Double-humped fission barrier and statistical mechanism of formation of angular anisotropy of fission fragments

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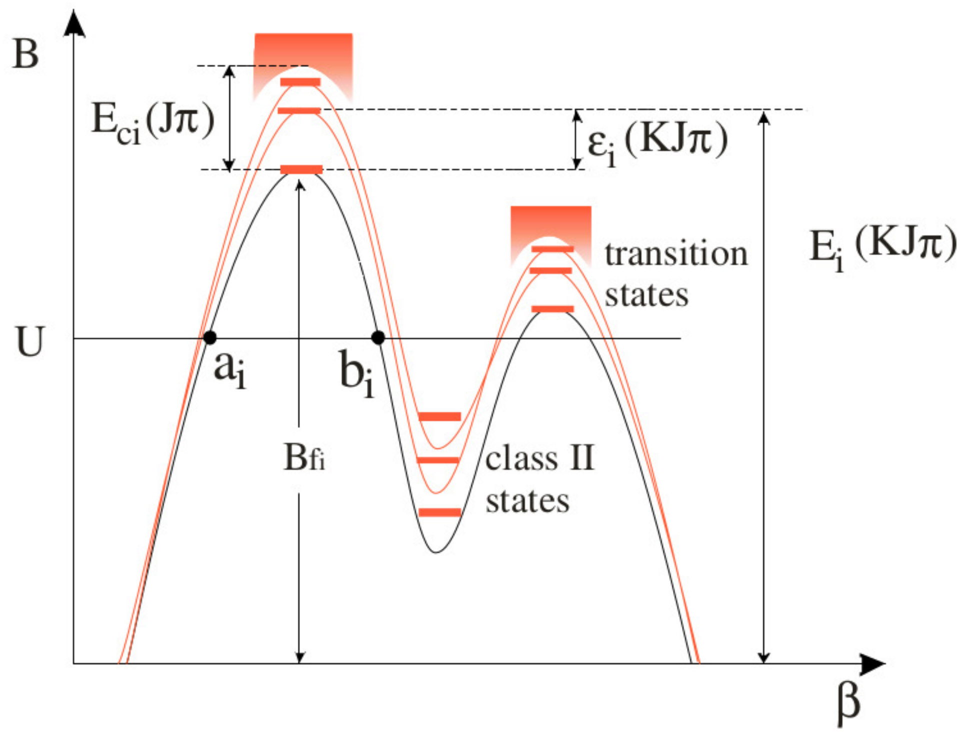
Motivation

There are at least two reasons why nuclear fission is an important topic to be interested in:

1. The significance of fission in nuclear power generation, both the current generation based on slow neutrons with thermal or several MeV energies, and the potential future generation based on relativistic proton accelerators, which can produce neutrons with up to several GeV energies.

2. The importance of fission for our understanding of nucleosynthesis. Fission, firstly, limits the mass and charge of nuclei formed in the r-process, and secondly, fission products replenish the range of medium-mass nuclei.

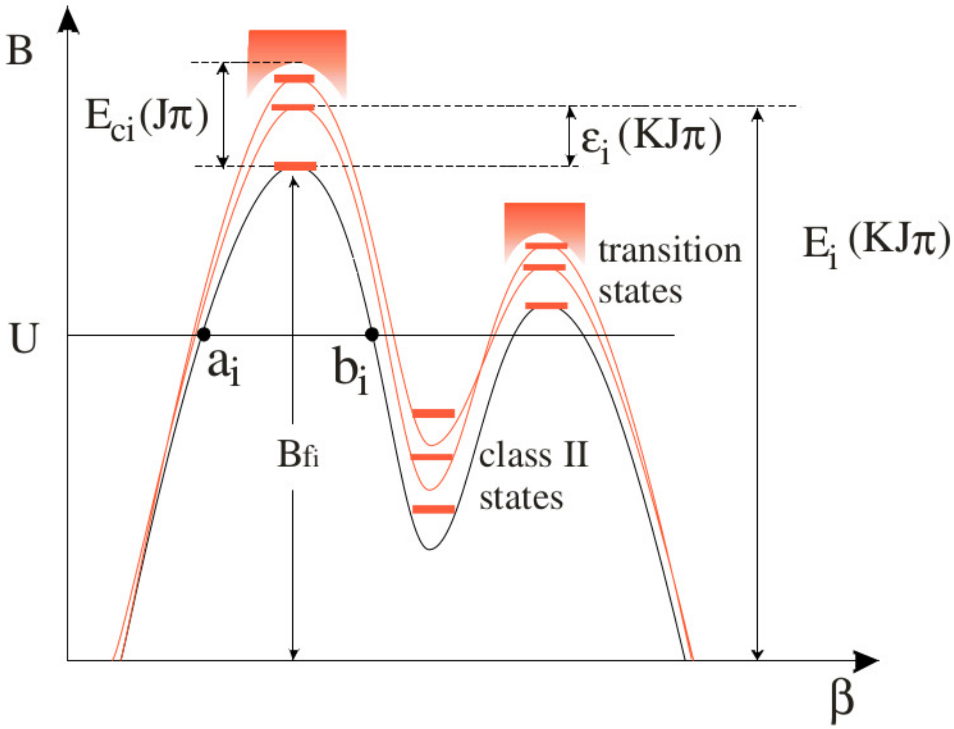
Two-humped fission barrier model

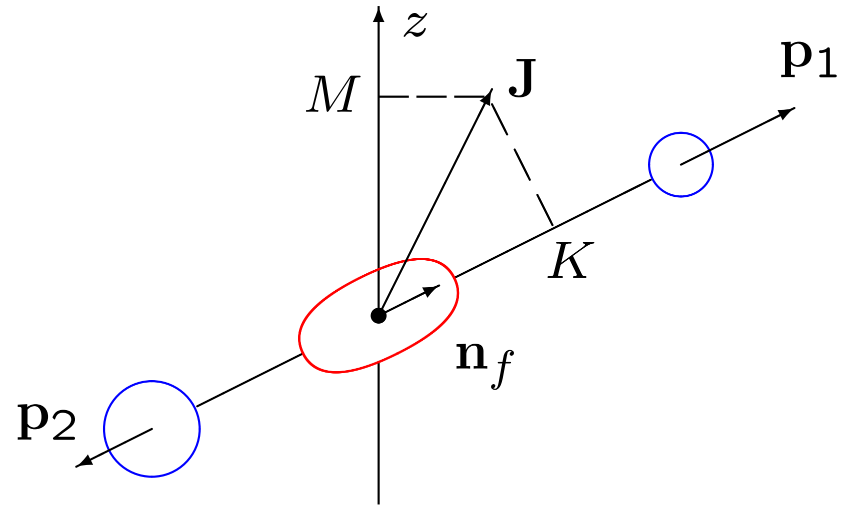


R.Capote et al. NDS **110**, 3107 (2009)

Microscopic approaches to the description of nuclear fission are currently being actively developed, but are still in their infancy. To describe fission, a phenomenological model of a double-humped fission barrier is used. It allows one to reproduce the energy dependence of the fission cross-section under the action of neutrons by selecting the appropriate parameters. Although the height and width of these humps are important, the density of excited states (transition states) of the deformed fissioning nucleus is no less important.

In the phenomenological model, it is possible to calculate not only the total fission cross-section, but also the angular distribution of fragments.





Indeed, the probability of fission is determined by the penetrability through a double-humped barrier for states with specific values of (J, π, K), and the angular distribution of fragments – by the distribution $\beta^{J\pi}(K)$ of states according to K:

$$\frac{dw^{J\pi}(\mathbf{n}_f)}{d\Omega} \sim \sum_M \eta^{J\pi}(M) \sum_K \beta^{J\pi}(K) \left|D^J_{MK}(\mathbf{n}_f)\right|^2$$

However, this model has so far only been tested on fission cross-section data obtained at neutron energies of up to 20 – 30 MeV. At the same time, data on the angular distribution of fragments have not yet been used to test or improve this phenomenological model.

Over the past 10 years, from 2015 to 2024, measurements of the angular distributions of fragments (and partially the total fission cross-sections) in neutron-induced fission of the following nuclei were carried out at the Petersburg Nuclear Physics Institute (PNPI – NRC KI):

nat Pb, ^{209}Bi, ^{232}Th, ^{233}U, ^{235}U, ^{236}U,
^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{243}Am

Their special feature is their coverage of a very wide range of neutron energies from 1 to 200 MeV, from low to intermediate. Most of the experimental results have been published, but some of the results are still being processed.

At the same time similar studies of the angular distributions of fission fragments are being carried out by the n-TOF (CERN) and NIFFTE (LANSCE) collaborations. To date, they have studied the fission of the following nuclei by neutrons of low and intermediate energy:

^{232}Th, ^{235}U, ^{238}U

Angular distribution of fission fragments:

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

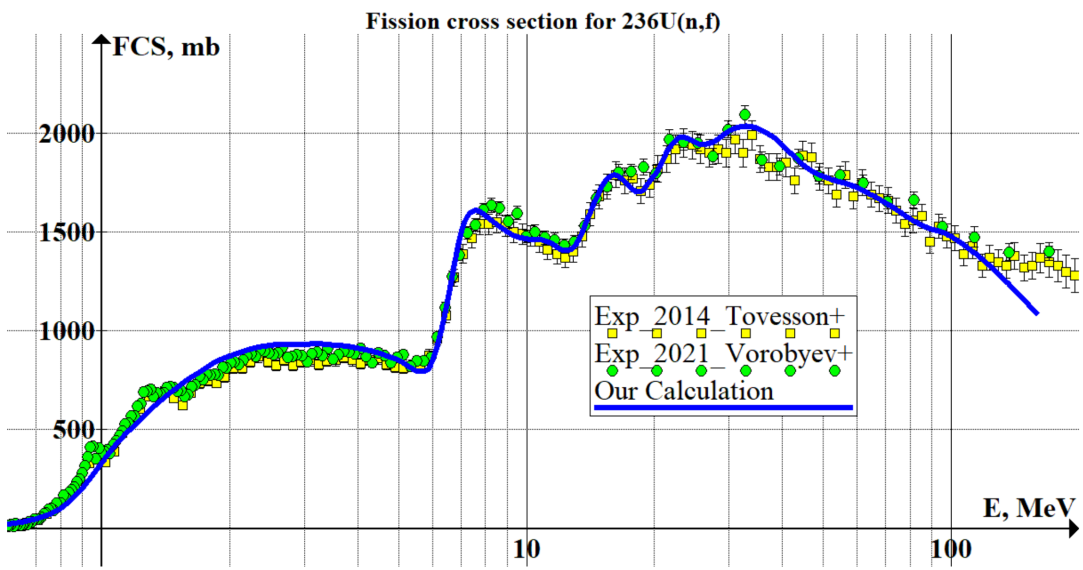
There are some technical issues with calculating the distributions over M, $\eta^{\mathbf{J}\pi}(\mathbf{M})$, and K, $\beta^{J\pi}(K)$. Consequently, all publicly available programs such as TALYS and EMPIRE, which calculate nuclear reaction cross-sections including fission, do not possess the capability to compute the angular distribution of fission fragments.

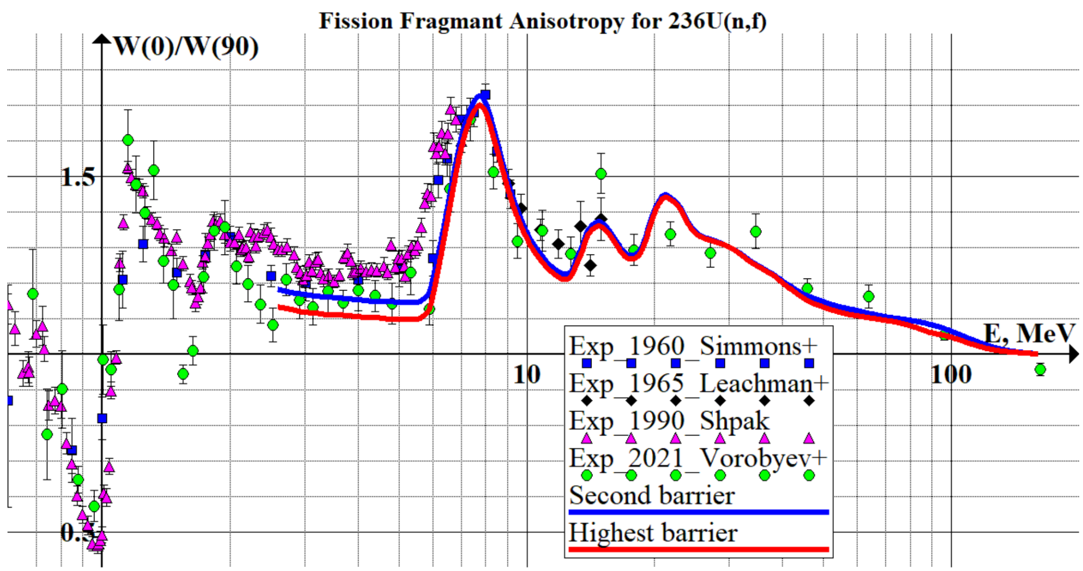
One of the achievements of our group in the field of fission theory is the overcoming of some difficulties with the calculation of $\eta^{\mathbf{J}\pi}(\mathbf{M})$ and $\beta^{\mathbf{J}\pi}(\mathbf{K})$. Thus, a modification of the TALYS-1.9 program has been carried out, which makes it possible to calculate the angular distributions of fragments of nuclear fission by neutrons with energies approximately above 3 MeV. In this case, the excitation energy of the resulting fissioning compound nuclei turns out to be high enough for the statistical mechanism of the formation of angular anisotropy of fragments to dominate:

$$\beta^{\mathbf{J}\pi}(\mathbf{K}) \sim \mathbf{e}^{-\frac{\mathbf{E}(\mathbf{JK})}{\mathbf{T}}} \sim \mathbf{e}^{-\frac{\mathbf{K}^2}{2\mathbf{K}_0^2}}, \quad \mathbf{K}_0^2 = \frac{\mathbf{I}_{\text{eff}}\mathbf{T}}{\hbar^2}, \quad \mathbf{I}_{\text{eff}} = \frac{\mathbf{I}_\perp \mathbf{I}_\parallel}{\mathbf{I}_\perp - \mathbf{I}_\parallel},$$

$$\mathbf{E}(\mathbf{JK}) = \frac{\hbar^2(\mathbf{J}^2 - \mathbf{K}^2)}{2\mathbf{I}_\perp} + \frac{\hbar^2\mathbf{K}^2}{2\mathbf{I}_\parallel}$$

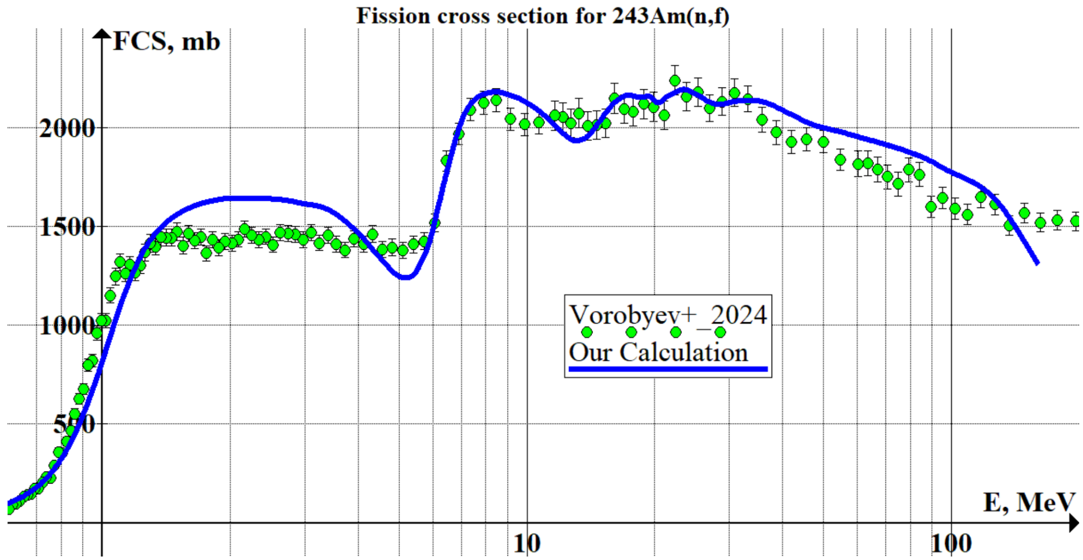
Reaction ^{236}U(n, f) (Phys. Rev. C, 2023)

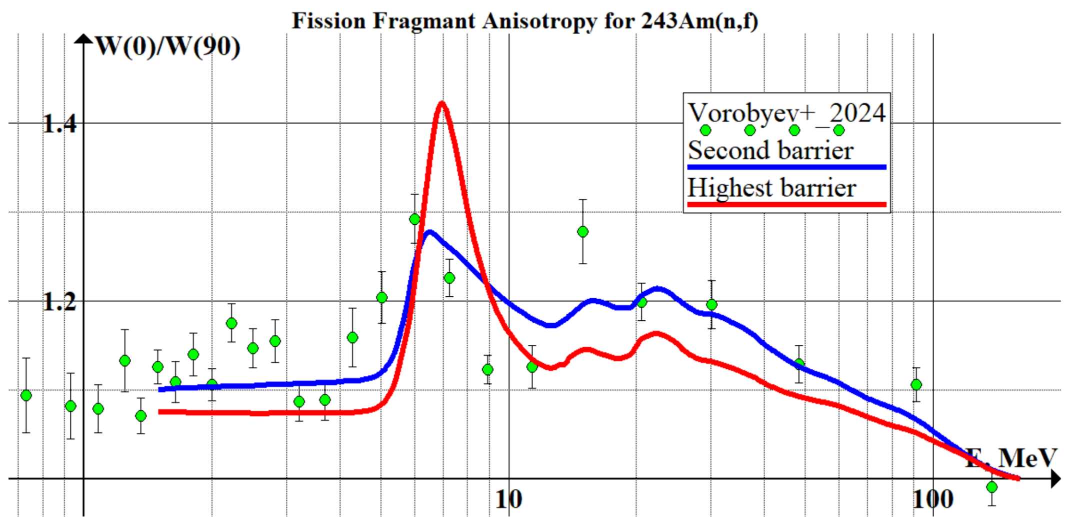




^{237}U		^{236}U		^{235}U		^{234}U		^{233}U	
B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
6.30	6.15	5.00	5.95	5.25	5.70	4.80	5.40	4.35	5.20

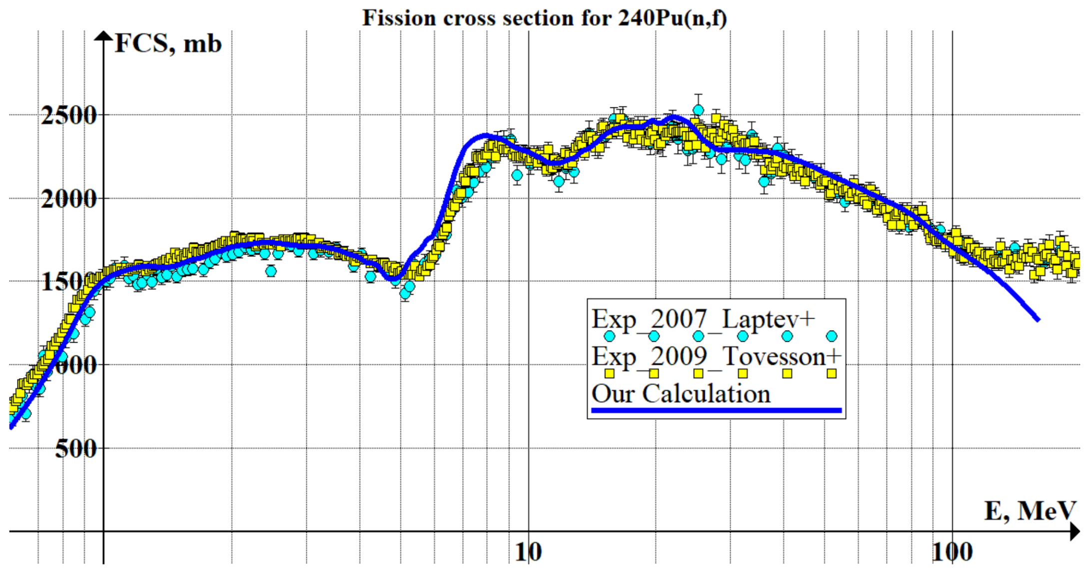
Reaction ^{243}Am(n,f) (Eur. Phys. J. A, 2024)

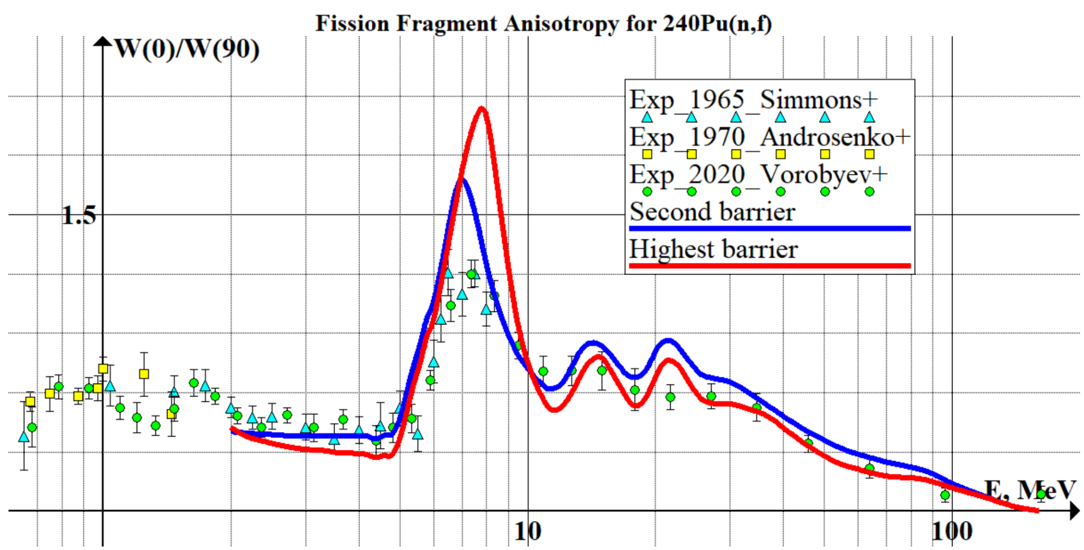




^{244}Am		^{243}Am		^{242}Am		^{241}Am		^{240}Am	
B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
6.10	5.90	5.85	5.05	5.95	5.78	5.70	5.35	5.90	5.80

Reaction ^{240}Pu(n,f) (JETP Lett., 2020)





^{241}Pu		^{240}Pu		^{239}Pu		^{238}Pu		^{237}Pu	
B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2	B_1	B_2
6.05	5.40	6.07	5.05	6.10	5.60	5.60	5.00	5.10	5.15

Summary

1. The anisotropy of the angular distribution of fragments of multi-chance fission of ^{236}U, ^{239}Pu, ^{243}Am nuclei by neutrons is calculated within the framework of the transition state model in the field of applicability of the statistical approach (the energy range of incident neutrons from 2-3 to 160 MeV) under various assumptions about the barrier on which the angular distribution is formed. The calculations do not involve any fitting parameters.

2. It was found that in all three cases, the calculated anisotropy is in better agreement with the measured one, assuming that the angular anisotropy is formed at the outer barrier, regardless of whether it is above or below the inner barrier.

3. Thus, it seems that the data on the angular anisotropy of nuclear fission fragments by low- and intermediate-energy neutrons represent independent evidence of the validity of the concept of a double-humped fission barrier.

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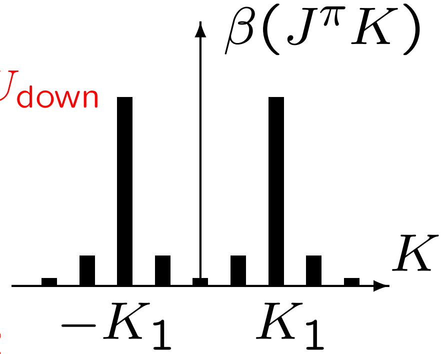
«Low» energies:

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

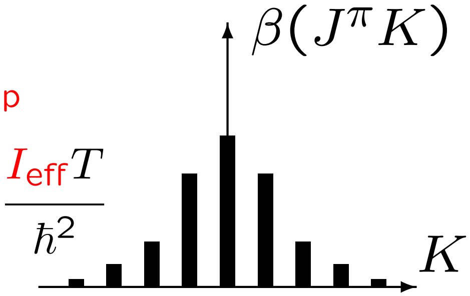
$$\beta(J^\pi K) \sim e^{-\alpha(|K|-K_1)^2}$$



«High» energies:

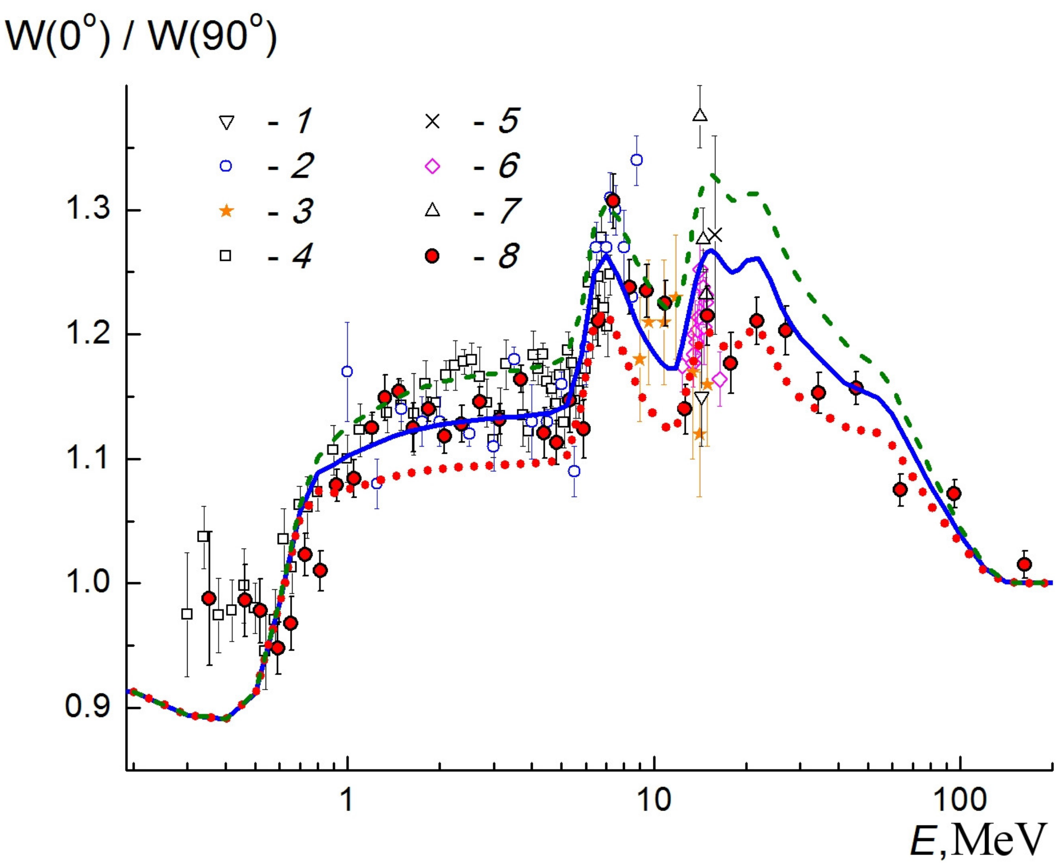
$$E^* = E_x - B_f > \Delta + U_{\text{up}}$$

$$\beta(J^\pi K) \sim e^{-\frac{K^2}{2K_0^2}}, \quad K_0^2 = \frac{I_{\text{eff}}T}{\hbar^2}$$



Additional parameters:

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



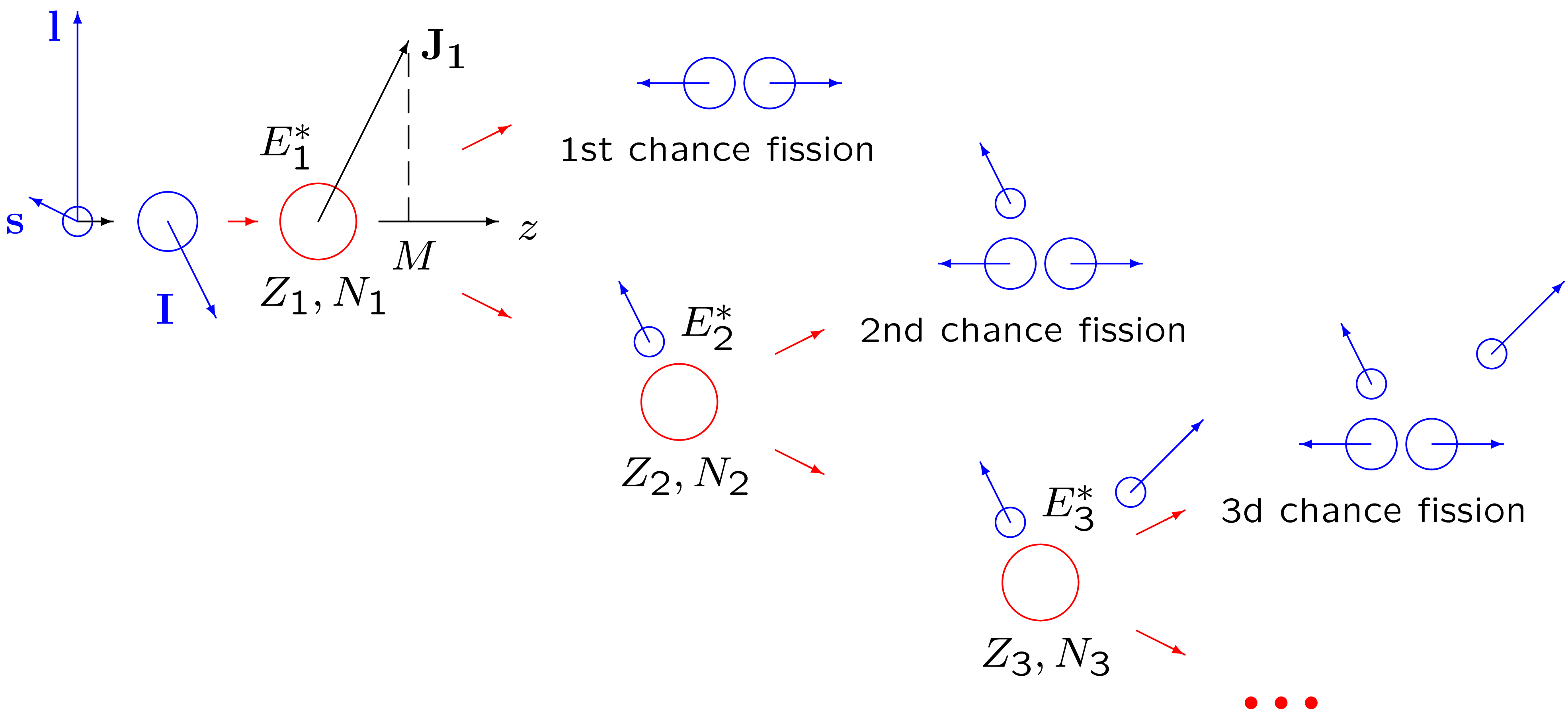
$$\frac{\hbar^2}{J_{\text{eff}}} = 0.022 \text{ MeV}$$

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

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

The difficulty in calculating the distribution over the projection M at high collision energies arises from the need to take into account the weakening of the spin alignment of nuclei during the sequential emission of particles prior to fission. This effect is shown schematically on the next slide.

Here $\vec{J}_1 = \vec{s} + \vec{I} + \vec{l}$. Since the orbital momentum $\vec{l}$ is perpendicular to the collision axis z, the total spin J_1 is aligned in a plane perpendicular to that axis. However, as particles are emitted, each of which carries some angular momentum, the overall alignment of the nucleus decreases. These effects are accurately accounted for in the modified version of the TALYS-1.9 code.



This model was first presented for the reactions ^{237}Np(n,f) (JETP Letter, 2019), ^{240}Pu(n,f) (JETP Letter, 2020) and ^{236}U(n,f) (PRC, 2023).