Perspectives on Measurements of Prompt Fission Neutron Spectra for Fission Induced by Fast Neutrons

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Perspectives on measurements of prompt fission neutron spectra

- Spontaneous fission ($^{252}\text{Cf}$)

- Neutron-induced fission
  - Thermal neutron-induced fission
  - Fast neutron-induced fission
Components for neutron-induced PFNS measurements

• Experiments
  – Neutron source – intense, low background neededs
  – Detectors – good neutron identification (psd or ?), good efficiency, “modelable” in MCNP, GEANT, …
  – Data acquisition – implementation of new hardware, firmware, software – good resolution, good timing, programmable, capable of handling high counting rates

• Modeling neutron transport as corrections to literature data, and design and analysis of new experiments
Predictions for PFNS measurement technologies

• Experiments
  – Neutron source – intense, low background needed -- no new facilities for this type of measurement (?)
  – Detectors – good neutron identification (psd or ?), good efficiency, “modelable” in MCNP, GEANT ... -- nothing for greatly advanced capabilities
  – Data acquisition – implementation of new hardware, firmware, software – good resolution, good timing, programmable, capable of handling high counting rates -- In progress

• Modeling neutron transport as corrections to literature data, and design and analysis of new experiments-- NOW and continuing
Predictions for PFNS measurements – work to be done

- $^{239}$Pu(n,f) – for incident neutron energies > 0.5 MeV and to requested accuracy
  - Resolve discrepancies for PFNS > 0.5 MeV – probable in 2-3 years
  - Produce new data for PFNS in range 0.05 to 0.50 MeV -- maybe in 3-4 years

- $^{235}$U(n,f) – for incident neutron energies > 0.5 MeV
  - Data for PFNS > 0.5 MeV – probable in 3-4 years
  - Produce new data for PFNS in range 0.05 to 0.50 MeV -- maybe in 4-5 years
Data in the literature: PFNS for $^{239}\text{Pu}(n,f)$ – incident monoenergetic sources
Discrepancy in monoenergetic data for high-energy end of PFNS

Data > ENDF for Eout > 7 MeV

Data < ENDF for Eout 7 to 12 MeV

Note: Staples also for Einc = 1.5, 2.5, 3.5 MeV
Literature data, discrepancies and target accuracies

\[ 239\text{Pu} \]

- Knitter, 1975 (0.215 MeV)
- Staples, 1995 (0.5 MeV)
- Lajtai, 1985 (thermal)
- Boytsov, 1983 (thermal)
- ENDF/B-VII.0
- Talou Monte Carlo, 2011
Data in the literature: PFNS for $^{239}$Pu(n,f) — incident continuous sources
Measurements made with “white” neutron source at LANSCE for $^{239}$Pu(n,f): CEA-LANL collaboration


Data > ENDF for Eout > 7 MeV

Data < ENDF for Eout > 7 MeV

Note: Data for both also for Einc = 1.0 to > 20 MeV
Chatillon data will also be reduced due to time resolution. Detector calibration difference needs to be included also.

- Correction will reduce data points above 7 MeV but not so much as Noda data because of better time resolution by Chatillon fission chamber.

- Major difference with Noda is in calibration of neutron detector efficiency, which explains why Chatillon < Noda above 7 MeV.

WNR/LANSCE provides neutrons from 100 keV to 200 MeV for PFNS Studies

Neutron spectrum

Double time-of-flight experiment

30 MeV
Fission sample and fission counter (LLNL) to contain ~ 100 mg of $^{239}\text{Pu}$

- Parallel-Plate Avalanche Counter (PPAC)

**In Beam**

10 cm diam. $\times$ 17 cm

**Cover Off**

Foil: 5 cm diam.
Sample: 4 cm diam.

**One Foil Stack** (of 10)

- Pt foil
- Al-mylar foil
- Sample
- Ti foil
- Al-mylar foil
- Al-mylar foil
- Pt foil

$t = 400 \, \mu\text{g/cm}^2$
Timing res.: 1–1.5 ns

Source – PPAC $\rightarrow$ Time of flight (1) $\rightarrow$ Energy of incident neutron
Chi-Nu array of fast neutron detectors measures prompt neutron spectra emitted in fission

- 22 $^6$Li-glass scintillation detectors
- 54 liquid scintillation neutron detectors

21.5 m from WNR source

$^6$Li-glass detector array

Neutron beam

Fission chamber (PPAC)

Double time-of-flight experiment
Neutron detectors – two types

54 Liquid scintillators – 1.0 m flight path

22 $^6\text{Li}$-glass scintillators – 0.4 m flight path

PPAC – neutron detector $\rightarrow$ Time of flight (2) $\rightarrow$ Energy of outgoing neutron
Modeling Neutron Transport in PFNS Experiments
Terry Taddeucci
MCNP simulations have been used to investigate some previous measurements of the PFNS

Two standard papers for $^{239}$Pu:

- H.H. Knitter, Atomkernenergie 26, 76 (1975)

Some possible sources of systematic error:

- multiple scattering in the target
- multiple scattering in the collimation
- detector efficiency
- background subtraction
- Calibrations (TOF, PH, flight path, etc)

these are not necessarily decoupled
Experimental layout for the measurements by Staples et al.

Fig. 1. Experimental arrangement in the target room.
Experimental layout for the measurements by Knitter


Fig. 1. Lay-out of the detecting system

1 Detector 1
2 Detector 2
3 Detector 3
4 Monitor
5 Paraffin
6 Lead
7 Shadow cone
8 Scatterer
9 Target can
10 Pick-up loop
11 Accelerator tube

scale: 10 cm

typical for this facility (CBNM, Geel)
How did Knitter and Staples handle target corrections?

Staples:
"Multiple scattering corrections and neutron attenuation corrections have not been performed because the samples are so small that these effects can be neglected."

Knitter:
"The result of the fit gave an average fission neutron energy of
\[<E> = \frac{3}{2}T = 2.12 \pm 0.01 \text{ MeV}\]
This result contains a small calculable systematic error, since the fission neutrons produced in the sample can make secondary interactions with the sample material. Correction calculations were done in the manner described in a previous paper [1]."


Multiple scattering plays a significant role in the $^{239}\text{Pu}$ measurements of Knitter.
Comparison of MCNP calculations to the $^{239}$Pu measurements of Knitter

**MCNP flux at the detector position**

- **target + shields**
- **target only**
- **data (0.215 MeV)**

Two effects:
- n-multiplication
- in-scattering

Calculations for $^{239}$Pu target
Target and collimator effects in the $^{239}$Pu data of Staples et al.

**MCNP output / input**

![Graph showing neutron energy vs. ratio and calculation: target (t), collimator (c), product (p = t \times c)]

- Data range:
- Target (t)
- Collimator (c)
- Product (p = t \times c)

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Target and collimator effects in the $^{239}$Pu data of Knitter

calculation:
  - target (t)
  - collimator (c)
  - product ($p = t \times c$)
Modeling of Our Present Experiments

Terry Taddeucci
The low-energy part of the PFNS is being measured with an array of $^6$Li-glass detectors

- active thin target (~100 mg)
- many detectors (22)
- open geometry
  (no shielding)
The Chi-Nu MCNP model accounts for neutron scattering from all nearby objects.

Model space \((\Delta x, \Delta y, \Delta z)\) = \(7.5 \times 7.6 \times 6.9 \text{ m}^3 = 393.3 \text{ m}^3\)
Multiple scattering is a significant problem for energies < 1 MeV

Energy spectra derived from TOF (det#03)

1 = Watt
2 = PPAC
3 = + det-frame
4 = + 21 dets
Multiple scattering effects are more accurately represented by including the detector response.

1 calculation = 46 cpu-h (MCNP-PoliMi)
A preliminary comparison of simulation and data shows good agreement.
PFNS for $^{239}\text{Pu}(n_{\text{th}},f)$ –
Is it a good guide for PFNS in fast-neutron-induced fission?
PFNS for $^{239}\text{Pu}(n_{th},f)$ – is it a good guide for PFNS in fast-neutron-induced fission?

- Prompt fission neutron spectra have been measured at thermal for $^{235}\text{U}$ and $^{235}\text{Pu}$. Reactions at thermal can be dominated by one or only a few resonances.

- Do the data at thermal have any relevance to PFNS for fission induced by higher energy neutrons?

- Zero order analysis – look at average number of neutrons emitted in fission. If they vary with incident neutron energy, then there could well be a change in the spectra of emitted neutrons.
Are PFNS measured at thermal relevant for higher incident neutrons?

- Nu-bar for $^{235}$U(n,f) has no structure
- Nu-bar for $^{239}$Pu has a lot of structure

Note also the scale: <<1% for $^{235}$U; up to 12 % for $^{239}$Pu
Correlate structure in nu-bar for $^{239}$Pu(n,f) with fission cross section

- Fission cross section from Weston [NSE 115,164 (1993)]
- Subtract a constant (2.82) from nu-bar for clarity of display
- Add spins and parities (all positive) from Mughabghab
  - $0^+$ resonance shows no effect in nu-bar
  - $1^+$ resonances show varying effects

Probably (n,$\gamma$ f) process
Now the good news (maybe)

- Nu-bar at thermal for $^{239}\text{Pu}(n,f)$ is almost the same as for 1-10 keV. Maybe the thermal neutron PFNS is relevant to higher energies.
- Q: Is nu-bar at thermal dominated by the $1^+$ resonance at 0.3 eV?
Prospects for PFNS measurements with fission induced by epithermal neutrons

- $^{239}$Pu(n,f) – for incident neutron energies in resonance region – not planned but would be interesting physics!
  - Note: gamma production from fission in resonance region has been studied. Yes, spectra do depend on incident neutron energy and correlate with variations in nu-bar!

Ref: S. Mosby et al., DANCE collaborations
Fission total $\gamma$-ray energy vs. incident neutron energy for $^{239}\text{Pu}(n,f)$

- Fluctuations in prompt fission gamma energy anti-correlated with neutron emission
- More detailed information on $^{239}\text{Pu}(n,\gamma_f)$ process (Lynn, 1965)
- Qualitative behavior reported by Shackleton in 1972
Advanced PFNS measurements

• Correlate PFNS with fission products (Z,A) – difficult – could improve models of fission physics
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