State of the EMPIRE

Progress, future, and issues

M. Herman, R. Capote, B. V. Carlson, T. Kawano,
G.P.A. Nobre, H. Sasaki, M. Sin, A. Trkov

July 12, 2024

Los Alamos NATIONAL LABORATORY EST. 1943

LA-UR-24-26517

Progress

Direct interaction – multi-band couplings to improve the direct contribution affecting neutron emission channels and indirectly fission.

Deuteron-induced reaction – including competition between elastic breakup, inelastic breakup with absorption of only a neutron or a proton or both.

Fission – the optical model for fission extended to be valid at deep sub-barrier energies can provide accurate cross sections in special cases such as triple humped barriers with very narrow third well, photo-fission, and now for (d,pf) probabilities.

Level density – a new model "Constant Temperature + EGSM Fermi Gas".

EMPIRE 3.2 Malta => EMPIRE 3.3 The Pyramids

Covariances - distinguish incoming and outgoing channel in sensitivities.

New formatting capabilities - formatting of γ-lines, discrete level cross sections in (n,d), (n,t), (n,He3), cross-reaction correlations in Kalman covariances using EMPIRE ENDF-6 infrastructure.

Plotting and comparison with exp data - operation on c4 files, plotting guided by the ENDF-file contents.

New GUI – under development.

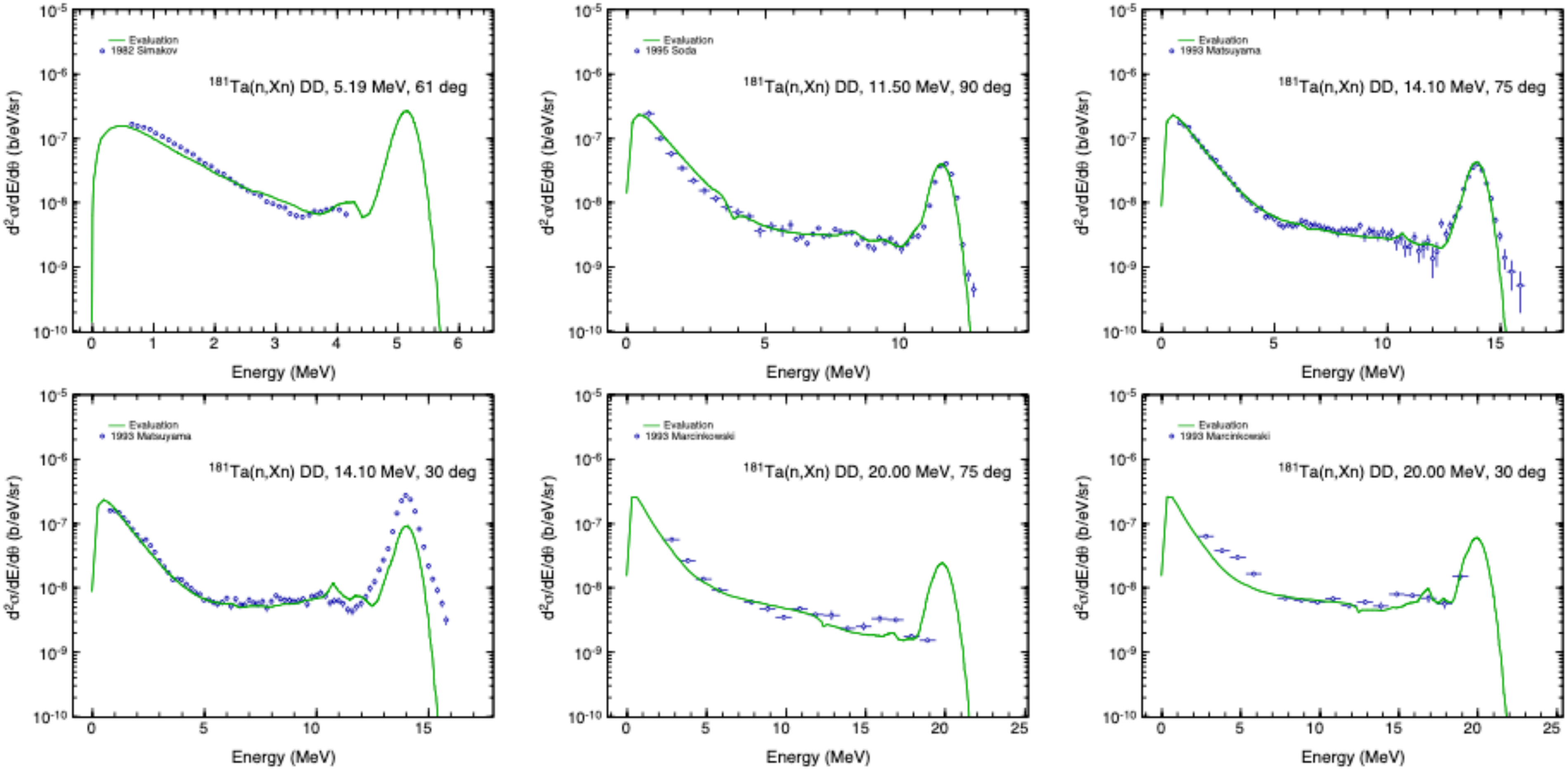
Future

- **Modernization -** moving physics sources to Fortran 90+
  - free style
  - no commons
  - better modularization
  - dynamically allocated memory
  - extensive use of derived types (e.g. type nucleus)
  - porting bash scripts to python
  - replacing Fortran in main control-unit by Julia?
  - FORD documentation
  - moving to GitHub (very soon!)

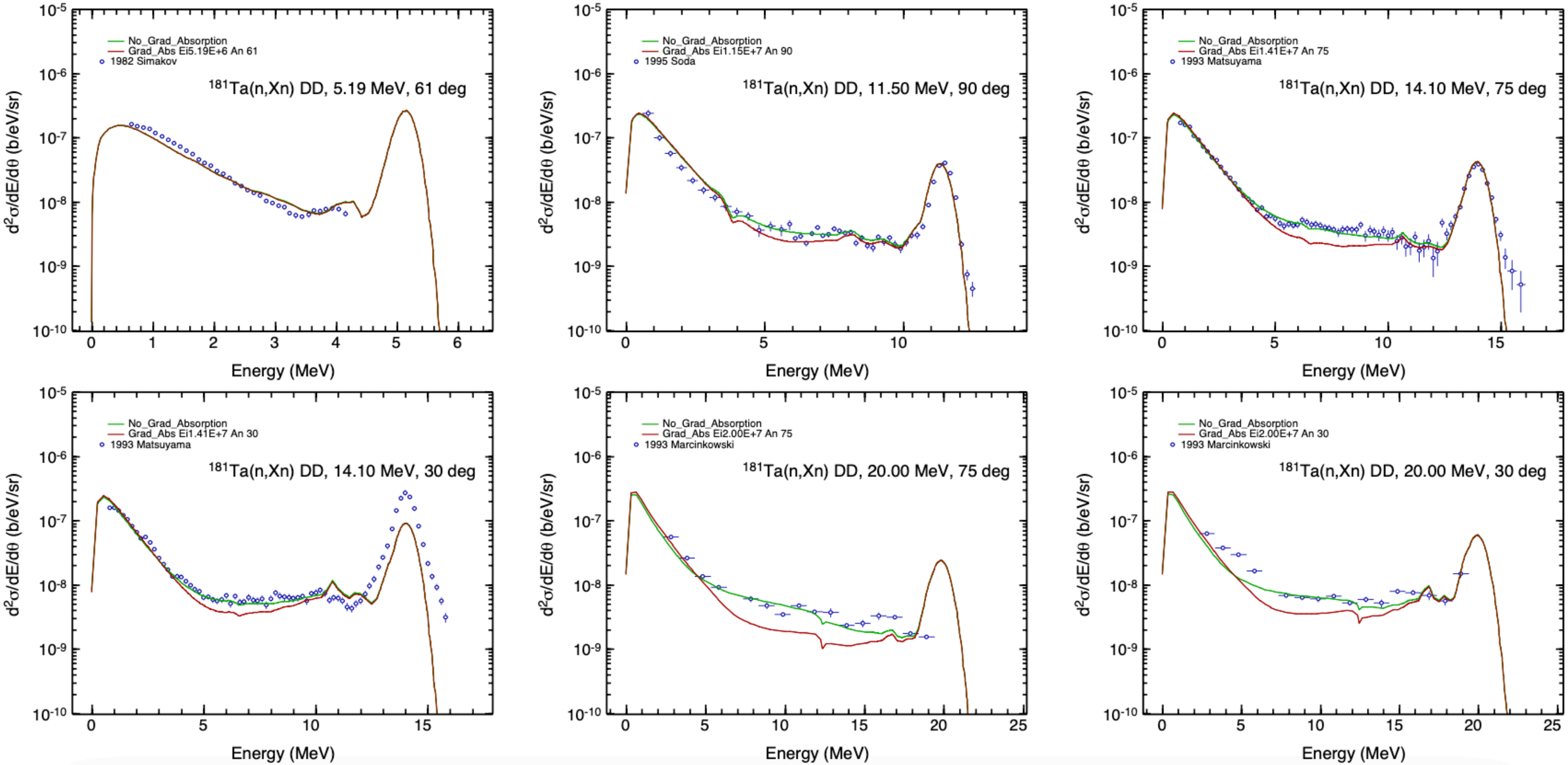
- **New extension -** FRESCO
- **ENDF -** make all first emissions exclusive

Use AI e.g. completing decay schemes, help with coding,…

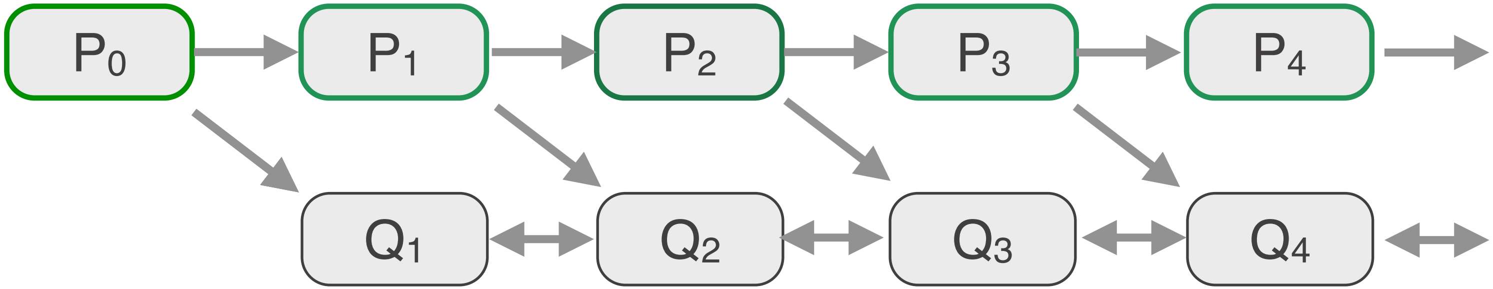
The issue - Ta181 spectra look great but …



...when we do it right, i.e. consider gradual absorption



Gradual absorption



$R =< V_{ub}^2 > / < V_{uu}^2 >$

$$T_1 = T_{om}\frac{< V_{ub}^2 > \rho_1^b(E)}{< V_{ub}^2 > \rho_1^b(E) + < V_{uu}^2 > \rho_1^u(E)} = T_{om}\frac{R}{(R-1)+\frac{\rho_1(E)}{\rho_1^b(E)}}$$

$$T_n = \left(T_{om} - \sum_{i=1}^{n-1} T_i\right)\frac{R}{(R-1)+\frac{\rho_n(E)}{\rho_n^b(E)}}$$

Gradual population of Q- stages

E (MeV)	Q1	Q2	Q3	Q4	Σ
5	0.60	0.35	0.04	0.001	0.991
11	0.26	0.38	0.27	0.08	0.99
14	0.19	0.30	0.30	0.16	0.95
20	0.11	0.18	0.24	0.23	0.76

Conundrum

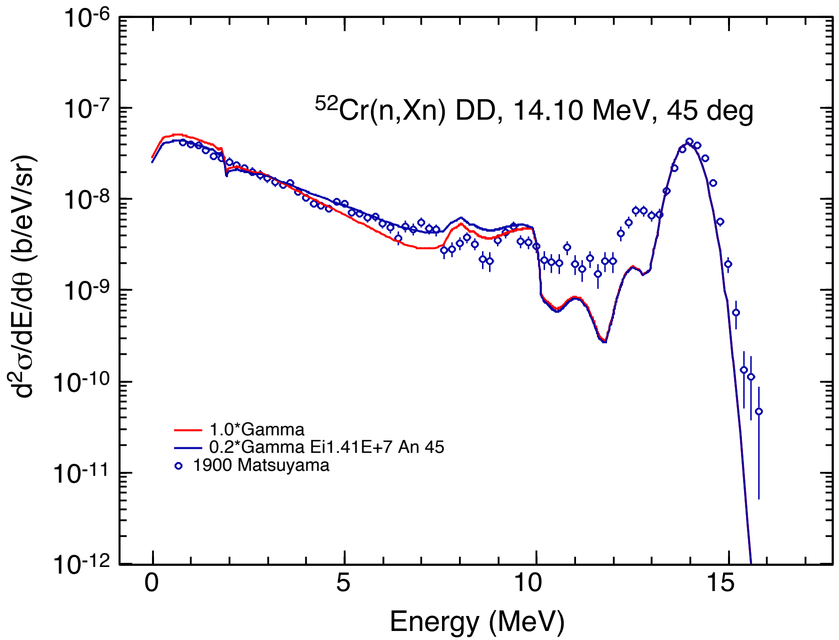
- There is solid justification for P-Q separation
- We can't expect full incoming flux to go to Q1 => under-calculation of neutron spectra
- At Varenna 2023 talk we discussed possible remedies:
  - *Ratio unbound->bound to unbound->unbound (2.5 - questionable)*
  - Strong backward transition P2 => Q1 (negligible)
  - More steps in MSD (unlikely)
  - More steps in MSC (improbable)
  - *Explicit use of spin and parity (? doubtful)*

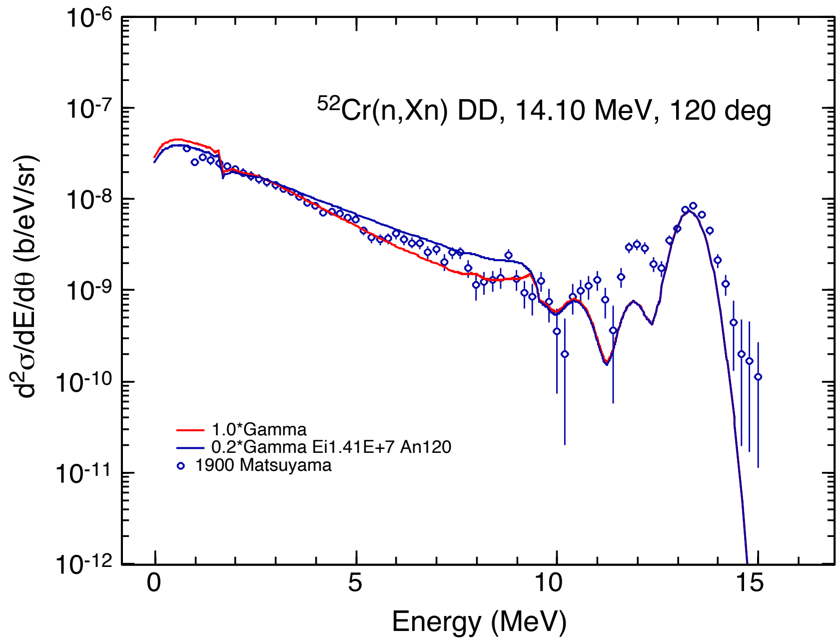
Consider slowing down equilibration process => lowering $\Gamma^{\downarrow}$ in Q space

$$\Gamma_n^{\downarrow} = 2\pi \sum_m \overline{V_{n,m}^2} \rho_m^b = 2(n+1) \int_0^B P_p(\epsilon) W(\epsilon) d\epsilon + 2n \int_0^E P_h(\epsilon) W(\epsilon) d\epsilon$$

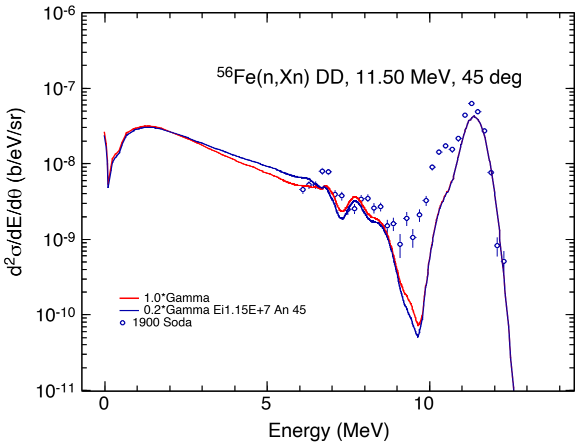
where $W(\varepsilon) = 0.003\varepsilon^2$ [MeV^{-1}]. **Default calculations with 0.003/5 follow…**

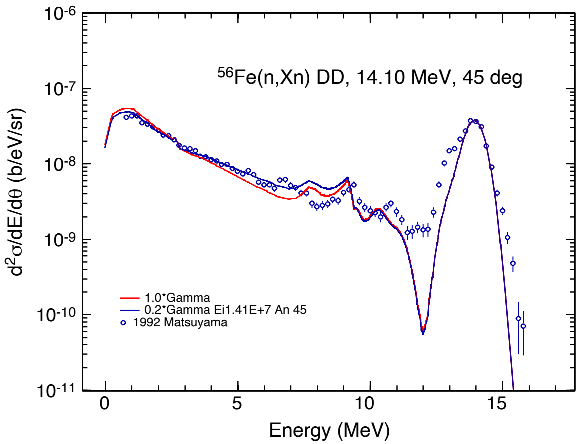
Neutron spectra (DD) for ^{52}Cr with grad. abs.

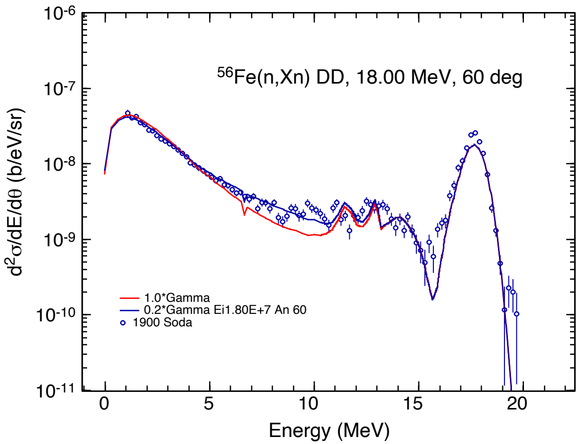




Neutron spectra (DD) for ^{56}Fe with grad. abs.

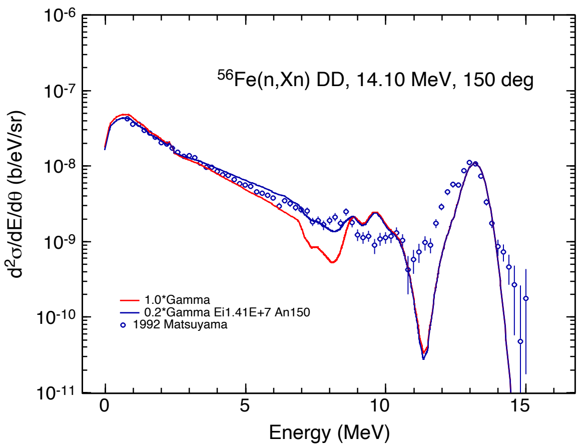


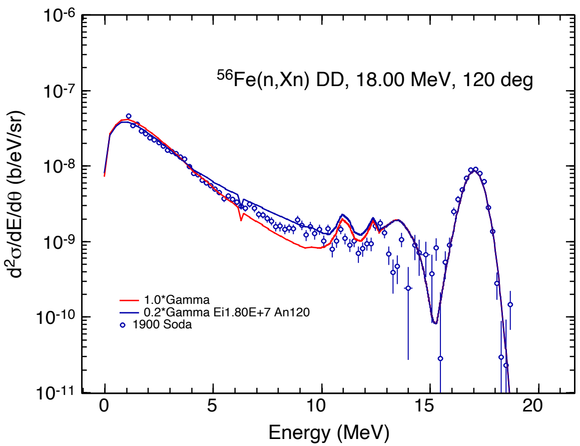




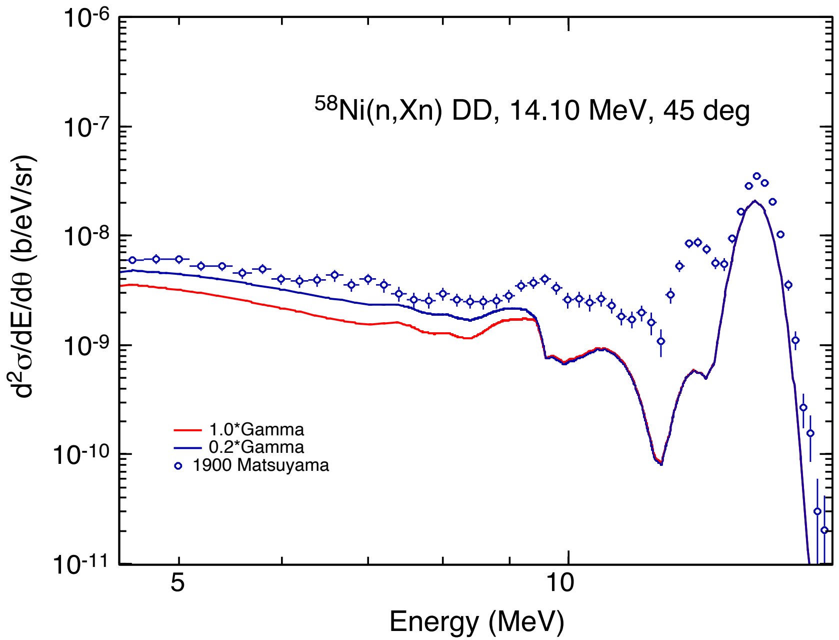
For Cr52 and Fe56 reducing Gamma-down seems to have positive effect.

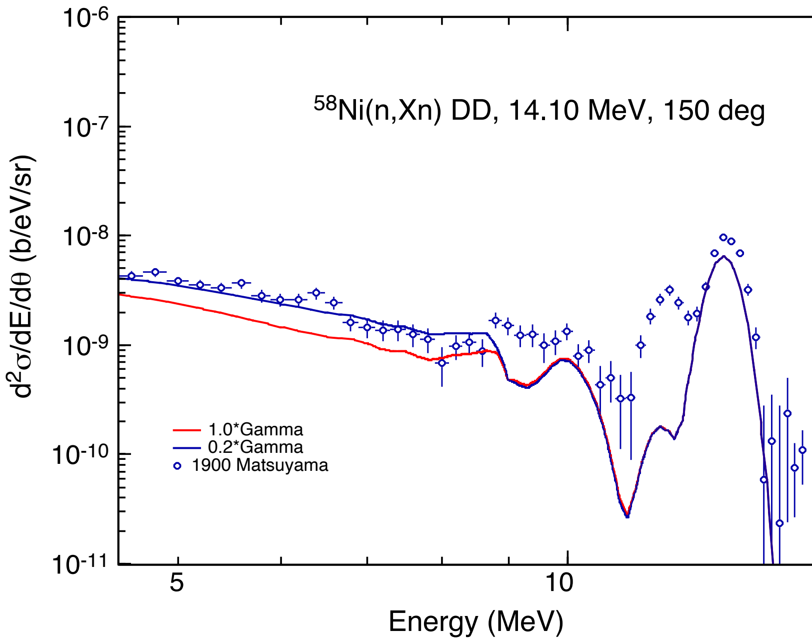
Similarly for Ni58 (next slide)



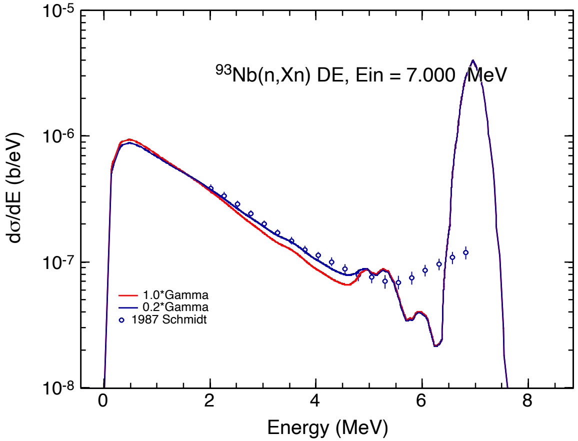


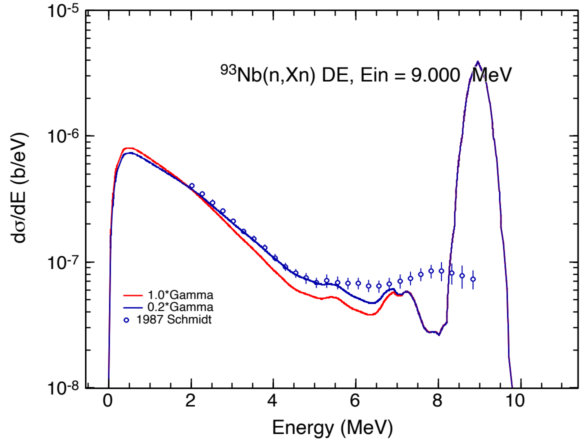
Neutron spectra (DD) for ^{58}Ni with grad. abs.

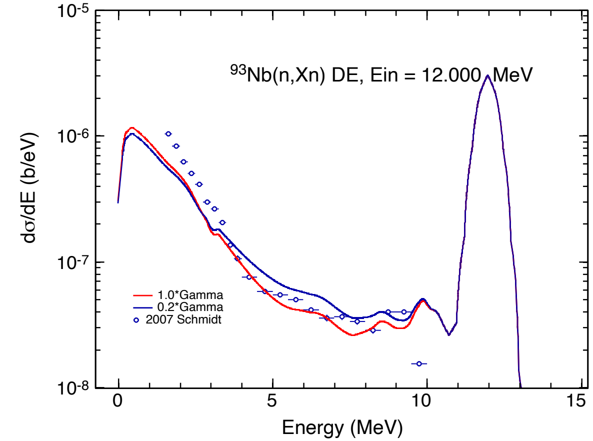


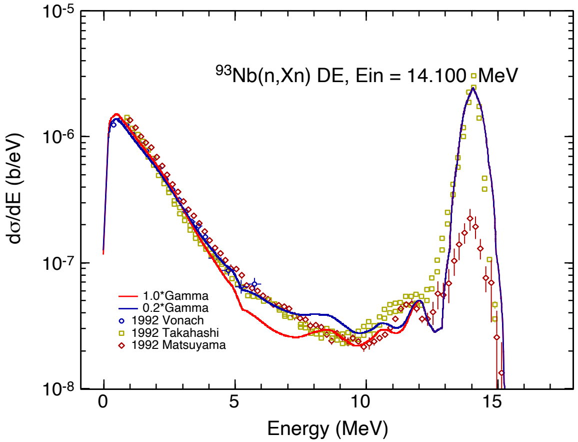


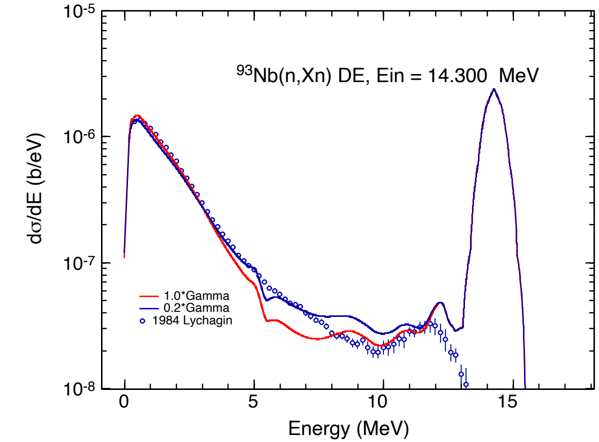
Neutron spectra (DE!) for ^{93}Nb with grad. abs.

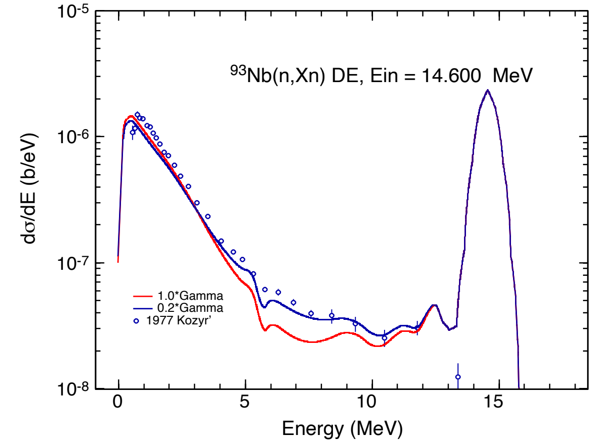




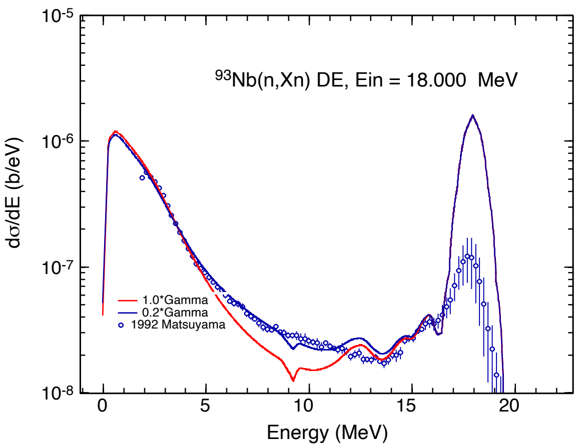


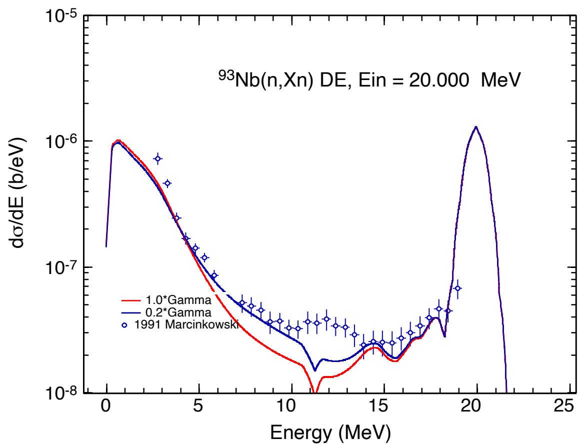


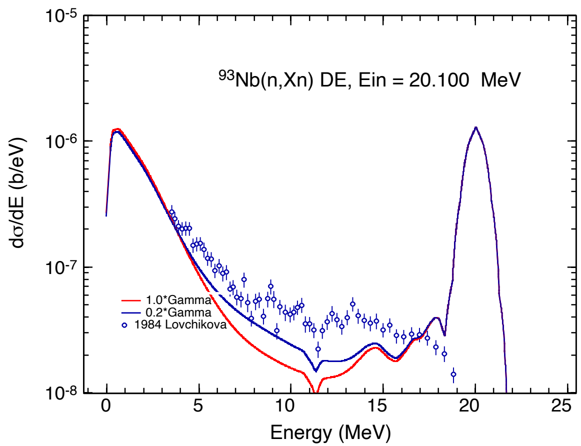


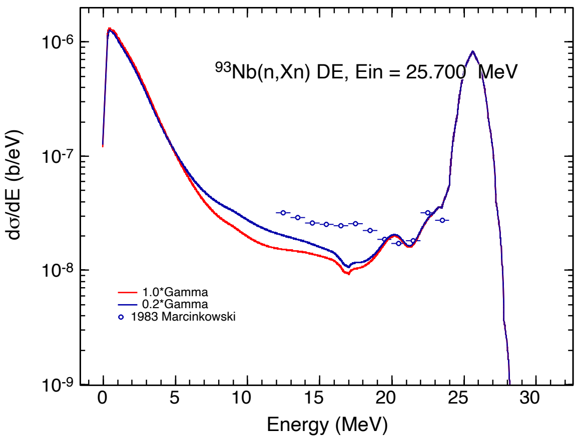


Neutron spectra (DE) for ^{93}Nb with grad. abs.





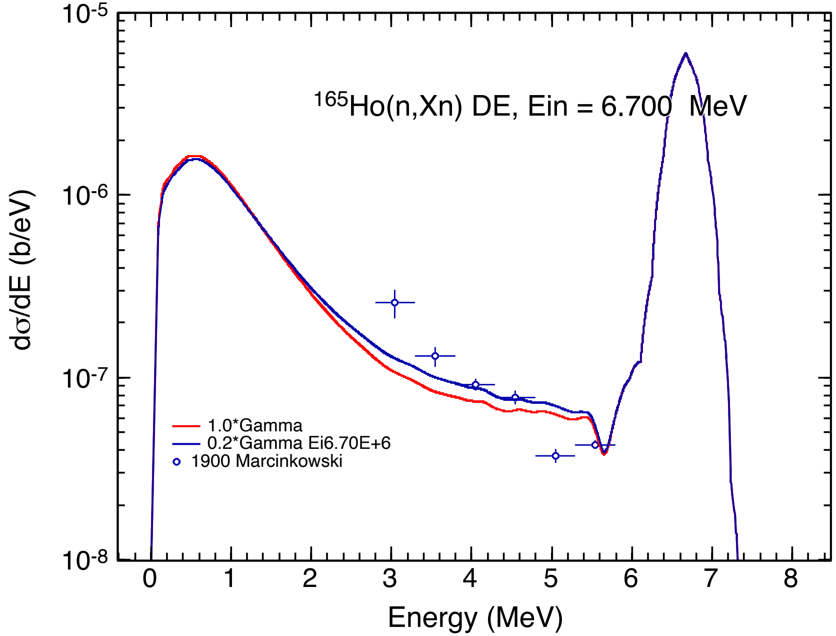


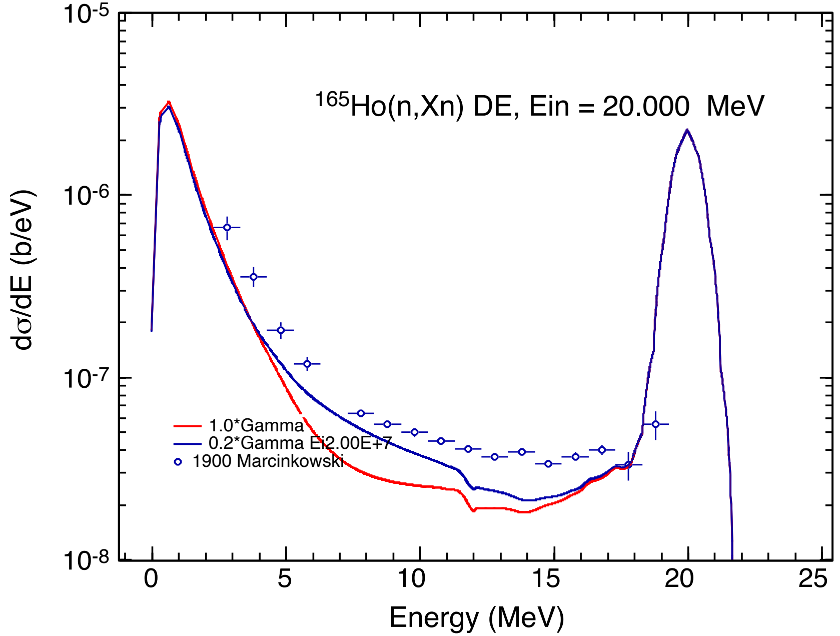


Also for Nb93 the results improve when reaching equilibrium is delayed but there is a clear under calculation at 20 and 25.7 MeV.

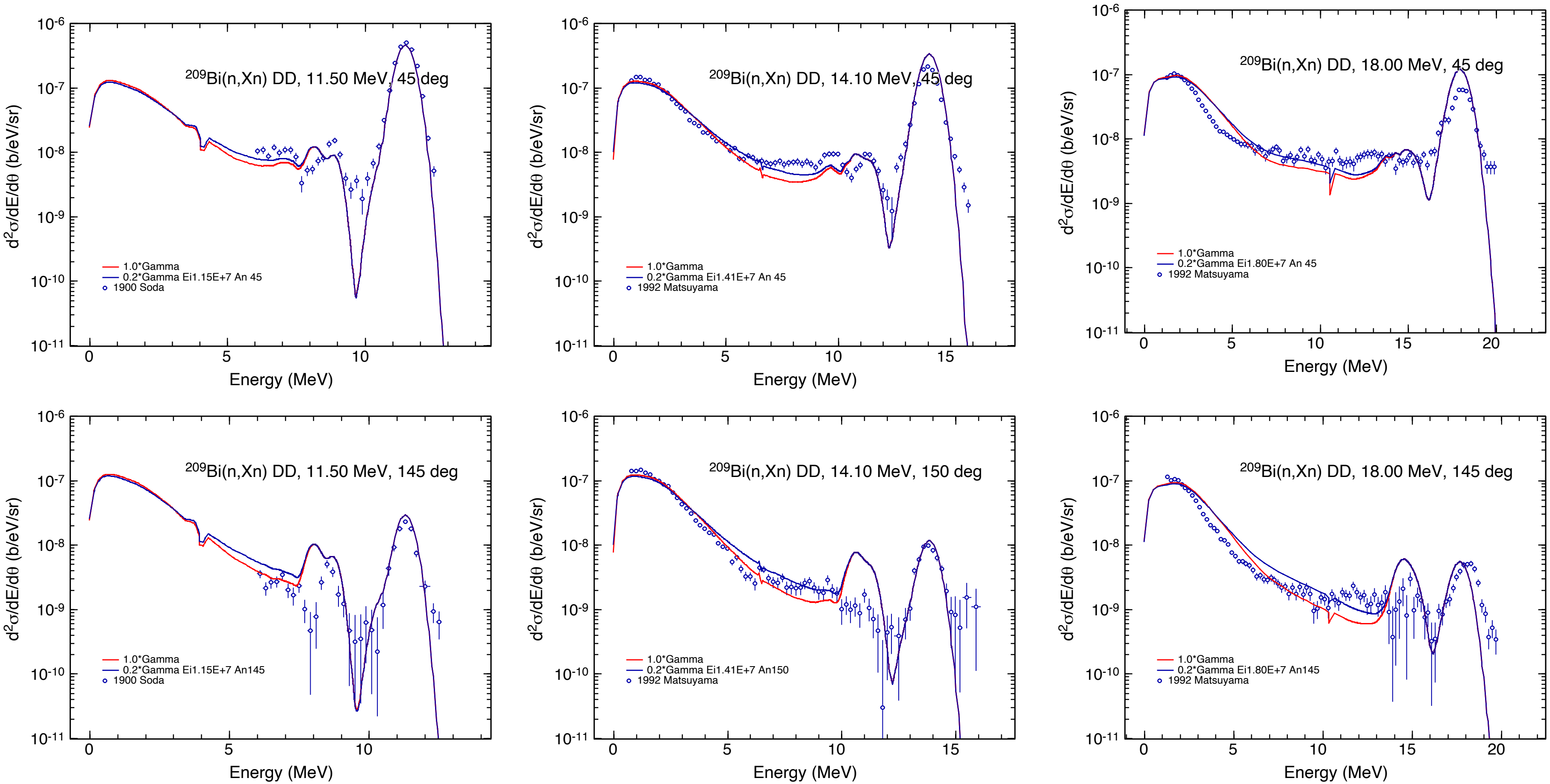
Note - experimental data are somewhat inconsistent.

Neutron spectra (DE) for ^{165}Ho with grad. abs.

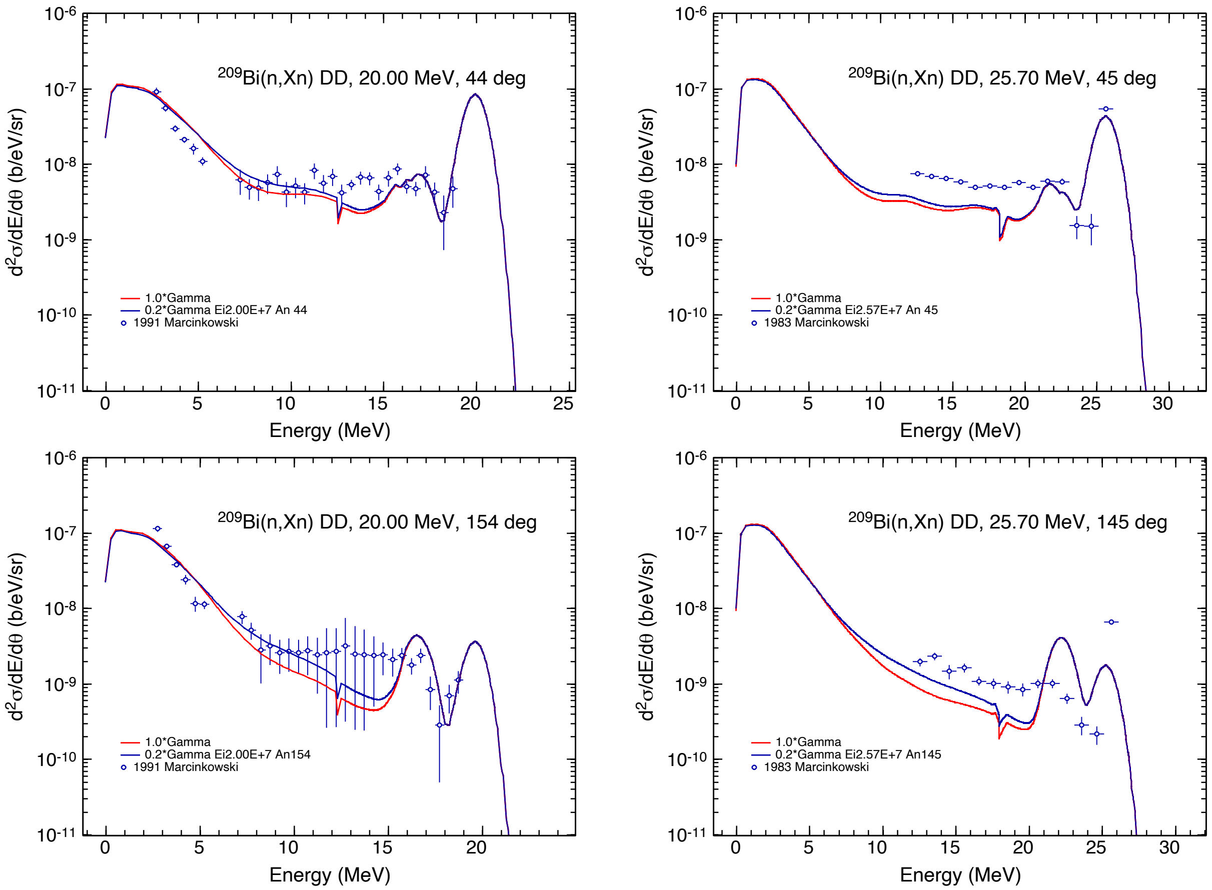




Neutron spectra (DD) for ^{209}Bi with grad. abs.



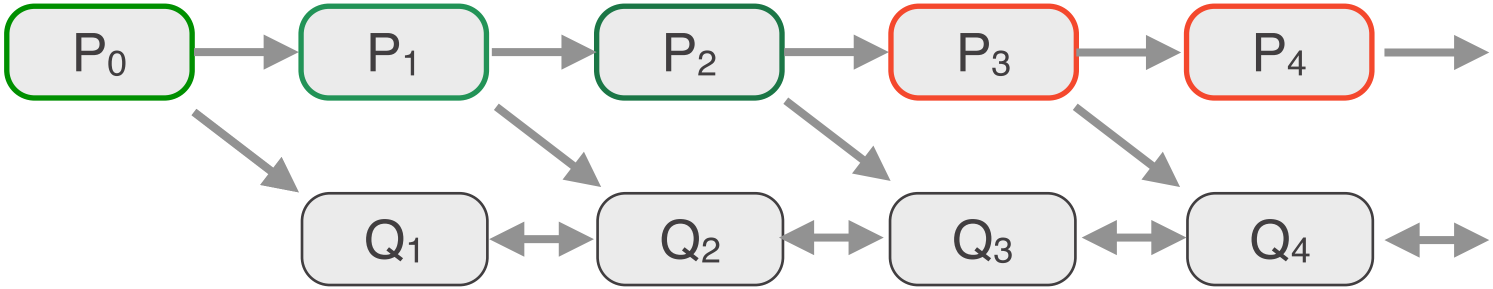
Neutron spectra (DD) for ^{209}Bi with grad. abs.



Considering these are default calculations agreement for Ho165 and Bi209 up to 18 MeV is acceptable and effect of lowering Gamma-down is positive.

20.0 MeV and especially 25.7 MeV are under-calculated.

Final thoughts



- MSD & MSC modeling is disconnected
  - Flux flow through P space and Q space population is based on phase-space arguments independently of MSD and MSC
    - Clue to the solution is in increasing population of Q_1 (Q_2) stages, or significant contribution to middle of the spectrum by $P_{3,4\ldots}$ decay (unrealistic)

Conclusions

- Good job for bad reasons
  - MSC without gradual absorption
  - exciton model
- Effect of $\Gamma^{\downarrow}$ is limited but generally makes improvement
- Compensating grad. abs. with decrease of $\Gamma^{\downarrow}$ is possible but only below 20 MeV
- **The problem of gradual absorption remains open!**

- Possible solutions:
  - switching to 1p-1h level densities following Jens Bisplinghoff (MSC and exciton are using level densities incompatible with two-body interaction)
  - proper accounting for spins and parities could change Q-space population (?)
  - microscopic p-h level densities (?)
  - **allow for** $R = < V_{ub} > / < V_{uu} >$ **grater than 1**

The End

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…but there are things TO DO!