energy S_{2n}(N+2). The correlations are compact albeit region and structure dependent. They provide a new approach to predicting capture cross sections, even quite far from stability, of relevance to nucleosynthesis and the delineation of the stellar sites where this occurs. This work is based on Ref. [8].

Acknowledgments

We are grateful to Toshihiko Kawano, Matthew Mumpower, Klaus Blaum, and Keegan Kelly for discussions. This material is based upon work supported by the U.S. Department of Energy, National Nuclear Security Administration, under contract number DE-AC52- 06NA25396. R.F.C. acknowledges support from MSU- FRIB and LANL. R.B.C. acknowledges support from the Max-Planck Partner group, TUBA-GEBIP, and Istanbul University Scientific Research Project No. 54135.

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