Uncertainties & Correlations in Nuclear Fission Data
The role of models and experiments

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Second International Workshop on
“Perspectives for Nuclear Data for the Next Decade”
Oct. 14-17, 2014, Bruyères-le-Châtel, France

LA-UR-14-27975
Nuclear Fission Data
Selected examples

Fission Cross Sections
(n,f), (p,f), (γ,f), (t, pf), etc

Diagram showing the cross section vs. incident neutron energy for 235U (n,f) reaction.
Nuclear Fission Data
Selected examples

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Fission Fragment Yields
Y(A,Z,KE)
Nuclear Fission Data
Selected examples

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\( Y(A,Z,KE) \)

Prompt Fission Neutrons and Gamma Rays
(multiplicity, spectrum, correlations)
Nuclear Fission Data
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- **Fission Cross Sections**
  - $(n,f)$, $(p,f)$, $(\gamma,f)$, $(t,pf)$, etc

- **Fission Fragment Yields**
  - $Y(A,Z,KE)$

- **Prompt Fission Neutrons and Gamma Rays**
  - (multiplicity, spectrum, correlations)

- Others?
  - $\beta$-delayed neutrons and gammas, fission fragment angular distributions, pre-scission neutrons and photons, prompt X-rays, etc.
Uncertainties & Correlations
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- Stemming from both experiments and models
Uncertainties & Correlations

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- Some examples:
  - Experiments:
    - Fission fragment yields
    - Prompt fission neutrons
  - Theory:
    - Uncertainties in modeling fission cross sections and “empirical fission barriers”
    - Modeling the prompt fission neutron spectrum
Uncertainties in Fission Experiments
Two examples
Fission Fragment Yields

- Typical resolutions:
  - 3-5 amu for Y(A)
  - 1-2% in Kinetic Energy
  - ΔZ~1

- Neutron emission from fragments
  - Products, not fragments, are measured!

- Very little data on E* dependence
Fission Fragment Yields

- Typical resolutions:
  - 3-5 amu for Y(A)
  - 1-2% in Kinetic Energy
  - $\Delta Z \sim 1$
- Neutron emission from fragments
  - Products, not fragments, are measured!
- Very little data on $E^*$ dependence

Prompt Fission Neutrons

- Multiplicity measurements ($\nu$)
  - Large Gd-loaded tanks
  - No energy resolution
- Spectrum ($\chi$)
  - Low-energy (<500 keV) very sensitive to multiple scattering
  - High-energy (>5 MeV) poor statistics
Uncertainties in Fission Theories & Modeling
Two examples
Fission Cross Sections

- Fission barrier
- Double- or triple-humped
- Deviations from simplified parabolas
- Inertia tensor
- Transition states, level densities at saddle points
- Class-I,II states coupling
Uncertainties in Fission Theories & Modeling

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**Prompt Fission Neutrons**
- Simple models
  - Madland-Nix, Watt, Maxwellian
  - Few model parameters, easy to adjust but strong correlations
- More sophisticated
  - Monte Carlo Weisskopf & Hauser-Feshbach
  - Many parameters, more difficult to adjust but (possibly) more faithful
  - Various data calculated
The Nuclear Data Evaluation Process
(in a nutshell)
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(differential)
Experimental Data
The Nuclear Data Evaluation Process  
(in a nutshell)

(differential)  
Experimental Data

Theory/Modeling
The Nuclear Data Evaluation Process (in a nutshell)

(differential) Experimental Data

Theory/Modeling

Model Input Parameters

ENSDF RIPL-3...
The Nuclear Data Evaluation Process
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(differential) Experimental Data

Comparisons

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"Least-Square Fits"

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“Least-Square Fits”

Uncertainty Quantification

Chi-Nu

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- Comparisons
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- "Least-Square Fits"
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- Comparisons with integral benchmarks
- Model Input Parameters
- ENSDF RIPL-3...
- Feedback
The Nuclear Data Evaluation Process
(in a nutshell)

Model Input Parameters

(differential) Experimental Data

Comparisons

“Least-Square Fits”

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Feedback

ENSDF
RIPL-3...

For fission... limited use of correlated data to constrain evaluations → PFNS, $\sigma_f(E^*)$, FFAD, ...
Modern Fission Experiments
Some examples from Los Alamos

- **Time-Projection Chamber** for fission cross-section measurements

- **Chi-Nu setup** (22 6Li glass detectors) to measure prompt fission neutron spectra

- **SPIDER 2E-2v** for fission fragment yield measurements

- **DANCE w/ NEUANCE** for correlated measurements on prompt fission neutrons and γ rays with fission fragments
Modern Fission Experiments
Some examples from Los Alamos

Many other facilities and detector setups in construction worldwide:

- EAR2 at CERN
- NFS @ SPIRAL2 @ GANIL
- IGISOL-JYFLTRAP
- SOFIA: Studies On Fission with Aladin (reverse kinematics) at GSI
- STEFF
- ...

- cf. Talk by X.Ledoux

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- New data to fill obvious gaps in our experimental database
- Better accuracy
- Innovative measurements
- Correlated data
- ...

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Modern Fission Experiments Elsewhere

SOFIA: Studies on Fission with Aladin @ GSI
reverse kinematics, GSI: ΔA~0.6-0.8, ΔZ~0.4

FALSTAFF @ NFS
Four Arm cLover for the STudy of Actinide Fission Fragments

EAR2 @ n_TOF @ CERN
Fission x/s measurements of actinides with half-lives ~years

NFS @ SPIRAL 2 @ GANIL
NFS – Neutrons For Science
Modern Fission Theories & Models
Time-Dependent Microscopic Approaches
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Time-Dependent Microscopic Approaches

From ascr-discovery.science.doe.gov
Credit: A. Staszczak et al., ORNL

W. Younes, FIESTA school,
Sep. 8-9, 2014, Santa Fe

N. Dubray, FIESTA workshop,
Sep. 10-12, 2014, Santa Fe
Modern Fission Theories & Models
Time-Dependent Microscopic Approaches

Uncertainties & Errors...

- Fundamental n-n force
- Constrained calculations; parameter space?
- Class-3 PES (N.Dubray)
- Correlations s.p. and collectivity (H.Goutte)
- Need for very large scale computations

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A.J.Sierk, FIESTA workshop, Sep. 10-12, 2014, Santa Fe
Modern Fission Theories & Models
Dynamics in the macro-micro theory

- Macro-micro fundamental assumptions
- Inertia tensor
- Temperature
- Sub-barrier fission


A.J.Sierk, FIESTA workshop, Sep. 10-12, 2014, Santa Fe

Uncertainties & Errors...
Monte Carlo codes to follow the de-excitation of fission fragments:
CGM/F, FREYA, FIFRELIN, GEF, ...

Uncertainties & Errors...
- Nuclear structure data
- OMP for neutron-rich nuclei
- Excitation sorting mechanisms at scission
- ...

Modern Fission Theories & Models
Prompt neutrons and photons
Modern Fission Theories
Fission Cross Sections

- Modern Theory of Fission Cross Section
  - Numerical integration of V(fission path)
  - Inertia tensor along the path
  - Coupling between Class-I and Class-II states
  - Class-III states
  - Fission transition states
  - Level densities
  - Different fission paths/modes?
  - Microscopic input?

Goriely, Hilaire, Koning, Sin, Capote
PRC 79, 024612 (2009)

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Uncertainties & Errors...

- Many adjustable parameters
- Can be reduced but not eliminated
- Need for correlated data

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- Simultaneous measurements of $\sigma_f(E_n)$ and $dY_{FF}/d\Omega$
- Work at LANSCE w/ TPC and CERN n_TOF
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- $<\nu_p>$ and $<E_{\gamma}^{\text{tot}}>$ fluctuations in resonance region

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- New DANCE measurement of $\langle E_{\gamma}^{\text{tot}} \rangle(E_n)$
- Theoretical interpretation based on the $(n,\gamma f)$ process
- New $\langle \nu_p \rangle(E_n)$ measurements would be welcome!

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Reducing Uncertainties in our Predictions of Fission Observables
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- Predictions for related data:
  - Fission cross sections across isotopes and incident channels, fission fragment angular distributions, fission modes, etc.
  - Prompt fission neutrons: multiplicity, spectrum, n-n correlations in energy and angle, etc., as a function of fragment (A,Z,KE)
  - Same for prompt fission gamma rays (cf. Oberstedt, Jandel)
  - Use of $\langle \nu \rangle, \langle \varepsilon_n \rangle, \langle \nu_\gamma \rangle, \langle \varepsilon_\gamma \rangle$ as function of (A,Z,KE) to constrain PFNS
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- Renewed need for original, exclusive, and accurate fission data – beware of old measurements & systematic biases (Haight)
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• Proper propagation of uncertainties from both experiments and models (de Saint-Jean, Rochman)
• Evaluated uncertainties can be kept small when nearby data are available – adjusted libraries – beware of extrapolations!
The next decade
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“Uncertainties in Nuclear Fission Data,”
P.Talou, T.Kawano, M.B.Chadwick, D.Neudecker, and M.E.Rising

to appear in a Special Issue of J. Phys. G: Nuclear and Particle Physics on

“Enhancing the interaction between nuclear experiment and theory through information and statistics”