Prompt fission photons from a modeler's perspective
OR
What we know about prompt fission photons
(not all that much)

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Ramona Vogt (LLNL & UC Davis)

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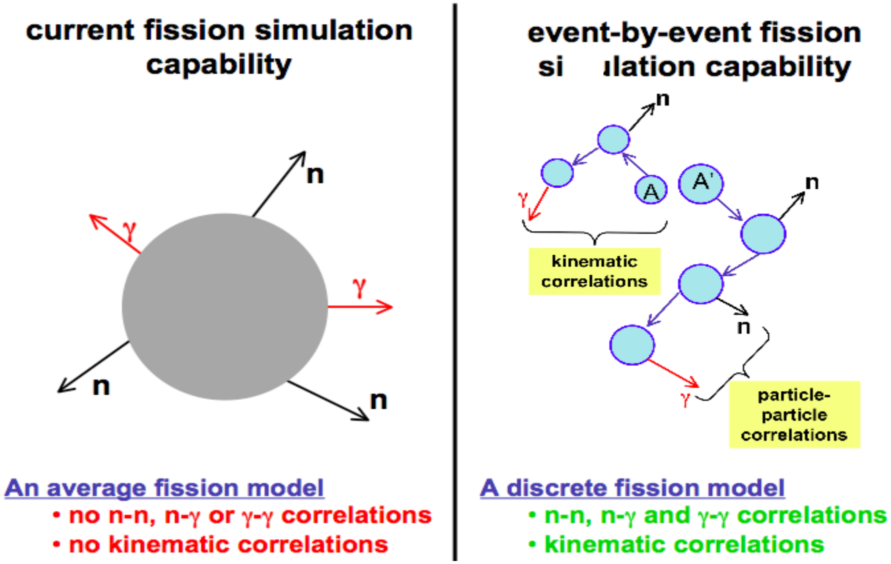
Modern simulations need to go beyond 'average' black box treatment of fission



- In 'average' models, fission is a black box, neutron and gamma energies sampled from same average distribution, regardless of multiplicity and energy carried away by each emitted particle; fluctuations and correlations cannot be addressed

- **Models** that generate complete fission events keep the energy & momentum of neutrons, photons, and products in each individual fission event; correlations are automatically included

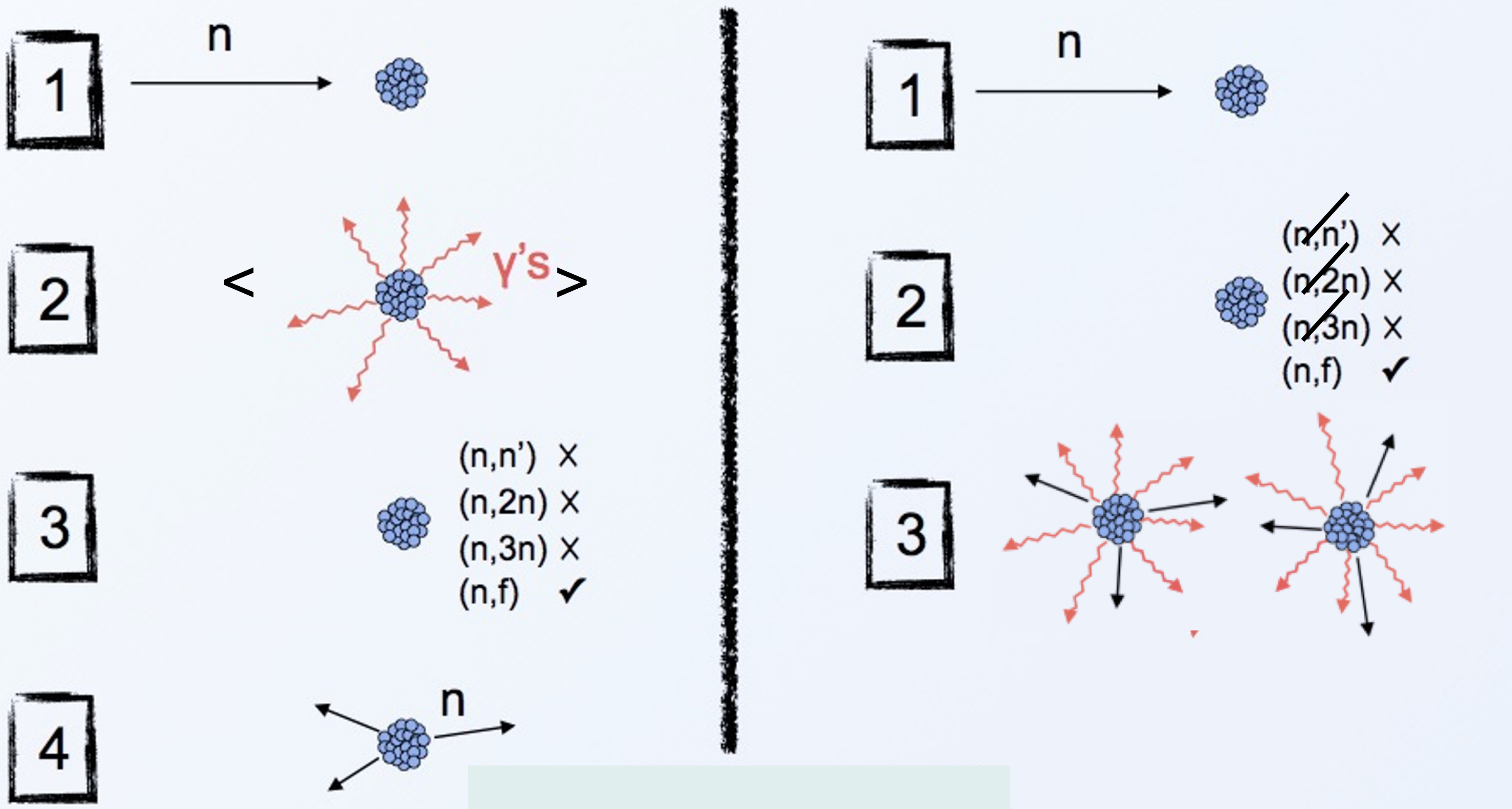
- More complex models require more data for verification and validation

Differences in photon emission between MCNP default and complete event Monte Carlos lead to mismatches

Illustrates the difficulty in marrying fast complete event Monte Carlos with larger neutron transport codes like MCNP (number of photons weighted by cross sections)

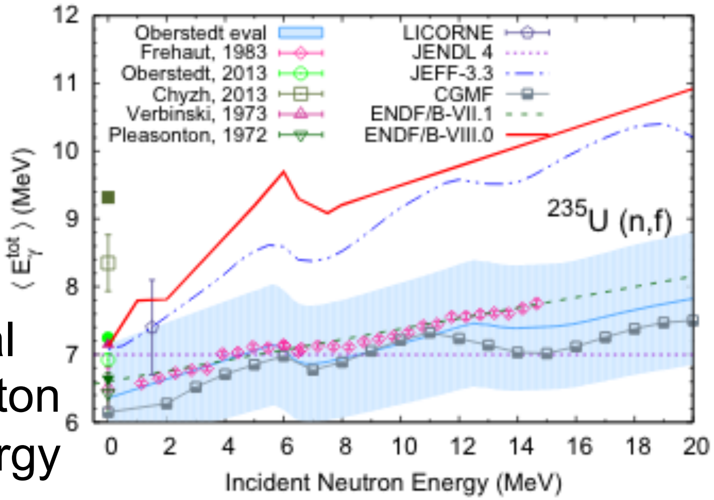
MCNP default procedure

Complete event Monte Carlo procedure:
Followed when LLNL library + FREYA called



Energy dependence of average quantities

New evaluation for photons in ENDF-B/VIII.0: Averages

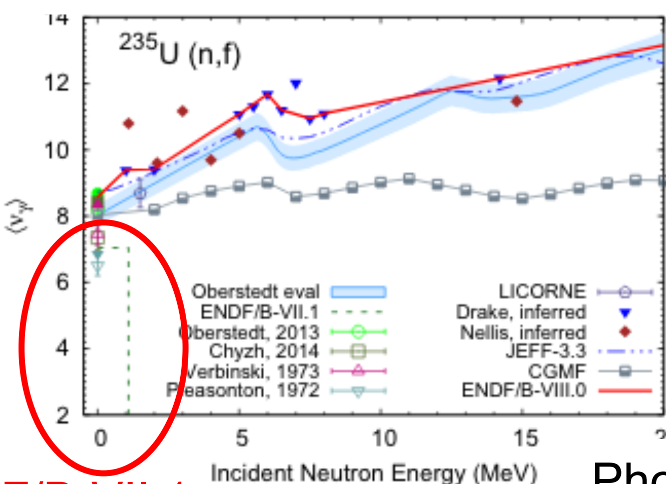


Total photon energy

Data are sparse and not in agreement

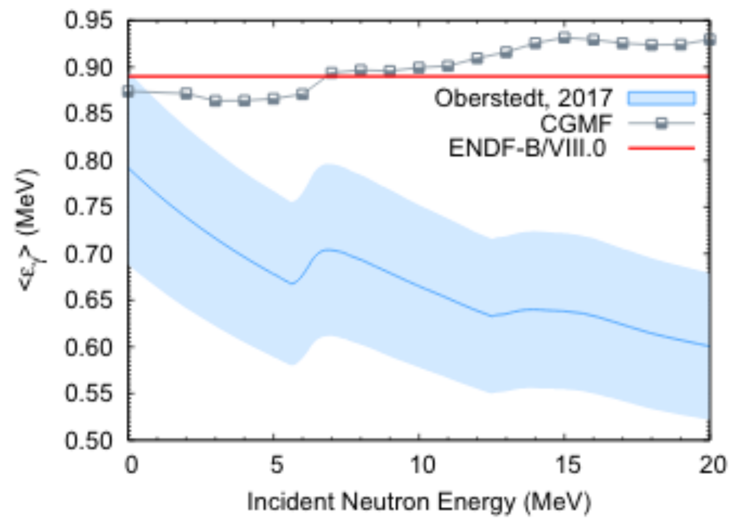
Results obtained for $^{235,238}U$ & ^{239}Pu, ^{235}U shown here

Clearly more data and more attention to simulations needed



ENDF/B-VII.1

Photon multiplicity



Energy per photon

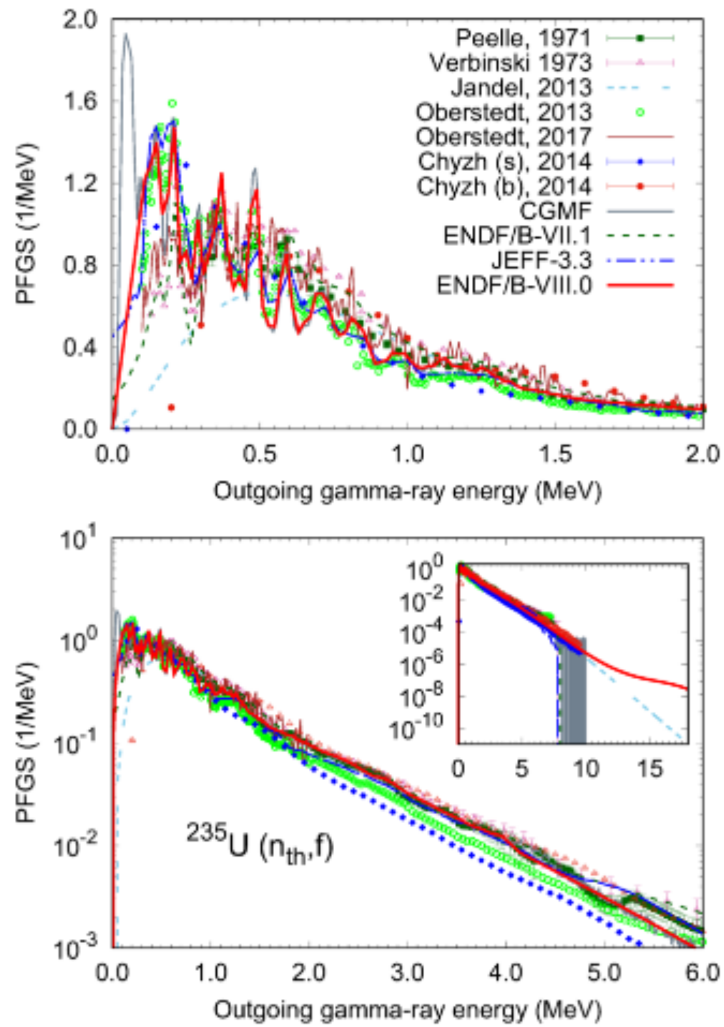
I. Stetcu et al, Nuclear Data Sheets 163, 261 (2020)

New evaluation for photons in ENDF-B/VIII.0: Spectra

Many data sets for thermal neutrons

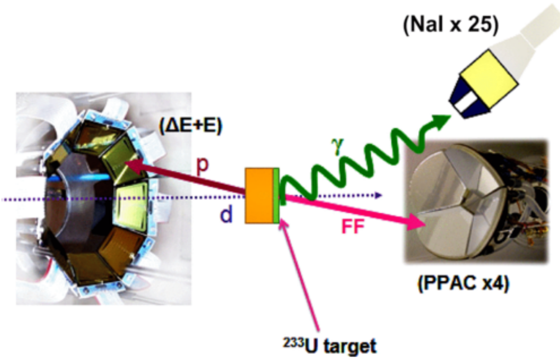
Not much similar data exist for higher neutron energies or for spontaneous fission

Even Oslo (d,pf) data (next slide) do not go above 2nd chance fission threshold

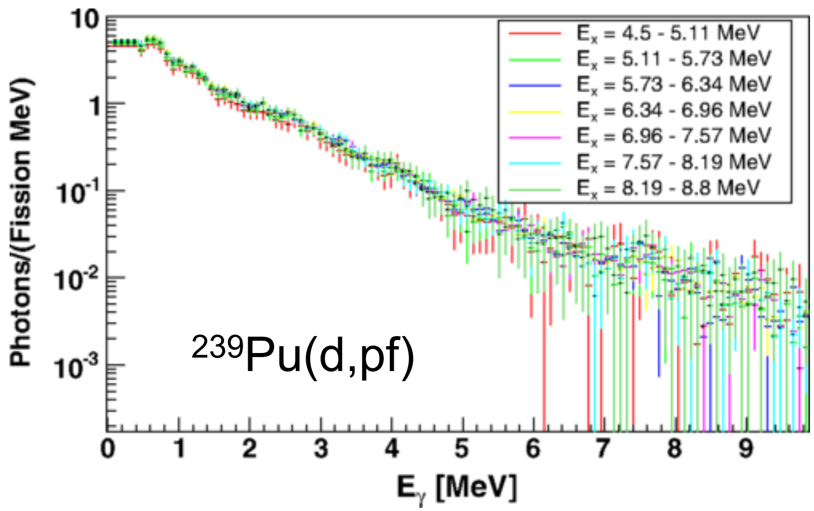


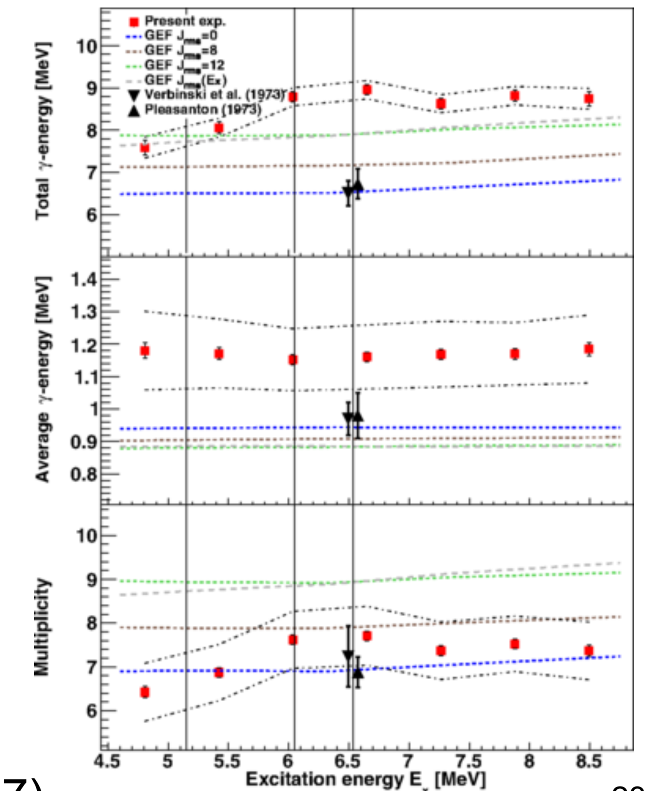
I. Stetcu et al, Nuclear Data Sheets 163, 261 (2020)

Prompt fission photons studied in (d,pf) reactions at Oslo



^{233}U and ^{239}Pu published so far, new data on ^{240}Pu taken and under analysis

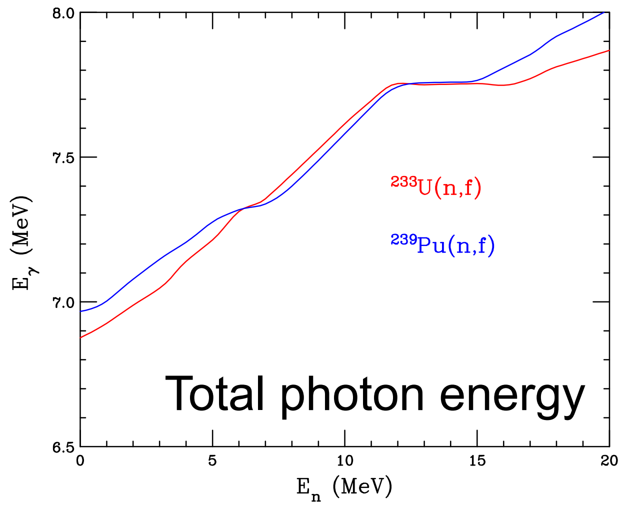




S. J. Rose et al, Phys. Rev. C 96, 014601 (2017)

^{239}Pu(d,pf)

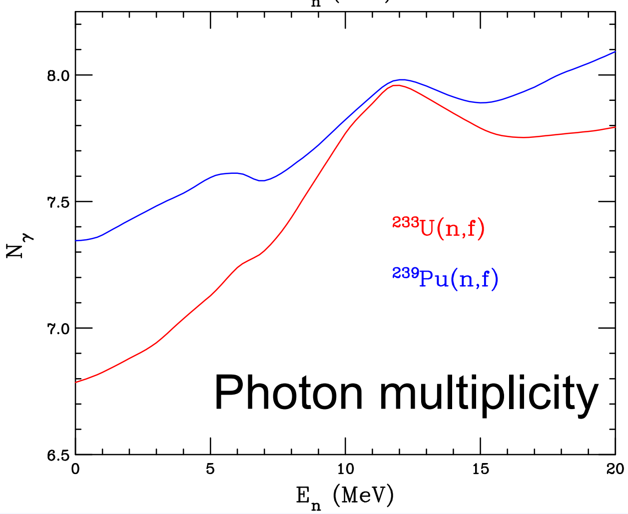
Simulated dependence of photon average quantities on neutron energy is slow

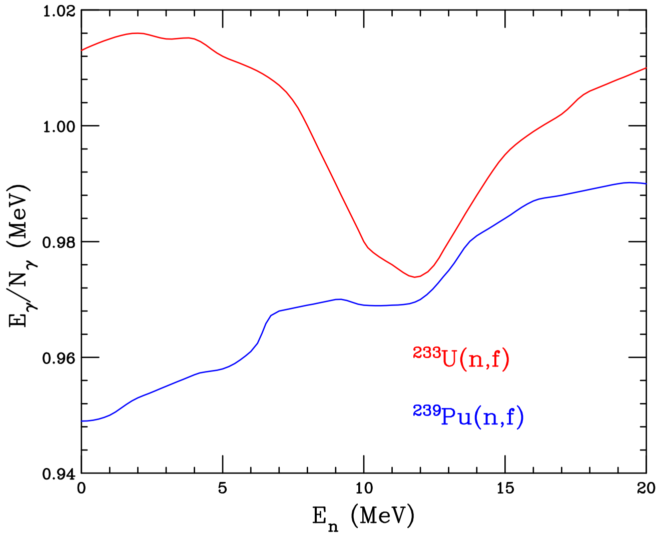


Clear trends in FREYA calculations for 2nd and 3rd chance fission thresholds in ^{233}U(n,f) and ^{239}Pu(n,f)

Dependence on energy is weak, consistent with residual excitation energy left for photon emission once neutron emission ceases

Small changes in emission pattern can lead to larger differences in energy/photon although variations small





Energy per photon

Photon data taken with fragments is limited, old, and of low statistical accuracy

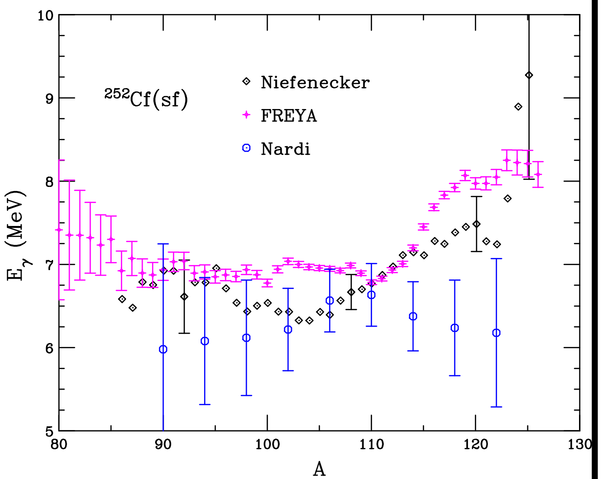
Some data but not much of it in agreement

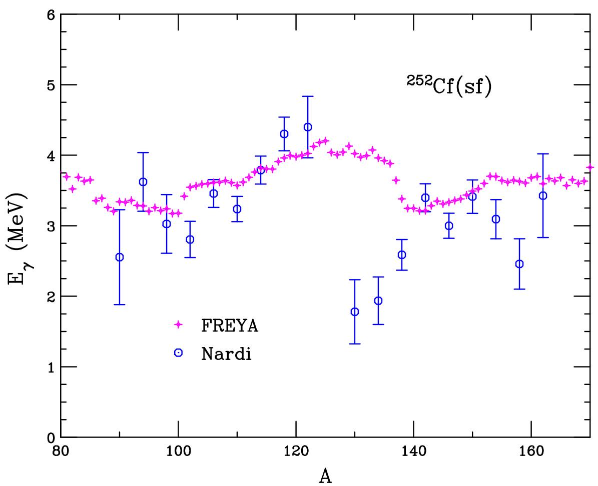
- Nifenecker et al. proposed that the total average photon energy increased linearly with neutron multiplicity, not inconsistent with sawtooth-like behavior of photon emission vs. A but with relatively poor statistics
- Frehaut observed an increase in both E_γ and $\nu(A)$ with E_n in ^{232}Th(n,f), ^{235}U(n,f) and ^{237}Np(n,f), consistent with increase of excitation energy with neutron energy
- These observations were turned into an assumption that E_γ increases with ν in all circumstances, due to competition between neutron and photon emission – a strong positive correlation is assumed
- Some versions of average fission models hardwire this in to match existing data, assuming that this positive correlation a la Nifenecker (and sawtooth-like behavior of $E_\gamma(A)$ and $N_\gamma(A)$) comes from strong linear dependence of spin on fragment excitation energy – essentially excluding statistical photon emission
- Event-by-event models suggest an anticorrelation related to energy-momentum conservation
- Indeed, dependence of photon emission on neutron energy should not be too strong because neutron emission dominates until near neutron separation energy

Few experiments have measured photons with fragments

- Nifenecker, Nardi, Johansson, and Pleasonton measured photons in relation to fragments for ^{252}Cf(sf)
  - Nifenecker and Nardi measured photon energies vs. A and TKE of fragments (Nifenecker only reported dependence on a single fragment)
  - Johansson and Pleasonton reported photon multiplicities, not energies vs. A for Cf
- Pleasonton report photon energy, E_γ; photon multiplicity, N_γ; and energy per photon, E_γ/ N_γ; vs. A (and TKE) for ^{235}U(n_{th},f), ^{233}U(n_{th},f), and ^{239}Pu(n_{th},f) with relatively limited statistics
- No measurements exist for higher incident neutron energies
- The data are compared to FREYA calculations with 1M events, considerably higher statistics than the data
- **The data shown on these next 4 slides are all measurements I know of**

^{252}Cf(sf) photon data vs. A and TKE

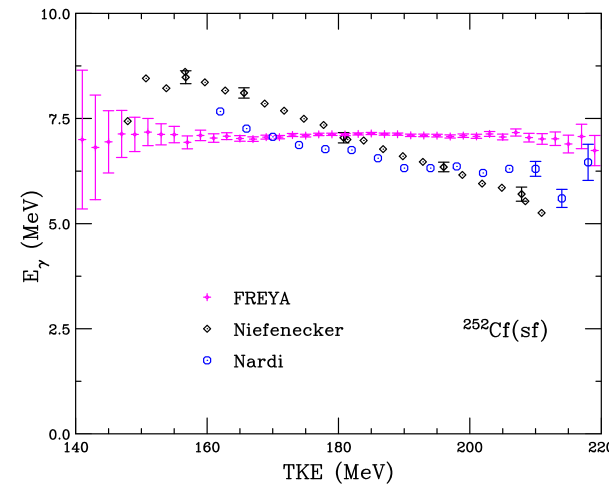


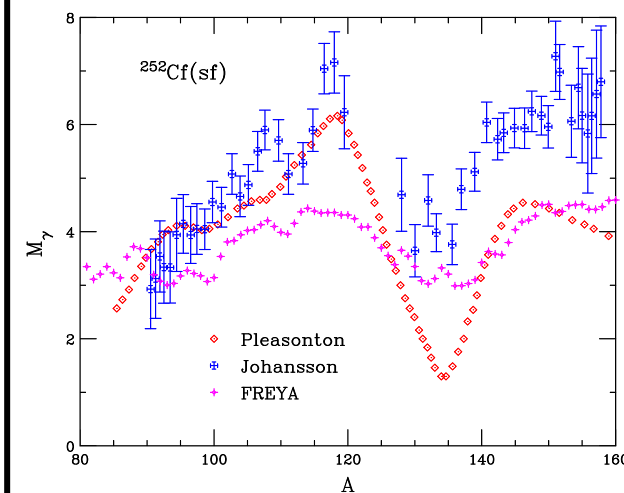


(Left) Total photon energy as a function of A_H and A compared to Nardi and Nifenecker data; agreement is relatively reasonable

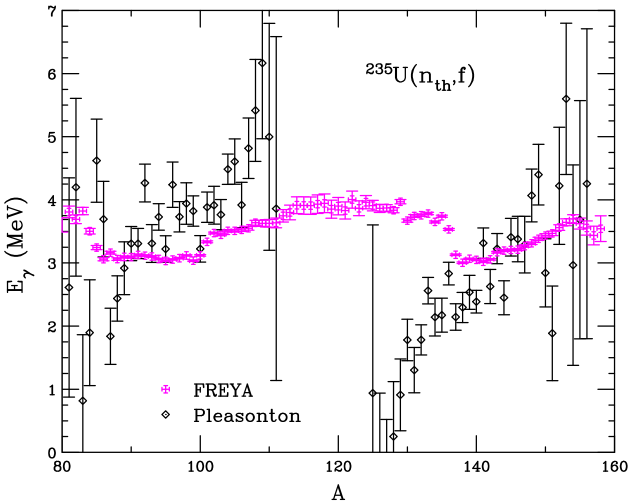
(Top right) Total photon energy as a function of total kinetic energy, compared to Nardi and Nifenecker data; **FREYA** result is rather flat compared to data

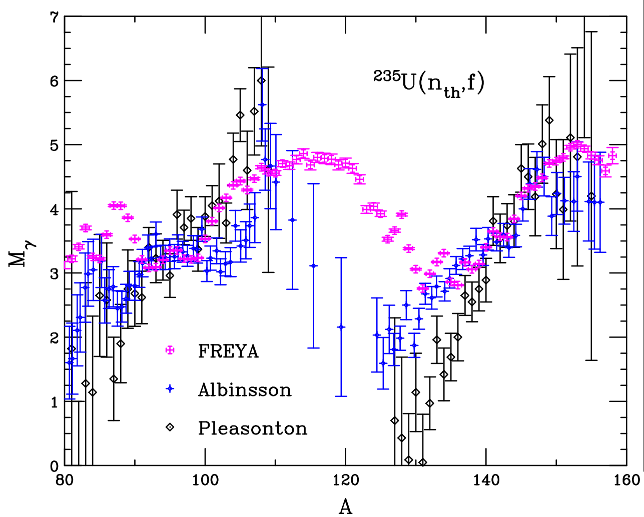
(Bottom right) Photon multiplicity compared to data from Pleasonton and Johansson as a function of A; data are inconsistent, **FREYA** is flatter than both





$^{235}U(n_{th},f)$ photon data vs. A and TKE

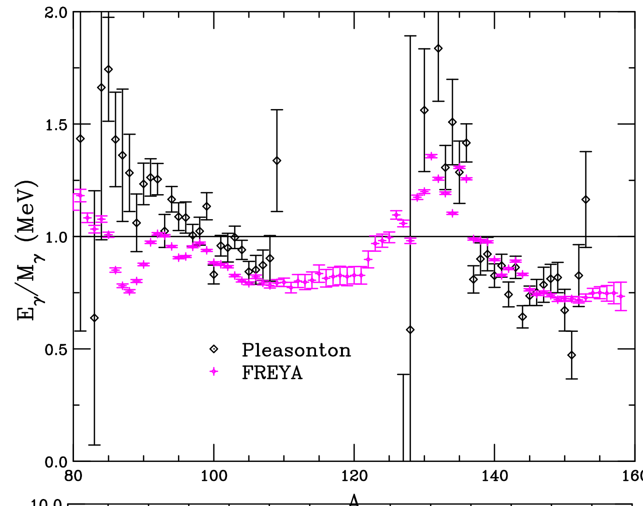


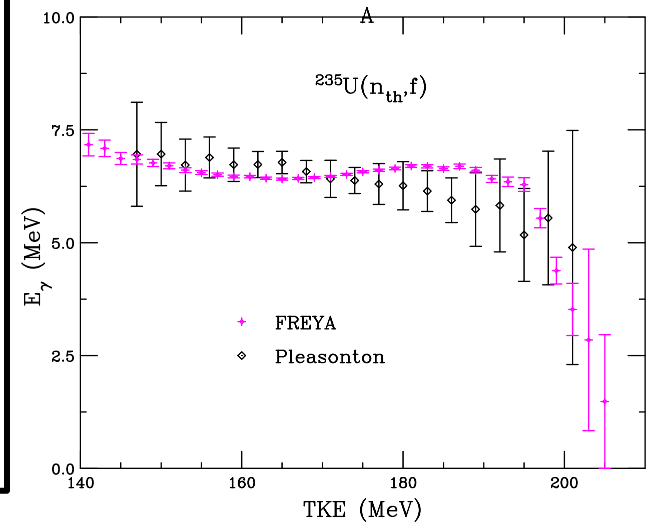


(Left) Photon energy (top) and multiplicity compared to data from Pleasonton (black) and Albinsson (blue) as a function of A; agreement relatively good given large uncertainties

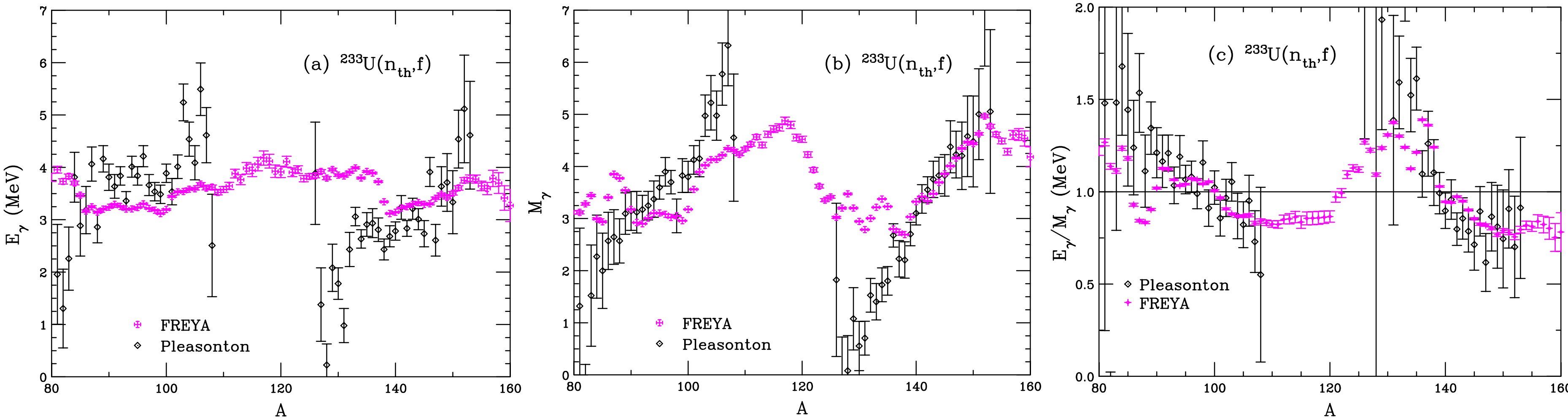
(Top right) Energy per photon as a function of A compared to Pleasonton data; agreement is good

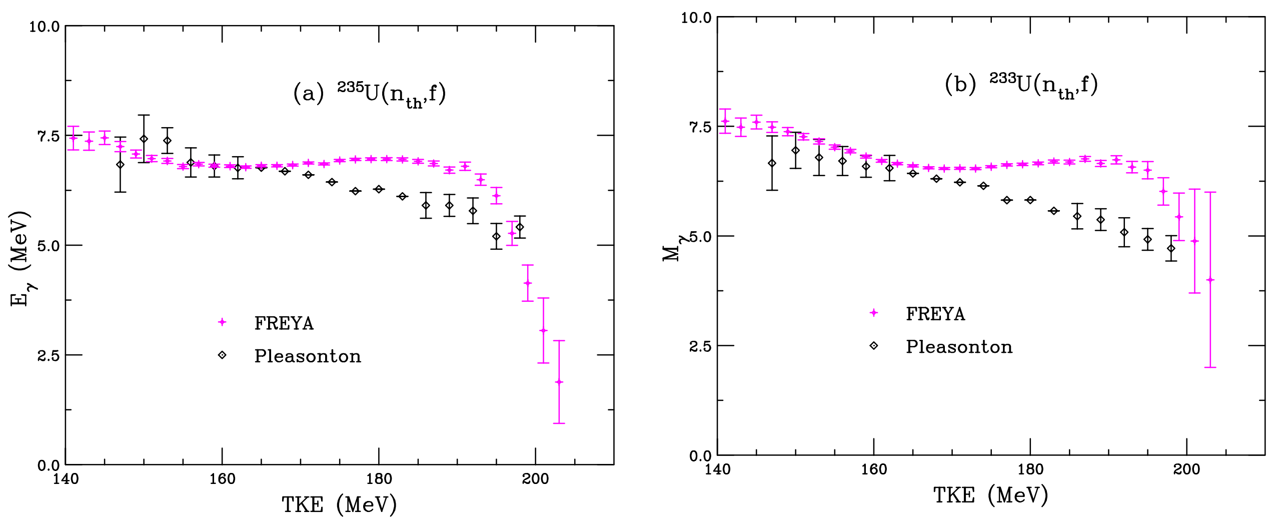
(Bottom right) Photon energy as a function of total kinetic energy compared to Pleasonton data; rather good agreement



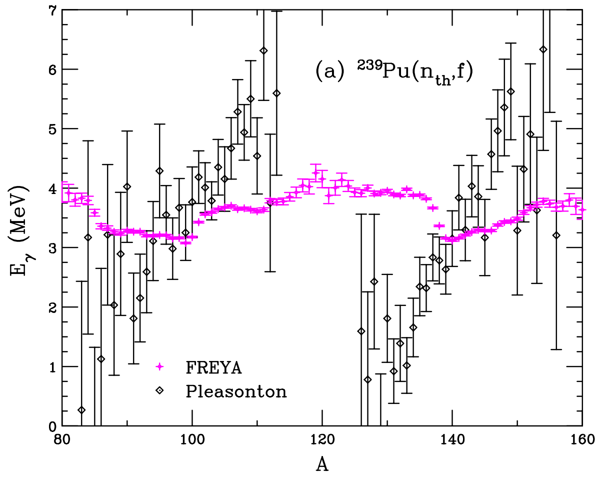


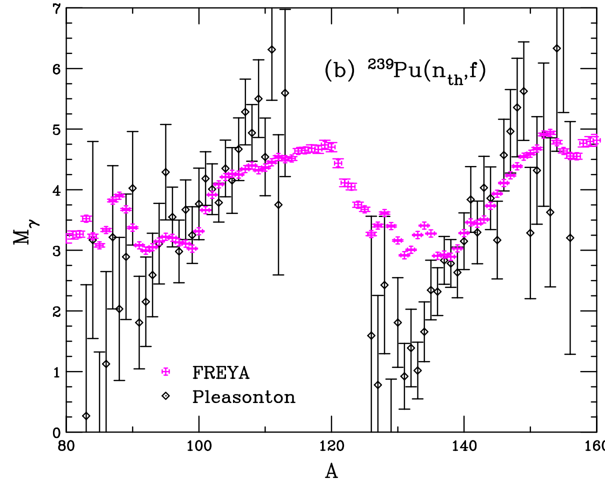
$^{233}U(n_{th},f)$ Data vs. A and TKE

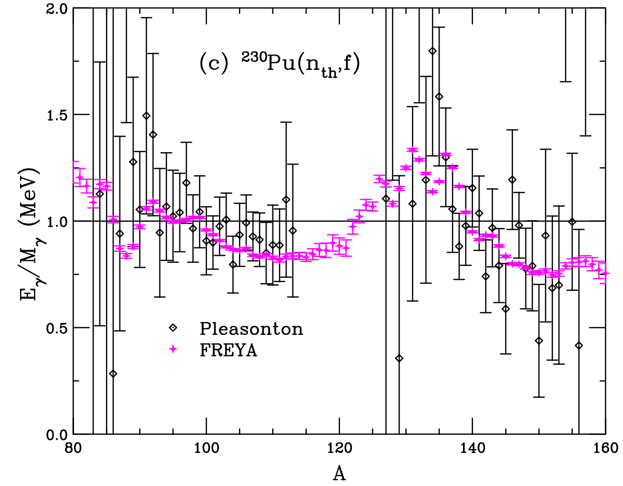


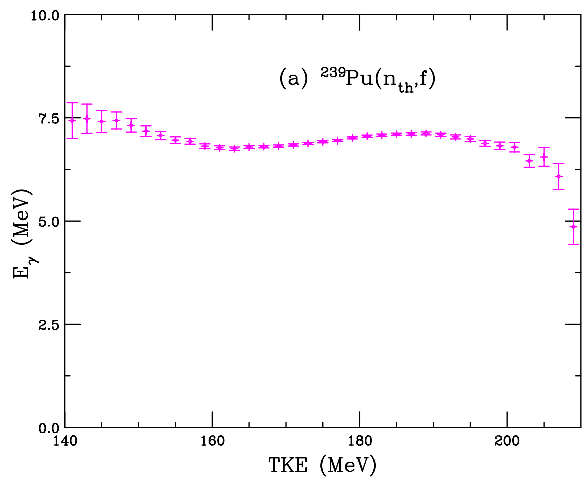


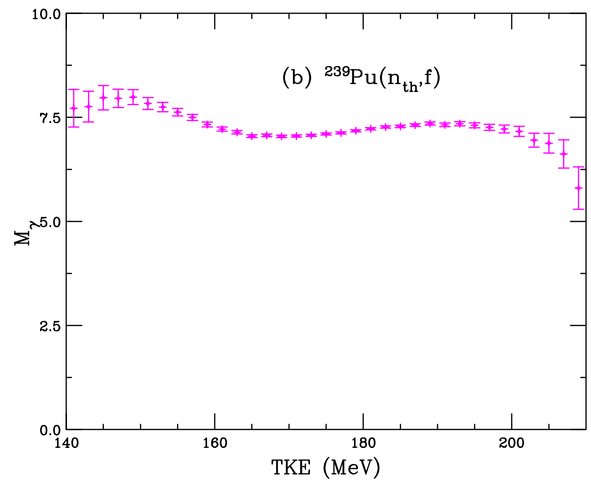
$^{239}Pu(n_{th},f)$ Data vs. A (and TKE)











Neutron-photon correlations contradictory; fragment-by-fragment and event-by-event data may not tell the same story

Frehaut data used in some models to related neutron and photon emission

Data available for ^{232}Th, ^{235}U and ^{237}Np

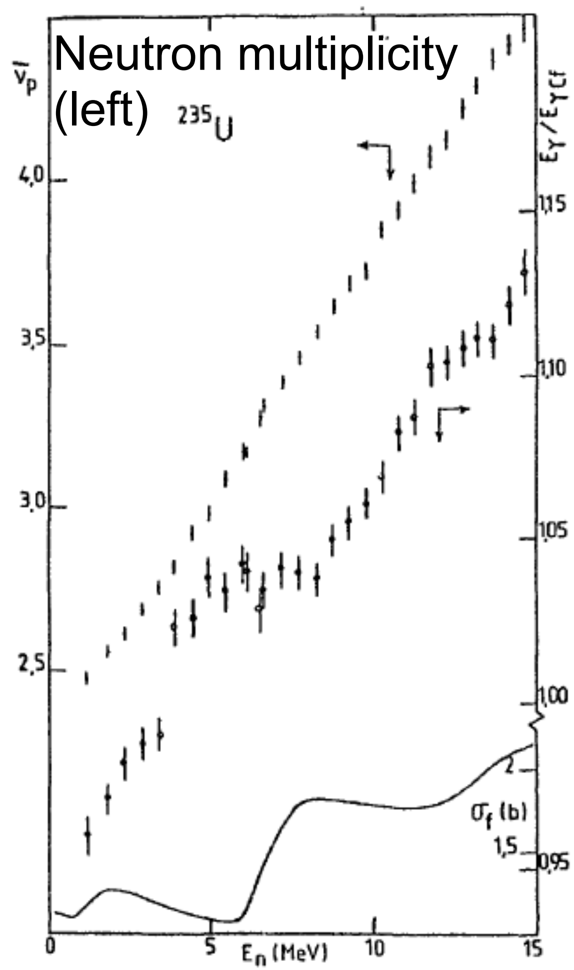
Photon energy given relative to ^{252}Cf(sf)

Below 2nd chance fission, linear relationship derived between ν and E_γ:

$E_\gamma/E_{\gamma Cf} = (0.1275 \pm 0.011)\nu + (0.623 \pm 0.028)$

Above thresholds for 2nd and 3rd chance fission, there is no competition for photon emission, the nucleus fissions with less excitation energy following neutron emission, leading to lower energy of photon emission

Relationship determined by Frehaut has been assumed to hold also as a function of fragment mass, leading to assumed photon sawtooth



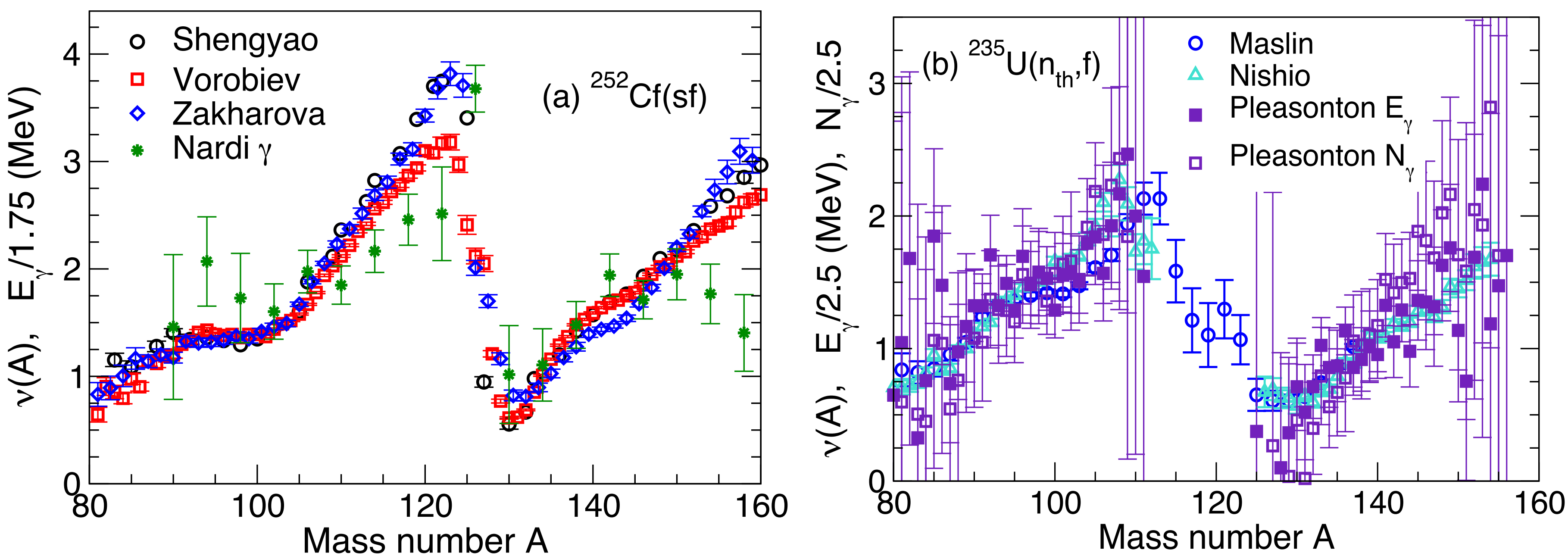
Total photon energy relative to ^{252}Cf(sf) (right)

Frehaut, INDC(NDS)-220 (IAEA doc)

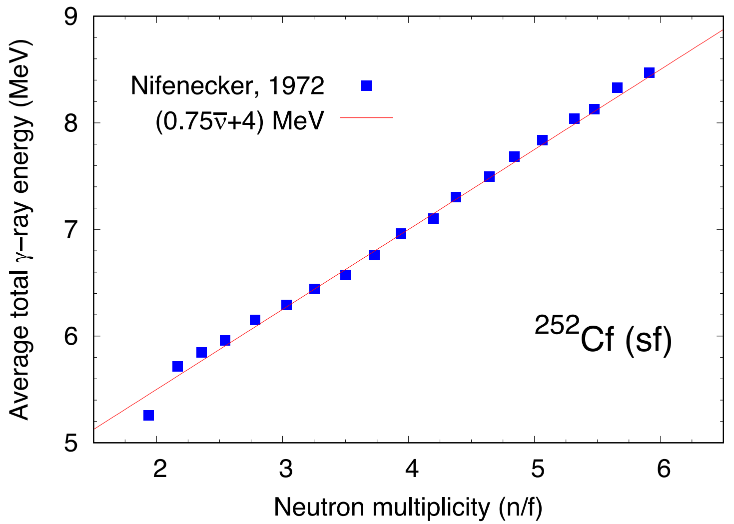
Is the photon multiplicity and energy dependence on fragment mass number also a sawtooth? Maybe…

Both show a sawtooth shape but the slopes of the 'teeth' are not necessarily the same:

E_γ for ^{252}Cf(sf) seems to be flatter while N_γ seems to have a stronger A dependence than E_γ for ^{235}U(n,f) while E_γ is more similar to $\nu(A)$, within large uncertainties



Fragment-by-fragment neutron-photon correlation measurements are contradictory

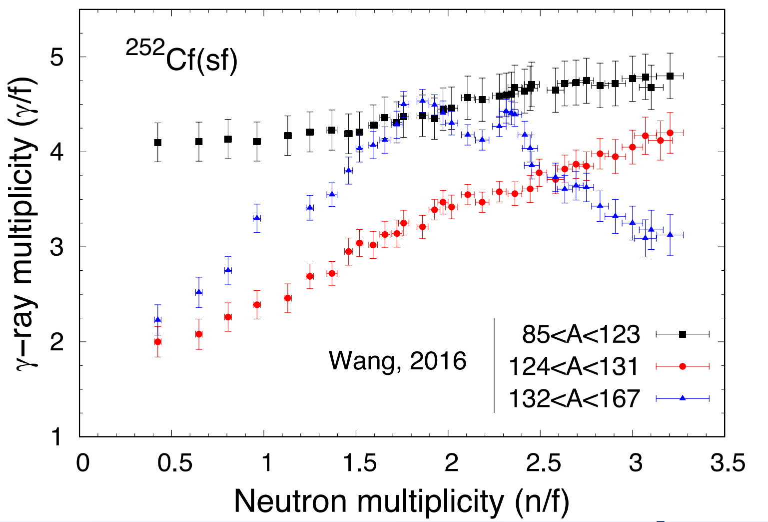


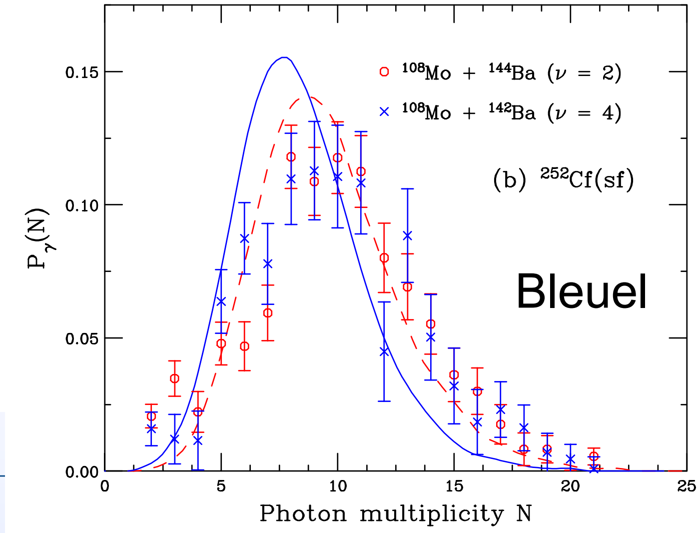
Niefenecker found a strong positive correlation, not yet reproduced (top left)

Glassel found weak negative correlation (not shown and unpublished)

Wang divided data into 3 mass regions (bottom left)

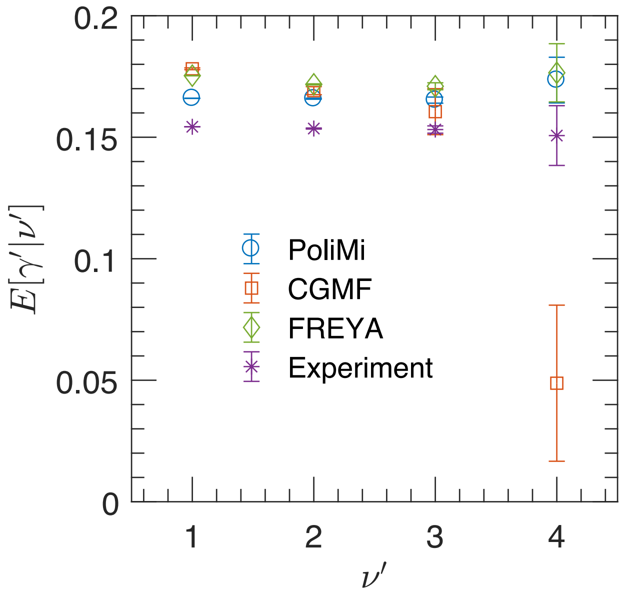
Bleuel measured Mo and Ba fragments with 2 & 4 neutrons emitted, saw no correlation (below)



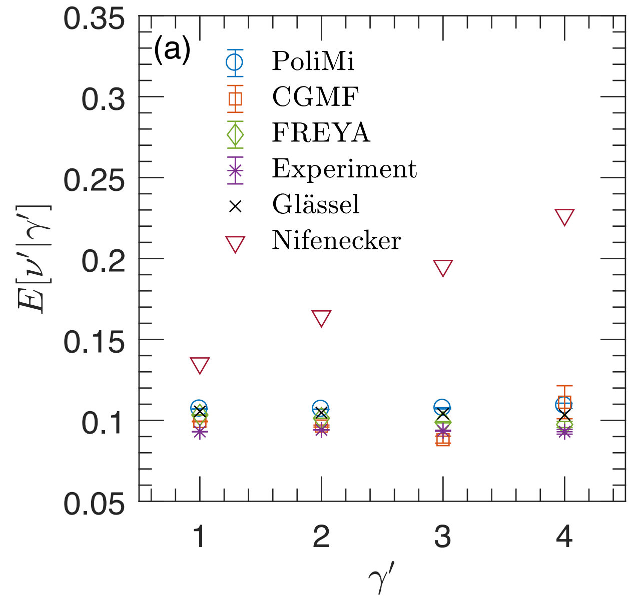


Event-by-event neutron-photon correlations measured more recently

Expected number of detected photons for ν' neutrons detected



Expected number of detected neutrons for γ' photons detected

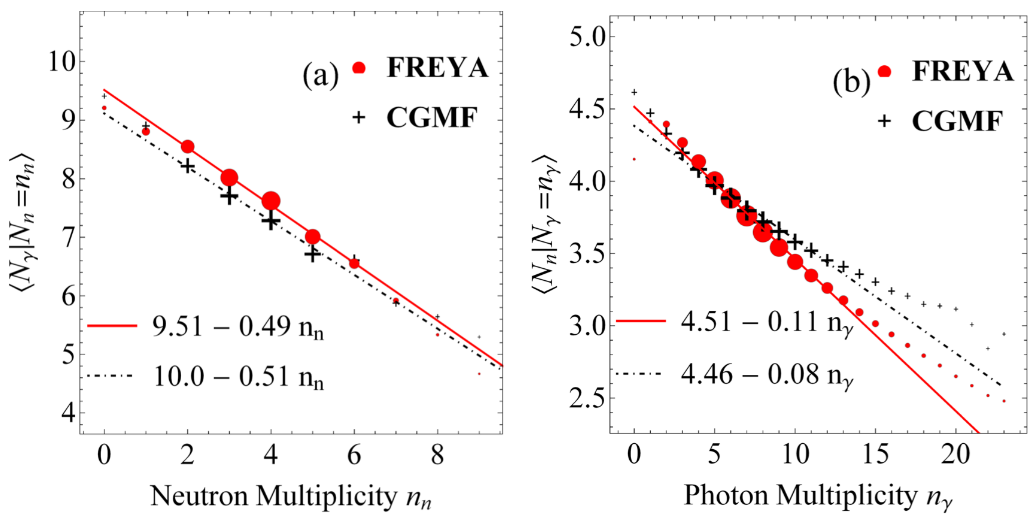


- Correlation is weak in both cases, as might be expected if photon emission follows neutron emission
- The strong neutron-photon correlation suggested by Nifenecker is ruled out
- Fragments were not detected in Chi-Nu array

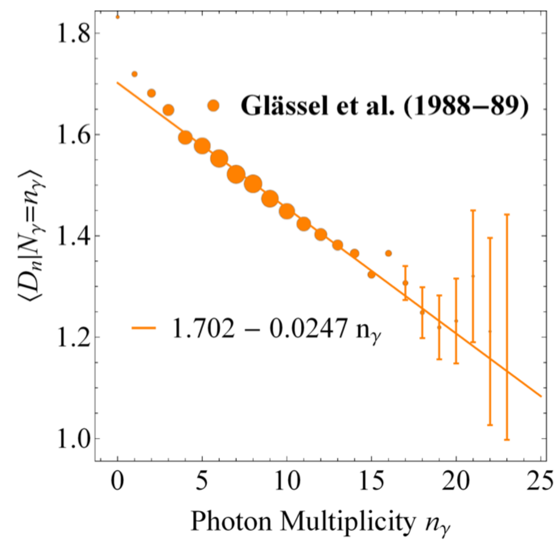
Marcath et al., PRC **97**, 044622 (2018)

Covariances between neutron and photon emissions studied by UMichigan group with Chi-Nu array

Simulation



Glassel data



Simulations don't take actual energy spectrum into account, Marcath et al result was based on reduced energy range relative to CGMF and FREYA simulations, can influence results

Determination	$cov(N_n, N_\gamma)$	
CGMF	–0.839	0.004
FREYA	–0.8200	0.0004
Glassel et al.	–0.71	0.17
Bleuel et al.	–0.69	0.10
Marcath et al.	–0.58	0.06

Data and simulations coming closer together

Marin et al., arxiv:1907.01483

What types of data are most helpful for models?

- Everything, really…
- Measure photons with fragments (and neutrons) to knock down uncertainties in older data (and see if they're right also, e.g. is there a photon sawtooth?)
- Neutron-photon correlations need to be reconciled and both fragment-by-fragment and event-by-event measurements understood
- More data at incident neutron energies above thermal
- More isotopes
- Correlation measurements (better with spontaneous fission) should also be done with e.g. ^{240}Pu