# PROMPT NEUTRON CHARACTERISTICS IN THE SPONTANEOUS FISSION OF HEAVY AND SUPERHEAVY NUCLEI.

***V.A. Rubchenya***

***V.G. Khlopin Radium Institute, St.-Petersburg – 194021***

***Department of Physics, University of Jyväskylä – 40351, Finland***

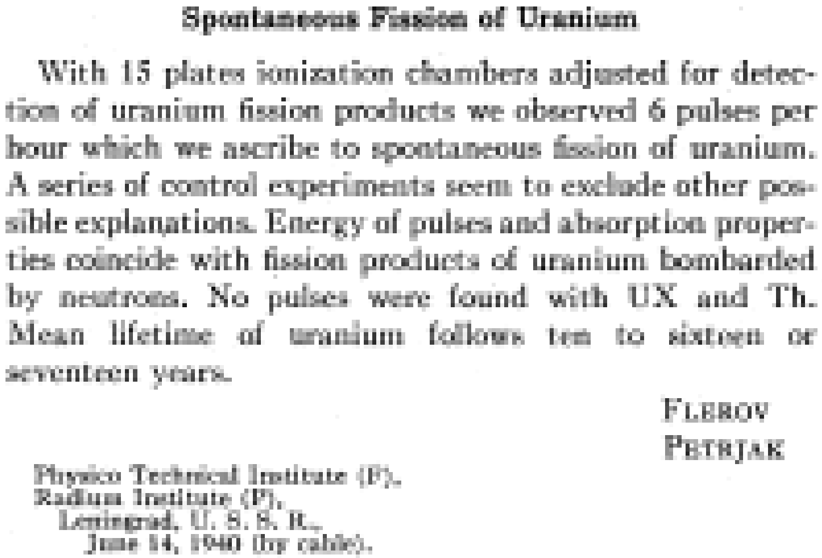
**LXV International Conference on Nuclear Physics "Nucleus 2015.**
**June 29-July 3, 2015, St. Petersburg**

# 75th ANNIVERSARY

discovery of

# SPONTANEOUS FISSION of URANIUM

Phys. Rev. 58 (1940) 89
[published 1 July 1940]



## Spontaneous Fission of Uranium

With 15 plates ionization chambers adjusted for detection of uranium fission products we observed 6 pulses per hour which we ascribe to spontaneous fission of uranium. A series of control experiments seem to exclude other possible explanations. Energy of pulses and absorption properties coincide with fission products of uranium bombarded by neutrons. No pulses were found with UX and Th. Mean lifetime of uranium follows ten to sixteen or seventeen years.

FLEROV
PETRJAK

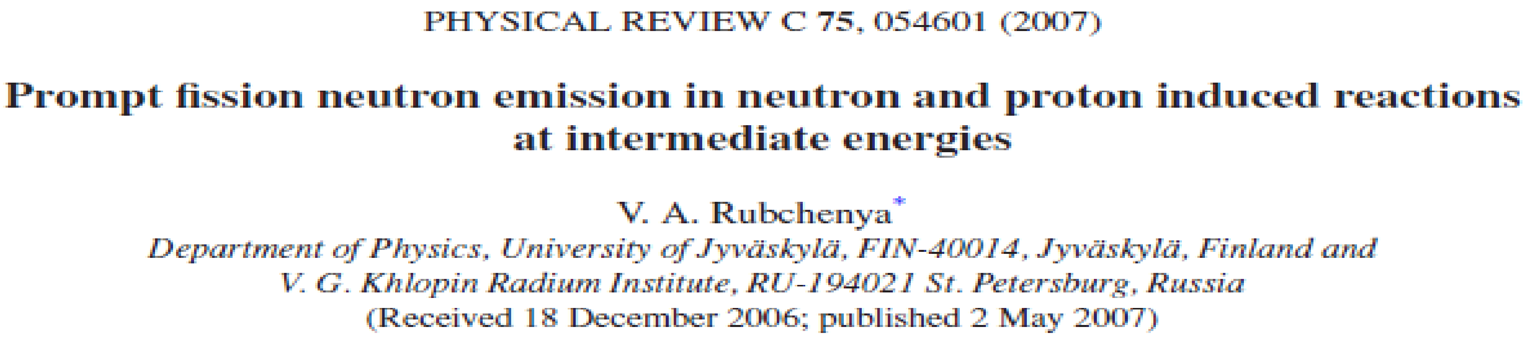
Physico Technical Institute (F),
Radium Institute (P),
Leningrad, U. S. S. R.,
June 14, 1940 (by cable).

# PROMPT NEUTRONS FROM THE LOW-ENERGY FISSION OF ATOMIC NUCLEI

B. F. Gerasimenko and V. A. Rubchenya

**Atomnaya Energiya** (USSR), Vol. 59, No. 5, pp. 335-339, 1985.

---



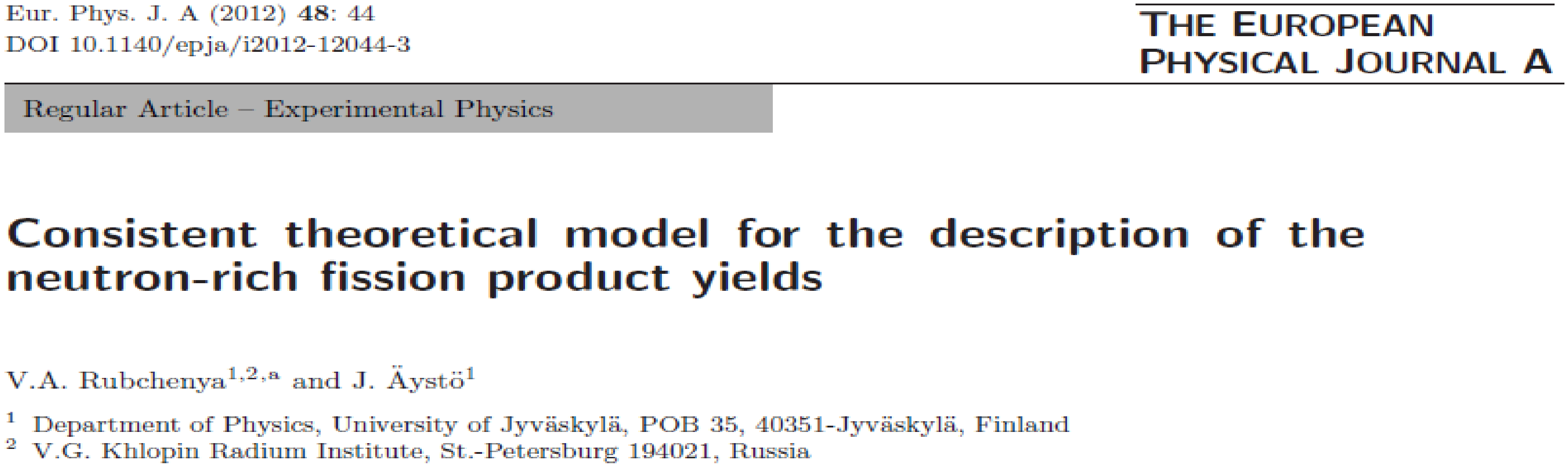
PHYSICAL REVIEW C 75, 054601 (2007)

## Prompt fission neutron emission in neutron and proton induced reactions at intermediate energies

V. A. Rubchenya[*]
*Department of Physics, University of Jyväskylä, FIN-40014, Jyväskylä, Finland and*
*V. G. Khlopin Radium Institute, RU-194021 St. Petersburg, Russia*

(Received 18 December 2006; published 2 May 2007)

---



Eur. Phys. J. A (2012) **48**: 44
DOI 10.1140/epja/i2012-12044-3

THE EUROPEAN
PHYSICAL JOURNAL A

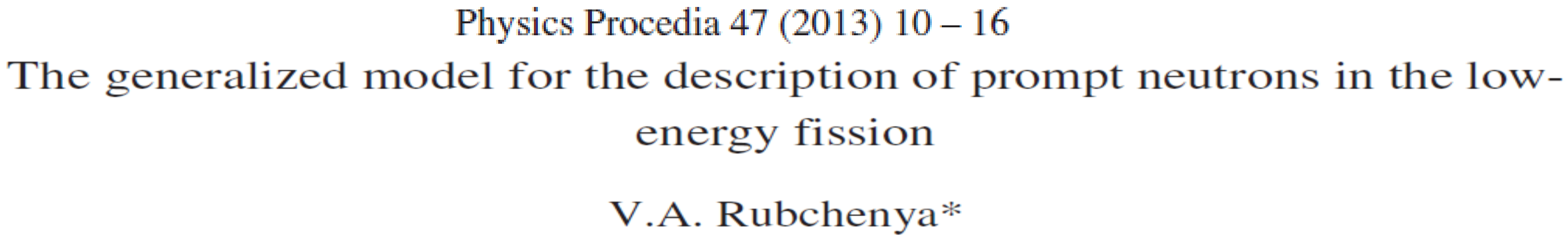
Regular Article – Experimental Physics

## Consistent theoretical model for the description of the neutron-rich fission product yields

V.A. Rubchenya[1,2,a] and J. Äystö[1]

[1] Department of Physics, University of Jyväskylä, POB 35, 40351-Jyväskylä, Finland
[2] V.G. Khlopin Radium Institute, St.-Petersburg 194021, Russia

---

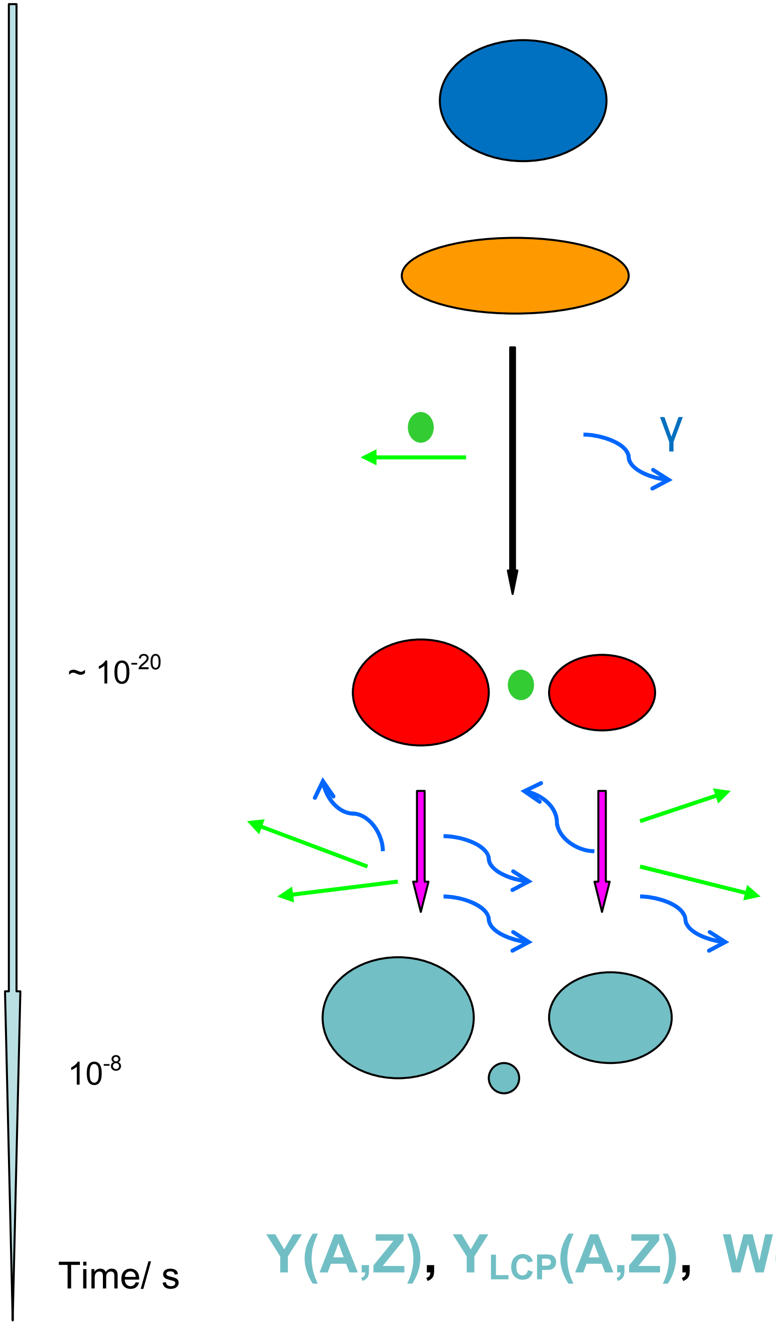


Physics Procedia 47 (2013) 10 – 16

## The generalized model for the description of prompt neutrons in the low-energy fission

V.A. Rubchenya*

# MODEL



Ground state

Saddle point

Emission at the descent from saddle

$$\tau_{desc} \sim 10^{-20}\ \text{s}$$

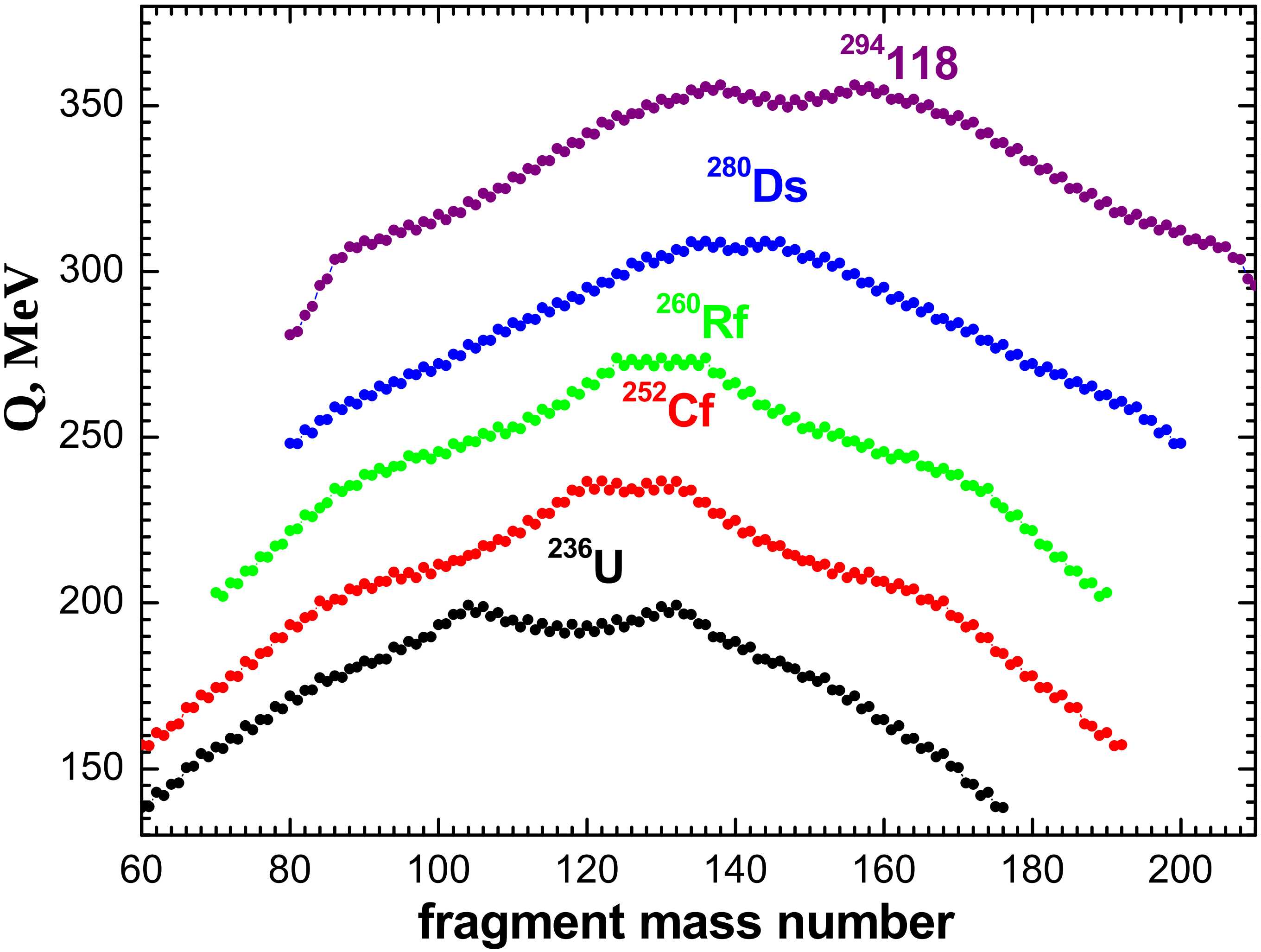
Scission neutrons

Post-scission evaporation

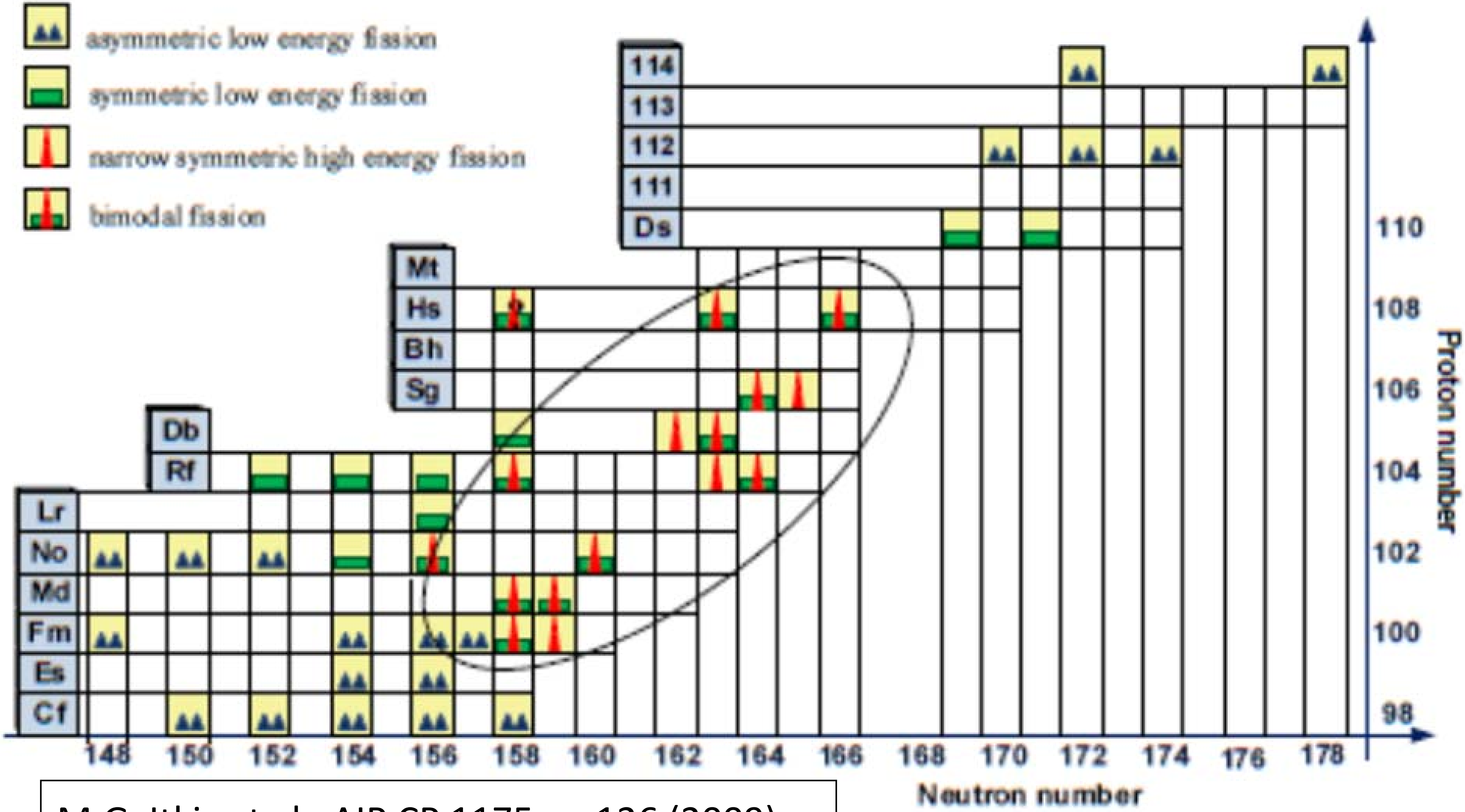
Fission products

$Y(A,Z)$, $Y_{LCP}(A,Z)$, $W(\Theta_F,E_{kin})$, $M_n(E_n,\Theta_n)$, $M_\gamma(E_\gamma,\Theta_\gamma)$

# Huge Q-fission value for SHE



# Bimodal symmetric fission



M.G. Itkis et al., AIP CP 1175, p. 126 (2009)

# The main dynamical effects in SF

1. Nuclear friction in the fission:
   - overdamped collective motion at the descent from saddle to scission
   - particle emission at the descent ($M_n^{pre\text{-}sc}$, $E_{elapsed}^{pre\text{-}sc}$ )
2. Charge polarization during the descent from sadlle to scission: charge distribution for isobaric chains: Y(Z/A)
3. Competion between different fission modes
4. Distribution of excitation energy between fragments: $M_n(A, Z, E^*_{scp})$
5. Shell structure for very deformed nuclei: shell corrections, fission barriers, mass parameters, fission modes, level density

# The prompt fission neutron double differential spectrum integrated over fragment mass and charge distributions consist from five summands

$$\frac{d^2M}{dEd\Omega} = \underline{\frac{d^2M^{sdsc}}{dEd\Omega}} + \underline{\frac{d^2M^{dyn}}{dEd\Omega}} + \underline{\frac{d^2M^{post}}{dEd\Omega}}$$

- emission at the descent from saddle to scission;
- scission neutrons due to the dynamical processes (ternary fission: $^5He \rightarrow {}^4He + n$ etc);
- post scission emission from moving exited fragments.

# Saddle-to-scission descent stage

- saddle-to-scission time is altered by the nuclear dissipation

$$\tau_{sdsc} = \tau_{sdsc}(\gamma = 0)\left(\left(1+\gamma^{2}\right)+\gamma\right).$$

**saddle-to-scission time is defined by the dynamics and may be different for the different fission modes**

**Averaged dissipation energy may be approximated by expression**

$$E_{diss} = \varepsilon A^{2/3}\left(\frac{Z^2}{A} - p\right)$$

**Neutron multiplicity** $M^{sdsc}$ **depends on the ratio** $$\frac{\hbar/\Gamma_n}{\tau_{sdsc}}$$

# Post-scission evaporation

The post-scission neutron multiplicity and spectra are formed as the result of neutron emission from the primary fission fragments which have distributions over mass, kinetic energy, excitation energy, and spin.

In the center-of-mass frame

of the fissioning compound nucleus the double-differential

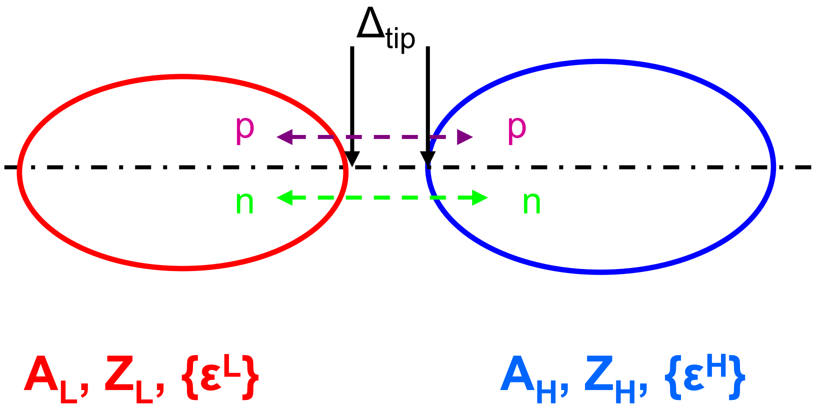
spectra can be presented in the simplified form

$$\frac{d^2M^{post}}{dE\,d\Omega} = \sum_{A_{sc}} \sum_{J_{sc}} \sum_{A} \sum_{Z} \int dE_{sc}^{ex} W_{sc}(E_{sc}^{ex}, A_{sc}, Z_{sc}, J_{sc}) *$$

$$\frac{M_n^F(A,Z)}{4\pi} \sqrt{\frac{E}{E_n^F}} W_F\left(E_n^F, A, Z, E_{kin}^F\right) Y(A,Z).$$

The kinetic and excitation energies and spins of fragments have been calculated in the framework of the fission scission point model.

# Scission point configuration



$$V_{pot} = V_{Coul} + V_{nucl} + E_{def}^{L}(\{\varepsilon^{L}\}) + E_{def}^{H}(\{\varepsilon^{H}\})$$

$$E_{def} = E_{def}^{LDM} + \delta U + \delta E_{pair}$$

**The temperature at the scission point is determined from the energy balance**

$$Q_f(A_{CN}^{sc}, Z_{CN}^{sc}, A, Z) + E_{CN}^{*sc} = V_{pot}^{sc} + E_{sc}^{*} + E_{kin}^{sc} + A_{rot}^{rel} L(l+1).$$

**Shell structure of the fission fragment at the scission point plays a decisive role in the fragment mass dependence of the mean neutron multiplicity** $M_n^F(A, Z, J)$.

At scission point the spin of the compound nucleus is divided between fission fragments and the relative motion degree of freedom according to the relation

$$\overrightarrow{J_{CN}} = \overrightarrow{I_H} + \overrightarrow{I_L} + \vec{L} \qquad \underline{K_{CN} = K_H + K_L}$$

Kinetic energy of the fragments is a sum of Coulomb interaction energy, kinetic energy at scission point, and rotational energy

$$E_{kin} = V_{Coul} + A_{rot}^{rel} L(L+1) + E_{kin}^{sc}$$

Thermal energy $E_{sc}^{*}$ is divided between fragments according to the thermal equilibrium condition

$$\frac{E_{sc}^{*H}}{E_{sc}^{*L}} = \frac{a^H}{a^L}, \qquad a^{L(H)}$$

- level density parameters.

Fission fragment spins are mainly defined by excitation energies at scission point

Total fragment excitation energy consists from the thermal, deformation and rotation energy at the scission point

$$E^{*}_{H(L)} = E^{*H(L)}_{sc} + E^{H(L)}_{def} + E^{H(L)}_{rot}$$

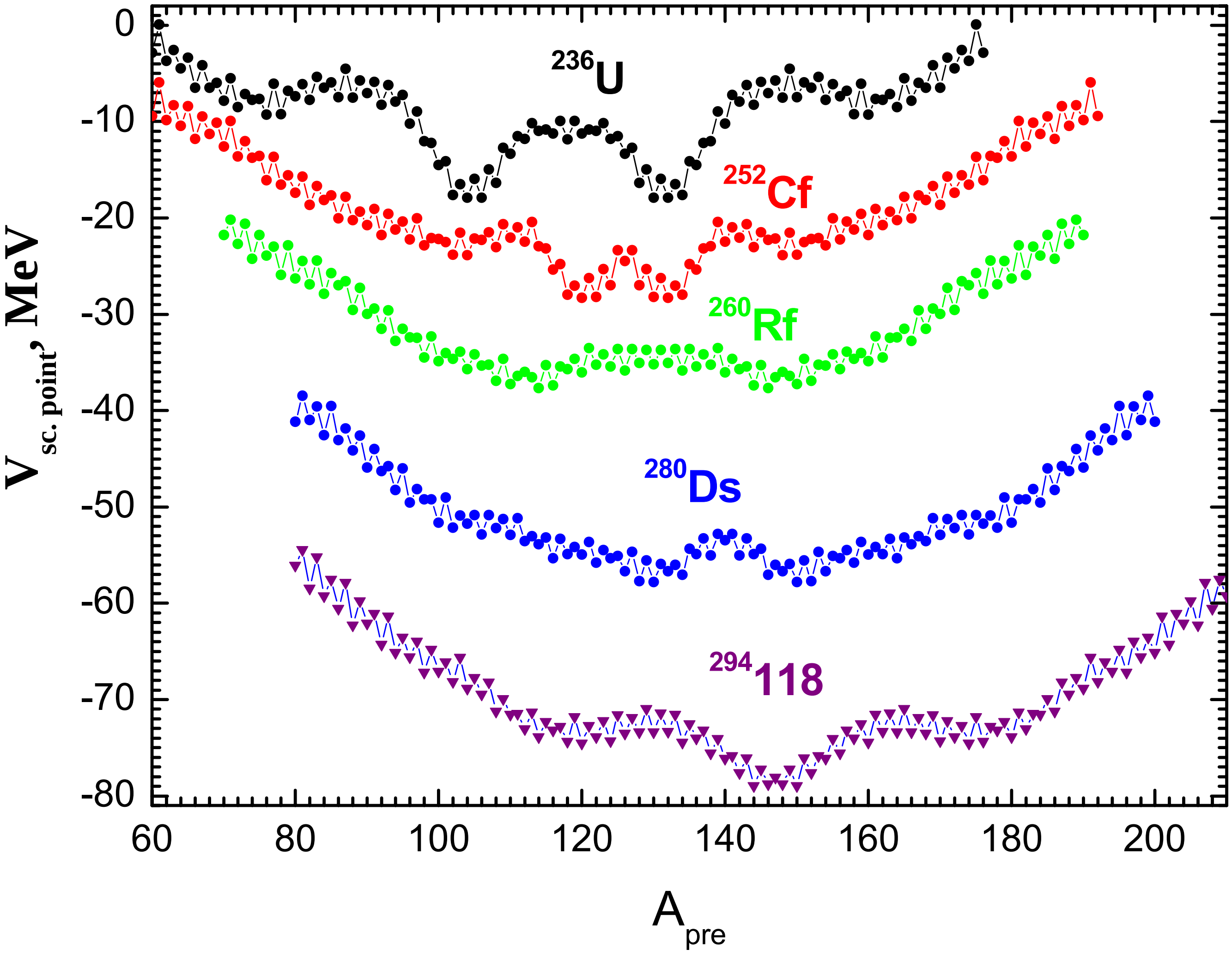
Total fission fragment kinetic energy is equal to the sum of the Coulomb interaction energy and of the fragment kinetic energy at the scission point

$$TKE = V_{Coul} + E^{sc}_{kin}.$$

The fragment kinetic energy at the scission point is supposed to be equal approximately 8 - 10 MeV.

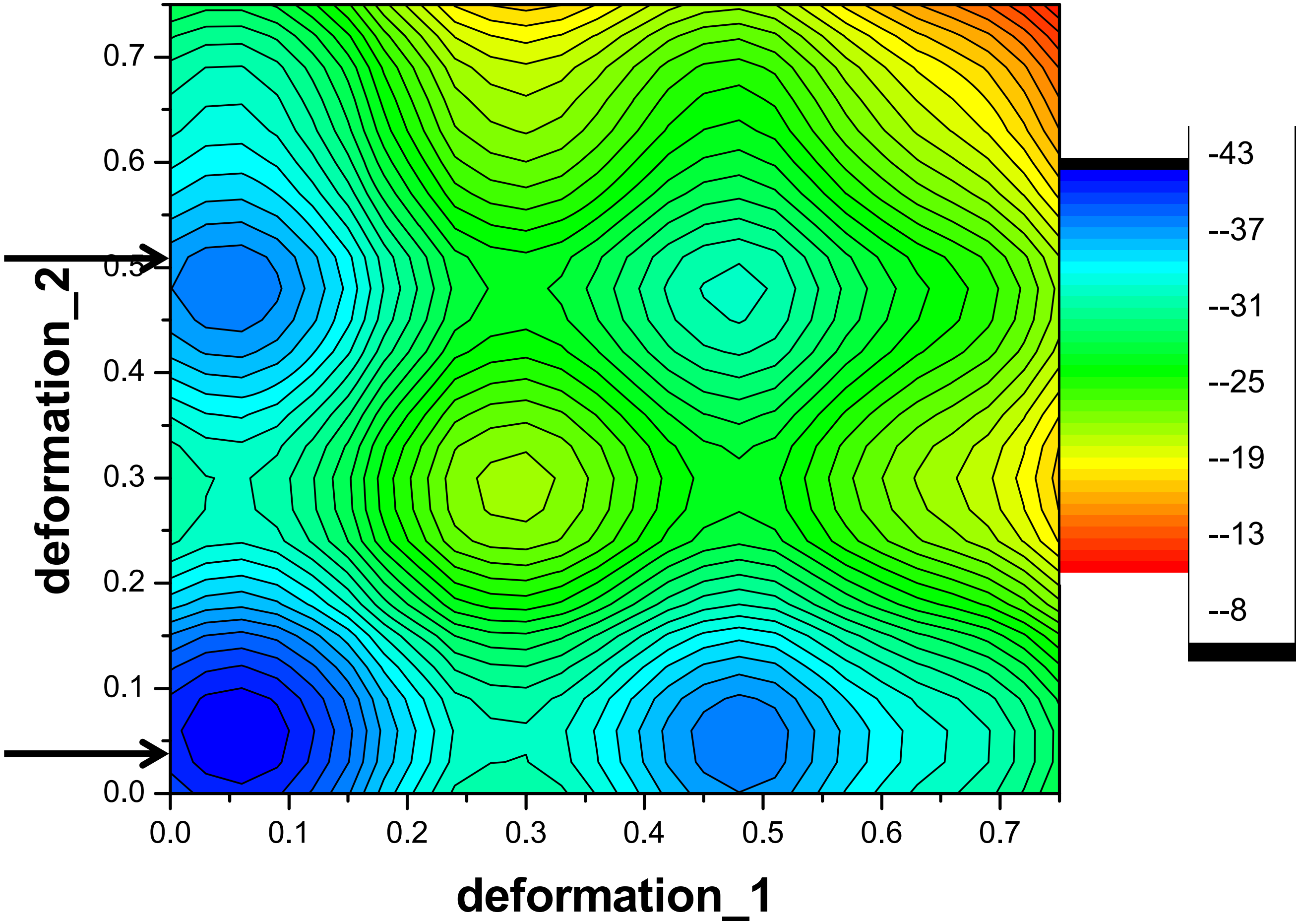
The time of the fragment acceleration up to 95 per cent of TKE is order of $10^{-20}$ c, what is much less than the fragment thermalization time and characteristic time of neutron emission from fragment at low energy fission. Therefore neutrons evaporate practically from the fission fragment moving with full TKE. Corresponding corrections can be included in the model.

# Potential energy at the scission point



# POTENTIAL ENERGY SURFACE AT THE SCISSION POINT

$^{264}\mathrm{Fm} \longrightarrow {}^{134}\mathrm{Sn} + {}^{134}\mathrm{Sn}$



**Stretched mode**

**Compact mode**

- **Saddle and bifurcation points and valleys on the potential-energy surface of fissioning nucleus determine the properties of fission modes**

**Smoothed primary mass distribution is formed by 5 fission modes:**

$$\tilde{Y}_{pre}(A)=C_{SY}Y_{SY}(A)+C_{SI}Y_{SI}(A)+C_{SII}Y_{SII}(A)+C_{SA1}Y_{SA1}(A)+C_{SA2}Y_{SA2}(A$$

Each asymmetric component is influenced by corresponding nuclear shells:

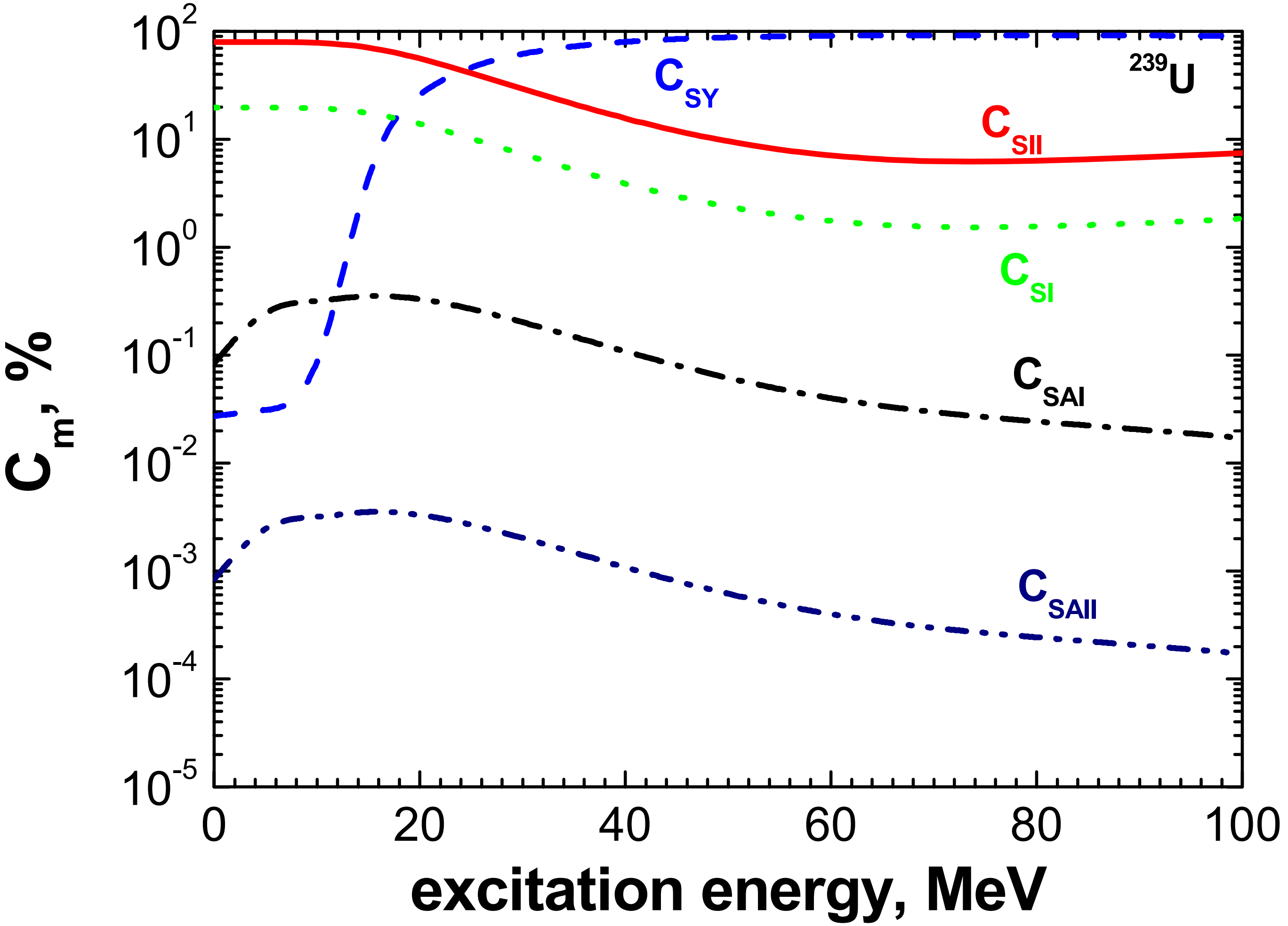
$Y_{SI}$ is defined by $^{132}$Sn shells : Z = 50 , N = 82

$Y_{SII}$ is defined by deformed shelll : N = 86 – 90

Superasymmetric $Y_{SA1}$ $Y_{SA2}$ modes are defined

by splitted $^{78}$Ni shells : Z = 28 , N = 50

# Fission mode weights as function of the excitation energy for $^{239}$U compound nucleus



# Primary isobaric charge distribution parametriztion

$$P_{pre}(Z/A) = \widetilde{P}_{pre}(Z/A)F_{oe}(Z)$$

$$\widetilde{P}_{pre}(Z/A) = \frac{1}{\sigma_Z(A)\sqrt{2\pi}}\exp\left\{-\frac{(Z-\overline{Z}(A))^2}{2\sigma_Z^2(A)}\right\}$$

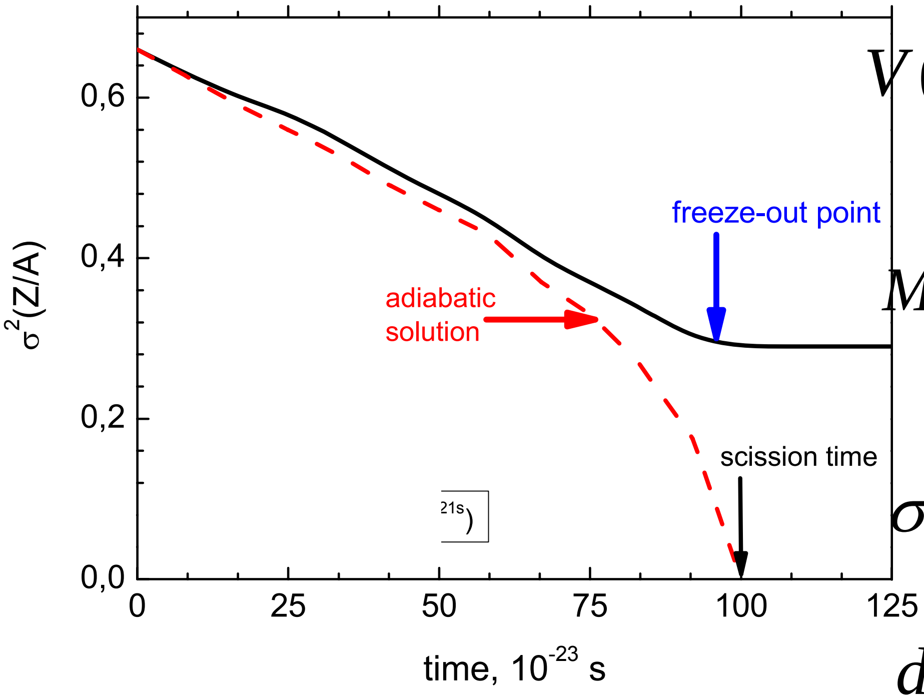
$$F_{oe}(Z) \propto \exp((\Pi_Z^H + \Pi_Z^L)\delta_Z(A_c, Z_c, E_c))$$

$$\delta_Z(A_c, Z_c, E_c) = \frac{\delta_Z(A_c, Z_c, 0)}{1+\exp((E_c - 10)/2)}, \qquad \Pi_Z^{H(L)} = \begin{cases} +1 & if \quad Z \quad is \;\; even \\ -1 & if \quad Z \quad is \;\; odd \end{cases}$$

$$\delta_Z(A_c, Z_c, 0) = \begin{cases} 1 - 0.1(Z_c^2/A_c - 35.22)^2, & Z_c^2/A_c > 35.22 \\ 1, & Z_c^2/A_c \le 35.22 \\ 0, & \delta_Z < 0. \end{cases}$$

# • Frozen quantal fluctuatuations in the charge equlibration mode

## Time evolution of isobaric width in the harmonic approximation

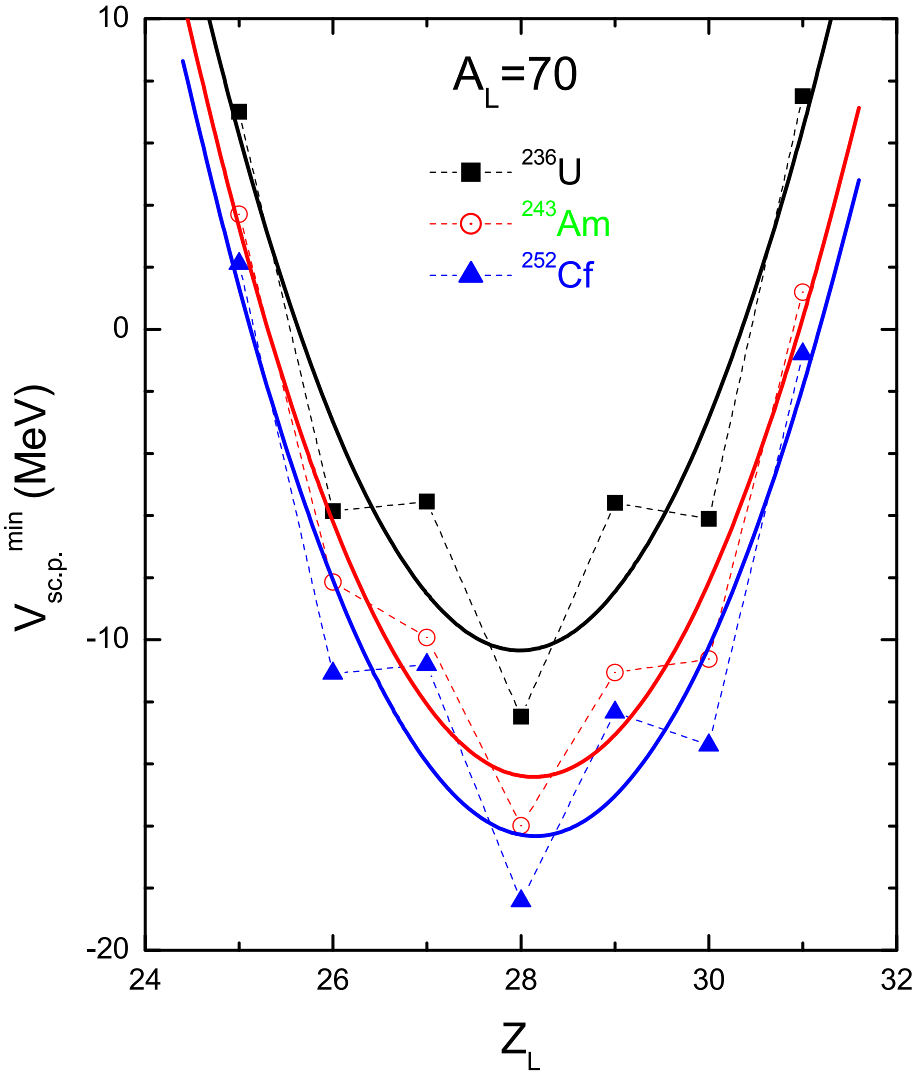


$$V(Z) = V(\bar{Z}) + \tfrac{1}{2} C_{ZZ} (Z - \bar{Z})^2$$

$$M_{ZZ} = \frac{16}{9} r_0^3 m \frac{A_c^2}{Z_c N_c} \frac{L_{neck} + 2r_{neck}}{r_{neck}^2}$$

$$\sigma_Z^2(A) = \frac{1}{2} \frac{\hbar}{\sqrt{M_{ZZ} C_{ZZ}}} = \frac{1}{2} \frac{E_{GDR}^{\|}}{C_{ZZ}}$$

$$\frac{dr_{neck}}{dt} \approx 2 \, {fm}/{10^{-21} s}$$



$$C_{ZZ}=\frac{\partial^2\widetilde{V}_{pot}^{\min}(A;Z)}{\partial^2 Z}\bigg|_{Z=\overline{Z}}$$

$$V(Z) = V(\overline{Z}) + \tfrac{1}{2} C_{ZZ} (Z - \overline{Z})^2$$

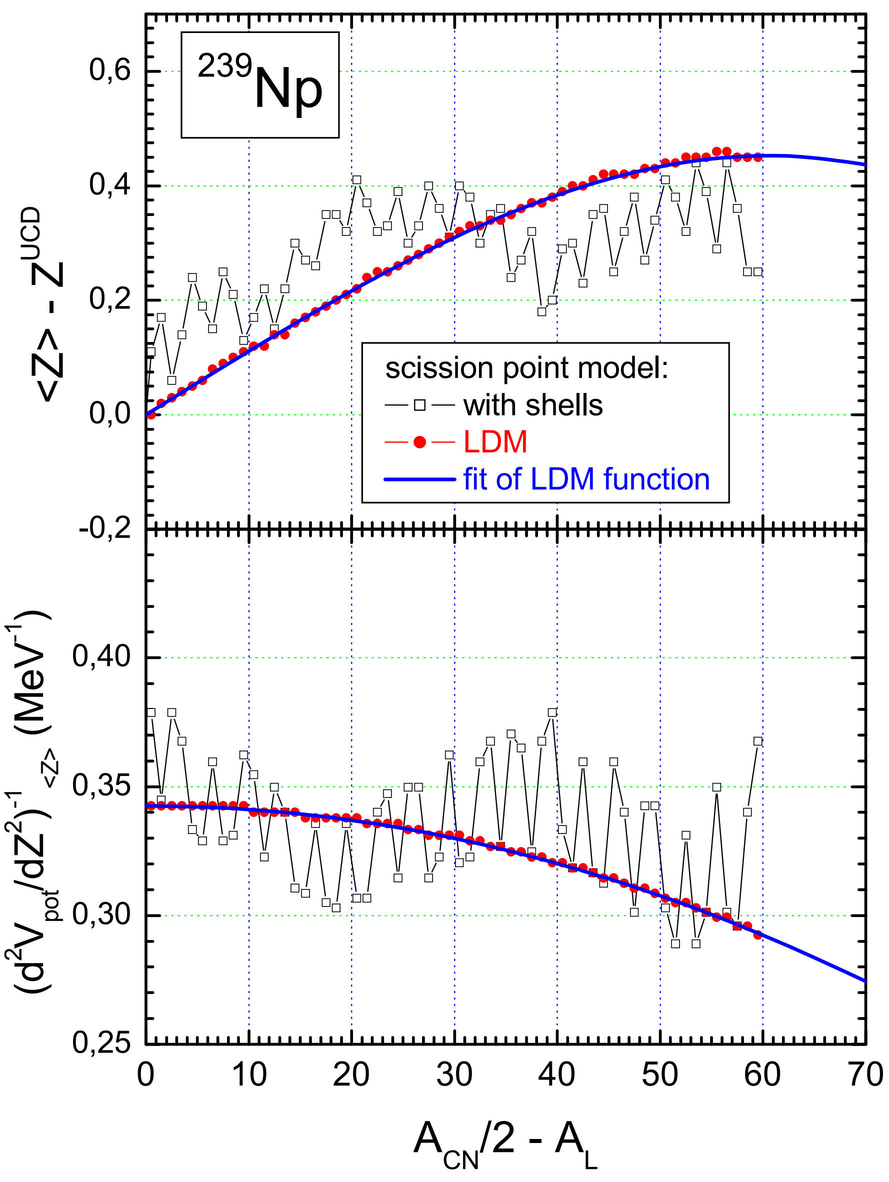
$$M_{ZZ} = \frac{16}{9} r_0^3 m \frac{A_c^2}{Z_c N_c} \frac{L + 2r_{neck}}{r_{neck}^2}$$

$$\Psi_n = \left( \frac{1}{\sigma_{ZZ} \sqrt{\pi}\, 2^n n!} \right)^{\frac{1}{2}} H_n \left( \frac{Z - \overline{Z}}{\sigma_{ZZ}} \right) \exp\left\{ - (Z - \overline{Z})^2 \Big/ 2\sigma_{ZZ}^2 \right\}$$

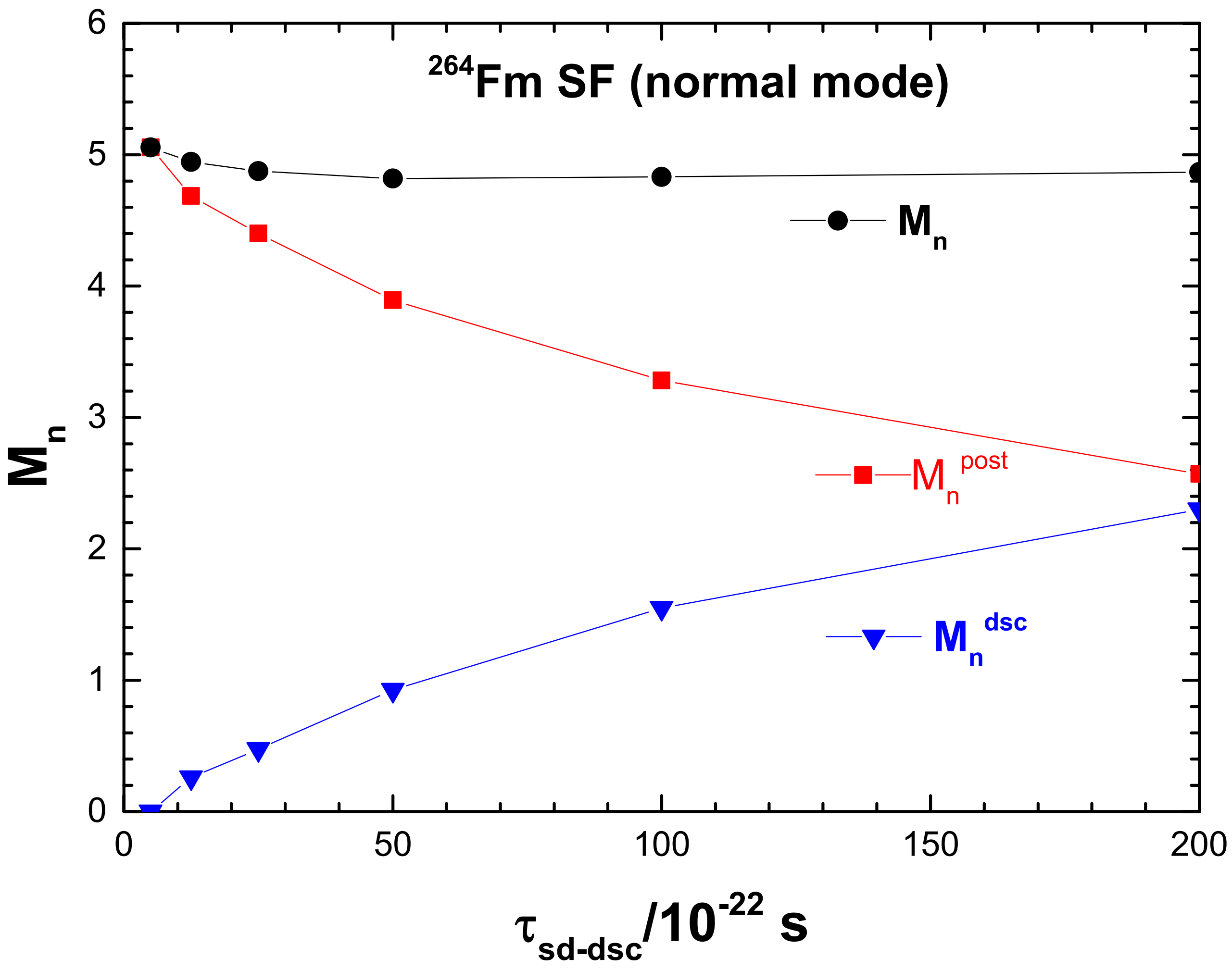
$$E_n = (n + \tfrac{1}{2}) \hbar \omega_Z , \qquad \hbar \omega_Z = \hbar \sqrt{\frac{C_{ZZ}}{M_{ZZ}}}$$

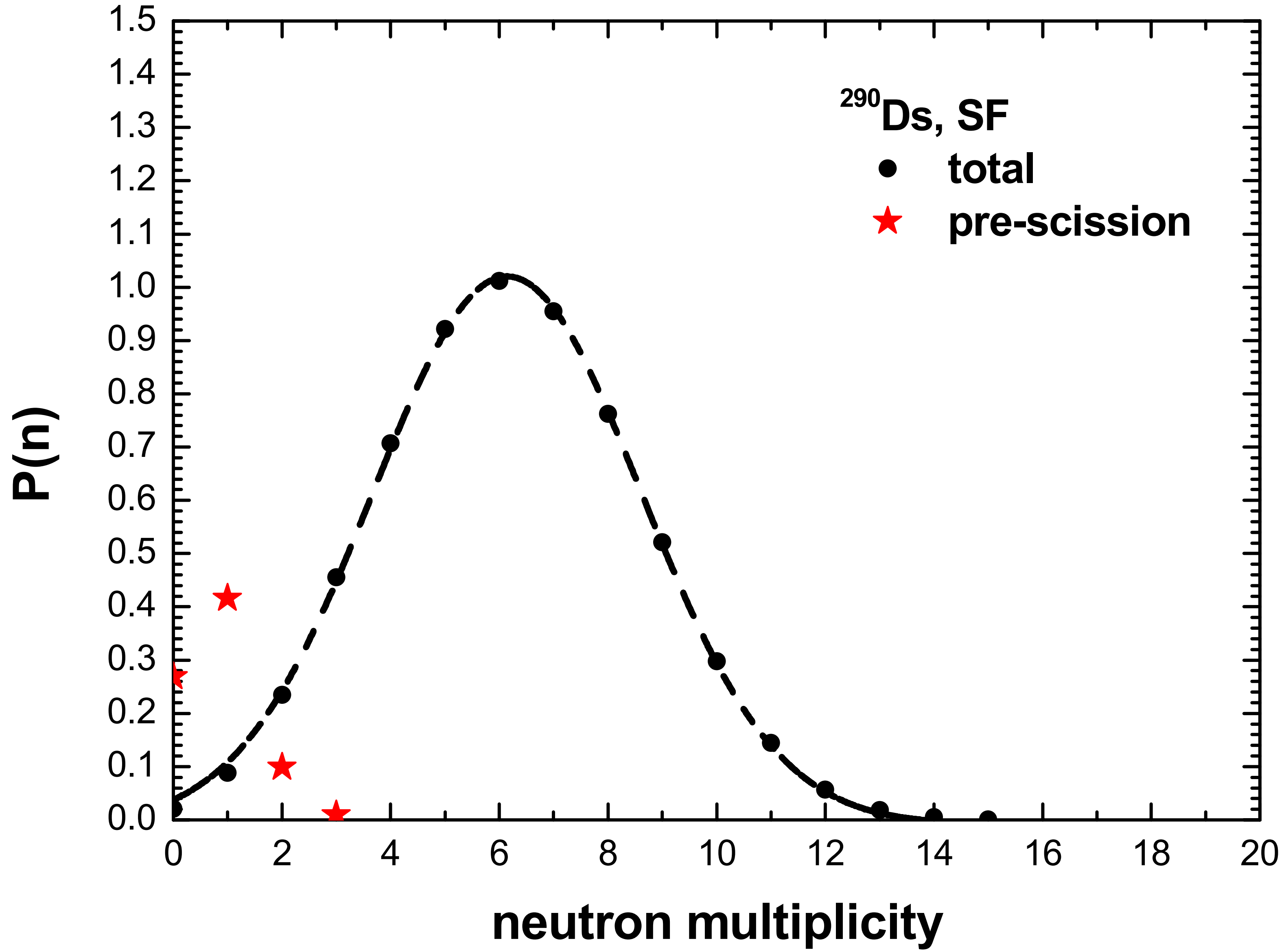
$$\widetilde{P}(Z/A) \propto \left| \Psi_0 \right|^2 = \frac{1}{\sigma_{ZZ} \sqrt{\pi}} \exp\left\{ - (Z - \overline{Z})^2 \Big/ \sigma_{ZZ}^2 \right\}$$

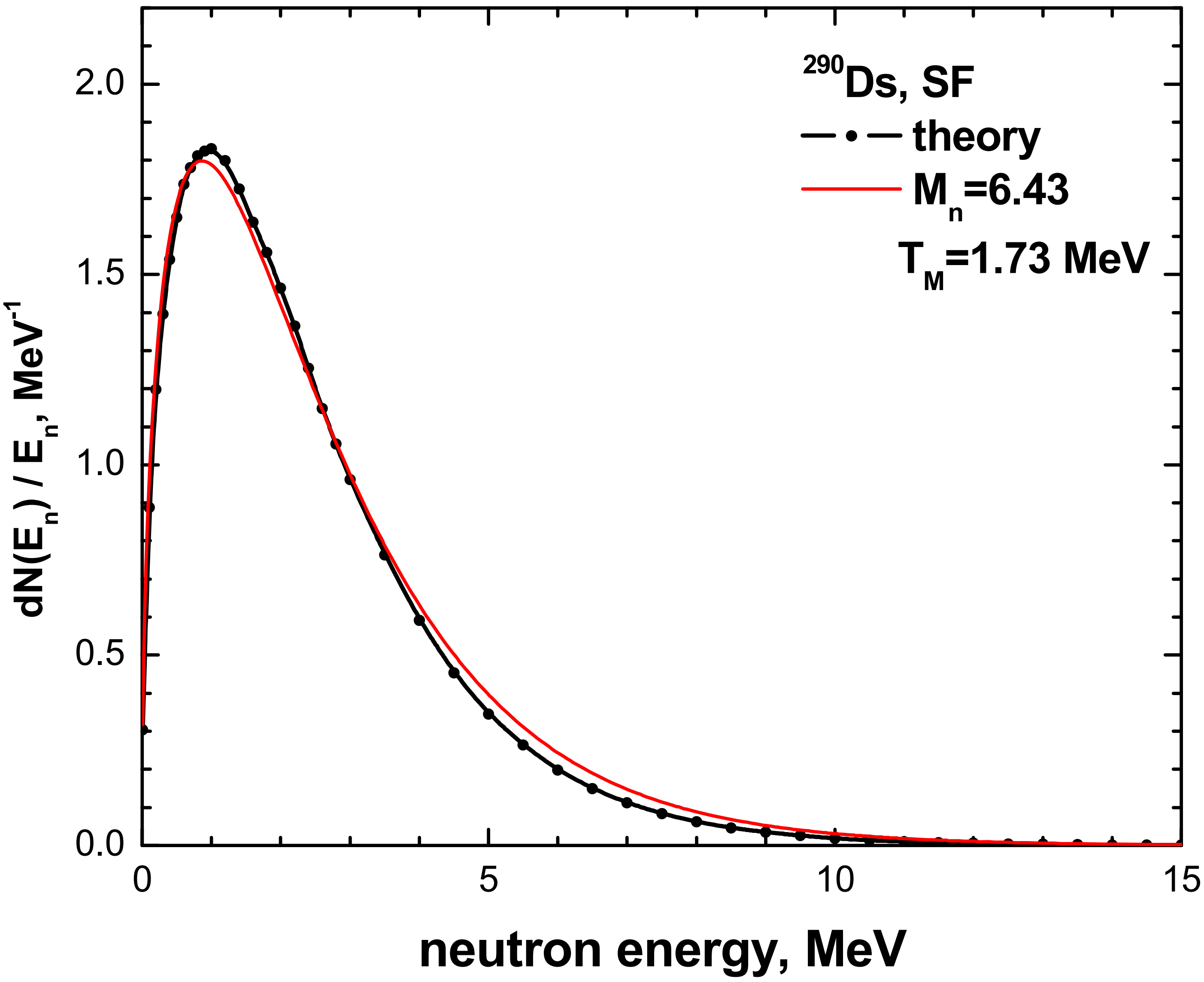
$$\sigma_Z^2(A,0) = \frac{1}{2} \frac{\hbar}{\sqrt{M_{ZZ} C_{ZZ}(A,0)}}$$


$^{239}$Np
$\langle Z \rangle - Z^{UCD}$
0,6
0,4
0,2
0,0
-0,2
scission point model:
with shells
LDM
fit of LDM function
$(d^2V_{pot}/dZ^2)^{-1}_{\langle Z \rangle}$ (MeV$^{-1}$)
0,40
0,35
0,30
0,25
0
10
20
30
40
50
60
70
$A_{CN}/2 - A_L$

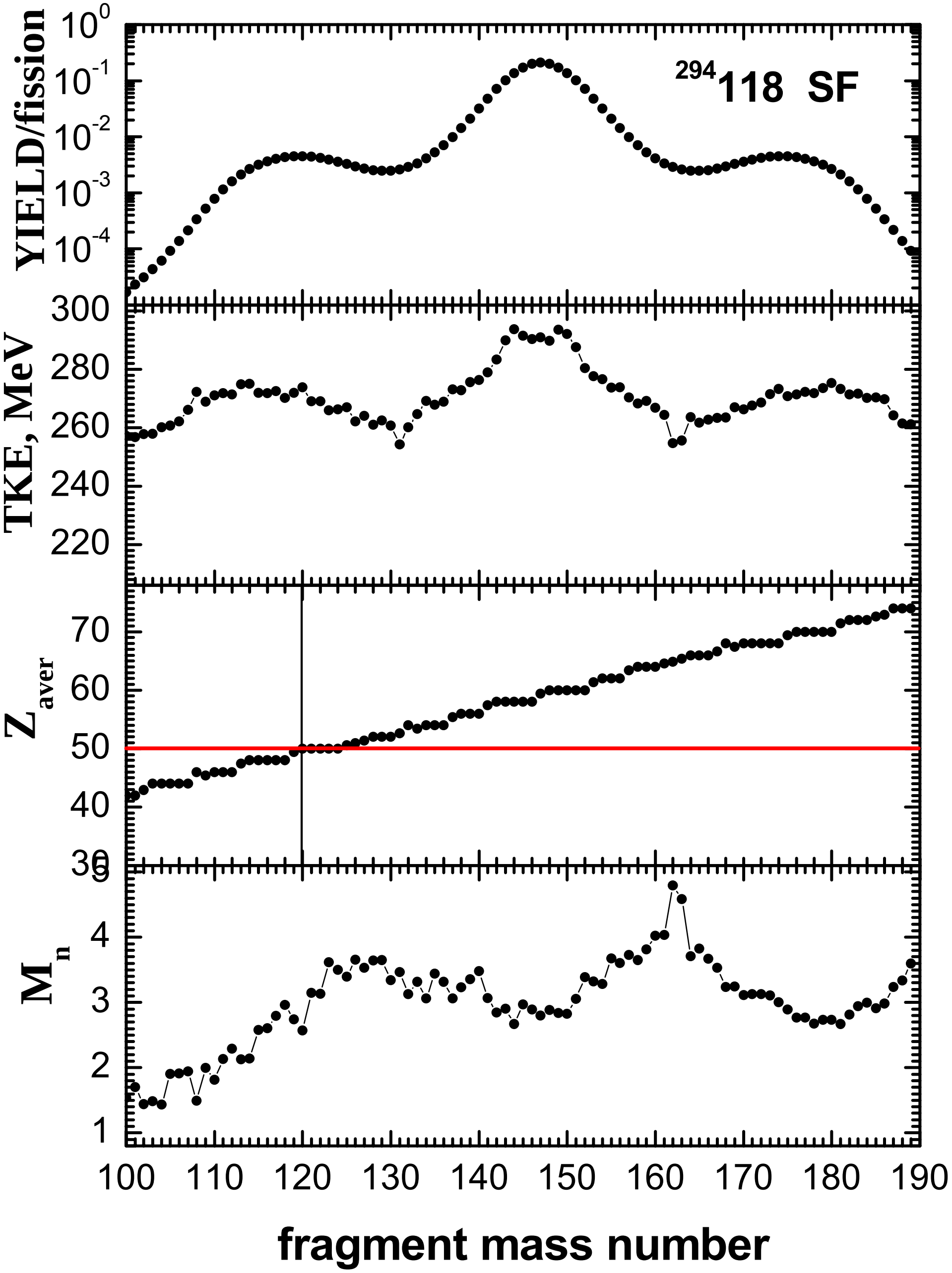
# Dependences of neutron multiplicities on the saddle-to-scission time.

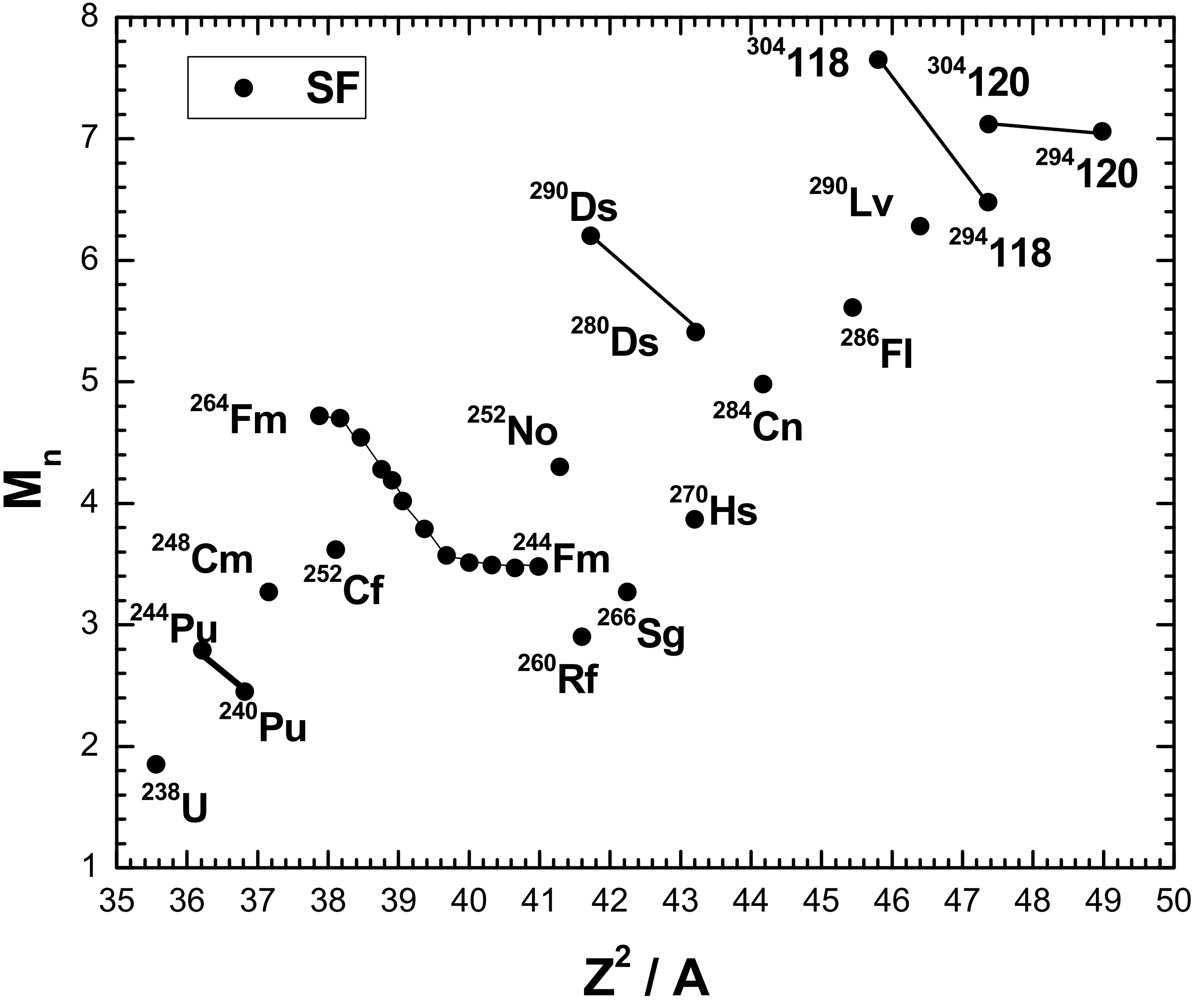



$^{290}$Ds, SF
● total
★ pre-scission
P(n)
neutron multiplicity
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
12
14
16
18
20

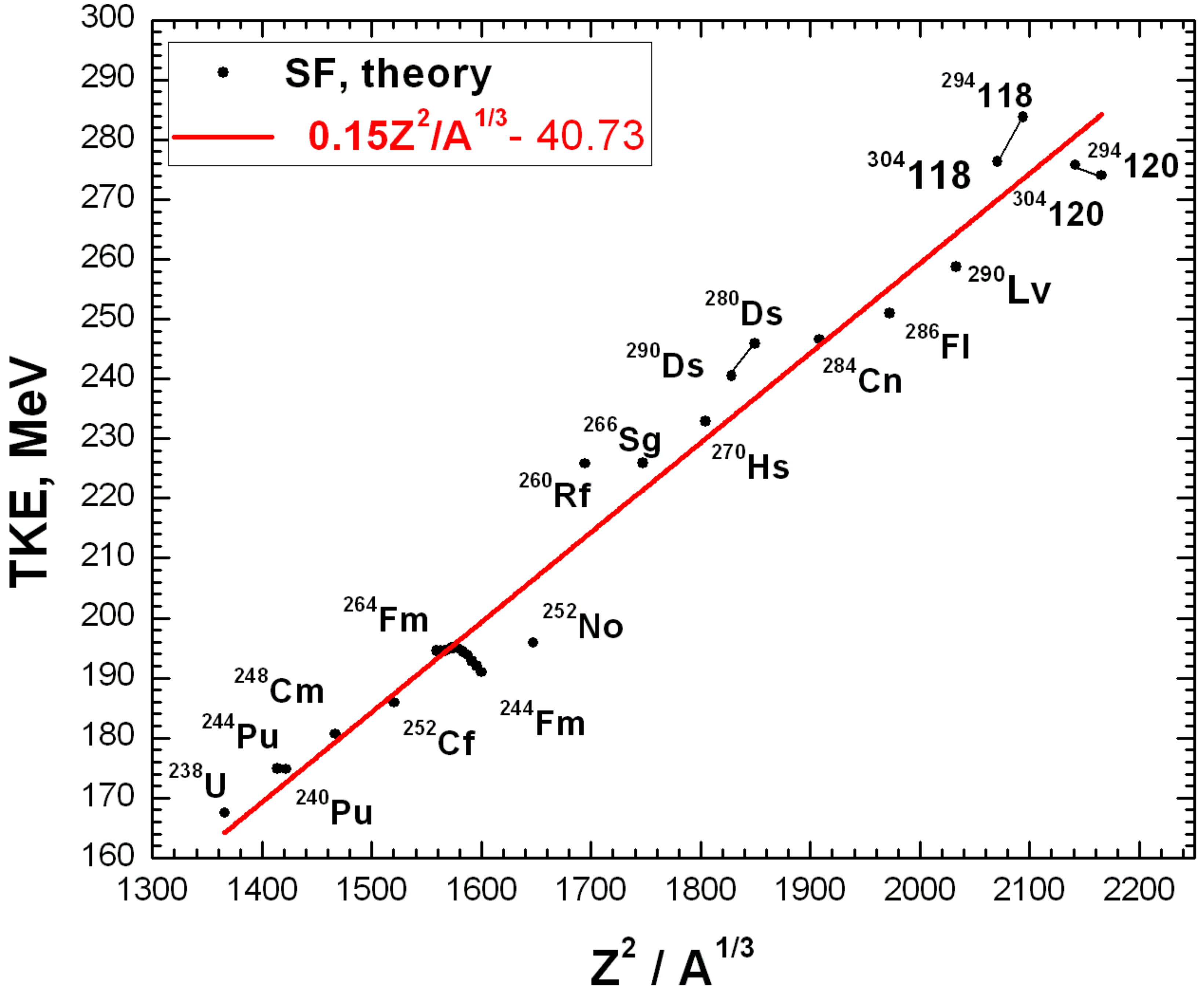


$^{290}$Ds, SF
theory
$M_n$=6.43
$T_M$=1.73 MeV
dN($E_n$) / $E_n$, MeV$^{-1}$
neutron energy, MeV
0.0
0.5
1.0
1.5
2.0
0
5
10
15


$^{294}$118 SF
YIELD/fission
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
TKE, MeV
300
280
260
240
220
$Z_{aver}$
70
60
50
40
30
$M_n$
5
4
3
2
1
100
110
120
130
140
150
160
170
180
190
fragment mass number



SF
M_n
Z^2 / A
1
2
3
4
5
6
7
8
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
304 118
304 120
294 120
290 Ds
290 Lv
294 118
280 Ds
286 Fl
264 Fm
252 No
284 Cn
270 Hs
248 Cm
252 Cf
244 Fm
244 Pu
266 Sg
260 Rf
240 Pu
238 U


SF, theory
0.15Z²/A^{1/3} - 40.73
TKE, MeV
Z² / A^{1/3}
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
294 118
304 118
294 120
304 120
290 Lv
286 Fl
284 Cn
280 Ds
290 Ds
270 Hs
266 Sg
260 Rf
252 No
264 Fm
244 Fm
252 Cf
248 Cm
244 Pu
240 Pu
238 U

# Conclusions

**This model may be useful for:**

- **fission dynamics studies with neutron probe**
- **predictions of fission neutron characteristics of SHE**
- **evaluation of prompt fission neutron data (GEN-IV).**

## Problems:

- **Scission neutrons.**
- **Fragment excitation energy partition at scission point.**
- **Dispersion of the excitation energy.**
- **Fragment spin generation mechanism.**
- **Nuclear friction.**

Thank you for your attention!