Physics

Nuclear Data Needs for Fission

NDNCA Workshop

May 29th, 2015

W. Younes

Physical and Life Sciences

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

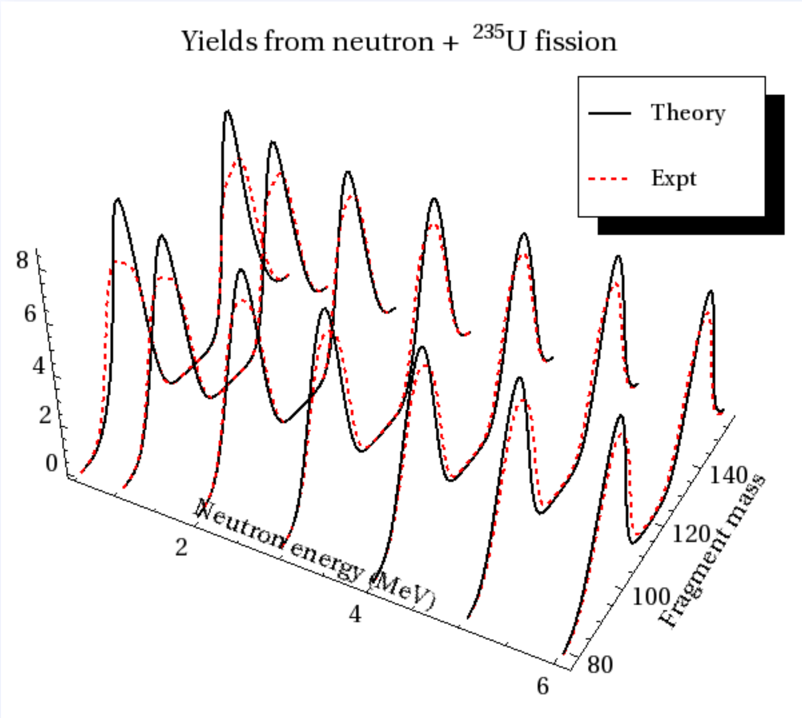
Part I: theorist's perspective

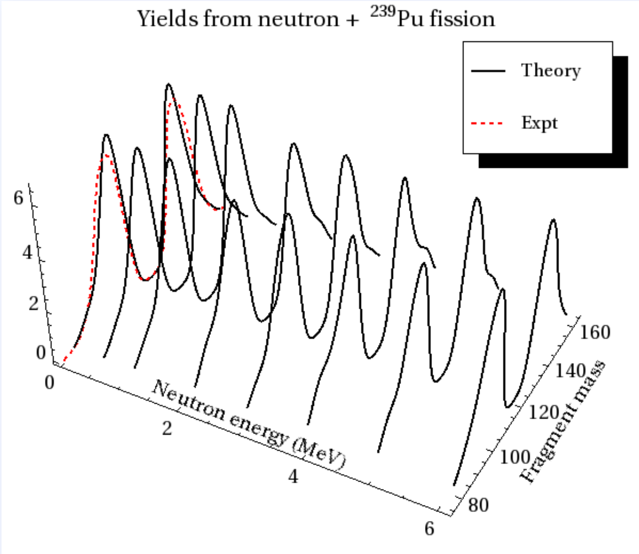
- Working on microscopic theory of <u>induced</u> fission:
  - Start from neutrons, protons, effective interaction
  - All the phenomenology is relegated to the interaction
  - Interaction parameters adjusted a-priori to:
    - Properties of infinite and semi-infinite nuclear matter
    - Properties of ^{16}O,^{18}O, ^{90}Zr, a few Sn isotopes
    - Slight adjustment in 1984 to better reproduce ^{240}Pu fission barrier
  - Never adjusted to the fission data we calculate!
  - Time-dependent treatment, going all the way to scission

- **Theory can fill in gaps where data are lacking**
- **But how can nuclear data improve the theory?**

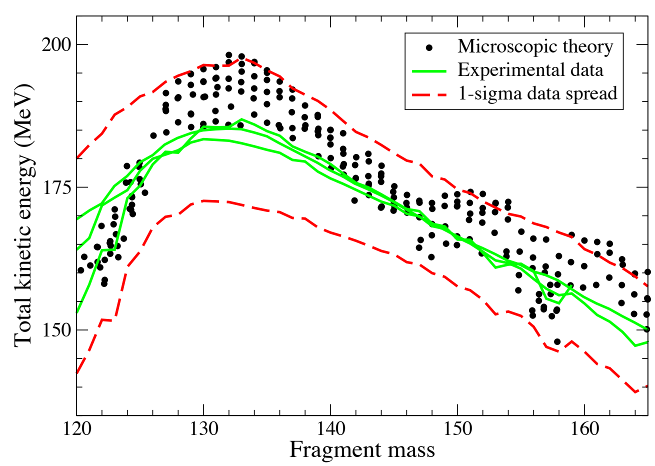
Example: Calculations for ^{235}U(n,f) and ^{239}Pu(n,f)

Younes et al., Proc. ICFN5, p. 605 (2012)





Thermal neutrons + ^{239}Pu



Starting from protons, neutrons, and effective interaction:
Results consistent with experiment!

Where do nuclear data come in?

- We don't adjust parameters to reproduce the data
- What happens when experiment and theory don't agree (and you believe the data)? How do we improve the theory?
- What must be done to improve the theory
  - Form of the interaction can be improved: does not require fission data
  - Restore broken symmetries in the calculations, e.g. to get states with good angular momentum: does not require fission data, just lots of formalism and computer time
  - Include all relevant degrees of freedom (esp. single-particle): this is where fission data can help guide the theory
    - $\Rightarrow$ more realistic calculations
    - $\Rightarrow$ explosion in complexity of formalism, computer time

Need measurements that directly probe fission dynamics (i.e., before scission)

Example: induced fission timescale measurements

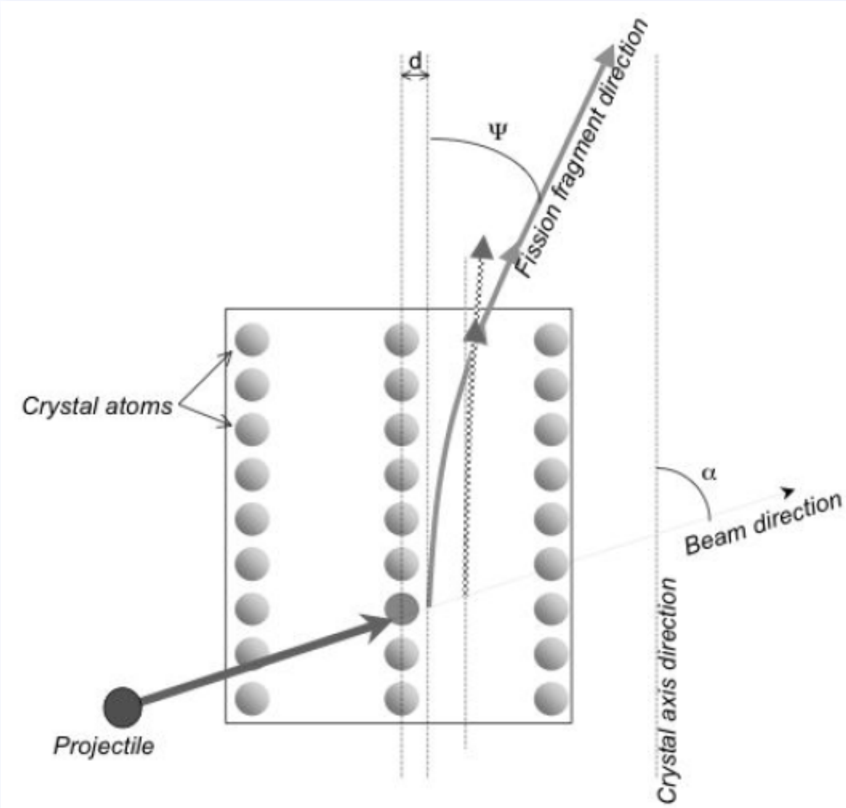
- Probes "friction" = coupling between degrees of freedom
- But times scales can be very short:

	Nuclei	Atoms	Molecules
Size	~ 10^{-14} m	~ 10^{-10} m	~ 10^{-9} m
Time scale	10^{-21} s = 1 zs	10^{-18} s = 1 as	10^{-15} s = 1 fs

- Nevertheless, fission times have been measured for the last 30+ years:
  - Direct techniques (⇒ little or no dependence on nuclear models)
    - Blocking effect in single crystals
    - Filling of vacancies in inner electronic shells
  - Indirect techniques (⇒ dependent on nuclear models)
    - Pre-scission multiplicities (p, n, and γ)
    - Fission probabilities

Caution: theory distinguishes pre- and post-saddle times

Direct fission time measurement by crystal blocking technique

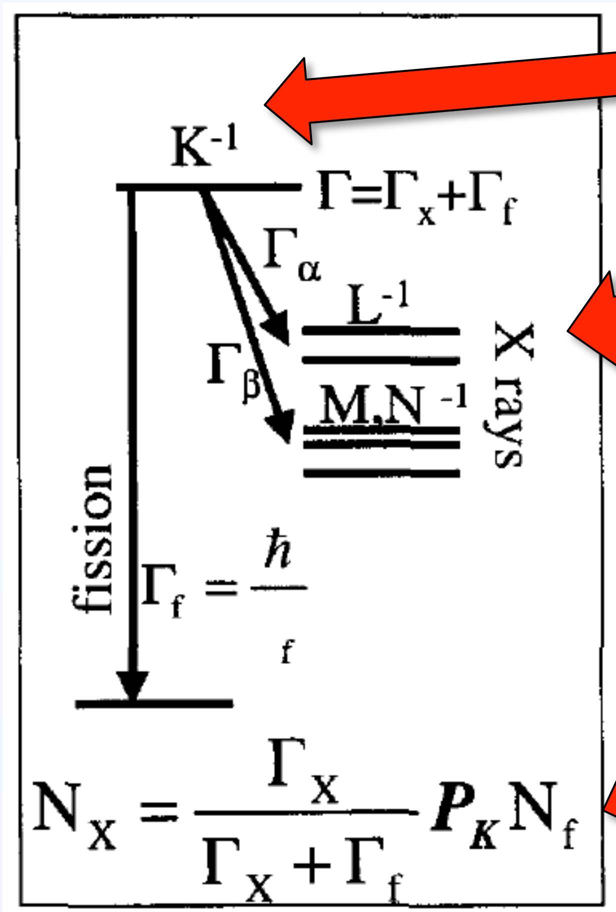


Morjean et al., Eur. Phys. J. D 45, 27 (2007)

- Effect discovered in 1965
- Composite system recoils away from crystal plane
- Fragment emitted close to and in the direction of crystal row will be deflected through angle ψ
- Dips near crystal axis, with shape related to <u>reaction time</u>
- Min time limited by thermal vibrations of crystal atoms (best $t_{min} = 3\times10^{-19}$ s)
- Max time ~ travel time between adjacent rows (e.g., 5×10^{-17} s)

Measures <u>total</u> fission times down to ~ 10^{-19} s

Direct fission time measurement by electronic vacancy technique



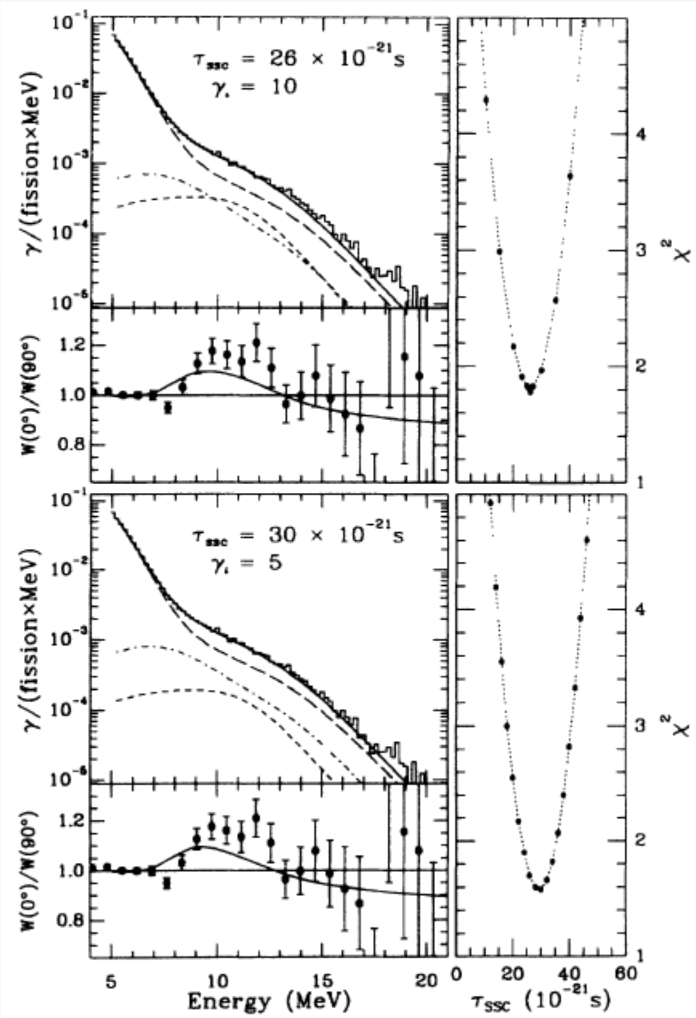
Wilschut & Kravchuk, NPA 734, 156 (2004)

- K-shell hole is created by projectile collision, which also excites nucleus
- K-shell hole is destroyed by either x-ray emission or fission

- P_K = K-shell hole probability (measured using non-fission reaction)
- Number of x-rays (N_X) to fissions (N_f) = branching ratio × P_K
- Solve for $\tau_f = \hbar/\Gamma_f$

Measures <u>total</u> fission times down to ~ 10^{-18} s

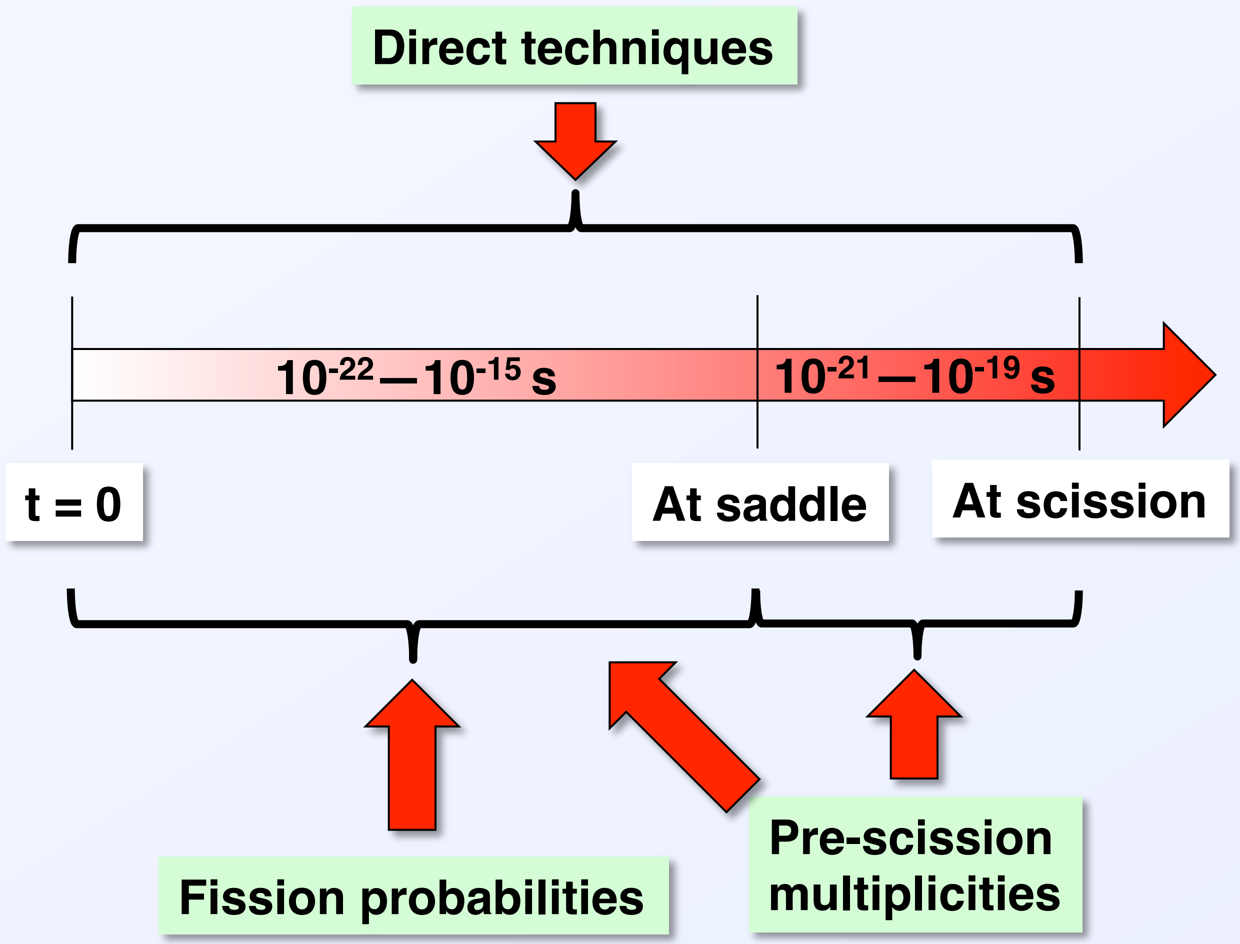
Indirect fission time measurement from pre-scission GDR γ-rays



D. J. Hofman, PRL 72, 470 (1994)

- Measure γ-fragment spectrum & angular correlations
- Pre- and post-scission GDR γ-ray yields can be separated by energy ($E_\gamma \propto A^{-1/3}$)
- Average deformation of γ-emitting nucleus prior to fission can be deduced from splitting of energies
- To deduce fission times, still need reliable level densities as a function of deformation and temperature

Different fission time regimes probed by different techniques



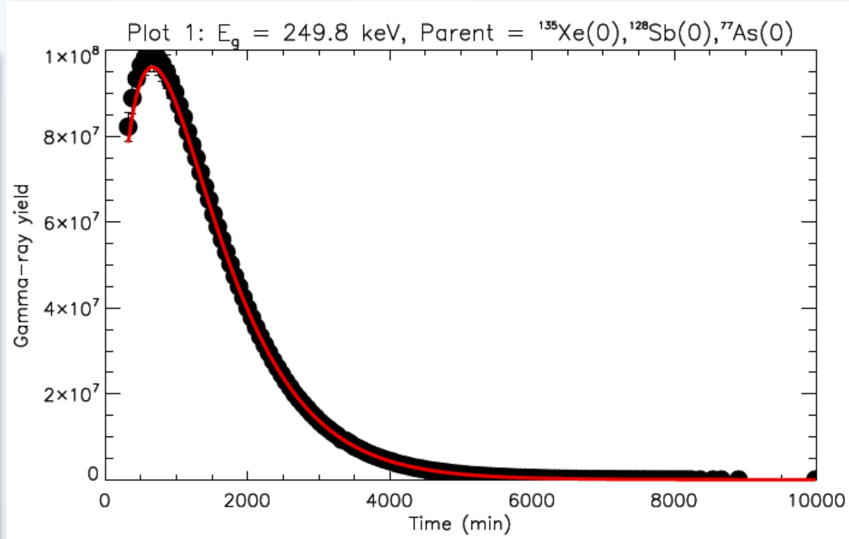
The different techniques give complementary info

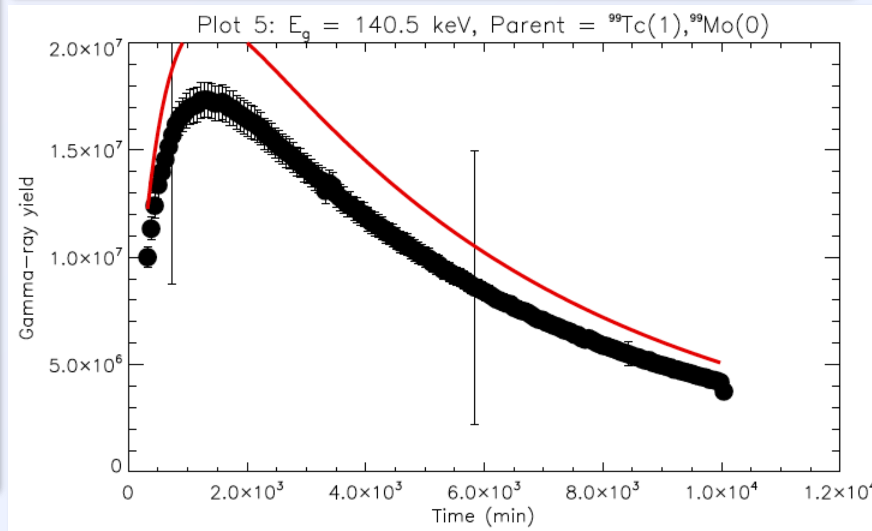
Part II: Experimentalist's perspective

- Example: irradiation of ^{235}U at Godiva reactor in Aug 2014
  - PNNL-LLNL-LANL collaboration
    - J. J. Ressler, W. Younes, J. T. Burke, A. Tonchev, R. Haslett, K. Roberts, P. Torretto, T. F. Wang, T. Woody, A. Prinke, S. Stave, L. Greenwood, LLNL-TR-666417 (2014)
    - W. Younes, LLNL-TR-665698 (2014)
  - Delayed gammas (1 hr < t < 7 days) measured with 2 HPGe detectors
  - Extracted: γ-ray yields as function of time
  - Compare with FIER prediction
    - Solves Bateman eqs. using England & Rider yields and γ-ray info from several databases
    - D. H. Chivers et al., UCB (2011)
    - ^{235}U calculations of γ-ray yields by E. Matthews

Sample γ-ray yields compared to FIER model

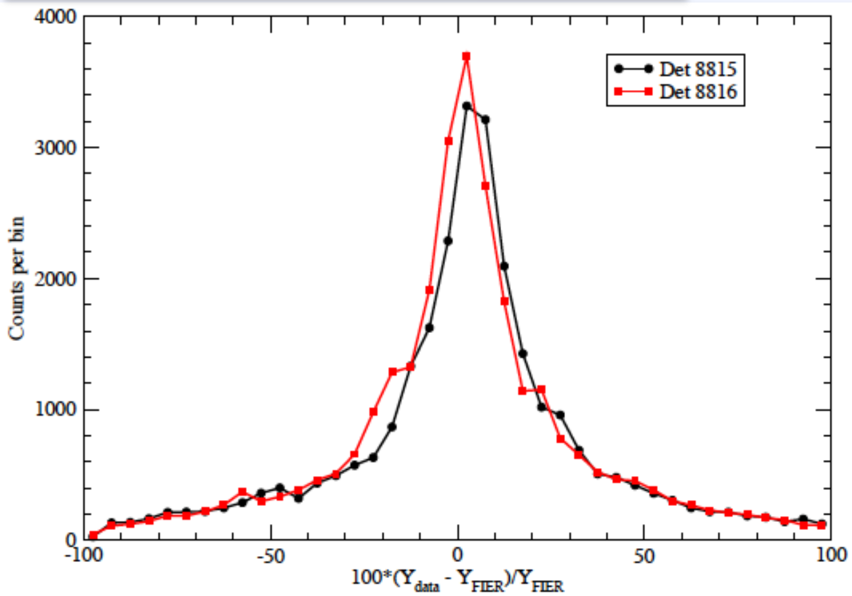
- Measured γ-ray yields as function of time for 469 lines from products with $32 < Z < 63$ and $76 < A < 157$
- Yields binned in 1-hr increments
- Generally good agreement between experiment and model, but significant differences exist





Overall comparison between experiment and model

Generally good agreement, but can be improved

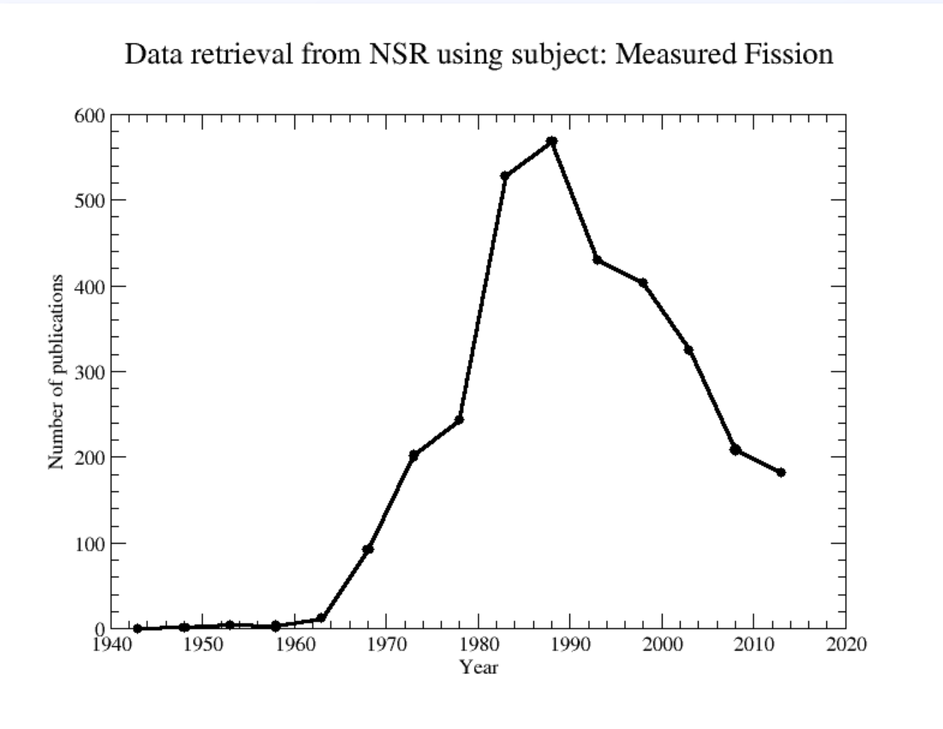


- Main source of uncertainty: γ-ray branching ratios, but
  - Disparate interests/motivations basic and applied communities
    - Which data are needed and to what accuracy depends on application
    - Good raw data are sometimes discarded
- Yields of metastable states
- Yield compilations tend to focus only on 3 neutron energies

Conclusions

- (My biased) theorist's perspective:
  - Need data that directly probe fission dynamics (e.g. fission times)
    - Evaluators: database of existing data and calculations?
    - Experimentalists: can we reduce or constrain model dependence, especially for pre-scission gammas?
    - Theorists: what are ideal cases for study (long saddle-to-scission times, lots of pre-scission emission)?
- (My biased) experimentalist's perspective:
  - Need accurate data on
    - γ-ray branching ratios
    - Fission yields for metastable states
    - (n,f) yields systematically measured & compiled at energies other than thermal, fast and 14 MeV

Finally: a homework problem on the status of fission data



- **Evaluators:**
  - **Is this trend real or an artifact?**
  - **How would you generate this plot?**
- **Experimentalists & theorists, if the trend is real**
  - **Is this acceptable?**
  - **What is the takeaway message, if any?**

Selected bibliography

- Fission time data needs
  - D. Jacquet & M. Morjean, Prog. Part. Nucl. Phys. 63, 155 (2009), and refs therein
  - R. Butsch et al., Phys. Rev. C 44, 1515 (1991)
  - H. W. Wilschut & V. L. Kravchuk, Nucl. Phys. A734, 156 (2004)
  - F. Goldenbaum et al., Phys. Rev. Lett. 82, 5012 (1999)
- γ-ray yield data needs
  - W. Parker, LLNL-TR-417081 (2009)
  - C. W. Reich, Rad. Eff. 93, 311 (1986)
  - D. L. Smith & B. J. Micklich, INDC(NDS)-428 (2001)
  - See also references in W. Younes et al., LLNL-TR-648488-DRAFT (2014)