DETAILED STUDY OF N-N ANGULAR CORRELATIONS IN SLOW-NEUTRON-INDUCED FISSION OF ^{233}U, ^{235}U AND ^{239}Pu

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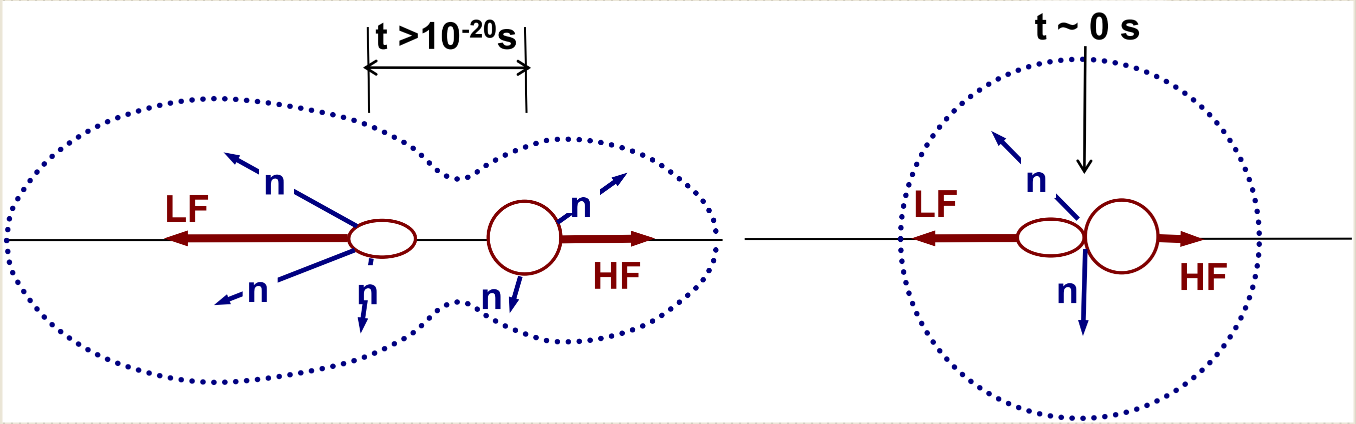
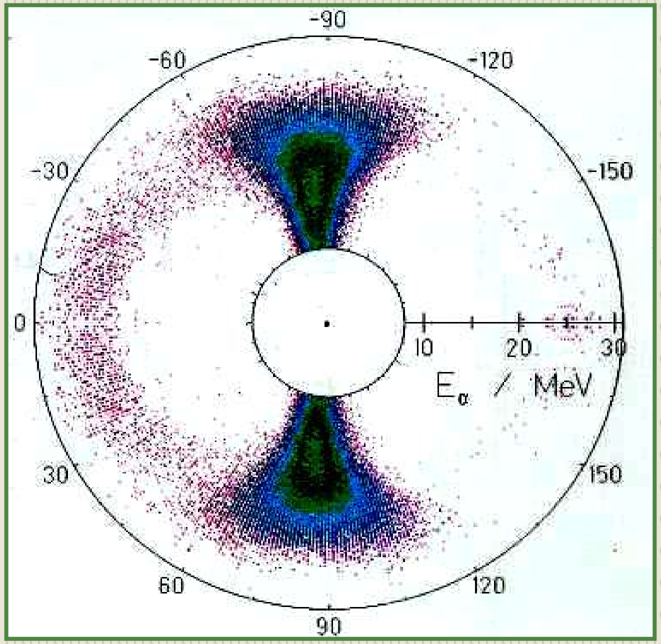
Prompt neutrons

Neutrons from fragments



Scission neutrons

Ternary α-particles from ^{252}Cf (M. Mutterer et al.)



In contrast to alpha-particles Scission Neutrons are not focused by the Coulomb field

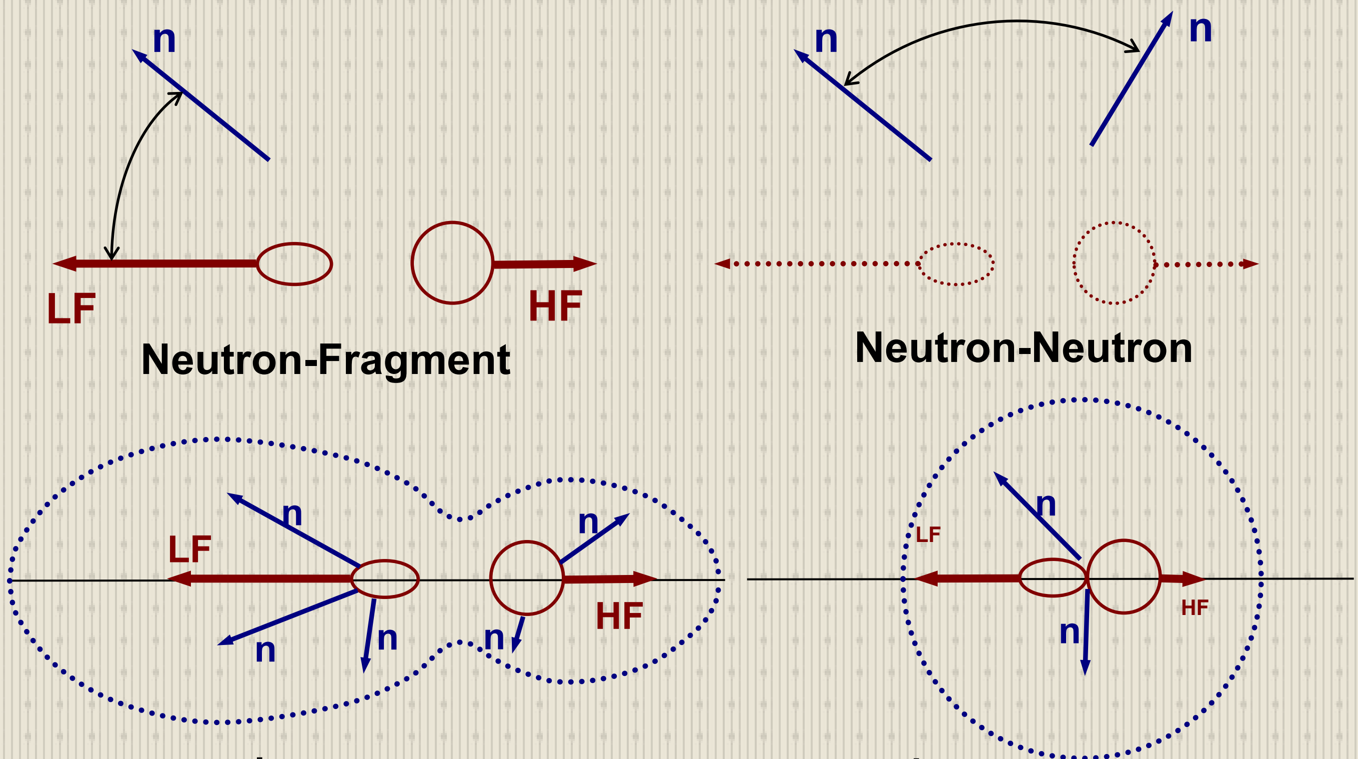
Theoretical predictions

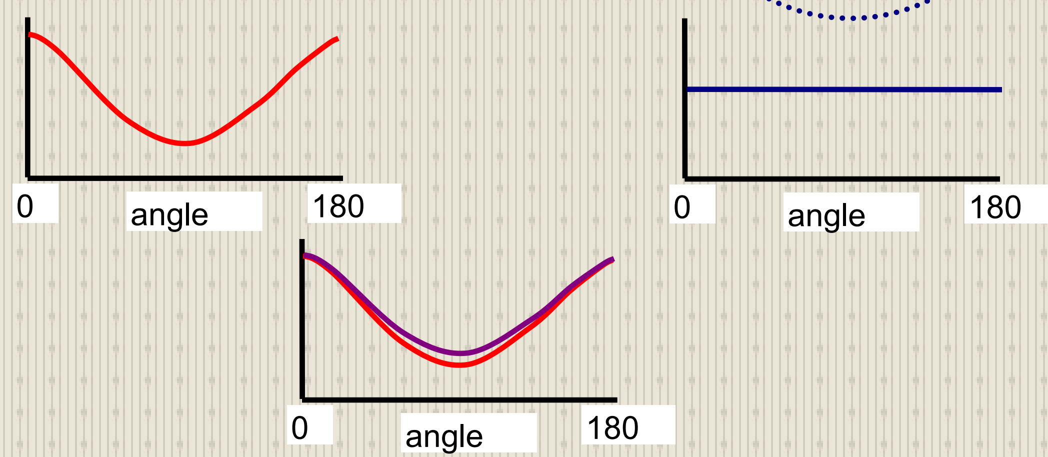
~5% for ^{252}Cf(sf) and ~20% for ^{235}U(nth,f).
[G.V. Val'sky, Physics of Atomic Nuclei. Vol. 67 (2004) 1264]

Up to 30% of the total number of neutrons for ^{235}U(nth,f).
[N. Carjan, et al., Nuclear Physics A 792 (2007) 102.]

Scission neutrons – Ways to study

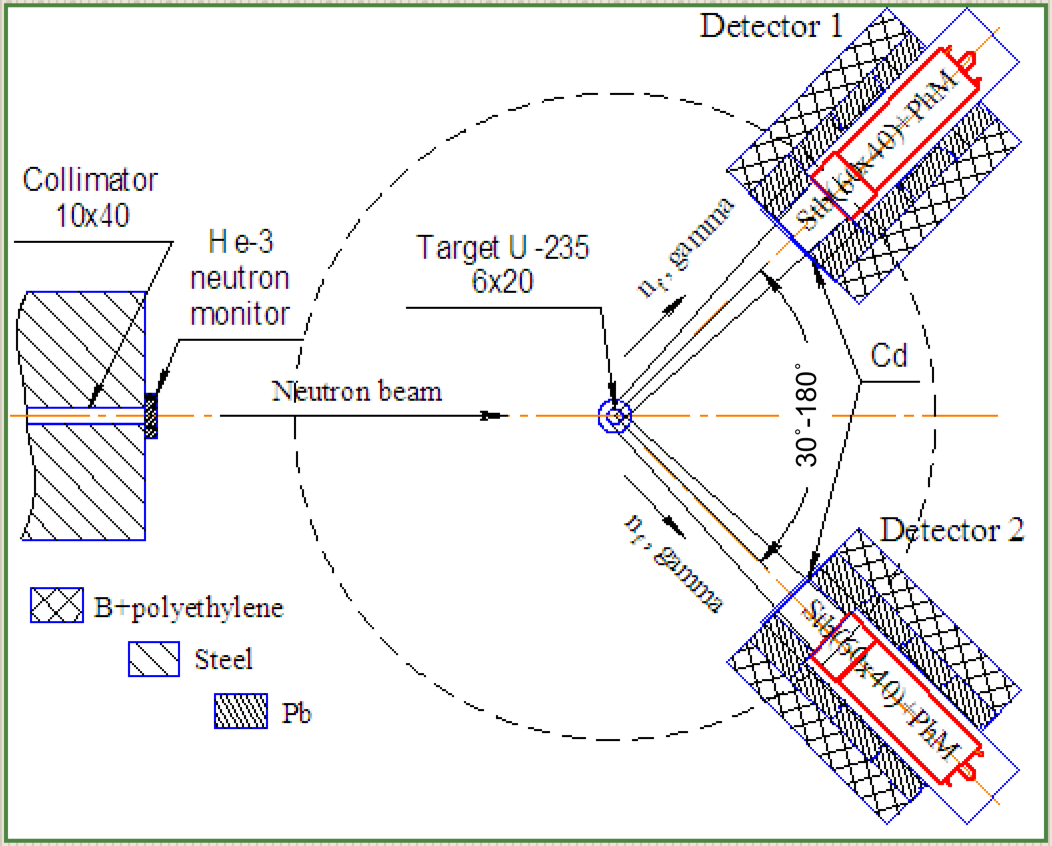
Measurements of the angular and energy correlations for prompt neutron yields.



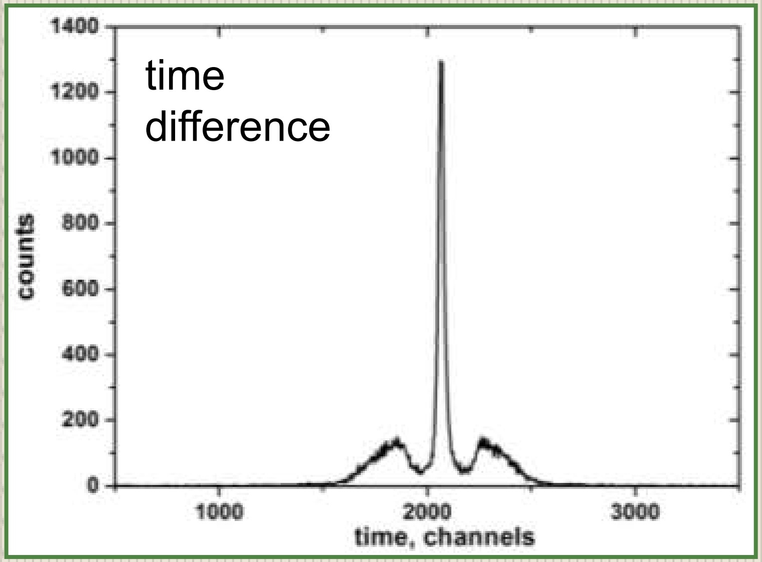


The SNs manifest themselves as a deviation of the measured distributions from ones calculated in assumption that all neutrons are emitted from accelerated fragments.

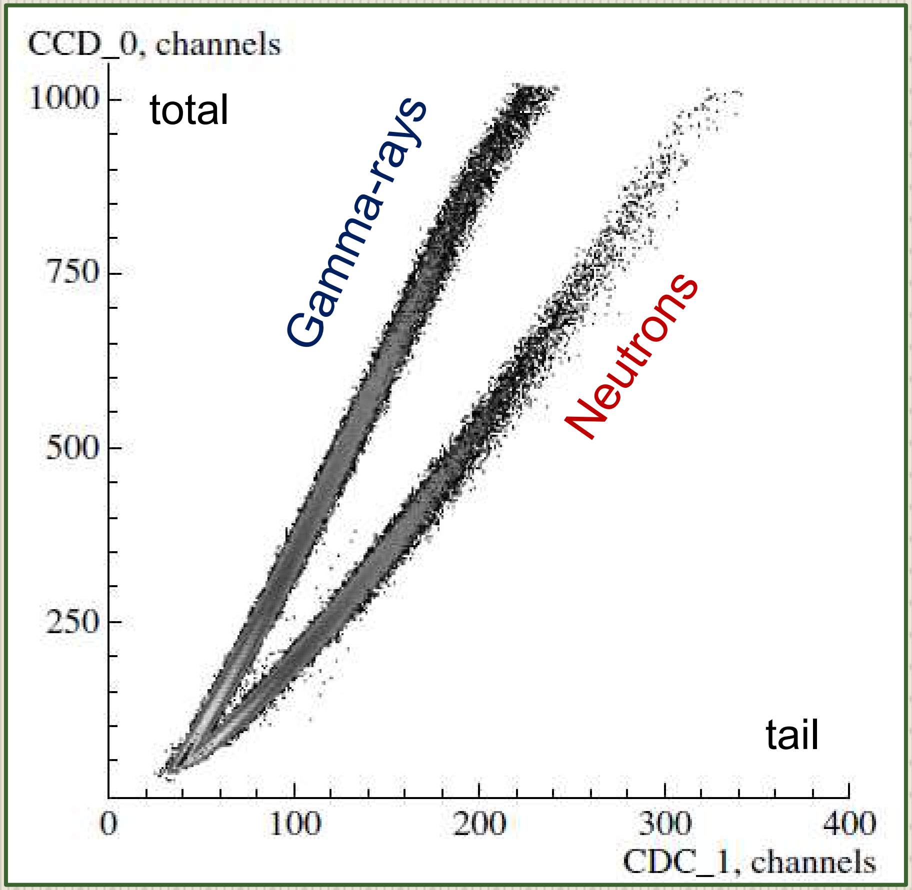
Experimental setup

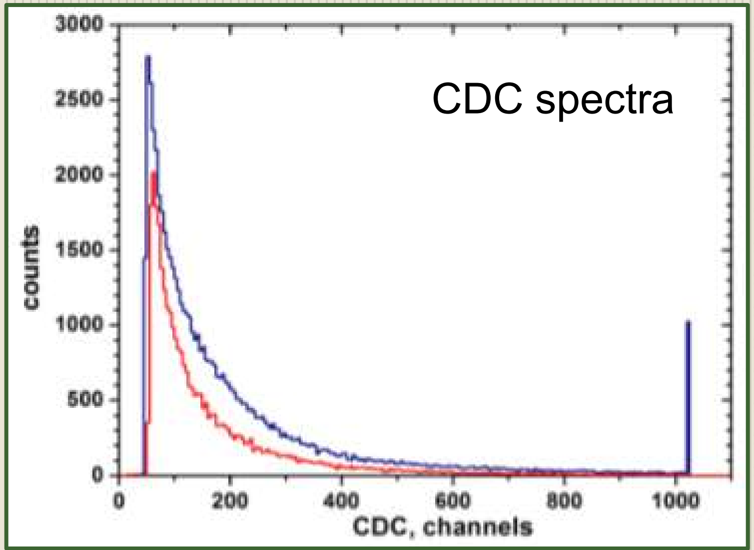


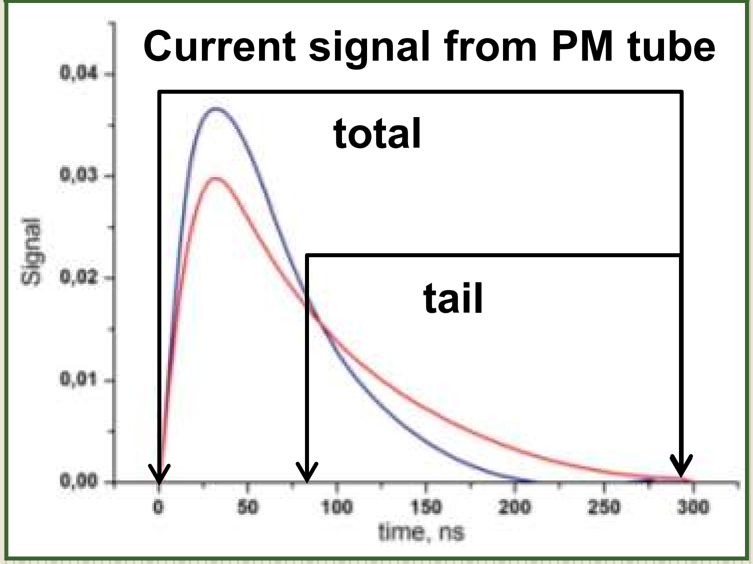
- Two Stilbene crystals 60x40mm
- PM tubes (Hamamatsu R13107)
- Polyethylene and Lead shielding
- μ-metal magnetic shielding
- Everything on 8 mm thick Aluminium table.



Gamma-neutron separation

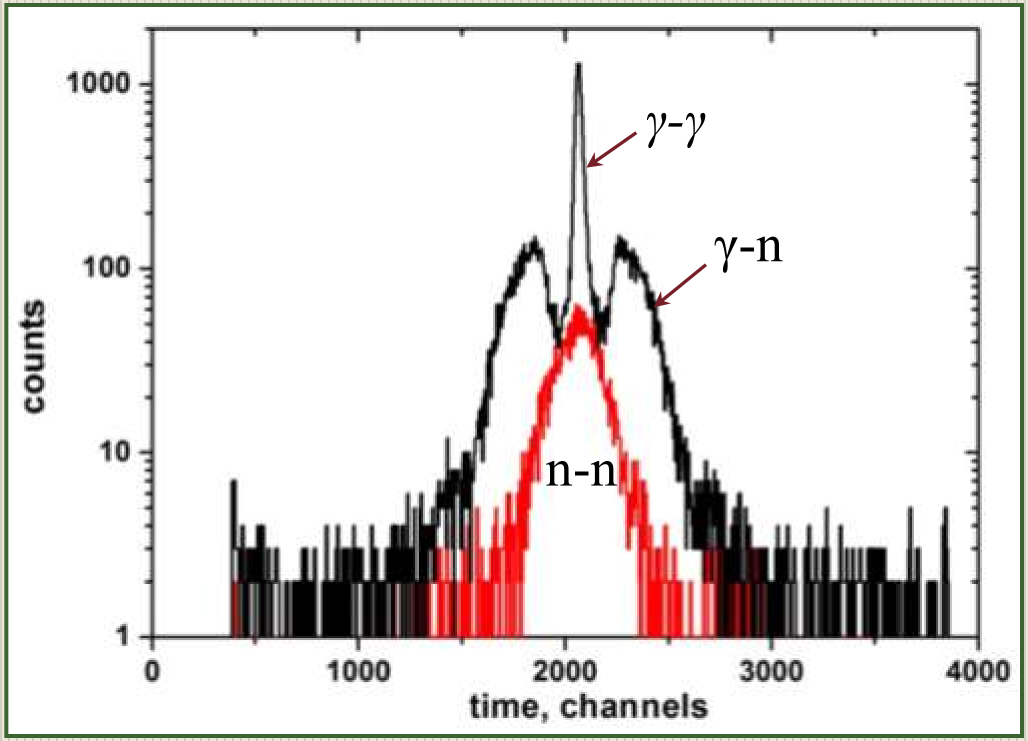






Two-dimensional distributions for the parameters of the PMT signals: CDC_0 (total integral) × CDC_1 (slow component). The signals characterized by larger CDC_1 (slow component) with identical CDC_0 (total integral) correspond to the detected neutrons

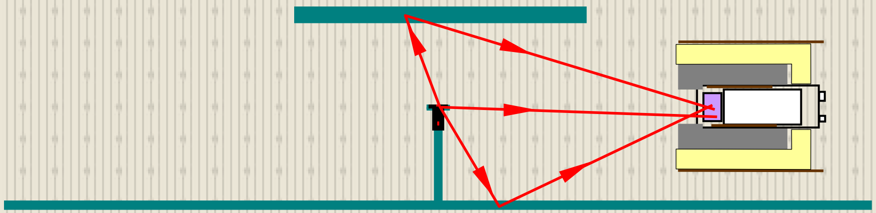
Time-of-flight spectrum



In this experiment we are interested only in the count rate of n–n events as a function of the angle between the detectors.

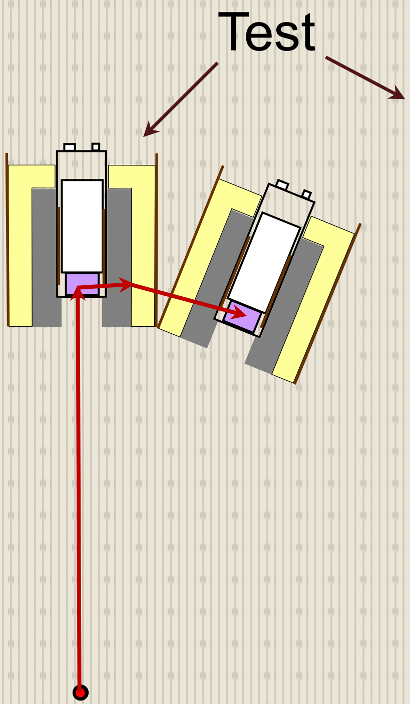
In such experiment the direction of motion of fission fragments is not fixed; therefore, the number of n–n coincidences for a particular angle between the neutrons is averaged over all orientations of fission axis and over all neutron energies above the energy threshold.
To determine neutron energy thresholds we have used γ-n distributions.

Neutron scattering



This effect leads to a flattening of the investigated curve and can simulate the number of additional events, which falsely can be considered as scission neutrons.

Cross-talks of the detectors



The estimation of cross-talks effect in real experimental conditions gives for 30° between two detectors:
9% - ^{239}Pu, 14% - ^{233}U, 13% - ^{235}U
of the total number of n-n coincidences.

This effect falls down with increasing angle between the detectors and it is practically negligible at 60°.

The set of control experiments allowed us to estimate the systematic data uncertainty, which should be added to statistical errors, on the level of 1%.

Monte-Carlo simulation

It was simulated 10^8 of fission events.

For every fission event these values were determined:

ν_L, ν_H, ν_{sci} – the number of neutrons evaporated from light and heavy fragment, respectively, with the addition of scission neutrons

$$\bar{\nu}_L + \bar{\nu}_F + \bar{\nu}_{sci} = \bar{\nu}_{tot}$$

$\bar{\nu}_{sci} / \bar{\nu}_{tot}$ – **fitting parameter**

The actual numbers of neutrons evaporated by each fragment were selected randomly by two-dimensional Gaussian distribution $(\bar{\nu}_L, \sigma_L^2, \bar{\nu}_H, \sigma_H^2, \mathrm{cov}(\nu_L, \nu_H))$ with experimentally defined dispersion of the total neutron multiplicity and known ratio of the partial neutron multiplicities for fission fragments.

$$2 \cdot \mathrm{cov}(\nu_L, \nu_H) = \sigma^2(\nu_{tot}) - \sigma^2(\nu_L) - \sigma^2(\nu_H)$$

We took into account the presence of neutron emission anisotropy connected with the angular momentum of each fragment: $\varphi(\cos\theta_{CM}) \propto (1 + b(E_{CM}) \cdot P_2(\cos\theta_{CM}))$.

The dependence of neutron emission anisotropy on neutron energy was also considered.

Monte-Carlo simulation

The neutron spectrum for each fragment in its center of mass was assumed to be Maxwellian form:

$$N_{L,H}(E) \sim \frac{\sqrt{E}}{T_{L,H}^{3/2}} \cdot \exp(-E/T_{L,H})$$

This type of spectrum was considered because of the evaporation by each fragment of more than one neuron per fission.

It was supposed that the energy form of scission neutron component corresponds to Weisskopf distribution:

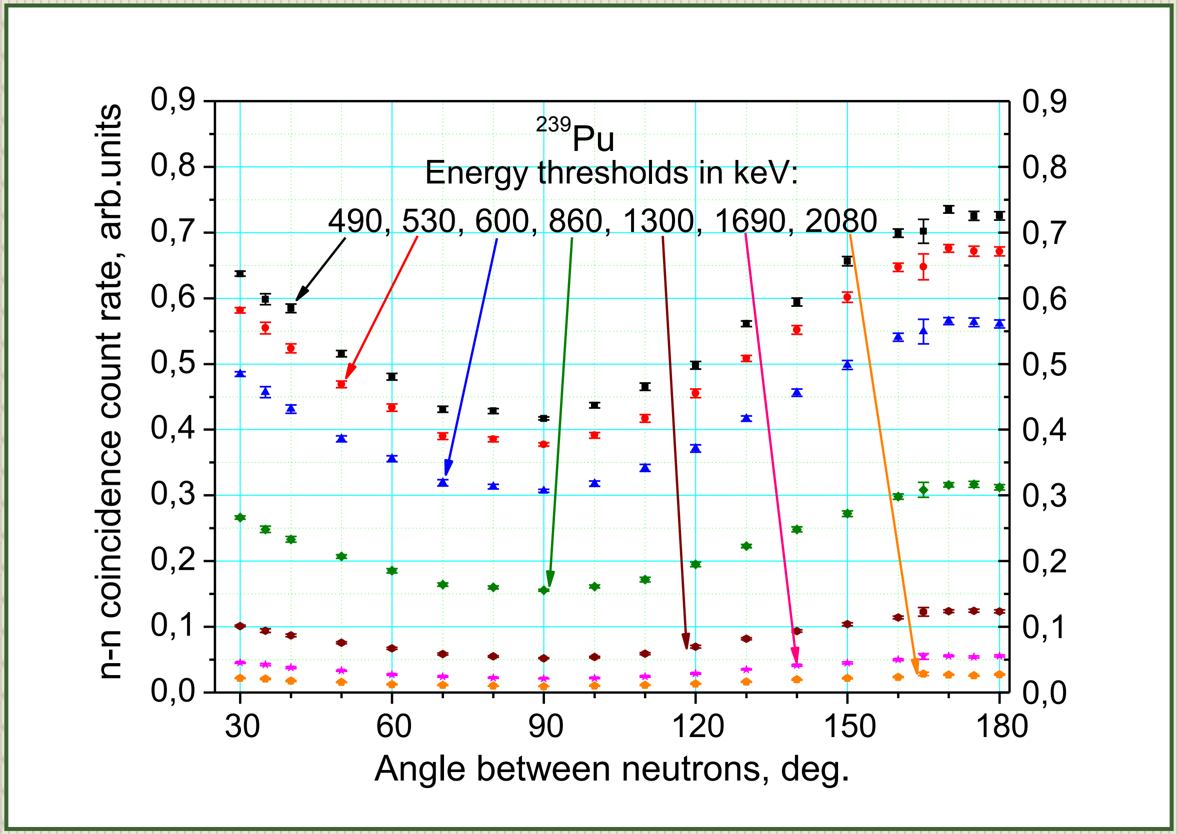
$$N(E) \sim \frac{E}{T_{sci}^{2}} \cdot \exp(-E/T_{sci})$$

and can be described by a single parameter, namely temperature (**fitting parameter**).

In process of calculation were used averaged values of neutron-weighted kinetic energy per nucleon for light and heavy fragment groups.

In this experiment we did not register the energy of each neutron. However the experimental results of the angular dependence were distributed over 7 energy thresholds.

Experimental data for n-n coincidences of ^{239}Pu (the seven neutron energy thresholds)



In this Figure experimental data errors are statistical only.

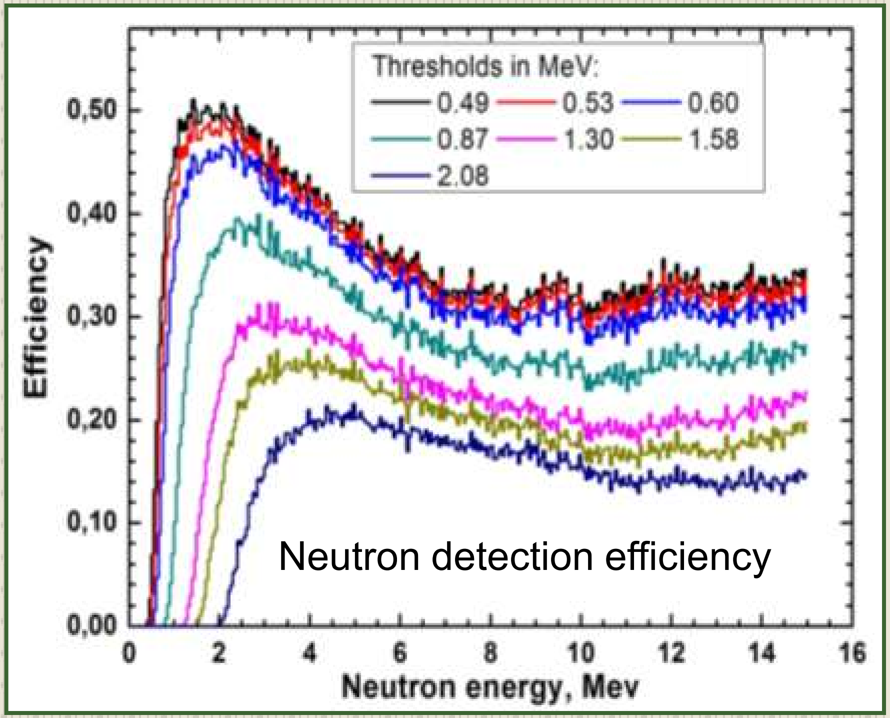
The distances between experimental curves, corresponding to different energy thresholds, are given without any correction.

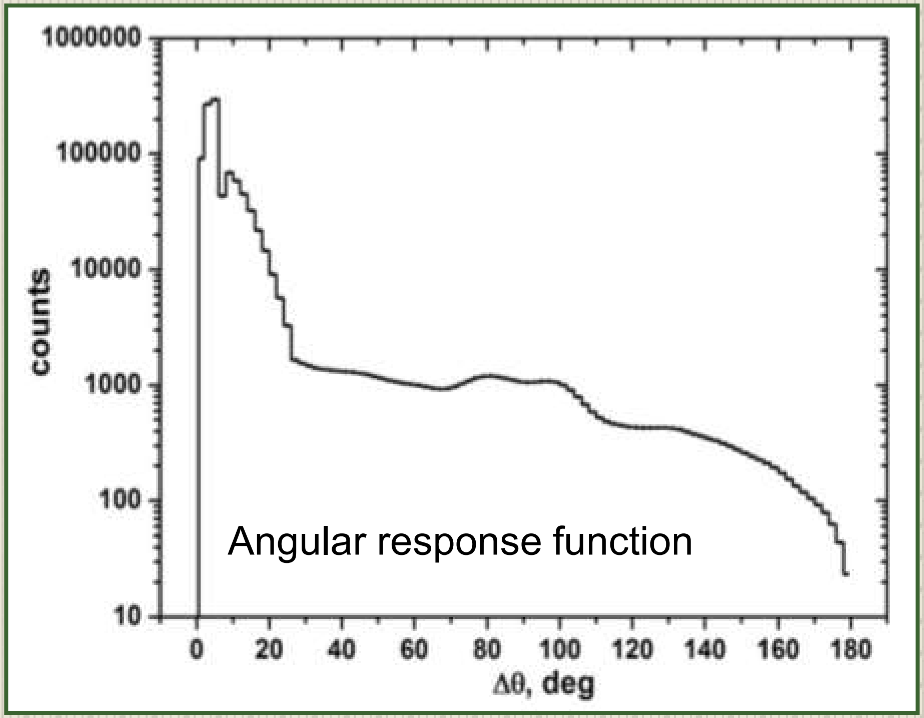
Such an amount of energy thresholds allowed us to get the information not only about the contribution of scission component but also about its energy composition.

The curve corresponding to the lowest energy threshold is the most sensitive to the contribution of scission neutron component while the temperature parameter of this component can be determined more precisely using experimental data with higher energy thresholds.
To fit all these experimental data of n-n angular distributions measured with seven different energy thresholds we had **only two free parameters** (the contribution of scission neutrons and their temperature) .

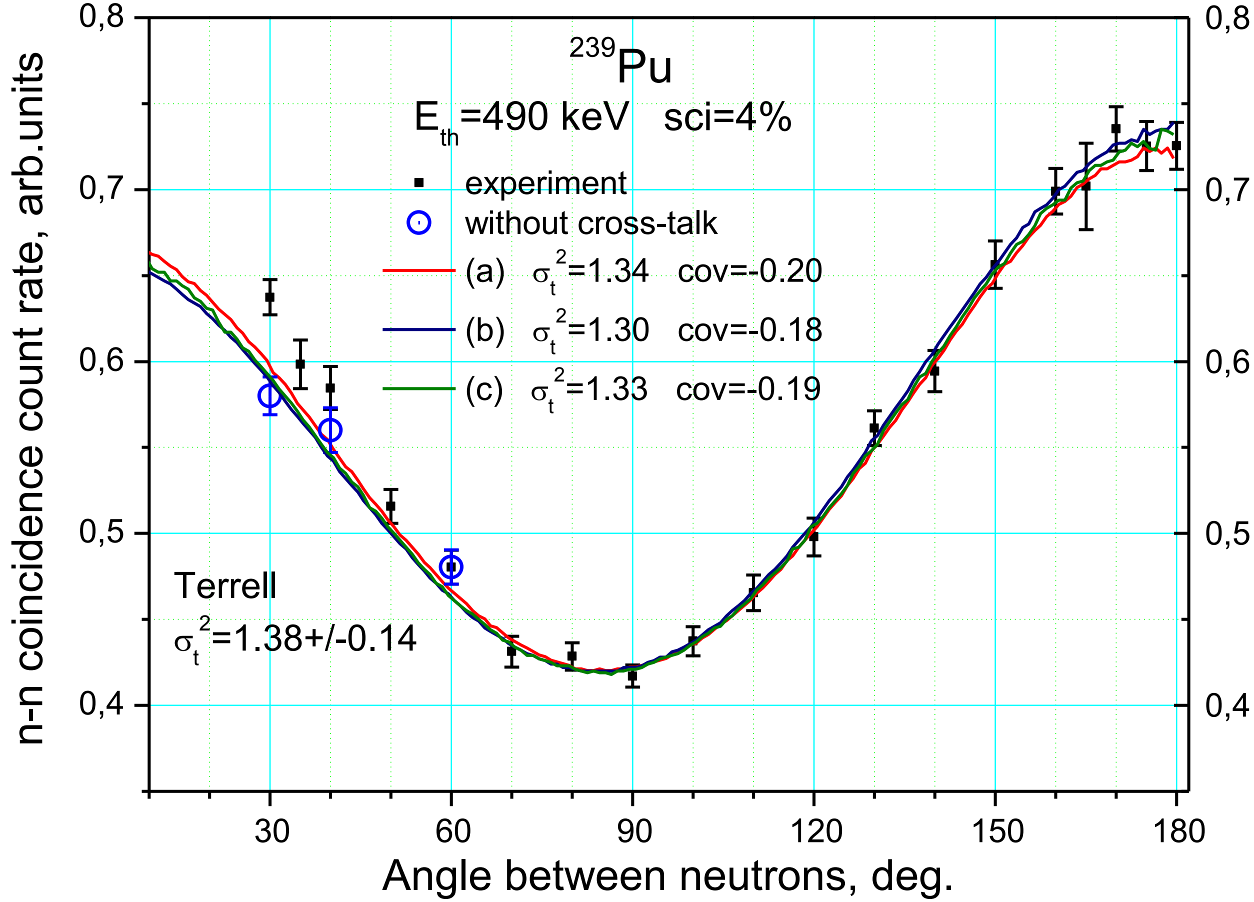
GEANT4 simulation of the detectors efficiency and angular response function

Before our Monte-Carlo calculations the detector efficiencies for seven neutron energy thresholds and angular response function were obtained.

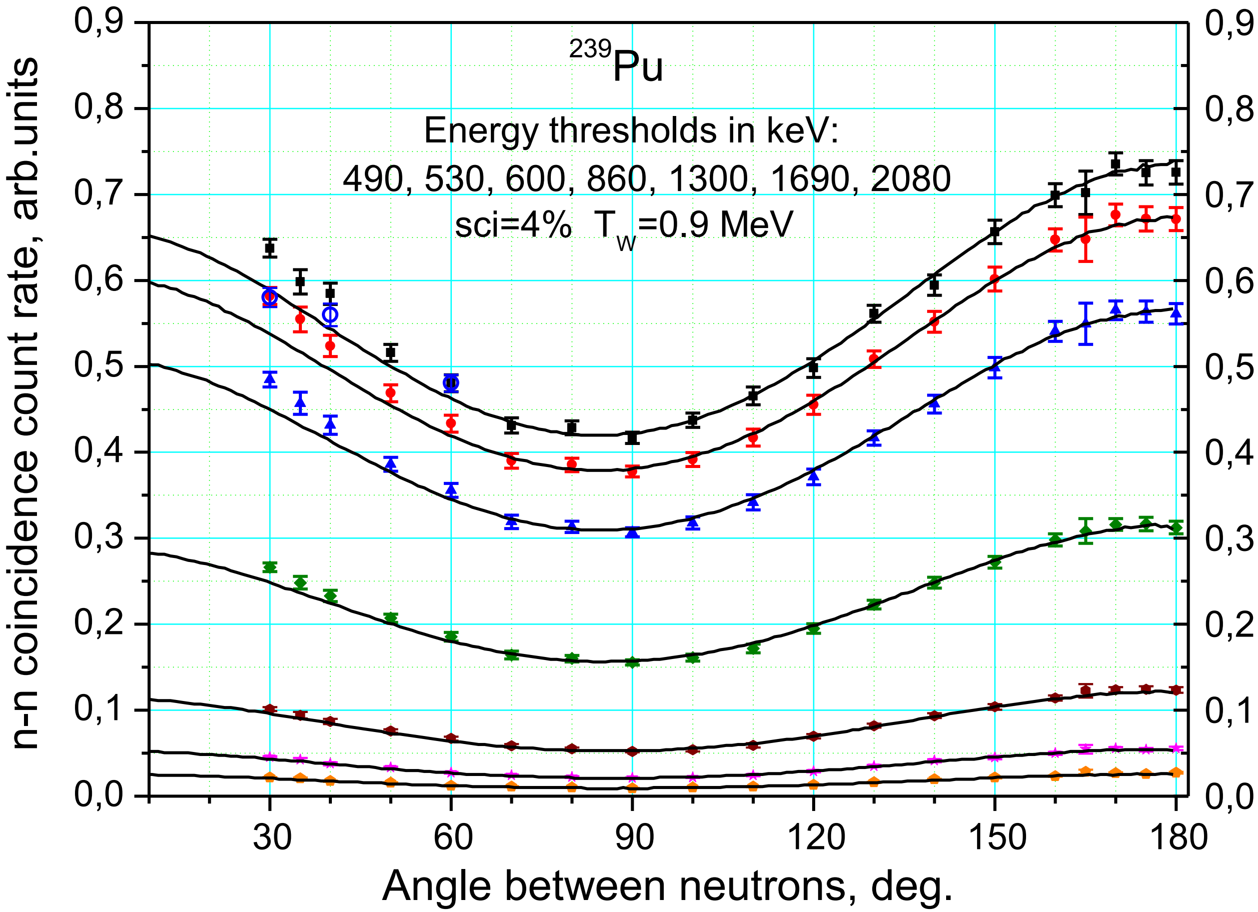




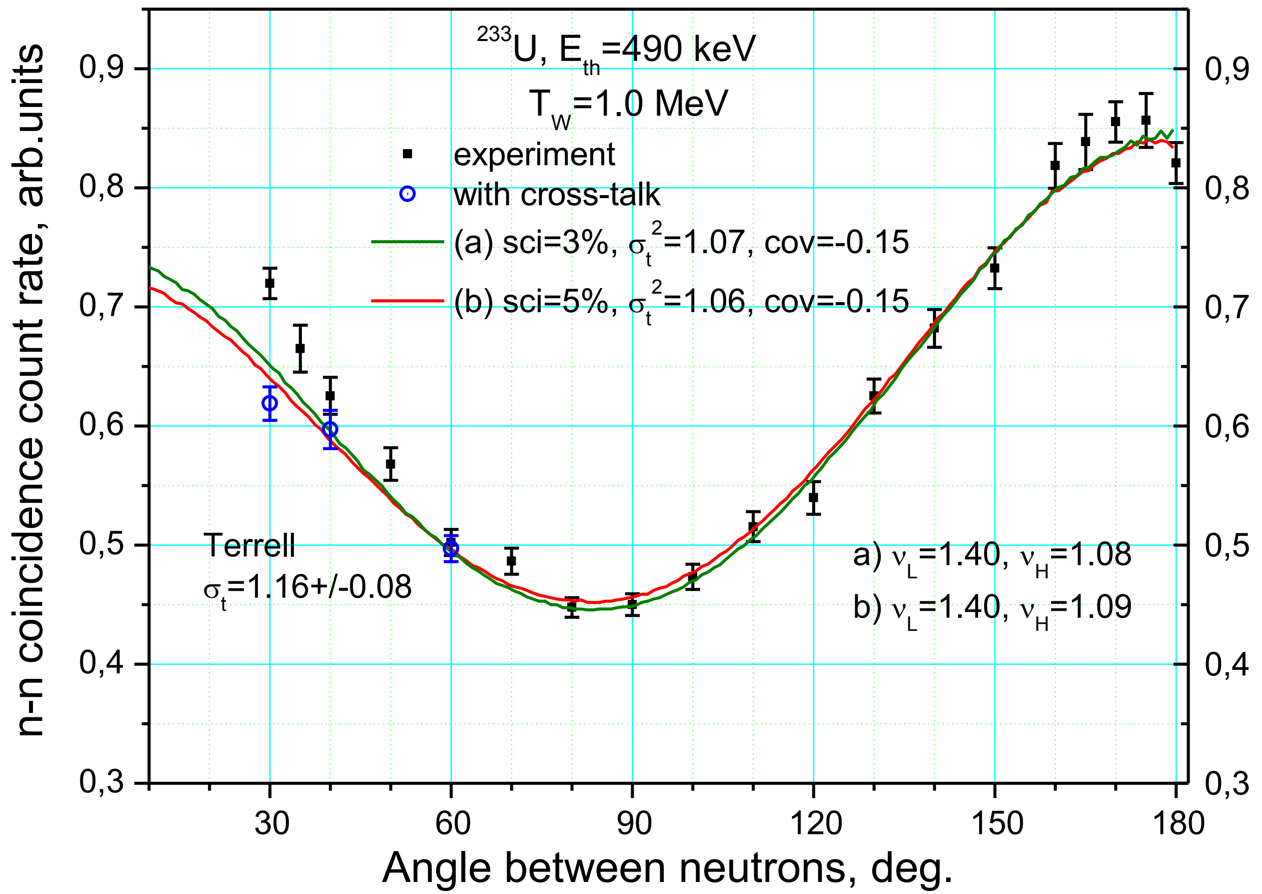
Experimental data and calculated results for n-n coincidences of ^{239}Pu (the lowest neutron energy threshold)



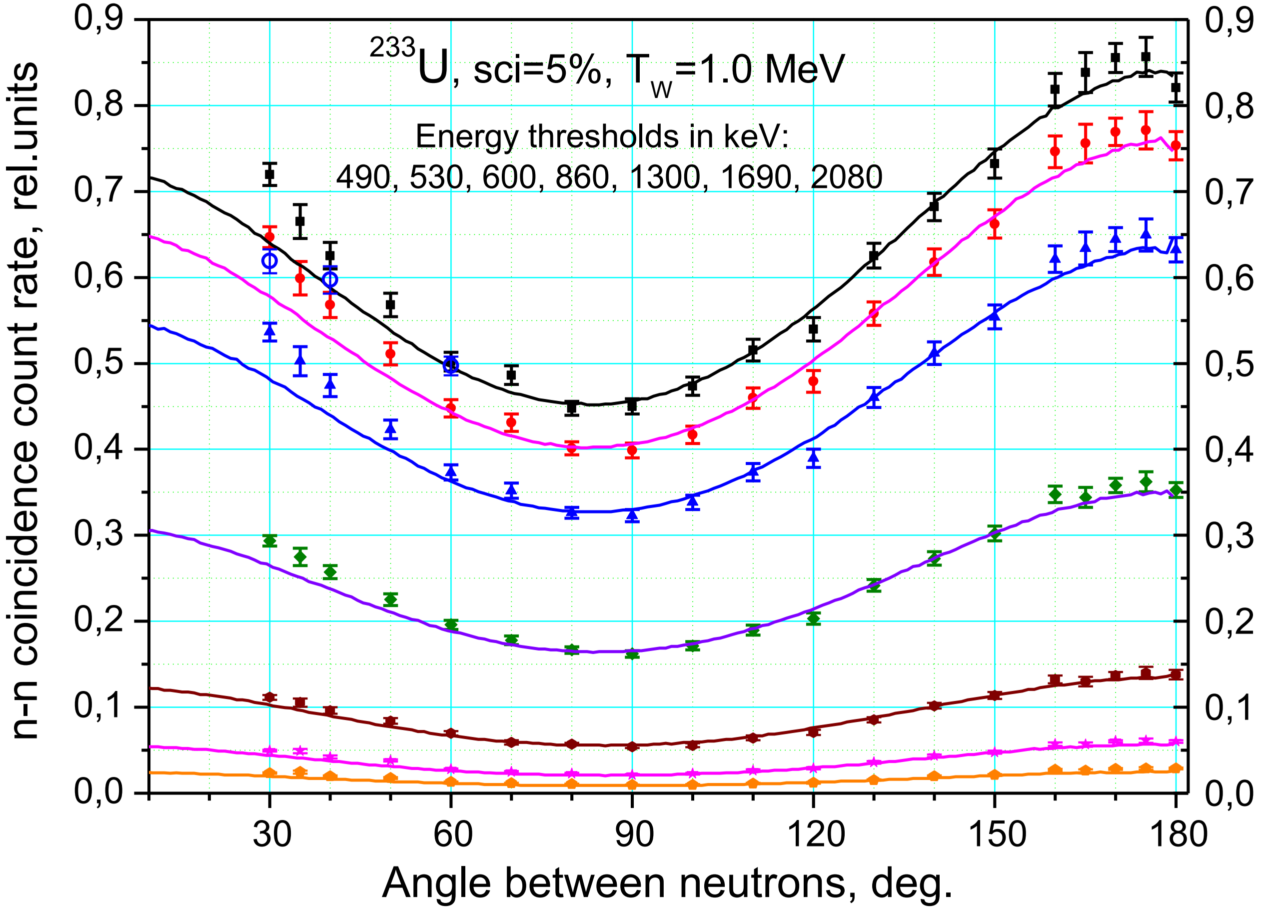
Experimental data and calculated results for n-n coincidences of ^{239}Pu (the seven neutron energy thresholds)



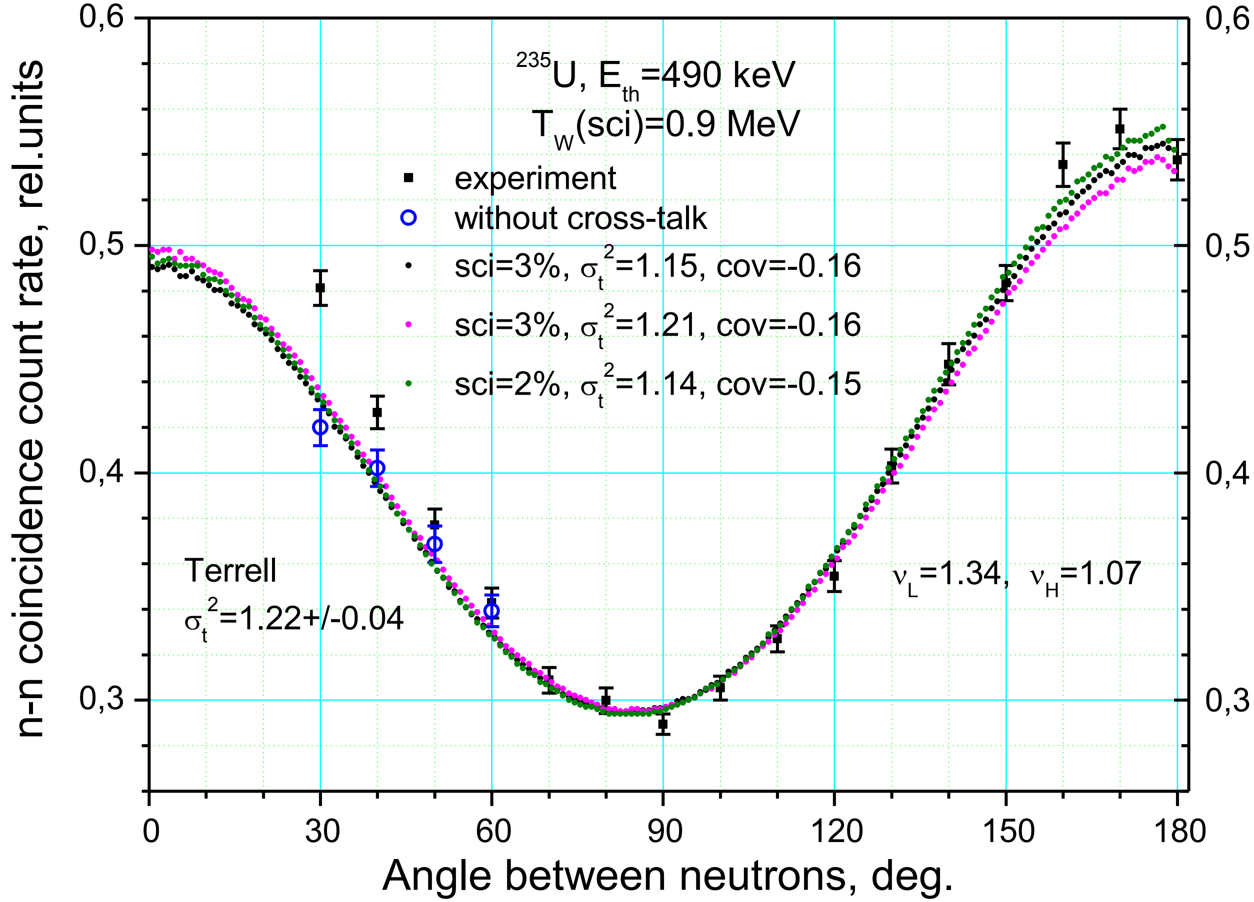
Experimental data and calculated results for n-n coincidences of ^{233}U (the lowest neutron energy threshold)



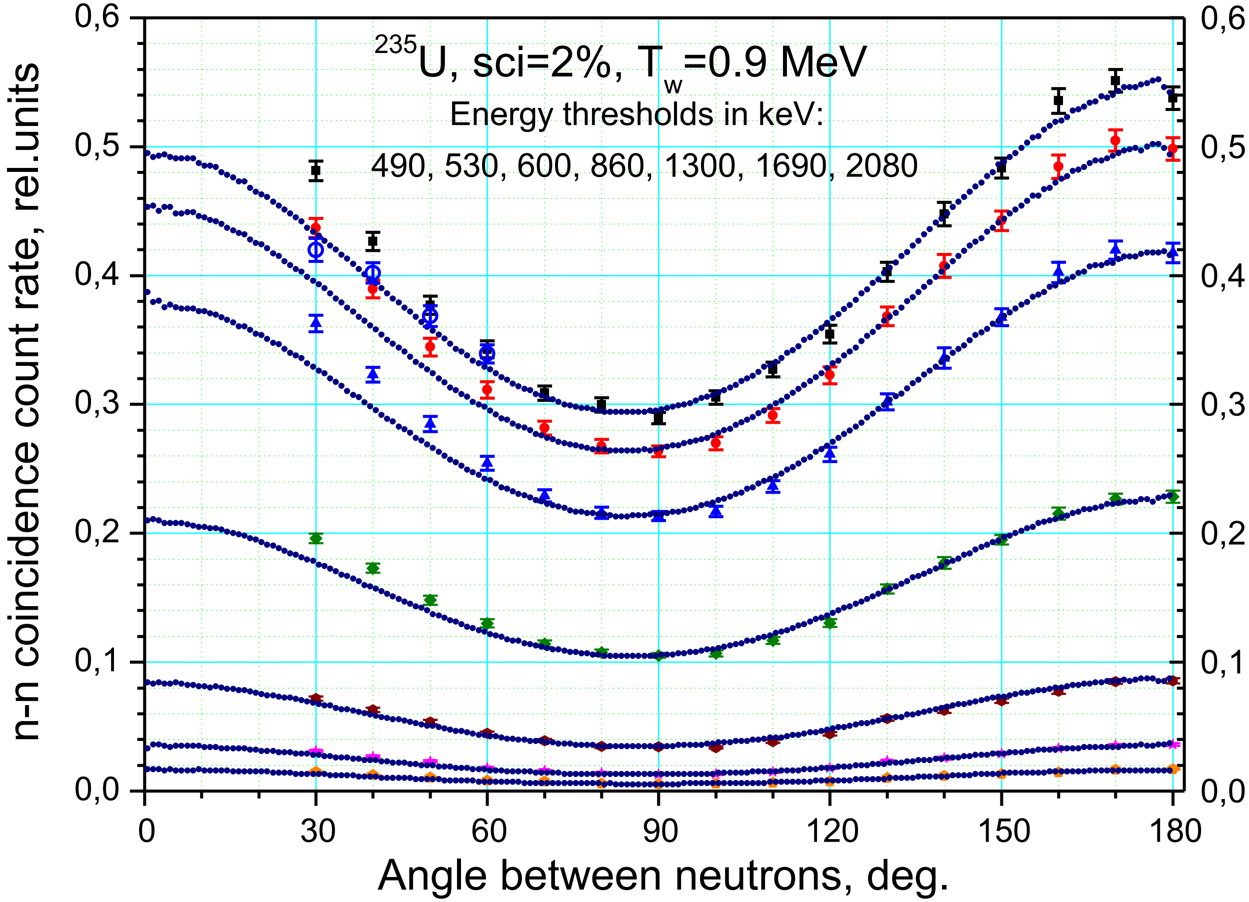
Experimental data and calculated results for n-n coincidences of ^{233}U (the seven neutron energy thresholds)



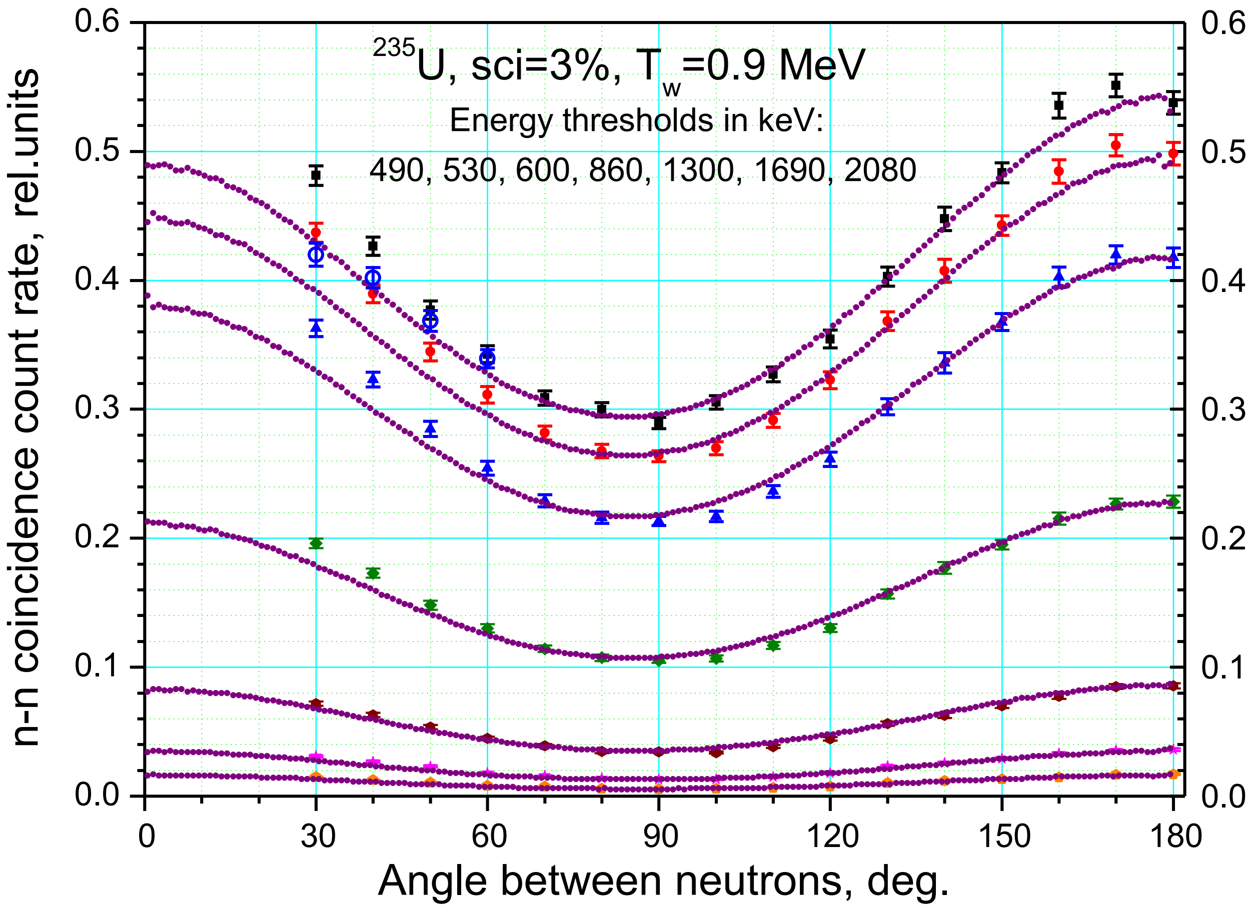
Experimental data and calculated results for n-n coincidences of ^{235}U (the lowest neutron energy threshold)



Experimental data and calculated results for n-n coincidences of ^{235}U (the seven neutron energy thresholds)



Experimental data and calculated results for n-n coincidences of ^{235}U (the seven neutron energy thresholds)



Comparison of the results obtained from n-n coincidences with the results corresponding to the angular n-f correlations (Vorobiev et al.)

If neutron spectrum corresponds to Weisskopf distribution, then $< E_{sci} > = 2 \cdot T_{sci}$

target	$\bar{\nu}_{sci} / \bar{\nu}_{tot}$		$< E_{sci} >, MeV$	
	This work	Vorobiev et al.	This work	Vorobiev et al.
U-233	(5.0±1.5)%	≤4%	2.0±0.2	2.1±0.2
U-235	(2.0±1.5)%	≤3%	1.8±0.2	1.8±0.2
Pu-239	(4.0±1.5)%	≤7%	1.8±0.2	1.8±0.2

Conclusions:

- Precise measurements of the angular dependence of n-n coincidence count rates in ^{233}U(*n,f*), ^{235}U(*n,f*) and ^{239}Pu(*n,f*) were performed.
- All possible experimental effects which can distort the experimental distributions are analyzed and taken into account with accuracy ~1% . (Control experiments and GEANT4 simulation).
- Experimental data of n-n angular correlations for these isotopes can not be well described only with neutrons evaporated from fully accelerated fragments.
- These distributions can be described if all neutrons of additional component are supposed isotropically emitted in the laboratory system. This component assumed to be Weisskopf energy spectra with $T_{sci} \approx 1$ MeV. These neutrons can be attributed as scission neutrons.
- The results obtained due to n-n angular distributions are practically coincide with those obtained in neutron-fragment correlations.

Thank you for attention