Neutron–induced fission of actinides at energies up to 200 MeV: Problems of describing fission cross sections and angular anisotropy of fission fragments

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O. Bohr model of nuclear transition states on the barriers

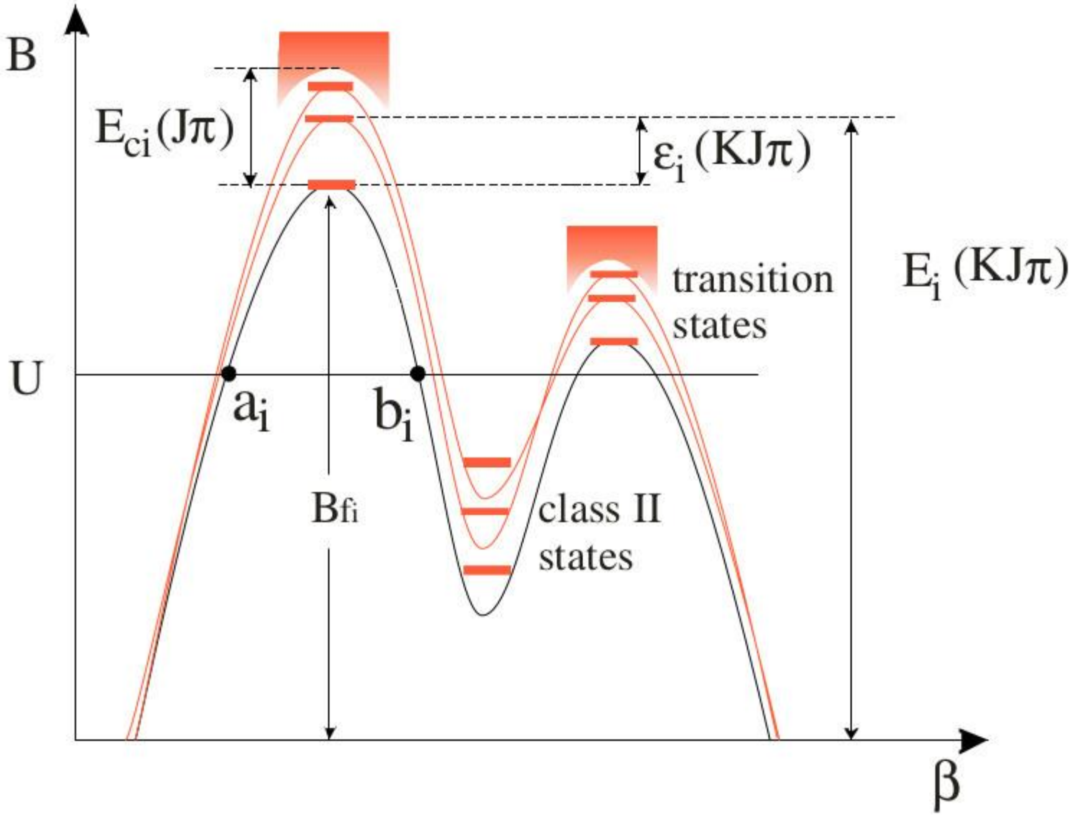


Figure: R. Capote et al. *Nuclear Data Sheets*, 2009, v. 110, p. 3107

The problem of calculating the angular distribution of fragments from nuclear fission is as old as the problem of calculating the fission cross sections.

Because in both cases we refer to the same O. Bohr model of transition states of a strongly deformed nucleus at the fission barriers.

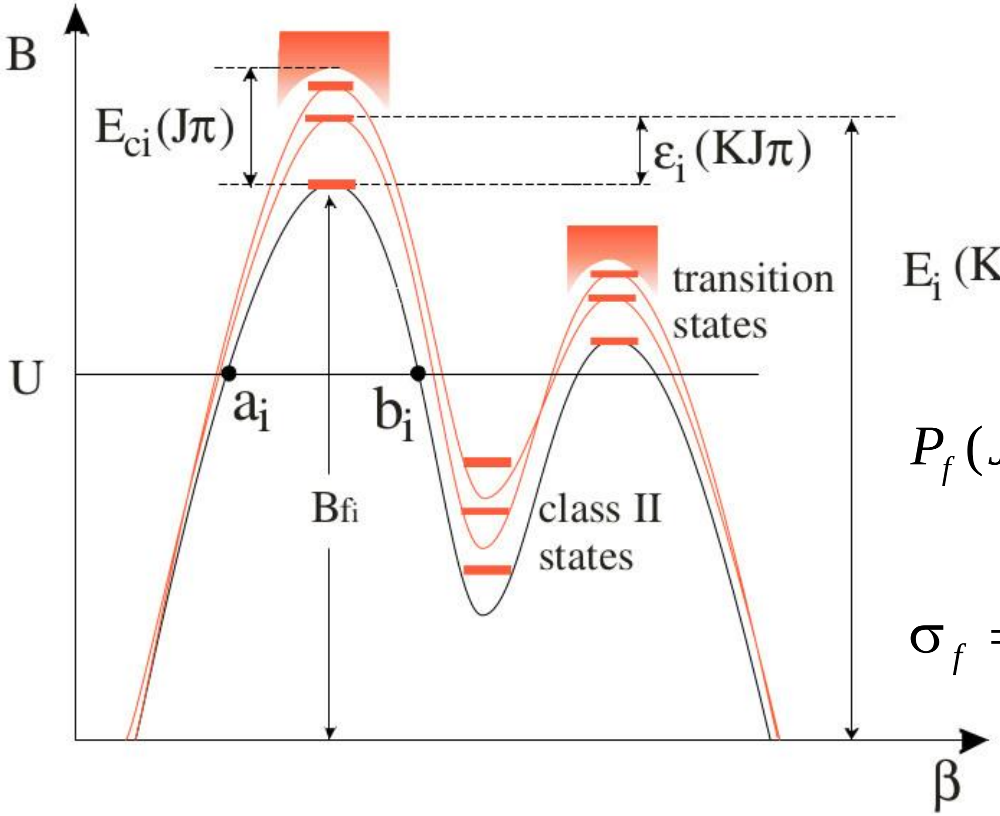
Indeed, the fission cross section is determined by the density of transition states, while the angular distribution of fragments is determined by the projections K of the fragment's spin onto the deformation axis of the same transition states.

However, we see that the current interest in these two problems - angular distributions and cross sections - is very different. There are many computer programs for nuclear reactions, such as TALYS and EMPIRE, that calculate fission cross sections, but none of them calculate the angular distribution of fragments.

Algorithm for calculation the fission cross section

"Nuclear fission remains the most complex topic in applied nuclear physics…"

R. Capote et al. RIPL – Reference Input Parameter Library for Calculations of Nuclear Reactions and Nuclear Data Evaluations. *Nuclear Data Sheets*, 2009, v. 110, p. 3107



$$E_i\,(KJ\pi) = B_{fi} + \varepsilon_i(K\pi) + \frac{\hbar^2}{2I_i}(J(J+1) - K(K+1))$$

$$P_f(J\pi) \sim \sum_i T_f^{J\pi}(E_{ex} - B_f - E_i(KJ\pi)) + \int_{E_c(J\pi)}^{E_{ex}} \rho(\varepsilon J\pi)\; T_f^{J\pi}(E_{ex} - B_f - \varepsilon)d\varepsilon$$

$$\sigma_f = \sum_{J\pi} \sigma(J\pi) P_f(J\pi)$$

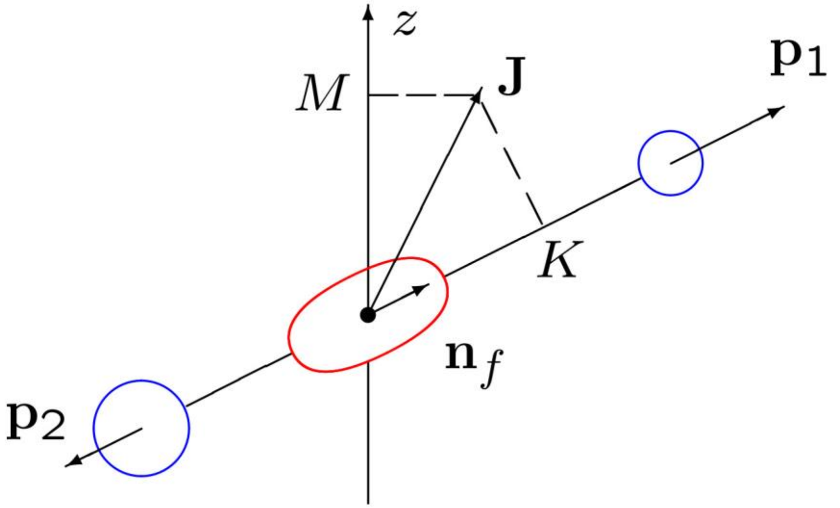
Hill-Wheeler Transmission Factor:

$$T_i(U - B_i) = \frac{1}{1 + e^{-2\pi(U - B_i)/\hbar\omega_i}}$$

"This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations."

Algorithm for calculation the angular distribution of fission fragments

$$W(\theta) = \frac{d\sigma_f(\theta)/d\Omega}{\sigma_f}$$



$$\Psi_{JMK} \sim D^J_{MK}(\vec{n}_f)$$

$$\frac{dw^J_{MK}(\vec{n}_f)}{d\Omega} = \frac{2J+1}{4\pi}\left|D^J_{MK}(\vec{n}_f)\right|^2$$

$$\frac{dw^{J\pi}(\vec{n}_f)}{d\Omega} = \sum_M \eta^{J\pi}(M) \sum_K \rho^{J\pi}(K) \frac{dw^J_{MK}(\vec{n}_f)}{d\Omega}$$

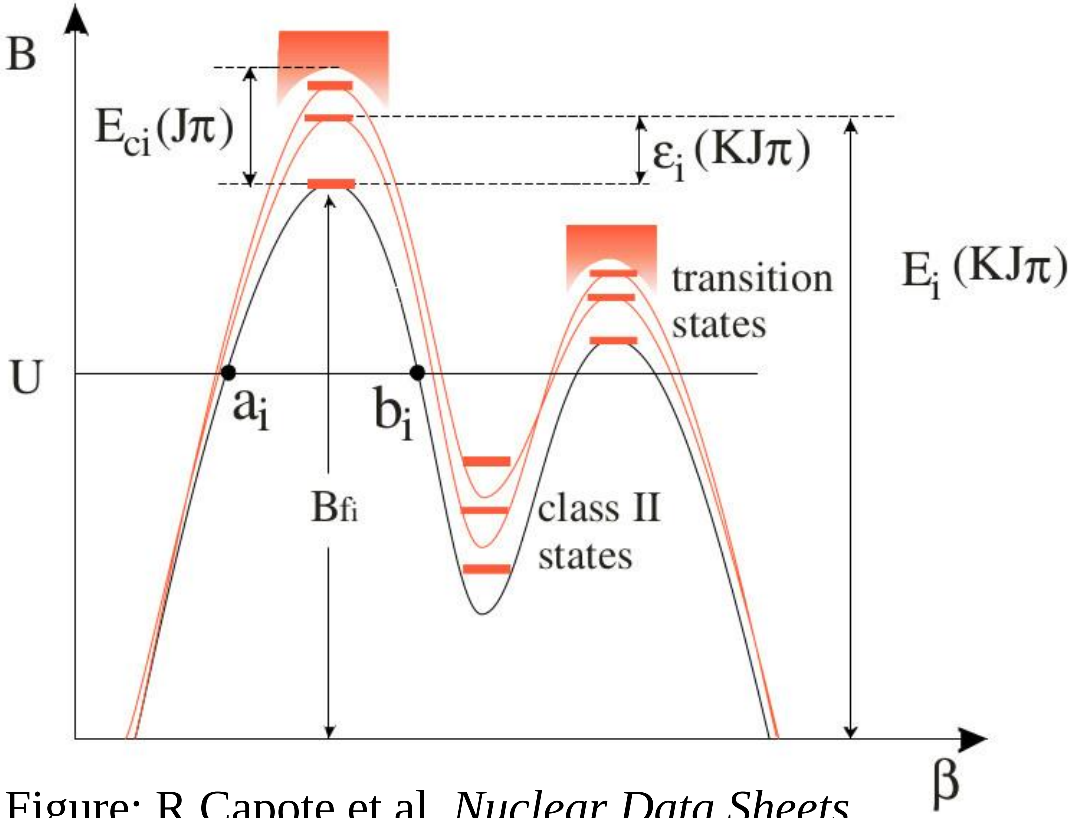


Figure: R.Capote et al. *Nuclear Data Sheets*, 2009, v. 110, p. 3107

To calculate $\frac{d\sigma_f(\theta)}{d\Omega} = \sum_{J\pi} \sigma(J\pi) P_f(J\pi) \frac{dw^{J\pi}(\theta)}{d\Omega}$ we need $\eta^{J\pi}(M)$ and $\rho^{J\pi}(K)$

Studies of angular distributions of fission fragment in neutron-induced fission at energies above 20-30 MeV began quite recently:

Ryzhov et al. (up to 100 MeV, 2005), n_TOF and NIFFTE (up to 200 MeV, 2014-2020): ^{232}Th, ^{235}U, ^{238}U

Petersburg Nuclear Physics Institute (PNPI), Gatchina

Spallation neutron source at 1 GeV proton synchrocyclotron

and

Gatchina Neutron time-of-flight Spectrometer (GNeiS)

1-200 MeV, 2015-2020: ^{209}Bi, Pb (nat), ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu;
2021: ^{236}U

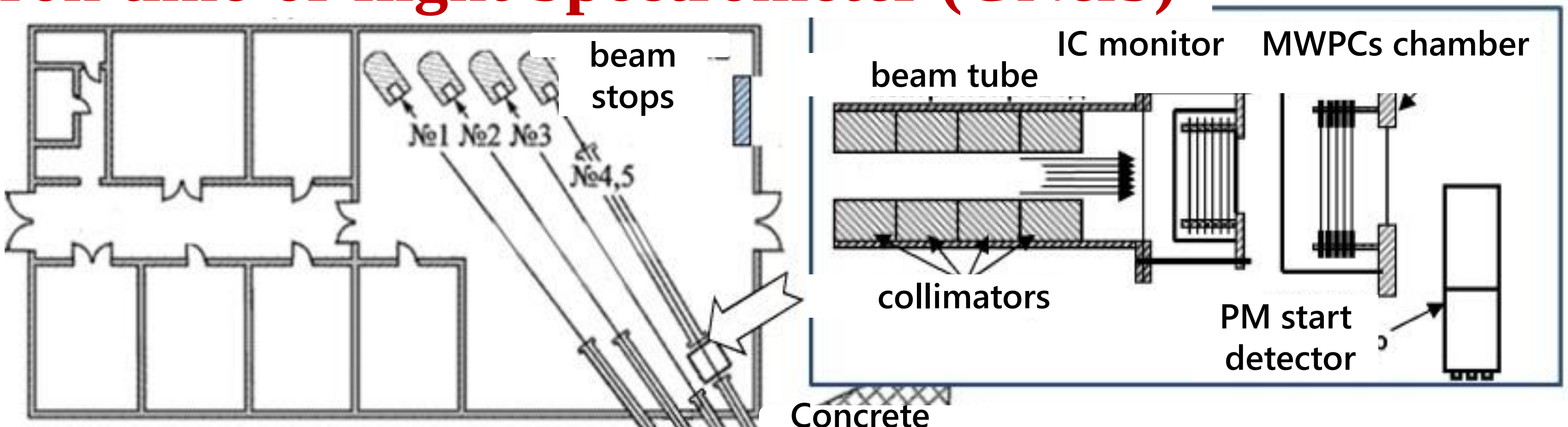
Motivation:

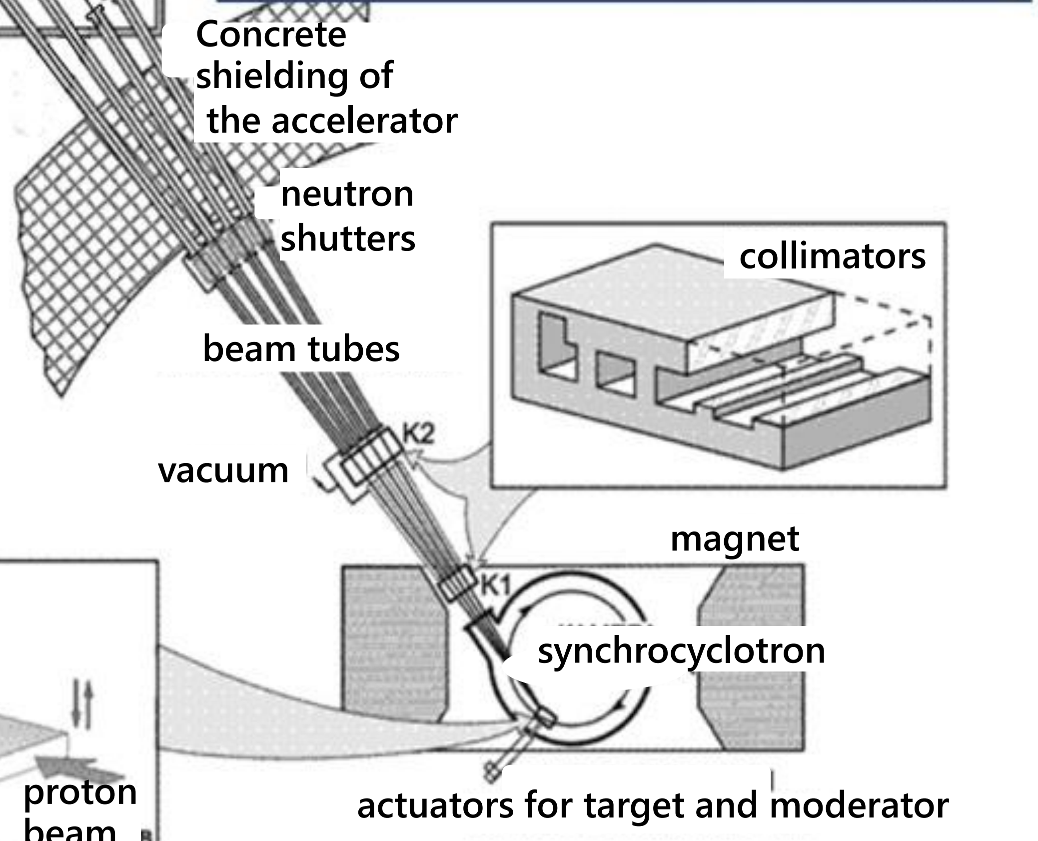
- new nuclear technologies, e.g., ADS
- new information on fission process

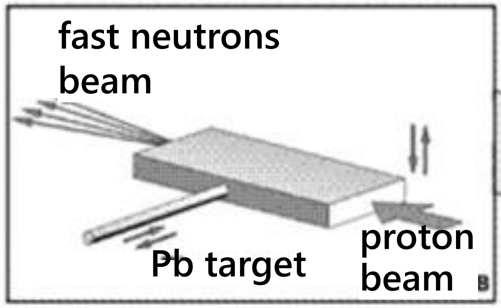
In our last publications:

A.S. Vorobyev et al. JETP Lett. 110, 242 (2019): ^{237}Np
A.S. Vorobyev et al. JETP Lett. 112, 323 (2020): ^{240}Pu
not only experimental data were presented, but results of calculation with the use of the TALYS-based code

Gatchina Neutron time-of-flight Spectrometer (GNeiS)







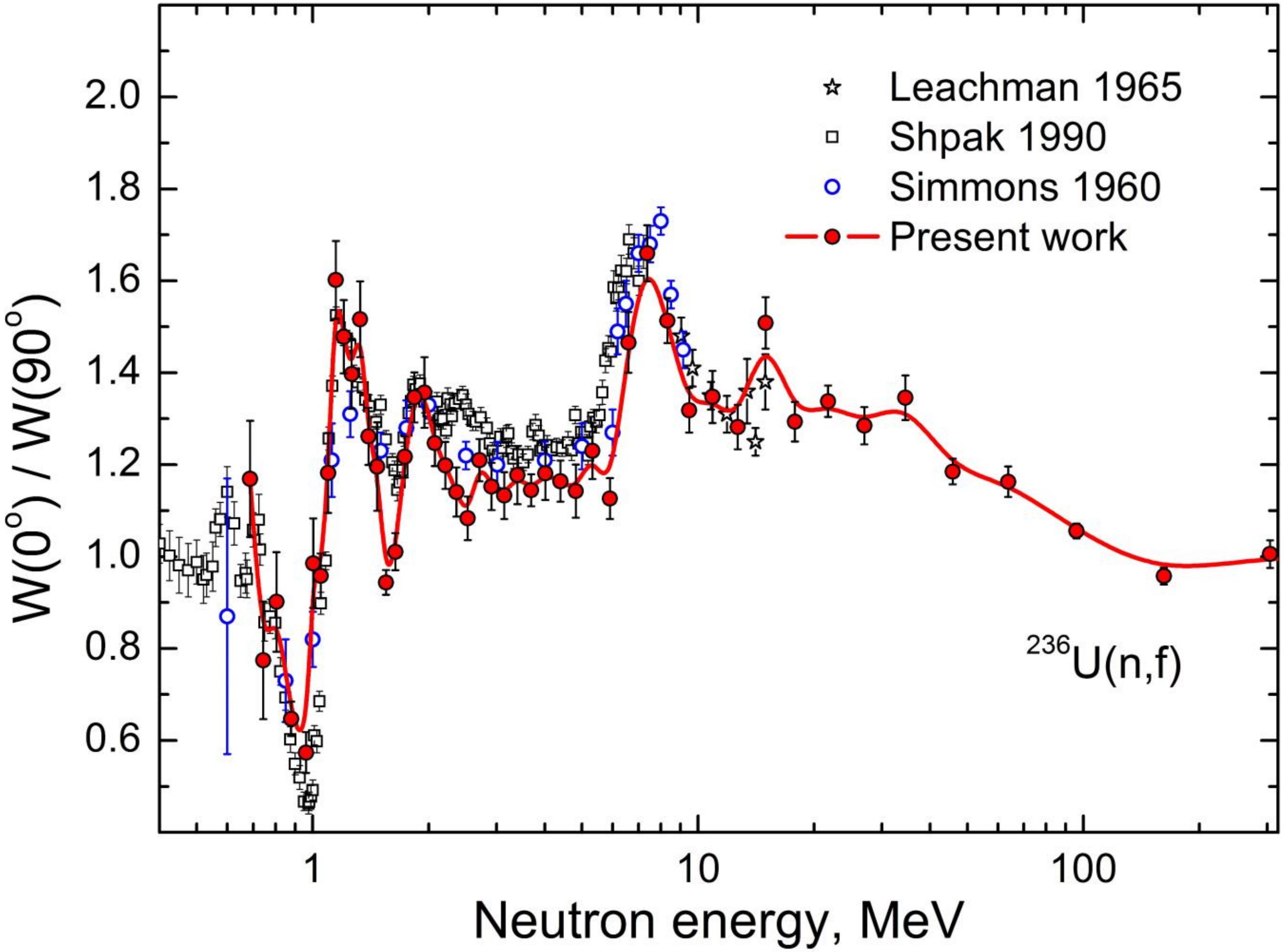
Main parameters:

$$E_p = 1\ GeV,\ \ f \approx 50\ \ Hz,\ \ \Delta t \approx 10\ \ ns,\ \ \Phi \sim 3\cdot 10^{14}\ \frac{n}{s}$$

$$L = 35.5\ \ m,\ \ \frac{\Delta E}{E}(1\ \ MeV) \approx 1\%,\ \ \frac{\Delta E}{E}(200\ \ MeV) \approx 12\%$$

Spallation neutron source at
1 GeV proton synchrocyclotron

Preliminary data for 236-U(n,f)



PNPI, Gatchina

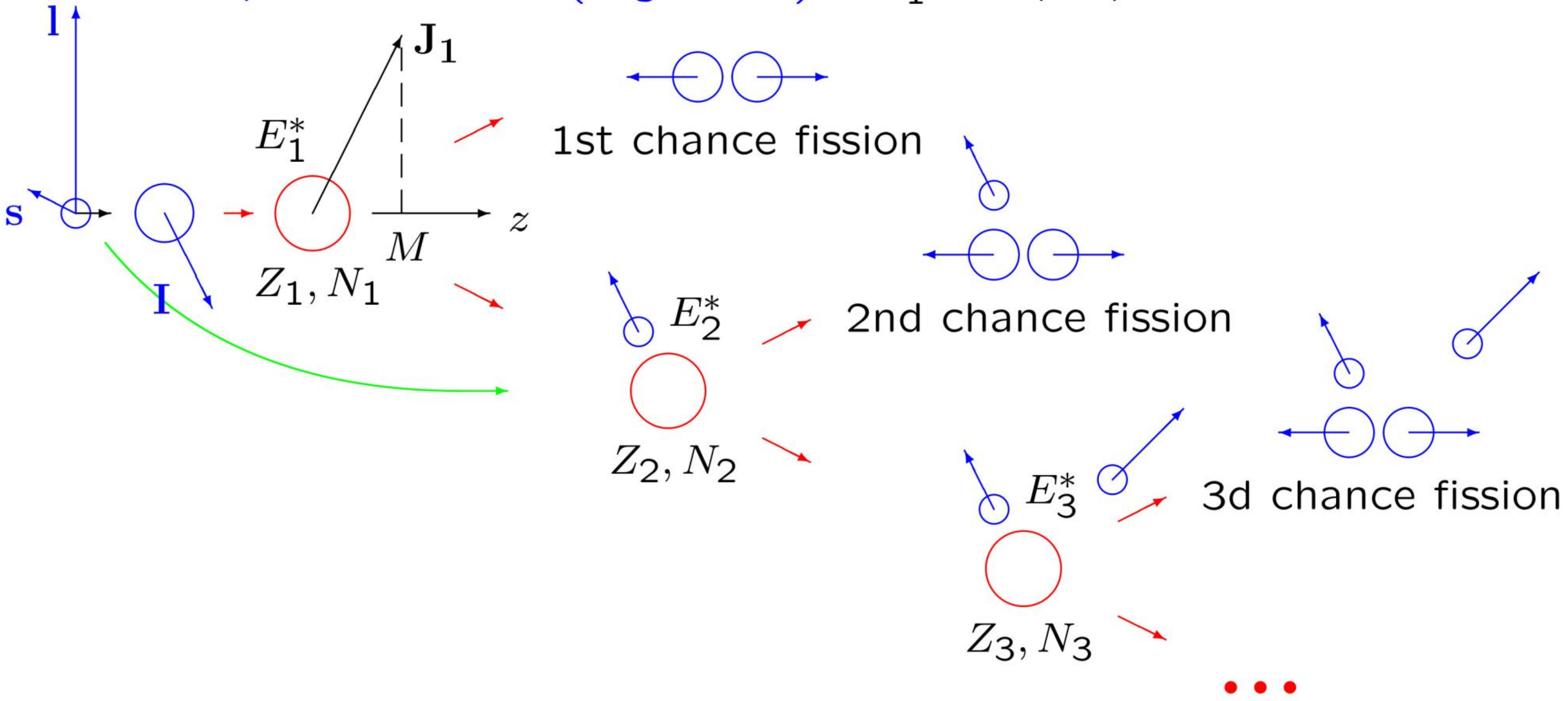
Spallation neutron source at 1 GeV proton synchrocyclotron and Gatchina Neutron time-of-flight Spectrometer (GNeiS)

$$W(\theta) = \frac{d\sigma_f(\theta)/d\Omega}{\sigma_f} \approx \frac{1}{4\pi}\left(1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)\right),$$

$$\frac{W(0)}{W(90)} = \frac{1 + A_2 + A_4}{1 - A_2/2 + 3A_4/8} \approx \frac{1 + A_2}{1 - A_2/2}$$

$$|A_4| \ll |A_2|$$

Nuclear spin orientation (alignment): $\mathbf{J}_1 = \mathbf{s} + \mathbf{l} + \mathbf{I}$



Outline of our approach for calculating the fission fragment angular distribution

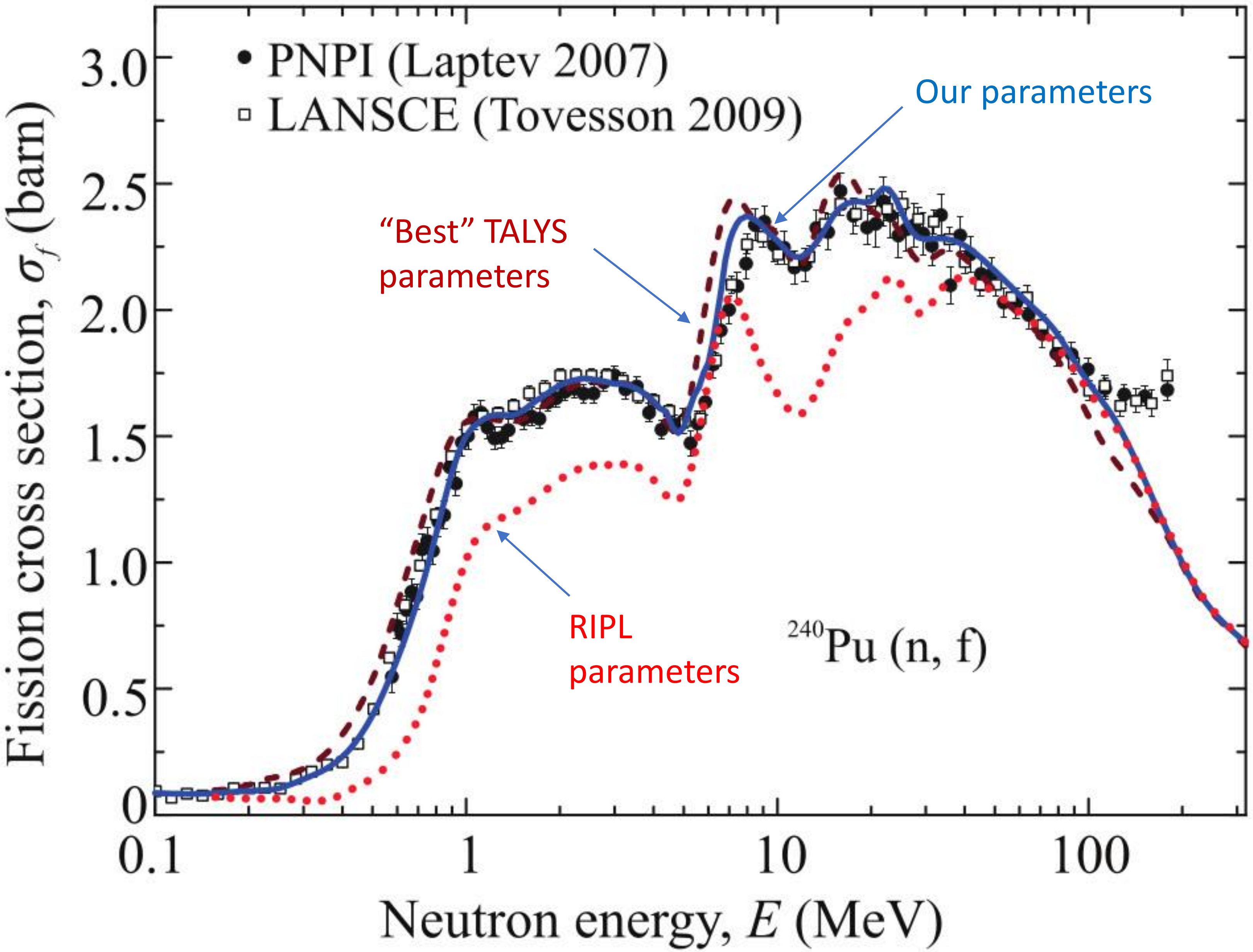
$$\frac{d\sigma_f(\mathbf{n}_f)}{d\Omega} = \frac{\sigma_f^{DPE}(\mathbf{n}_f)}{4\pi} + \sum_{ZNJ\pi i} \sigma_{ZN}^{C}(J\pi i) P_f^{ZN}(J\pi i) \frac{dw_{ZN}^{J\pi i}(\theta)}{d\Omega}$$

$$\frac{dw_{ZN}^{J\pi i}(\theta)}{d\Omega} = \sum_M \eta_{ZN}^{J\pi i}(M) \sum_K \rho_{ZN}^{J\pi i}(K) \frac{dw_{MK}^{J}(\theta)}{d\Omega}, \quad \eta_{ZN}^{J\pi i}(M) = \frac{\sigma_{ZN}^{C}(J\pi M i)}{\sigma_{ZN}^{C}(J\pi i)}$$

M-dependence is calculated in the extended TALYS

$^{240}Pu(n, f)$: Results for fission cross section

A.S. Vorobyev et al.
JETP Lett. 112,
323 (2020)



$^{240}Pu(n, f)$: Results for fission cross section

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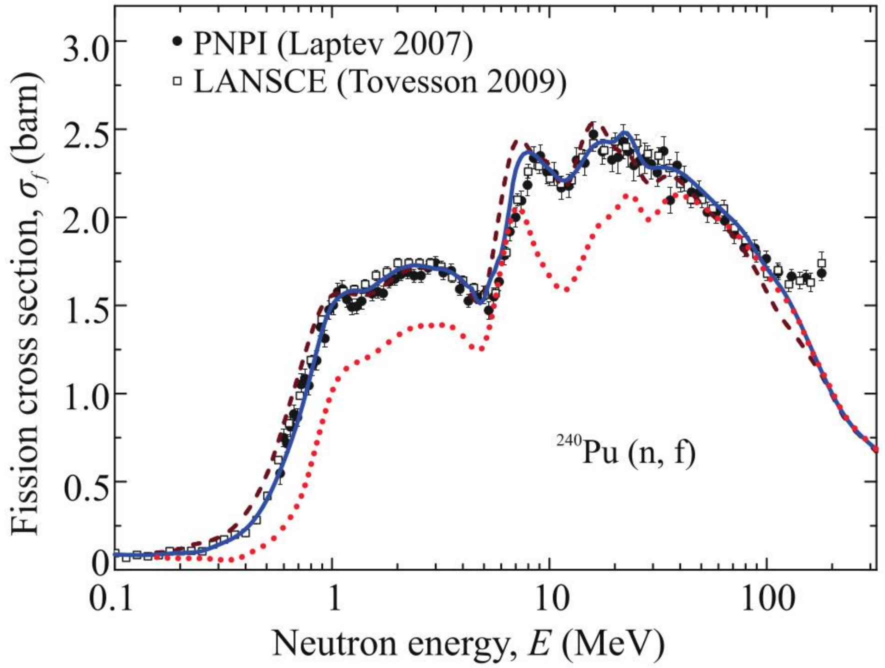
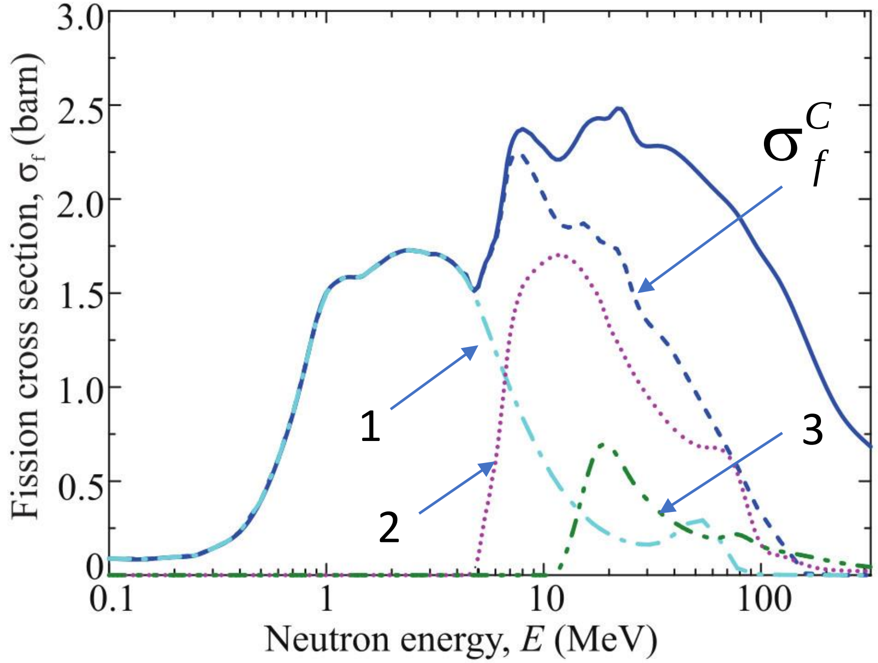
JETP Lett. 112,
323 (2020)



Our parameters for barriers and level densities at barriers

	1				2			
A	B	$\hbar\omega$	R_{tm}	K_{rc}	B	$\hbar\omega$	R_{tm}	K_{rc}
241	6.05	0.78	0.7	1.5	5.4	0.5	1.0	1.5
240	6.07	0.9	8.0	2.0	5.05	0.6	8.0	4.0
239	6.1	0.8	0.7	1.5	5.6	0.5	1.0	1.5
238	5.6	0.9	4.0	1.0	5.0	0.6	4.0	2.0

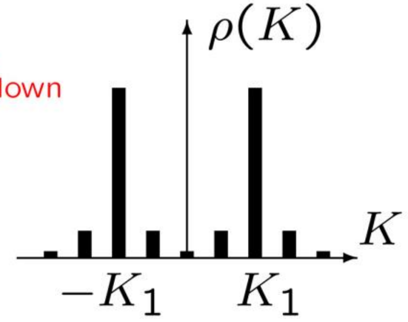


$^{237}Np(n,f)$: Results for Angular anisotropy

«Low» energies:

$E^* = E_{ex} - B_f < \Delta + U_{\text{down}}$

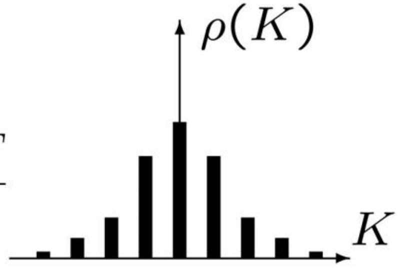
$\rho_{ZN}^{J\pi i}(K) \sim e^{-\alpha(|K|-K_1)^2}$



«High» energies:

$E^* = E_{ex} - B_f > \Delta + U_{\text{up}}$

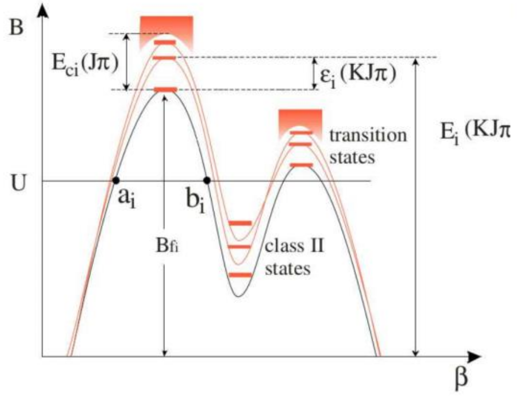
$\rho_{ZN}^{J\pi i}(K) \sim e^{-\frac{K^2}{2K_0^2}}, \; K_0^2 = \frac{J_{\text{eff}}T}{\hbar^2}$

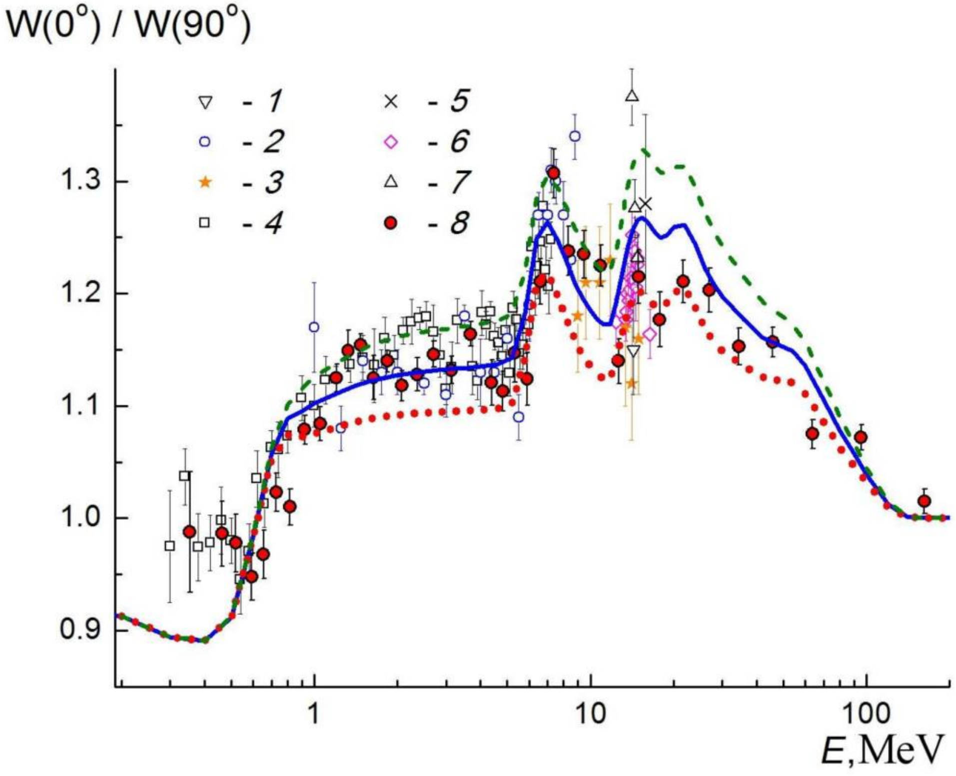


Additional parameters:

$U_{\text{up}} = 0.4$ MeV, $U_{\text{down}} = -0.1$ MeV, $\alpha = 0.15$, $K_1 = \begin{cases} 0.0, & {}^{238}\text{Np}, \\ 0.5, & {}^{237}\text{Np}, \\ 1.5, & \text{all other isitopes.} \end{cases}$

A.S.Vorobyev et al. JETP Lett. 110, 242 (2019)





$\frac{\hbar^2}{J_{\text{eff}}} = 0.022$ MeV

$\frac{\hbar^2}{J_{\text{eff}}} = 0.017$ MeV

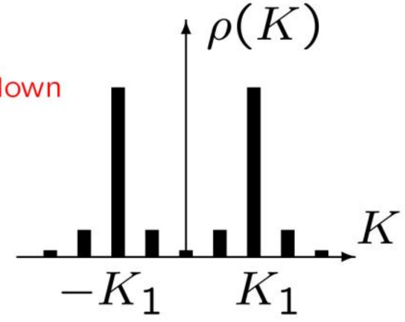
$\frac{\hbar^2}{J_{\text{eff}}} = 0.012$ MeV

$^{240}Pu(n,f)$: Results for Angular anisotropy

«Low» energies:

$E^* = E_{ex} - B_f < \Delta + U_{\text{down}}$

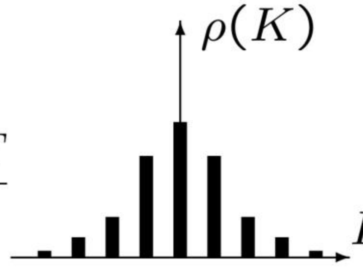
$\rho_{ZN}^{J\pi i}(K) \sim e^{-\alpha(|K|-K_1)^2}$



«High» energies:

$E^* = E_{ex} - B_f > \Delta + U_{\text{up}}$

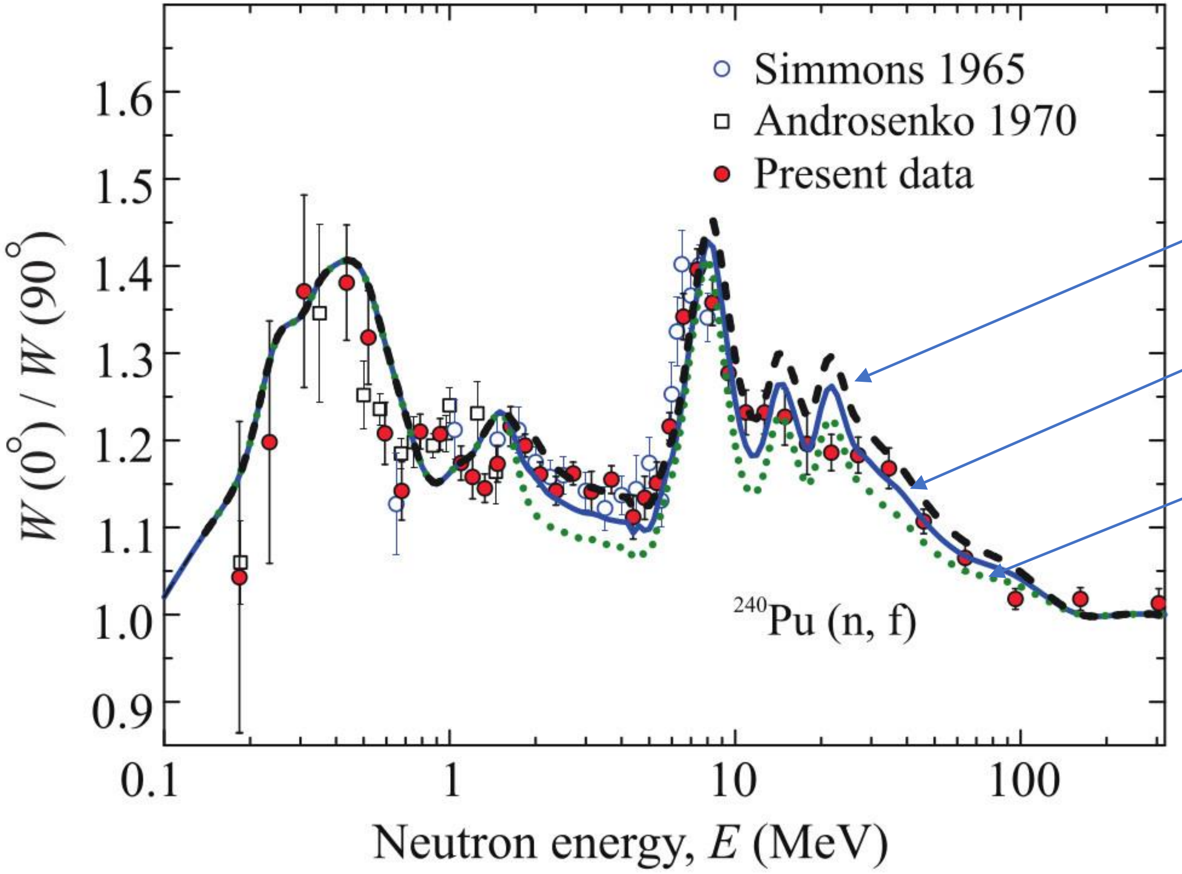
$\rho_{ZN}^{J\pi i}(K) \sim e^{-\frac{K^2}{2K_0^2}}, \quad K_0^2 = \frac{J_{\text{eff}}T}{\hbar^2}$



Additional parameters:

$$U_{\text{up}} = 0.4 \text{ MeV}, \quad U_{\text{down}} = -0.1 \text{ MeV}, \quad \alpha = 0.15, \quad K_1 = \begin{cases} \text{“special” choice}, & {}^{241}\text{Pu} \\ 1.9, & {}^{240}\text{Pu} \\ 1.5, & \text{all other isitopes.} \end{cases}$$

A.S. Vorobyev et al. JETP Lett. 112, 323 (2020)



$\frac{\hbar^2}{J_{eff}} = 9 \; keV$

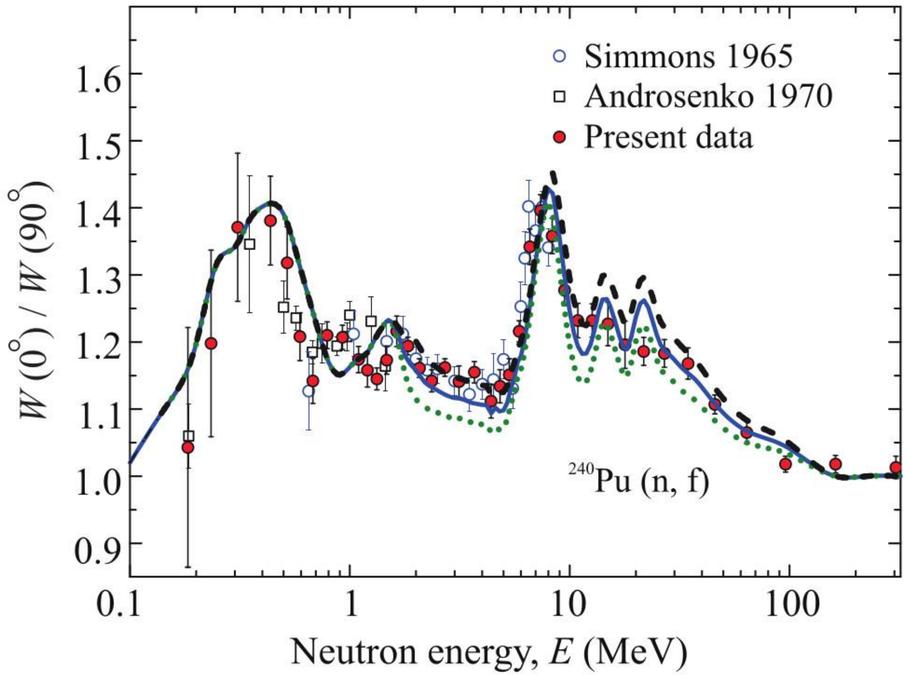
$\frac{\hbar^2}{J_{eff}} = 7 \; keV = \frac{\hbar^2 (J_\perp - J_\parallel)}{J_\perp J_\parallel}$

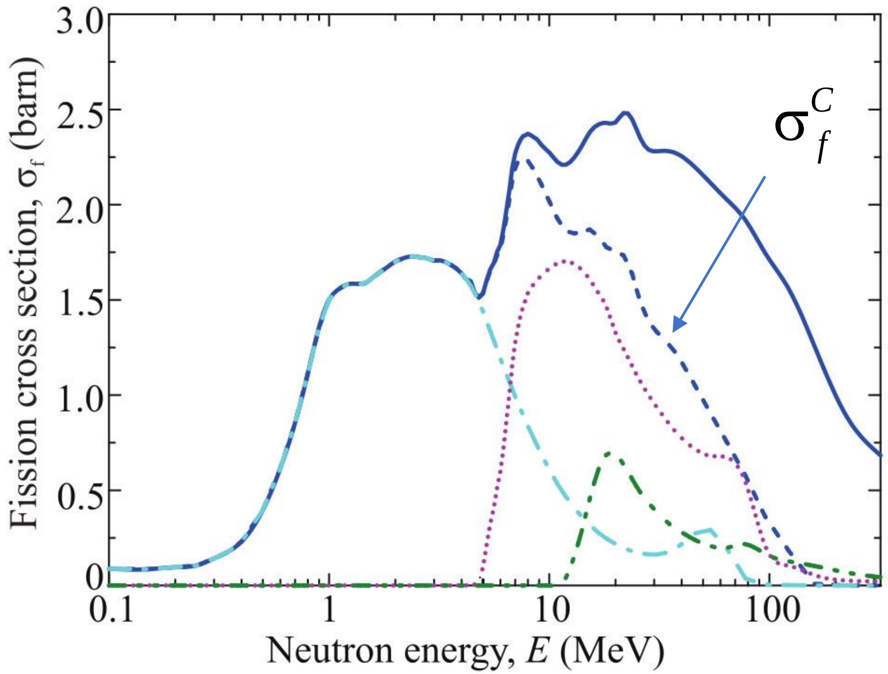
$\frac{\hbar^2}{J_{eff}} = 5 \; keV$

6.5 keV for TALYS parameters!

$^{240}Pu(n, f)$: Results for angular anisotropy

The calculated cross-section σ_f^C and the observed angular anisotropy of the fission fragments W(0)/W(90) decrease similarly at E > 20 MeV. Thus, at high energies the angular anisotropy seems be mainly related to the decay of primary compound nucleus.





Summary

- TALYS-based method for calculation of fission fragment angular distribution for neutron-induced reaction is successfully tested for ^{237}Np(n,f) and ^{240}Pu(n,f) reactions at 1-200 MeV.

- In both reactions the gross structure of energy dependence of fission fragment angular anisotropy is described by the same minimal set of “universal” parameters of distribution on quantum number K.

- Accurate account of the collectivity enhancement of the level density gives a reasonable value for effective moment of inertia of fissioning nuclei directly from the gross structure of fission fragment angular anisotropy.

- To obtain new information on the fission process from a joint analysis of the data on the fission cross section and angular anisotropy of fission fragments, we may need an improved nuclear fission model that reproduces fission cross sections without significant parameter deviations from standard values.