Nuclear Fission

from fundamental research to applications

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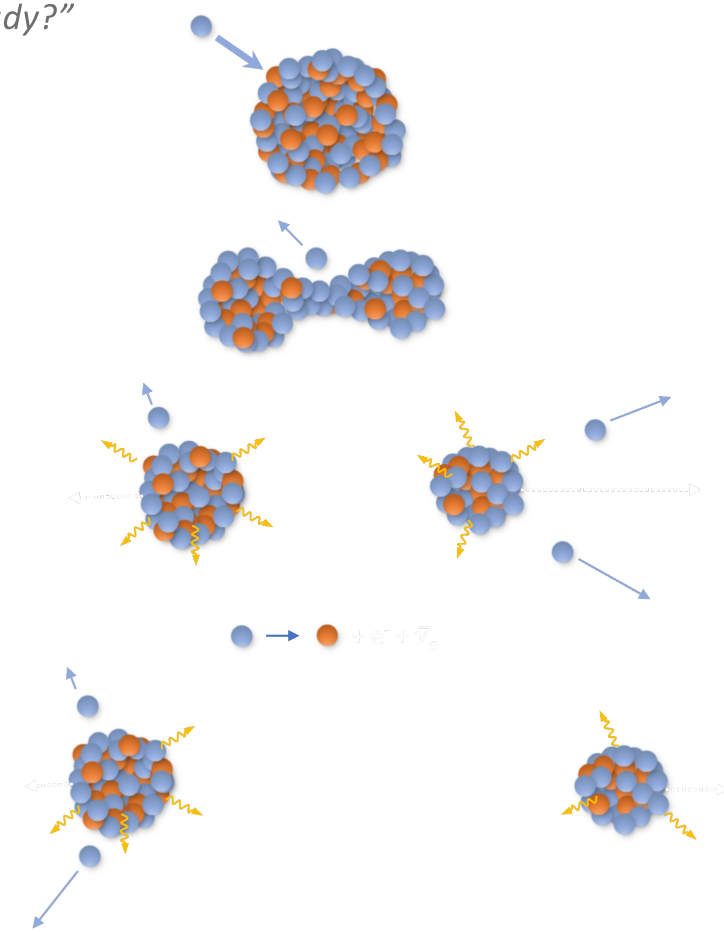
Nuclear fission: fundamental and applied

“Do we know everything we need already?”



FUNDAMENTAL – Of course not!

- A complex collective quantum rearrangement of nuclear matter we still cannot predict from first principles
- Fundamental theoretical models remain crude; we fall back on phenomenology with uncertain parameters
- And yet: 10–20 years of real progress: yields, event generators, microscopic theory, fragment spins, ^{180}Hg

APPLIED – It’s complicated...

- A widespread sense that the useful isotopes and reactions are already measured well enough
- Most data “adjusted” to applications
- Very small uncertainties
- And yet...
- New needs & requirements: safeguards, nonproliferation, advanced reactor designs

A taxonomy of mismatch

Both communities need the same isotopes and reactions, but...

1 **Different projection**
the mean vs the distribution vs the correlation
Prompt neutron and gamma emission

2 **Different energy window**
same nuclide, ranges orders of magnitude apart
^{237}Np(n,f): a dosimetry spectral index, and sub-threshold structure

3 **Different accuracy**
one needs 1%, the other 20% — somewhere else
^{252}Cf $\bar{\nu}$ to 0.13%, against ν(A) to 10%

4 **Different channel**
fission vs capture on the same nuclide
^{232}Th: capture drives the fuel cycle, fission constrains the barrier

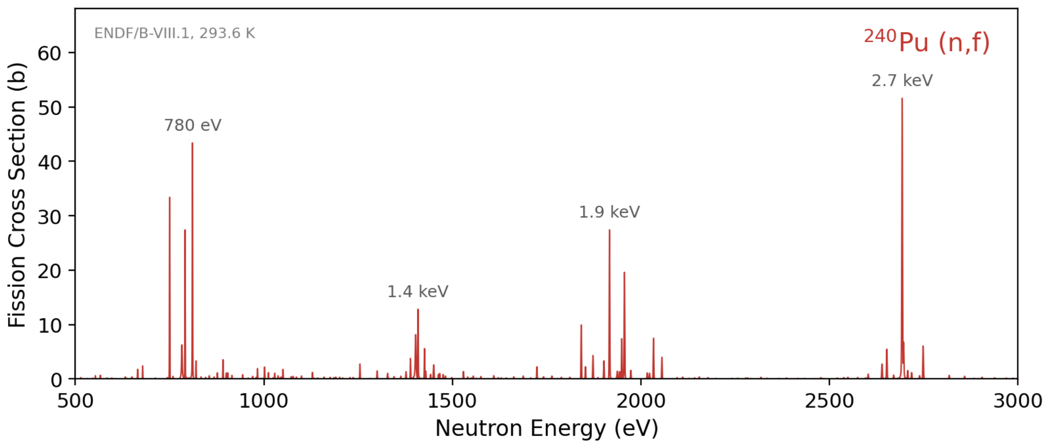
5 **Different nuclide**
coupled by a model — the model is the shared object
Fission cross sections and fragment angular distributions

6 **Genuine alignment**
Rather rare
$\bar{\nu}$ fluctuations in the resonance range

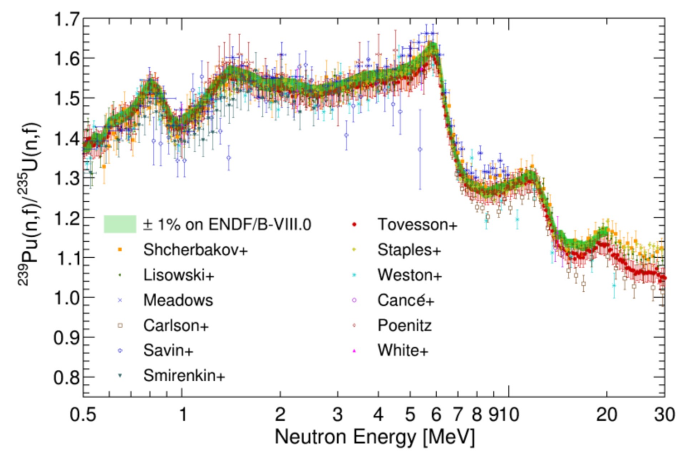
Alignment is not required

Fission cross sections

Fission barriers are NOT observables.



^{240}Pu(n,f) sub-threshold class-II clusters



*^{239}Pu(n,f)/^{235}U(n,f) ratio – **Snyder** et al., Nucl Data Sheets 178, 1 (2021)*

FUNDAMENTAL

Class-II structure fixes the second-well depth and the inner / outer barrier heights

APPLIED

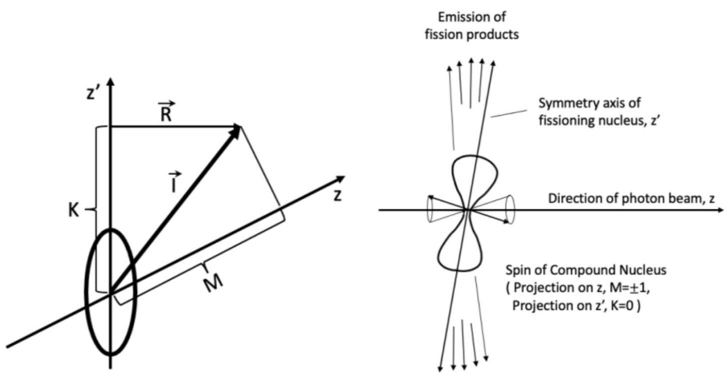
1–2% target (WPEC-26); the largest single σf contributor to keff in fast systems

The model is the bridge

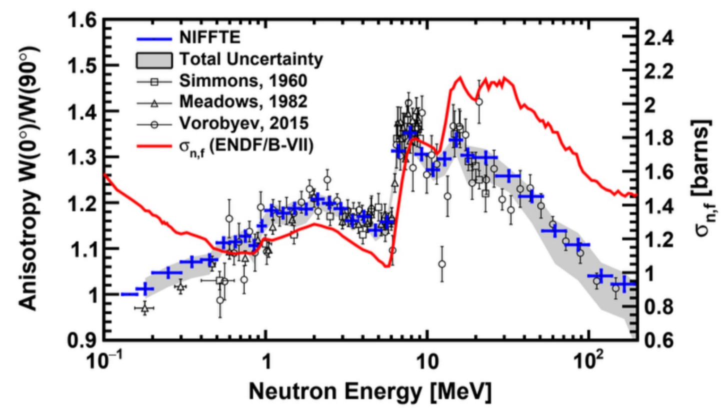
Most nuclear reaction codes used in fission cross section evaluations do not use class-I/II coupling explicitly. Uncertainties are too large. Model parameter constraints too loose.

Fragment angular distributions

(K,J,M) at the outer saddle point dictates the fission fragment angular distributions.



K and M: the spin projections that set W(ϑ)



^{235}U(n,f) anisotropy — Geppert-Kleinrath et al, Phys. Rev. C 99, 064619 (2019)

FUNDAMENTAL

K-bands at the saddle; K-mixing; dissipation saddle-to-scission

APPLIED

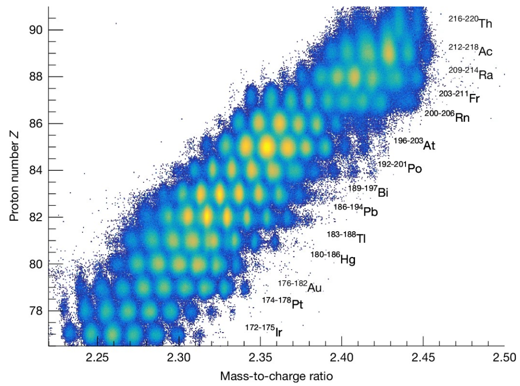
Chamber efficiency: a percent-level correction on σf itself (NIFFTE, ^{238}U/^{235}U)

No MF/MT section (evaluator's jargon) exist — and the reaction codes never use these data.

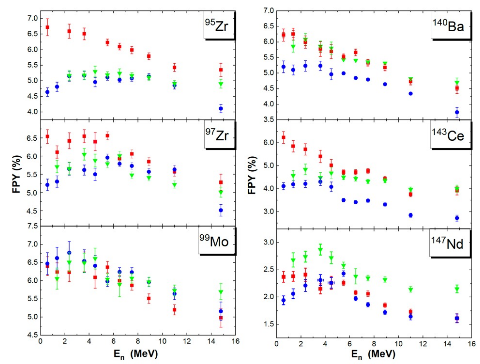
TALYS, CoH and EMPIRE carry transition states in the formalism, but do not constrain their parameters against measured anisotropies.

Fission product yields

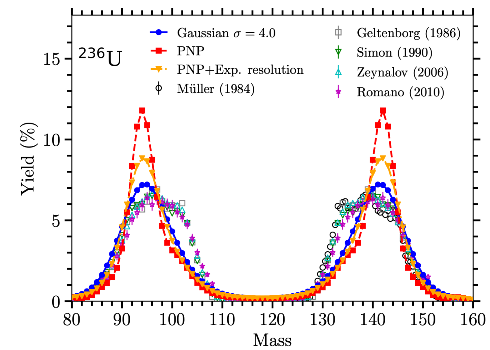
Much progress has been made in both experiments and theory this past decade



*R3B-SOFIA at GSI: full isotopic identification of both fragments in inverse kinematics — **Morfouace** et al., Nature 641 (2025)*



*TUNL: chain yields vs incident energy for six products — **Tonchev** et al., Nucl. Data Sheets 202, 12 (2025)*



*Microscopic yields with and without experimental resolution — **Verriere**, Schunck, Regnier, Phys. Rev. C 103, 054602 (2021)*

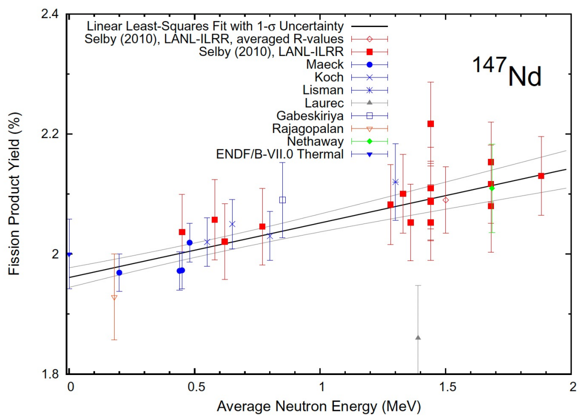
Experiment: inverse kinematics gives A and Z for both fragments, event by event — and quasi-monoenergetic beams finally give the incident-energy dependence. **Theory:** macro-micro and microscopic calculations now predict Y(A) and Y(Z) with some accuracy. **Caution:** experiments and theory do not measure/calculate the same quantities!

Meanwhile the evaluated libraries carry only 3 or 4 “effective” incident energies.

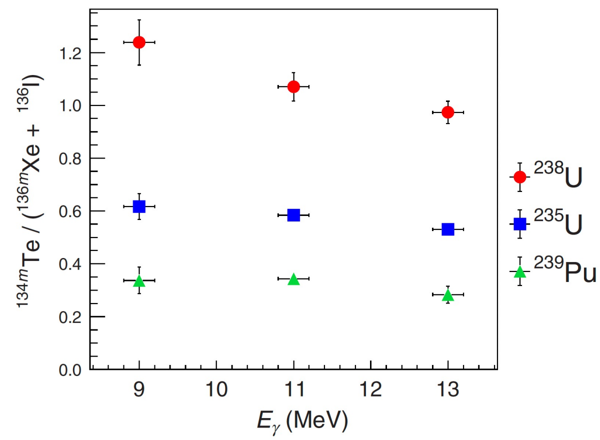
Very poor description of a rich physics. New theoretical & evaluation work in progress (BeOH, Kawano) to capture a more faithful energy dependence: A.E. Lovell, T. Kawano, P. Talou, Nucl. Data Sheets 212, 1 (2026).

Fission product yields — the applied demand

Stockpile stewardship. Nuclear fuel cycle & waste management, nonproliferation.



*^{147}Nd yield vs average neutron energy, with the historical LANL-ILRR data — the re-examination that reopened the applied case (**Chadwick** et al., 2010)*



*Isomeric yield ratio ^{134m}Te/(^{136m}Xe + ^{136}I) in photofission — **Finch** et al., Phys. Rev. Applied 15, 034037 (2021)*

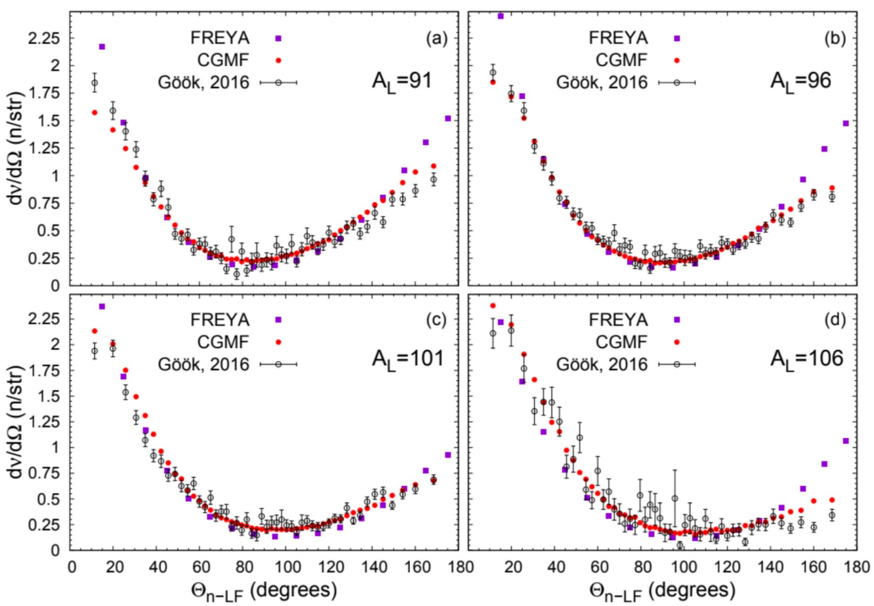
WHAT THE YIELDS ARE FOR

- Decay heat: shutdown cooling, spent fuel pools, dry casks, accident source terms
- Burnup assessment to get number of fission in a neutron environment
- Short-lived isomeric ratios produced in photofission as signature of special nuclear materials (Finch et al)

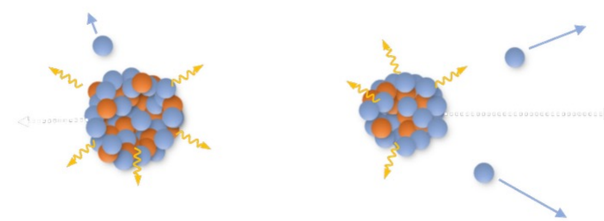
FPY workshop at Livermore, CA, USA – January 11-14, 2027.

Prompt emission

Neutrons are (mostly) evaporated from fully accelerated fragments — so the angles remember the fragments.



dν/dΩ vs ϑ(n–LF) for four light-fragment masses — CGMF and FREYA against Göök (2016)
Talou, Vogt, Randrup, Rising et al, EPJ-A (2018) 54: 9



an excited fragment: prompt γ, prompt n, then β decay

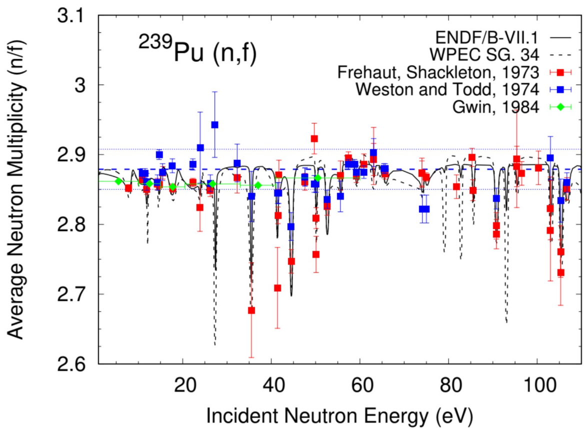
The real object is the joint distribution: ν correlated with A, with TKE, with emission angle

- More neutrons along the light-fragment axis means more excitation energy went to the light fragment — the angular distribution is a direct read-out of energy sharing at scission
- The sawtooth ν(A) is the same physics, integrated over angle

Models of energy sharing at scission remain poorly constrained experimentally, especially as a function of E* and TKE.

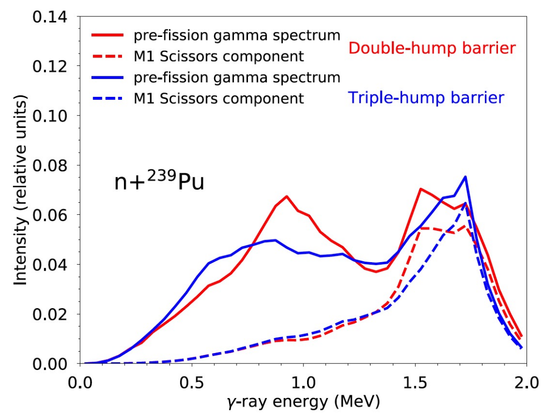
ν̄ fluctuations in the resonance region

Resonance to resonance, ν̄ moves by a few percent. Why?



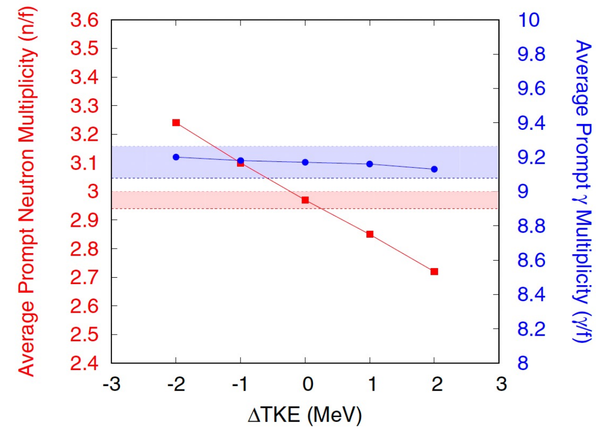
the observation

^{239}Pu(n,f): ν̄ varies from resonance to resonance, well outside the evaluated band.



(n,γf)

A γ emitted before the barrier lowers the excitation energy available to the fragments. The size of the effect depends on whether the barrier is double- or triple-humped — so ν̄ reports on barrier topology.



fluctuations in (A, TKE)

Different resonances populate slightly different transition states, and so slightly different mass and TKE splits. ν̄ follows ΔTKE steeply; Mγ barely moves.

J.E. Lynn, Phys. Lett. 18, 31 (1965)

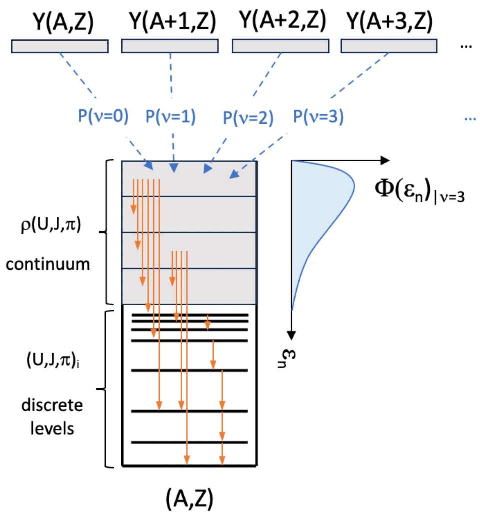
J.E. Lynn, P. Talou, O. Bouland, Phys. Rev. C 97, 064601 (2018)

Intriguing, unsolved, physics process, important for reactor simulations.

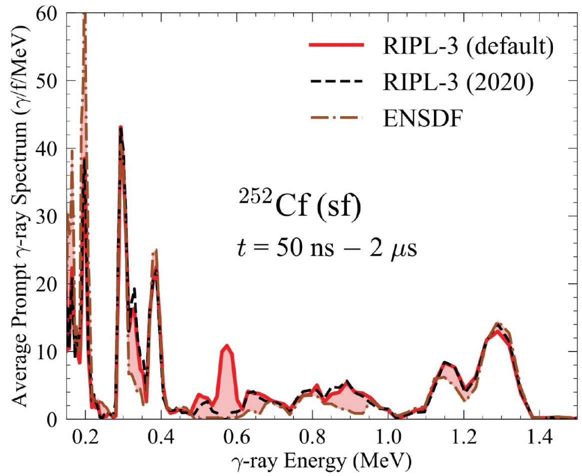
“Late prompt” fission gammas

Talou et al., Phys. Rev. C 112, 014601 (2025) – Rusev et al., Phys. Rev. C 111, 064613 (2025)

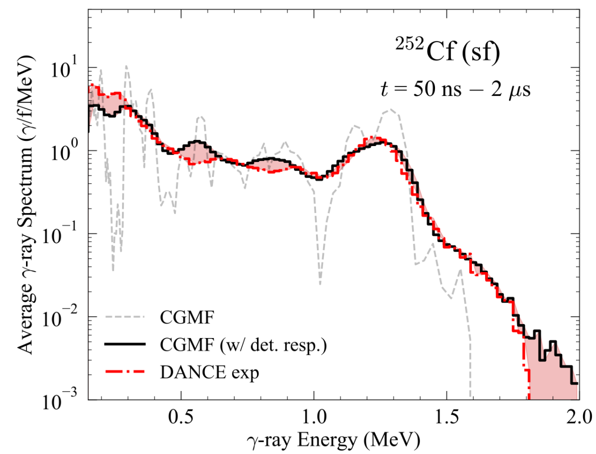
Post-scission de-excitation of fission fragments is (mostly) nuclear structure!



Hauser–Feshbach decay of each fragment through its own level scheme



^{252}Cf(sf), t = 50 ns – 2 μs: the same calculation with three different structure files



CGMF with detector response against DANCE

Important for simulations of subcritical experiments, accurate determination of “standard” ^{252}Cf (sf) <ν>, correct experimental estimation of prompt γ-ray multiplicity, gamma heating in reactors, etc.

Four applications, four projections

Same physics. Four different reductions of it.

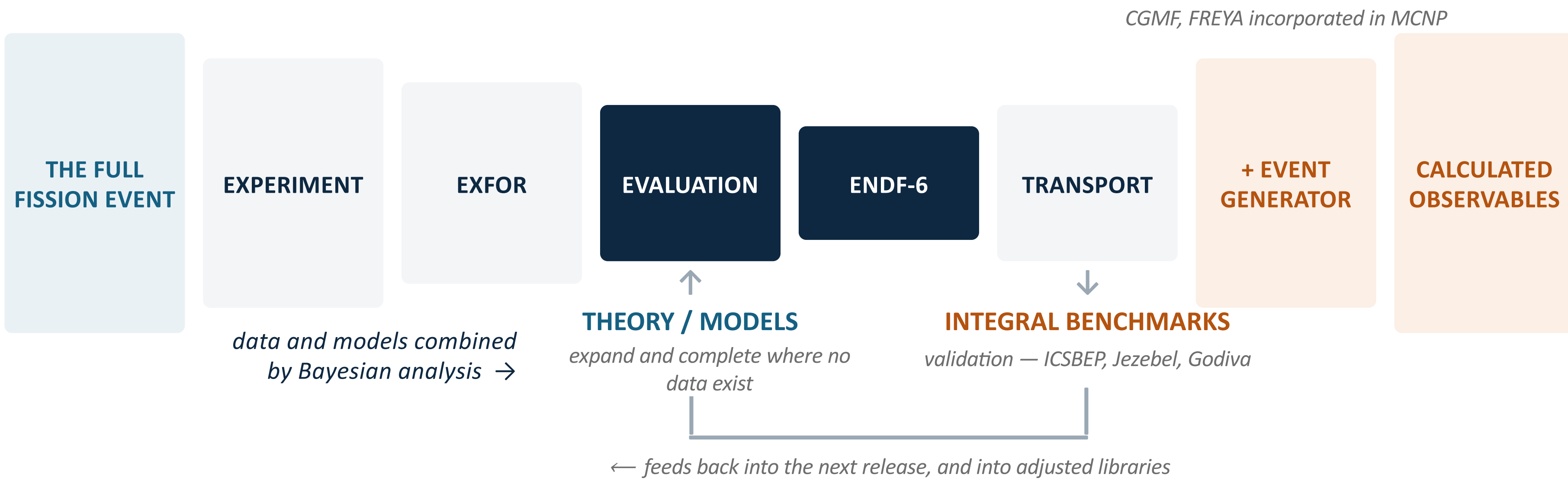
Consumer	Needs	Accuracy
Reactor physics	$\bar{\nu}$	~0.5% — k_{eff} scales directly
Safeguards multiplicity counting	$P(\nu)$ — factorial moments	0.1-2%
Subcritical measurement (Feynman-α)	Diven factor $\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	Less than 1%
Fission dynamics	$\nu(A)$ — the sawtooth	~10%, but fragment-resolved

The delayed cousin, same structure. Applications need aggregate β_{eff} to a few percent — the reactivity scale itself, every rod worth and every transient. Structure physics needs P_n precursor by precursor, far from stability.

ENDF evaluations carry only the first row...

The nuclear data pipeline

How to encapsulate our knowledge (experimental & theoretical) into one single file and library?



Models complete experimental data.

A transport code needs a file that is complete — every energy, every channel, every angular distribution.

Evaluation and models rarely match exactly.

The event generators do not necessarily reproduce the evaluated values.

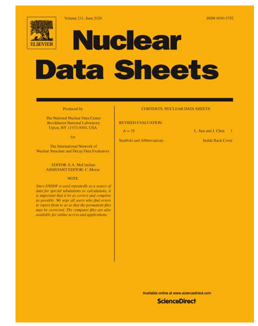
You need to know what's inside the "black box" of transport codes and evaluated nuclear data.

What an evaluation actually is

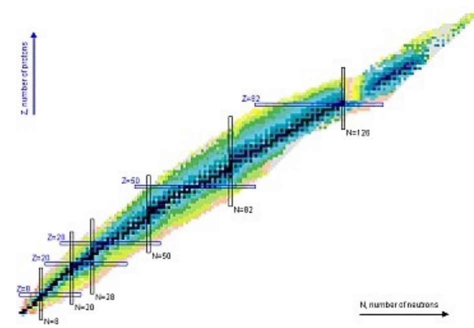
Not an average of measurements.

- A **Bayesian optimization** of model parameters against differential experimental data — SAMMY in the resolved resonances; TALYS / EMPIRE / CoH_3 + KALMAN in the fast range
- …with adjustments to a selected set of integral benchmarks, and then validation across a much wider set
- The output is a **complete**, documented file for every nuclide a transport code might ask for — thousands of them, maintained across decades
- **Covariances** exist for only a fraction of the evaluated data. Where they are absent, that does not mean the uncertainty is zero
- And **some of the physics we already know is missing**, because it lives in correlations the format cannot carry — a challenge for the databases, and for experimentalists: how do we preserve, store and communicate those correlations?

Bayes



Nuclear Data Sheets

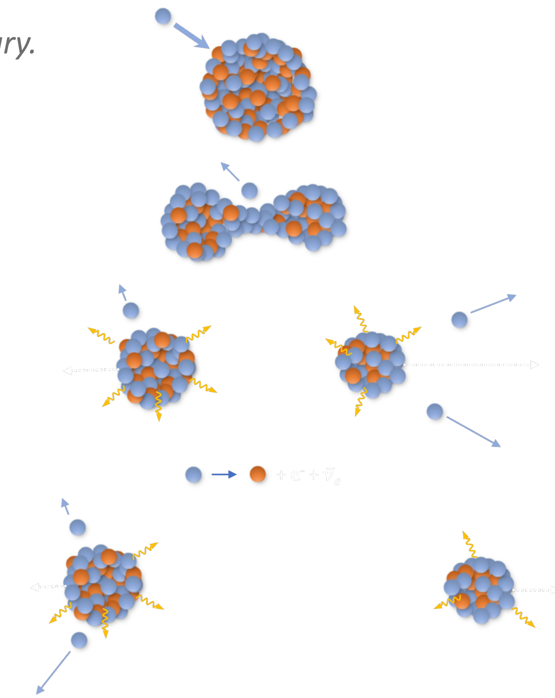


and every nuclide the codes may ask for

The three current general-purpose libraries. ENDF/B-VIII.1 — G.P.A. Nobre et al., Nucl. Data Sheets (2026), in press; arXiv:2511.03564. JENDL-5 — O. Iwamoto et al., J. Nucl. Sci. Technol. 60, 1–60 (2023). JEFF-4.0 — JEFF Project, OECD NEA (2025), doi:10.82555/e9ajn-a3p20; EPJ A topical collection in preparation.

Where the format ends

The boundary is moving — but there is a boundary.



ALREADY THERE, OR COMING

- $P(\nu)$: in ENDF/B-VIII.1 for a handful of important isotopes
- Yield covariances: under evaluation, with a new format proposed
- $\nu(A)$ and $\nu(TKE)$: nothing prevents these in an updated format
- Fragment angular distributions: feasible, at least in part

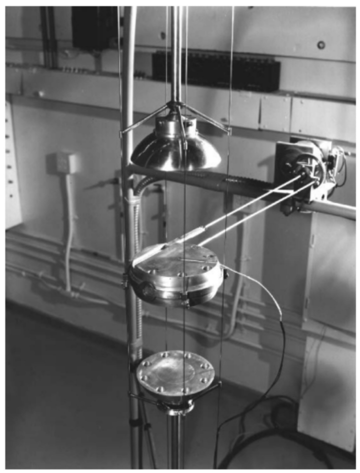
BEYOND ANY FORMAT

- n–γ correlations in energy, angle and multiplicity simultaneously
- A near-infinite number of combinations
- They must be modelled or calculated inline, inside the transport code
- Which is why the event generators exist, and will keep existing

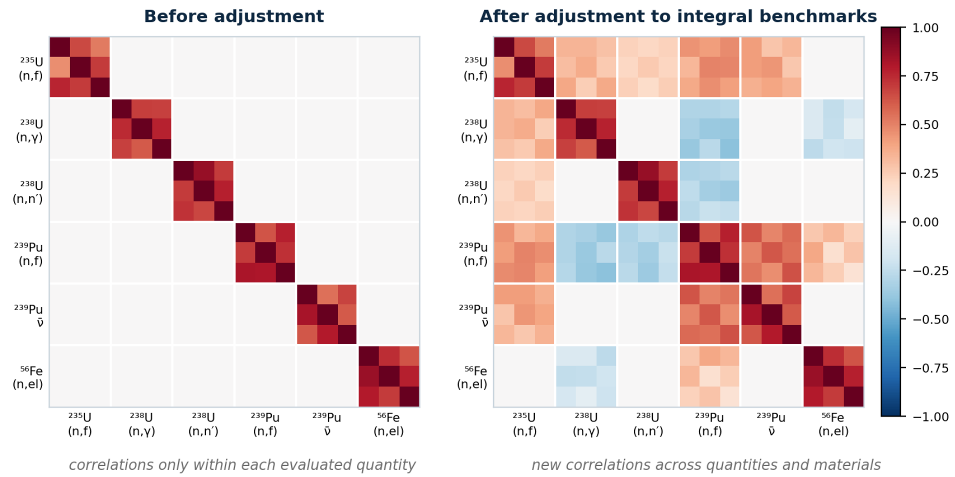
There is more physics in fission than any library will ever encapsulate.

General-purpose vs adjusted libraries

Adjusting to integral benchmarks adds real information, reduce uncertainties (for a specific application domain!), but/and brings correlations



Jezebel, ^{239}Pu, built in the 1950s — still calibrating ENDF/B-VIII.1



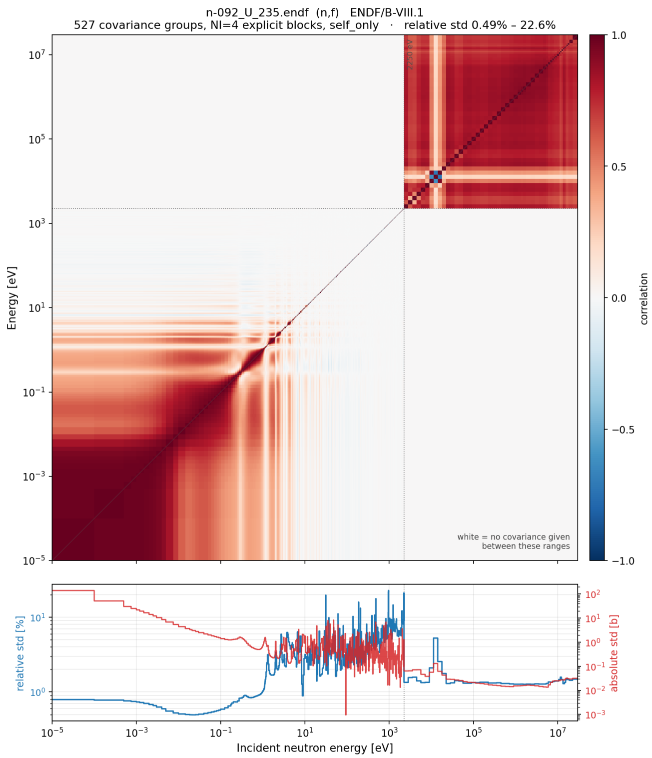
Schematic – before and after adjustment

Shrinking uncertainties is a feature, not a bug. An integral measurement representative of the application you are simulating is a very efficient route to accurate simulation — even though compensating errors are present and the adjusted library does not represent truth.

The price: correlations that did not exist before. Adjustment induces correlations across quantities and materials, so an adjusted library works beautifully inside its validated domain and must not travel outside it.

How uncertainty is represented in evaluated libraries

A covariance matrix is how uncertainty is carried in an ENDF file.



^{235}U(n,f) covariances, ENDF/B-VIII.1 — white = no covariance given

Where it comes from

Model calculations and their uncertainties, and experimental data and their uncertainties, combined through a Bayesian process — the same process that produced the central values.

Not all covariances are created equal

Some follow a careful examination of the data and the models. Some are expert estimates written in matrix form. And many simply do not exist — which does not mean the uncertainty is zero.

How much is in the white space?

No reported uncertainty does not equate to great accuracy!
Covariance matrices assume Gaussian-distributed uncertainties.

What is beyond the white space?

Beyond the models and their representations.

The danger/curse of AI and optimization in a limited representation of reality.

Where to aim

If you want a fundamental result to reach the evaluation world.

1 **Report correlated uncertainties**

A result without a **breakdown of sources and nature of uncertainties** cannot be weighted properly in a Bayesian evaluation. It can get down-weighted or even dropped.

2 **State your assumptions and normalizations**

Very difficult for an evaluator to know for every EXFOR entry, if not given.

3 **Publish the raw observable**

Ratio data vs interpretation into absolute quantities. Pre-neutron emission fission yields vs observed yields.

4 **Get it into EXFOR, with metadata**

Outside EXFOR, a result does not exist to an evaluator. And yet... EXFOR format is limited. **Important bottleneck for fission entries**

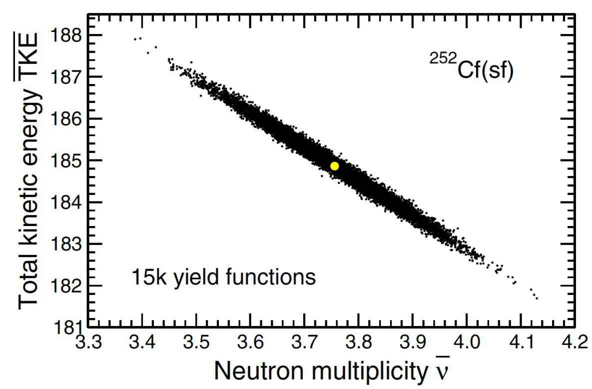
AND TWO THAT GO BEYOND THE EVALUATION WORLD

5 **Constrain model parameters, not only observables**

Barriers, level densities at deformation, transition states. Needed for nuclei and reactions that can't be measured.

6 **Measure what no library can hold**

The correlations are needed now, by the event generators, whether or not a format ever takes them. Important for theoretical models and for various applications.



*Strong anti-correlation between <TKE> and <ν> - **Randrup**, Talou, Vogt, PRC 99, 054619 (2019)*

Conclusions

1 **The libraries are a thin projection** of a collective quantum process we cannot yet fully predict — but a thin projection carrying a great deal of the right physics.

2 **Experimental data carry most of the weight** in an evaluation, especially for fission data. Where there is none, the models carry all of it. Documenting the data, metadata, uncertainty sources and quantification are all very important.

3 **What we calculate is rarely what we measure**. Data evaluators need to appreciate this point carefully.

4 **Genuine alignment between fundamental and applied needs is rare**, but also not required: hopefully, models carry information across the mismatch.

Fundamental research will always remain crucial to many existing and yet-to-come nuclear applications.

But some engineering solutions exist that genuinely don't need new nuclear data. And that's okay.

One last thing.

"The map is not the territory"

Alfred Korzybski, Polish-American scientist and philosopher, in General Semantics, 1931.

Magritte, "This is not a pipe" or "The Treachery of Images", 1929

Thank you.