PARAMETERIZATION OF NEUTRON YIELDS FOR FIRST CHANCE PHOTOFISSION FRAGMENTS

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A recent analysis of experimental data on neutron yields from fragments of thermal neutron fission of ^{233}U, ^{235}U, ^{239}Pu and spontaneous fission of ^{252}Cf showed that for a detailed account of "saw-tooth" particularity of dependence of fission neutron yield from a mass, an efficient tool is the value of model function *R(A)*, introduced by Wahl [1], which is defined as

$$R\left(A\right) = v_{L,H}(A) / \bar{v}(A), \qquad (1)$$

where $v_{L,H}(A)$ - prompt neutron yield of light and heavy fragment mass respectively, $\bar{v}(A)$ - total neutron yield, *A* - fragment mass and consists of several segments to reflect the observed features, depending on the complexity of the experimental behavior of *R(A)*.

Therefore, the whole range of fragments mass was divided for 2 x 2 segments. "Experimental" values of *R(A)* (with errors) can be determined using formula (1) from experimental values of $v_{L,H}(A)$ and $\bar{v}(A)$

Model function *R(A)* is chosen as a linear function for each segment for light and heavy fragments:

$$R_i^L\left(A\right) = a_i^L + b_i^L\left(A - A_L\right), \quad (2) \qquad R_i^H\left(A\right) = 1 - R_i^L(A - A_H) \quad (3)$$

respectively, i - number of the segment a_i^L, b_i^L, A_L - parameters, $A_H = A_f - A_L$, A_f - mass of compound nucleus.

To parameterize neutron emission and identify general prediction patterns we will use the results of *v(A)* calculation for the photofission ^{235}U and ^{238}U at bremsstrahlung boundary energies of 12 ÷ 30 MeV (E* = 9.7-14.1 MeV) [2].

Here we simulate the behavior of neutrons from photofission of ^{235}U and ^{238}U actinides depending on the energy and nucleon composition in the giant dipole resonance energy range. As a result, we get the following picture (Fig. 1).

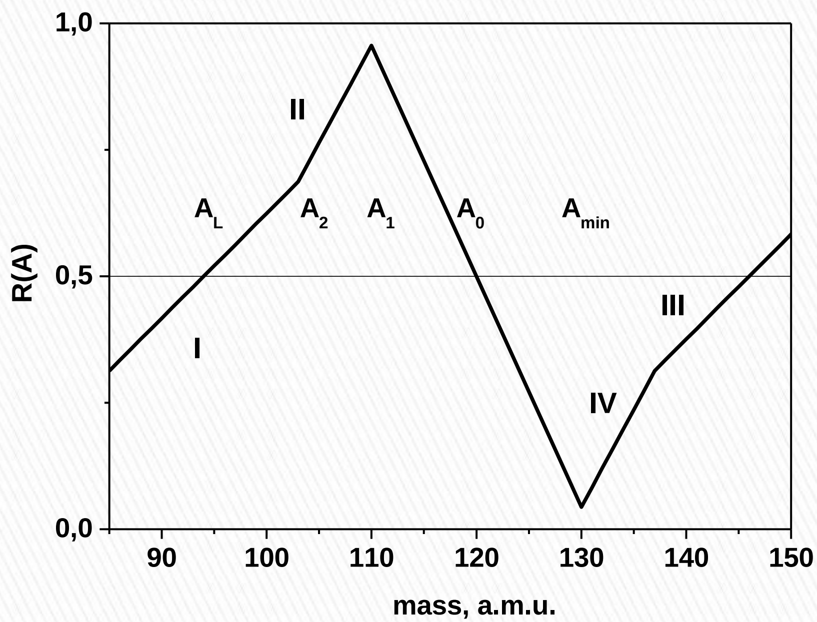


Fig. 1. An example of model function *R(A)* function. The segments I-II and III-IV correspond to our parameterization.

Let us consider some features of *R(A)* function. At the point of symmetric fission $A_0 = A_F/2$; $R(A_0) = 0.5$ and $R(A_L) = 0.5$, where A_L is determined from fitting.

Kink points A_{min}, A_1 and A_2 are chosen from physical considerations and experiment: $A_{min} = 130$ corresponds to the mass of nearly magic nucleus fragment associated with spherical shells $Z = 50$ and $N = 82$, where fission neutron yield is minimal. Then maximum neutron fission yield for light fragments will match point A_1, which is symmetrical to A_{min} relative to A_0,

$$A_1 = 2A_0 - A_{min} \quad (4)$$

The kink point A_2 corresponds to the average fragment mass of light fragments, $A_2 = \langle A_L \rangle = A_F - \langle A_H \rangle$ (5)
and related to the intermediate deformation of the fissioning nuclide.

The parameters a_i, b_i and A_L are determined by calculating the function *R(A)* for 4 segments I - IV (see Fig.1). The number of free parameters can be reduced using the conditions

$$a_1 = R(A_L) = 0.5, \quad (6) \qquad a_2 = a_1 + (b_1 - b_2)(A_2 - A_L). \quad (7)$$

The dependence of b_i slopes on excitation energy is noticed on the Fig. 1 for R(A), so we have chosen $b_i = x_i + yE_\gamma$. The value of A_L varies significantly with changes of actinide mass, at least for neutron-induced actinide fission.

Therefore, we chose a similar parameterization [3]:

$$A_L = 90 + B \times A_0 \,. \qquad (8)$$

B=1.45. To take even-even and even-odd effect into account we introduce the factor

$$P\left(N_F\right) = 2 - c\left[(-1)^{N_F} - (-1)^{Z_F}\right], \quad N_F = A_F - Z_F \,. \qquad (9)$$

As a result *b_i* slopes will look as

$$b_i = (x_i + yE_\gamma)P(N_F), \qquad i = 1,2\,. \qquad (10)$$

We calculate the function *R(A)* for the photofission of actinides ^{235}U and ^{238}U according to (1) - (10) by fitting of 356 "experimental" values of *R(A)*.

Using the least squares method the five parameters *x_1, x_2, c, b* and *y* were defined to satisfactorily describe the characteristic "saw-tooth" behavior of prompt neutrons from the photofission of actinides with A = 235 a.m.u. and A=238 a.m.u.

The results of *R(A)* calculation at the bremsstrahlung maximum energy 12 MeV are shown in Fig. 2.

Table 1. Calculated parameters of *R(A)* function.

Parameter	Value	Error
x_1	$1.66 \cdot 10^{-2}$	$0.35 \cdot 10^{-2}$
x_2	$1.08 \cdot 10^{-2}$	$0.29 \cdot 10^{-2}$
y	$-0.384 \cdot 10^{-3}$	$0.212 \cdot 10^{-3}$
c	-0.282	0.159
b	$1.26 \cdot 10^{-2}$	$0.52 \cdot 10^{-2}$

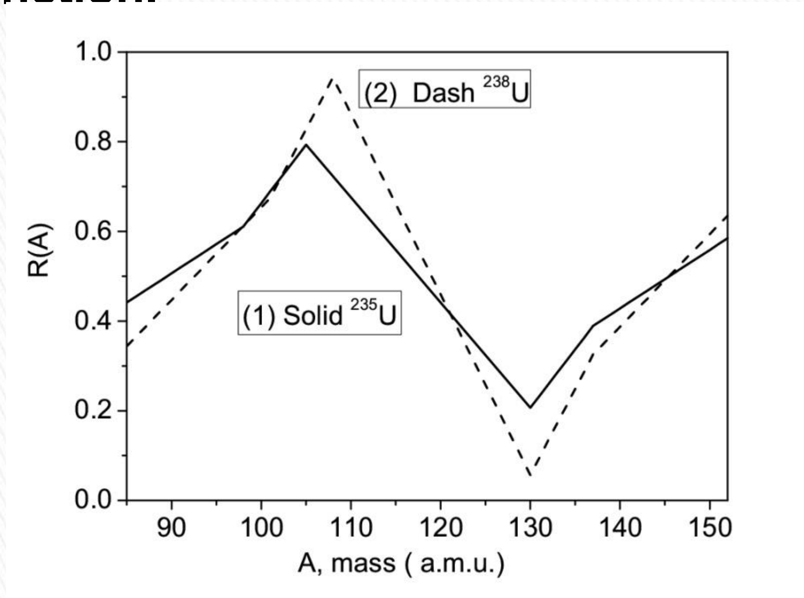


Fig. 2. The result of *R(A)* functions calculation for ^{235}U (1 Solid), ^{238}U (2 Dash) photofission at the bremsstrahlung maximum energy 12 MeV.

The curves for prompt neutrons yield $\nu_{L,H}(A)$ can be calculated with help (1), if the value of the prompt neutrons averaged number for photofission of the actinides is known.

Otherwise instead the experimental values of $\bar{\nu}(A)$ in (1) one may use the results of empirical calculations of $\bar{\nu}(A_F)$, presented in [4] and described below.

The initial formula has been chosen:

$$\bar{\nu}(A_F, Z_F, E_\gamma) = \bar{\nu}_0(A_F, Z_F) + a(A_F, Z_F)\cdot(E_\gamma - E_s), \qquad \textbf{(11)}$$

where the slope $\bar{\nu}_0(A_F, Z_F)$ **and the intercept** $a(A_F, Z_F)$ **are :**

$$\bar{\nu}_0(A_F, Z_F) = C_1 + C_2\,(Z_F - Z_0) + C_3\,(A_F - A_0) + C_4\,P(A_F, Z_F), \qquad (12)$$

$$a(A_F, Z_F) = C_5 + C_6(Z_F - Z_0) + C_7(A_F - A_0) + C_8 P(A_F, Z_F), \qquad (13)$$

where $P(A, Z)$ **– parity factor,** E_s **– nucleon separation energy.**

Coefficients C_i **were calculated by the least-square method. The final formula for calculating the averaged number of prompt neutrons for photofission of actinides (fig 2a) was:**

$$\bar{\nu}_0(A_F, Z_F) = (1{,}97 \pm 0{,}05) + (0{,}165 \pm 0{,}028)(Z_F - 90) +$$
$$+ (0{,}0341 \pm 0{,}0093)\,(A_F - 232) - (0{,}0853 \pm 0{,}0094)\cdot P(A_F, Z_F) \qquad (14)$$

$$a(A_F, Z_F) = (0{,}0963 \pm 0{,}75\cdot 10^{-2}) + (0{,}0371 \pm 0{,}43\cdot 10^{-2})\,(Z_F - 90) -$$
$$- (0{,}566 \pm 0{,}138)\cdot 10^{-2}\cdot(A_F - 232) \qquad (15)$$

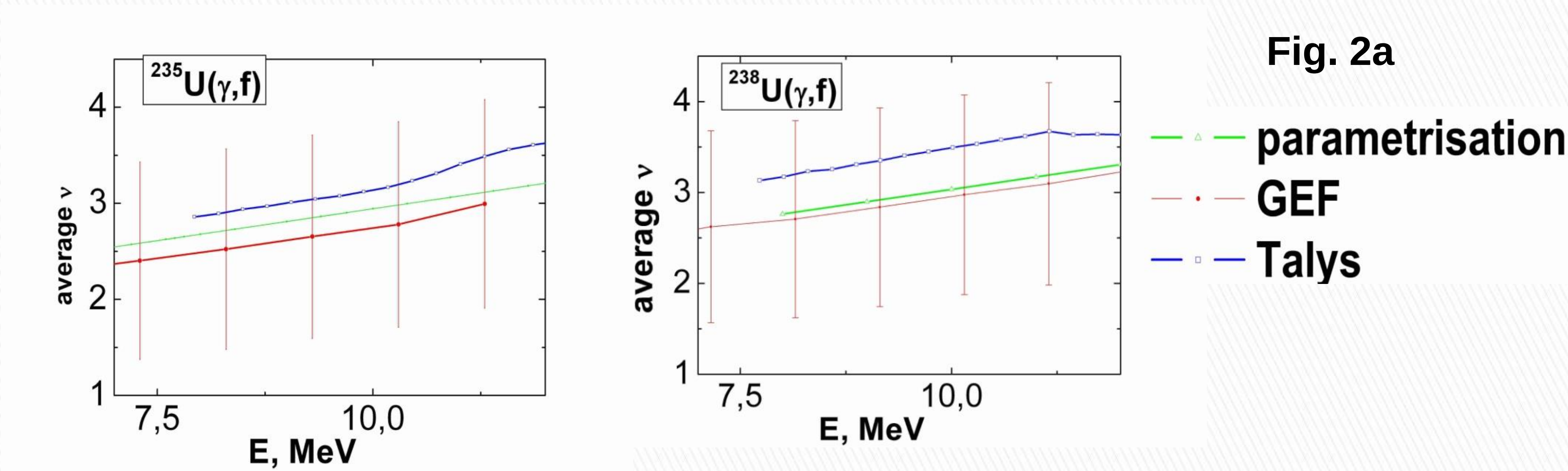


Fig. 2a

The results of the $v_{L,H}(A)$ calculation using (1)-(11), (14), (15) and Table 1 are shown in Fig. 2. and Fig. 3 (solid curve).

As can be seen from the figures the calculated values for prompt neutrons yield are everywhere within the errors.

For comparison we repeated our calculations, confining ourselves to two 2 x 1 segments in Fig. 3.

Both calculations are indistinguishable from the χ2 criterion, but we prefer the first variant of the approximation *v(A)*, as such, in which physical considerations are taken into account.

These observations allow to estimate the possible values of fission neutrons yield from light and heavy fragments with known total yields just through the mass distributions of fission fragments using the modified Terrell method [5].

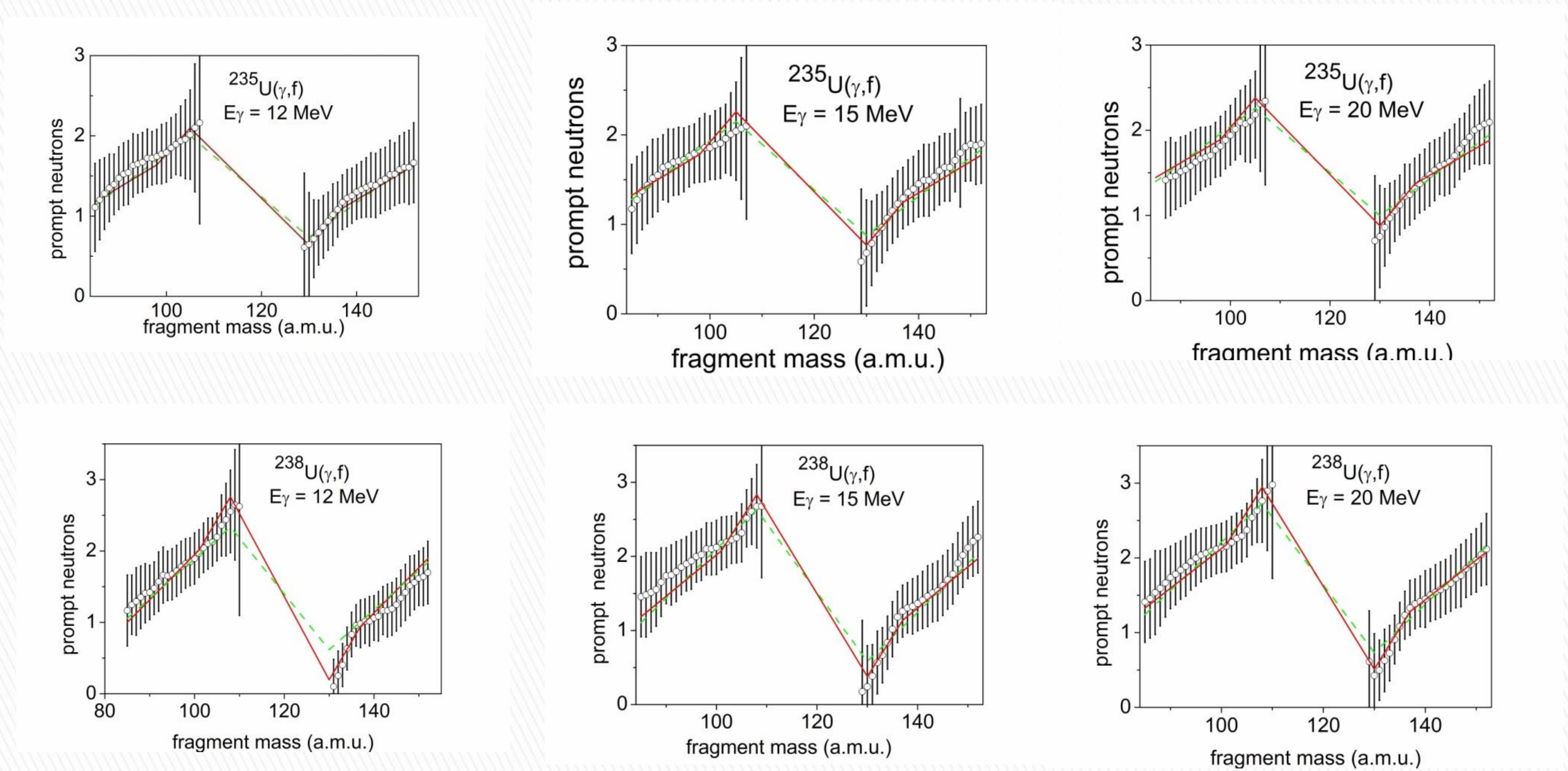


Fig. 3. - Results of 2x2-segmenti calculation of $v_{L,H}(A)$ (solid lines) of ^{235}U (left) and ^{238}U (right) photofission with bremsstrahlung maximum energy of 12, 15, 20 MeV. (Dashed lines correspond to 2x1-segmenti variant. Circles – points of $v_{L,H}(A)$ [2])

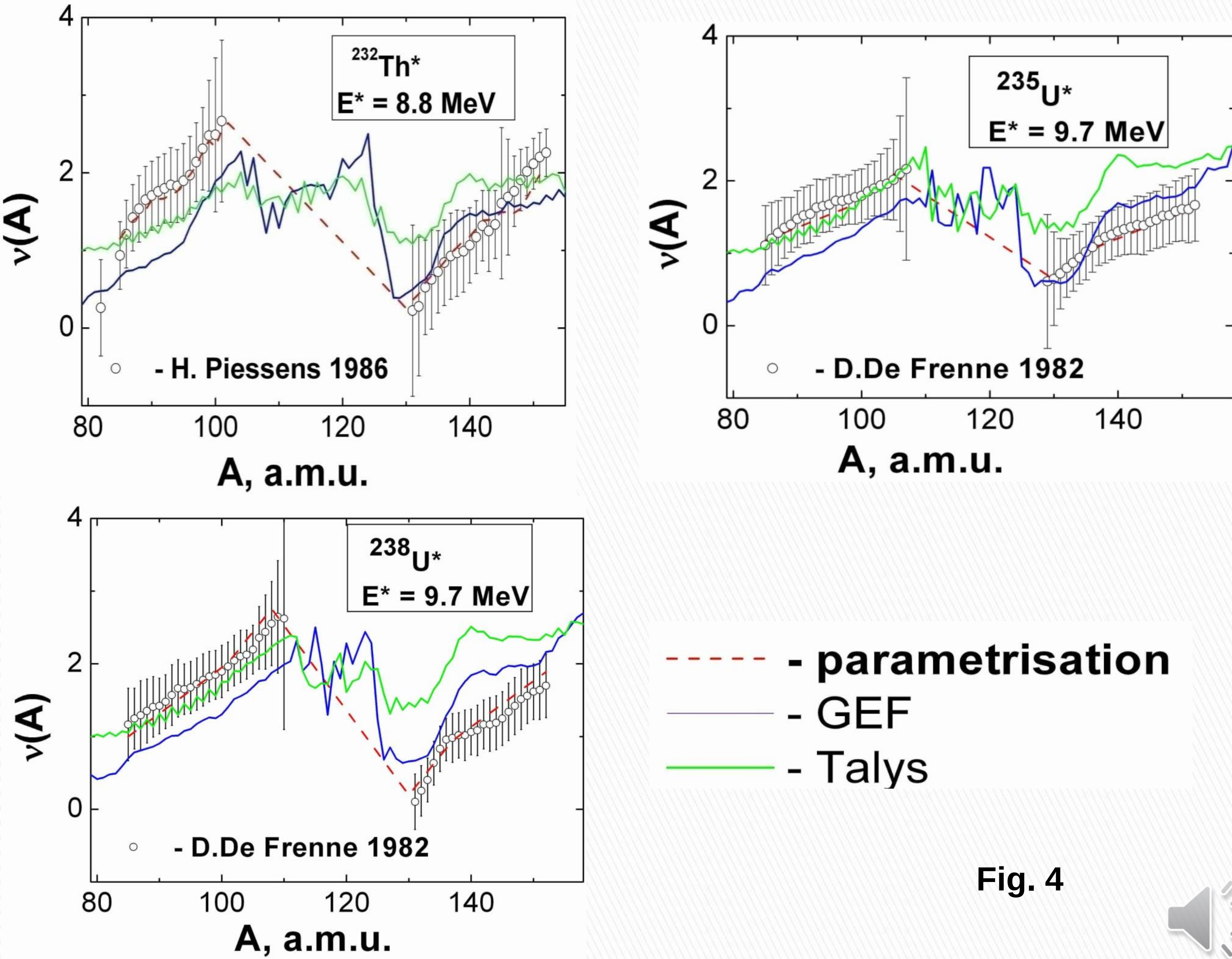
CONCLUSION:

With *R(A)* function parameterization, which fairly well reproduces the characteristic features of its behavior and parameterization of averaged number of prompt neutrons , we can calculate the expected values of prompt neutrons yield for arbitrary neighboring actinides, such as ^{237}Np or ^{239}Pu.

Thus, to determine the photofission yield for neutron yield on fragment mass *v(A)* of arbitrary actinides we need to know the value $\bar{\nu}(A)$, which is determined by the general empirical formulas (11), (14-15).

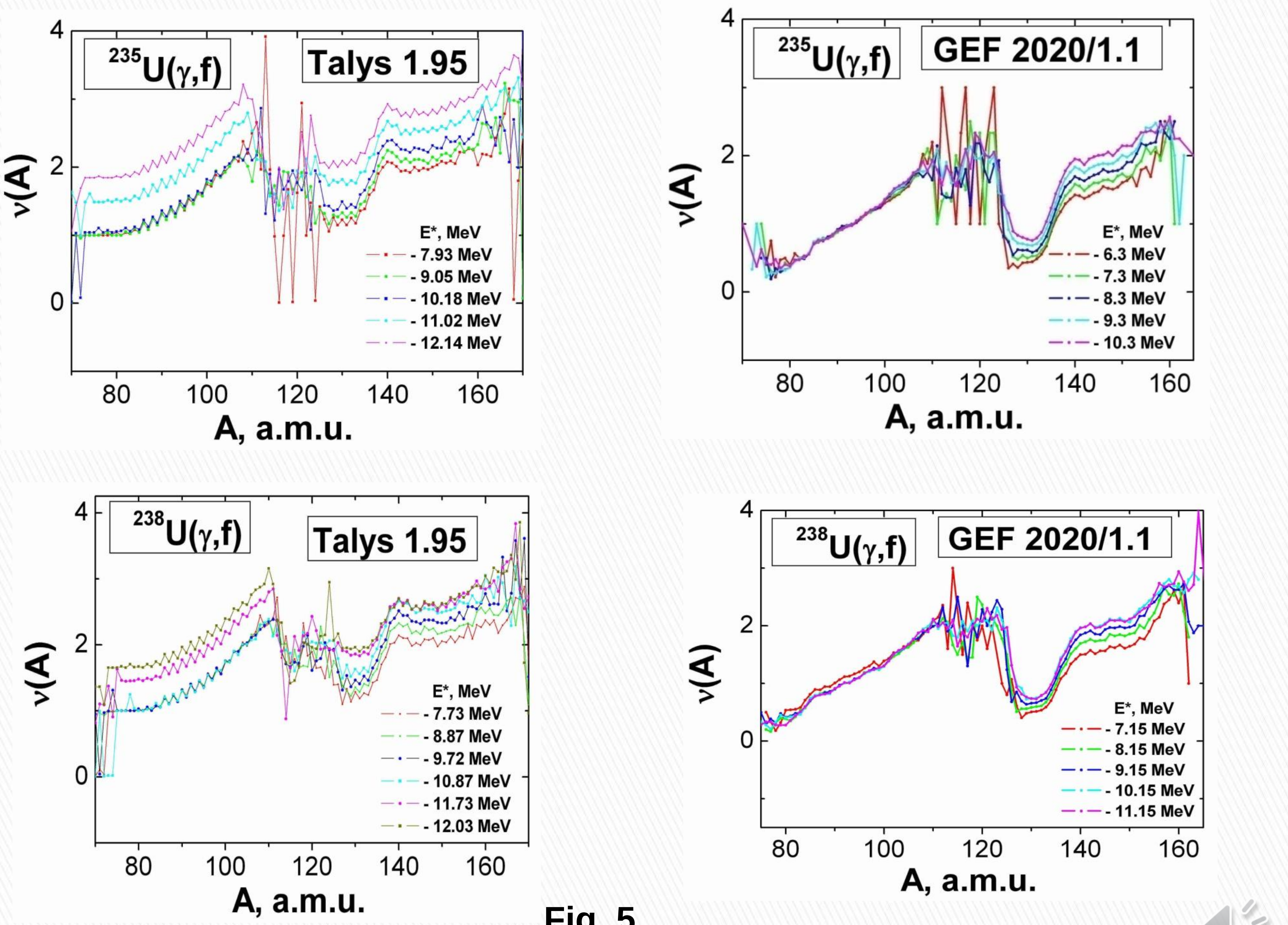
The resulting formulas of prompt neutron yield on fragment mass *v(A)* of photofission of actinide nuclei can be used as initial (seed) for solving the integral equations [5] in these processes.

The obtained results of the estimation of the dependence of the prompt neutron yields from light and heavy fragments for the first chance of actinide photofission are compared with the results of calculations (modeling) by the program codes GEF [6] and Talys1.9 [7] (Fig. 2a, 4, 5). Our calculations are in qualitative agreement with the results of modeling by GEF and Talys codes.



232Th*
E* = 8.8 MeV
- H. Piessens 1986
235U*
E* = 9.7 MeV
- D.De Frenne 1982
238U*
E* = 9.7 MeV
- D.De Frenne 1982
ν(A)
A, a.m.u.
4
2
0
80
100
120
140
- parametrisation
- GEF
- Talys

Fig. 4



^{235}U(γ,f)
Talys 1.95
ν(A)
A, a.m.u.
E*, MeV
- 7.93 MeV
- 9.05 MeV
- 10.18 MeV
- 11.02 MeV
- 12.14 MeV
^{235}U(γ,f)
GEF 2020/1.1
E*, MeV
- 6.3 MeV
- 7.3 MeV
- 8.3 MeV
- 9.3 MeV
- 10.3 MeV
^{238}U(γ,f)
Talys 1.95
E*, MeV
- 7.73 MeV
- 8.87 MeV
- 9.72 MeV
- 10.87 MeV
- 11.73 MeV
- 12.03 MeV
^{238}U(γ,f)
GEF 2020/1.1
E*, MeV
- 7.15 MeV
- 8.15 MeV
- 9.15 MeV
- 10.15 MeV
- 11.15 MeV

Fig. 5

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Geant4 modifications for accurate fission simulations

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Near-barrier photofission in ^{232}Th and ^{238}U

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