Quantifying the Impact of Fission Yields on Prompt Particle Emission

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Qualitative Expectations

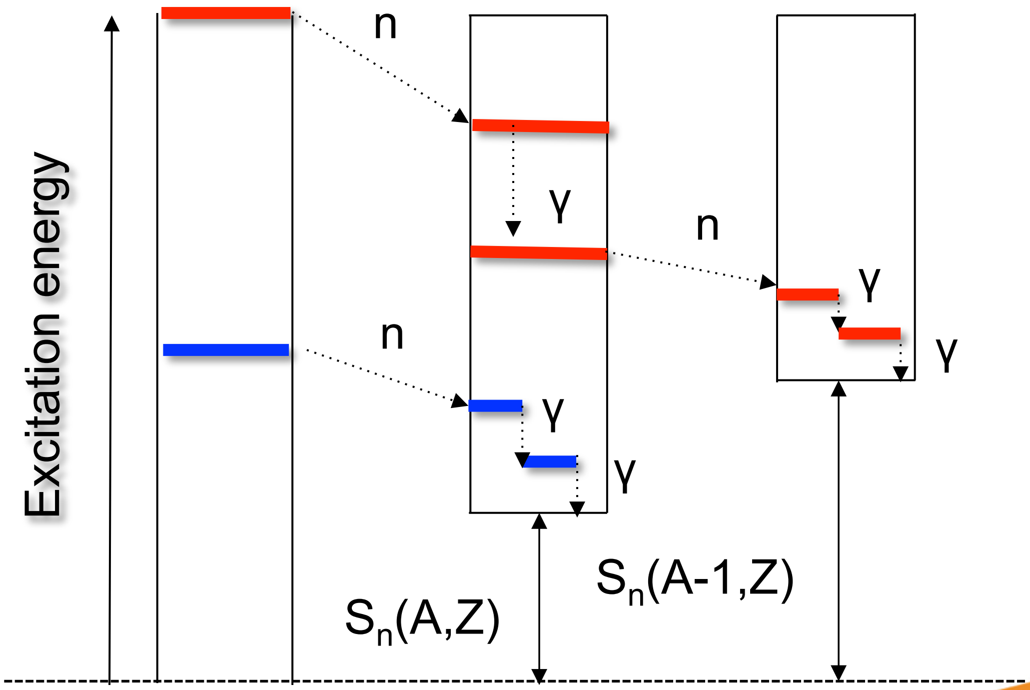
- Energy in fission shared between TKE and TXE

$$TXE = \boxed{E_n + B_n + M(A_C, Z_C)c^2 - M(A_1, Z_1)c^2 - M(A_2, Z_2)c^2} - TKE$$

Q-value: E_n and B_n are zero for spontaneous fission!

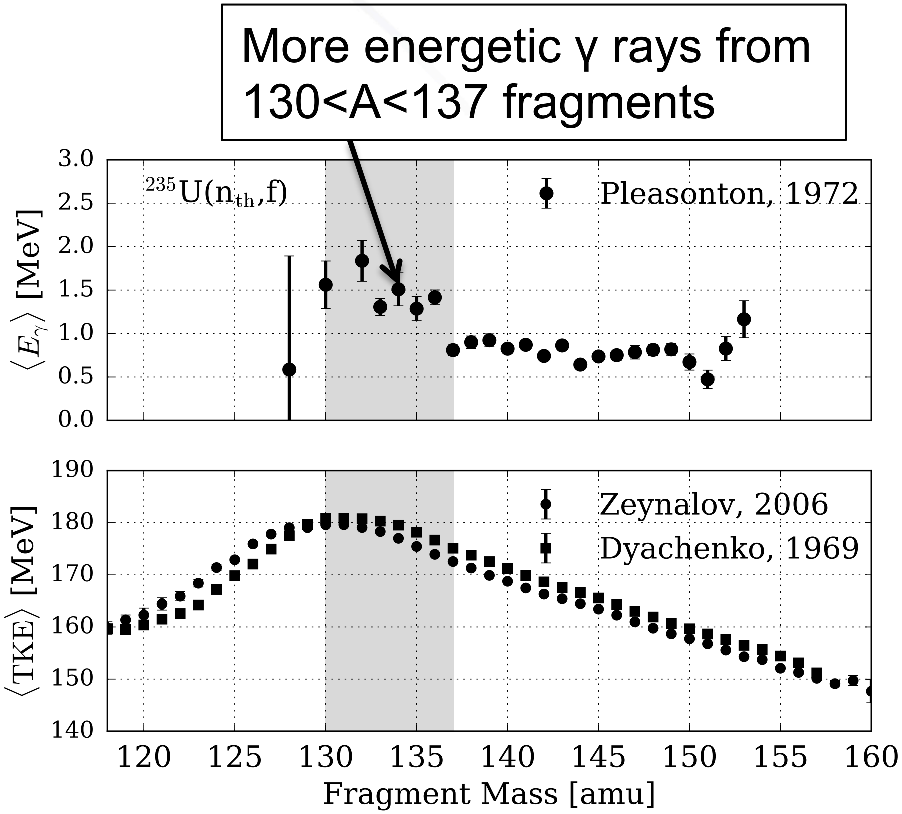
- Each γ-ray or n emitted conserves the E & J^{π} in Hauser-Feshbach

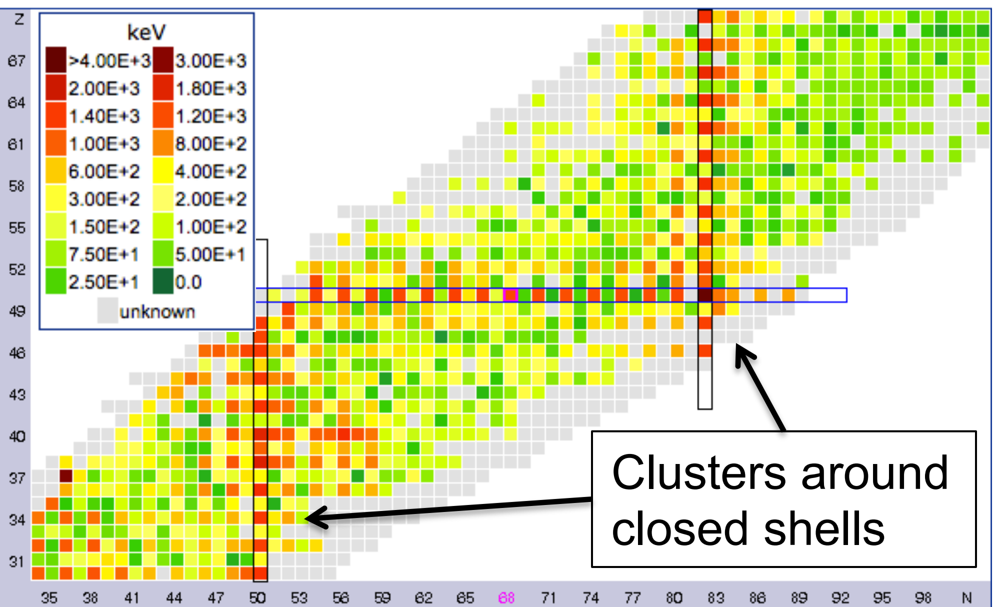
- Fragments with large S_n will emit fewer n



Qualitative Expectations

- Gamma transitions will depend on the initial angular momentum distribution (spin-cutoff α)
- Fragments with high-lying 1st excited states can lead to higher $<E_\gamma>$





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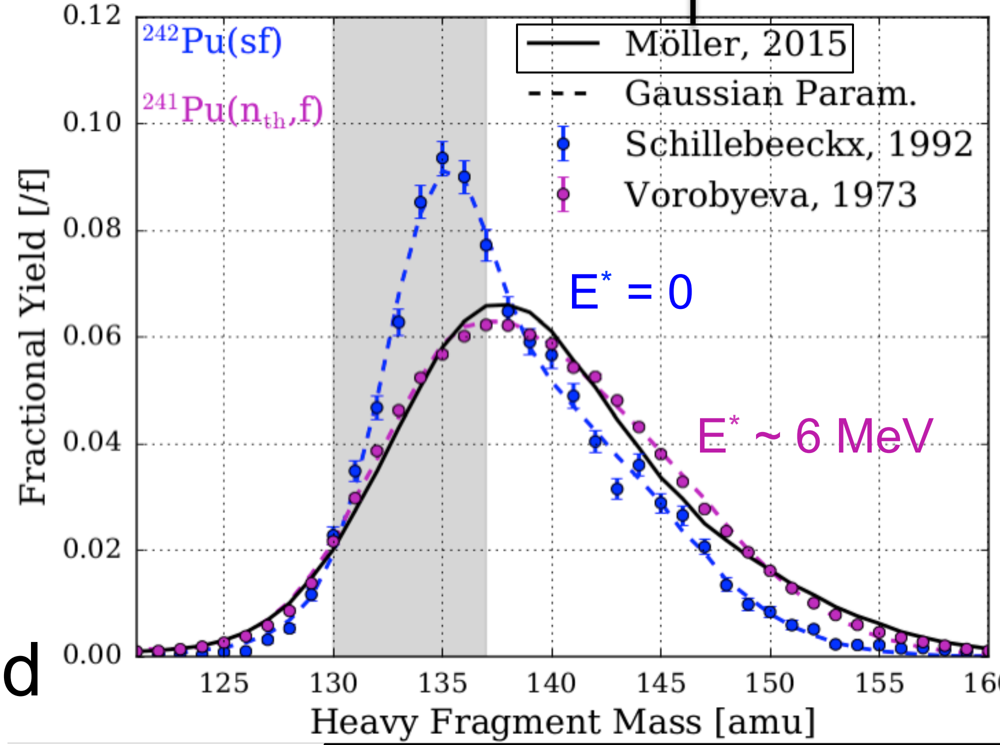
Trends in Experimental Yields

- Mass yields vary significantly with fission reaction and excitation energy!
- Increase in E^* fills in symmetric region
- Calculated yields can reproduce data with good agreement

From macro-micro model [1]

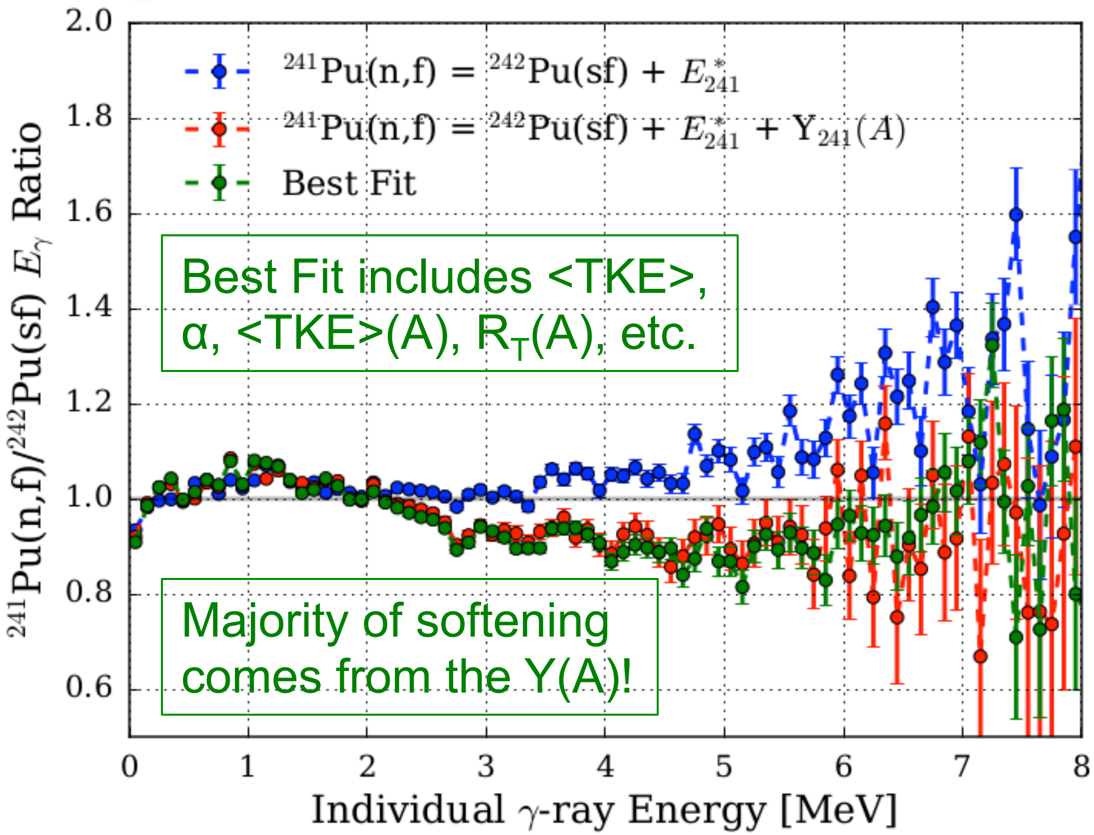


[1] P. Möller, T. Ichikawa EPJ A **51** 173 (2015)

If the Y(A) are very different for each fission reaction, the prompt particle emission should be too!

Spectral Hardening in Pu242

- Start with identical fission reactions, then add in E^* for Pu241(n_{th},f), then add different yields, etc.



- More E^* leads to harder PFGS
- Lower Y(A) in the 130<A<135 mass region softens Pu241(n_{th},f) PFGS

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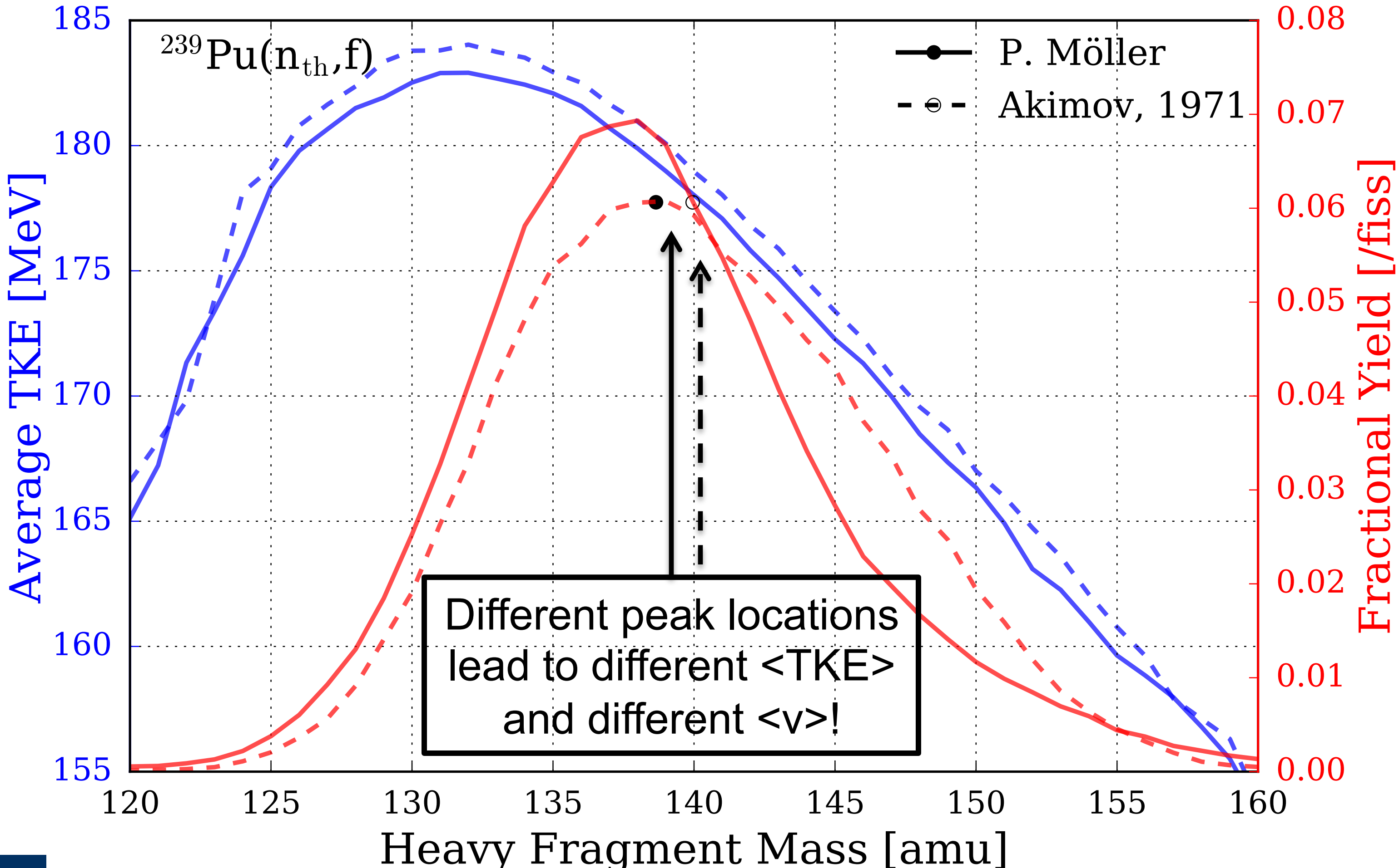
Calculated Yields and <ν>

$$Q = TXE + TKE$$

- <A_H> of Y(A) sets the <TKE>
- <TKE> sets the prompt neutron multiplicity



Uncertainty with Calculated Yields

- Swapping out the experimental for calculated Y(A) generates an error on the <v> or <TKE>

$$\delta\langle TKE\rangle \sim 1.0 \text{ MeV}$$

$$\delta\partial\langle TKE\rangle / \partial E_n \sim 0.18 \text{ MeV}$$

OR

$$\boxed{\delta\bar{\nu} \sim 0.13}$$

$$\delta\partial\bar{\nu} / \partial E_n \sim 0.05$$

Pu239(n_{th},f) <v> exp. error is ~0.005

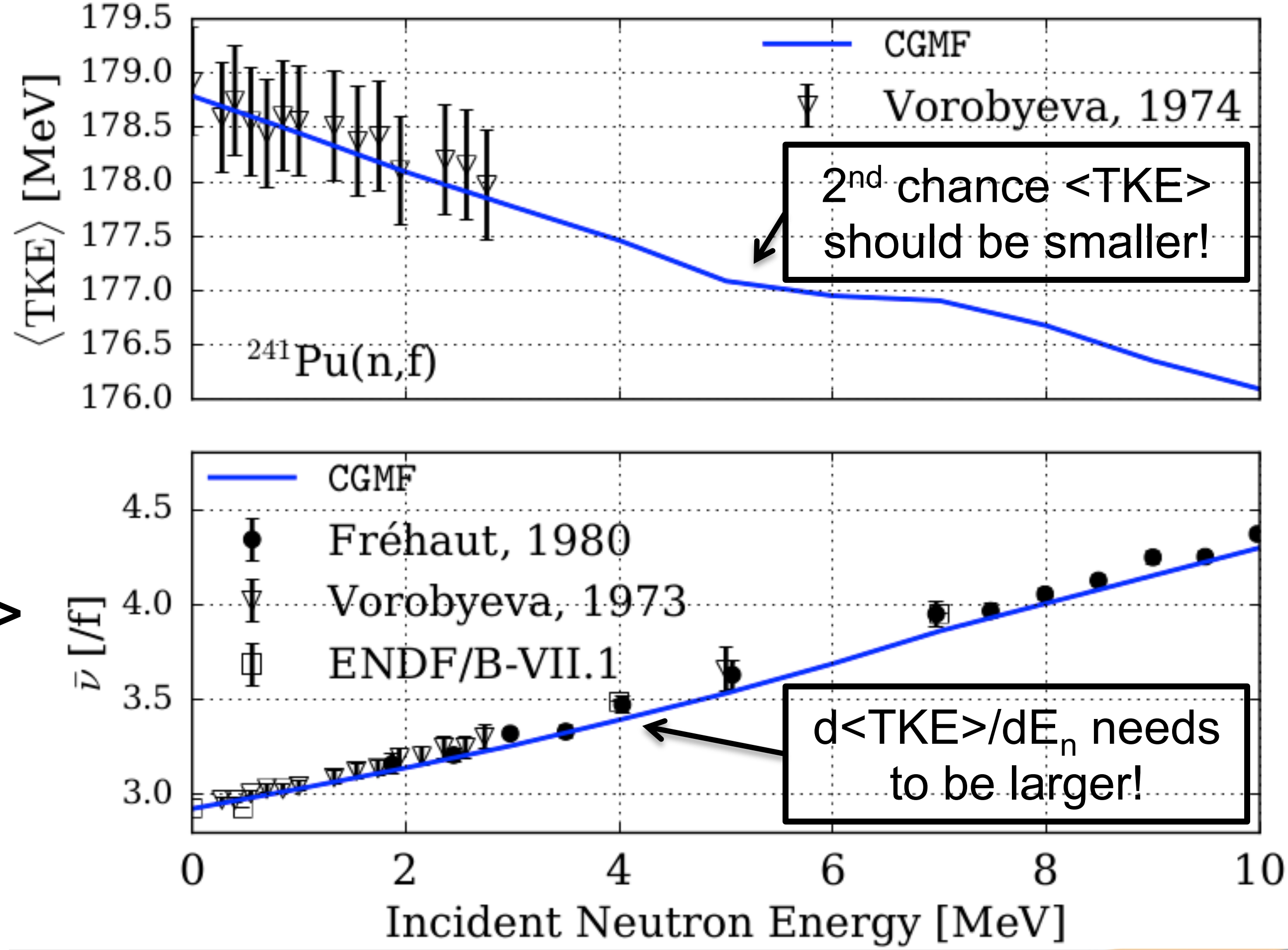
Worst-case scenario is for Pu239(n,f)

1. Improving Y(A) models
2. Excellent precision for unknown fission reactions!
3. Not at the precision needed for criticality, benchmarks, etc. yet

PFGS mostly unaffected by exp. vs. calculated Y(A)!

Pu241(n,f)

- Calculated yields perform well for Pu241(n,f)
- <TKE> errors are large…
- Use <v> to put constraints on unknown <TKE> parameters!



Conclusions

- Prompt n and γ-ray emission depends on Y(A)
  - Harder PFGS for fission reactions with larger Y(A) in 130<A<135 mass region
  - Lower <A_H> leads to larger <TKE> or a larger <v>

- Calculated Y(A) can reproduce <TKE> and <v> simultaneously in some fission reactions
  - In others, the error is about 1-3% on <v>

Thanks!

Funding Sources
NA-22
DOE

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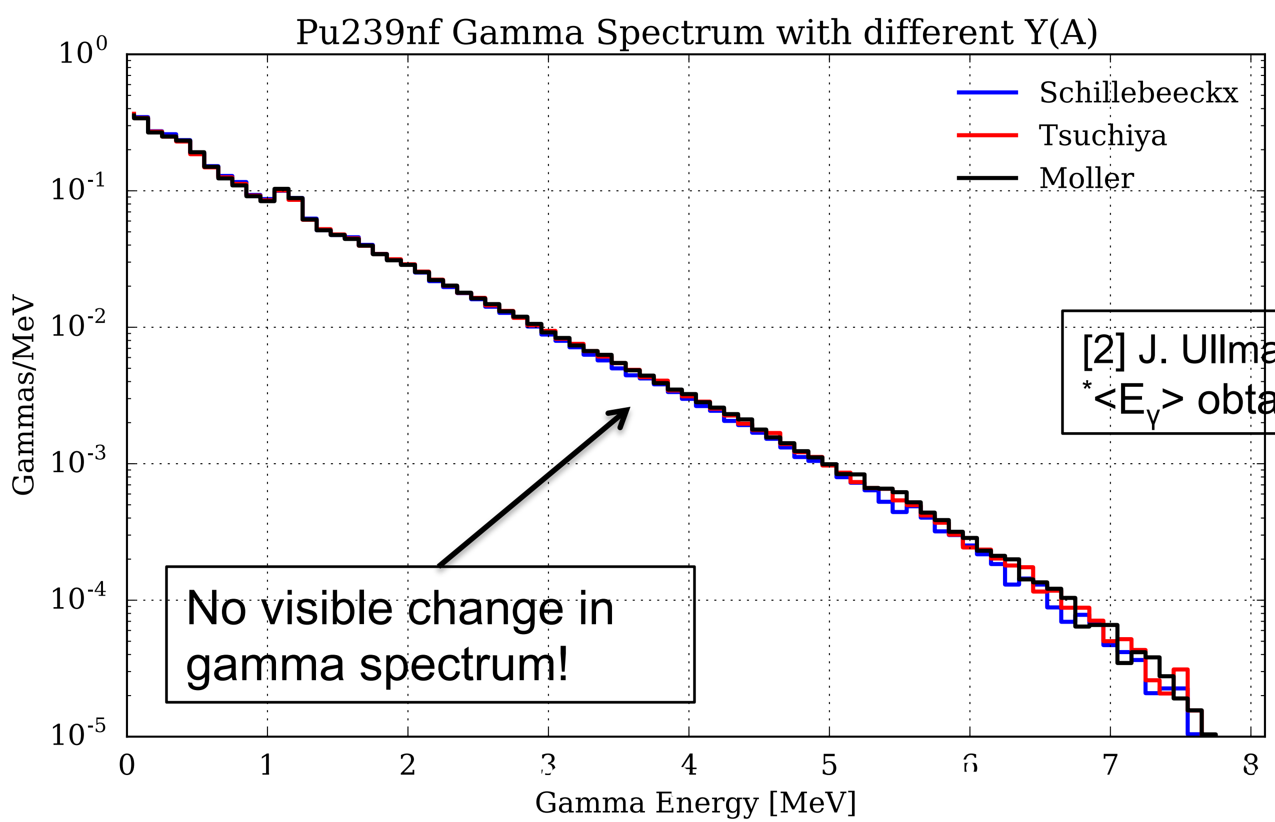
Extra

Pu239(n_{th},f) with calculated Y(A)

<1% change for different Y(A)!

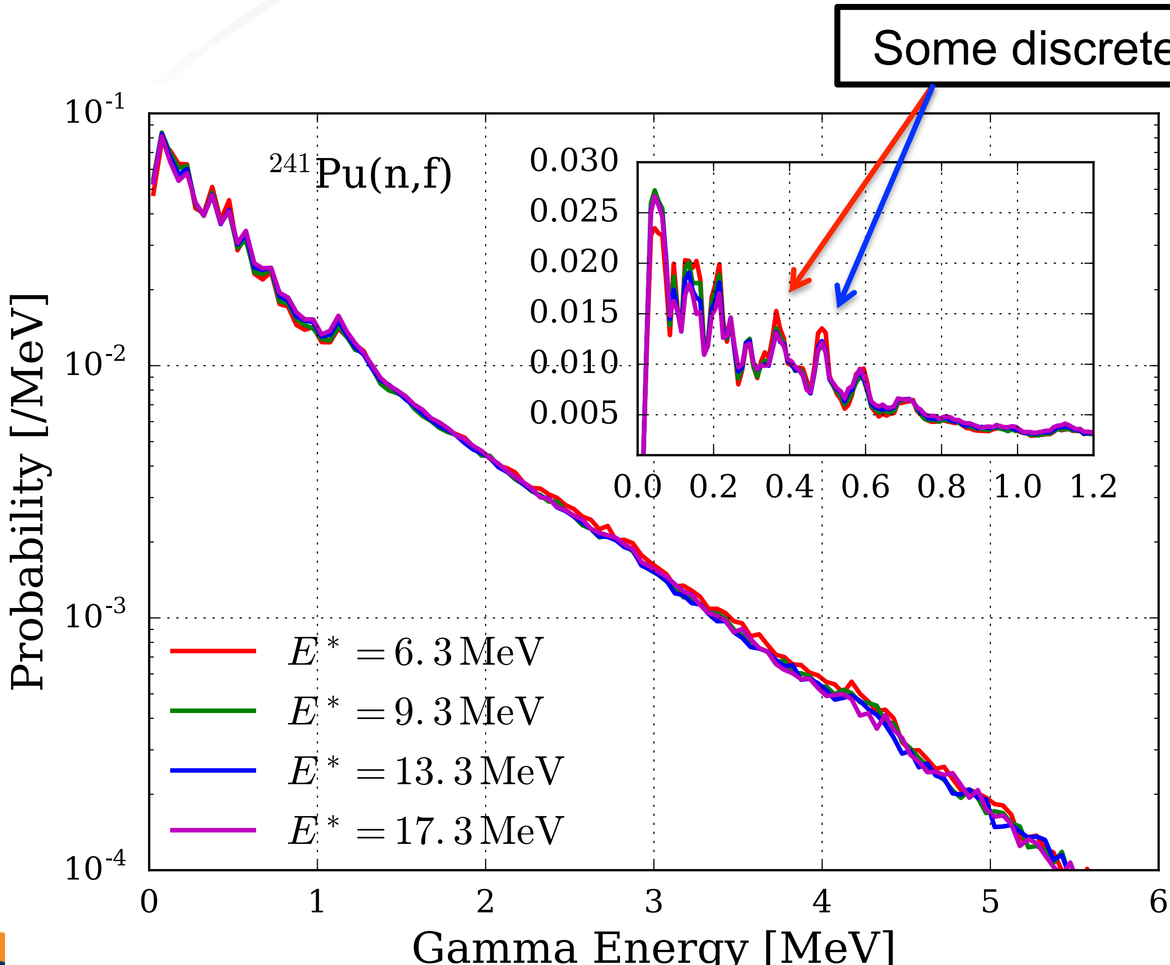
	$\langle N_\gamma \rangle$	$\langle E_\gamma \rangle$ [MeV]	$\langle E_{\gamma,Tot} \rangle$ [MeV]
Möller Y(A) [1]	7.24	0.91	6.59
Wagemans Y(A)	7.31	0.90	6.55
Tsuchiya Y(A)	7.26	0.91	6.60
Ullmann [2]	7.15±0.09	1.04*	7.46±0.06



[2] J. Ullmann *et al.* PRC **87** 044607 (2013)
*$\langle E_\gamma \rangle$ obtained by $\langle E_{\gamma,Tot} \rangle / \langle N_\gamma \rangle$

Prompt γ-ray Spectrum with E_n

- Very little dependence on excitation energy!

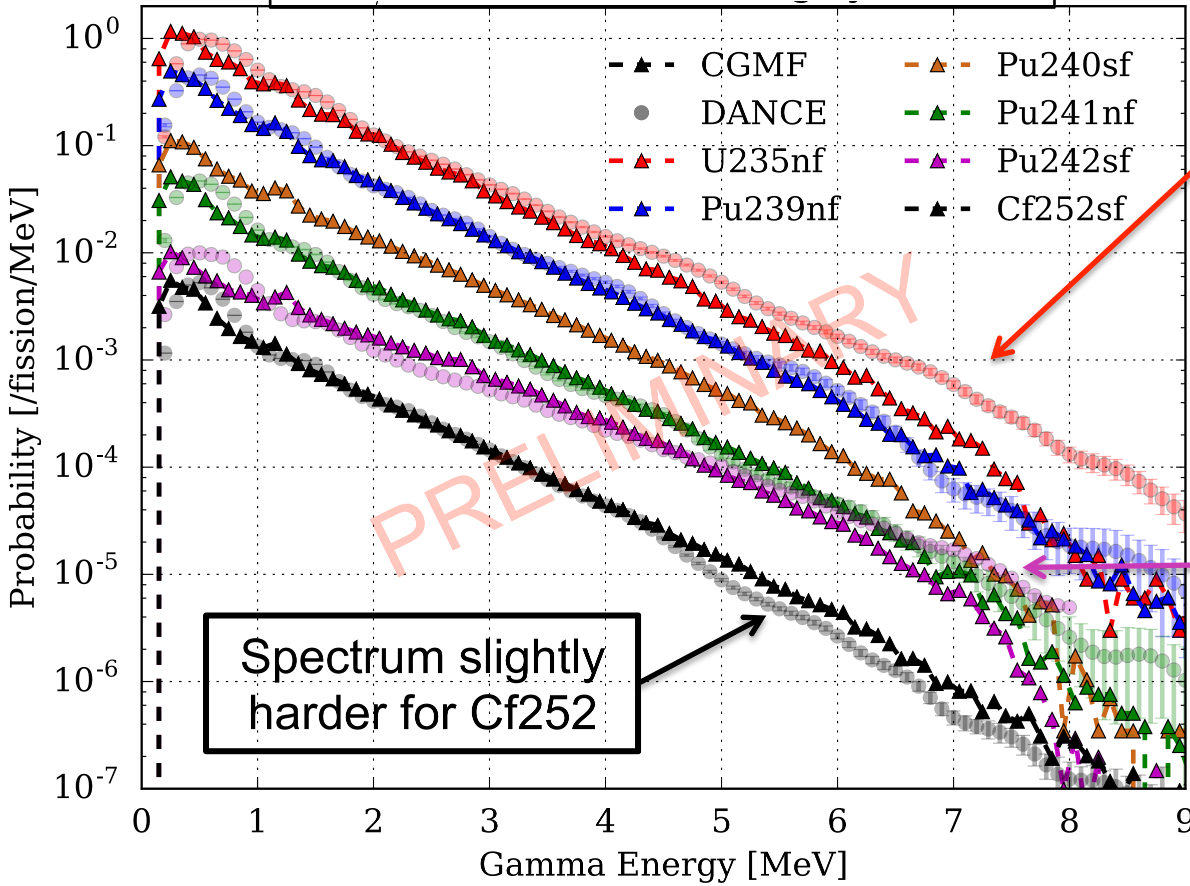


- Discrete lines decrease/increase corresponding to the Y(A,Z) change
- Zr100, Zr102, Mo104, Xe140, Xe138 are all 4+ → 2+ → 0+ chains!

Overall Comparison of PFGS

- Overall, good agreement between DANCE [3] and CGMF when using <TKE> from exp.

[3] A. Chyzh *et al.* PRC **90** 014602 (2014)



U235 a bit softer: can get with lower spin

Getting high-E tail for Pu239

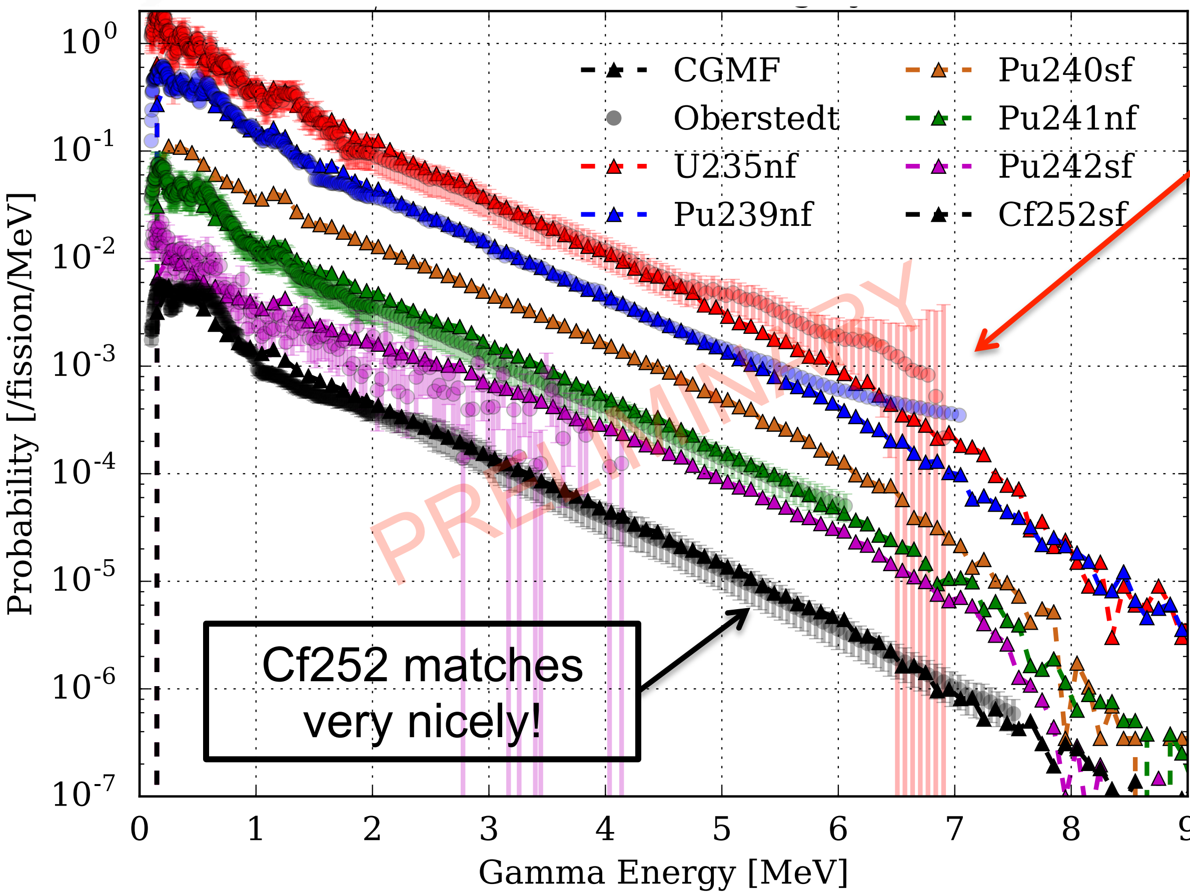
Same for Pu241

Pu242 shows some shape differences

***Can be hard to get <E_γ> **and** <M_γ>

Comparison of PFGS with Oberstedt

- Again, good agreement between Geel group and CGMF when using <TKE> from exp.



U235 a bit harder: can get with lower spin

Pu239 discrete lines look good!

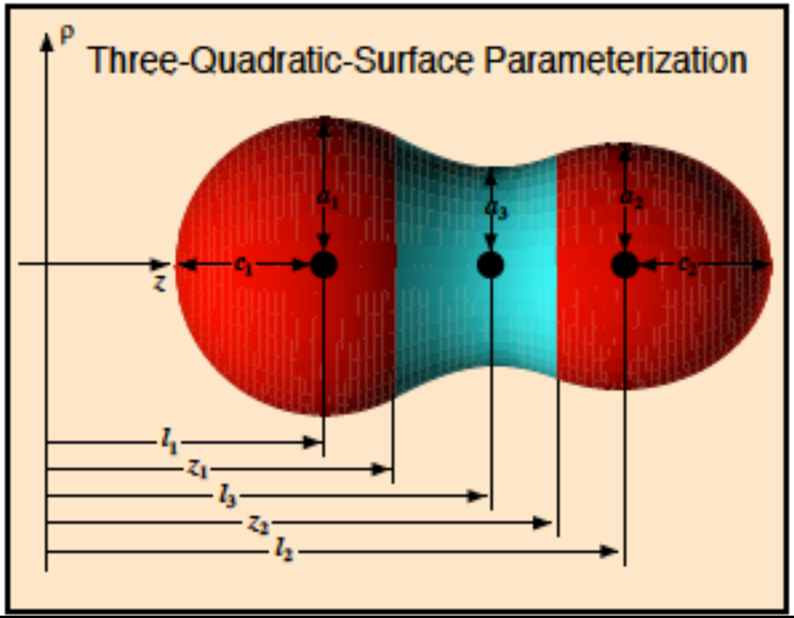
Pu241 a bit softer

Pu242 data has very low statistics!

***Can be hard to get $\langle E_\gamma \rangle$ **and** $\langle M_\gamma \rangle$

Macroscopic-Microscopic Approach: A Brief Primer

- Compound nucleus traverses PES parameterized by its nuclear shape
  - Using 6 parameters to govern shape and nucleon asymmetry
  - Macroscopic shape + microscopic shell/pairing corrections



P. Möller & T. Ichikawa EPJ A **51** 173 (2015)

Nuclear shape

$$E_T(Z,N,q_i) = \boxed{E_M(Z,N,q_i)} + E^p_m(Z,\cancel{N},q_i) + E^n_m(\cancel{Z},N,q_i) + E_{odd}$$

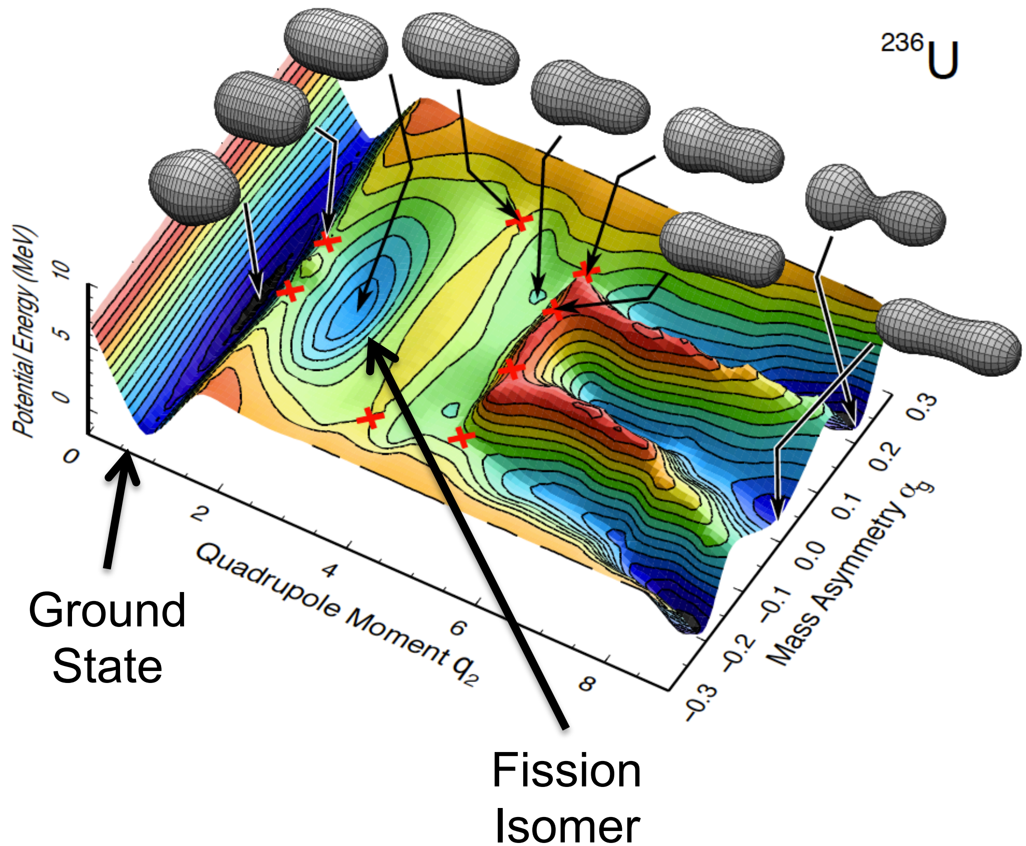
Loose dependence on N/Z

Nucleon corrections

Macroscopic-Microscopic Approach: A Brief Primer

T. Ichikawa *et al.* arXiv:1203.2011v2 (2011)

- Heavily damped shape evolution – use BSM
  - Nuclear temperature & potential drive evolution
  - ‘Friction’ between shape and internal excitations dampen motion
- Scission occurs when neck reaches critical radius (r_c=2.5fm)

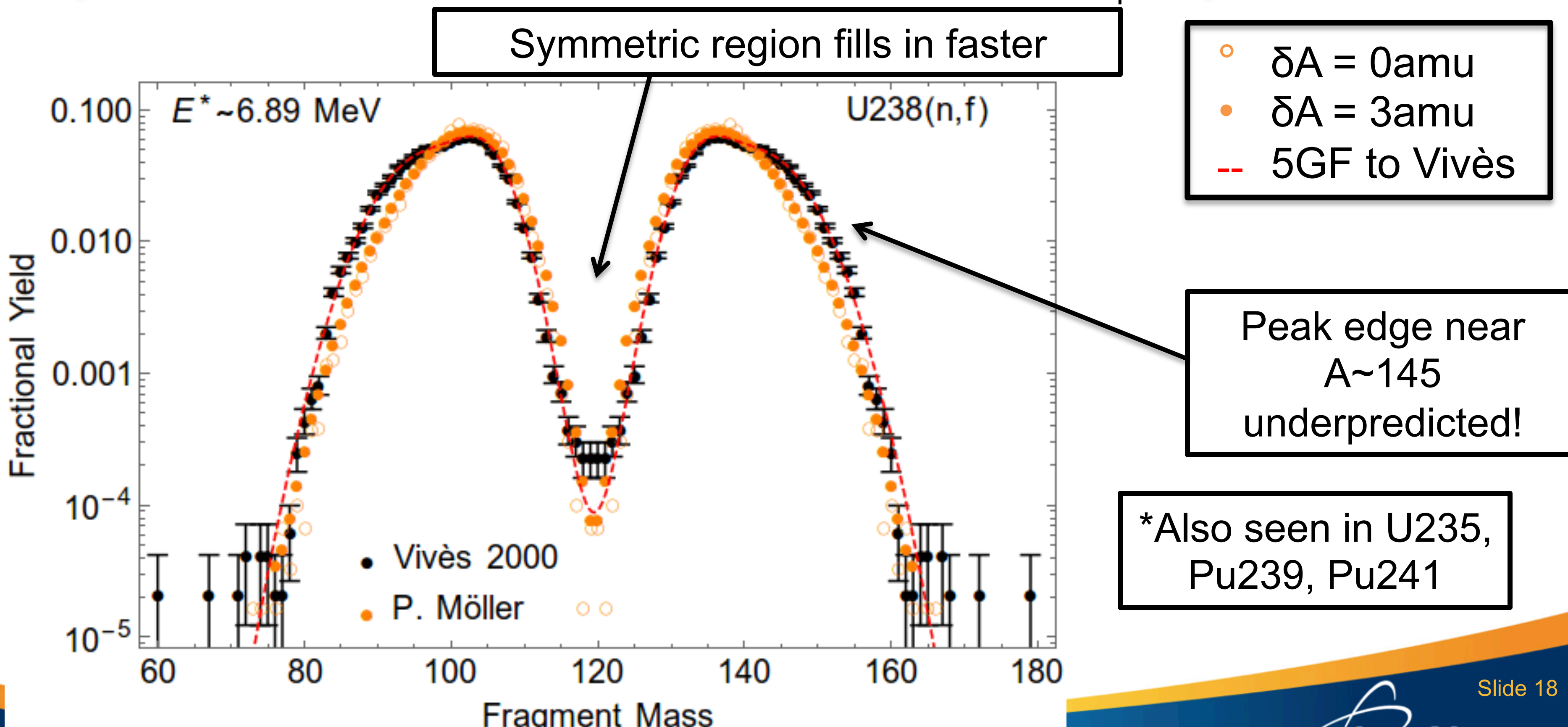


- Perform random walk along PES and log fragment yields

Comparisons at Higher E_n

- Similar trends seen:
  - Fill in symmetric, peaks widen, etc.

- Do Y(A) differences dramatically impact <ν>, $<M_\gamma>$, etc.?



*Also seen in U235, Pu239, Pu241

Excitation Energy Sharing

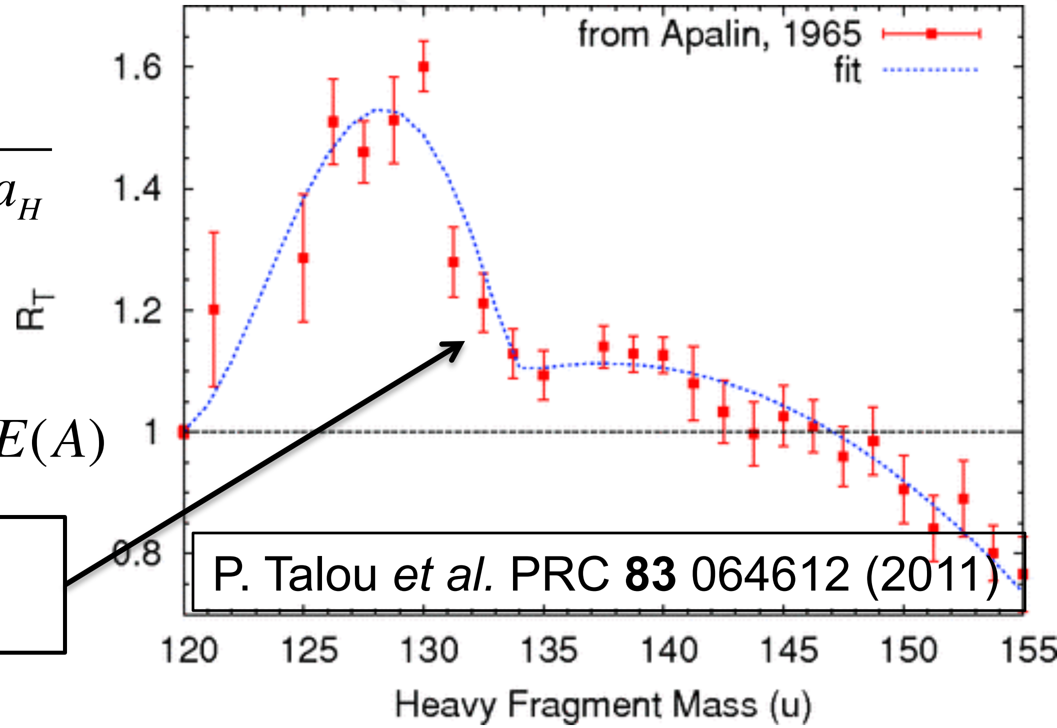
- Currently: nuclear temperature ratio sets sharing

$$\frac{E_L^*}{E_H^*} = \frac{a_L}{a_H} R_T^2 \longrightarrow E_H^* = \frac{E_T^* a_H}{a_L R_T^2 + a_H}$$

TXE from energy conservation

$$E_T^* = E_n + B_n + \Delta M(A_C, Z_C, A, Z) - TKE(A)$$

Fitting the ratio of ν_L/ν_H approximates this $R_T(A)$



- Next: use E_{def} to solve for E_{int} and share via

$$\langle E_H \rangle = \int_0^{E_{\text{int}}} \varepsilon \rho_H(\varepsilon) \rho_L(E_{\text{int}} - \varepsilon) d\varepsilon \Big/ \int_0^{E_{\text{int}}} \rho_H(\varepsilon) \rho_L(E_{\text{int}} - \varepsilon) d\varepsilon$$

Fitting <ν> and <TKE>

- A = Akimov, B = Möller, D = Möller + TKE changes
  - Calculated Y(A) with TKE shifts can provide good <ν> fit but tension arises between <TKE> and <ν>
  - TKE shifts offset the differences in Y(A)