Inelastic Scattering Gamma Validation using the Baghdad Atlas

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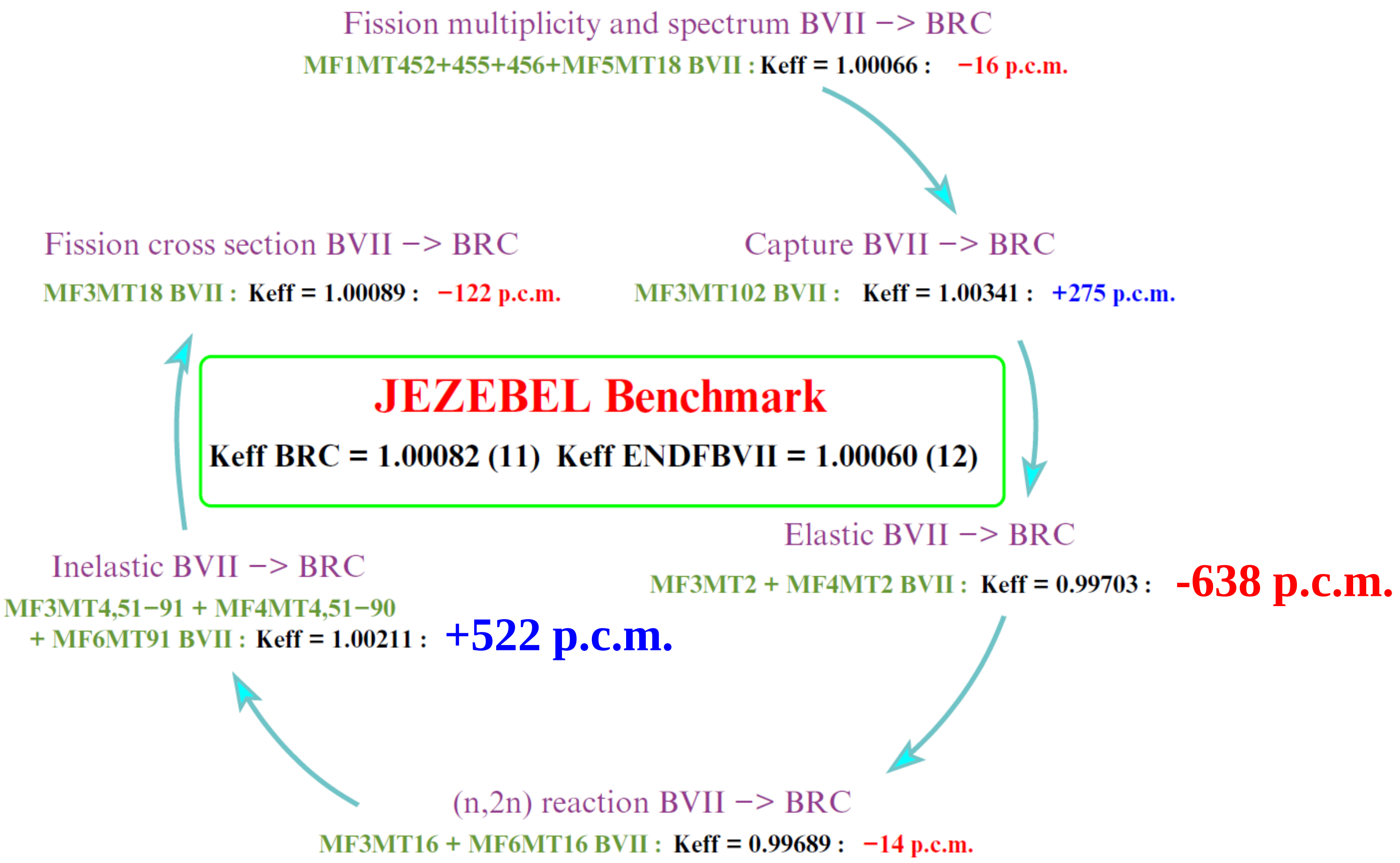
Improved validation is needed for elastic and inelastic scattering reactions



E. Bauge, et. al., Eur. Phys. J. A. 48 (2012) 113.

- There is little sensitivity in our current benchmarks to:
  - Elastic/inelastic ratio
  - Inelastic gammas
- Inelastic scattering to discrete states provides important information for
  - Nuclear energy (neutron slowing down)
  - Nuclear physics (optical models, level densities, gamma strength functions)
  - Evaluations (consistency between reactions)

A campaign of consistent measurements of inelastic scattering gammas was performed at the Baghdad Reactor in the 1970s, and the results were compiled into one report

The data are gamma cross sections integrated over the reactor spectrum, and are presented in ratio to the 847 keV gamma in ^{56}Fe

Iron $_{26}$Fe

E_γ	I_γ	^AZ	E_i	E_γ	I_γ	^AZ	E_i
122.1(2)	2.2(2)	^{57}Fe	122.1	1165.9(6)	0.08(3)		
126.0(2)	1.6(2)	^{55}Mn	126.0	1173.[illegible](8)	0.25(10)	^{56}Fe	3830.6
156.5(2)	0.40(10)	^{54}Mn	156.5	1175.0(8)	0.15(10)	^{56}Fe	4297.4
211.0(3)	0.22(3)	^{56}Mn	211.0	1213.0(7)	0.06(3)		
352.5c	1.6(2)	^{57}Fe	367.0	1238.3(2)	10.5(5)	^{58}Fe	2085.1
367.1(2)	0.54(5)	^{57}Fe	367.0	1271.9(10)	0.05(2)	^{56}Fe	4395.4
757.3(4)	0.10(3)	^{53}Fe	757.3	1298.9(4)	0.12(4)		
810.3(2)	0.43(3)	^{58}Fe	810.3	1303.2(3)	0.64(10)	^{56}Fe	3388.3
846.78c	100	^{56}Fe	846.8	1334.6(4)	0.18(3)	^{56}Fe	4457.6
992.8(4)	0.10(3)			1359.9(3)	0.40(4)	^{56}Fe	3445.4
1037.85c	2.15(10)	^{56}Fe	3122.9	1386.6(10)	0.06(3)		
1130.0(3)	0.39(4)	^{54}Fe	2538.2	1408.2(2)	3.5(2)	^{55}Fe	1408.2
1152.8(4)	0.14(3)	^{54}Fe	2561.0	1434.2(10)	0.05(2)		

ATLAS

OF GAMMA-RAY SPECTRA FROM THE INELASTIC SCATTERING OF REACTOR FAST NEUTRONS

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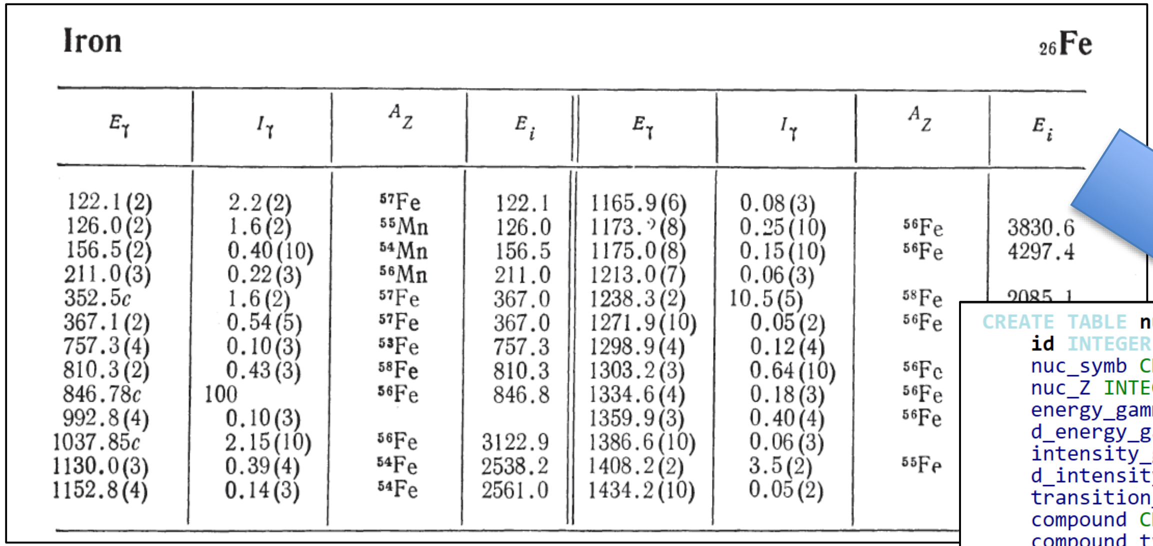
The ATLAS data has been digitized, verified, and turned into a SQL database



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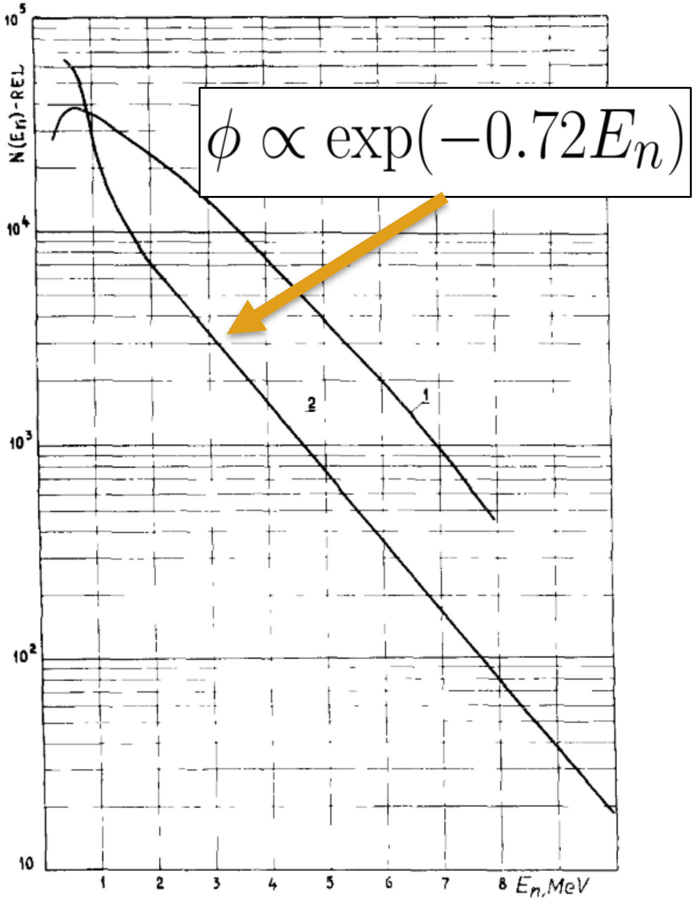
```
CREATE TABLE nucleus (
    id INTEGER PRIMARY KEY,
    nuc_symb CHAR(5),          /* Chemical symbol (with mass number for enriched isotopes) of the irradiated sample */
    nuc_Z INTEGER,             /* Atomic number of irradiated sample */
    energy_gamma FLOAT,        /* Gamma-ray transition energy [keV] */
    d_energy_gamma FLOAT,      /* Uncertainty: Gamma-ray transition energy [keV] */
    intensity_gamma FLOAT,     /* Gamma-ray transition intensity [RI] */
    d_intensity_gamma FLOAT,   /* Uncertainty: Gamma-ray transition intensity [RI] */
    transition_type CHAR(2),   /* Gamma flag: f (firm); d (doublet); t (tentative); c (calibration); m (multiply placed) */
    compound CHAR(16),         /* Activated compound nucleus; usually the (n,n') product */
    compound_type CHAR(2),     /* Compound-identification flag: f (firm); t (tentative) */
    energy_ex FLOAT,           /* Excitation energy in compound nucleus [keV] */
    ex_type CHAR(2),           /* Excitation-energy flag: f (firm); t (tentative); u (unknown) */
    sample CHAR(1)             /* Sample flag: E (isotopically enriched); N (natural elemental abundance) */
);

CREATE TABLE sample (
    id INTEGER PRIMARY KEY,
    flag CHAR(1),              /* Meta-data identification flag: X */
    element TEXT,              /* Name of element/enriched isotope */
    Z INTEGER,                 /* Atomic number of element/enriched isotope */
    symbol TEXT,               /* Chemical symbol for element/enriched isotope */
    N FLOAT,                   /* Normalization factor for determination of absolute partial gamma-ray cross sections */
    dN FLOAT,                  /* Uncertainty: Cross-section normalization factor */
    e_gamma_norm FLOAT,        /* Gamma-ray transition energy used for normalization [keV] */
    A INTEGER,                 /* Atomic mass of enriched isotope (A=0 for natural elemental samples) */
    mass FLOAT,                /* Mass [g] of irradiated sample */
    exposure_time FLOAT,       /* Measurement period [h] of irradiated sample */
    enrichment FLOAT,          /* Enrichment factor [%] of principal isotope in sample (0 for natural elemental samples) */
    sample_composition TEXT,   /* Chemical composition of irradiated sample */
    isotope_norm TEXT          /* Isotope used for gamma-ray intensity normalization */
);
```

More information and access at https://nucleardata.berkeley.edu/

The flux shape is a large source of uncertainty in the modeling, and the available information is not specific enough



Ahmed, M. R., *et. al.*, NIM 117(1974)

- The flux was measured using threshold reactions and fit to an exponential
  - No data points were shown, and there was no uncertainty given on the fit parameter 0.72

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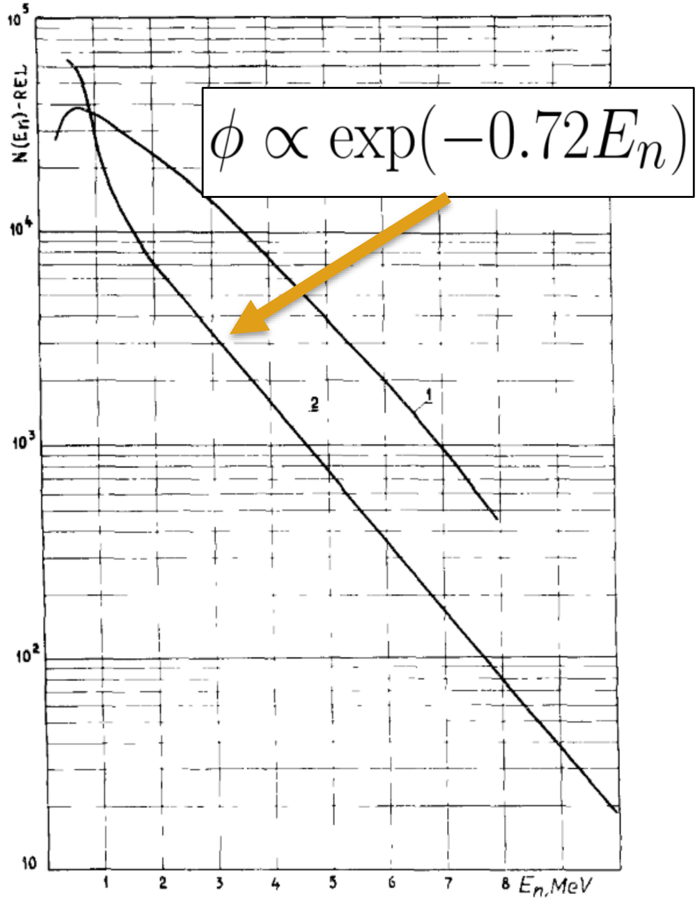
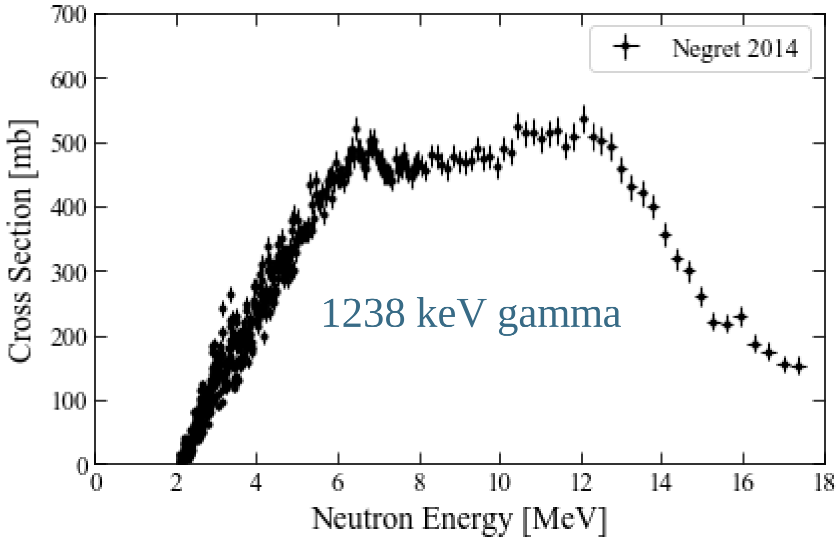


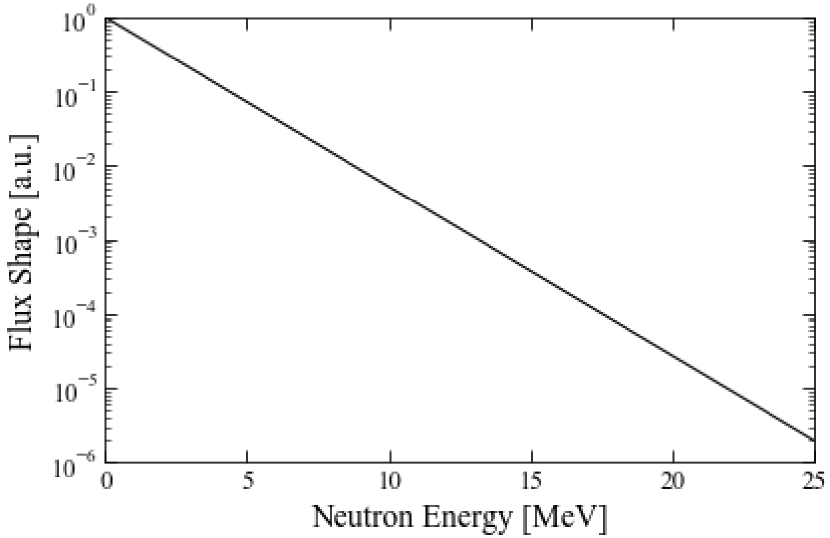
Ahmed, M. R., *et. al.*, NIM 117(1974)

- The flux was measured using threshold reactions and fit to an exponential
  - No data points were shown, and there was no uncertainty given on the fit parameter 0.72
- The flux was therefore re-fit using GELINA measurements of ^{56}Fe and $^{47,48,49}Ti$
  - ^{56}Fe : A. Negret, et. al., Cross-section measurements for the $^{56}Fe(n, xn\gamma)$ reactions, Phys. Rev. C 90 (2014) 1–15.
  - Ti: A. Olacel, et. al., Neutron inelastic scattering measurements on the stable isotopes of titanium, Phys. Rev. C. 96 (2017) 1–12.

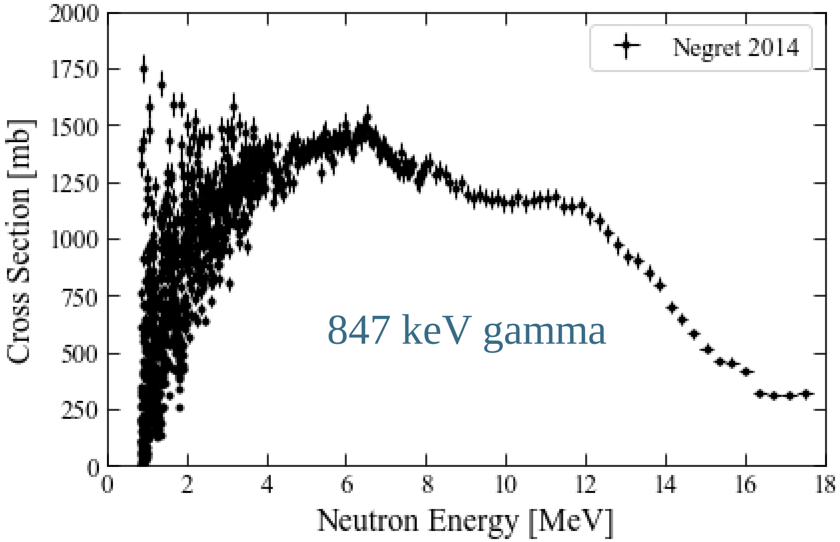
The differential data was integrated over the spectrum functions



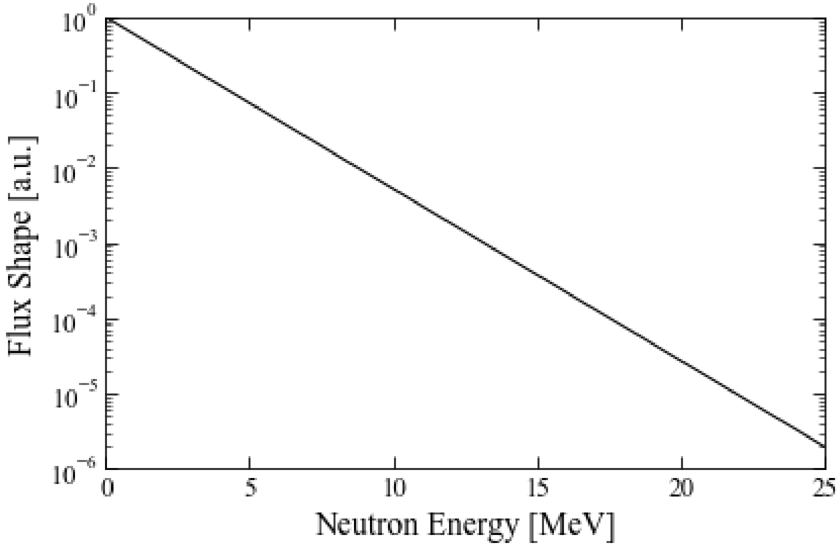
$\otimes$



$= \sigma_{1238}$



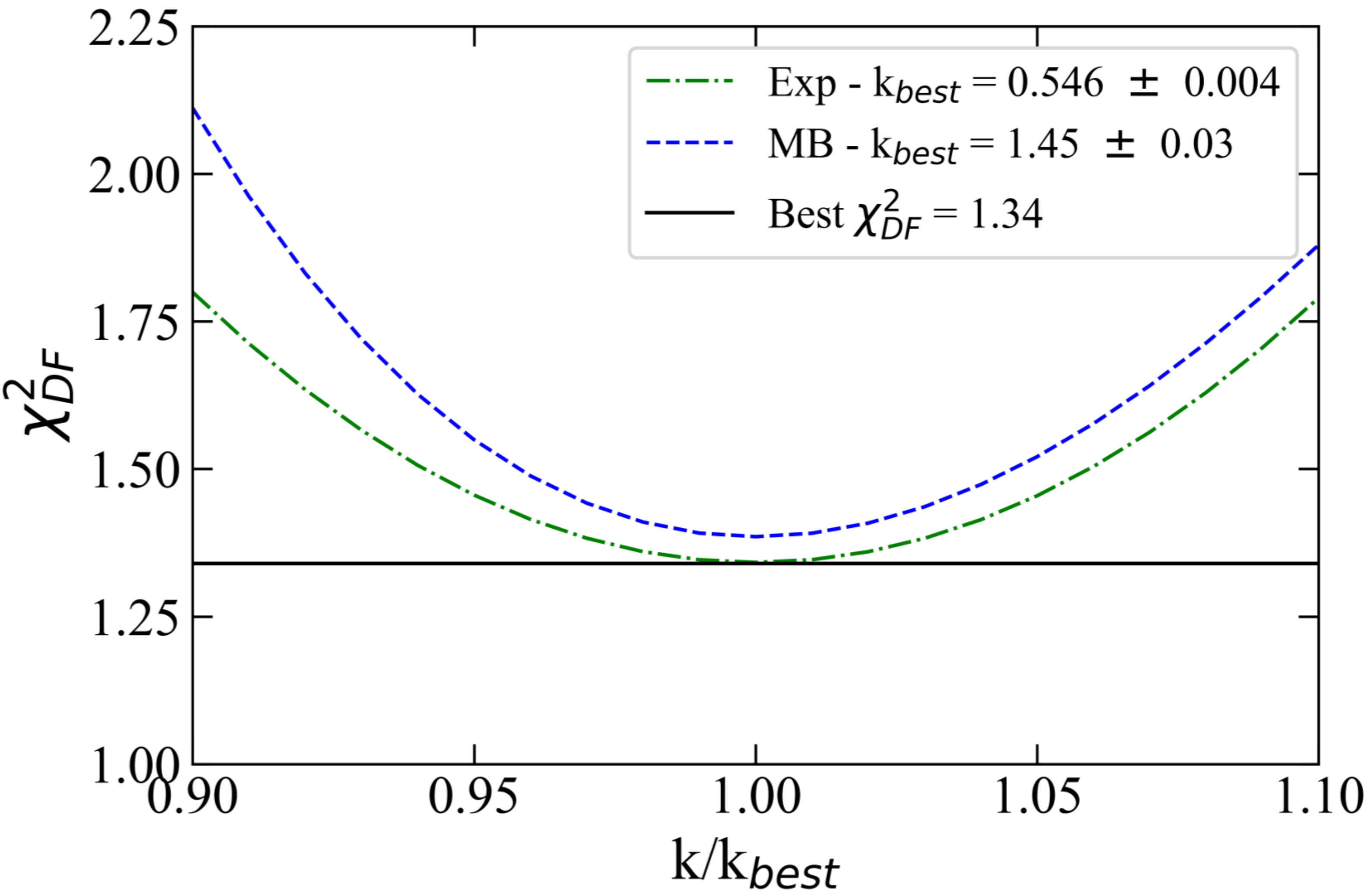
$\otimes$



$= \sigma_{847}$

$$\frac{\sigma_{1238}}{\sigma_{847}} = I_{1238}$$

An exponential flux shape provided the best fit to the ATLAS ratios



Pure Exponential

$$\phi(E_n) \propto \exp(-kE_n)$$

$\chi^2_{DF} = 1.34$

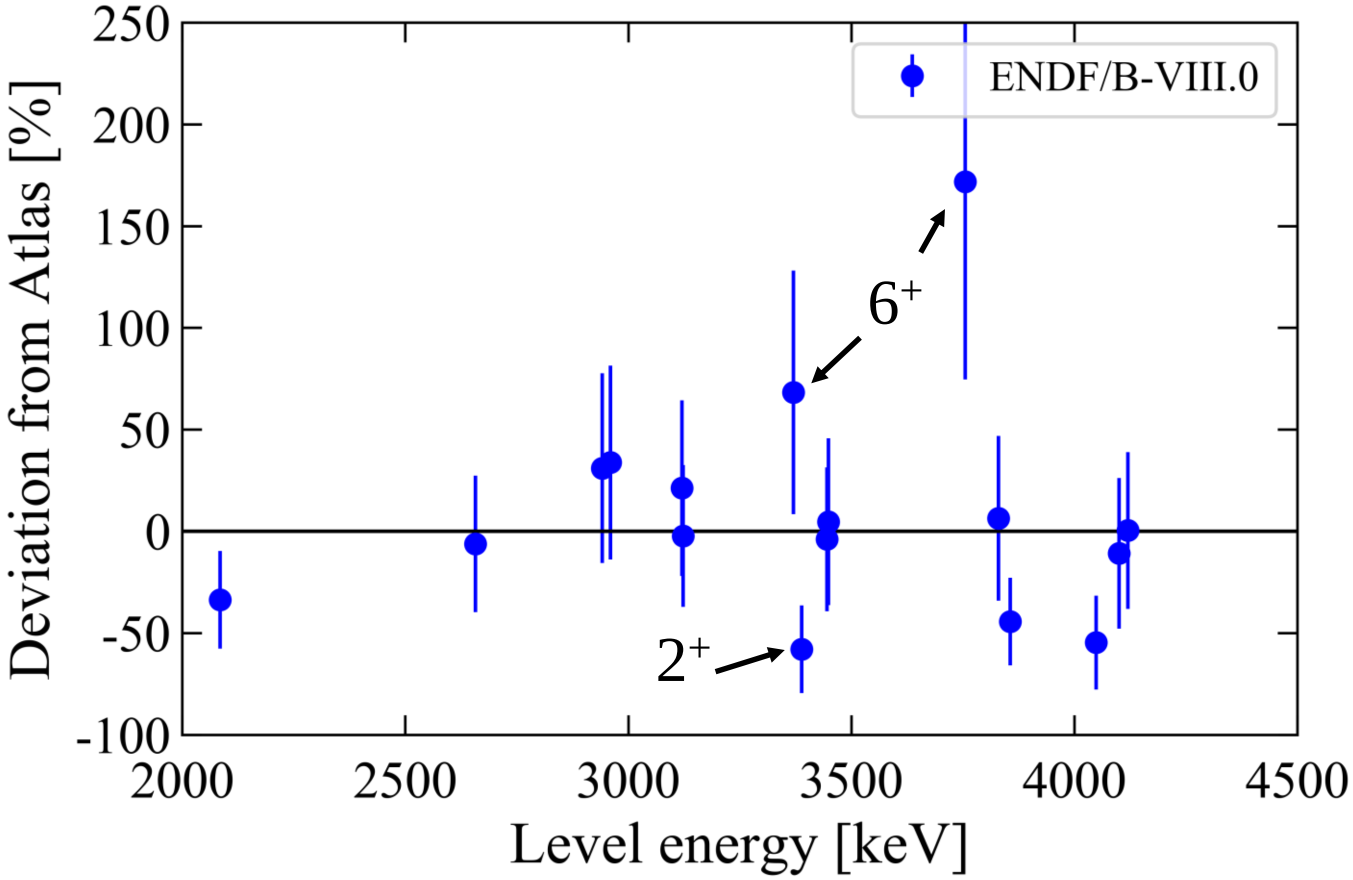
Maxwell-Boltzmann

$$\phi(E_n) \propto \sqrt{\frac{E_n}{k^{3/2}}} \exp\left(-\frac{E_n}{k}\right)$$

$\chi^2_{DF} = 1.38$

With the flux shape determined, this database can be used as a benchmark to check ENDF evaluations of inelastic scattering gammas

The first step is to check ^{56}Fe, as validation of this method



- Differences relative to the dominant gamma in the nucleus give insight into the gamma cross sections within the inelastic channel
- Absolute differences give insight into the elastic/inelastic ratio as well
- For ^{56}Fe, these give the same information because the dominant gamma is the Atlas normalization

Conclusions

- The final flux shape is an exponential, with k = 0.546 ± 0.004
- This large, consistent database will allow for large-scale, consistent benchmarking of the evaluated inelastic scattering gammas in ENDF
- Many isotopes without sufficient differential data are in the ATLAS
- This can help quantify uncertainties on those evaluations

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