Predicting Neutron Capture Cross Sections from Nuclear Masses

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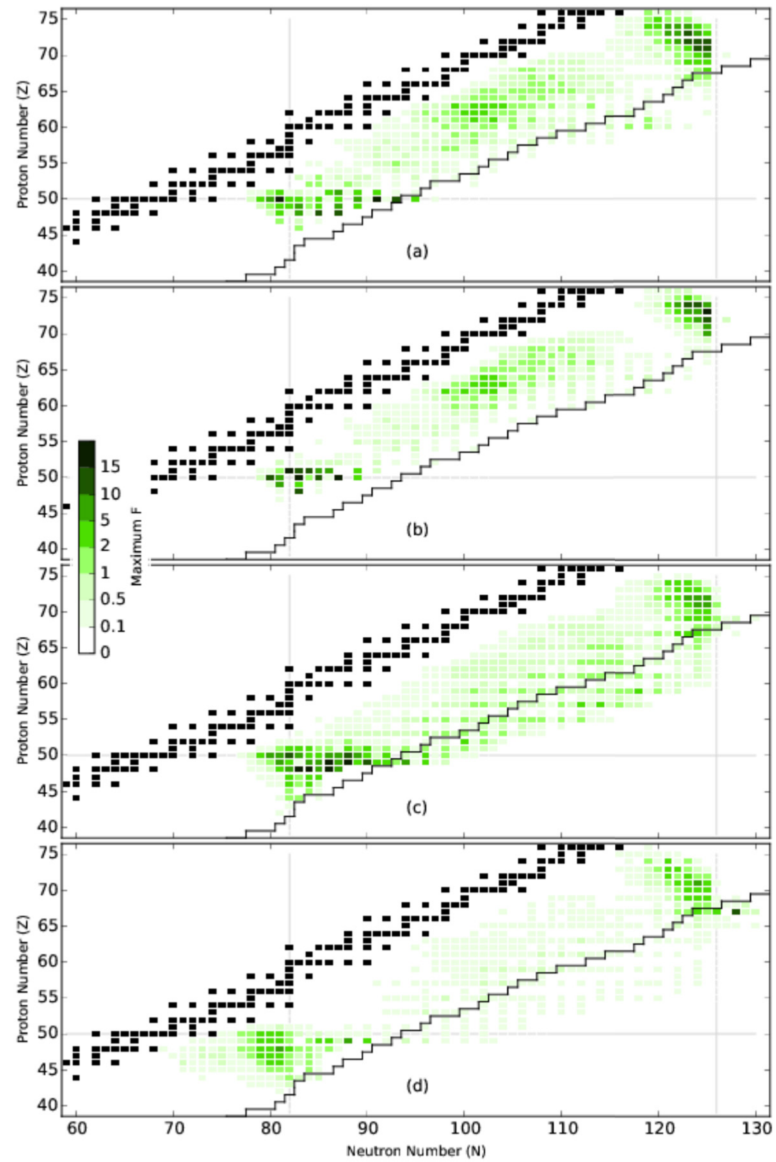
Shapes and Symmetries in Nuclei:
Experiment and Theory
Gif-sur-Yvette, France
5-9 November 2018

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Neutron capture is a key piece to understanding r-process abundances

- Color intensity indicates sensitivity
- Different scenarios highlight different isotopes
- All tested scenarios require (n,γ) far from stability
- NS-merger r-process scenarios are at least as sensitive to (n,γ) as any sort of hot freeze-out



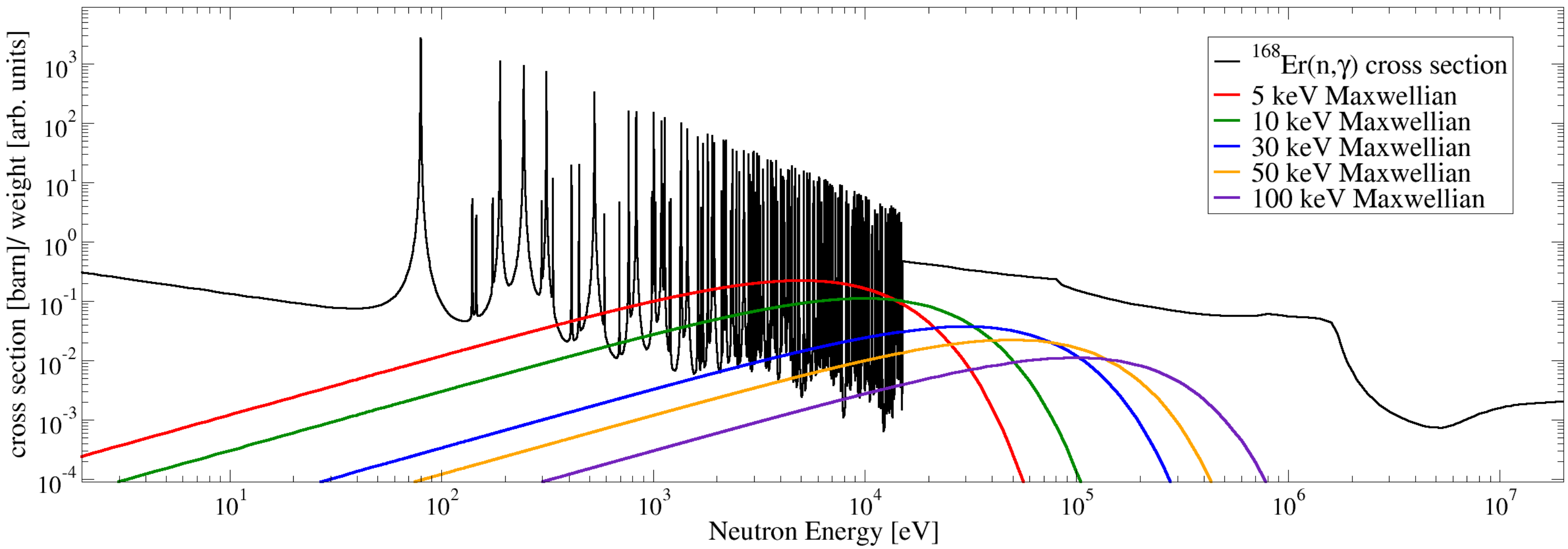
Mumpower *et al. Prog. Part. Nucl. Phys.*. **86** 86-126 (2016).

What is a Maxwellian Averaged Cross Section?

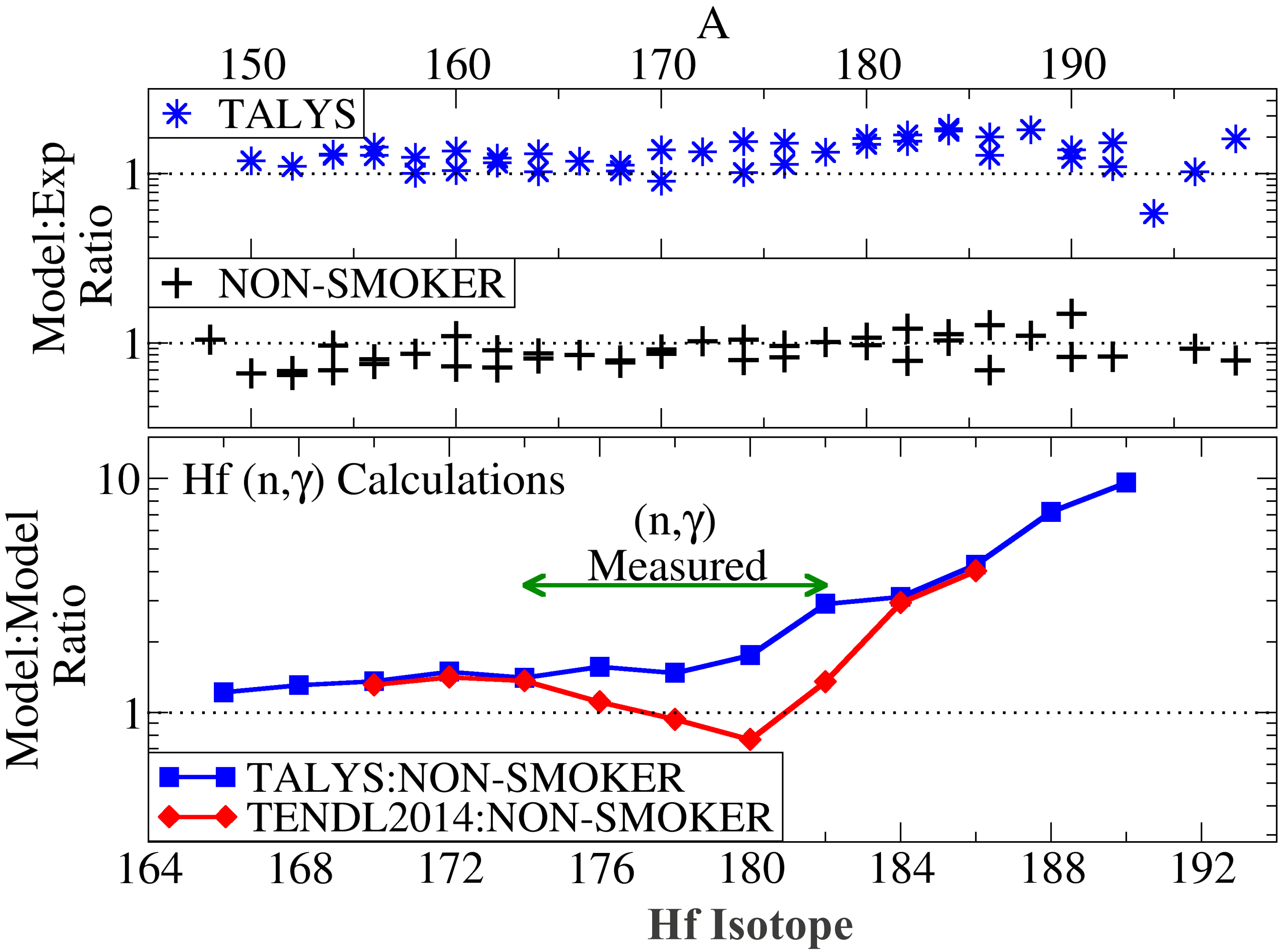
- The quantity of interest is the reaction rate-per-particle-pair, $\langle \sigma v \rangle$, in a Maxwell-Boltzmann velocity distribution

$$\sigma_{MACS} \equiv \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \int_0^\infty E\sigma(E) exp\left(-\frac{E}{kT}\right) dE$$

- This typically simplifies the problem as resonance details wash out.



Unfortunately, neutron capture is challenging to predict accurately, even in “well-behaved” nuclei



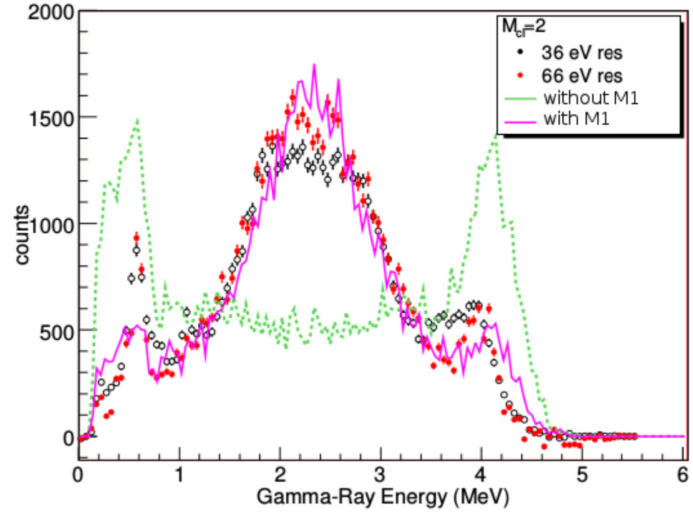
TALYS, NON-SMOKER, TENDL,

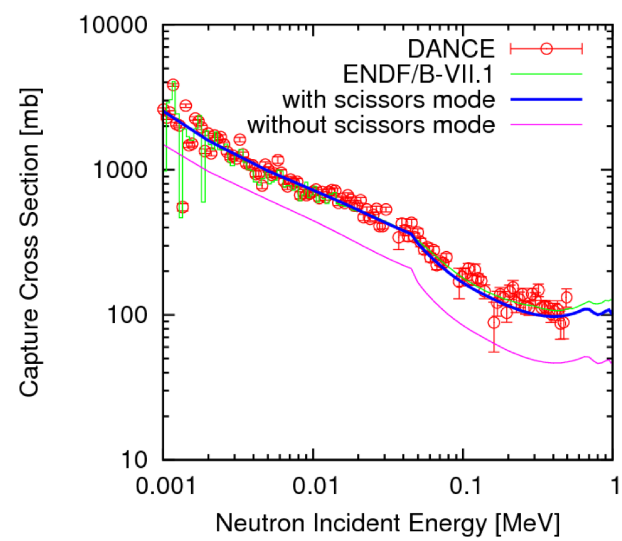
While agreement is reasonable where data exists, the models quickly diverge without data

Can nuclear structure help?

- Recent work has shown improvement in statistical model predictions from improved understanding of M1 strength
- There are known connections between nuclear deformation and the M1 scissors mode
- The original goal was to try find a better way to predict the onset and strength of the scissors mode as an input for statistical model calculations

Ullmann *et al. Phys. Rev C.* **89** 034603 (2014).

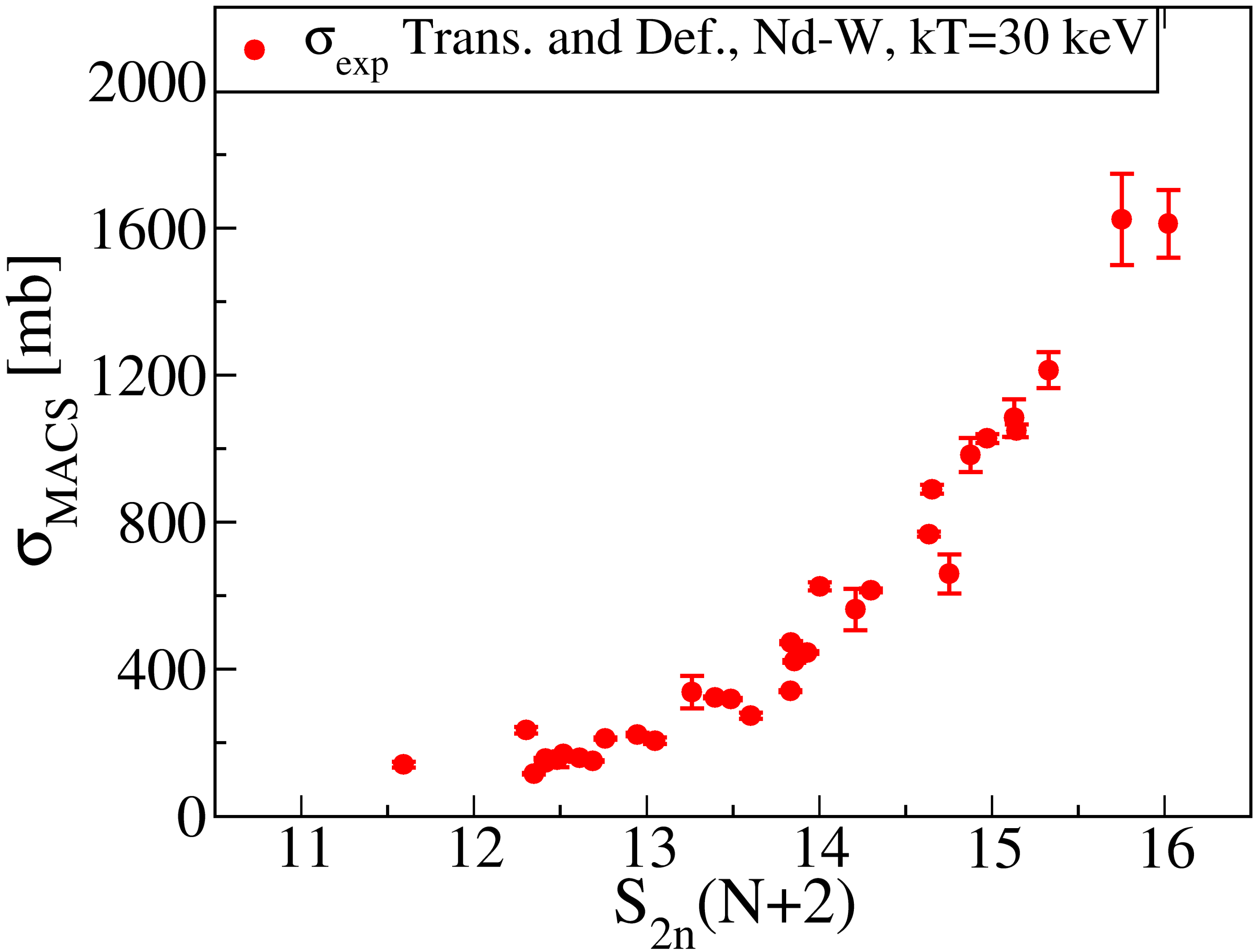




What we found instead

- 30 keV MACS taken from KADONIS *experimental* data

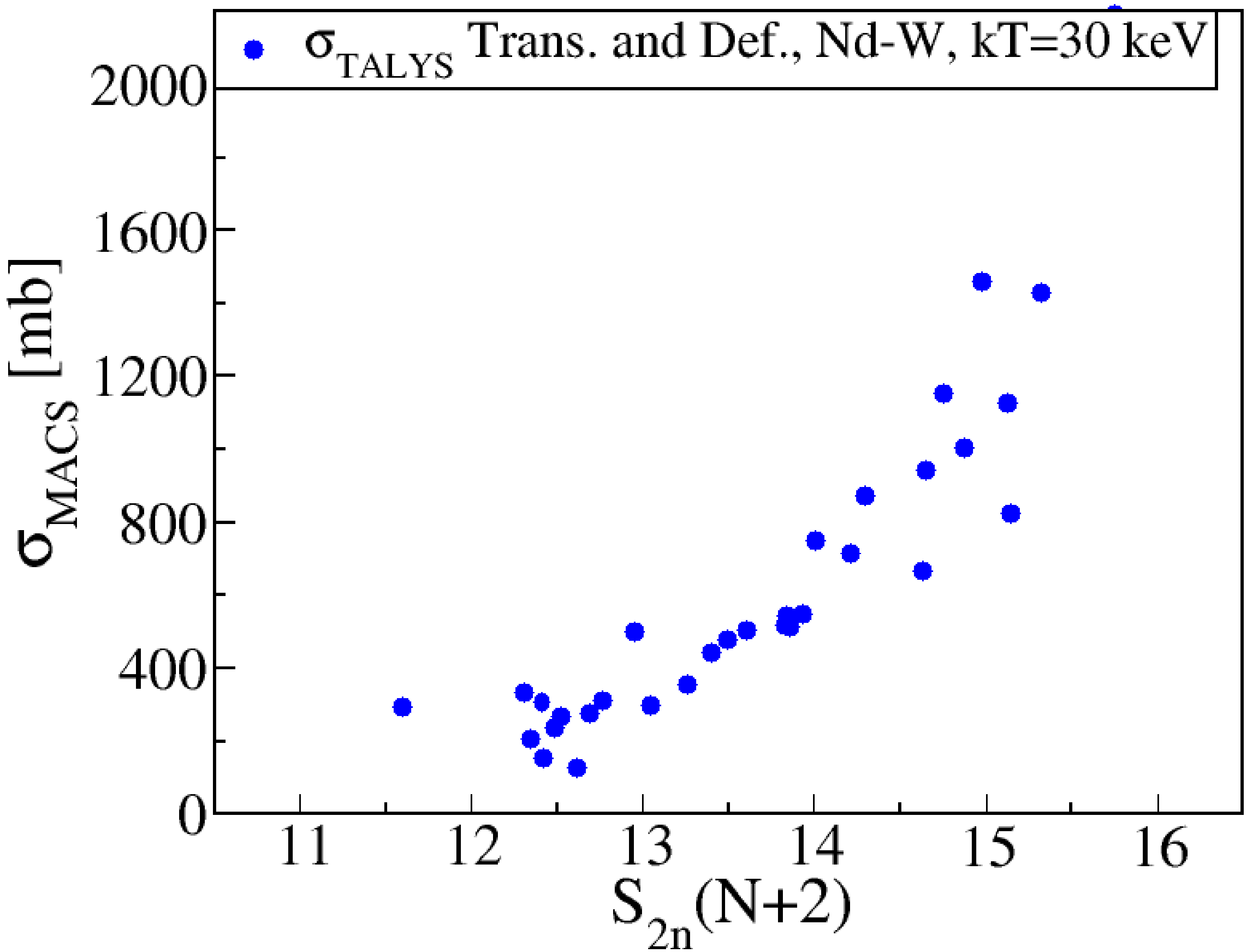
Experimental Cross Sections



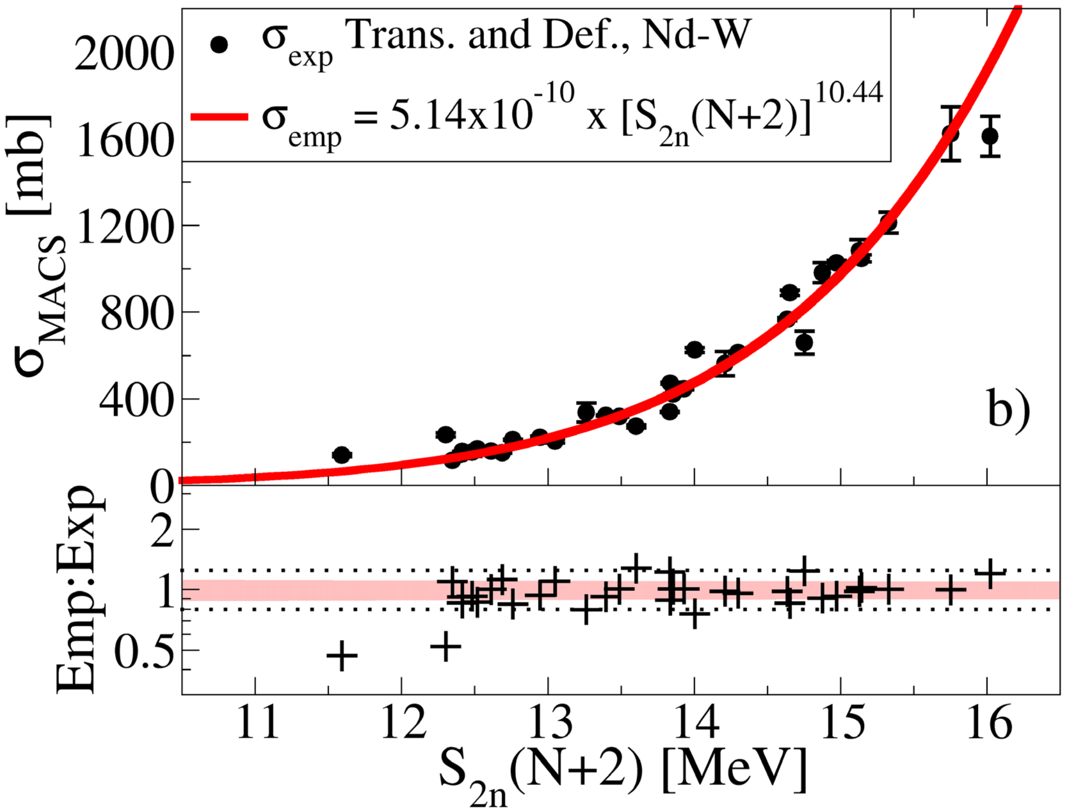
Experimental correlations are tighter than statistical model predictions

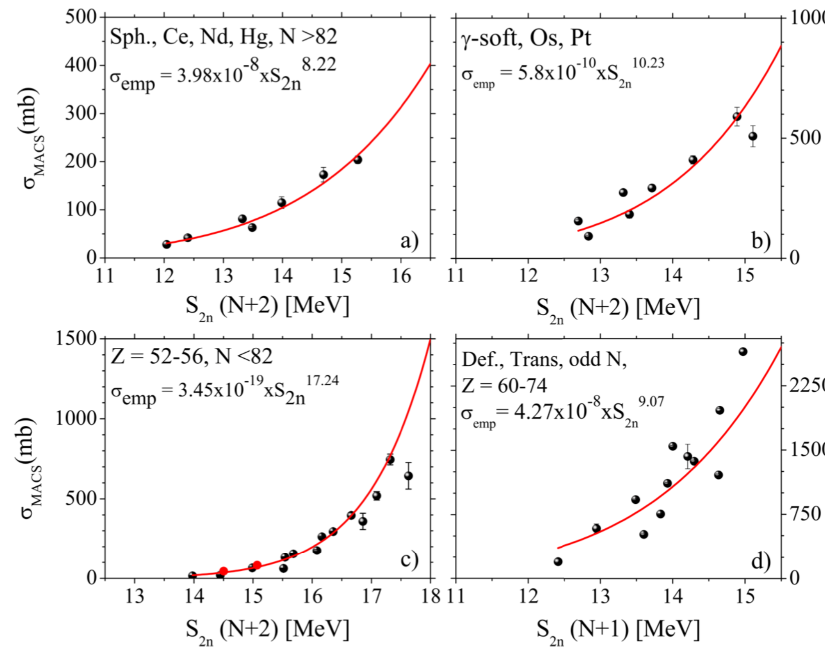
- 30 keV MACS taken from KADONIS *experimental* data

Calculated Cross Sections



The general trend with S_{2n} for regions of different deformation

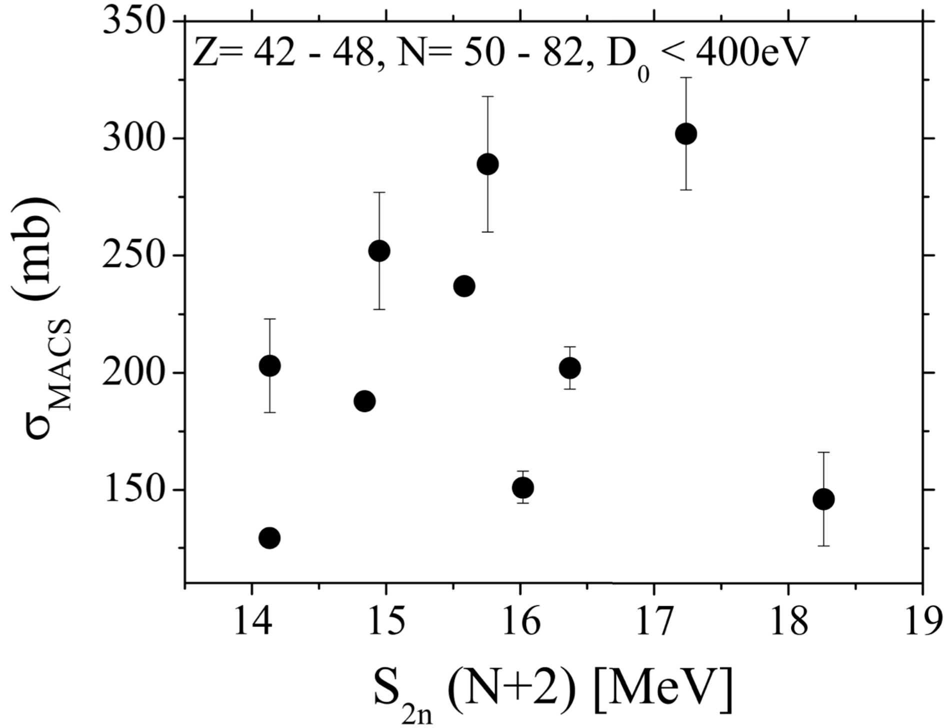




- These are even-even nuclei, unless called out separately
- There is insufficient data for odd-Z nuclei and *most* odd-N nuclei
- Actinide data do not disagree with the trend

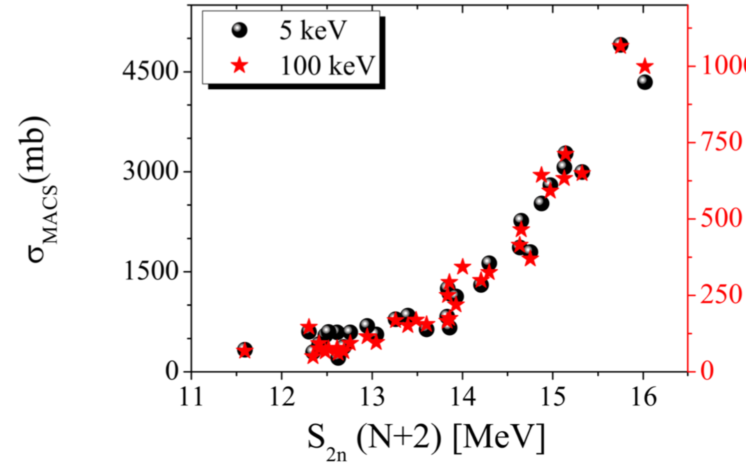
Lighter isotopes do not show this behaviour

- Direct capture may play a role in deviations
  - Direct capture is a small component of the cross section in the regions of tight correlation
- σ vs D_0 shows less tight correlation
- That being said, the regions where the correlation holds are regions of relatively high level density



(n,γ) predictions and limitations: ca. Jan 2018

- The Good
  - This is not an "accident" at 30 keV
  - We can use existing data to make predictions
    - Measurements in Pt isotopes will provide additional tests
    - In general, more measurements improve the situation
  - Uncertainties come out naturally from the uncertainty in the fit
- The Bad
  - Data is needed to calibrate each region
  - For odd-Z this will still require hard (n,γ) measurements
    - The isotopes needed simply are not stable
- The Ugly
  - To produce *abundance* predictions, we need complete, energy-dependent cross sections



Nucleus	S_{2n}(N+2) [MeV]	σ_{MACS} [mb]	$\Delta\sigma_{MACS}$ (fit)	$\Delta\sigma_{MACS}$ (ΔS_{2n})
^{156}Nd	9.881 (40)	12.6 (17)	(16)	(5)
^{158}Nd	8.970 (80)	4.57 (78)	(64)	(44)
^{160}Nd	8.060 (120)	1.50 (34)	(23)	(25)
^{162}Nd	7.149 (160)	0.43 (13)	(8)	(11)
^{158}Sm	11.127 (8)	43.4 (51)	(51)	(3)
^{160}Sm	10.167 (40)	16.9 (23)	(21)	(7)
^{162}Sm	9.206 (80)	6.00 (100)	(82)	(57)
^{164}Sm	8.246 (120)	1.90 (42)	(29)	(31)
^{166}Sm	7.286 (160)	0.52 (16)	(9)	(13)
^{168}Sm	6.325 (200)	0.12 (5)	(2)	(5)
^{168}Gd	8.849 (160)	3.97 (99)	(56)	(82)
^{154}Dy	16.278 (9)	2310 (233)	(233)	(10)
^{156}Dy	16.021 (7)	1950 (198)	(198)	(10)
^{174}Dy	8.030 (160)	1.44 (40)	(22)	(33)
^{174}W	16.557 (40)	2750 (286)	(277)	(70)
^{176}W	15.908 (40)	1810 (190)	(184)	(50)
^{178}W	15.372 (32)	1270 (133)	(130)	(30)

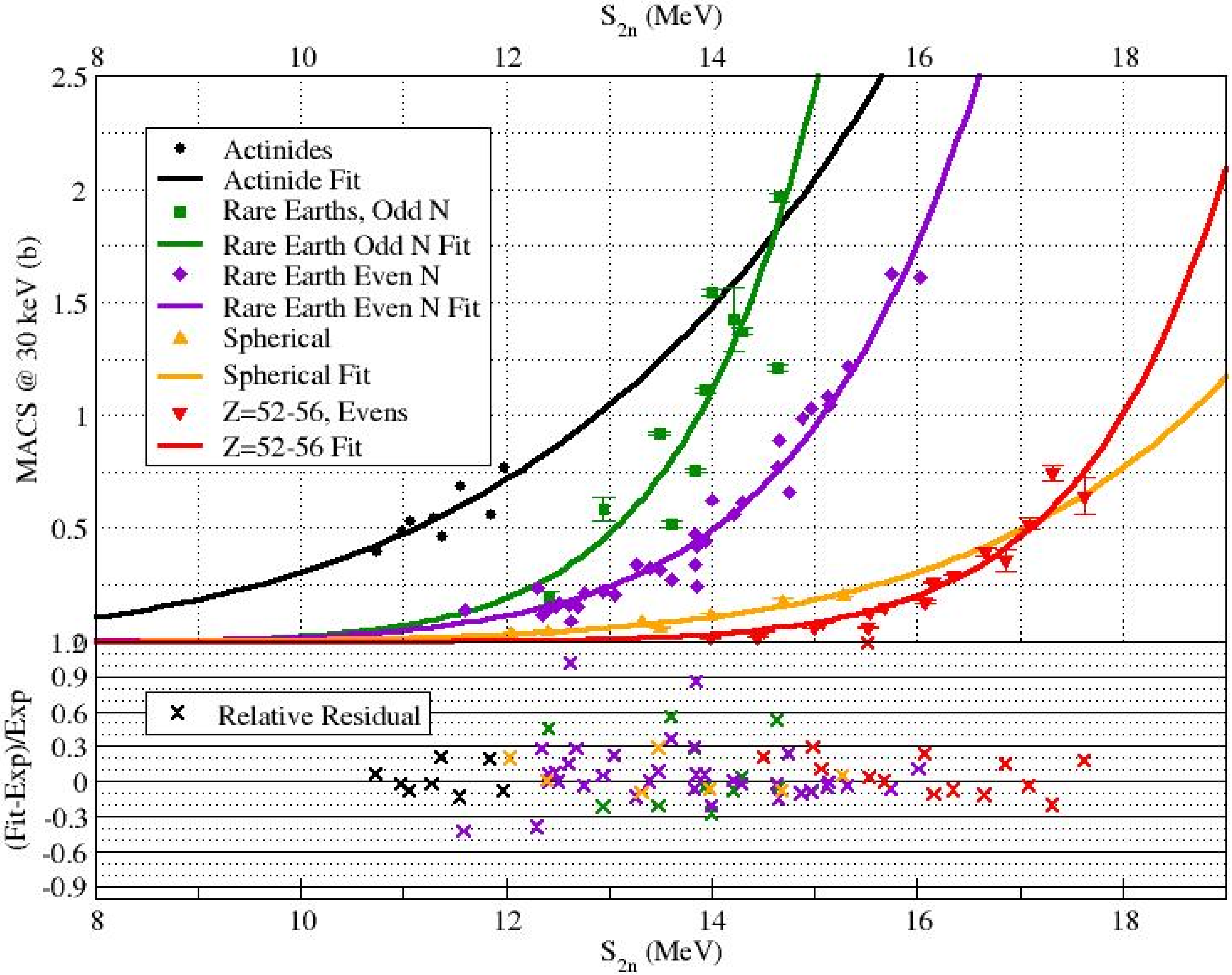
For Details: Couture *et al. Phys Rev. C.*. **96** 061601 (R) (2017).

Isolating the Energy Dependence

- For MACS, the behavior is smooth for reasonably heavy nuclei
- The cross section energy dependence is nominal 1/v
- We have calculated a ”correction factor” to evaluated the cross sections *as if* they were the 30 keV cross section
  - Rare-Earth Even-Even region was used for the correction factor determination
  - This same set of correction factors was used for all nuclei
- This does not address issue at kT>100 keV where other channels may be open
  - Good data are scarce at higher energy

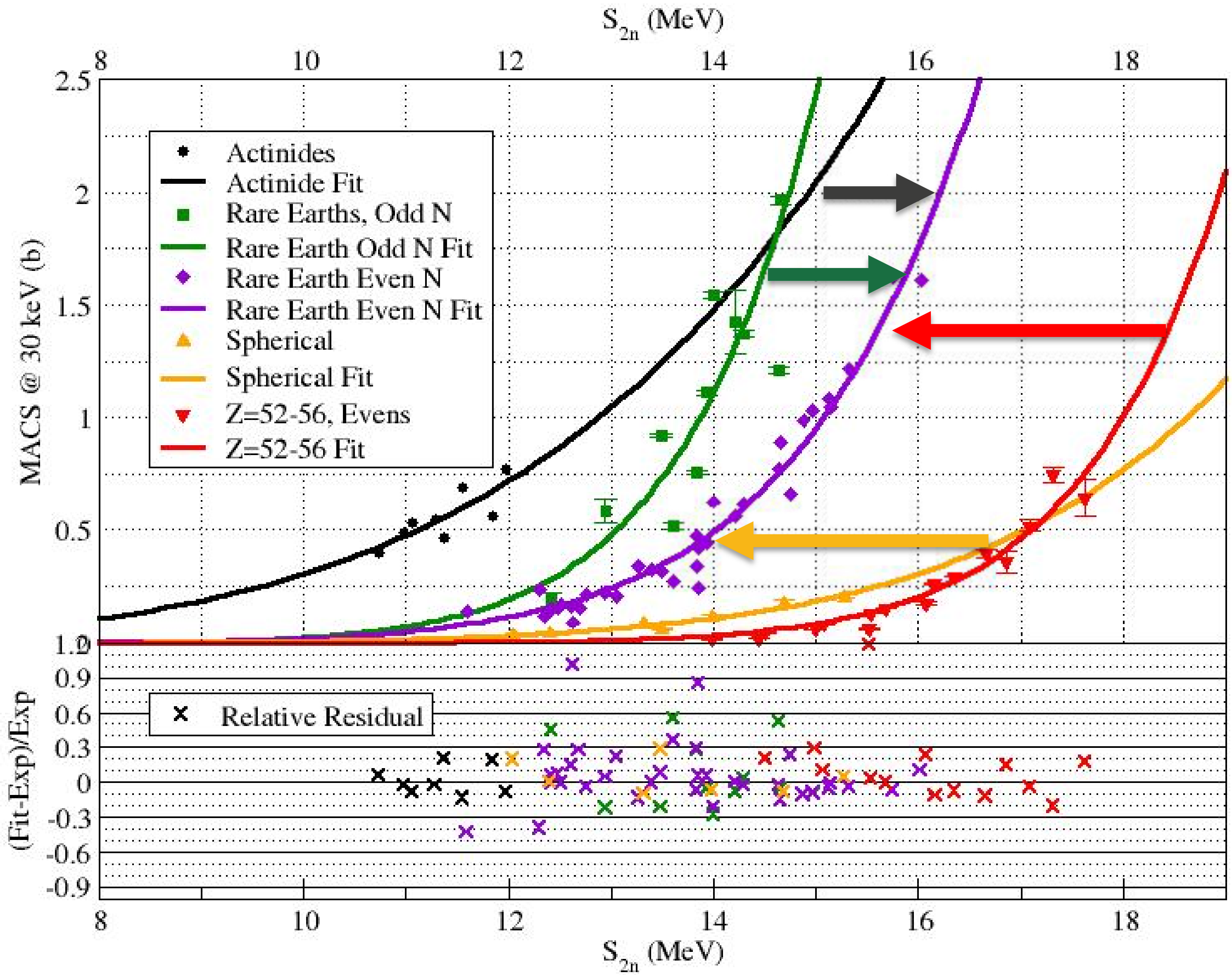
Are different regions actually different?

- While the functional form is similar, and independent fit appears to be needed in each region

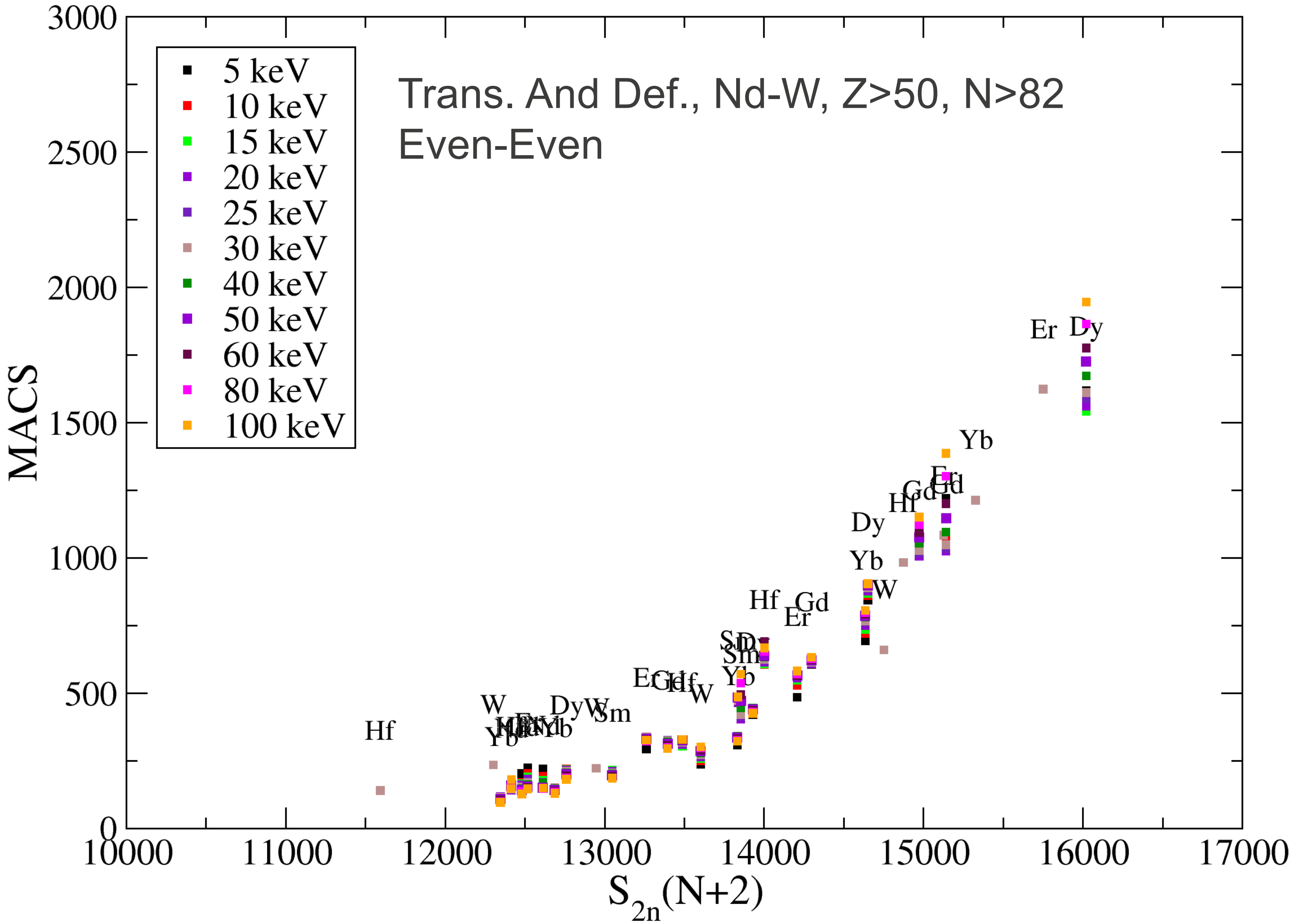


Does a "shift" do it?

- The idea is to introduce a linear shift in effective S2n
- This is still 1 parameter per region, but (potentially) less sensitive than a power-law fit.



Consistency of S2n Shift + Energy Dependence Correction



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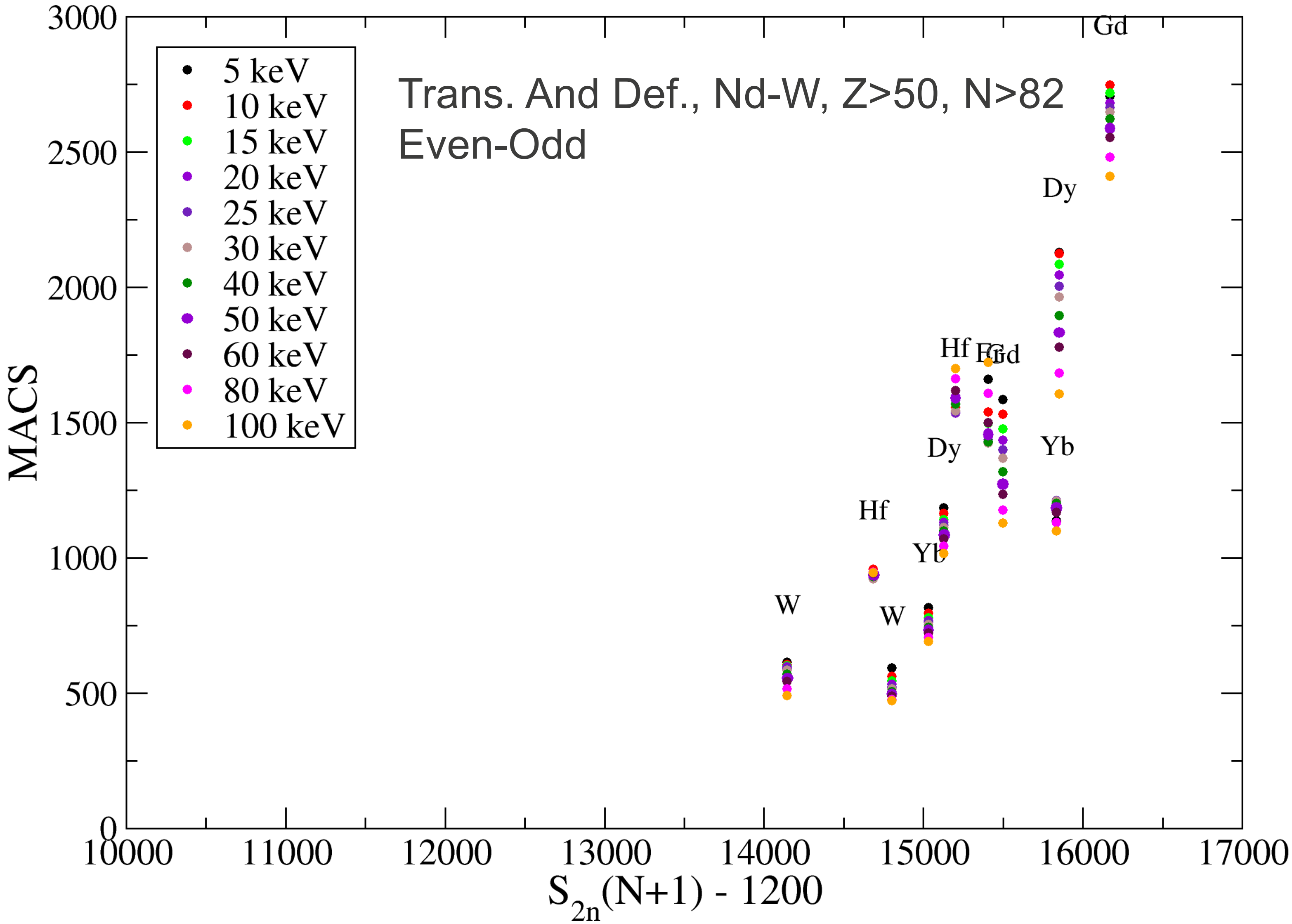

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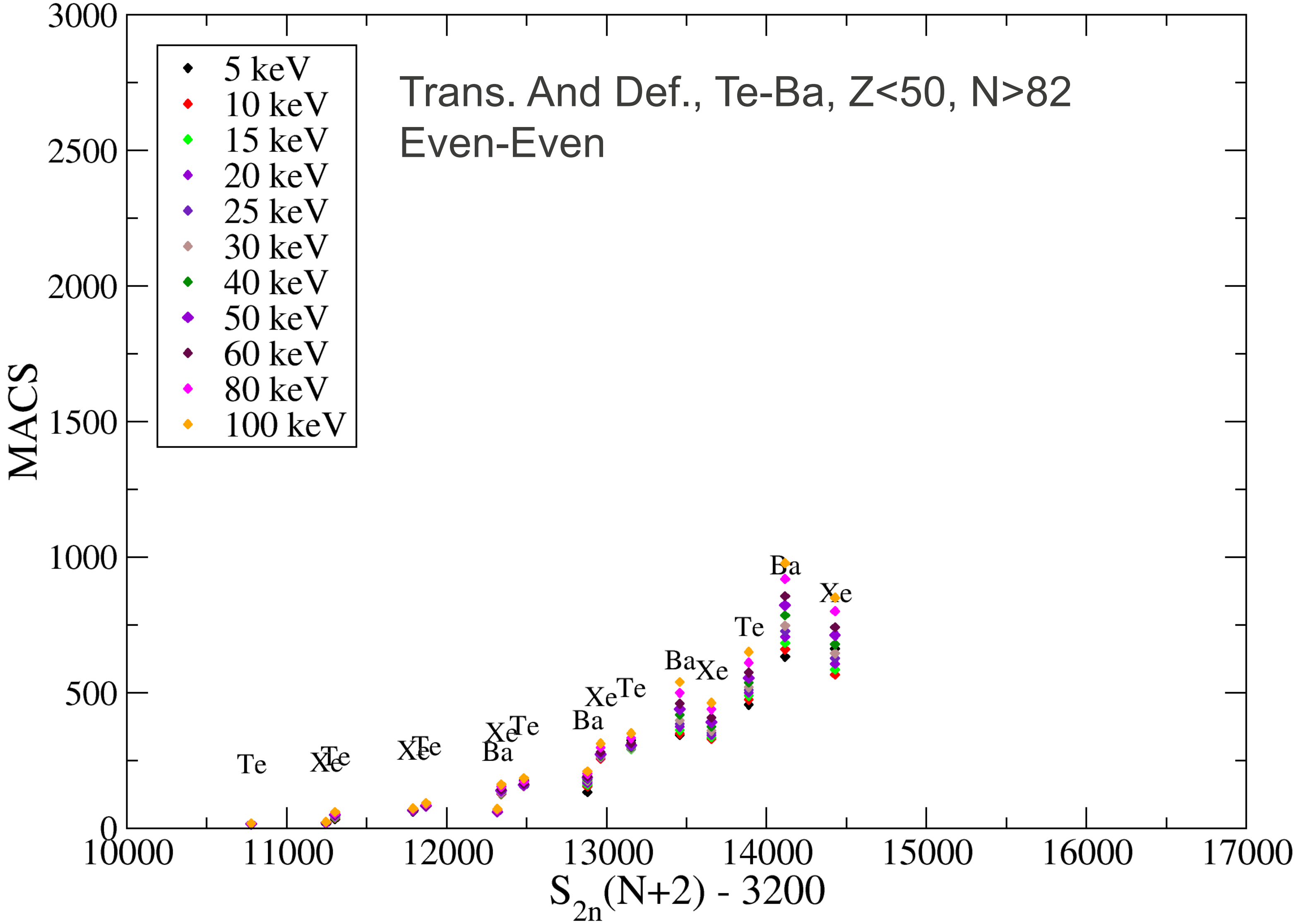

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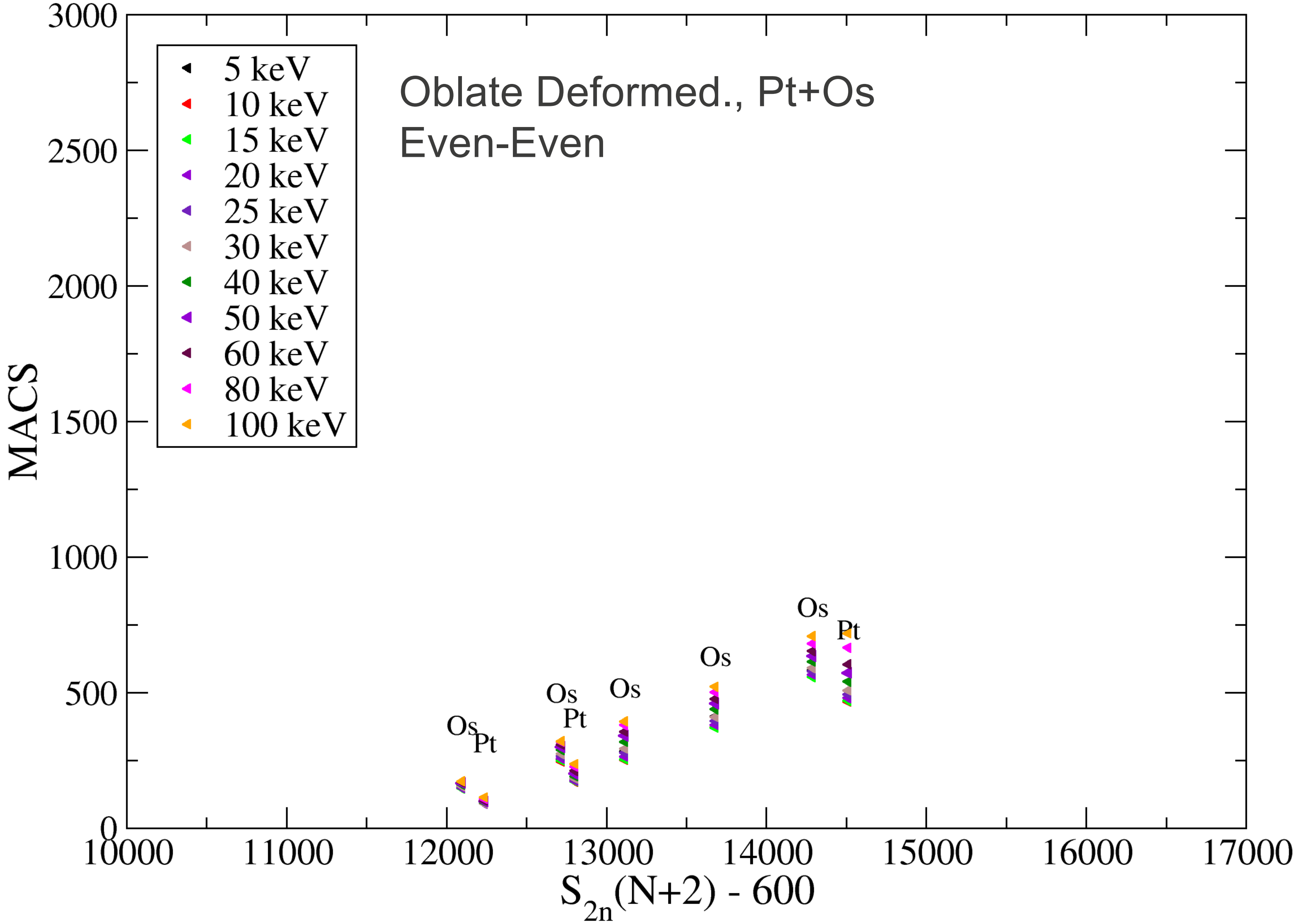

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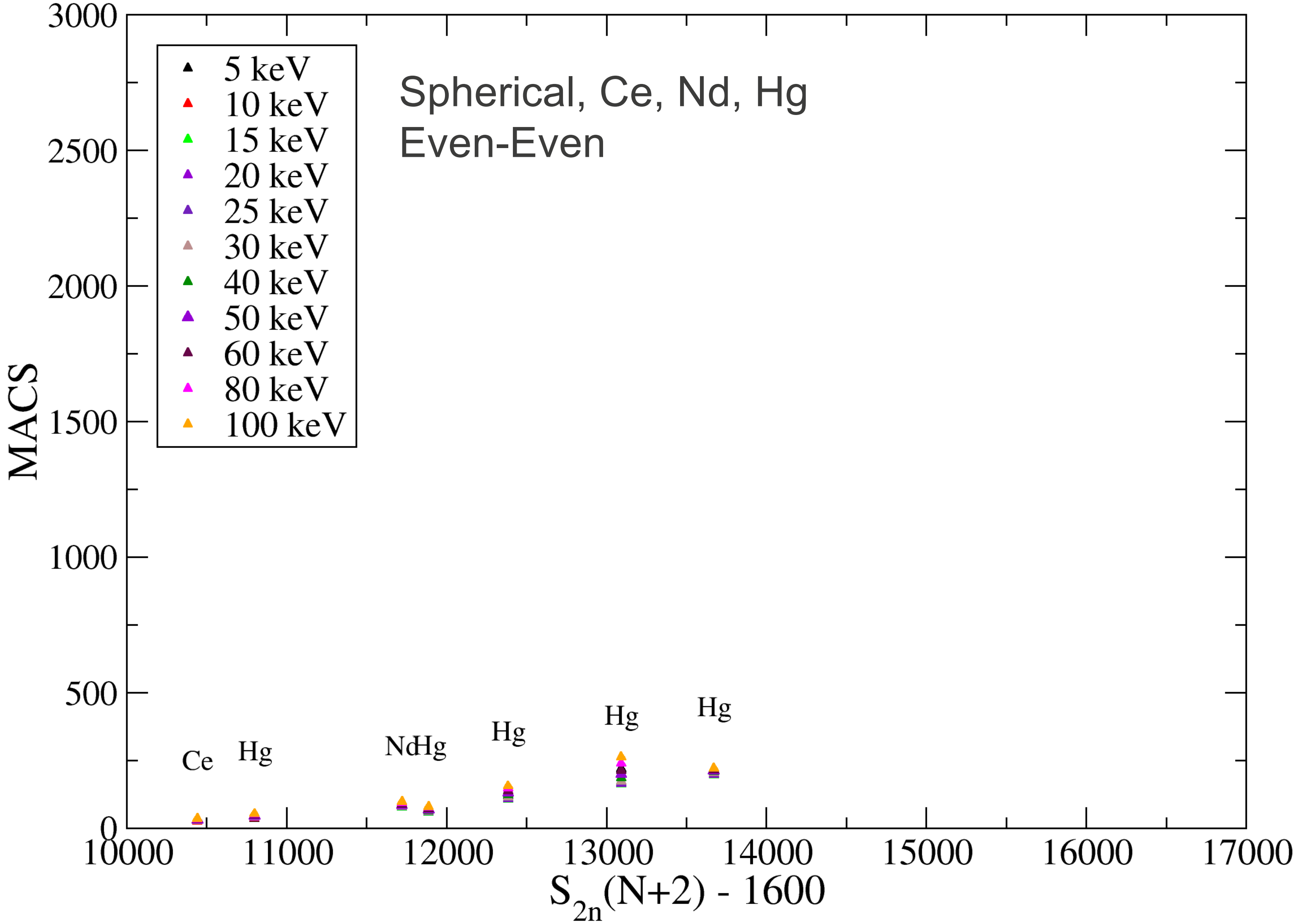

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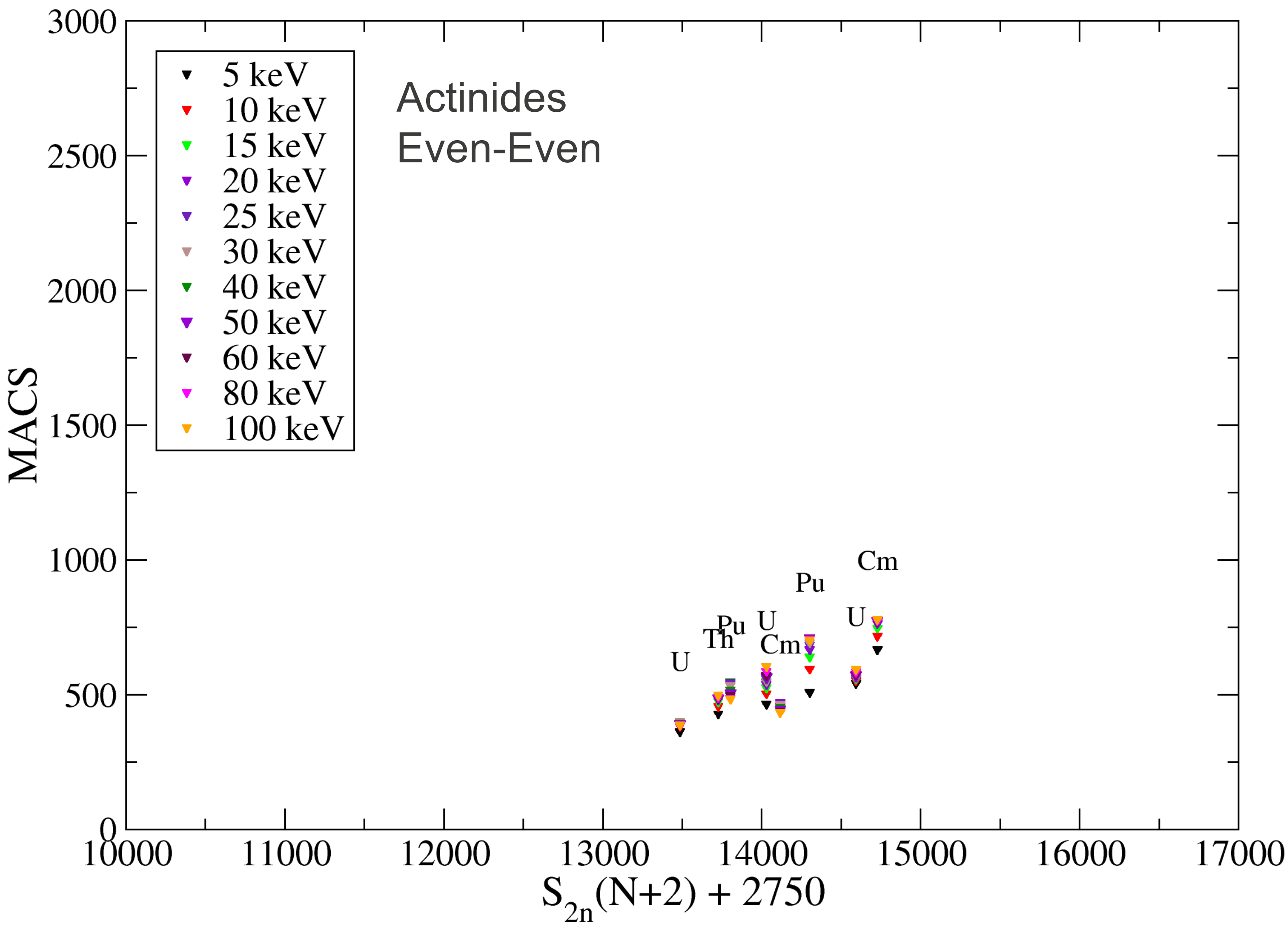
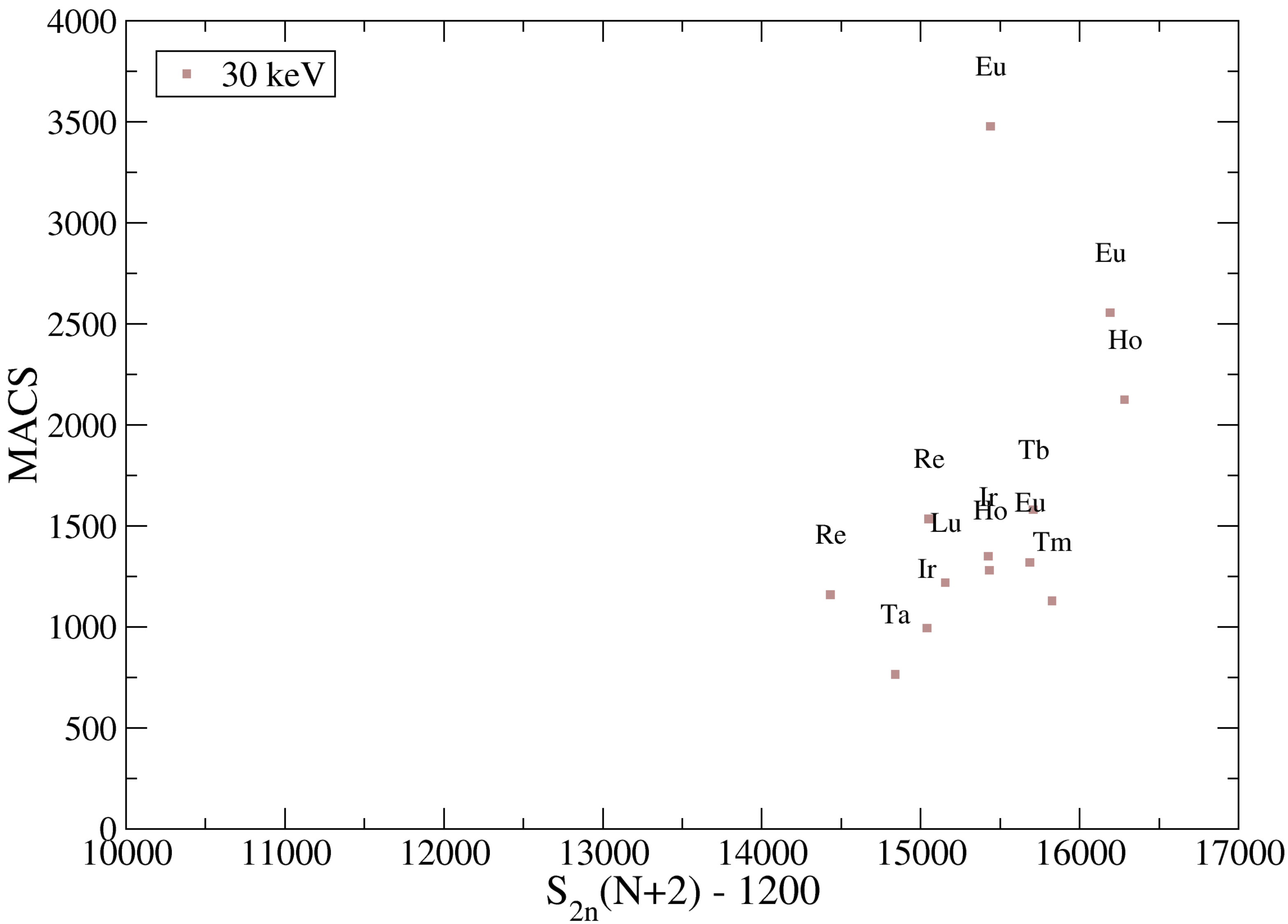
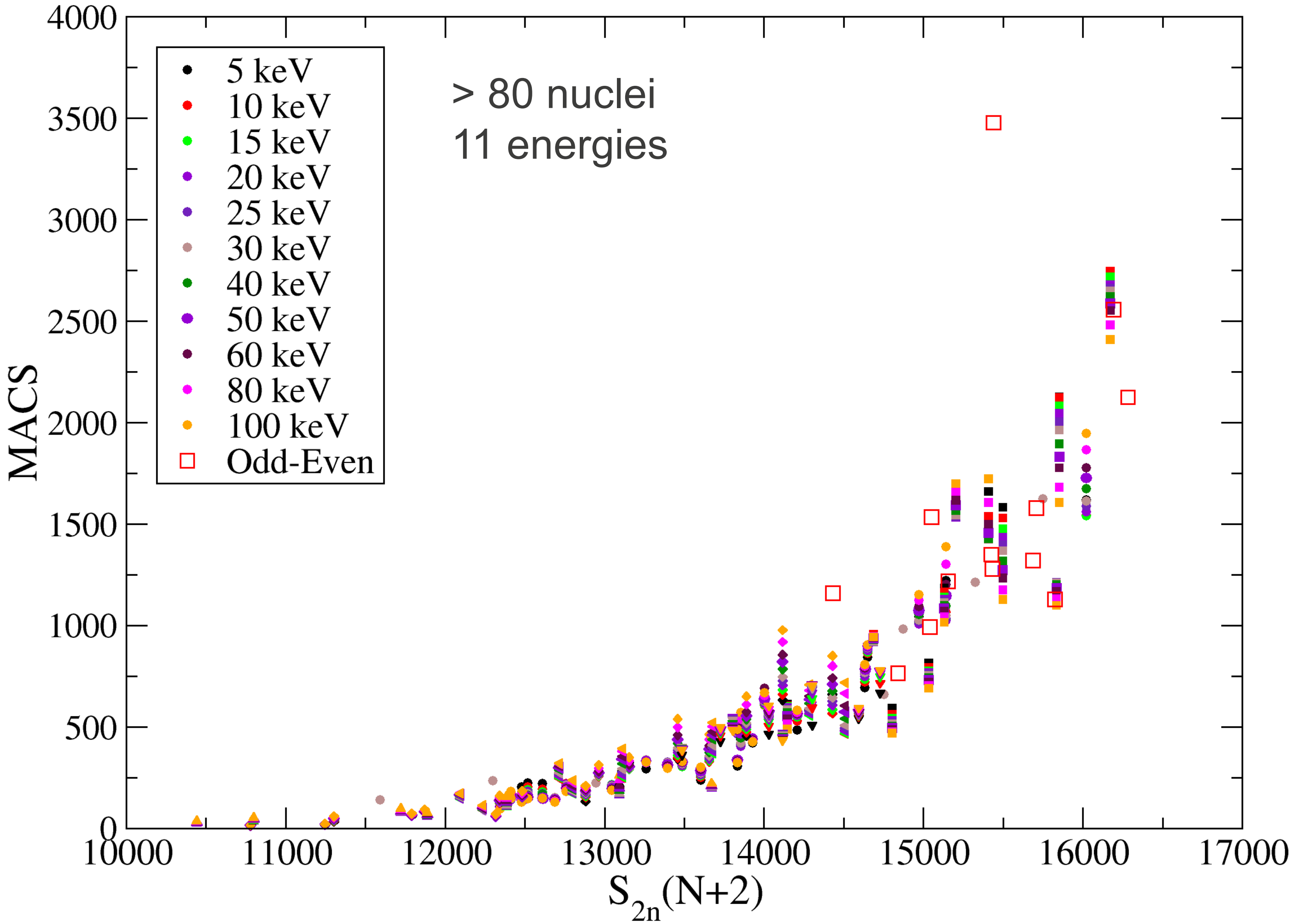


Odd-Z nuclei still present challenges:

Trans and Def., Z>50, N>82 Eu-Re



Even considering outliers, this correlation is very robust



Status of extending to "everything" needed for r-process

- Energy dependence *up to kT=100 keV* is largely understood
- Extension of the formalism to even-even and even-odd nuclei for Z>50 seems feasible
- We have ideas for how to address odd-Z (pairing), but there are outliers.
- For odd-odd nuclei, data are very sparse, making validation difficult

Conclusions and Outlook

- There is a surprisingly strong correlation between neutron capture cross sections and nuclear masses
- We may be able to exploit this to infer unmeasured cross-sections that are challenging to measure
  - Nuclear masses are easier to measure than cross sections
- There are outstanding questions as to the behaviour in nuclei where direct capture plays a significant role

- We still need to go back to investigate our original question…