Reaction cross sections and prompt neutron emission and spectra calculations for $^{238}\text{U}(n,f)$ and $^{237}\text{Np}(n,f)$

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• **Introduction**

• **Theoretical modeling**
  – Neutron induced cross sections ($^{238}\text{U}(n,f)$)
  – PbP calculations for $^{238}\text{U}(n,f)$
  – Neutron induced cross sections ($^{237}\text{Np}(n,f)$)
  – PbP calculations for $^{237}\text{Np}(n,f)$

• **Conclusions**
Introduction

- Model prediction of mass distributions
- Investigate the predictive power of the model
Introduction

Mono-energetic neutron source

• 7 MV Van-de-Graaff accelerator
  - $^7$LiF(p,n)$^7$Be, TiT(p,n)$^3$He, D$_2$(d,n)$^3$He, TiT(d,n)$^4$He
  - DC ($I_{p,d} < 50 \mu A$), pulsed beam available
  - 4 + 1 non-T beam line
• $\Phi_n < 10^9 /s/sr$
  • **NEPTUNE** isomer spectrometer
• ionisation chambers, NE213 neutron/gamma-ray detectors, BF$_3$ counters, HPGe detectors
• Bonner spheres
• fast rabbit systems ($T_{1/2} > 1s$) for activation studies

GELINA neutron TOF spectrometer

• 70 - 140 MeV electron accelerator
• repetition frequency: 40 - 800 Hz
• neutron pulse: 2 $\mu s$ - 1 ns @ FWHM
• $\Phi_n = 3.4 \times 10^{13}/s @ 800 Hz$
• 12 different flight paths with a length between 8 and 400 m
• ionisation chambers, C$_6$D$_6$ detectors
• high-resolution $\gamma$-ray detectors
• fission chambers for flux monitoring
Theoretical modeling of reaction cross sections and prompt neutron multiplicity and spectra
Concept of the model calculations

- Experimental input: fission-mode branching ratio ($w_m$) as a function of the incident neutron energy
  - ENDF/B-VI fission cross section data
- Statistical treatment of the CN mechanism within the code
  - **STATIS** extended for MM-RNR model (NP A707 (2002) 32)
    - one CN (incident neutron energies below 2nd chance fission)
    - 3 most dominant fission modes: asymmetric S1, S2 and symmetric SL
    - parabola-shaped inner and outer barriers
    - elastic and inelastic neutron scattering, radiative capture, fission
- Direct interaction with **ECIS** code (coupled channel method, Raynal CEA-N-2772, 1994):
  - total cross-section, partial direct scattering cross-sections for the first four rotational bands and the neutron transmission coefficients
Multi-modal fission barrier

$^{238}$U(n,f)

$V_A = 6.40$ MeV $\hbar \omega_A = 0.73$ MeV

$V_I = 1.31$ MeV $\hbar \omega_I = 0.78$ MeV

without fission modes

$V_B = 5.71$ MeV $\hbar \omega_B = 0.50$ MeV

$S1$ $V_B = 6.70$ MeV $\hbar \omega_B = 1.20$ MeV

$S2$ $V_B = 6.08$ MeV $\hbar \omega_B = 0.51$ MeV

$SL$ $V_B = 9.05$ MeV $\hbar \omega_B = 2.10$ MeV

Barrier height (MeV) vs Deformation (relative unit)
$^{238}\text{U}(n,f)$
Fission Cross-section for $^{238}\text{U}(n,f)$

$^{238}\text{U}(n,f)$ cross section (b)

$V_A = 6.40 \text{MeV}$, $\tilde{v}_A = 0.70 \text{MeV}$, $V_I = 1.50 \text{MeV}$, $\tilde{v}_I = 1.00$

- $S2$ $V_B = 6.10 \text{MeV}$, $\tilde{v}_B = 0.48 \text{MeV}$; Goverdovski
- $S1$ $V_B = 6.65 \text{MeV}$, $\tilde{v}_B = 1.20 \text{MeV}$; Goverdovski
- $SL$ $V_B = 9.00 \text{MeV}$, $\tilde{v}_B = 2.10 \text{MeV}$

ENDF/B-VI Present evaluation

EXFOR (other) Blons DFilippe

$E_n$ (MeV)
Branching Ratio for $^{238}$U(n,f)

![Graph showing branching ratios for different reactions at various energies. The graph includes data from S1 Russian, S1 IRMM, S2 Russian, S2 IRMM, and SL IRMM.]
$^{238}\text{U Mass Distribution at } E_n = 1.2 \text{ MeV}$

![Graph showing mass distribution of $^{238}\text{U(n,f)}$ with experimental data and calculated curves for different models.](graph.png)
$^{238}\text{U Mass Distribution at } E_n=0.9 \text{ MeV}$

![Graph showing the mass distribution of $^{238}\text{U(n,f)}$ at $E_n=0.9$ MeV.](image)
This work \( d_{\text{min}} > 11.8 \text{ fm} \)

Vivés et al.

Goverdovski

Theoretical predictions

\[ \sigma_f(E_n)^{238}\text{U}(n, f) \text{ Calc} \]
Improved barrier parameters

- **238U(n,f)**
- "Experimental" modal cross-sections:
  - S1, S2
  - present calculation
- **Fission cross section (b)**
  - S1
  - S2
  - sum of modal fission c.s.

- Sets given as absolute data (1983-1957):
  - Difilipo 80 USALAS
  - En (MeV)
  - 0 1 2 3 4 5
  - 0.00 0.01 0.02 0.03

- Sets given as ratio to 235U (1985-1972):
  - IRMM 2008
  - IRMM 2000
  - Shcherbakov 2001 RUSLIN
  - Merla 91 GERDRE
  - Lisowski 91 USALAS (as ratio U235)

- Present calculation:
  - S1, S2
  - S1, S2, SL

- **238U(n,f)**
  - IRMM 2008
  - IRMM 2000
  - En (MeV)
  - 0.8 1.0 1.2 1.4 1.6 1.8 2.0
  - 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
  - 0.00 0.01 0.02 0.03

- **W(%)**
  - IRMM 2008
  - IRMM 2000
  - En (MeV)
  - 0.8 1.0 1.2 1.4 1.6 1.8 2.0
  - 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
  - 0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10
- Assumption: Neutron evaporation from fully accelerated fission fragments (Los Alamos model)
- PbP takes into account the full range of possible fragmentations of the fissioning nucleus
- FF mass and total kinetic energy distributions are input quantities for the PbP calculations
- above the second chance threshold only most probable fragmentation used
- split of the total excitation energy between the two fragments of each pair is based on $\nu_H/\nu_{\text{pair}}$ ratio
- mass excesses are based on Audi and Wapstra
Prompt neutron multiplicity

$^{238}\text{U}(n,f)$

- Tudora NPA 2004, JEFF3.1
- Madland NPA 2006
- Systm. of param.
- PbP 2006
- PbP 2008

Data renormalized to $^{252}\text{Cf}(\text{SF})$ or $^{235}\text{U}(n_{\text{th}},f)$

- Asplund-Nilsson 64 SWDOFA
- Batchelor 65 UKALD
- Mather 65 UKALD
- Nurpeisov 75 CCPFEI
- Malynovsky 83 CCPFEI
- Frehaut 80 BRC Fr

Data without renormalization

- Savin 72 CCPKUR
- Vorob'jova 74 CCPFEI
- BaoZongyu 75 CPRAEP

Other data sets from EXFOR

- Manero and Konshin 72 eval.

Other data requiring renorm

- Batchelor 65 UKALD
- Savin 72 CCPKUR
- Vorob'jova 74 CCPFEI
- BaoZongyu 75 CPRAEP

Average param. (IRMM 08)
Prompt fission neutron spectrum

En = 2 MeV
Baba 1989 JPNTIOH
- set 1,
- set 2

En = 3 MeV
Boykov 1991 RUSFEI
(En = 2.9 MeV)

En = 5 MeV
Trufanov 2001 RUSFEI
(given as ratio to $^{252}$Cf(SF))
Level densities and share of TXE

$^{238}U(n,f)$

$E_n = 1.4 \text{ MeV}$

Level density parameter (MeV$^{-1}$)

$A / 11$

Level density parameter: superfluid model (Ignatiuk)

- $E^*_L/E^*_H = \nu_L/\nu_H$, Tudora 2006
- $E^*_L/E^*_H = a_L/a_H$, Talou 2005

NUP of FF pair

$A$ of FF

$^{238}U(n,f)$

$E_n = 1.4 \text{ MeV}$

NUP of FF

$A$ of FF
$^{237}$Np fission cross section up to 50 MeV

- Present calculation
- NPA 767(2006) 112
- ENDF/B-VII (2008)
- JEFF3.1, JENDL3.3

The fission cross-section for $^{237}$Np(n,f) is shown with data from various sources.

- EXFOR (2006):
  - Merla 91 GERDRE
  - Shcherbakov 2001 Dubna (absolute data)
  - Shcherbakov (as ratio) with 235U BRC eval.

- Other sets of EXFOR

- Plattard 75 FRSAC
- Moore 72 USALAS (nucl.expl.)
- Henkel 57 USALAS
- Gokhberg 59 CCPFEI
- White 65 UKALD
- Behrens 82 USALRL
- Varnagy 82 HUN
- Goverdovski 85 CCPFEI

The figure shows the fission cross-section versus energy (MeV) for $^{237}$Np(n,f).
$^{237}$Np(n,γ) cross section

- ENDF/B-VI
- JENDL3.3 and JEFF3.1
- ENDF/B-VII.0

EXFOR:
- Lindner 76 USALAS
- Stupgija 67 USAANL
- Trofimov 83 CCPRI
- Buleeva 88 CCPFEI
- Criccho 82 FR(Rapsodie)
- Trofimov 87 CCPRI
- Weston and Todd 81 ORL

Previous evaluation NPA 767 (2006) 112

Present calculation
Prompt neutron multiplicities

\[ \text{Prompt neutron multiplicity} \]

\[ \frac{237}{237} \text{Np(n,f)} \]

EXFOR data without renorm.
- Boykov 1994 RUSRI
- Malinovski 1983 CCPFEI
- Mueller 1981 GERKFK
- Taieb 2007 USALAS
- Thierens 80 BLGHT and
- Borzakov 2000 ZZZDUB

Prompt Fission Neutron Multiplicity

\[ 237 \text{Np(n,f)} \]

EXFOR data with renorm. to \( ^{252}\text{Cf(SF)}=3.759 \)
- Khokhlov 1994 RUSEPA
- Veeser 1978 USALAS
- Frehaut 1982 FR BRC

Prompt Fission Neutron Multiplicity

\[ \text{total prompt neutron multiplicity} \]

contributions of:
- \( \text{Np main nucleus chain} \)
- \( \text{U secondary chain "proton" path} \)
- \( \text{U secondary chain "neutron via proton" path} \)

EXFOR data with renorm. to \( ^{252}\text{Cf(SF)}=3.759 \)
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- \( \text{U secondary chain "neutron via proton" path} \)
Prompt fission neutron spectra

For $^{237}$Np(n,f), $E_n=7.8$ MeV:
- Most probable fragment approach
- Using $^{238}$Np param. of systematics
- Using $^{238}$Np param from PbP 2009

For $E_n=4.9$ MeV:
- Trufanov 1992 RUSFEI
- ENDF/B-VII (Madland 84)

For $E_n=0.52$ MeV:
- Kornilov 1997 RUSFEI
- ENDF/B-VII (Madland 84)

Prompt Fission Neutron Spectrum (1/MeV)
Conclusions

- Model calculations within a statistical model in good agreement with many experimental results, but predictive power of the model is limited.

- Point by point calculation of the prompt fission neutron multiplicities and spectra gives good agreement with experimental data.
Thank you for your attention 😊