# ISOMERIC YIELD RATIOS OF FISSION FRAGMENTS $^{131}$Te, $^{132}$Sb, $^{133}$Te, $^{132,134}$I, $^{135}$Xe IN (γ, f), (γ, nf) REACTIONS ON $^{235}$U, $^{237}$Np, $^{239}$Pu

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# Plan of report

- Aim of the study;
- Experimental methods;
- Photo-fission spectrum of fragments;
- Values of isomeric yield ratios;
- Average angular momentum of the primary fragments;
- Influence of shapes of radiate strength functions (RSF) and nuclear level densities (NLD);
- Comparison with other results;
- Conclusions.

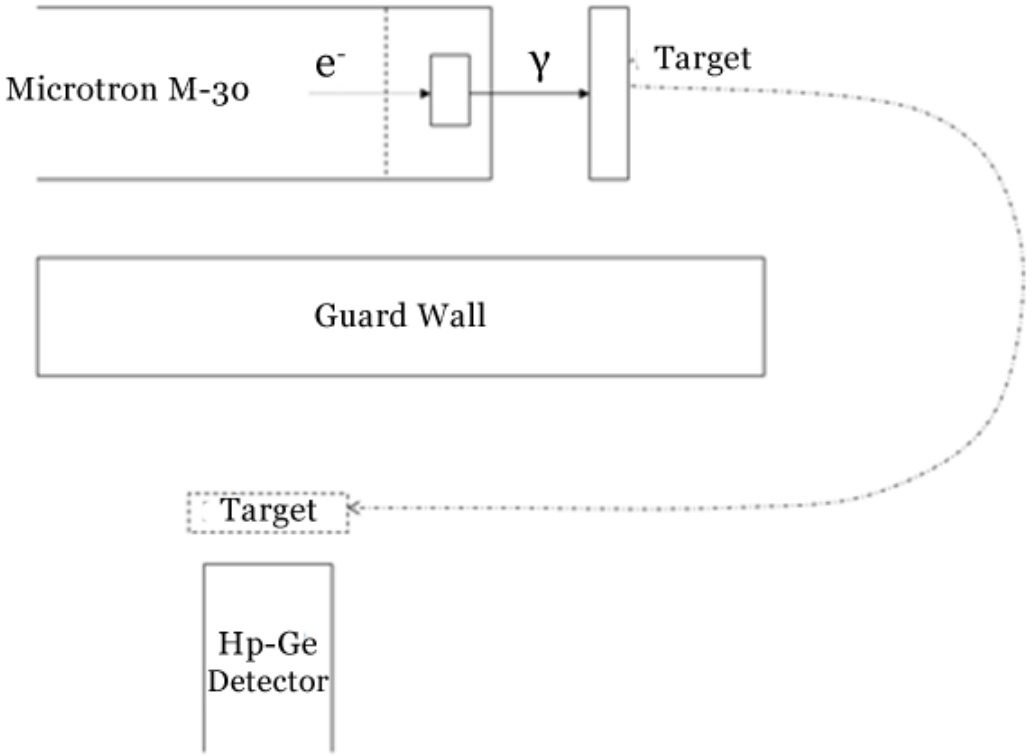
# Scientific interest and purpose of the study

- The study of the scission configuration and mechanism of the spin generation in the fissioning nuclei;
- Scientific interest for nuclear science and engineering;
- Influence of different RSF and NLD on average angular momentum of studied isotopes;
- Influence of paired and unpaired effects on isomeric yields ratios;
- Effect of (γ, nf), (γ, 2nf) fission channel.

# Experimental methods

- $^{235}U$, $^{237}Np$, $^{239}Pu$ samples were irradiated by bremsstrahlung from microtron M-30 (The Laboratory of Photonuclear Reactions of the Institute of Electron Physics, National Academy of Sciences of Ukraine, Uzhgorod, Ukraine).
- Targets of $^{235}U$, $^{237}Np$ and $^{239}Pu$ were enriched: $^{235}U$ - 90% ($^{238}U$ - 10%), $^{237}Np$ - 100% and $^{239}Pu$ - 95.5% ($^{240}Pu$ - 4.5%).
- The weight of $^{235}U$, $^{237}Np$ and $^{239}Pu$ samples was respectively: 514mg, 853mg and 400mg.

# Scheme of the experiment




- A cooled tantalum disk (2-mm thick) was used as a bremsstrahlung producing target after hits of the electron beam. The end-point energy of the bremsstrahlung was equal to 18MeV.

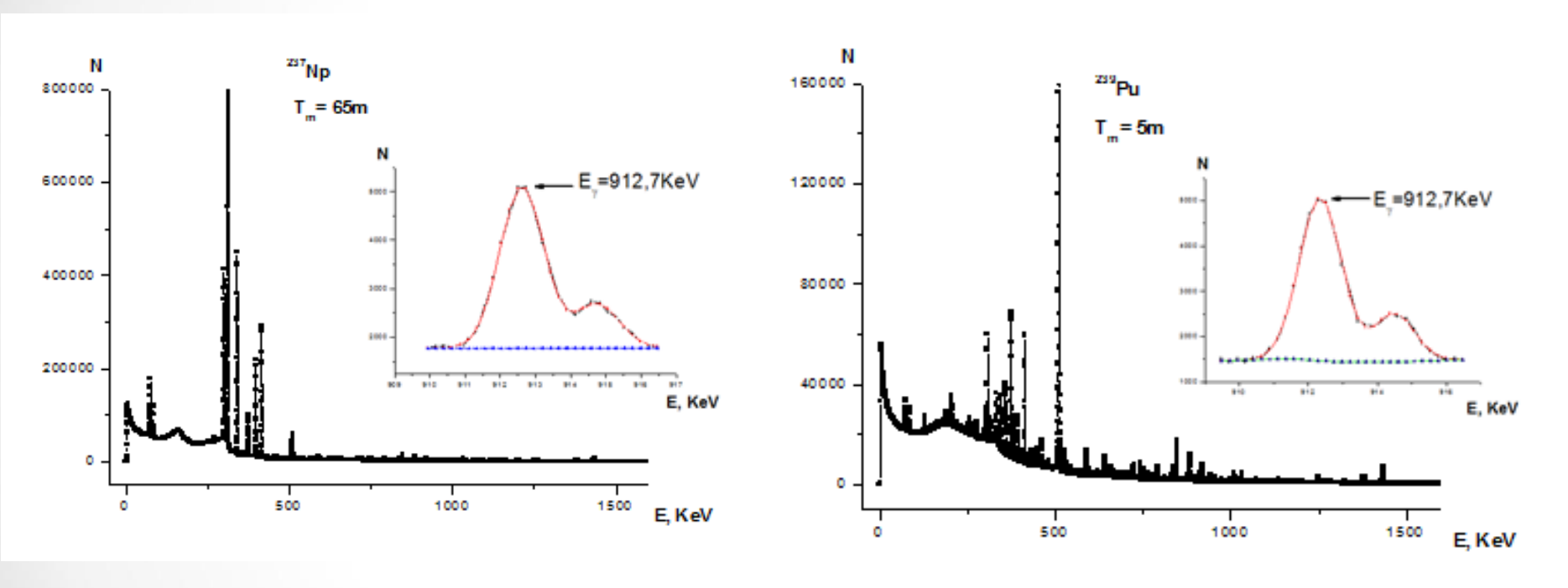
# Characteristics of cyclotron M-30

- Maximal end-point energy of the bremsstrahlung – 18MeV;
- Average current of electrons – 1.5 mkA;
- Time of one impulse – 1 mks;
- Frequency of impulses – 1000Gz;
- Outlet size of electron beam – 12x4mm;
- Energy error – 0.5%;

# Characteristics of spectrometers

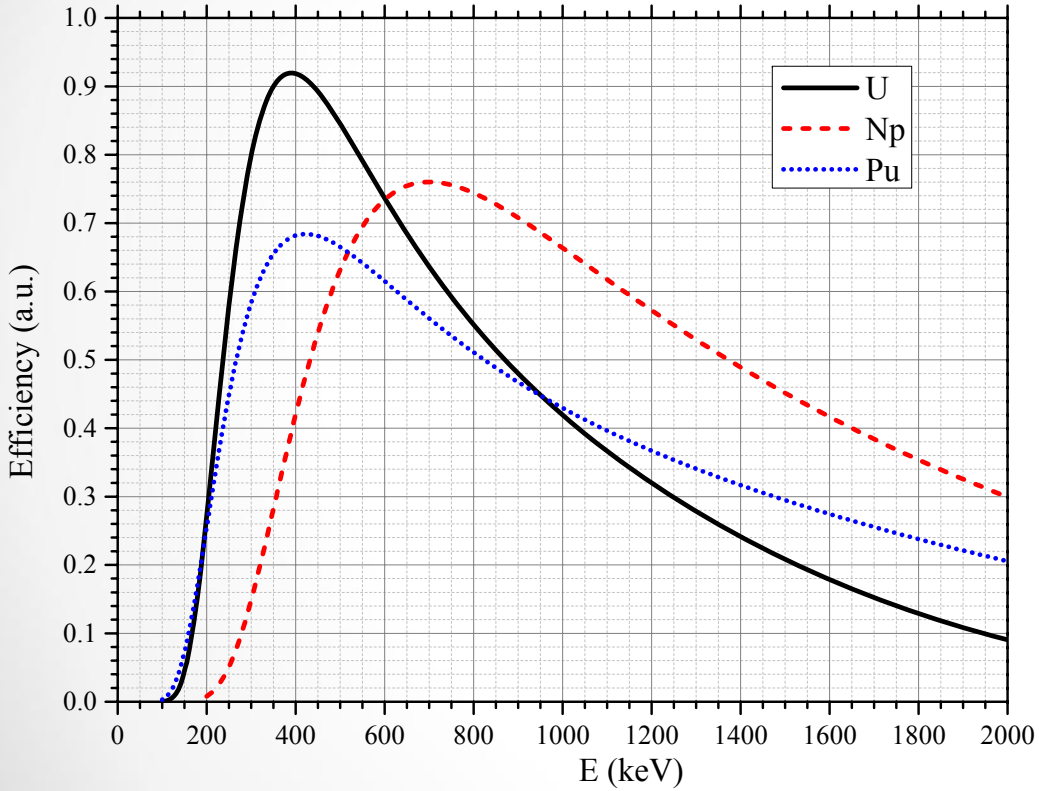
- The $\gamma$ -spectra of the photoreaction products were measured by the system of HPGe detectors of CANBERRA with 1.8keV energy resolution (for $\gamma$ -line 1330 keV $^{60}$Co).

# Photo-fission fragments of spectrums for $^{237}Np$, $^{239}Pu$



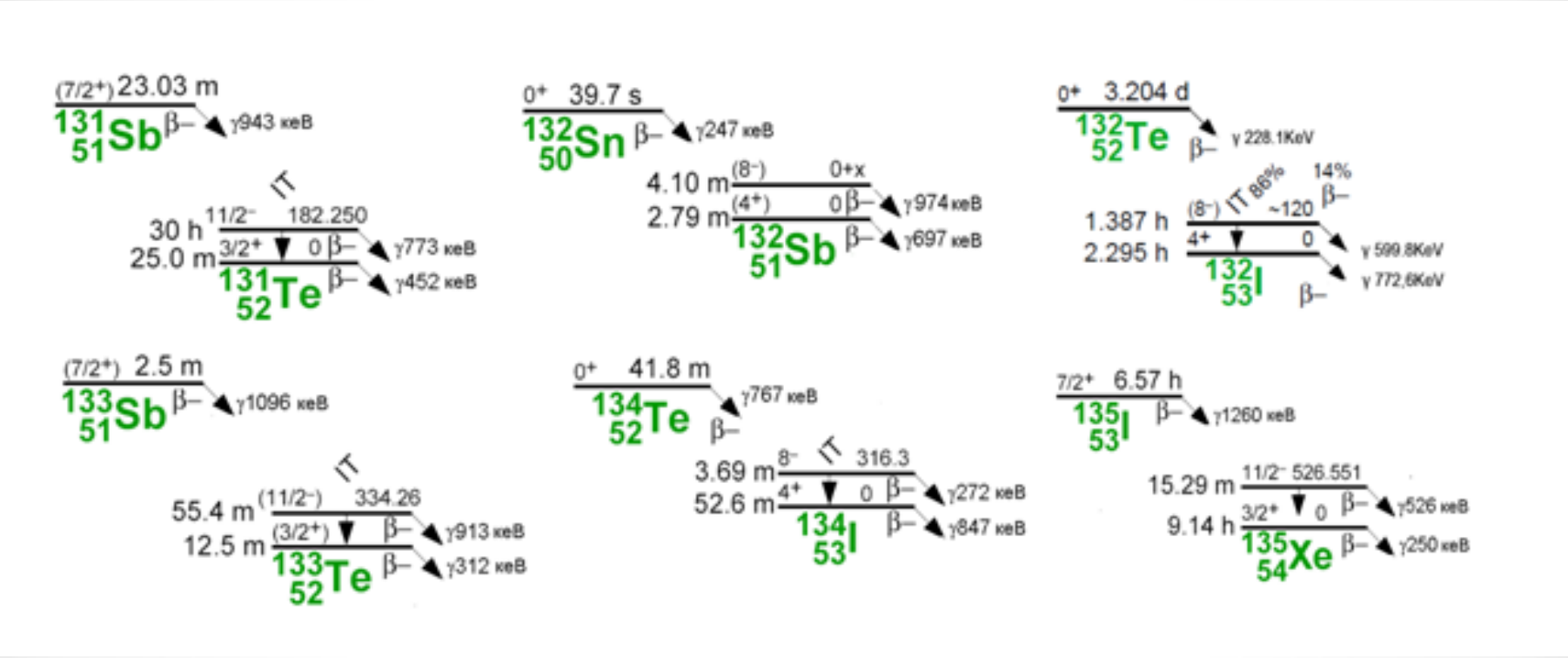

Typical total gamma-spectra of photofission products after different time periods, that were used to determine the intensity of the peaks of studied isomeric pairs. Also was carried out intensity of peaks of nuclei isobaric chain.

# Spectrometer calibration on the effectiveness




Relative calibration on the effectiveness γ-transitions of nuclei: $^{101}$Mo, $^{101}$Tc, $^{130}$Sb, $^{134}$I, $^{134}$Te, $^{138}$Xe, $^{138}$Cs photofission products of $^{235}$U, $^{237}$Np, $^{239}$Pu. Internal calibration was performed due to large size of targets.

# Decay schemes of studied isotopes




- The contributions to the isomeric yield ratios for given nuclide produced by β-decay from nuclei of parent isobaric chain must be removed

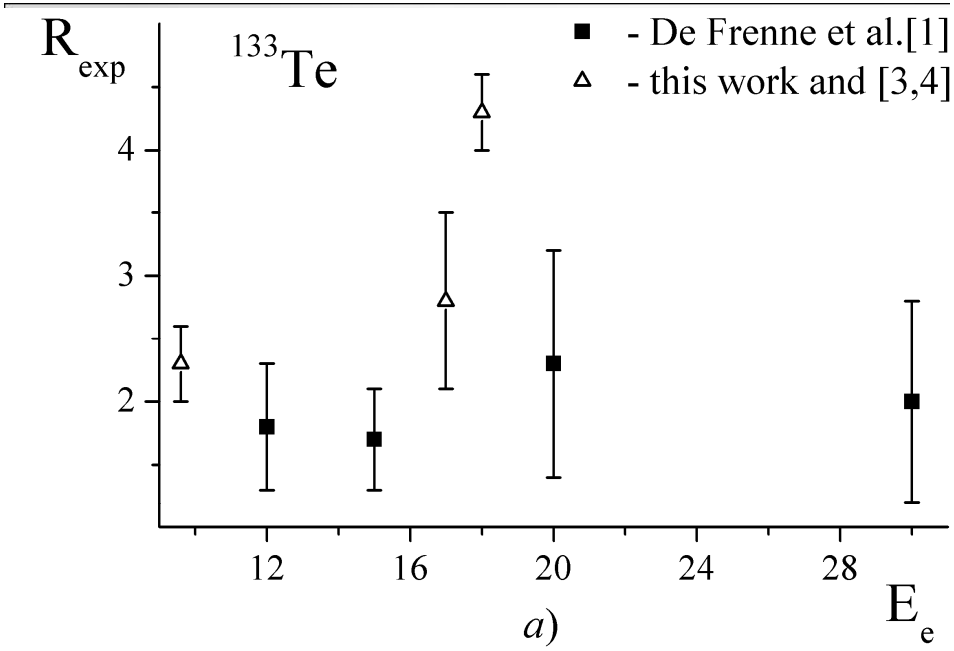
# Data processing

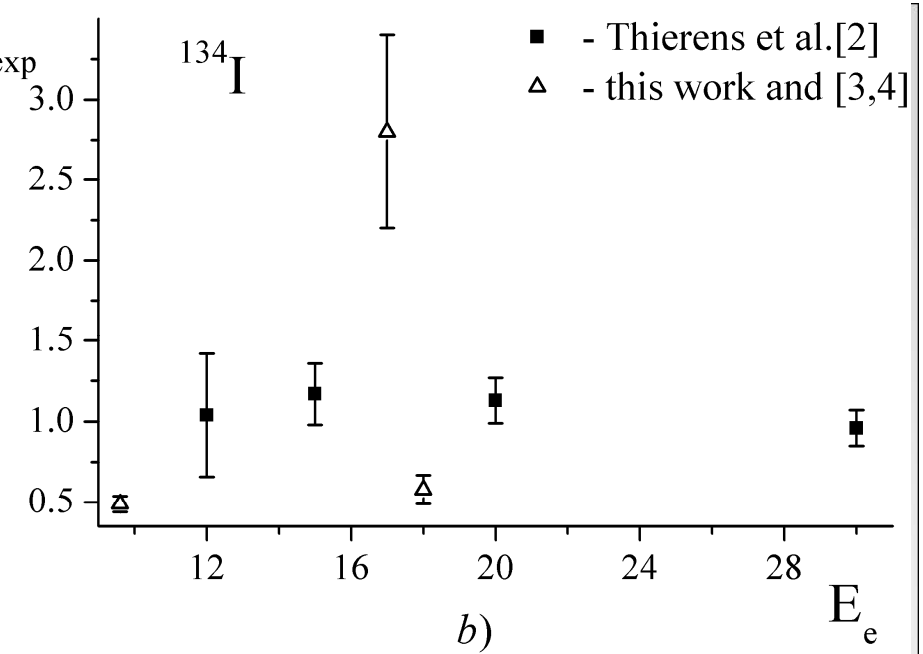
- Measuring time (2 hours) was divided on 5 individual intervals according to half-live times of studied isotopes;
- All studied peaks were fitted by Gaussian and polynomial curves;
- Intensities of all peaks with uncertainties were found and analyzed using WINSPECTRUM code (KINR, Nuclear spectroscopy Dep.). This code permits to analyze total spectra in different time periods. It allows identification of the isotopes by the $\gamma$ -ray energies and the lifetimes. The experimental values of isomeric yield ratios were determined with removing the contributions to populations of $^{131}Te$, $^{132}Sb$, $^{133}Te$, $^{132,134}I$ and $^{135}Xe$ states from β-decay of nuclei of parent isobaric chains.

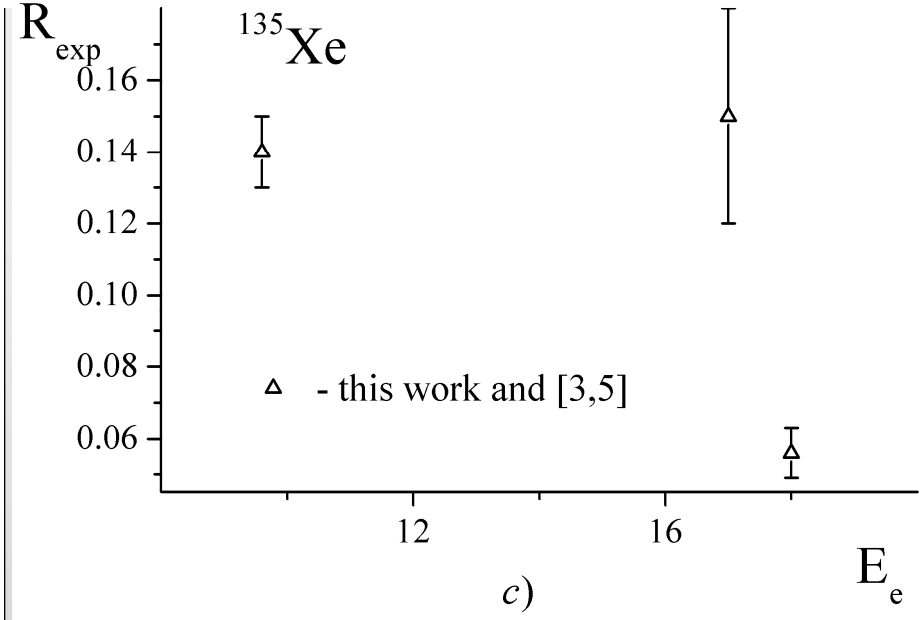
# Results of measurements

| Nuclei | $^{235}$U | $^{237}$Np | $^{239}$Pu |
|---|---|---|---|
| $^{131}$Te | 2.6(0.5) | 1.9(0.3) | 3.2(0.6) |
| $^{132}$Sb | 1.46(0.22) | 1.01(0.12) | 1.48(0.16) |
| $^{132}$I | 2.2(0.4) | 0.95(0.15) | 0.51(0.06) |
| $^{133}$Te | 4.3(0.3) | 9.0(0.9) | 5.3(0.3) |
| $^{134}$I | 0.58(0.09) | - | 1.26(0.25) |
| $^{135}$Xe | 0.056(0.007) | 0.041(0.006) | 0.066(0.007) |

- The values of nuclei isomeric yield ratios $R_{exp}=Y_m/Y_g$ of $^{131}$Te, $^{132}$Sb, $^{132}$I, $^{133}$Te, $^{134}$I, $^{135}$Xe for bremsstrahlung end-point energy 18MeV, where $Y_g$ ($Y_m$) fission product yields for ground (isomer) state. The numbers in parentheses are the uncertainties (one-sigma standard deviation) of the isomeric ratio values.




Isomeric yield ratios $R_{exp}$ of the primary fragments $^{133}$Te and $^{134}$I in photofission of $^{235}$U with bremsstrahlung with different end-point energy $E_e$


• 1. *De Frenne D., Proot B., Thierens H., De Gelder P., Jacobs E., De Clercq A.* // Phys. Rev. C. – 1984. - Vol. 29, № 5. - P.1777 – 1783.

2. *Thierens H., Proot B., De Frenne D., Jacobs E.* // Phys. Rev. C. – 1982.- Vol.25, № 3. - P.1546-1550.

3. *Vishnevskii I.N., Davidovskaya O.I., Zheltonozhskii V.A. et al.*, // Izv. Akad. Nauk, Ser. Fiz. – 2010.- Vol.74. – P.538-541. [*Bull. Russian Acad. Sci.* (Engl. Transl.) – 2010. - Vol.74 - P.500-503].

4. *Vishnevskii I.N., Zheltonozhskii V.A., Savrasov A.N., Rovenskykh E.P., Plujko V.A., Gorbachenko O.M.* // Proc. of ISINN21 (in press)

# Calculations of average angular momentum of primary fission fragments

The average angular momentum: $$\bar{J} = \sum_J JP(J) / \sum_j P(j) \qquad (1)$$

The angular momentum distributions:

$$P(J) = P(J,\lambda) = (2J+1)\exp(-J(J+1)/2B^2 - \lambda J) \qquad (2)$$

$$P(J) = P(J,\mu) = (2J+1)\exp(-J(J+1)/2(B+\mu)^2) \qquad (3)$$

$\chi = \lambda,\ \mu$ - free parameters were found from fitting of the calculated isomeric ratios $R_{th}$ to the to $R_{\exp} = Y_m / Y_g$

$$R_{th} = \frac{\sum_{J,\pi} \int dU \cdot \varphi(U) \cdot P(J,\chi) \cdot \sigma_m(U,J,\pi)}{\sum_{j,\pi} \int dU \cdot \varphi(U) \cdot P(j,\chi) \cdot \sigma_g(U,j,\pi)} \qquad (4)$$

$$R_{th} = \frac{\sum_{J,\pi} \int dU \cdot \varphi(U) \cdot P(J,\chi) \cdot \sigma_m(U,J,\pi)}{\sum_{j,\pi} \int dU \cdot \varphi(U) \cdot P(j,\chi) \cdot \sigma_g(U,j,\pi)}$$

Energy distribution function: $\varphi(U) = \begin{cases} 1, & U_{\min} \le U \le U_{\max} \\ 0, & U < U_{\min} \text{ or } U > U_{\max} \end{cases}$

$$U_{\min} = 0.5S_n + n\Delta_0 + E_{rot}(J), \qquad U_{\max} = S_n + n\Delta_0 + E_{rot}(J)$$

$n\Delta_0$ is pairing energy correction with $\Delta_0 = 12/\sqrt{A}$

$n = 2,1,0$ for even-even, odd, odd-odd nuclei

$$E_{rot}(J) = J(J+1)/(2F)$$

$F$ -moment of inertia: $F = 0.0194\, A^{5/3}$, $\hbar^2 MeV^{-1}$

The parameter $B$ was fixed: $B^2 = F \cdot T$, $T = \sqrt{\bar{U}/a}$,

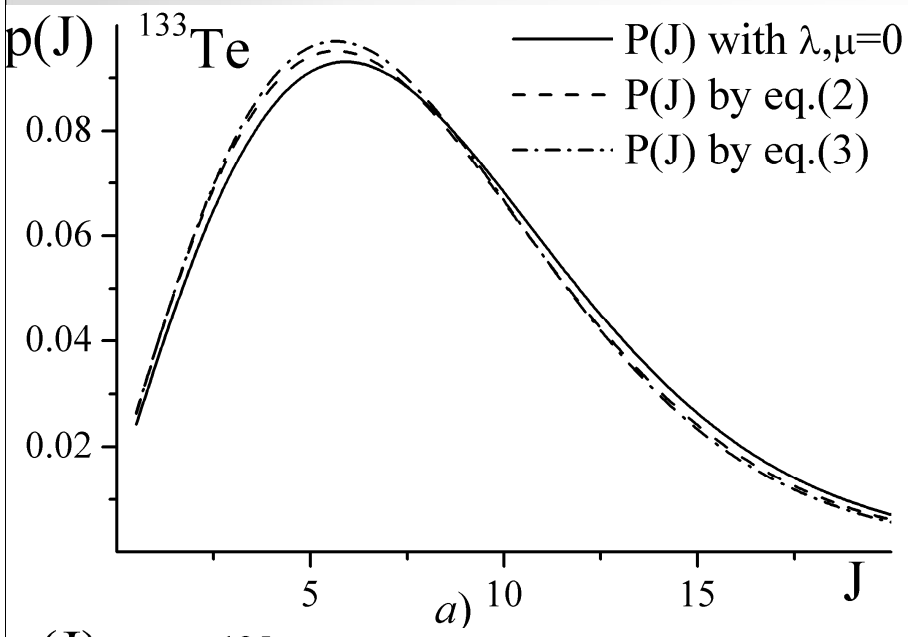
$\bar{U} = (U_{\min} + U_{\max})/2$, $a = A/10$, MeV$^{-1}$

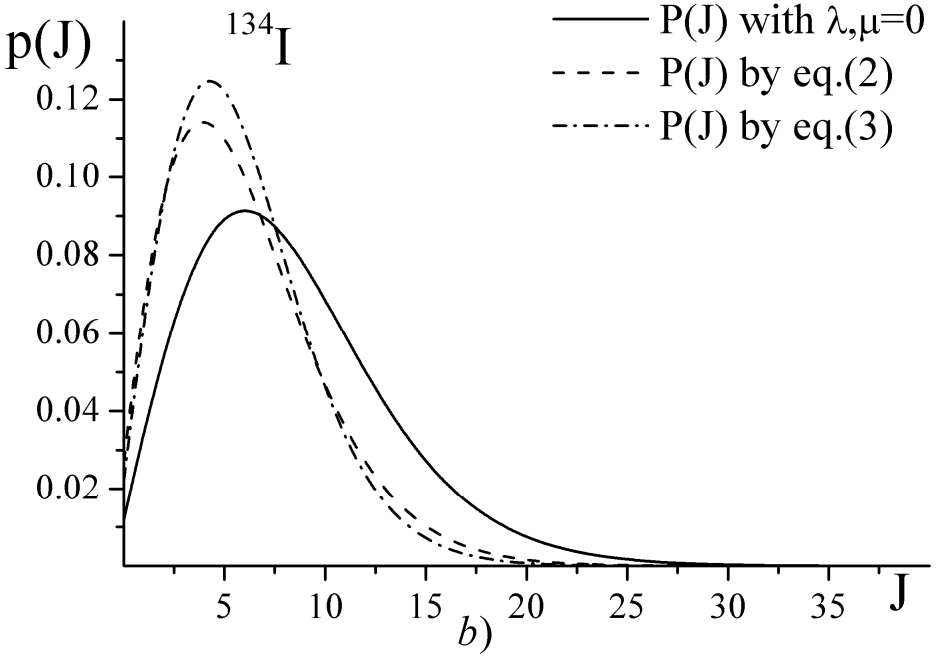
$\sigma_m(U,J,\pi)$ $(\sigma_g(U,J,\pi))$ - is probability of population by the gamma-decay of the isomeric (ground) state from the states with excitation energy $U$, spin $J$, and parity $\pi = \pm 1$, which were calculated by the codes of the EMPIRE 3.2 and TALYS1.4 codes

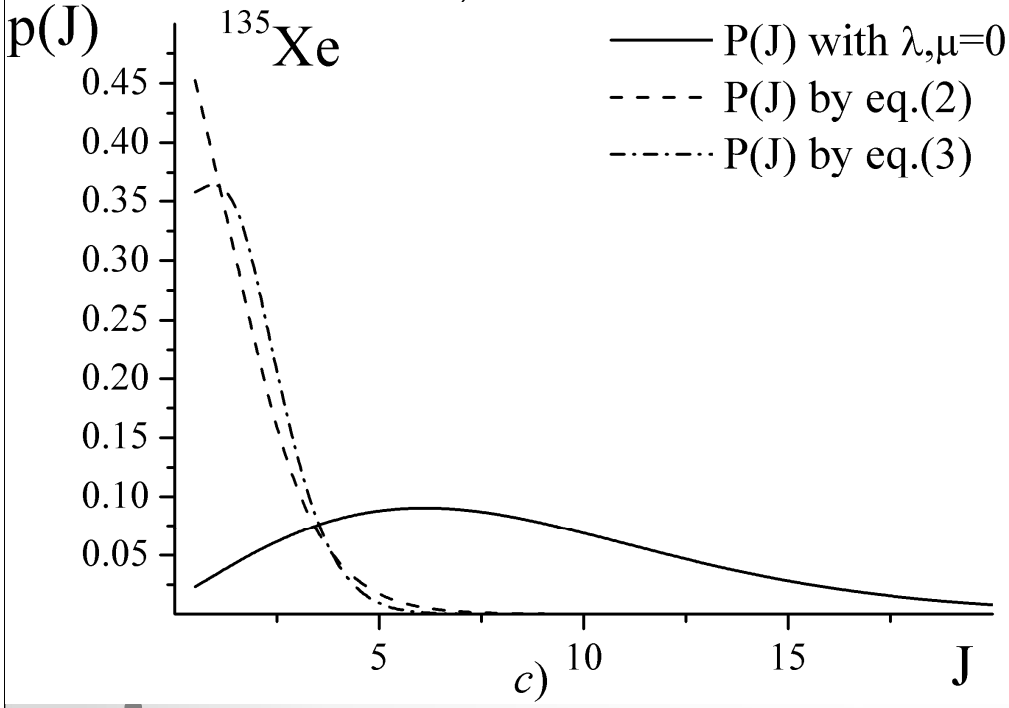
# Average angular momentum $\bar{J}$ of the primary fragments

| Nuclei | $^{235}$U | $^{237}$Np | $^{239}$Pu |
|---|---|---|---|
| $^{131}$Te | 6.5(0.9) | 5.5(0.8) | 7.2(0.9) |
| $^{132}$Sb | 4.2(0.5) | 6.8(0.7) | 8.2(0.8) |
| $^{132}$I | 10.2(1.3) | 6.5(0.8) | 5.1(0.6) |
| $^{133}$Te | 7.5(0.7) | 12.5(1.2) | 8.5(0.7) |
| $^{134}$I | 5.5(0.7) | 5.4(0.7) | 7.7(0.9) |
| $^{135}$Xe | 1.5(0.5) | 1.3(0.5) | 1.5(0.5) |

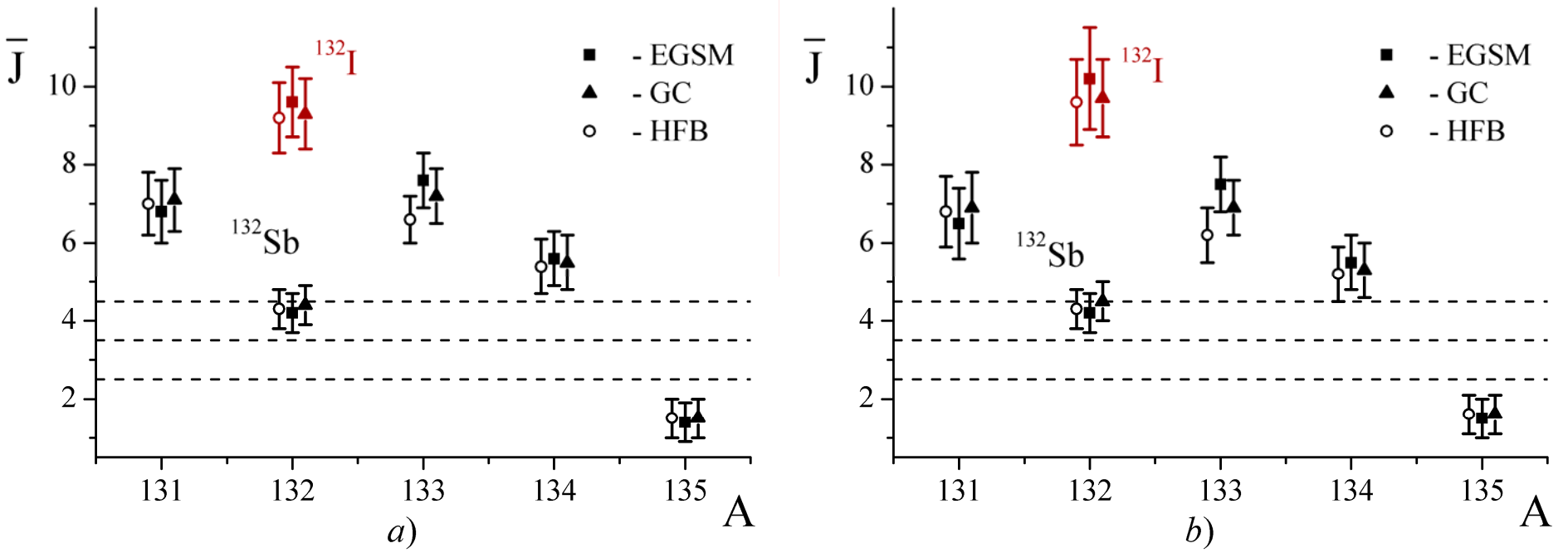
The population probabilities were calculated by EMPIRE 3.2 code with the RSF within MLO1 approach and NLD by EGSM approach. All other input parameters in the code were taken by default. The angular momentum distribution was given by (3).



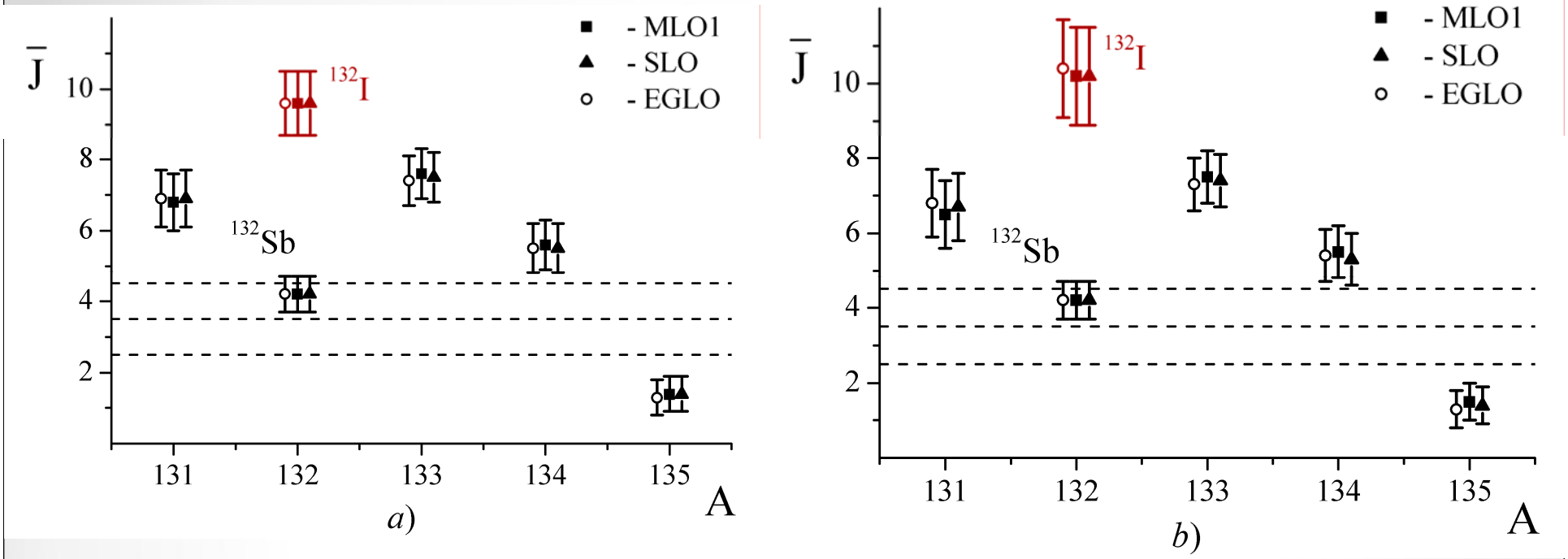



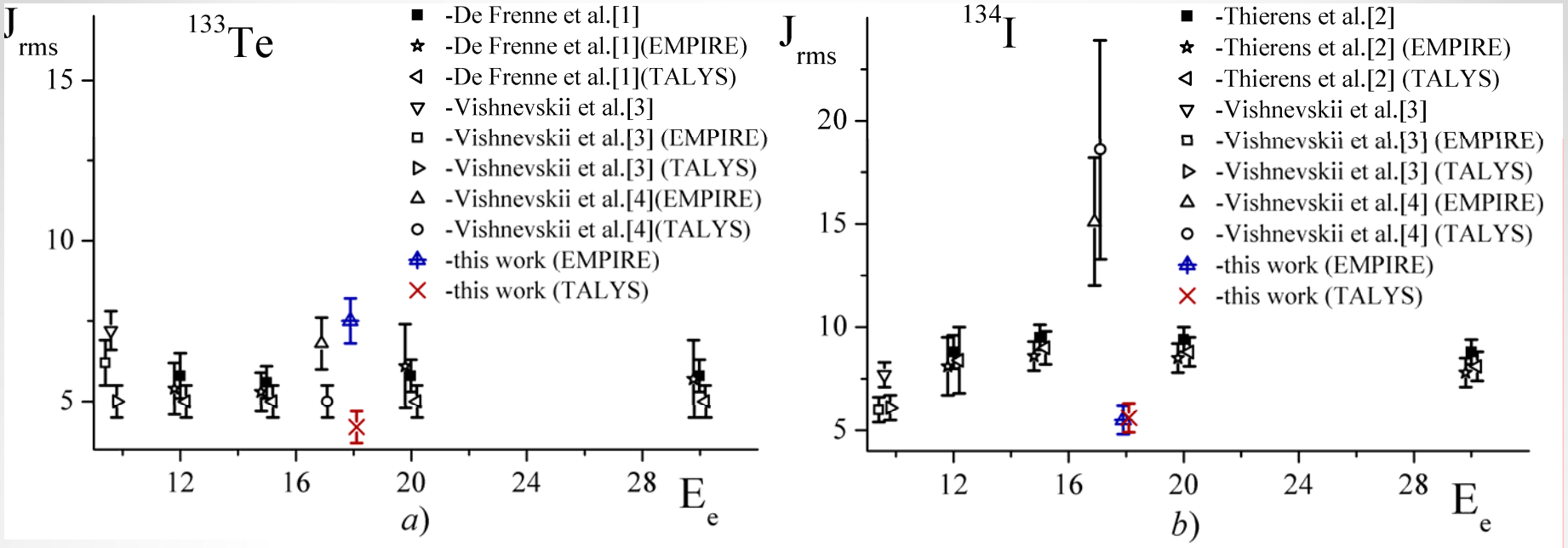

The normalized angular momentum distributions $p(J) = P(J) / \sum_j P(j)$ of primary fission fragments $^{133}$*Te-a),* $^{134}$*I-b),* $^{135}$*Xe-c)* calculated by the Eqs.(2), (3) with EMPIRE 3.2 default parameters.




Average angular momentum $\bar{J}$ of primary fragments $^{131}Te$, $^{132}Sb$, $^{133}Te$, $^{132,134}I$, $^{135}Xe$ of $^{235}U$ fission calculated with population probabilities within the EMPIRE 3.2 code with different models of the NLD (EGSM, GC, HFB): *a*) – results with the angular momentum distribution given by (2); *b*) – results with (3). For clear representation, the values $\bar{J}$ are scattered for given nuclide and NLD model. Dashed lines mark spins (5/2, 7/2, 9/2) of compound nucleus states of $^{235}U$ formed after dipole gamma-ray absorption.




Average angular momentum $\bar{J}$ of primary fragments $^{131}Te$, $^{132}Sb$, $^{133}Te$, $^{132,134}I$, $^{135}Xe$ of $^{235}U$ fission calculated with population probabilities within the EMPIRE 3.2 code with different shapes of the RSF (SLO, EGLO, MLO1): *a*) – results with the angular momentum distribution given by (2); *b*) – results with (3). For clear representation, the values $\bar{J}$ are scattered for given nuclide and RSF model. Dashed lines mark spins (5/2, 7/2, 9/2) of compound nucleus states of $^{235}U$ formed after dipole gamma-ray absorption.




Comparison of calculated average root mean square angular momentum $J_{rms} = \left(\overline{J^2}\right)^{1/2}$ of the primary fragments $^{133}$Te and $^{134}$I in photofission of $^{235}$U with bremsstrahlung with different end-point energy $E_e$


- 1. *De Frenne D., Proot B., Thierens H., De Gelder P., Jacobs E., De Clercq A.* Independent isomeric yield ratios and primary angular momenta in the photofission of *235,238U* with 12—30-MeV bremsstrahlung // Phys. Rev. C. – 1984. - Vol. 29, № 5. - P.1777 – 1783.

2. *Thierens H., Proot B., De Frenne D., Jacobs E.* Independent isomeric yield ratio of *134I* in the photofission of *235U* and *238U* // Phys. Rev. C. – 1982.- Vol.25, № 3. - P.1546-1550.

3. *Vishnevskii I.N., Davidovskaya O.I., Zheltonozhskii V.A. et al.*, Investigation of $^{235}U$ and $^{239}Pu$ photofission // Izv. Akad. Nauk, Ser. Fiz. – 2010.- Vol.74. – P.538-541. [*Bull. Russian Acad. Sci.* (Engl. Transl.) – 2010. - Vol.74 - P.500-503].

4. *Vishnevskii I.N., Zheltonozhskii V.A., Savrasov A.N., Rovenskykh E.P., Plujko V.A., Gorbachenko O.M.* Isomer Yield Ratios of Fission Fragments 133Te, 134i, 135xe in (γ, *f*), (γ, *nf*) Reactions on 235U // Proc. of ISINN21 (in press)

# SUMMARY

• Isomeric yield ratios of fission fragments $^{131}$Te, $^{132}$Sb, $^{133}$Te, $^{132,134}$I, $^{135}$Xe in (γ, f), (γ, nf), reactions on $^{235}$U, $^{237}$Np, $^{239}$Pu were measured with bremsstrahlung with the end-point energy 18 MeV. The contributions to the isomeric yields from nuclei of isobaric chains due to β-decay were taken into consideration.

• The average value and distribution of angular momentum of the primary fragments $^{131}$Te, $^{132}$Sb, $^{133}$Te, $^{132,134}$I, $^{135}$Xe were determined by a statistical model analysis. New simplified statistical method for calculation of the isomeric yield ratios and thereby for determination of angular momentum distribution and average angular momentum in the primary fission fragments are proposed and tested.

• It is shown that the values of average angular momentum are not strongly dependent on models of radiative strength function and nuclear level density: their mean values agree within the uncertainties and their difference does not exceed ~ 8%.

•It is also demonstrated that there is difference between average angular momentum of primary fission fragments and the spins of compound nucleus states of $^{235}U$, $^{237}Np$, $^{239}Pu$ formed just after dipole gamma-ray absorption. It confirms the presence of a mechanism during the fission process which generates angular momentum in the final fragments.

Thank you for your attention!

# Measured reactions and their thresholds for $^{235}U$

- $E_{tr}$ (γ, f) = 5,5MeV
- $E_{tr}$(γ, n) = 5,3MeV
- $E_{tr}$(γ, 2n) = 12,1MeV
- $E_{tr}$(γ, p) = 6,7MeV
- $E_{tr}$(γ, t) = 10MeV
- $E_{tr}$(γ, $^{3}$He) = 9,5MeV
- $E_{tr}$(γ, α) = - 4,7MeV
- $E_{tr}$(γ, np) = 11,9MeV
- $E_{tr}$(γ, 2p) = 12,4MeV

**Possible reactions for maximal bremsstrahlung energy - 18MeV**