A method to compute fragment angular distributions from fission of highly excited nuclei

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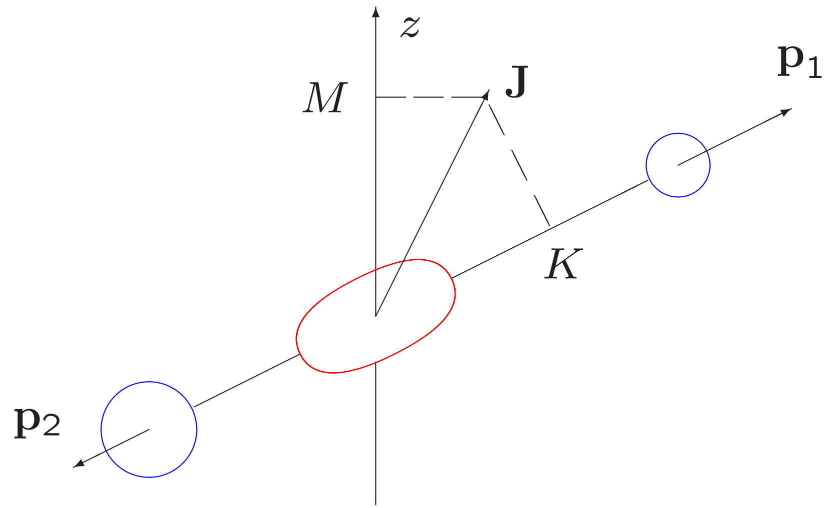
A. Bohr, 1955:

Angular distributions are due to transition states on the fission barrier.

To obtain angular anisotropy we need both
— non-uniformity by M and
— non-uniformity by K.



$$\Psi_J \sim \sum_M a_M(J) \sum_K g^{JK}\, \Phi_K(\tau) D^J_{MK}(\mathbf{n}_f)$$

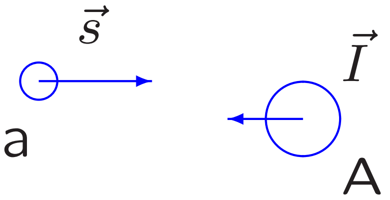
$$\frac{dw(\mathbf{n}_f)}{d\Omega} \sim \int |\Psi_J|^2\, d\tau \sim \sum_M |a_M(J)|^2 \sum_K |g^{JK}|^2\, |D^J_{MK}(\mathbf{n}_f)|^2 \equiv$$

$$\equiv \sum_{Q=0,2,4,\ldots} (2Q+1) \underbrace{\left(\sum_M C^{JM}_{JMQ0}\, |a_M(J)|^2\right)}_{\equiv\ \tau_Q(J)} \underbrace{\left(\sum_K C^{JK}_{JKQ0}\, |g^{JK}|^2\right)}_{\equiv\ b_Q(J)} P_Q(\cos\theta)$$

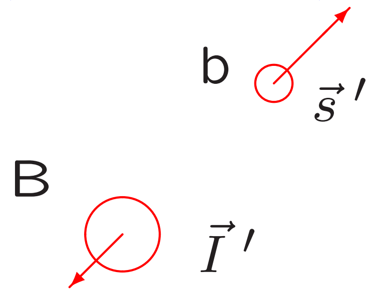
$\tau_Q(J)$ — spin-tensor of orientation, $b_Q(J)$ — parameter of anisotropy

J.M. Blatt, L.C. Biedenharn, 1951: Angular distribution for a+A $\rightarrow$ C$\rightarrow$ b + B

before (α):



after (α'):



$\vec{l}, \quad \vec{j} = \vec{s} + \vec{l}, \quad \vec{J} = \vec{I} + \vec{j}$ $\qquad$ $\vec{l}\,', \quad \vec{j}\,' = \vec{s}\,' + \vec{l}\,', \quad \vec{J} = \vec{I}\,' + \vec{j}\,'$

TALYS also computes the compound nucleus formula for the angular distribution. It is given by

$$\frac{d\sigma^{comp}_{\alpha\alpha'}(\theta)}{d\Omega} = \sum_L C^{comp}_L P_L(\cos\Theta), \tag{4.180}$$

where P_L are Legendre polynomials. The Legendre coefficients C^{comp}_L are given by

$$C^{comp}_L = D^{comp}\frac{\pi}{k^2}\sum_{J,\Pi}\frac{2J+1}{(2I+1)(2s+1)}\sum_{j=|J-I|}^{J+I}\sum_{l=|j-s|}^{j+s}\sum_{j'=|J-I'|}^{J+I'}\sum_{l'=|j'-s'|}^{j'+s'}$$
$$\times \quad \delta_\pi(\alpha)\delta_\pi(\alpha')\frac{T^J_{\alpha lj}(E_a)\left\langle T^J_{\alpha' l' j'}(E_{a'})\right\rangle}{\sum_{\alpha'',l'',j''}\delta_\pi(\alpha'')\left\langle T^J_{\alpha'' l'' j''}(E_{a''})\right\rangle} W^J_{\alpha lj\alpha' l' j'} A^J_{IljI'l'j';L}, \tag{4.181}$$

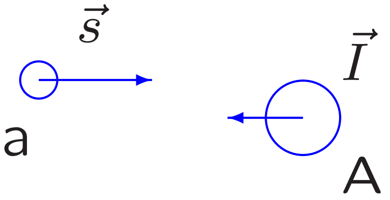
where the Blatt-Biedenharn factor A is given by

$$A^J_{IljI'l'j';L} = \frac{(-1)^{I'-s'-I+s}}{4\pi}(2J+1)(2j+1)(2l+1)(2j'+1)(2l'+1)$$
$$(ll00|L0)\,\mathcal{W}(JjJj;IL)\mathcal{W}(jjll;Ls)\,(l'l'00|L0)\,\mathcal{W}(Jj'Jj';I'L)\mathcal{W}(j'j'l'l';Ls'), \tag{4.182}$$

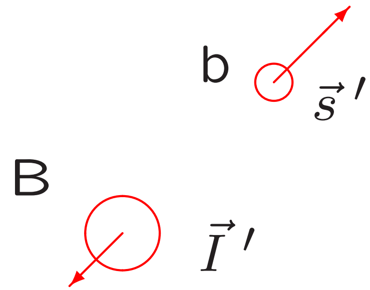
where (|) are Clebsch-Gordan coefficients and $\mathcal{W}$ are Racah coefficients.

Angular distribution for a+A $\rightarrow$ C$\rightarrow$ b + B

before (α):



after (α'):



$$\vec{l}, \quad \vec{j} = \vec{s} + \vec{l}, \quad \vec{J} = \vec{I} + \vec{j} \qquad\qquad \vec{l}\,', \quad \vec{j}\,' = \vec{s}\,' + \vec{l}\,', \quad \vec{J} = \vec{I}\,' + \vec{j}\,'$$

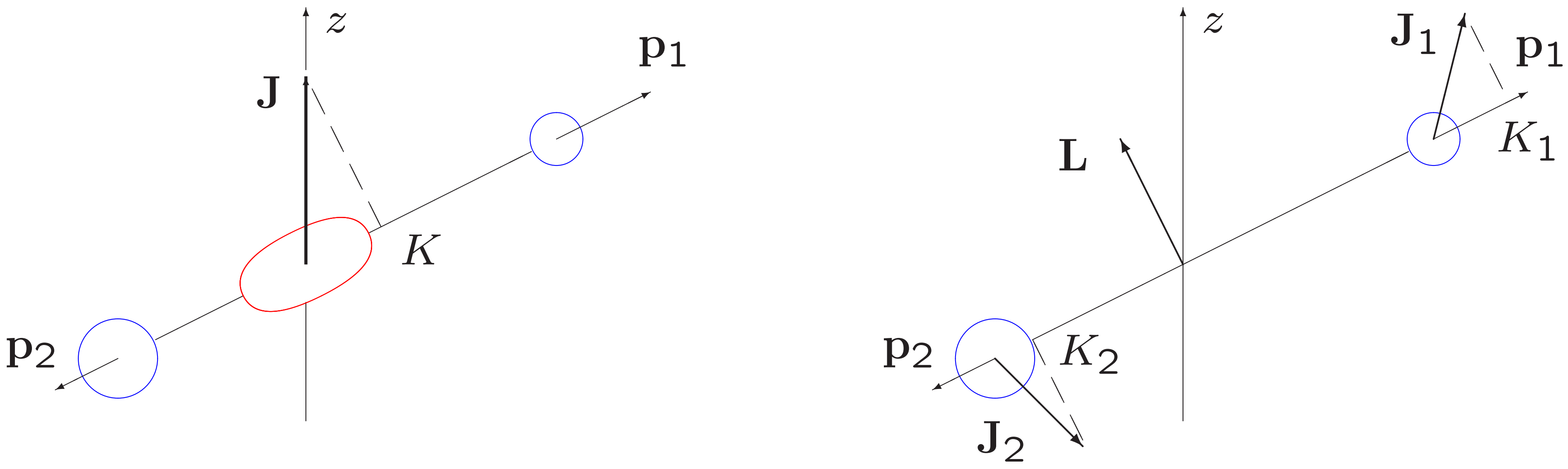
$$\frac{d\sigma^{comp}_{\alpha\alpha'}(\theta)}{d\Omega} \sim \sum_{J\pi} \frac{2J+1}{(2I+1)(2s+1)} \sum_{Q=0,2,4,\dots} \tau_Q(J\pi)\, b_Q(J\pi)\, P_Q(\cos\theta)$$

$$\tau_Q(J\pi) \sim (2J+1)^{1/2} \sum_{lj} T^{J\pi}_{\alpha lj} (2l+1)(2j+1) C^{Q0}_{l0l0} W(JjJj, IQ) W(jjll, Qs)$$

$$b_Q(J\pi) \sim (2J+1)^{1/2} \sum_{l'j'} \langle T^{J\pi}_{\alpha' l' j'} \rangle (2l'+1)(2j'+1) C^{Q0}_{l'0l'0} W(Jj'Jj', I'Q) W(j'j'l'l', Qs')$$

First problem: transformation of l' and j' to K in the exit (fission) channel

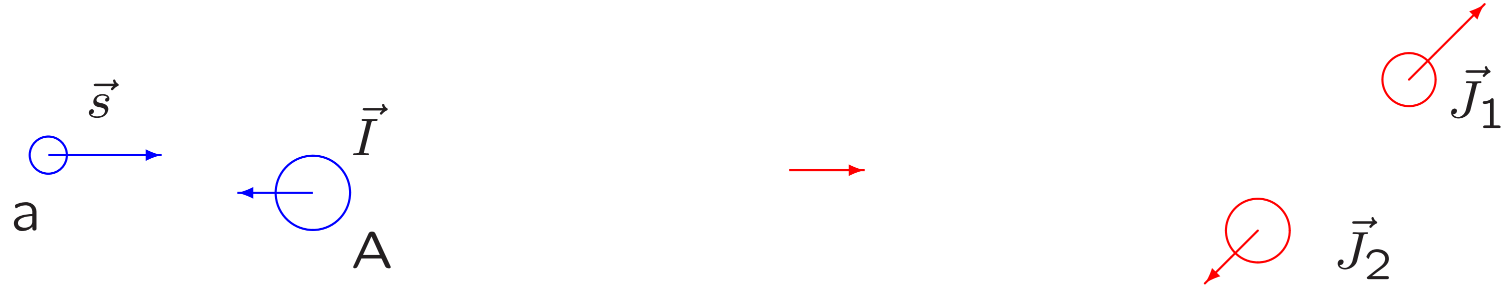
V.M. Strutinsky, 1956; A.L. Barabanov and W.I. Furman, 1997:
Helicity representation in fission channels



$$\mathbf{J} \rightarrow \mathbf{J}_1 + \mathbf{J}_2 + \mathbf{L}$$
$$K \rightarrow K_1 + K_2$$

K_1 and K_2 — fragment's helicities; K — total helicity

Angular distribution for fission (helicity representation)



$$\vec{l}, \quad \vec{j} = \vec{s} + \vec{l}, \quad \vec{J} = \vec{I} + \vec{j}$$

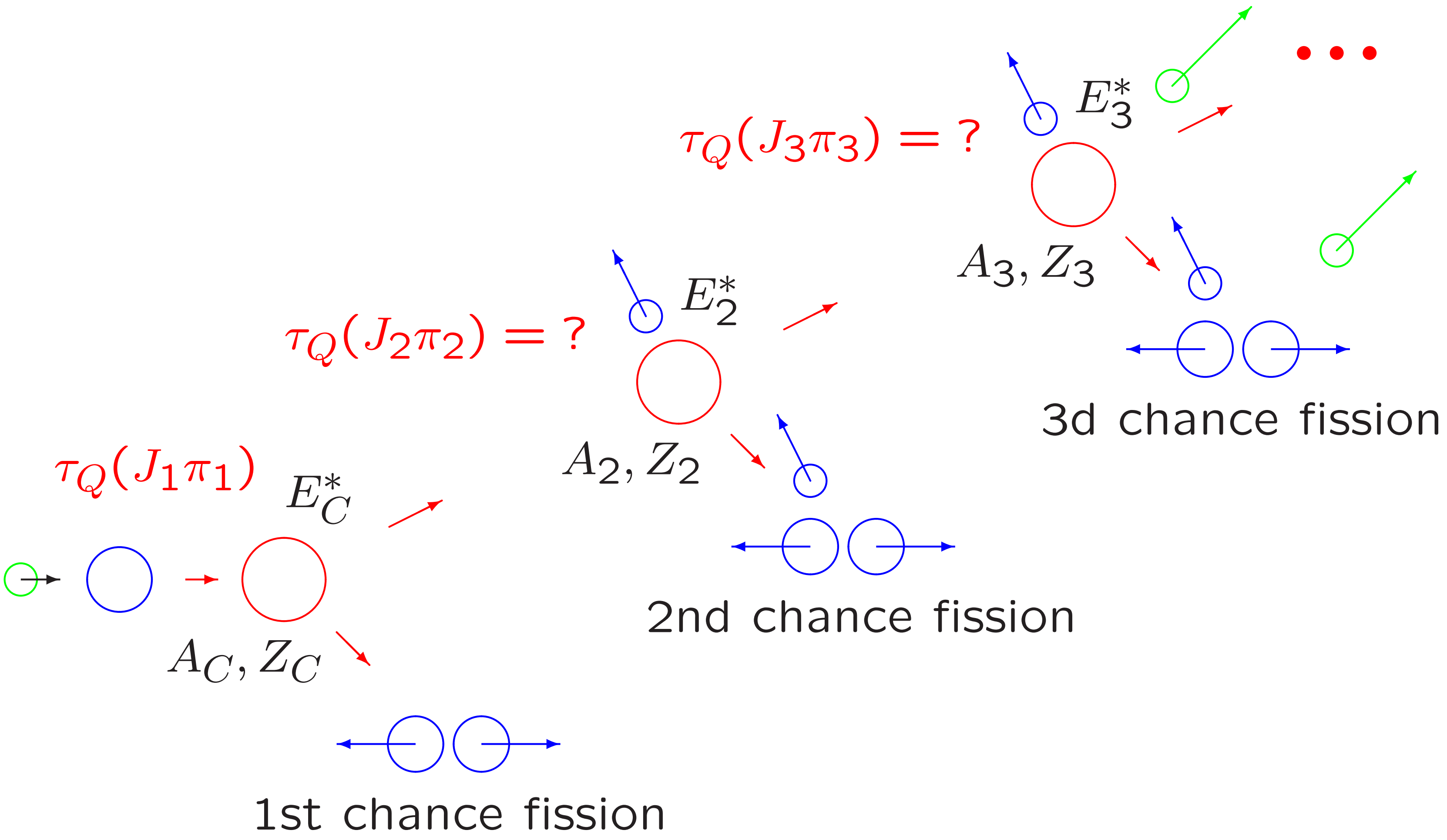
$$\vec{L}, \quad \vec{F} = \vec{J}_1 + \vec{J}_2, \quad \vec{J} = \vec{L} + \vec{F}$$

$$(L, F) \rightarrow (F, K)$$

$$\frac{d\sigma_f}{d\Omega} \sim \sum_{J\pi} \sigma_f(J\pi) \sum_{Q=0,2,4,\ldots} (2Q+1)\, \tau_Q(J^\pi)\, b_Q(J^\pi)\, P_Q(\cos\theta)$$

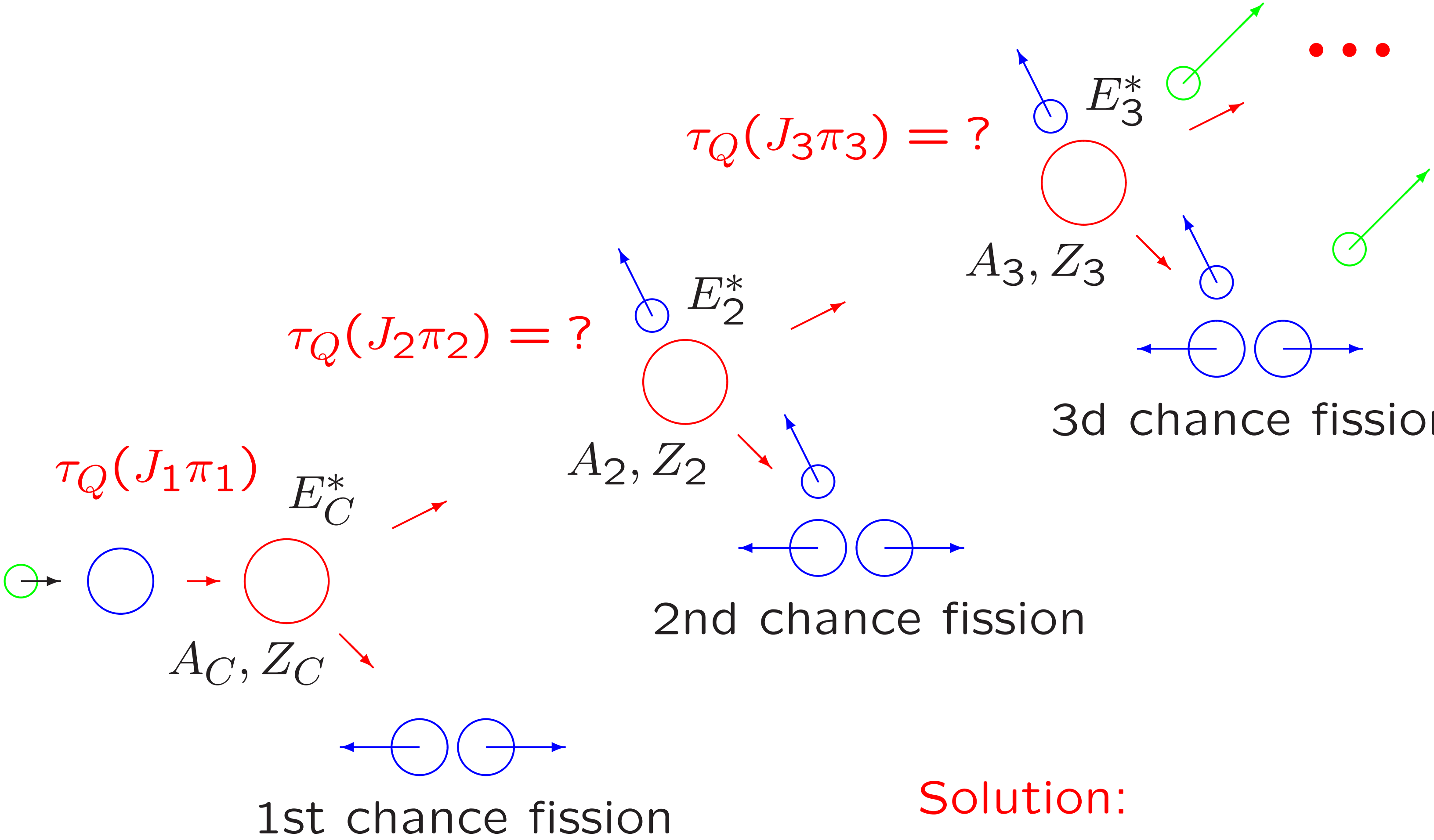
$$b_Q(J\pi) \sim \sum_K C^{JK}_{JKQ0} \left(\sum_F \left| g^{J\pi FK} \right|^2 \right)$$

Second problem: cascade deexcitation of highly excited nucleus and fission



particle: γ, n, p, d, t=^{3}H, h=^{3}He, α, . . .

Second problem: cascade deexcitation of highly excited nucleus and fission



Solution:

$\tau_Q(J_2\pi_2) \sim W(jJ_1J_2Q, J_2J_1)\tau_Q(J_1\pi_1)$

particle: γ, n, p, d, t=^{3}H, h=^{3}He, α, . . .

TALYS-1.8

New Edition December 26, 2015

A nuclear reaction program

User Manual

Arjan Koning
Stephane Hilaire
Stephane Goriely

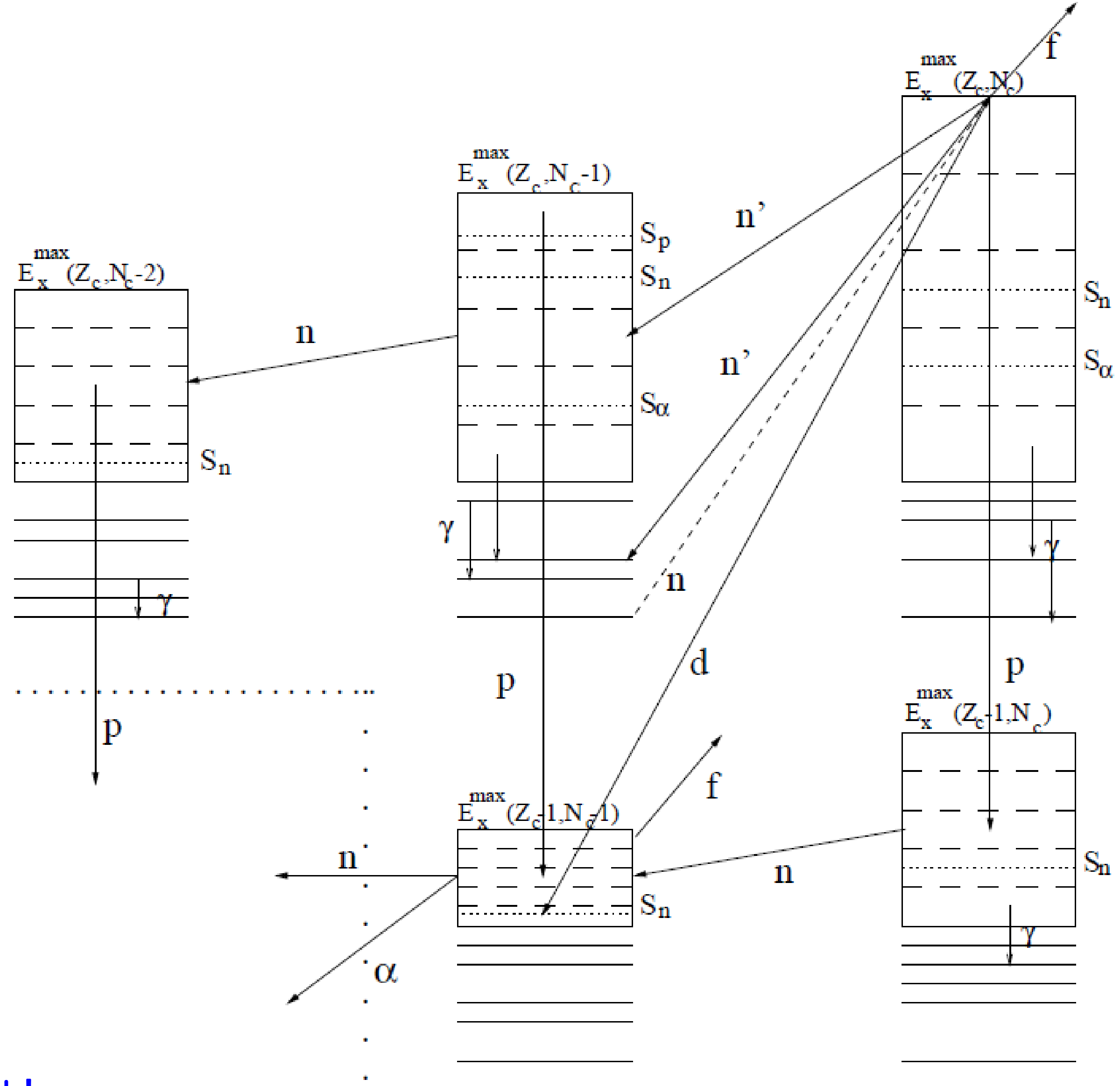
Talys is a computer code system for the analysis and prediction of nuclear reactions.

The basic objective is the simulation of nuclear reactions that involve neutrons, photons, protons, deuterons, tritons, 3He- and alpha-particles, in the 1 keV – 200 MeV energy range and for target nuclides of mass 12 and heavier.

Free use, open software, always under development: from TALYS-1.0 — December 2007 to TALYS-1.8 — December 2015.

More than 300 subroutines, more than 100 000 lines (commands), more than 500 pages in the Manual.

Completely integrated optical model and coupled-channels calculations by the ECIS-06 code, All partial cross sections can be found, due to



the calculation of
all transition probabilities:

$w(i \to i')$, where

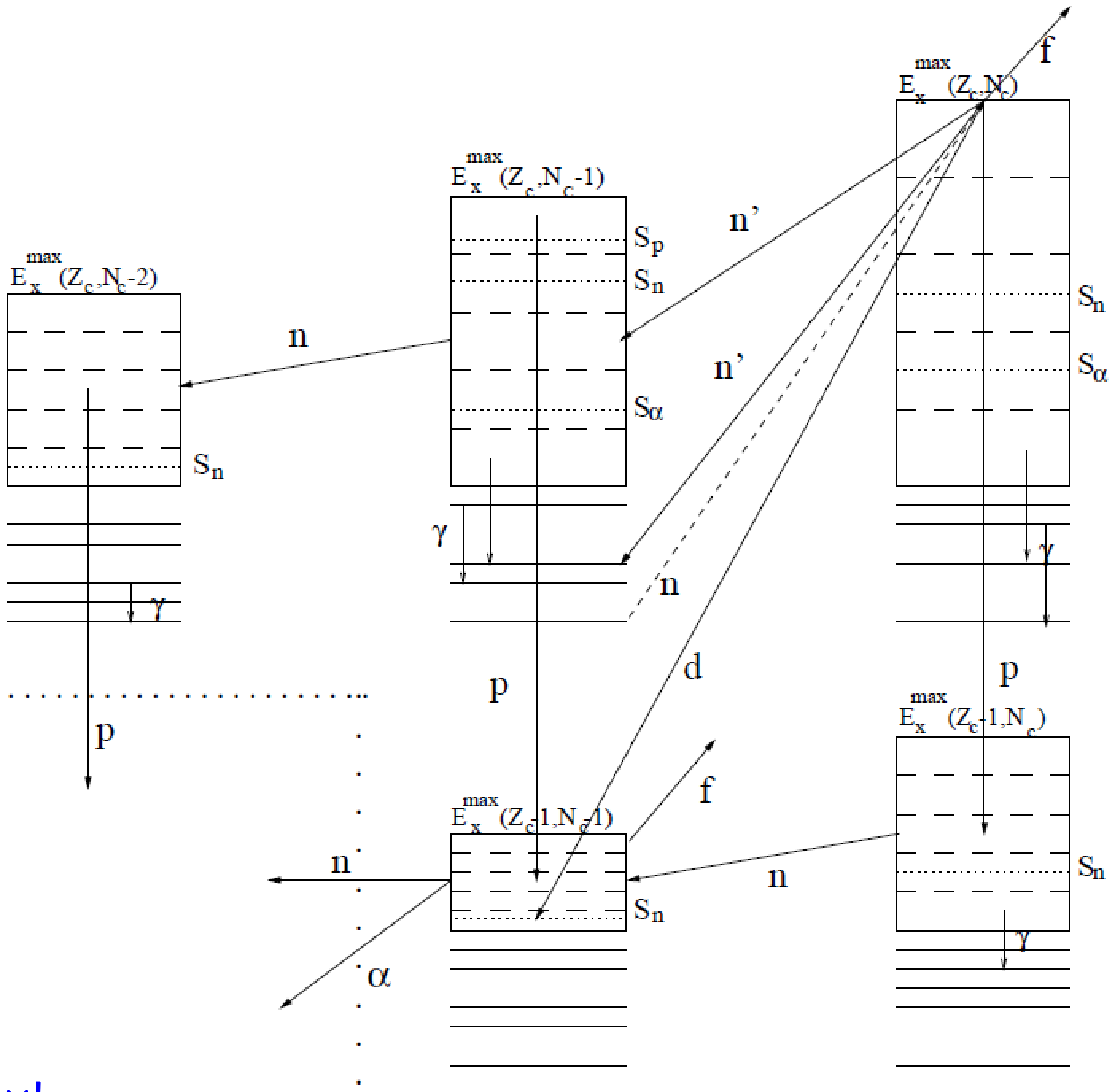
$i \equiv (Z_i, N_i, E_i^*, J_i, \pi_i)$

But!

— angular distributions — only for the first step reaction: a+A → C→ b + B

— angular distribution for fission fragments (even for the first step or first chance) can not be calculated

All partial cross sections can be found, due to



the calculation of
all transition probabilities:

$w(i \rightarrow i')$, where

$i \equiv (Z_i, N_i, E_i^*, J_i, \pi_i)$

Now!

— calculations of spin-tensors of orientation $\tau_Q(J\pi)$ and anisotropy coefficients $b_Q(J\pi)$ are included

— angular distribution for fission fragments can be calculated

Example: n + ^{232}Th, from 1 to 200 MeV

— I.V. Ryzhov et al. Nucl. Phys. A760, 19 (2005): quasi-monochromatic neutron beam

— D. Tarrio et al. Nuclear Data Sheets, 119, 35 (2014): n_TOF

— A.S. Vorobyev et al. JETP Letters 102, 203 (2015)

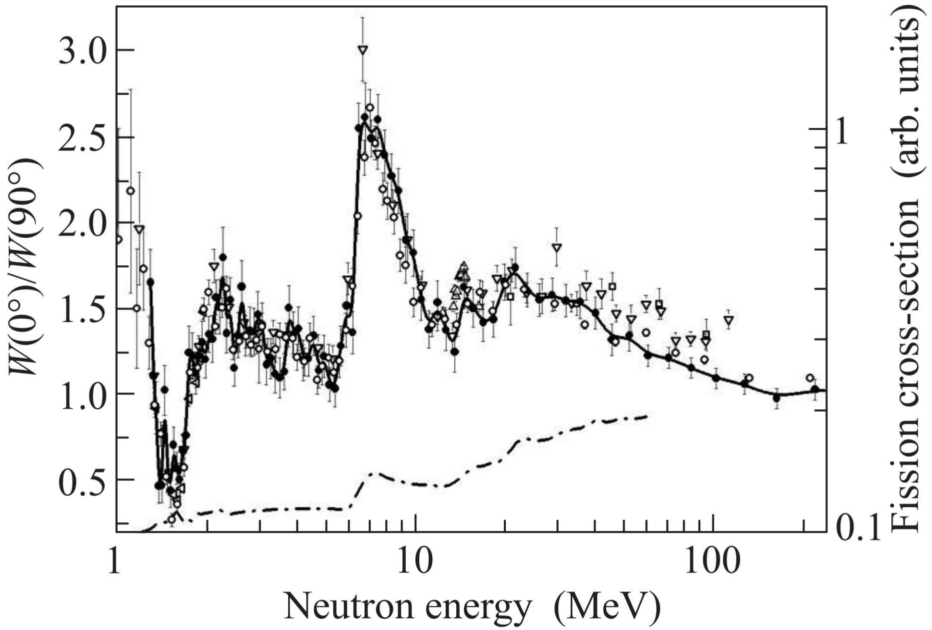
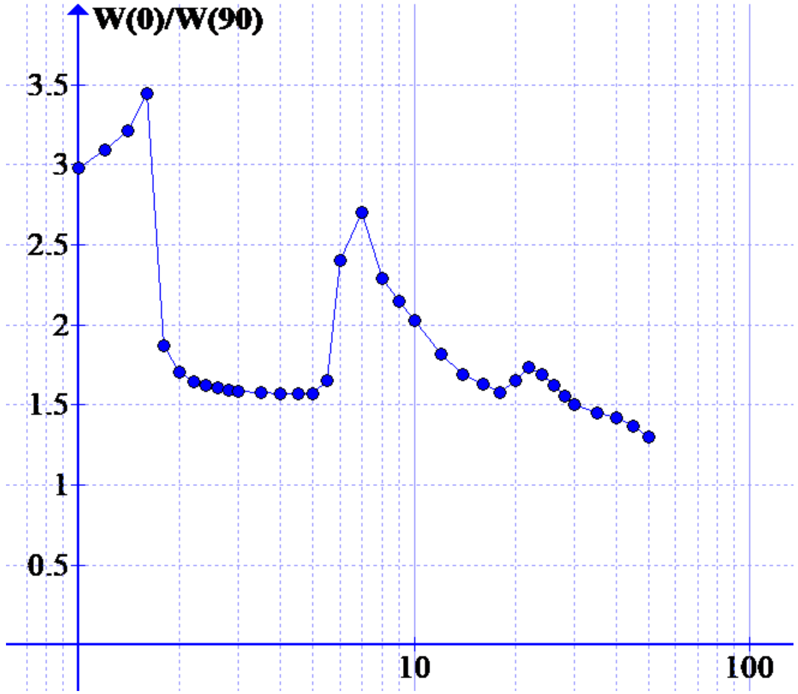
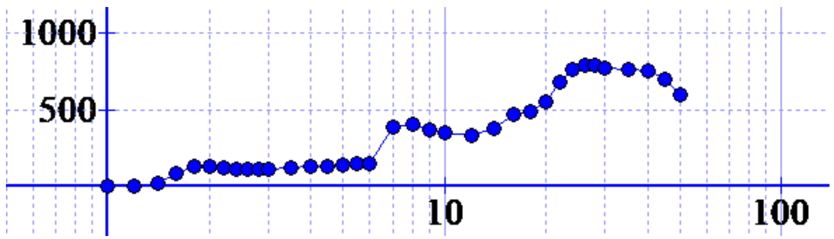


Fig. 3. Anisotropy of fission fragments of ^{232}Th: ▽ – [6], ◁ – [19], △ – [11], □ – [7], ○ – [8], ● – present data, -●- – fission cross-section [9]





Simplified model for anisotropy coefficients $b_Q(J)$:

If $U_{ex} < B_f$,

then the only channel $K = 0$ is open for integer spins J or $K = \pm\frac{1}{2}$ for half-integer spins J.

If $U_{ex} > B_f$,

then $|g^{JK}|^2 \sim e^{-\frac{\hbar^2 K^2}{2J_{eff}T^*}}$ (statistical distribution),

where $T^* = \sqrt{\frac{U_{ex} - B_f}{a}}$, a — level density parameter, $\frac{\hbar^2}{2J_{eff}} = 20$ keV

Summary

1. Cross sections and angular distribution of fission fragments are sensitive to the parameters of fission barriers, as well as to the characteristics of compound, preequlibrium and direct processes.

2. Modified TALYS seems to be an appropriate code for the simulation of heavy nuclei fission by neutrons with energy up to 200 MeV with extraction both the cross sections and fragment angular distributions.

3. We intend to use the modified TALYS to analyze the experimental data for a wide range of heavy nuclei to obtain new information about nuclear systems and processes.