Fission Cross Section Measurements at Intermediate Energies

A.B. Laptev

Japan Nuclear Cycle Development Institute
Tokai works, Tokai-mura, Ibaraki-ken 319-1194, Japan
E-mail: laptev@jnc.go.jp
OBJECTIVE:

-To carry out precise measurements of the neutron- and proton-induced fission cross-sections of long-lived actinides and some stable heavy nuclei in wide energy range.

MOTIVATION:

-A long standing need in information about fission of heavy nuclei induced by the particles at intermediate energies for many applications:
  - accelerator-driven transmutation of nuclear waste, especially actinides;
  - energy generation;
  - peaceful use of weapon plutonium, etc.
- Tasks of fundamental physics.
- The existing differences among the data of different measurements amount up to 30% that is outside the quoted experimental errors for the most part.
Neutron induced fission cross-sections of $^{233}\text{U}$, $^{238}\text{U}$, $^{232}\text{Th}$, $^{239}\text{Pu}$, $^{237}\text{Np}$, natPb and $^{209}\text{Bi}$ in neutron energy range from 1 MeV to 200 MeV have been measured at GNEIS facility.

About 900 points

Reference:

EXFOR file numbers are 41429 and 41430
Neutron induced fission cross-sections of $^{240}$Pu, $^{243}$Am, $^{nat}$W and $^{209}$Bi in neutron energy range from 1 MeV to 200 MeV have been measured at GNEIS facility.

About 400 points

References:

Proton induced fission cross-sections of $^{233}$U, $^{238}$U, $^{235}$U, $^{232}$Th, $^{239}$Pu, $^{237}$Np, natPb and $^{209}$Bi in proton energy range from 200 MeV to 1000 MeV at 100 MeV intervals have been measured at PNPI proton synchrocyclotron

Reference:
General layout of the PNPI synchrocyclotron
PNPI synchrocyclotron
PNPI SYNCHROCYCLOTRON

general information:

- Diameter of the magnet pole pieces: 685 cm
- Width of the gap between poles: 50 cm
- Magnet weight: 8,000 t
- Electric power supplied: 1 MWt
- Frequency range: 30 – 13 MHz
- Accelerating voltage: 10 kV
- Repetition rate: 40-60 Hz
- Internal beam intensity: < 3 μA
- Extraction coefficient: 30 %
- Duty cycle coefficient: 50 %
General layout of the Gatchina neutron time-of-flight spectrometer GNEIS and experimental arrangement for fission cross-section measurements
Pulsed neutron source:

- average fast neutron intensity ........................................... $\sim 3 \times 10^{14}$ n/s
- duration of the fast neutron pulse ....................................... $\sim 10$ ns
- repetition rate ................................................................. $< 50$ Hz
- internal water-cooled rectangular lead target ..................... $40$ cm $\times$ $20$ cm $\times$ $5$ cm
- rectangular polyethylene moderator ................................. $30$ cm $\times$ $10$ cm $\times$ $5$ cm

Spectrometer:

- number of evacuated flight paths ................................. 5
  (one beam #5 looking at the target and others #1-4 looking at the moderator)
- length of flight paths ..................................................... $35 - 50$ m
- experimental area (GNEIS building) ............................. $45 \times 30$ m$^2$

Internet URL: http://hepd.pnpi.spb.ru/~gneis
The neutron flux at the 48.5-m flight path normalized to a value of 1 $\mu$ A of the proton beam on the neutron-producing target.
Neutron energy resolution for the flight path length 48.5 m
Examples of gamma flash detector (a and b) and fission chamber signal
Signal identification has been made by a method of digital filtering:

\[ y'(i) = \sum_{j=i-n}^{i+n} \left\{ 2y(j) - y[j-(2n+1)] - y[j+(2n+1)] \right\} \]

- \( y(i) \) – initial data in TOF channel \( i \)
- \( y'(i) \) – filtered data in TOF channel \( i \)
Average pulse height spectra observed in the neutron energy range 0.5 – 200 MeV

Counts / channel

Pulse height channel
Pulse height spectra observed at different neutron energies for $^{235}$U

![Pulse height spectra](image-url)

- $E_n = 200$ MeV
- $E_n = 100$ MeV
- $E_n = 50$ MeV
- $E_n = 20$ MeV
- $E_n = 10$ MeV
- $E_n = 5$ MeV
- $E_n = 2$ MeV
- $E_n = 1$ MeV
- $E_n = 0.6$ MeV

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Pulse height spectra observed at different neutron energies for $^{240}$Pu
Time-of-flight spectra (10 ns channel width) observed after background subtraction

The TOF vs energy calibration have been used:
- a position of the lead total cross-section resonances;
- a true time-zero of the scale from the position of the gamma-flash peak.

An accuracy of this calibration is ± 0.03 %
Pulse height spectra observed for one of $^{nat}\text{Pb}$, $^{209}\text{Bi}$ and $^{235}\text{U}$ targets for the neutron energy range 25 – 200 MeV (Pb, Bi) and 0.5 – 200 MeV ($^{235}\text{U}$).
Average pulse height spectra observed for W and Bi targets
Corrections due to neutron flux attenuation in case of $^{240}\text{Pu}$

- **(a)** - different flight path length of the of $^{240}\text{Pu}$ and of $^{235}\text{U}$ targets; (b and c) - absorption and scattering in the backing foil material (Al) and working gas (methane); (d) - fragment losses in the targets, neutron momentum transfer and angular anisotropy of fission fragments; (e) - total correction.
Ratio of the TOF-spectra for two $^{235}$U targets ($\Delta L = 200$ mm)

![Graph showing the ratio of TOF-spectra for two $^{235}$U targets with a linear fit equation: $R(E) = a \cdot E + b$. The linear fit equation is $a = (0.88 \pm 2.34) \cdot 10^{-5}$]
Fission cross-section of $^{233}\text{U}$, $^{238}\text{U}$, $^{232}\text{Th}$ and $^{239}\text{Pu}$ measured by Shcherbakov et al. (2001) in comparison with other data and evaluations
Fission cross-section of $^{237}\text{Np}$ measured by Shcherbakov et al. (2001) in comparison with other data and evaluations

Fission cross-section of $^{240}\text{Pu}$ and $^{243}\text{Am}$ measured by Laptev et al. (2004) in comparison with other data and evaluations
Fission cross-section of $^{243}$Am measured by Laptev et al. (2004) in comparison with other data and evaluations.

Neutron energy, MeV

Fission cross-section, b

- Laptev et al., 2004;  ○ Behrens et al., 1981
- Seeger, 1970;  △ Fomushkin et al., 1984
- Fursov et al., 1985;  ▲ Kanda et al., 1987
- Knitter et al., 1988;  ◆ Goverdovskiy et al., 1989
- JENDL-3.3;  — ENDF B-VI
- Maslov et al., 1996;  — Ignatyuk et al., 1999
Fission cross-section of $^{nat}$Pb and $^{209}$Bi measured by Shcherbakov et al. (2001) in comparison with other data and evaluations
Fission cross-section of $^{nat}\text{W}$ and $^{209}\text{Bi}$ measured by Laptev et al. (2004) in comparison with other data and evaluations.
Experimental set-up for proton-induced fission cross-section measurements of Kotov et al. (2003)

**SPECIFICATION:**

- both fission fragments registration in coincidence by two parallel plate avalanche counters;
- a large solid angle acceptance about 10 sr for fission fragment;
- 100% efficiency for fission fragments;
- good resolution fission events from events produced by other nuclear reactions;
- the proton beam monitoring:
  - at low beam intensity (~10^5 p/s) by direct count of scintillation telescopes;
  - at high beam intensity (~10^7 p/s) by registration of pp-elastic scattering on the CH₂ target;
- copper degrader to obtain proton energy variation.

**CORRECTIONS FOR:**

- solid angle acceptance of fission fragment;
- inefficiency of the proton monitor;
- a probability of two or more protons appearance in the single bunch;
- an anisotropy of fission fragments and their energy losses in target.

1. chamber; 2. thin windows; 3. PPAC's; 4. target.
Proton-induced fission cross-sections of $^{233}$U, $^{235}$U and $^{238}$U measured by Kotov et al. (2003) in comparison with other data.
Summary

- Neutron-induced fission cross-sections of actinide nuclei $^{233}$U, $^{238}$U, $^{232}$Th, $^{239}$Pu, $^{237}$Np, $^{240}$Pu and $^{243}$Am and sub-actinide nuclei natPb, $^{209}$Bi and natW have been measured in neutron energy range from 1 MeV to 200 MeV in two experiments at GNEIS facility.

- The fission cross-section of $^{243}$Am in the neutron energy range from 40 MeV to 200 MeV has been measured for the first time.

- The neutron-induced fission cross-section of natW has been measured for the first time with a "white" neutron source.

- Statistical accuracy of measured fission cross-sections of actinides $^{233}$U, $^{238}$U, $^{232}$Th, $^{239}$Pu and $^{237}$Np is less than 1%, that of actinides $^{240}$Pu and $^{243}$Am is about 2%, that of sub-actinides natPb and $^{209}$Bi varies from about 5% at 60 MeV to 1.5% at 200 MeV and that of natW varies from 19% at 100 MeV to 7% at 200 MeV.

- Detailed analysis of systematic errors has been done.

- In general, in the overlapping energy regions (below 20 MeV) our data are in reasonable agreement with previous data obtained mainly at electron linacs.
- There is a significant disagreement between data of Shcherbakov et al. (2001) and that of Lisowski et al. for $^{233}$U, $^{238}$U, $^{239}$Pu and $^{232}$Th above 20 MeV while for $^{237}$Np both data sets are not in contradiction.

- There is some disagreement between data of Laptev et al. (2004) and that of Staples and Morley for $^{240}$Pu above 40 MeV. On our opinion, most of the differences are in normalization rather than shape.

- For $^{243}$Am data of Laptev et al. (2004) shows a good agreement with that of Behrens et al. and Goverdovskiy et al., there are significant disagreements between previous data sets.

- The libraries’ evaluations, theoretical calculations of Maslov et al. and evaluation of Ignatyuk et al. correspond other data sets rather than Laptev et al. in case of $^{243}$Am. Normalization of data of Laptev et al. for $^{243}$Am to libraries' 14 MeV value withdraws this disagreement.

- There is a good agreement between data of Shcherbakov et al. for $^{nat}$Pb and $^{209}$Bi and previous data.

- There is generally good agreement between data of Laptev et al. for $^{nat}$W and those of Smirnov et al., except for a possible discrepancy in the 90-100 MeV region.

- Measured fission cross-section of $^{209}$Bi by Laptev et al. reproduces very carefully that measured in frame previous experiment of Shcherbakov et al.
- Proton-induced fission cross-sections of actinide nuclei $^{233}\text{U}$, $^{235}\text{U}$, $^{238}\text{U}$, $^{232}\text{Th}$, $^{239}\text{Pu}$ and $^{237}\text{Np}$ and sub-actinide nuclei nat$^{209}\text{Bi}$ have been measured in proton energy range from 200 MeV to 1000 MeV at PNPI proton synchrocyclotron by Kotov et al. (2003). Results of measurements in case of $^{233}\text{U}$, $^{235}\text{U}$ and $^{238}\text{U}$ are presented.

- A statistical accuracy of the measured fission cross section by Kotov et al. was better than 1.5%, the overall accuracy was better than 10%.

- The cross sections for proton induced fission of $^{233}\text{U}$ in the energy range 200-1000 MeV was obtained by Kotov et al. for the first time.

- According to opinion of Kotov et al., their results for $^{238}\text{U}$ in the energy range from 300 to 900 MeV do not agree with a majority of the early-obtained data.
Pulse height spectra observed at different neutron energies for $^{209}$Bi

- $E_n = 200$ MeV
- $E_n = 180$ MeV
- $E_n = 160$ MeV
- $E_n = 140$ MeV
- $E_n = 120$ MeV
- $E_n = 100$ MeV
- $E_n = 80$ MeV
- $E_n = 60$ MeV
- $E_n = 40$ MeV
Pulse height spectra observed at different neutron energies for natW

![Graph showing pulse height spectra for different neutron energies](image)