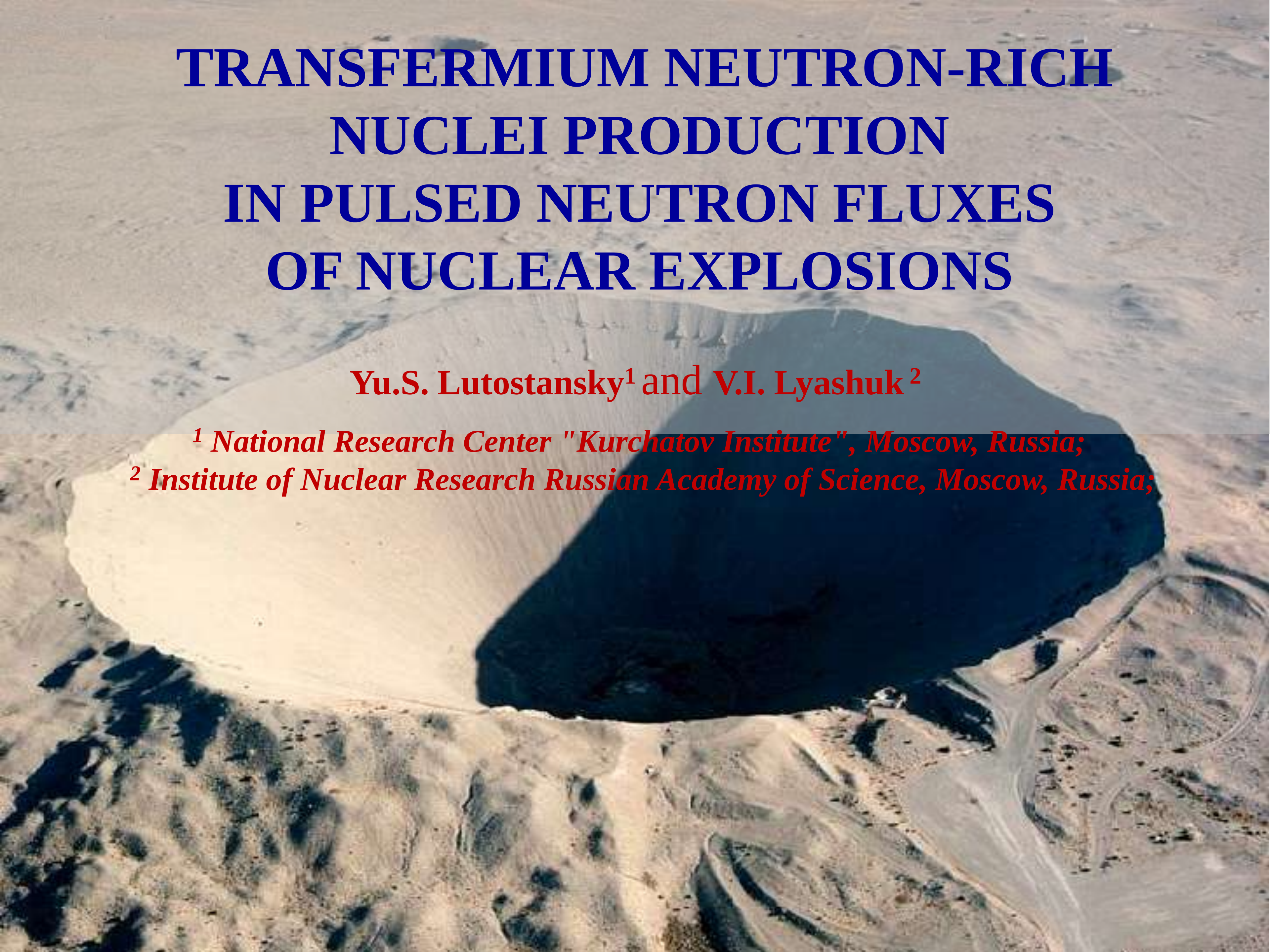
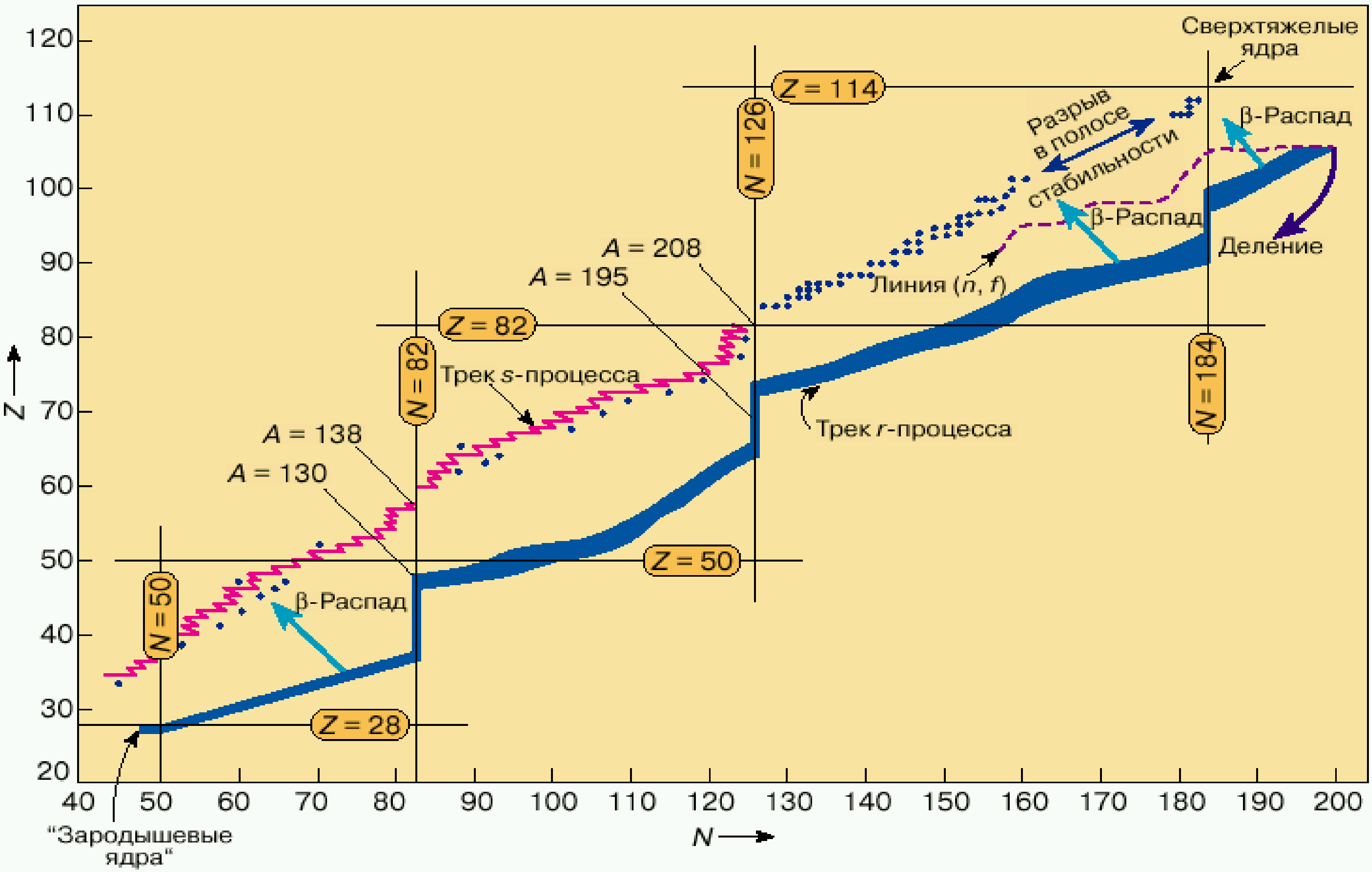


TRANSFERMIUM NEUTRON-RICH NUCLEI PRODUCTION IN PULSED NEUTRON FLUXES OF NUCLEAR EXPLOSIONS

Yu.S. Lutostansky[1] and **V.I. Lyashuk**[2]

[1] National Research Center "Kurchatov Institute", Moscow, Russia;
[2] Institute of Nuclear Research Russian Academy of Science, Moscow, Russia;

PROCESSES OF NUCLEOSYNTESIS.



The tracks of elements synthesis in s (slow)- and r (rapid)- processes.

NUCLEOSYNTHESIS OF THE HEAVY NUCLEI

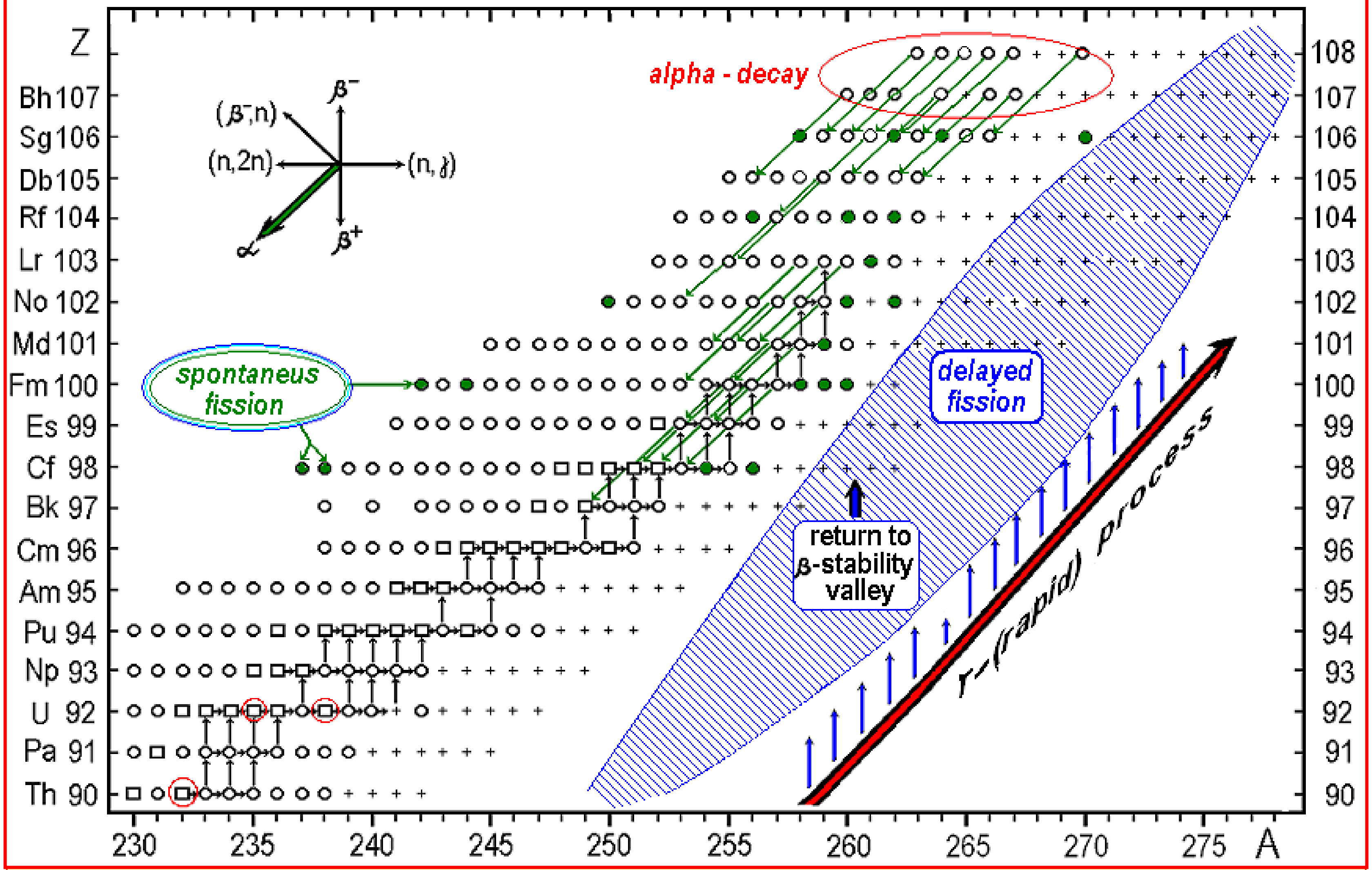


Схема образования актинидов в медленном (*s*-процесс) и быстром (*r*-процесс) нуклеосинтезе; □ – ядра с $T_{1/2} \geq 1$ г ; О – ядра с $T_{1/2} < 1$ г; + - прогнозируемые нейтронно-избыточные ядра из базы данных NDS JAEA (Япония).

I - METHOD: r –Process equations for the concentration calculations

Concentrations n(A,Z) are changing in time (may be more than 4000 equations):

$$\underline{dn(A,Z)/dt = -\lambda_{\beta}(A,Z)\cdot n(A,Z)} - \lambda_{n\gamma}(A,Z)\cdot n(A,Z) + \lambda_{\gamma n}(A+1,Z)\cdot n(A+1,Z) +$$

$$+ \lambda_{n\gamma}(A-1,Z)\cdot n(A-1,Z) - \lambda_{\gamma n}(A,Z)\cdot n(A,Z) +$$

$$+ \lambda_{\beta}(A,Z-1)\cdot n(A,Z-1) \quad P_{\beta}(A,Z-1) + + \lambda_{\beta}(A+1,Z-1)\cdot n(A+1,Z-1) \quad P_{1n}(A+1,Z-1) +$$

$$+ \lambda_{\beta}(A+2,Z-1)\cdot n(A+2,Z-1) \quad P_{2n}(A+2,Z-1) + \lambda_{\beta}(A+3,Z-1) n(A+3,Z-1) \quad P_{3n}(A+3,Z-1) +$$

$$+ \Phi_{\nu}(A,Z) + F_{f}(A,Z),$$

$\lambda_{n\gamma}$ and $\lambda_{\gamma n}$ — rates of (n,γ) and (γ,n) -reactions, $\lambda_{\beta}=\ln(2/T_{1/2})$ —β-decay rate, P_{β} - probability of (A, Z) nuclide creation after β^{-}-decay of (A,Z-1) nuclide. Branching coefficients of isobaric chains - P_{1n}, P_{2n}, P_{3n} corresponds to probabilities of one-, two- and three- neutrons emission in β^{-}- decay of the neutron-rich nuclei; the total probability of the delayed neutrons emission is the sum:

$$\boxed{P_n = \sum_k P_{kn}}$$

$F_f(A, Z)$ describes fission processes.

Neutrino capturing processes are not included $(\Phi_{\nu}(A, Z) = 0)$

Inner time scale is strongly depends on the nuclear reactions rates.

NUCLEOSYNTHESIS WAVE MOVEMENT

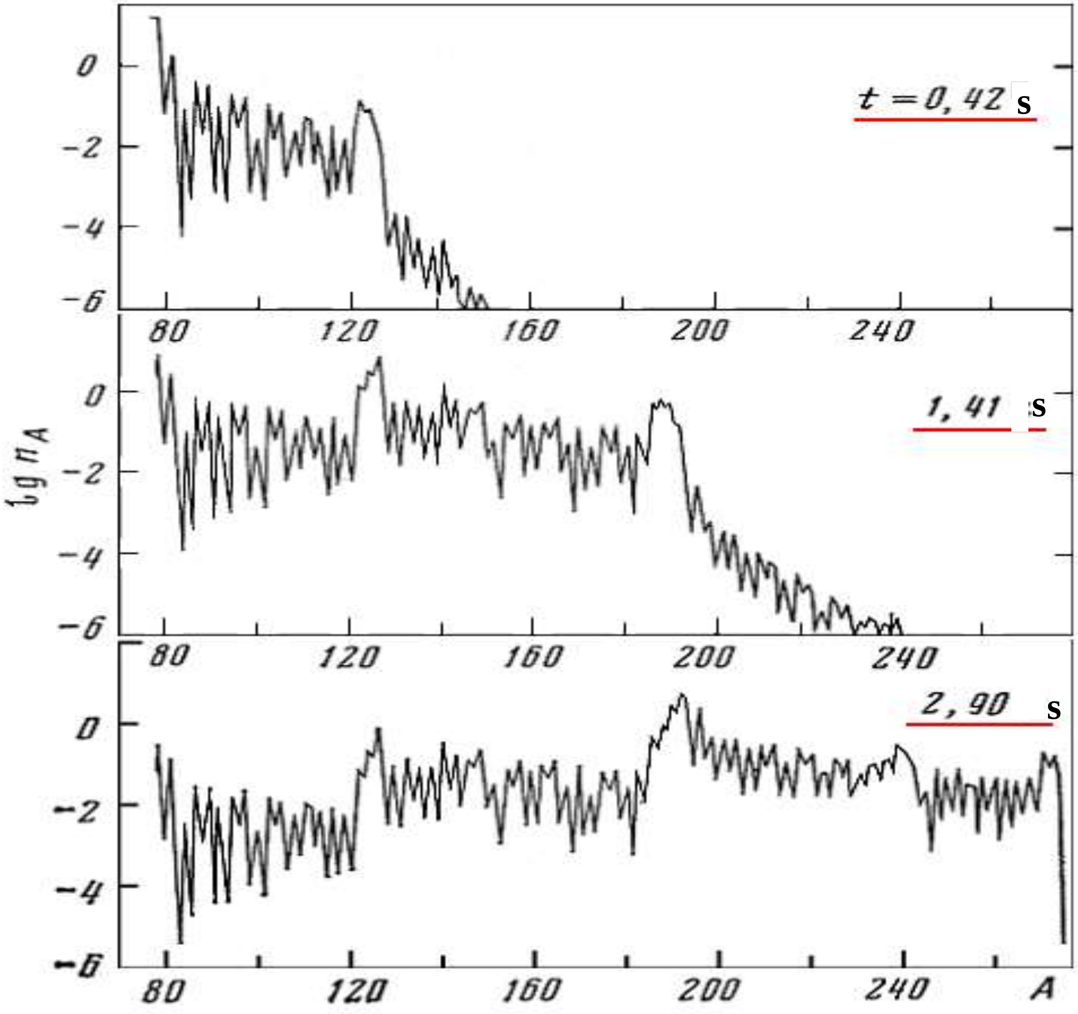
Concentrations:

$$n_A = \sum_z n(A, Z)$$

for three time moments calculated for r-process conditions

$n_n = 10^{24}$ cm^{-3}, $T_9 = 1. = 10^9$K

Лютостанский Ю.С., Птицин Д.А., Синюкова О.Н., Филлипов С.С., Чечеткин В.М. «Образование элементов с A > 80 в нейтронном потоке при астрофизических условиях» . Ядерная Физика 1985, т. 42, с. 215.



β-Delayed processes in very neutron-rich nuclei

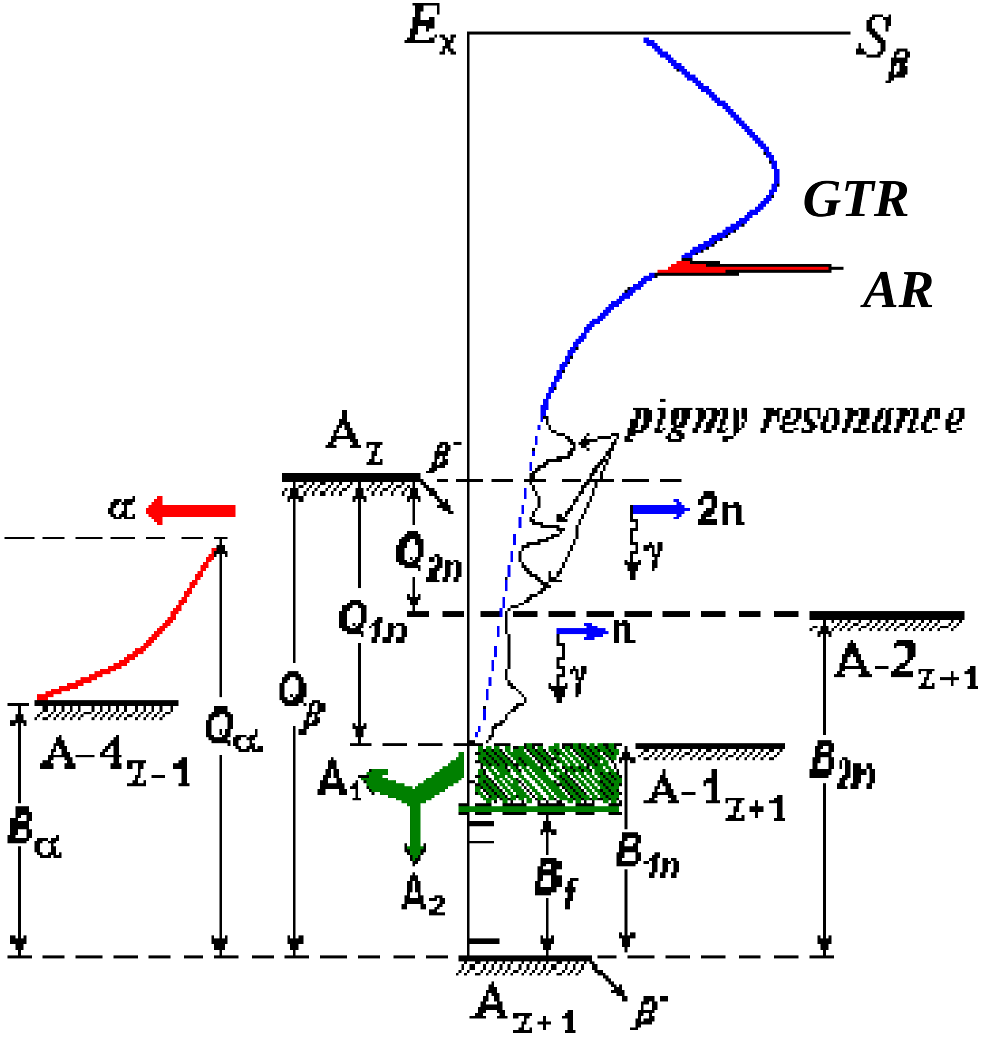
Delayed neutrons emission - (β,n)

Multi-neutron β – delayed emission - (β,kn)

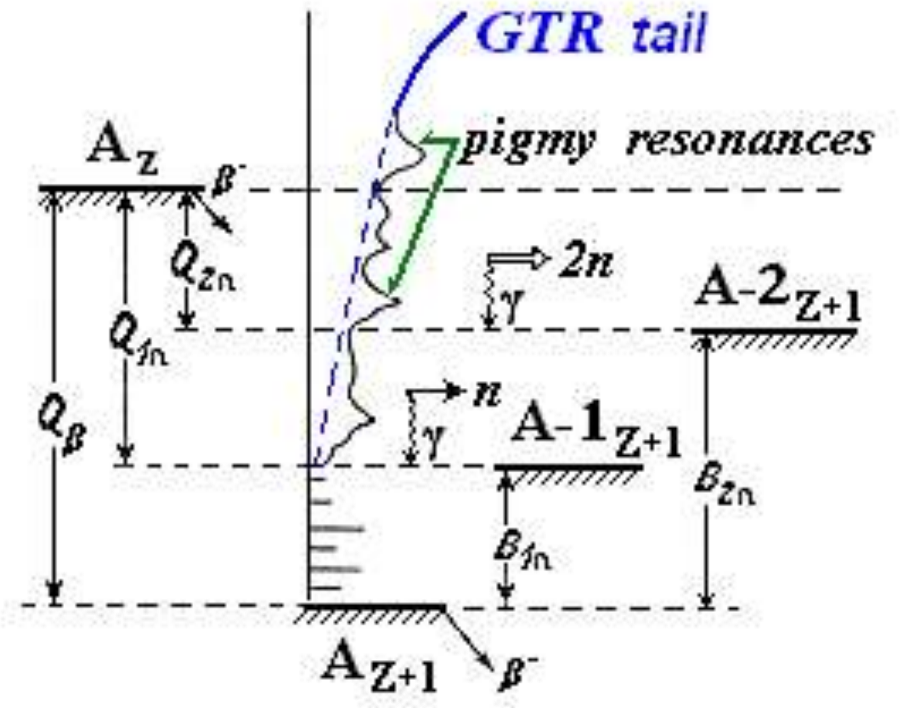
β – delayed α – emission - (β,α)

β – delayed protons emission -(β,p)

β – delayed fission - (β,f)



Beta – Delayed Multy-Neutron Emission



Probability for 2n - emission:

$$P_{2n} = \frac{\int_{B_{2n}}^{Q_\beta} \sum_{ijlm} f(Z+1, Q_\beta - E) S_\beta^i(E) W_2^{ijl}(E_n, E_m) dE}{\int_0^{Q_\beta} \sum_i f(Z+1, Q_\beta - E) S_\beta^i(E) dE}$$

Probability for kn - emission:

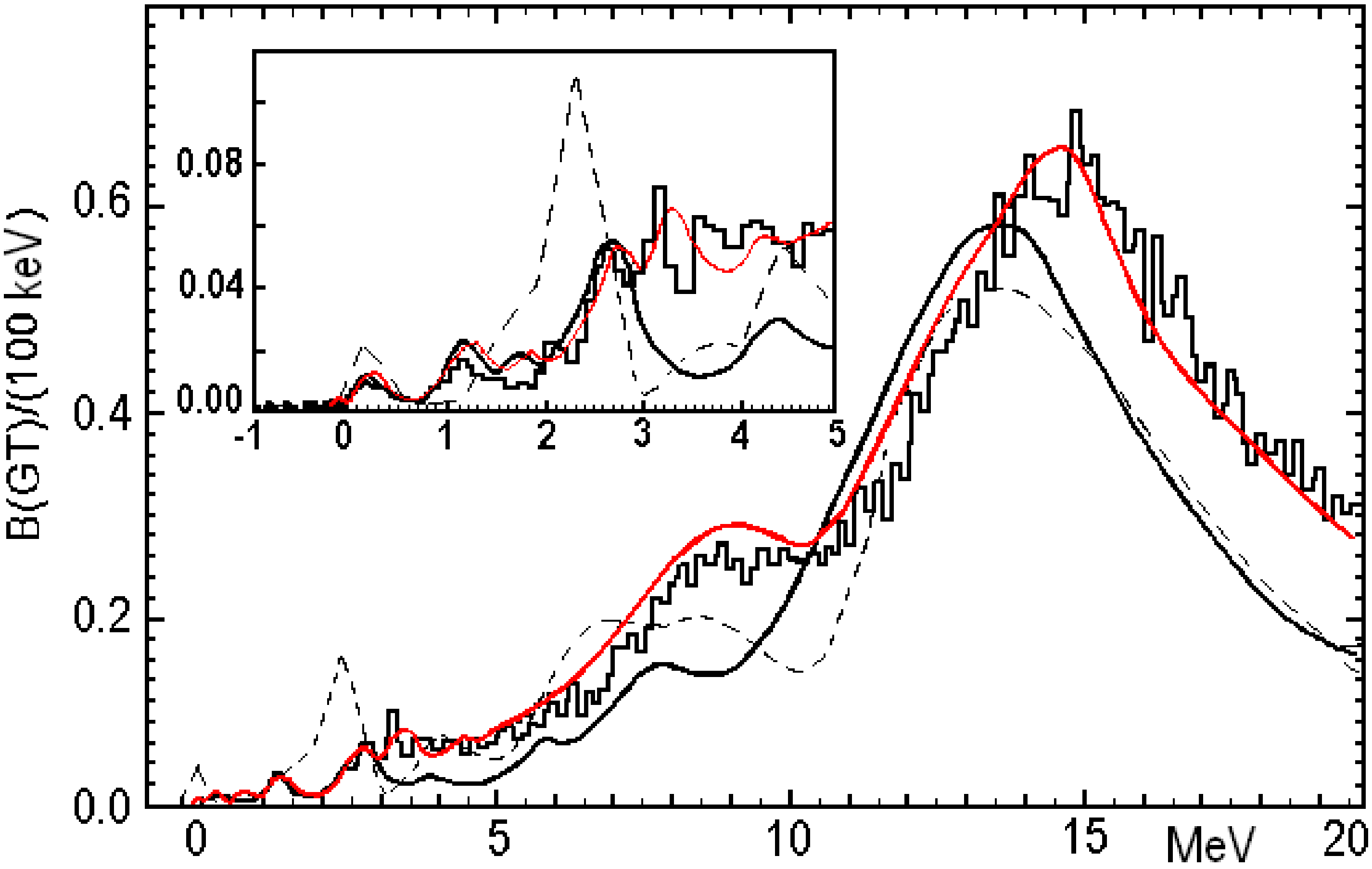
$$P_{kn} = \int_{B_{kn}}^{Q_\beta} \int_0^{Q_{kn}} I_\beta(U) W_n(U, E) dU dE$$

U, I_β(U) – energies and intensities in the daughter nucleus,
W_n(U, E) – probability of neutron emission:

$$W_n(U, E) = \frac{T_n(E) q_f(U - E - B_n)}{\int_0^{U - B_n} T_n(E') q_f(U - E' - B_n) dE' + 2\pi q_i(U) \Gamma_\gamma(U)}$$

q_i and q_f – level densities of compound and final nucleus,
T_n(E) — transitivity factor

BETA-STRENGTH FUNCTION FOR ^{127}Xe

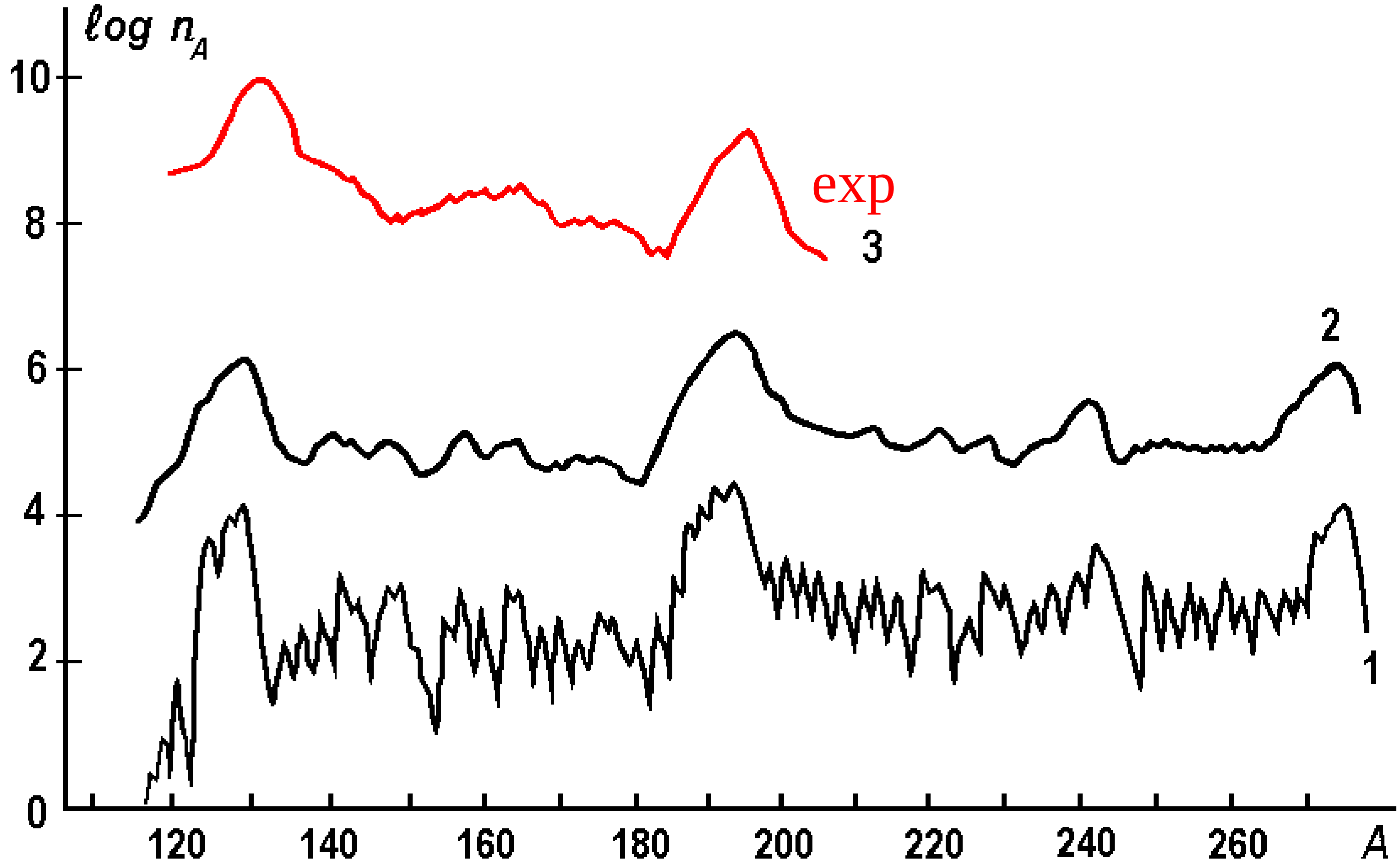


1 - **Breaking line – experimental data (1999):** **M. Palarczyk, *et. al*. Phys. Rev. 1999. V. 59. P. 500;**

2 – **Solid red line TFFS calculations with e_q= 0.9 ;**

3 - **Solid black line – calculations with e_q= 0.8 : Yu.S. Lutostansky, N.B. Shulgina. Phys. Rev. Lett. 1991. V.67. P. 430;**

BETA-DELAYED NEUTRONS IN NUCLEOSYNTESIS



Calculated abandancies: 1– with out (d,n)-effect; 2 – with (d,n)-effect; in the relative units ($T=10^9$ K, $n_n=10^{24}$ $см^{-3}$).

Расчет: **Лютостанский Ю.С., Панов И.В., Синюкова О.Н., Филлипов С.С., Чечеткин В.М. Роль запаздывающих нейтронов при образовании элементов в r –процессе. ЯФ. 1986. т.44. с.66.**

DYNAMIC MODEL OF NUCLEOSYNTHESIS

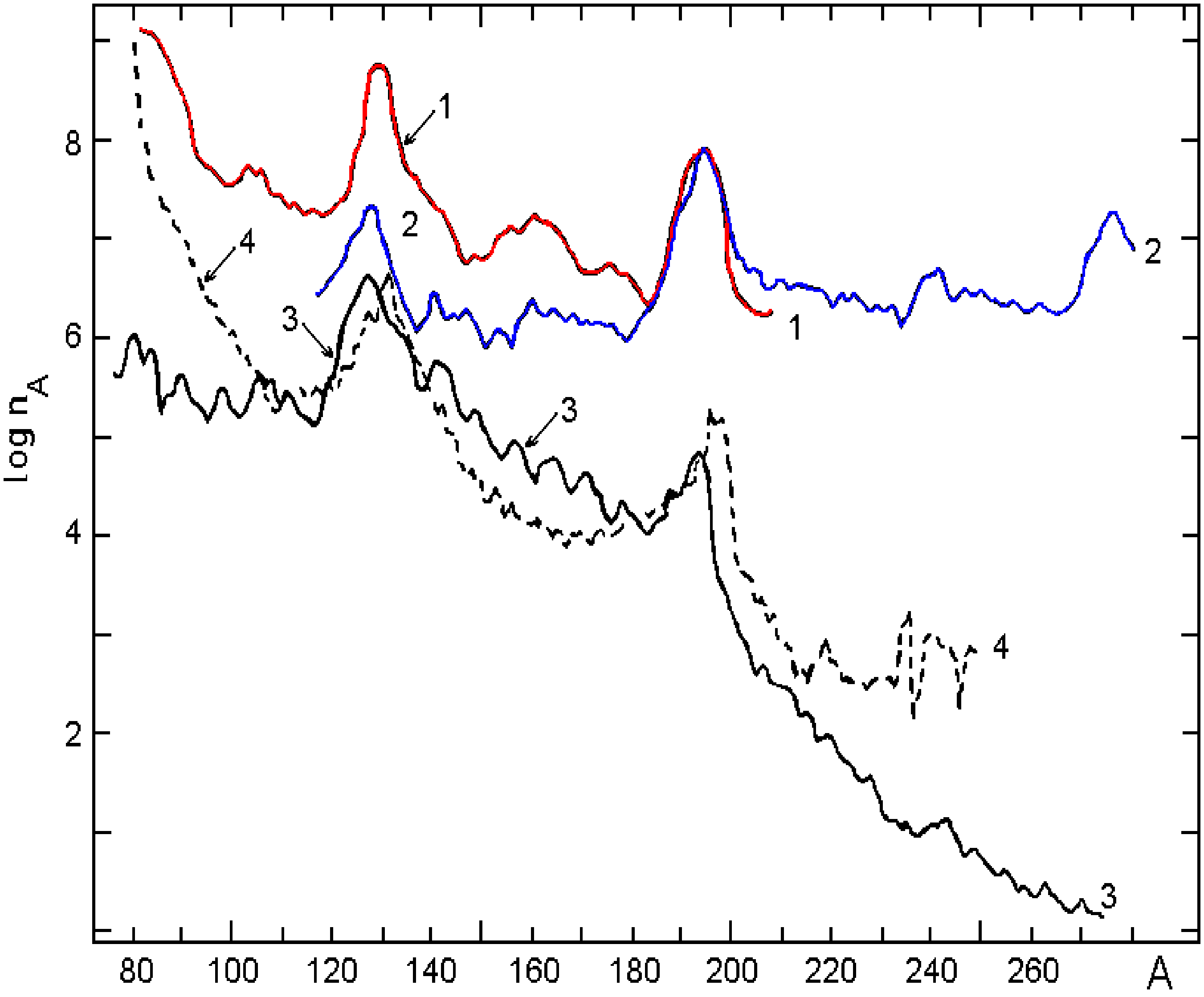
Yelds of Nuclei, calculated in static (curve 2) and dynamic pulse r – processes (curves 3 and 4).

Numbers denote:

1- exp abundance data.

Curves 2 and 3 - Calculations with different parameters.
Curve 2: $n_n=10^{24}$ cm^{-3}, $T_9=10^9$K, $\tau_н=\infty$;
Curve 3: $\rho_0 = 2\cdot10^5$ $g\cdot cm^{-3}$, $T_9=2x10^9$K, $\tau_н=1$ s.

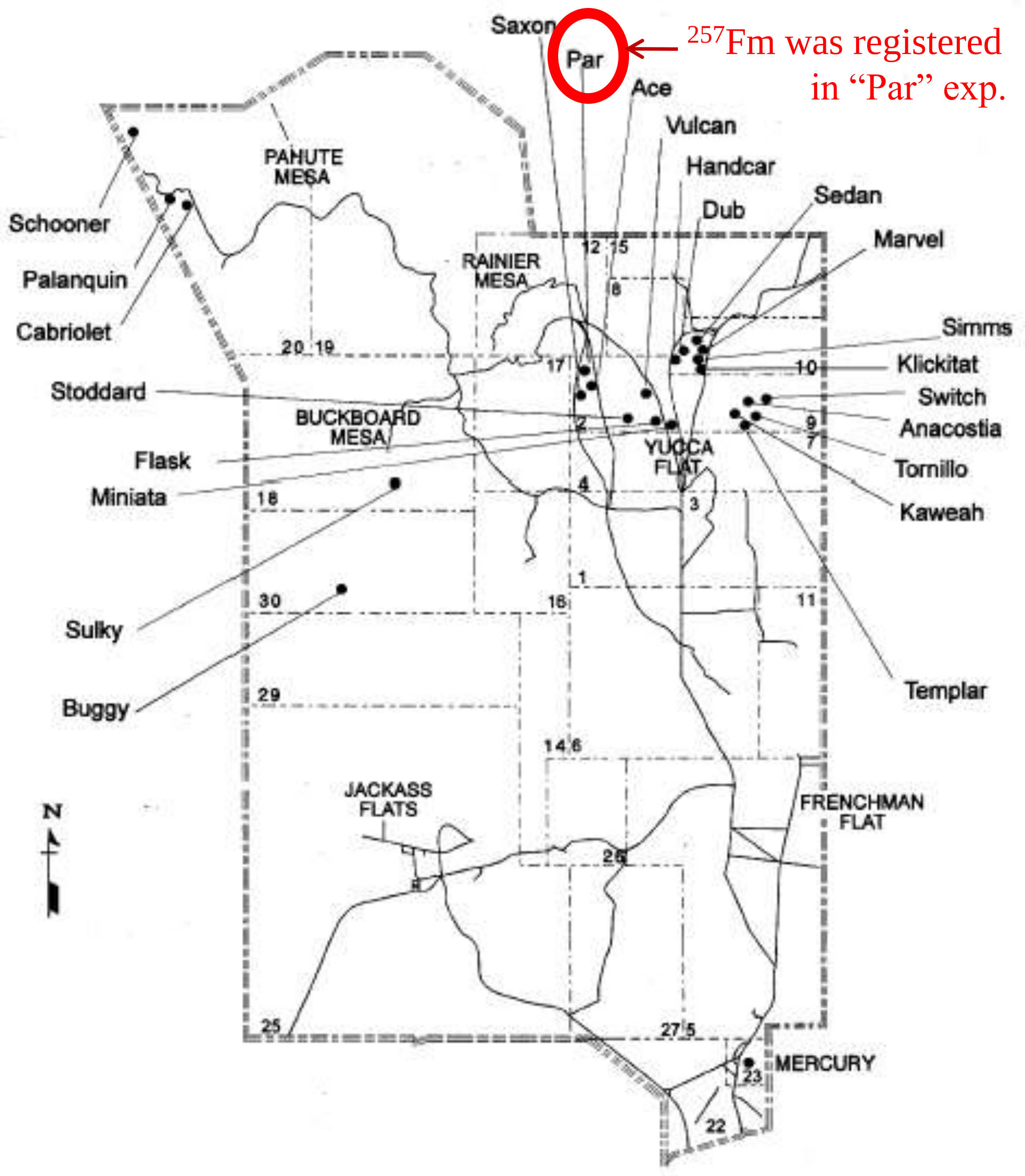
Curve 4 (doted line) – calculations with solar abundance initial nuclei concentration of s – elements.



The production of transuranium isotopes was accomplished for the first time in the “Mike” thermonuclear experiment. Under the “Plowshare” project (United States), a series of experiments were performed (“Anacostia,” “Par,” “Barbel,” “Tweed,” “Cyclamen,” “Kankakee,” “Vulcan,” “Hutch,” and so on) to study heavy isotope production .

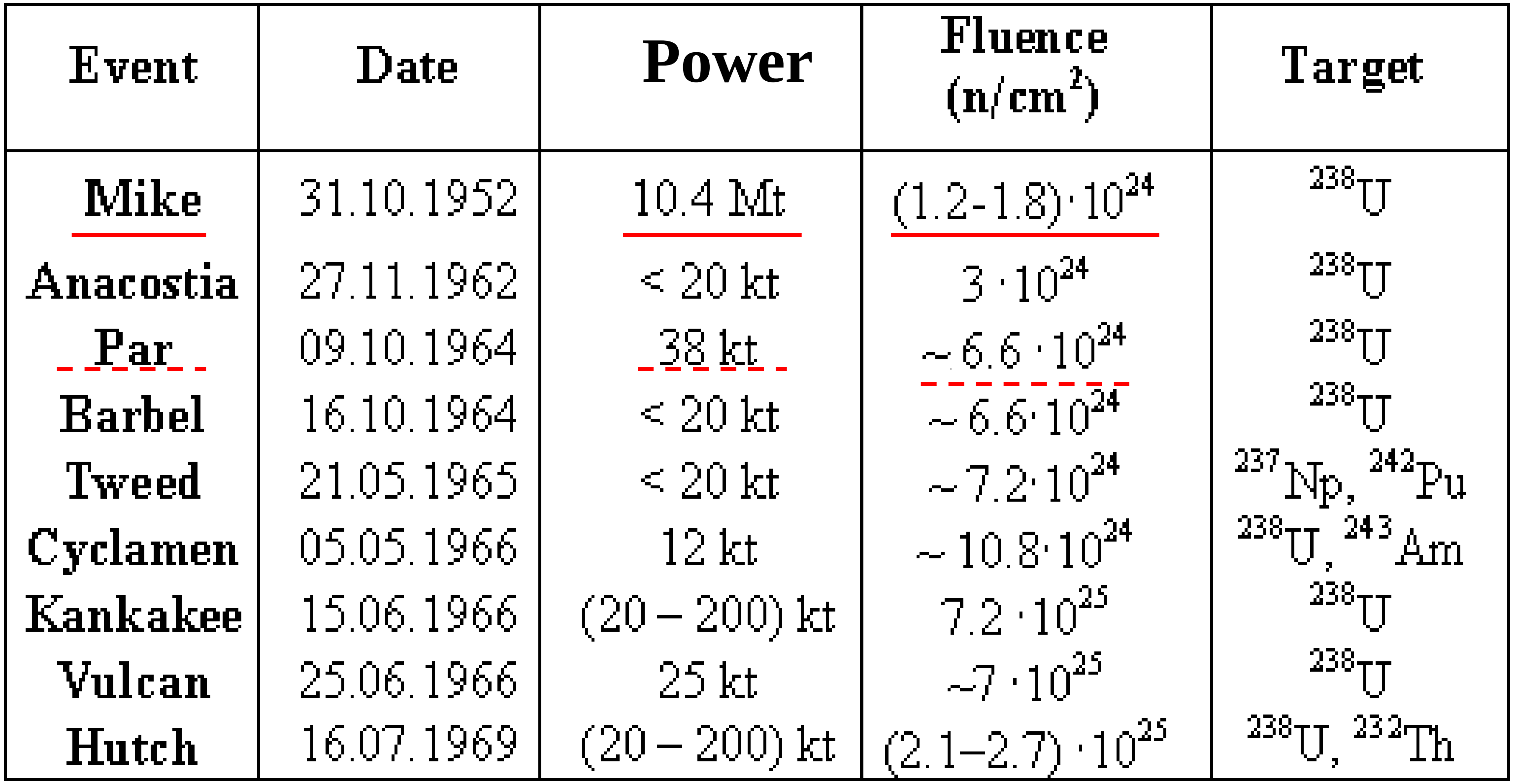
Программа “Плаушер” (США)
исследование образования
трансурановых
элементов в ядерных/термоядерных
взрывах

Nevada U.S.A.


^{257}Fm was registered in “Par” exp.

In the “**Cyclamen**” and “**Hutch**” experiments integral fluxes were **1.2·10^{25}** neutron cm^{-2} and **4.5·10^{25}** neutron cm^{-2}, respectively .

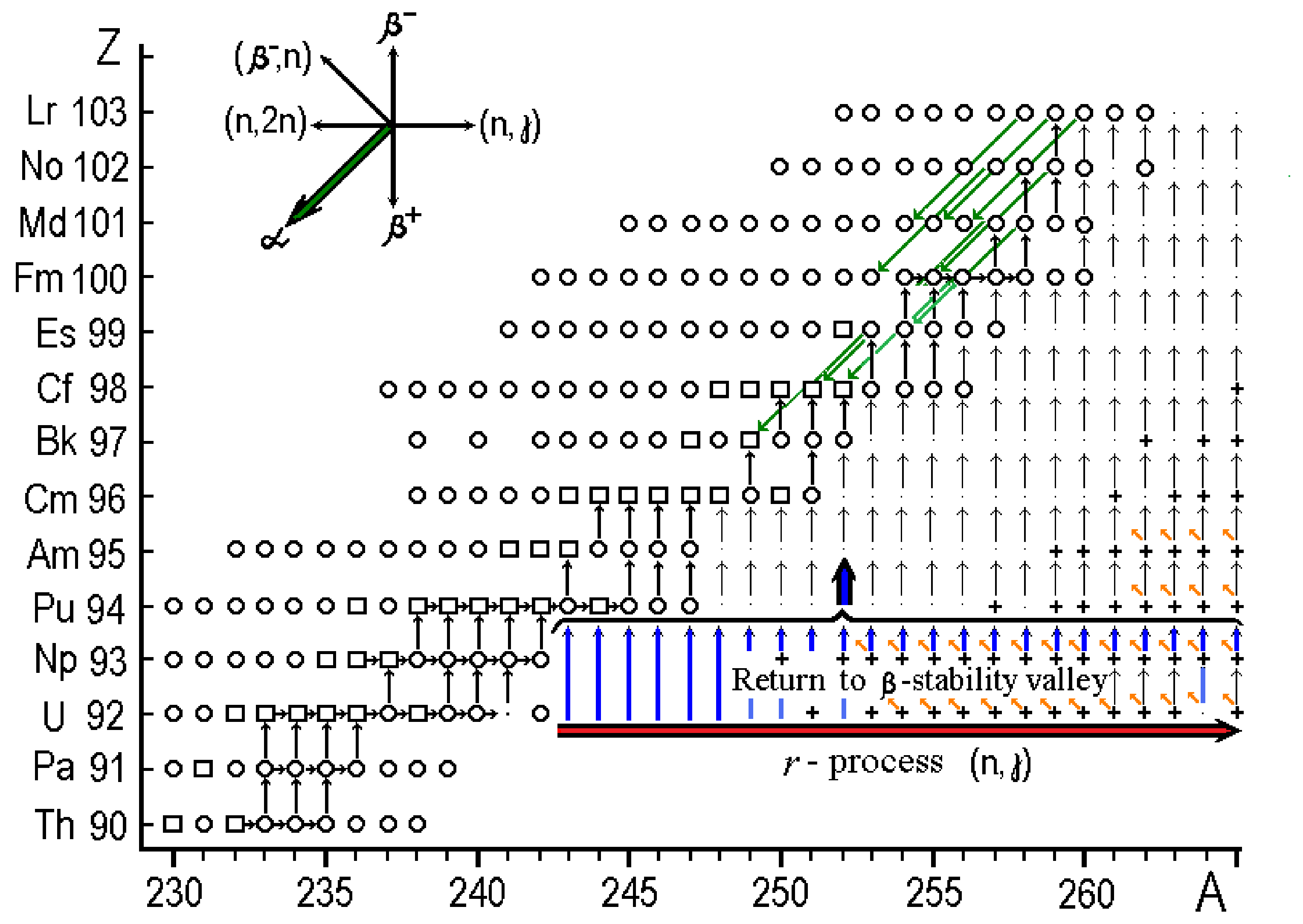
Significant Nuclear Tests in the U.S.A.
Heavy Element Program



Event	Date	Power	Fluence (n/cm^2)	Target
Mike	31.10.1952	10.4 Mt	$(1.2\text{-}1.8)\cdot 10^{24}$	^{238}U
Anacostia	27.11.1962	< 20 kt	$3\cdot 10^{24}$	^{238}U
Par	09.10.1964	38 kt	$\sim 6.6\cdot 10^{24}$	^{238}U
Barbel	16.10.1964	< 20 kt	$\sim 6.6\cdot 10^{24}$	^{238}U
Tweed	21.05.1965	< 20 kt	$\sim 7.2\cdot 10^{24}$	^{237}Np, ^{242}Pu
Cyclamen	05.05.1966	12 kt	$\sim 10.8\cdot 10^{24}$	^{238}U, ^{243}Am
Kankakee	15.06.1966	(20 – 200) kt	$7.2\cdot 10^{25}$	^{238}U
Vulcan	25.06.1966	25 kt	$\sim 7\cdot 10^{25}$	^{238}U
Hutch	16.07.1969	(20 – 200) kt	$(2.1\text{–}2.7)\cdot 10^{25}$	^{238}U, ^{232}Th

There is no obvious relationship between the power of the explosion and the neutron flux

r(rapid) – process in the explosive nucleosynthesis



Multiple neutron capturing process on Uranium material (U – target) , $t < 10^{-6}$ s.

II - METHOD: r –Process equations for the concentration calculations

Concentrations n(A,Z) are changing in time (may be more than 4000 equations):

$$\underline{dn(A, Z)/dt = -\lambda_{\beta}(A, Z)\cdot n(A, Z)} - \lambda_{n\gamma}(A, Z)\cdot n(A, Z) + \lambda_{\gamma n}(A+1, Z)\cdot n(A+1, Z) +$$

$$+ \lambda_{n\gamma}(A-1, Z)\cdot n(A-1, Z) - \lambda_{\gamma n}(A, Z)\cdot n(A, Z) +$$

$$+ \lambda_{\beta}(A, Z-1)\cdot n(A, Z-1)\cdot P_{\beta}(A, Z-1) + + \lambda_{\beta}(A+1,Z-1)\cdot n(A+1,Z-1)\cdot P_{1n}(A+1,Z-1)+$$

$$+ \lambda_{\beta}(A+2,Z-1)\cdot n(A+2,Z-1) \quad P_{2n}(A+2,Z-1) + \xcancel{\lambda_{\beta}(A+3,Z-1) n(A+3,Z-1)\cdot P_{3n}(A+3,Z-1)+}$$

$$+ \xcancel{\Phi_{\nu}(A, Z)} + F_{f}(A, Z),$$

$\lambda_{n\gamma}$ and $\lambda_{\gamma n}$ — rates of (n,γ) and (γ,n) -reactions, $\lambda_{\beta}=\ln(2/T_{1/2})$ —β-decay rate, P_{β} - probability of (A, Z) nuclide creation after β^{-}-decay of (A,Z-1) nuclide. Branching coefficients of isobaric chains - P_{1n}, P_{2n}, P_{3n} corresponds to probabilities of one-, two- and three- neutrons emission in β^{-}- decay of the neutron-rich nuclei; the total probability of the delayed neutrons emission is the sum:

$$\boxed{P_n = \sum_k P_{kn}}$$

$F_f(A, Z)$ describes fission processes.

Neutrino capturing processes are not included ($\Phi_{\nu}(A, Z) = 0$)

III - METHOD: (ADIABATIC MODEL) neutron capturing and β-decay process are separated in time and calculated separately.

All time scale of the explosion is divided on small nanoseconds time intervals where all parameters considered to be constant and the expansion process is - adiabatic. For subsequent steps, the initial conditions for all isotopes are nonzero and are equal to the accumulation of the given nuclides by the moment of the preceding time step's completion. Concentrations *N(A,Z)* in every time interval are changing in time:

$$\begin{cases} \frac{\partial N_z^n}{\partial t} = -(\lambda_{n,\gamma}N)_z^n \\ \frac{\partial N_z^{n+1}}{\partial t} = (\lambda_{n,\gamma}N)_z^n - (\lambda_{n,\gamma}N)_z^{n+1} \\ . \\ . \\ . \\ \frac{\partial N_z^{n+i}}{\partial t} = (\lambda_{n,\gamma}N)_z^{n-1+i} - (\lambda_{n,\gamma}N)_z^{n+i} \end{cases} \qquad (3)$$

The neutron capture rates were calculated in the statistical model [1]. The neutron rich isotopes half-lives, probabilities of β-delayed one and two neutrons emission, probabilities of β-delayed fission were calculated taking into account the β-strength function, which was obtained from the theory of finite-Fermi systems [2].

1. Panov I. V., Kolbe E., Pfeiffer B., Rauscher T., Kratz K.-L., Thielemann F.-K. Nucl. Phys. A. 2005. V.747, p.633.

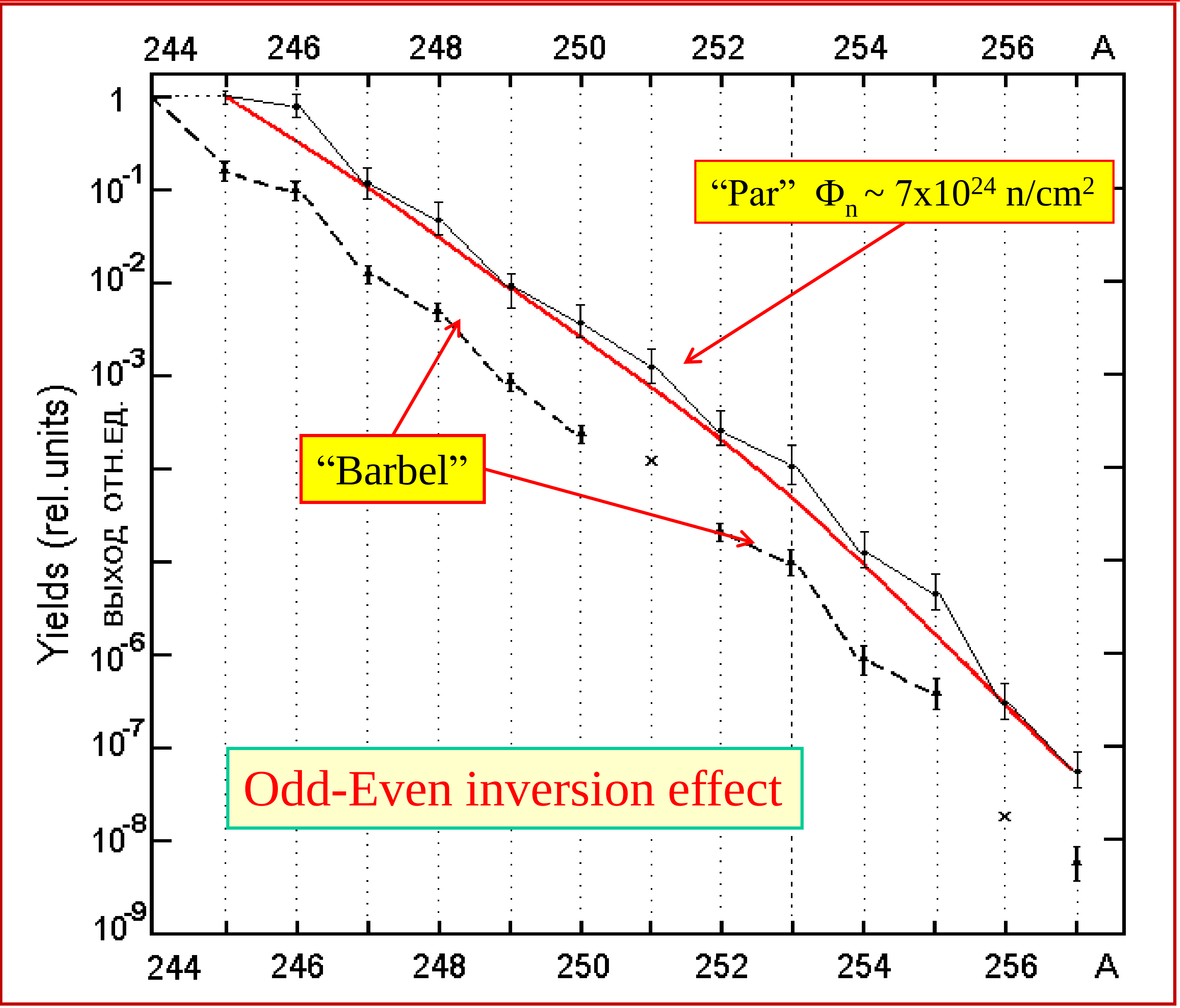
2. Gaponov Yu. V., Lutostansky Yu. S. Yad. Fiz. 2010, V.73, №8, p. 665

Yields (concentrations in relative units) for “Par” and “Barbel” experiments

Yields of transuranium nuclei measured in the thermonuclear explosions “Par” and “Barbel” (LANL data).

— Red line – approximation

$Y = \exp(-1.442A + 354.56)$



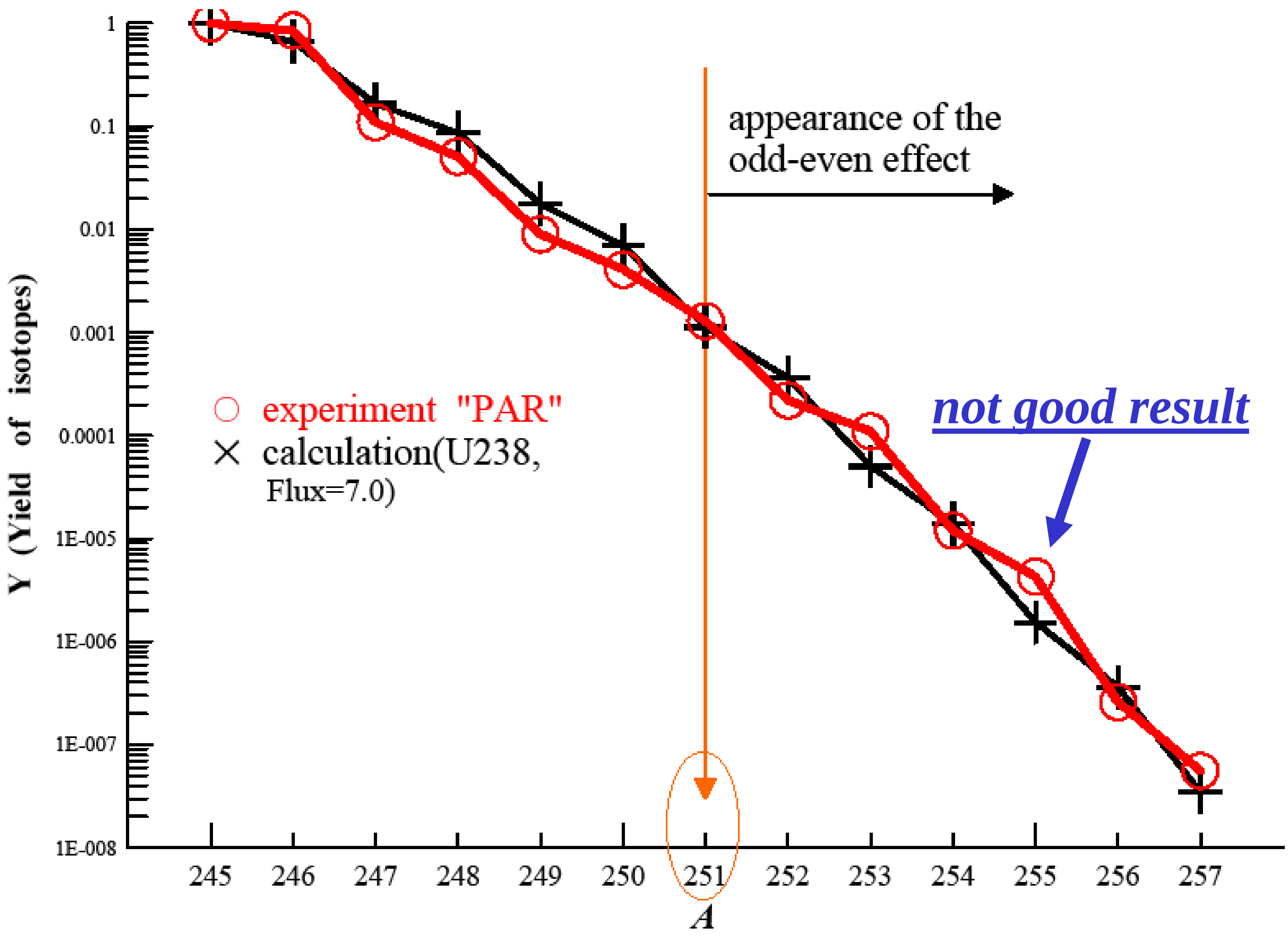
“Par” $\Phi_n \sim 7\text{x}10^{24}$ n/cm^2

“Barbel”

Odd-Even inversion effect

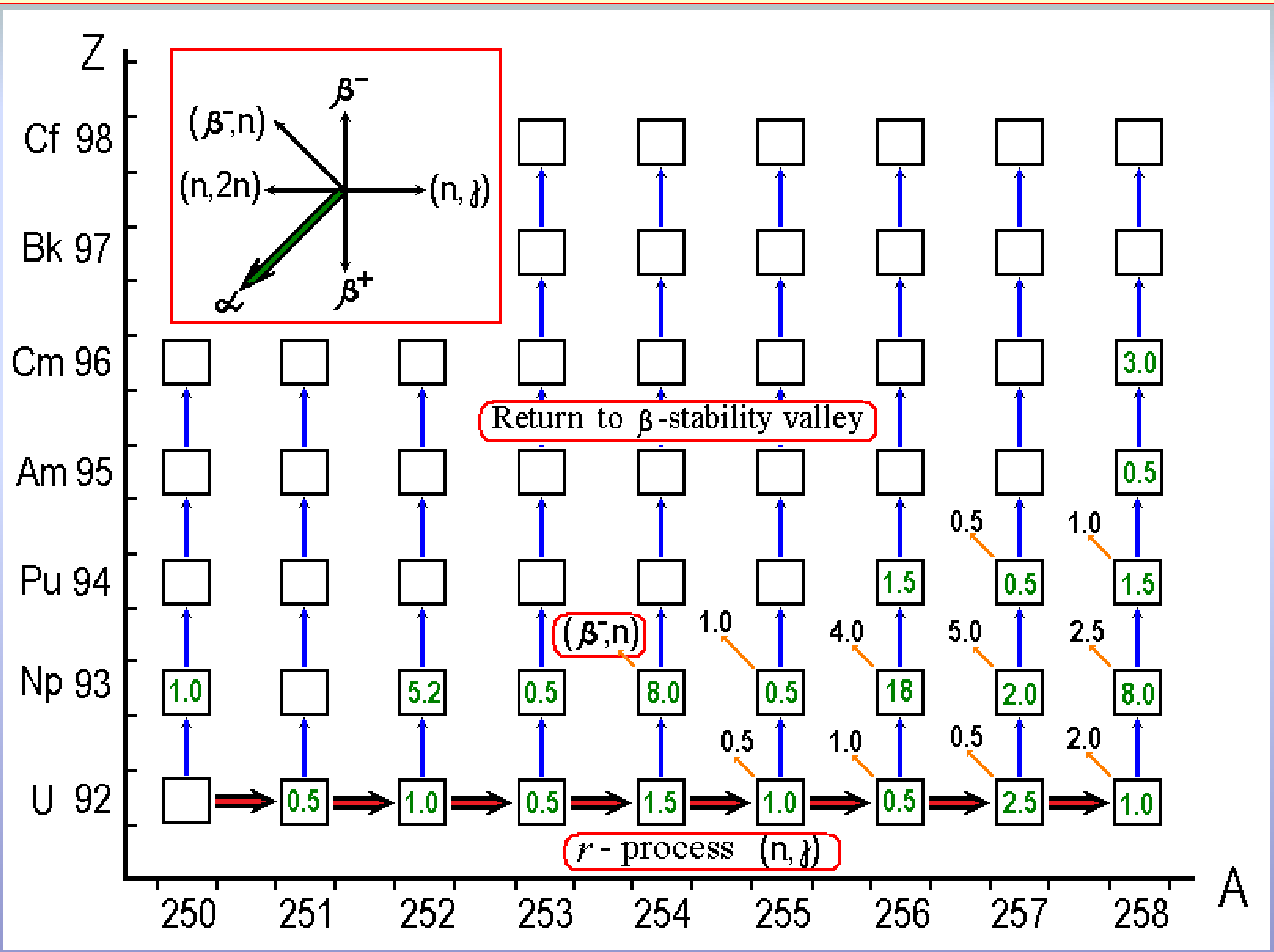
Yields (concentrations in relative units) for “Par” experiment with U - target

(calculations not including “Losing effects”)



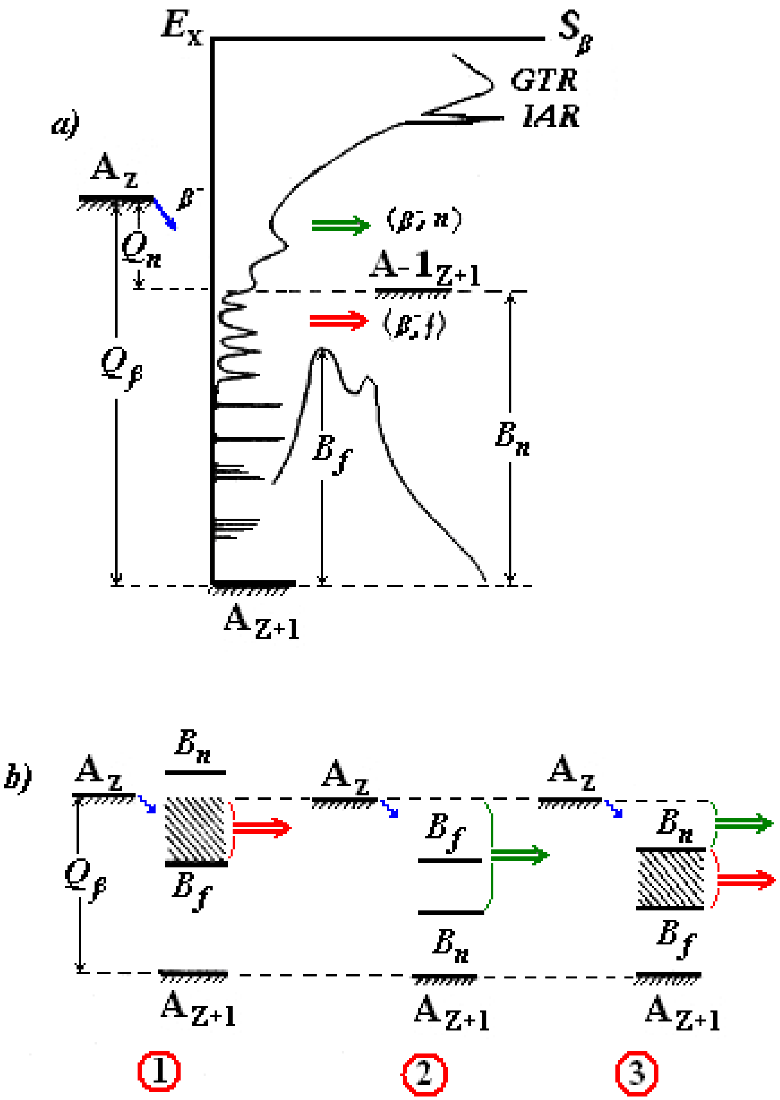
not good result

r(rapid) – process in the explosive nucleosynthesis



The initial concentration changed because of β-delayed fission and neutron emission during cooling processes (return to the value of β-stability).

BETA - DELAYED FISSION



Beta – Delayed Fission Calculations

Probabilities - $P_{\beta f}$:

$$P_{\beta f} = \frac{\int_0^{Q_\beta} \sum_i f(Z, Q_\beta - E) S_\beta^i(E) \frac{\Gamma_f}{\Gamma_{tot}} dE}{\int_0^{Q_\beta} \sum_i f(Z, Q_\beta - E) S_\beta^i(E) dE}$$

Beta Strength function:

$$S_\beta(E) = \frac{C_N}{2\pi} \sum_i M_i^2(E_i) \frac{\Gamma(E)}{(E_i - E)^2 + \frac{\Gamma^2(E)}{4}}$$

 # $\Gamma(E)$ widths approximation: $\Gamma(E) = \alpha \cdot E^2 + \beta \cdot E^3 + \ldots$

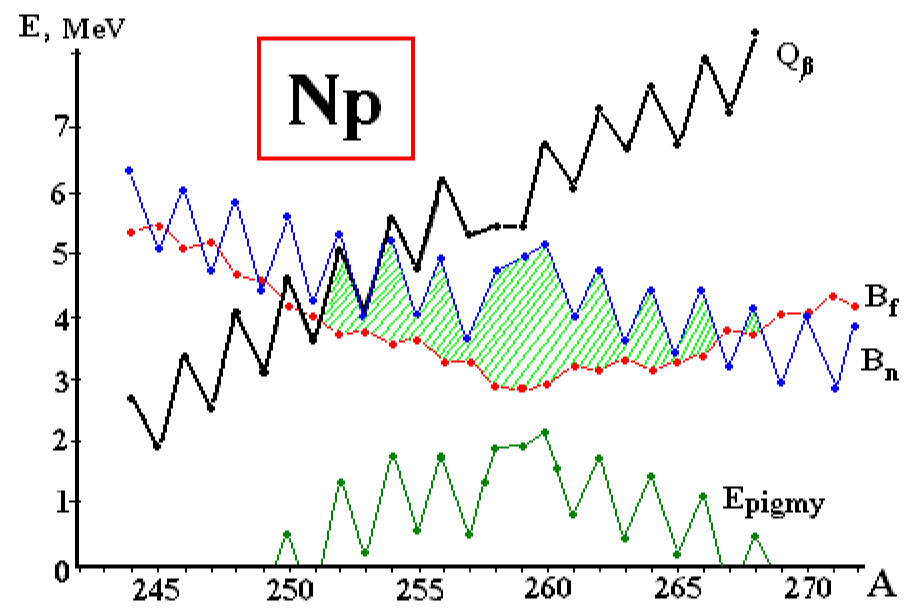
where $\alpha \approx 1/\varepsilon_F$ and $\beta \ll \alpha$, so we used only the first term.

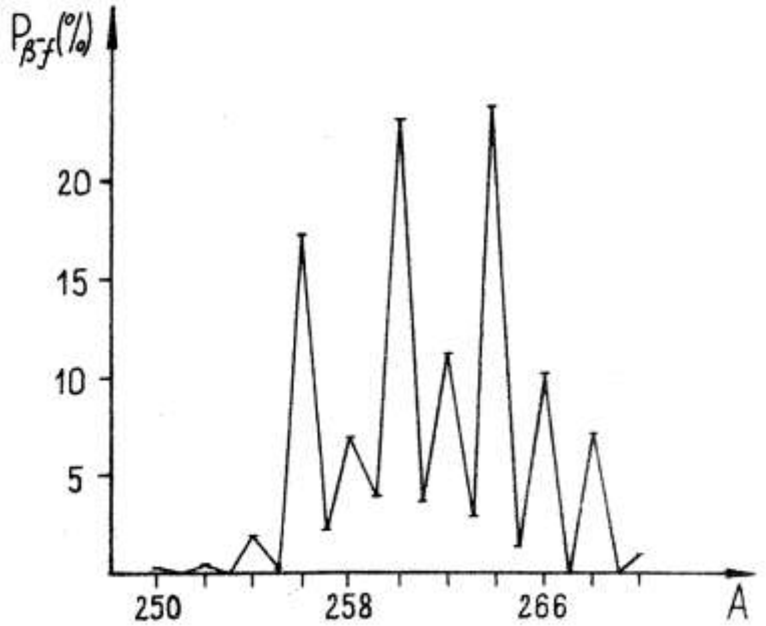
 # As $\Gamma_f \ll \Gamma_n$ so neutron emission dominates when this energetically possible.

 # Sub-barrier fission probabilities in the daughter nucleus are small to gamma decay of exited states (barrier was taken in standard parabolic form).

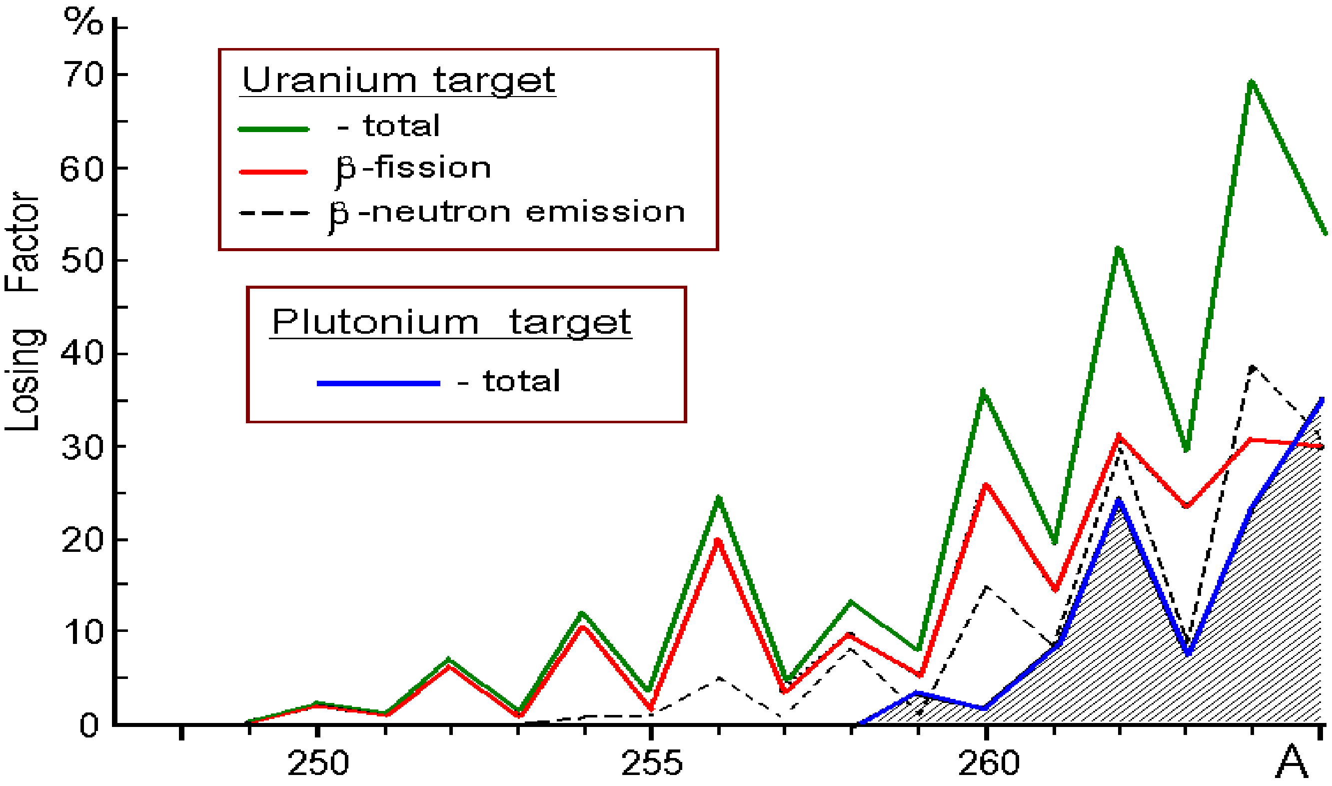
 # Main dependence of $P_{\beta f}$ is from barrier energy B_f but not from barrier thickness or form.

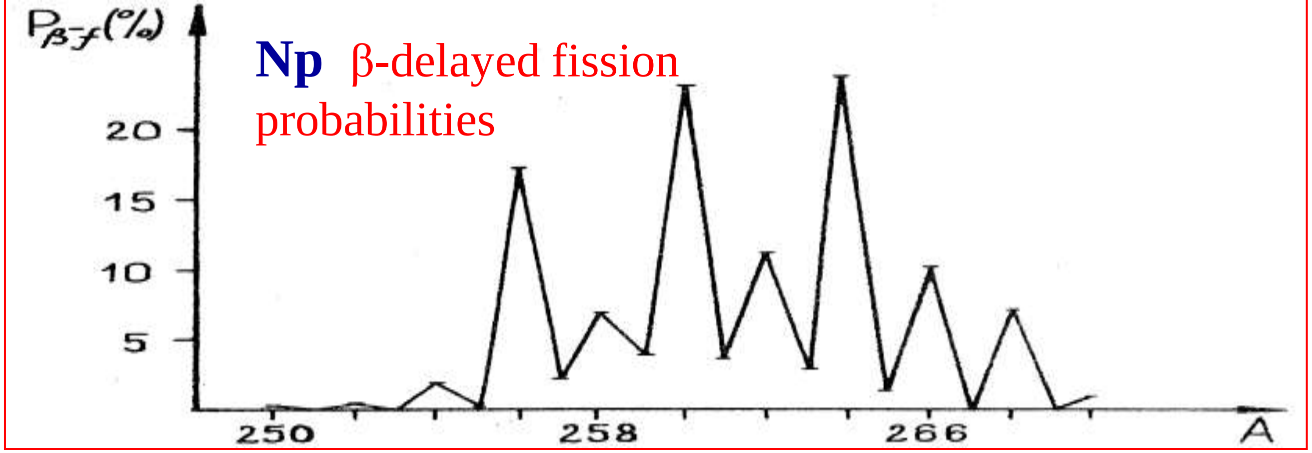
Neptunium Beta – Delayed Fission Calculations





Factor of the concentration losing

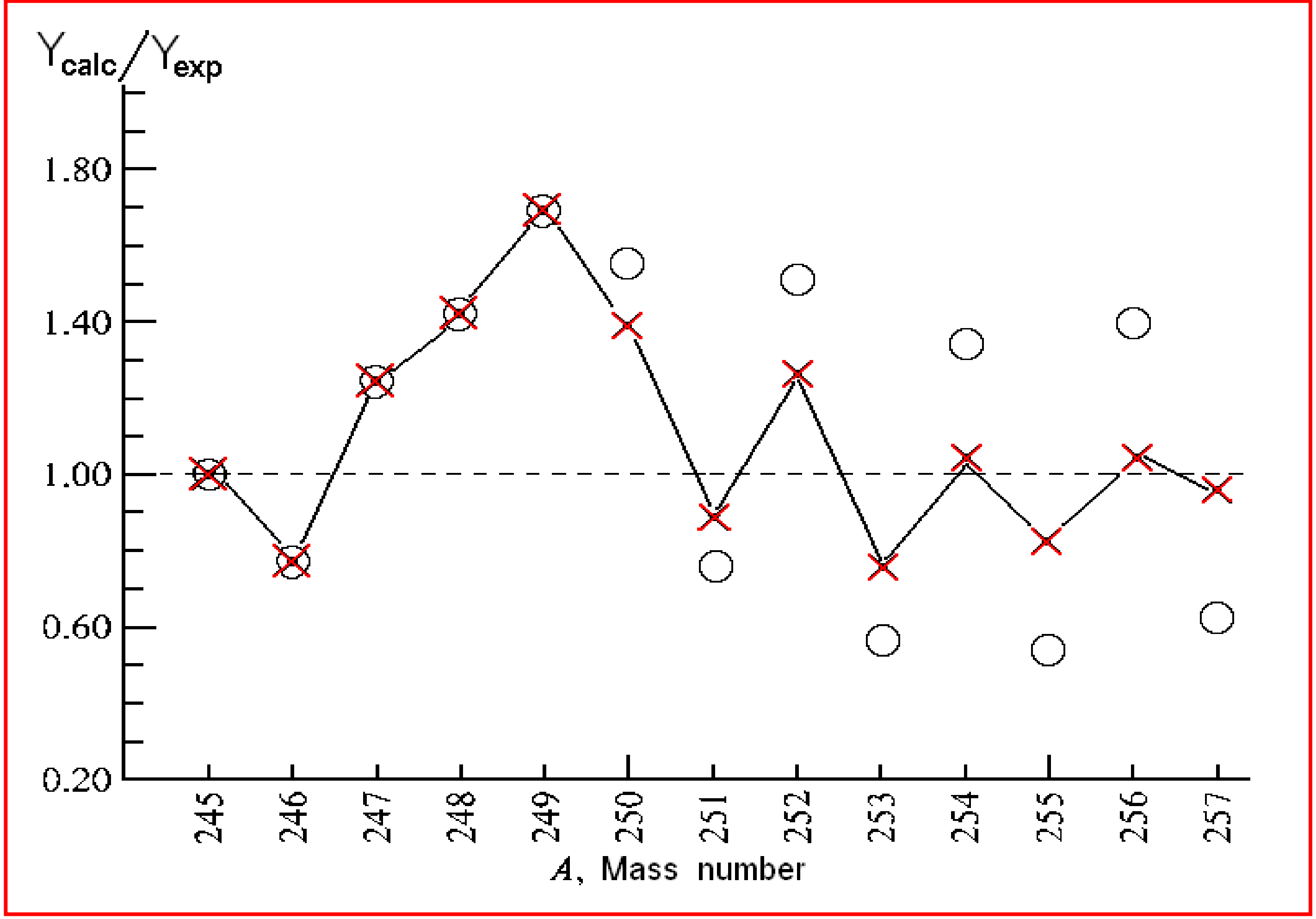




Np β-delayed fission probabilities

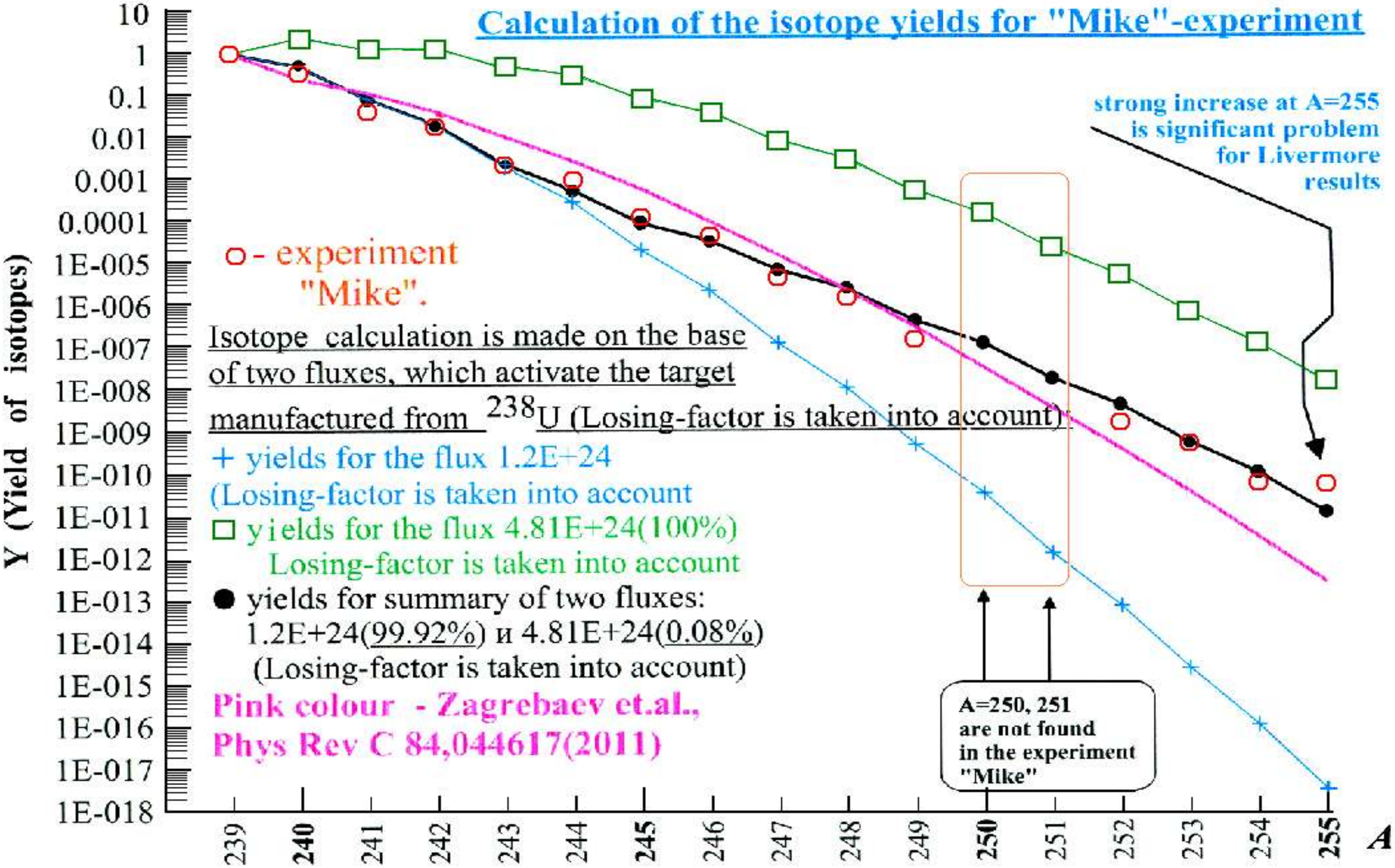
Calculations for “Par” experiment

(Calc. Yields rel. to exp. data)



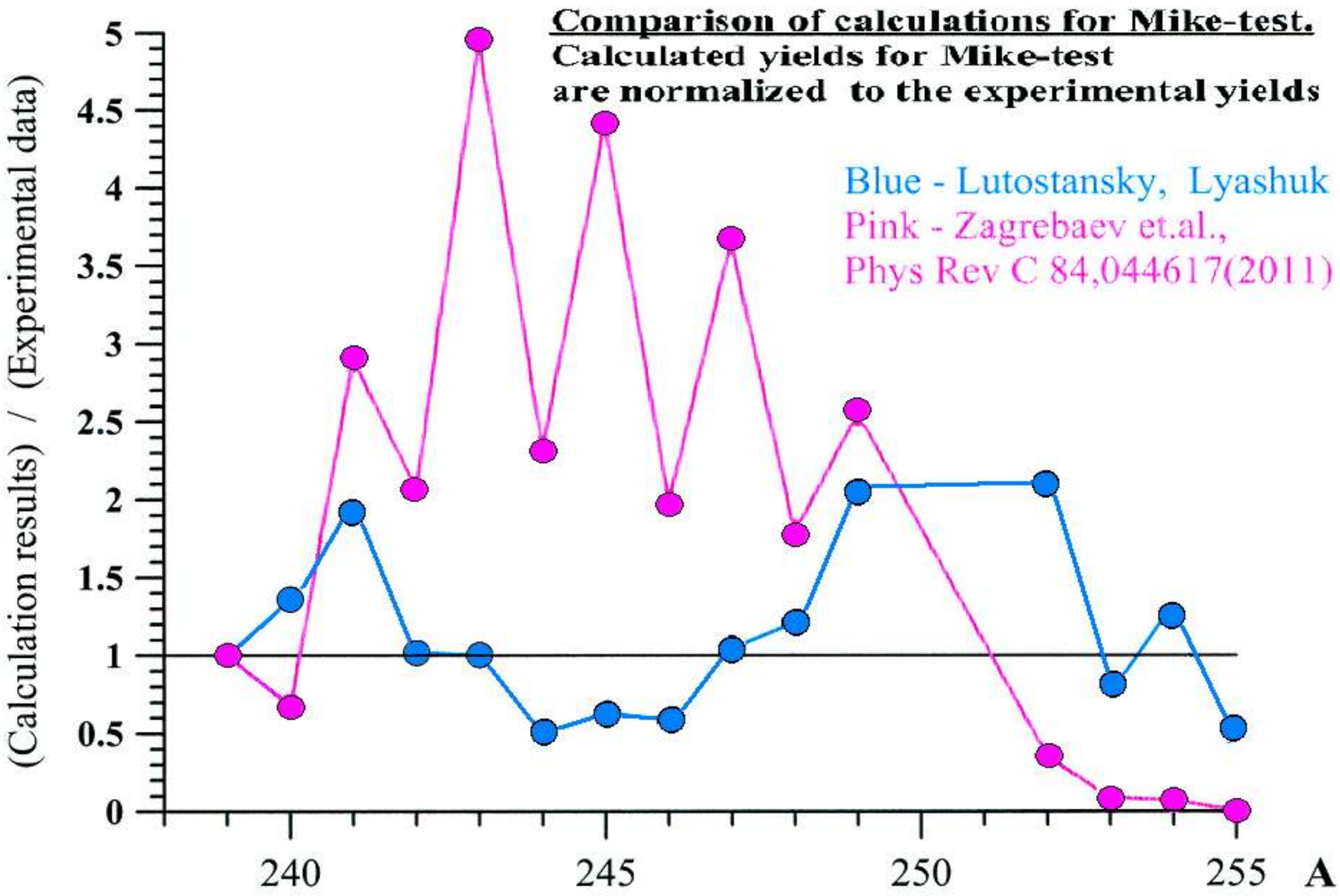
Отношение расчетных значений к экспериментальным выходам
О – расчетные результаты для адиабатической модели с ^{238}U как единственным изотопом в мишени; × - расчетные результаты, с учетом запаздывающего деления (соединены линией).

“Mike” experiment - 1



V. I. Zagrebaev, A. V. Karpov, I. N. Mishustin, and Walter Greiner
“Production of heavy and superheavy neutron-rich nuclei in neutron capture processes”
PHYSICAL REVIEW C 84, 044617 (2011)

“Mike” experiment - 2



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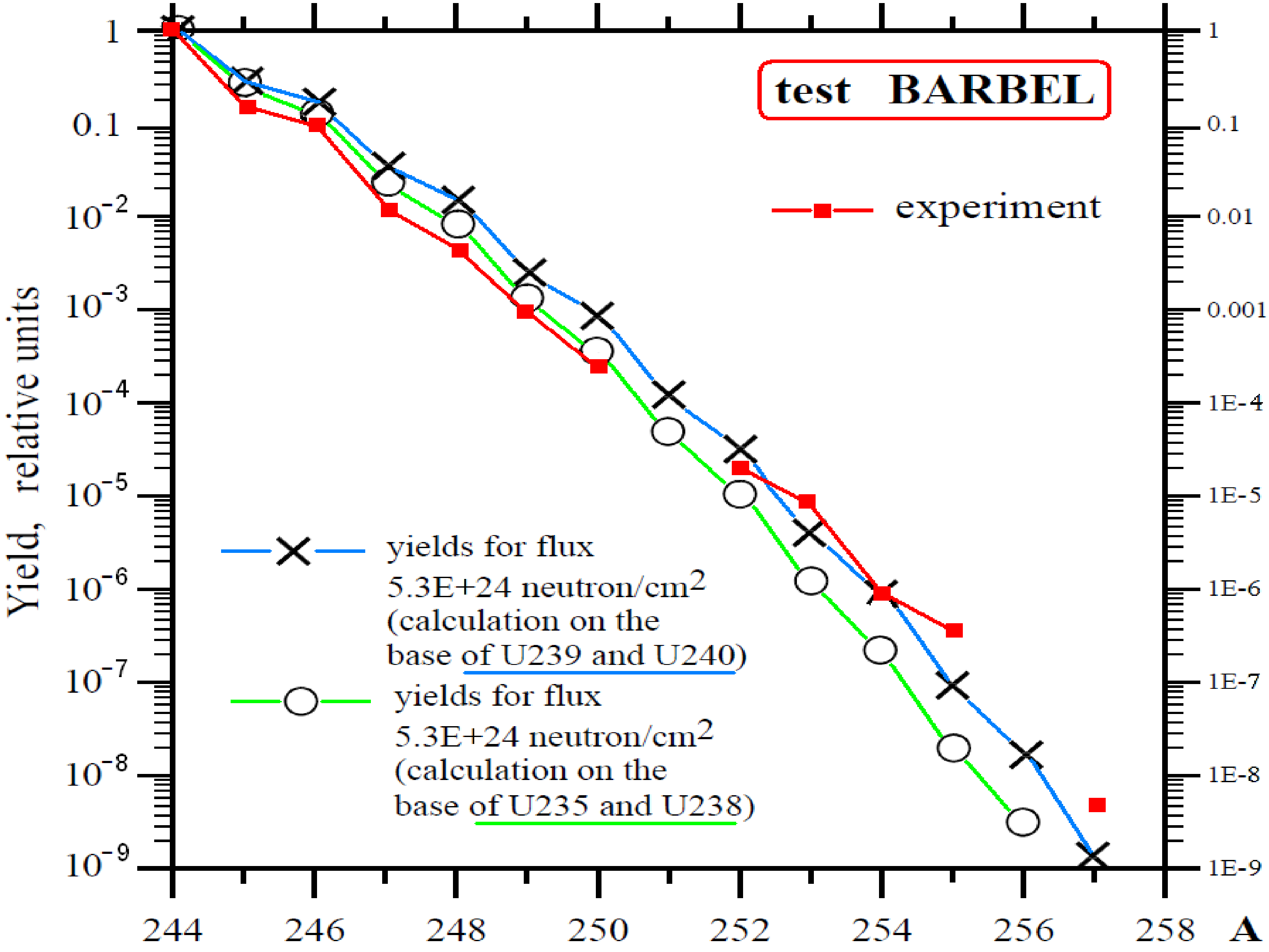
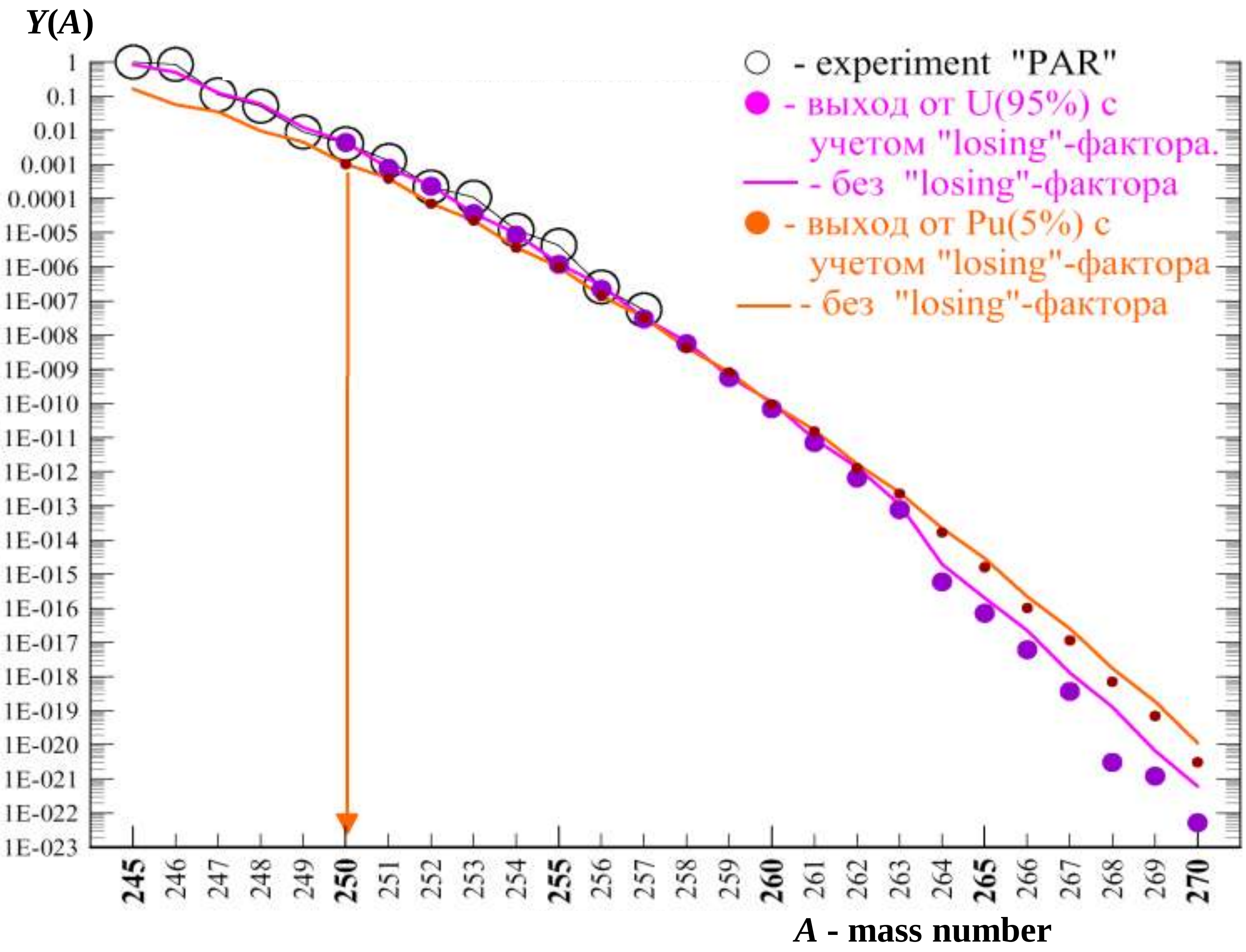
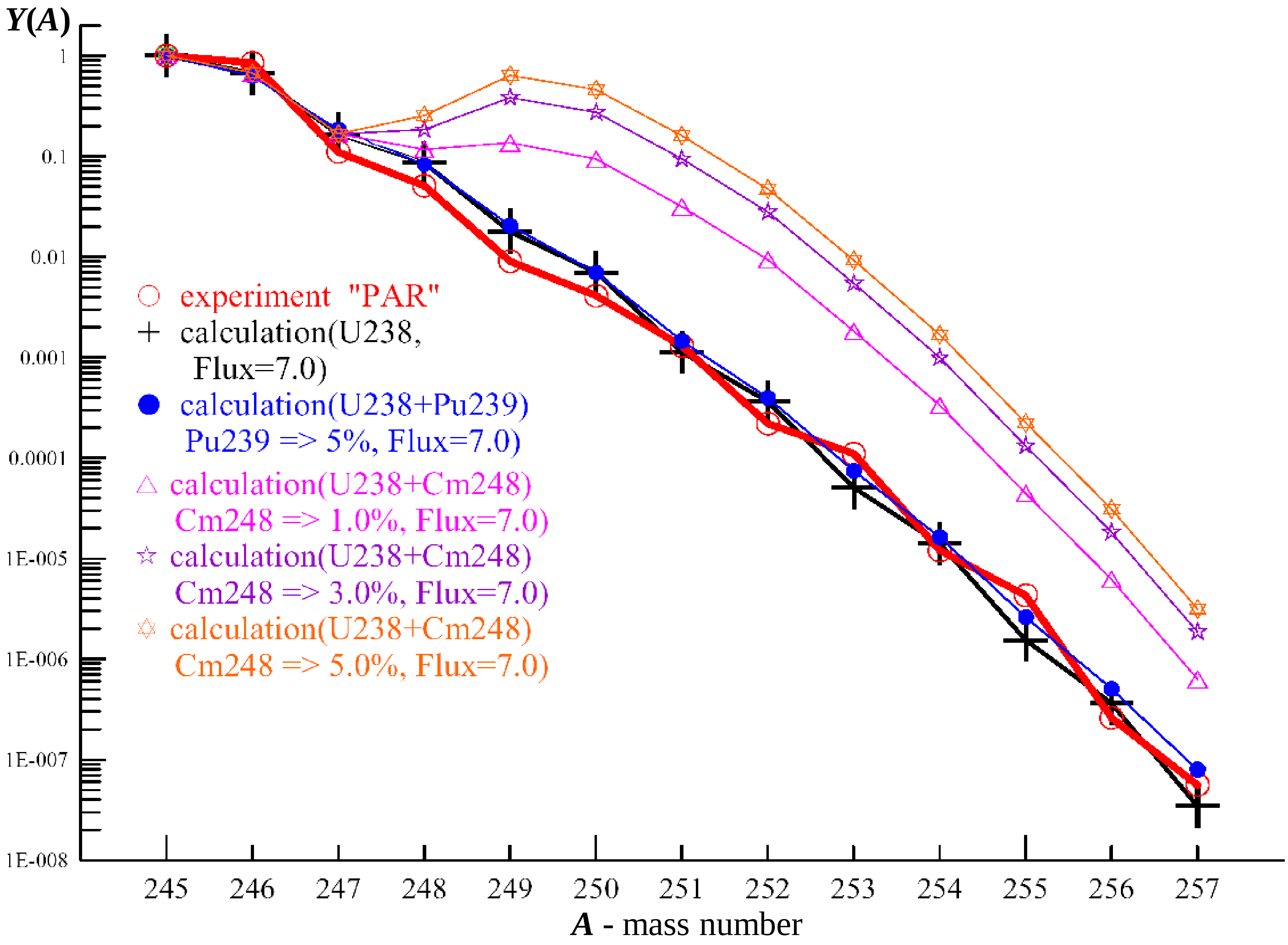


Strong dependence from target isotopes

Calculations for “PAR”- experiment to A = 270

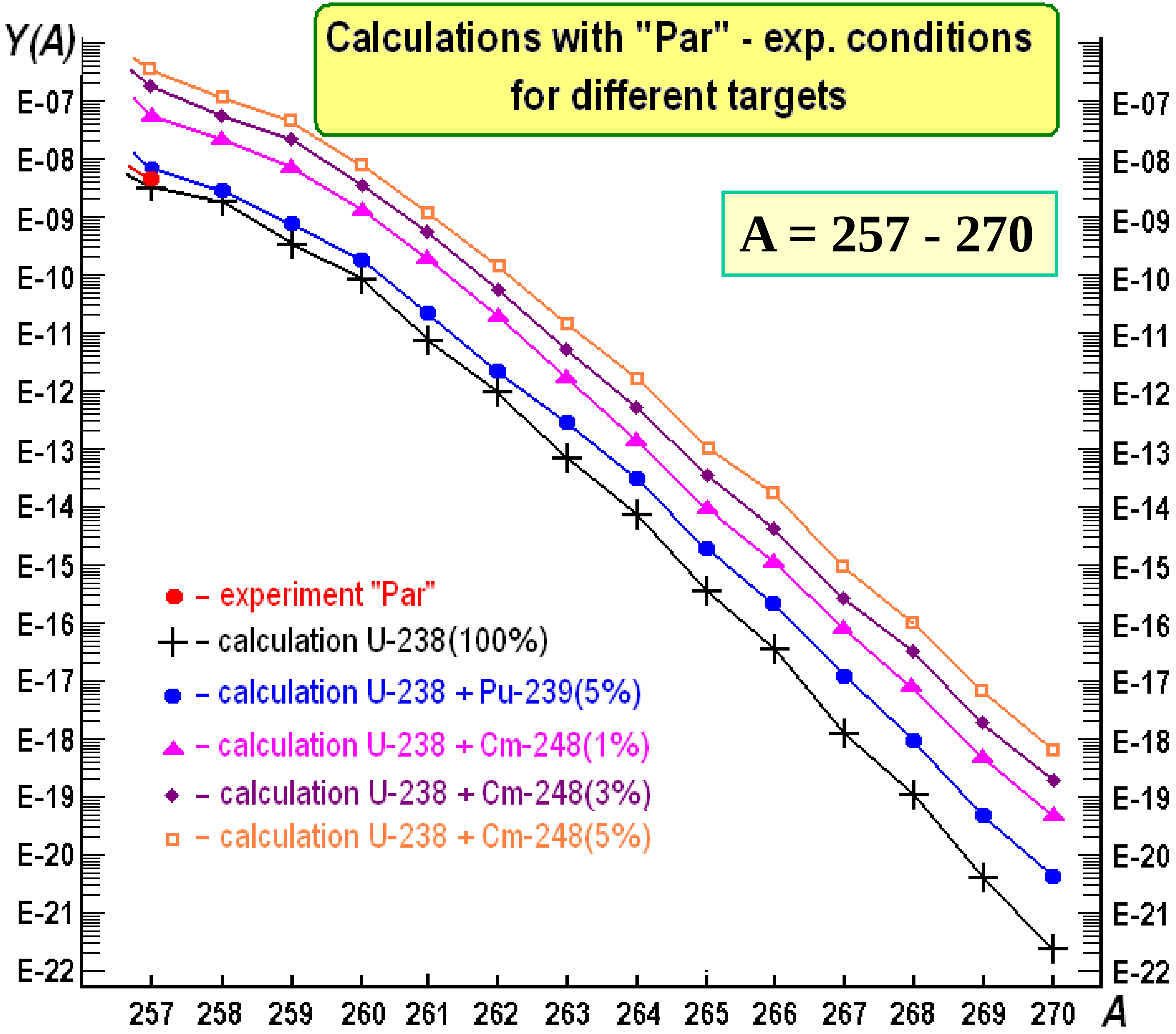


Calculations for “PAR”- experiment with ^{238}U + ^{248}Cm target

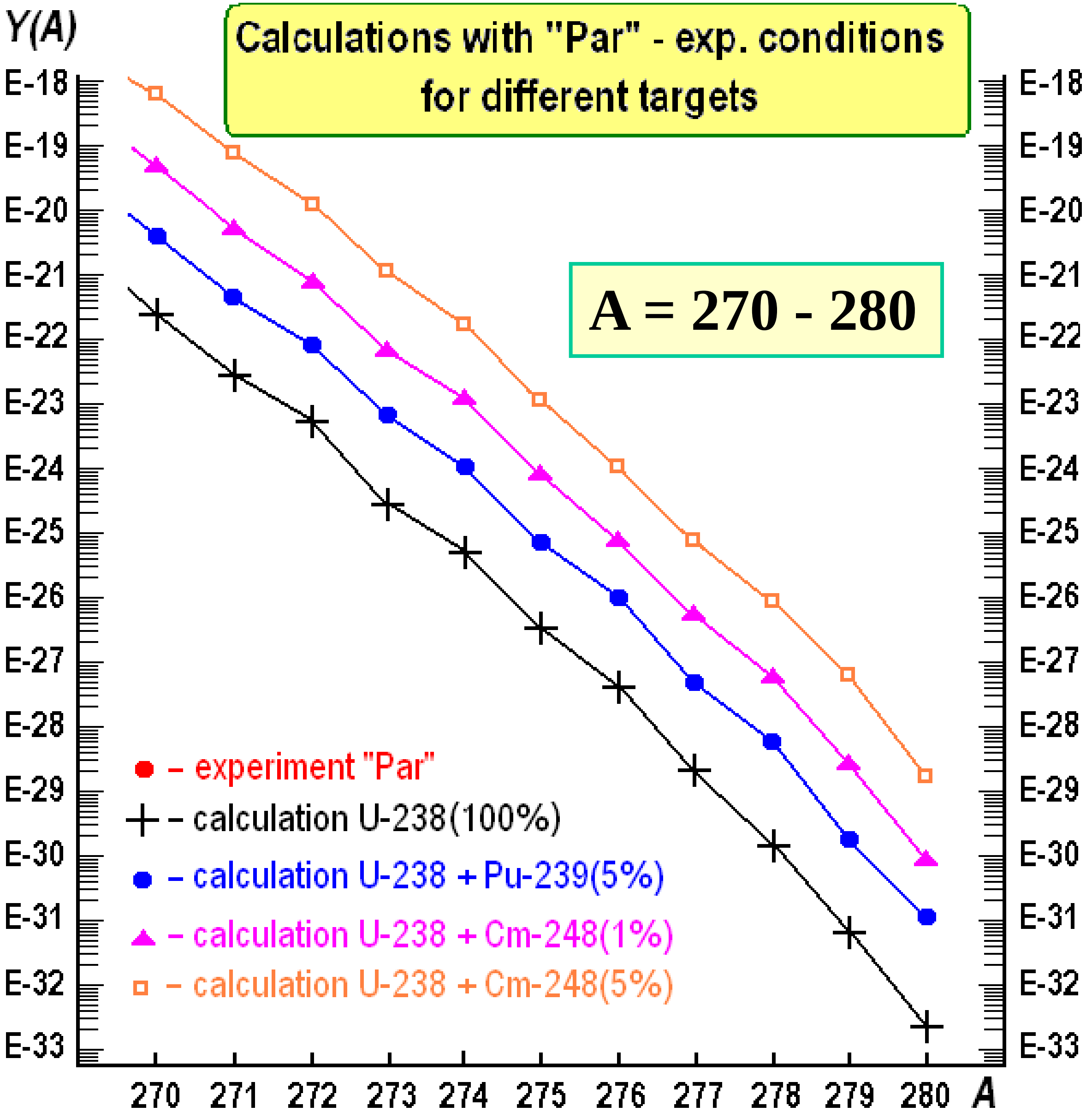


Calculations with "Par" - exp. conditions for different targets

A = 257 - 270



Calculations with "Par" - exp. conditions for different targets



A = 270 - 280

NUCLEOSINTHESIS AFTER NEUTRON PULSE – 1

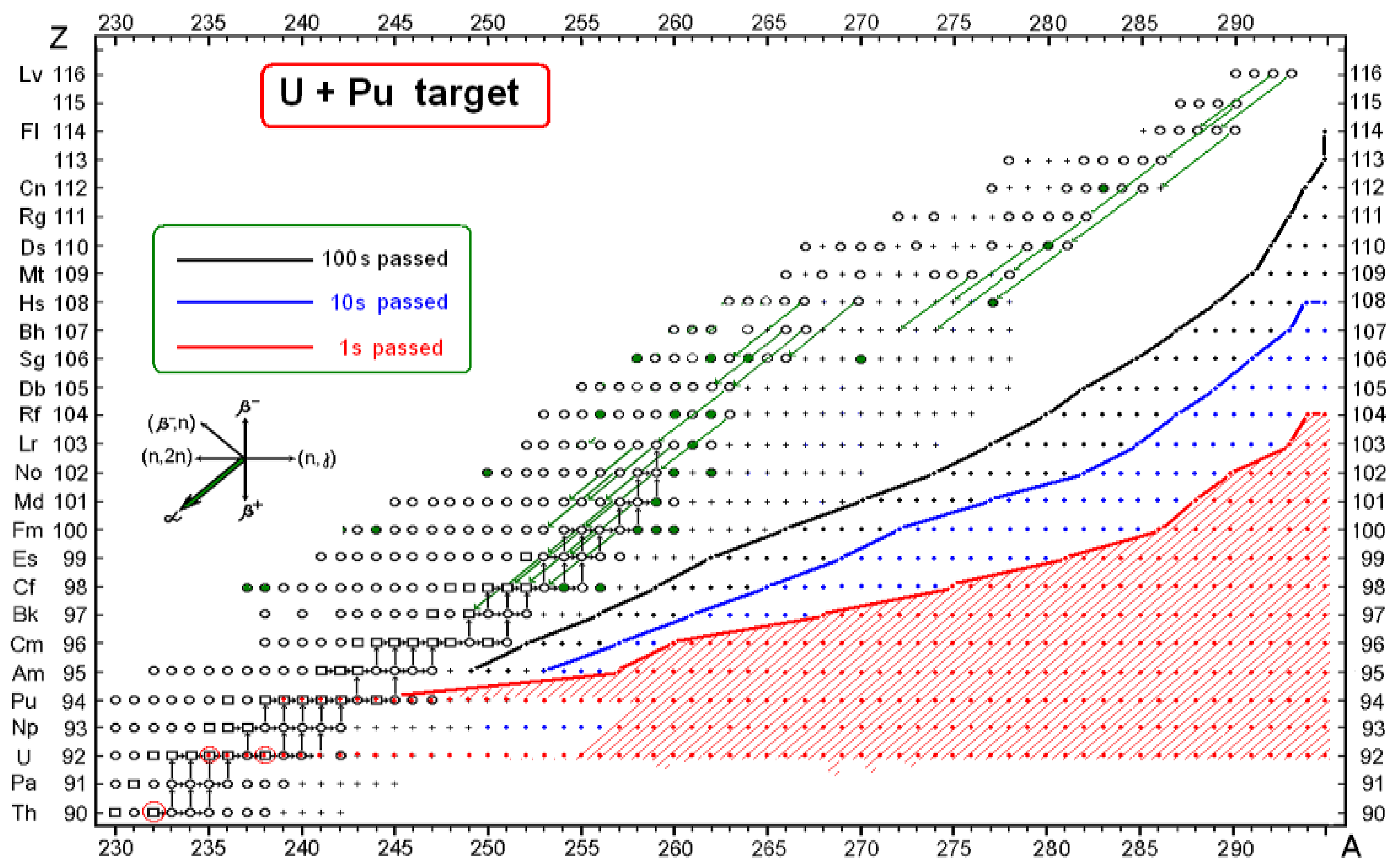
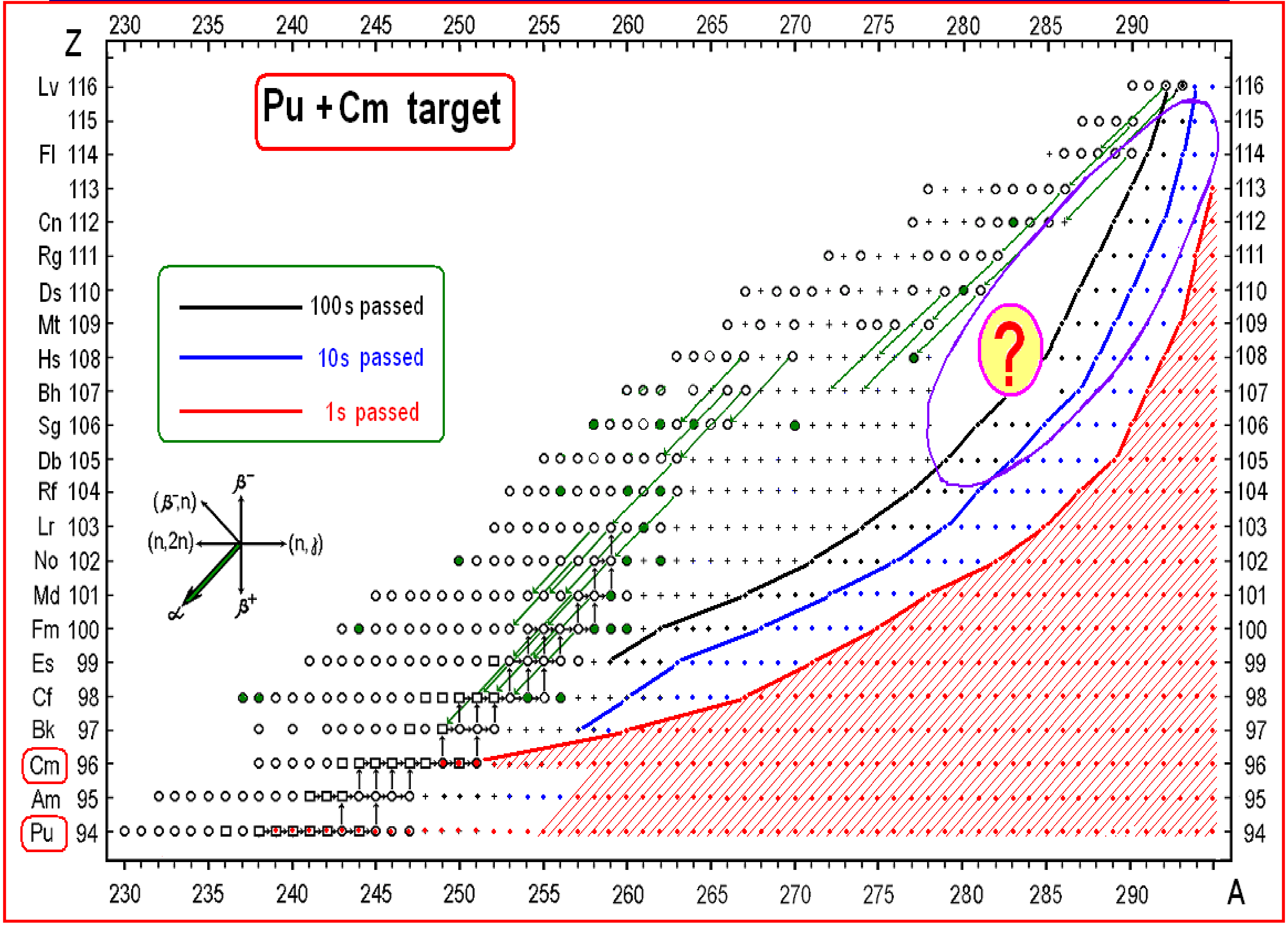


Схема образования актинидов в быстром (*r*-процесс) нуклеосинтезе (ядерный взрыв); □ – ядра с $T_{1/2} \geq 1$ г ; O – ядра с $T_{1/2} < 1$ г; + - прогнозируемые нейтронно-избыточные ядра

NUCLEOSINTHESIS AFTER NEUTRON PULSE – 2



Conclusion

-The binary model of transuranium elements production in pulse neutron fluxes is developed. The calculations of the transuranium isotopes yields up to $A = 295$ in pulsed neutron fluxes of high intensity in the adiabatic binary model were performed with start isotopes: ^{238}U, ^{239}Pu, ^{248}Cm and ^{251}Cf.

-Comparison of yields calculations up to $A = 257$ for binary targets with experiment data were carried out to "*Par*", "*Barbel*" and "*Mike*" thermonuclear explosions.

-Experimental data on the yields of transuranium isotopes in nuclear explosions revealed anomalous odd-even inversion effect, that is not small in the mass number $A > 250$, and may be explained by the delayed fission process, calculations with which leads to better agreement with experiment. The agreement of the calculated isotopes yields with the experimental data is up to 50%.

- The "eating away" effect – the losing effect, which gives the relative decreasing of the concentration of nuclei with fix A and which is due to the emission of delayed neutrons and delayed fission - the processes leading to changes in the concentrations of β-decay of short-lived intermediates, formed nuclei with large neutron excess. It is shown that the $L(A)$-effect associated with the observed even-odd inversion in yields of the transuranium nuclides.

- It is shown that nuclei with $A \approx 270$ can be obtained in the "Par" experiments with the yields ~ 10^{-22} using a uranium target, and – with the yields ~ $10^{-18} \div 10^{-20}$ using binary U+Pu and U+Cm targets.

- Heavier nuclei with $A \approx 280$ can be obtained with a yields ~ $10^{-29} \div 10^{-31}$ using binary U + Pu and U + Cm target. Such low concentrations can not be detected by modern experimental methods. Moreover, these nuclides decay rapidly.

- So the calculations were carried out up to the values of $A = 295$. It was obtained that the isotopic relations of some transuranium elements, for example - curium, depends on the value of the pulse neutron flux. This may be an indicator of the pulse component in cases of extreme accidents at the nuclear power stations.

Заключение

- Проведены расчеты выходов трансурановых изотопов до *A* = 295 в импульсных нейтронных потоках высокой интенсивности в адиабатической бинарной модели со стартовыми изотопами: ^{238}U, ^{239}Pu, ^{248}Cm и ^{251}Cf.

- Сравнение расчетов выходов до *A* = 257 для U - и (U + Pu)-мишеней проведено по данным экспериментов “*Par*”, “*Barbel*” и “*Mike*”.

- Экспериментальные данные по выходам трансуранов в ядерных взрывах выявили аномальный нечетно-четный эффект, проявляющийся при массовом числе *A* > 250, который объясняется введением в модель запаздывающего деления, что ведет к улучшению согласия с экспериментом. Получено согласие в выходах изотопов в пределах до 50%.

- Изучен эффект “выедания” (*losing*-эффект), который дает относительное снижение концентраций для ядер данного *A* и который объясняется эмиссией запаздывающих нейтронов и запаздывающим делением – процессами ведущими к изменению концентраций при β-распаде образовавшихся промежуточных короткоживущих ядер с большим избытком нейтронов. Показано, что этот *L*-эффект связан с наблюдаемой четно-нечетной инверсией в выходах трансурановых нуклидов.

- Показано, что ядра с *A* ≈ 270 могут быть получены в экспериментах типа “*Par*” с выходами ~ 10^{-22} при использовании урановой мишени и – с выходами ~ 10^{-18} 10^{-20} при использовании бинарной U + Pu или U + Cm мишени.

- Более тяжелые ядра с *A* ≈ 280 могут быть получены с выходами ~ 10^{-29} 10^{-31} при использовании бинарной U + Pu или U + Cm мишени. Такие малые концентрации не могут быть определены современными методами. Более того, такие нуклиды быстро распадаются.

THE END

СПАСИБО = THANK YOU

Экспериментальное исследование образования трансурановых элементов в интенсивных нейтронных потоках

Впервые трансурановые элементы были обнаружены в продуктах термоядерного взрыва “**Mike**” в 1952 г с мишенью **^{238}U**.
Ядерные и термоядерные взрывы обеспечивают большой поток нейтронов (10^{24} – 10^{25} нейтронов/см^{2}) при кратковременной экспозиции (~ <10^{-6} с – для реакций захвата) и тем самым являются уникальным инструментом для исследований в ядерной физике.

Для сравнения:

максимальный поток, достигнутый на реакторе **HFIR** – 5.5 * 10^{15} нейтронов/с;
в ловушке **ПИК** (проектное значение) – 4·10^{15} нейтр./(см^{2}с),
за 1 год работы - 1.2·10^{23} нейтр./см^{2} ;
в ловушке **СМ-2** – 5·10^{15} нейтр./(см^{2}с);
ИГР (импульсный графитовый) - максимальный интегральный поток – 1·10^{18} нейтр./см^{2}
БИГР (импульсный) - 1.2·10^{16} нейтр./см^{2} в центральном канале;
Гидра (импульсный растворный) – 8·10^{14} нейтр./см^{2} ;
ЯГУАР (импульсный растворный) – 2.5·10^{18} нейтр./(см^{2}с) в импульсе в выводящем канале.