Nuclear Data Needs for Fission

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Part I: theorist’s perspective

- Working on microscopic theory of induced 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 $^{16}\text{O}, ^{18}\text{O}, ^{90}\text{Zr}$, a few Sn isotopes
    - Slight adjustment in 1984 to better reproduce $^{240}\text{Pu}$ 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 $^{235}\text{U}(n,f)$ and $^{239}\text{Pu}(n,f)$

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
    ⇒ more realistic calculations
    ⇒ 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:

<table>
<thead>
<tr>
<th></th>
<th>Nuclei</th>
<th>Atoms</th>
<th>Molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$\sim 10^{-14}$ m</td>
<td>$\sim 10^{-10}$ m</td>
<td>$\sim 10^{-9}$ m</td>
</tr>
<tr>
<td>Time scale</td>
<td>$10^{-21}$ s = 1 zs</td>
<td>$10^{-18}$ s = 1 as</td>
<td>$10^{-15}$ s = 1 fs</td>
</tr>
</tbody>
</table>

- 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 $\gamma$)
    - Fission probabilities

Caution: theory distinguishes pre- and post-saddle times
Direct fission time measurement by crystal blocking technique

- 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 $\psi$
- Dips near crystal axis, with shape related to reaction time
- Min time limited by thermal vibrations of crystal atoms (best $t_{\text{min}} = 3 \times 10^{-19} \text{ s}$)
- Max time $\sim$ travel time between adjacent rows (e.g., $5 \times 10^{-17} \text{ s}$)


Measures total fission times down to $\sim 10^{-19} \text{ s}$
Direct fission time measurement by electronic vacancy technique

- 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 $\times P_K$
- Solve for $\tau_f = \hbar/\Gamma_f$

Measures total fission times down to $\sim 10^{-18}$ s

Wilschut & Kravchuk, NPA 734, 156 (2004)
Indirect fission time measurement from pre-scission GDR $\gamma$-rays

- Measure $\gamma$-fragment spectrum & angular correlations
- Pre- and post-scission GDR $\gamma$-ray yields can be separated by energy ($E_{\gamma} \propto A^{-1/3}$)
- Average deformation of $\gamma$-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

D. J. Hofman, PRL 72, 470 (1994)
Different fission time regimes probed by different techniques

- Direct techniques
  - $10^{-22} - 10^{-15}$ s
  - $10^{-21} - 10^{-19}$ s

- $t = 0$, At saddle, At scission

- Fission probabilities
- Pre-scission multiplicities

The different techniques give complementary info
Part II: Experimentalist’s perspective

- Example: irradiation of $^{235}\text{U}$ at Godiva reactor in Aug 2014
  - PNNL-LLNL-LANL collaboration
    - W. Younes, LLNL-TR-665698 (2014)
  - Delayed gammas ($1\text{ hr} < t < 7\text{ days}$) measured with 2 HPGe detectors
  - Extracted: $\gamma$-ray yields as function of time
  - Compare with FIER prediction
    - Solves Bateman eqs. using England & Rider yields and $\gamma$-ray info from several databases
      - D. H. Chivers et al., UCB (2011)
      - $^{235}\text{U}$ calculations of $\gamma$-ray yields by E. Matthews
Sample $\gamma$-ray yields compared to FIER model

- Measured $\gamma$-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

- Main source of uncertainty: $\gamma$-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
    - $\gamma$-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

- **γ-ray yield data needs**
  - W. Parker, LLNL-TR-417081 (2009)
  - C. W. Reich, Rad. Eff. 93, 311 (1986)
  - See also references in W. Younes et al., LLNL-TR-648488-DRAFT (2014)