Angular Correlations in the Prompt Neutron Emission in Spontaneous Fission of ^{252}Cf

Yuri Kopatch for the CORA collaboration

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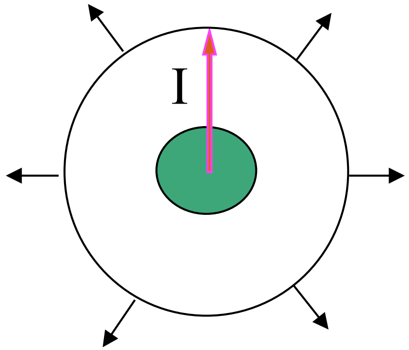
Introduction

- *It is well known that fission fragments are formed with rather high angular momenta (spins).*
- *Fragment spins are aligned perpendicular to the fission axis.*
- *Fragment spin properties (population, alignment etc) are usually probed by the correlation measurements of gamma-rays, emitted from fission fragments.*
- *Most of the neutrons are emitted from the fully accelerated fragments with a strong anisotropy in the laboratory system due to kinematic focusing in the direction of the fragments.*
- *Some of the neutrons can be emitted at scission (scission neutrons).*
- *In analogy with gamma-rays, some anisotropy of the neutron emission from the fragments in the C.M. can be expected.*
- *There are theoretical arguments / calculations, as well as indirect experimental evidences that such an anisotropy should exist. However, no direct observation of this effect is known until now.*

Neutron emission in the c.m. system

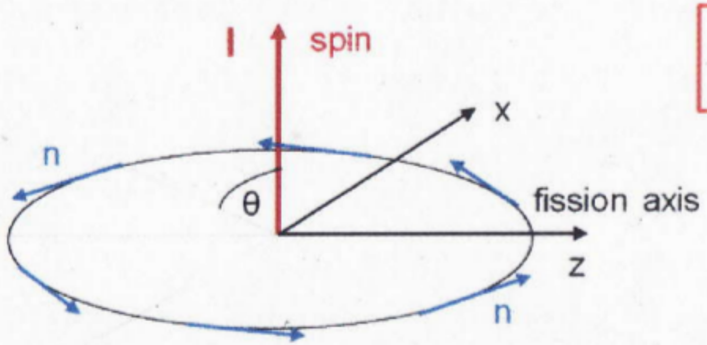
s-neutrons   l=0

Isotropic neutron emission



p-,d-,… neutrons   l=1,2,…

Anisotropic neutron emission



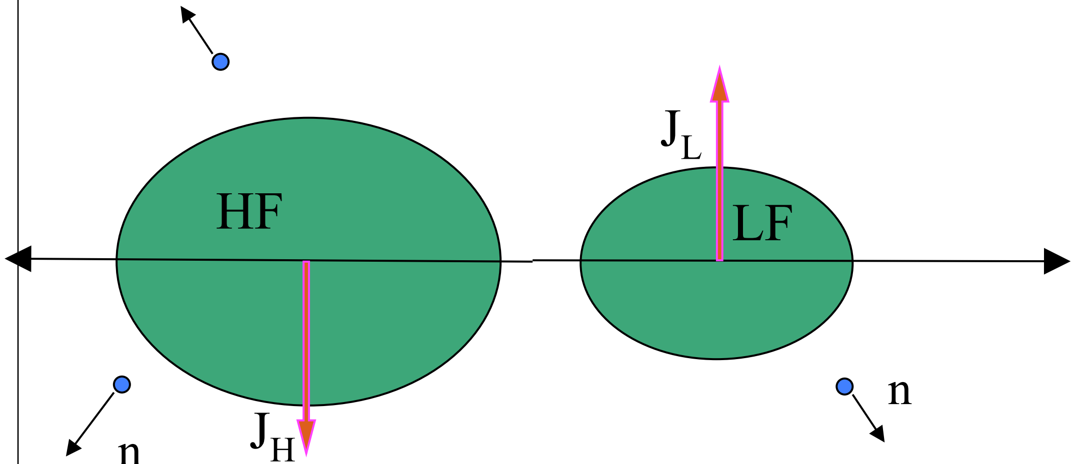
$$W(\theta_{nI}) \sim (1 + a_{nI} \sin^2\theta_{nI})$$

with $\theta_{nI} = \measuredangle$ (n, fragment spin I)

and the anisotropy

$$A_{nI} = [W(90°) / W(0°)] - 1$$

Neutron emission anisotropy in the c.m. system



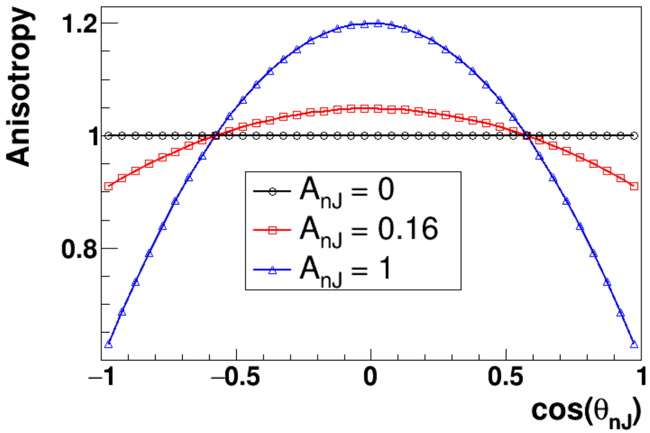
Only neutrons with l≠0 contribute to the anisotropy

Neutron angular distributions in the c.m. system

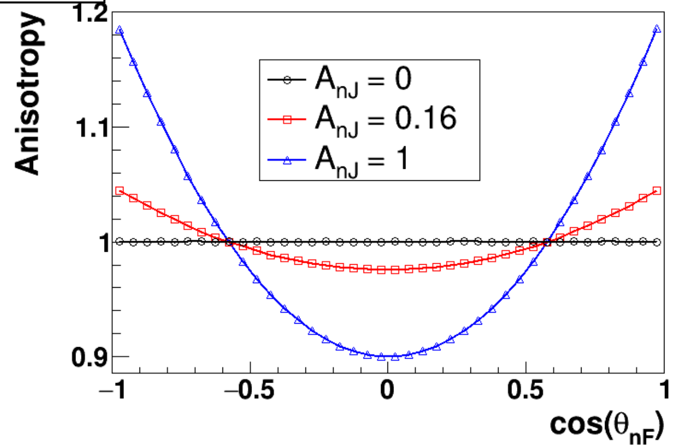
$$W(\theta_{nJ}) = 1 + A_{nJ} \sin^2 \theta_{nJ}$$

$$W(\theta_{nF}) = 1 + A_{nF} \cos^2 \theta_{nF}$$

A_{nf} ? ½ A_{nJ}

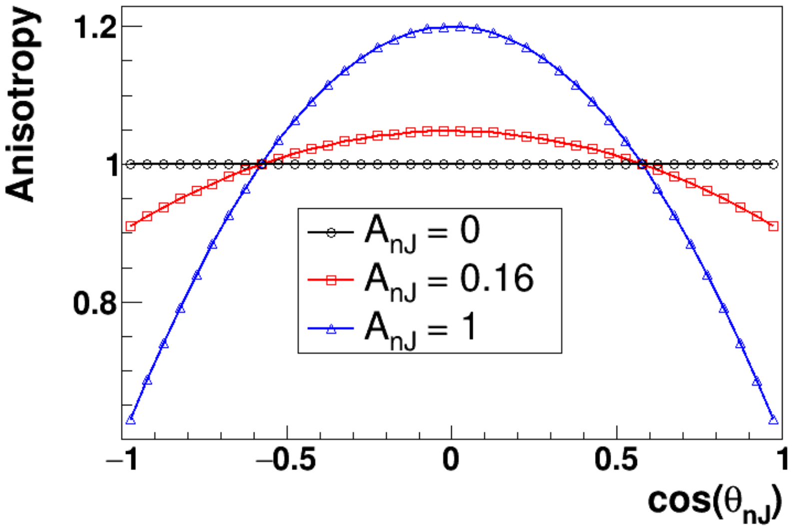


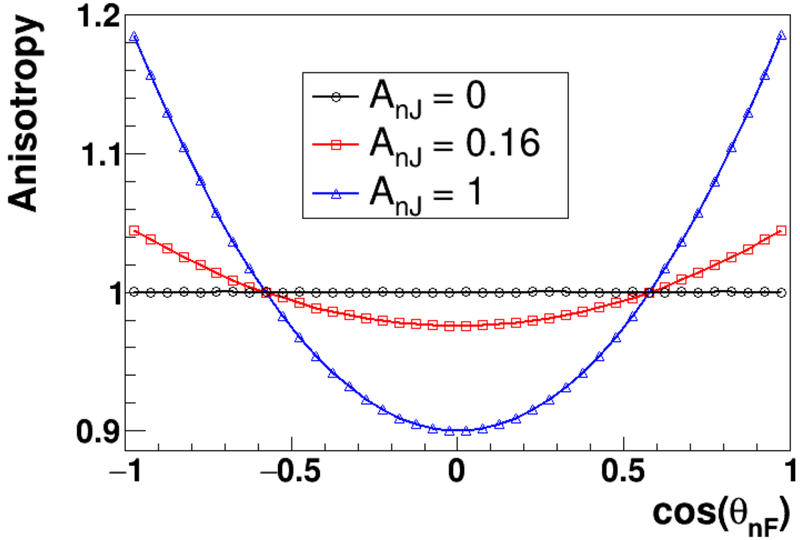
Relative to the fragment spin



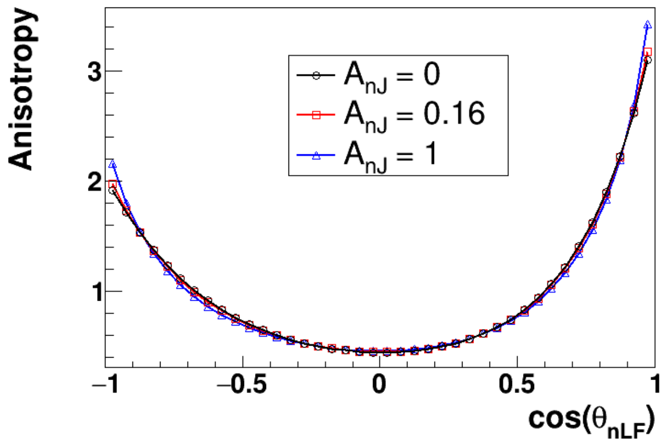
Relative to the fission axis

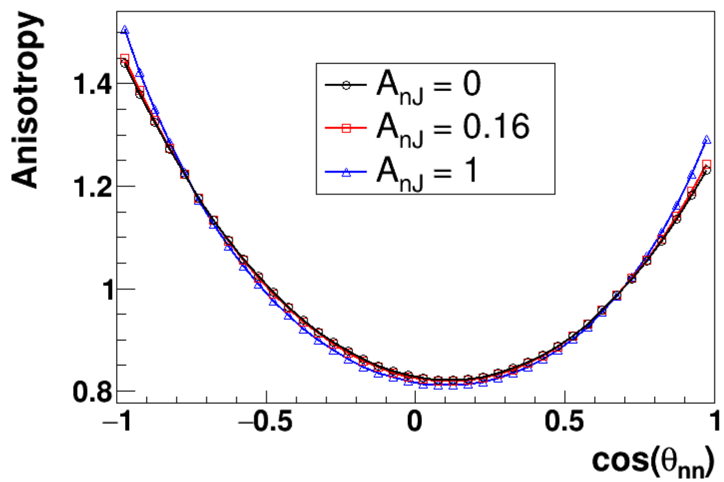
Neutron emission anisotropy in the c.m. system





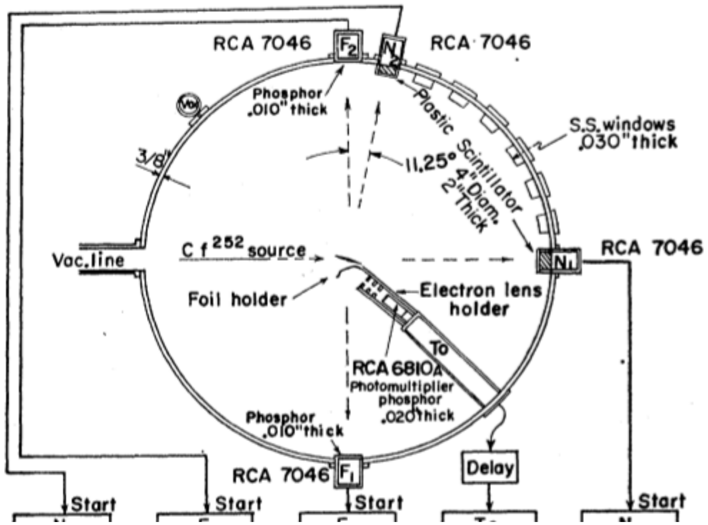
Neutron emission anisotropy in the lab. system



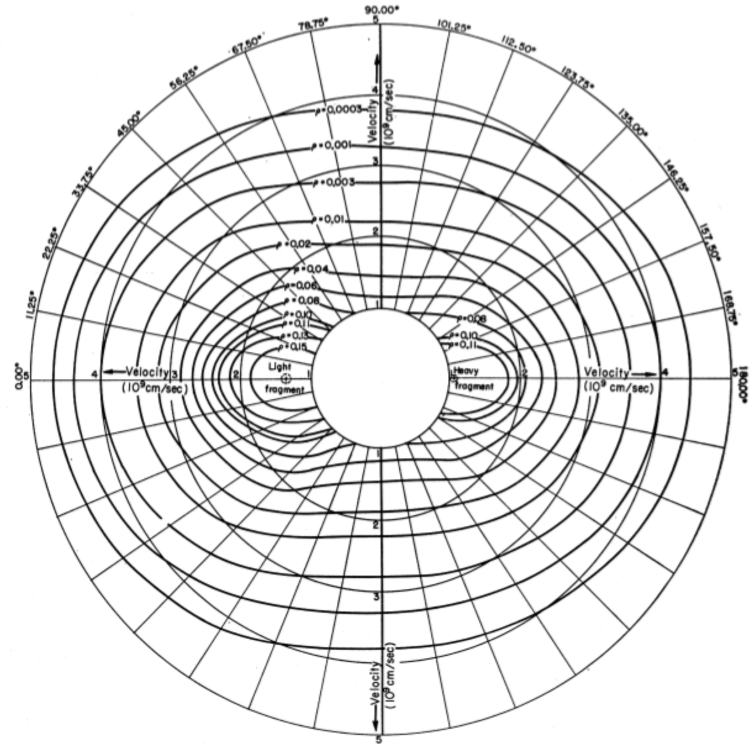


Experiments – Bowman et al.

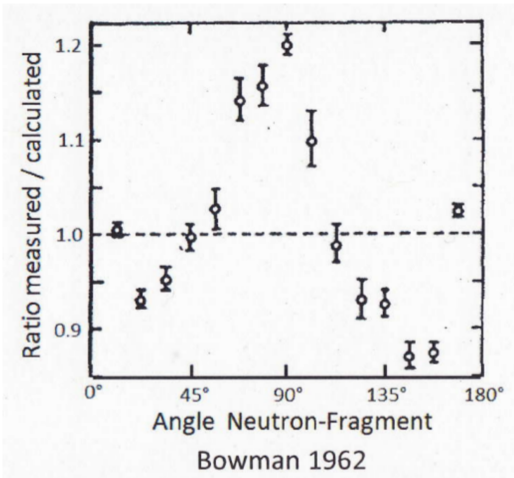
H.R.Bowman, S.G.Tompson, J.C.D.Milton, and W.J.Swiateski, Phys.Rev. 126 (1962) 2120.



Experimental set-up



Polar diagram of the neutron density distribution as a function of neutron velocity and angle

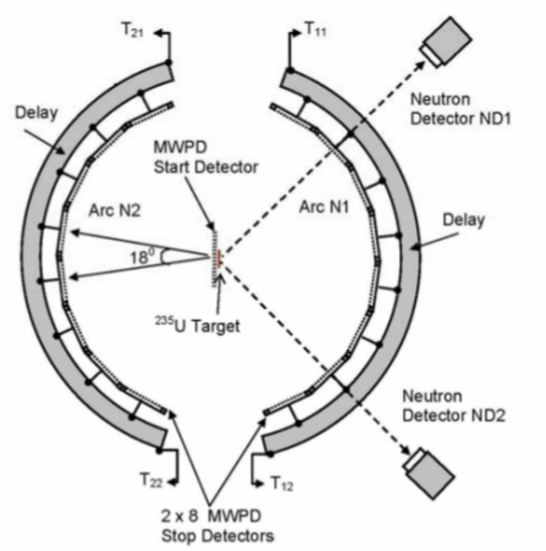


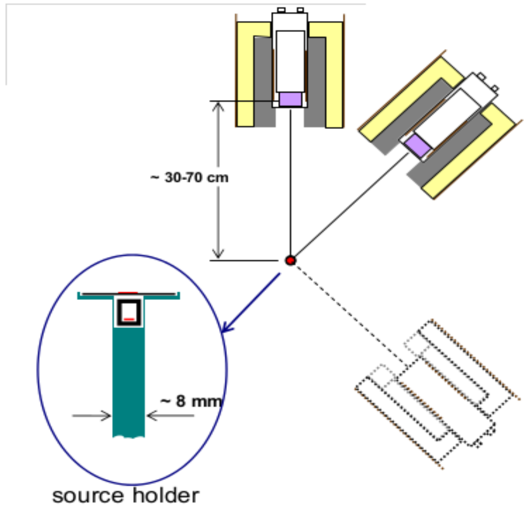
Deviation from the model calculations

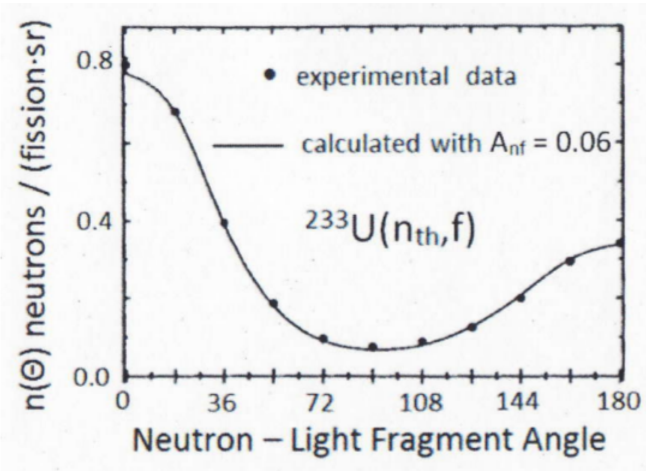
Experiments – Gatchina group

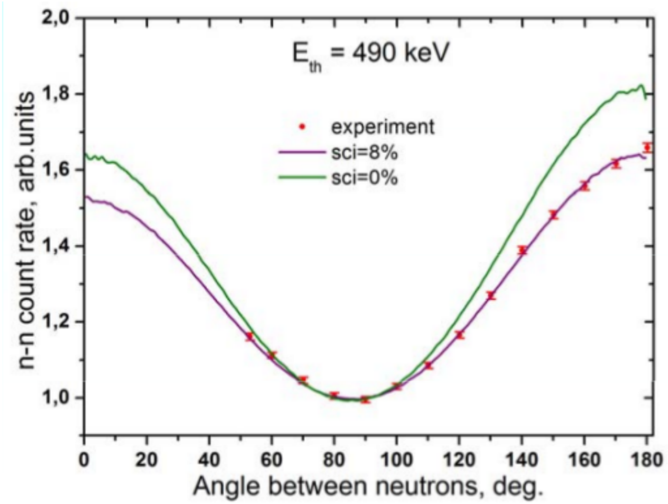
Vorobiev et al, 2009

Gagarski et al, 2012





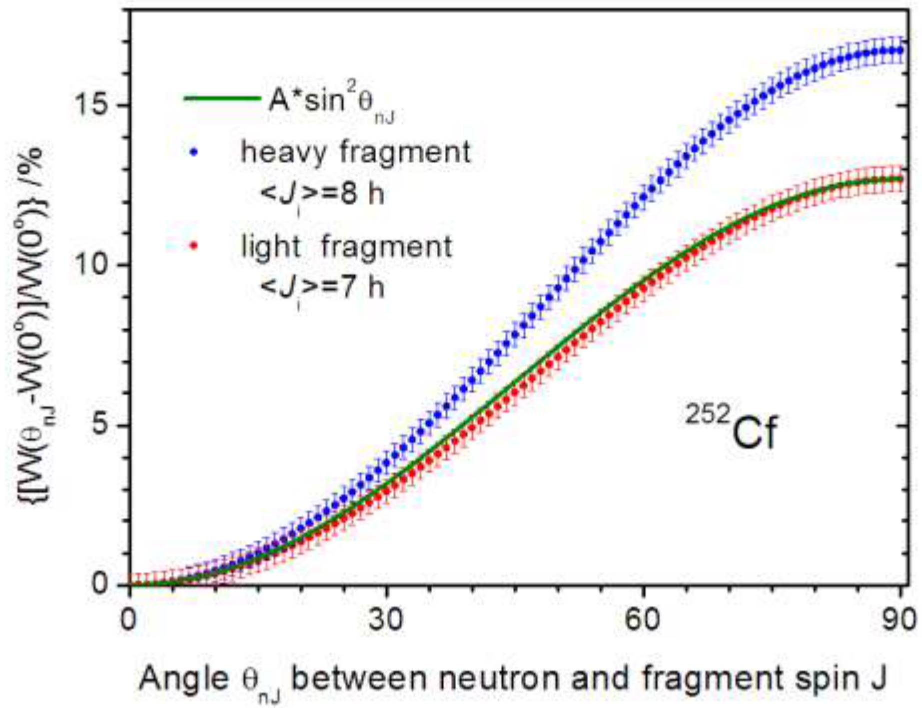




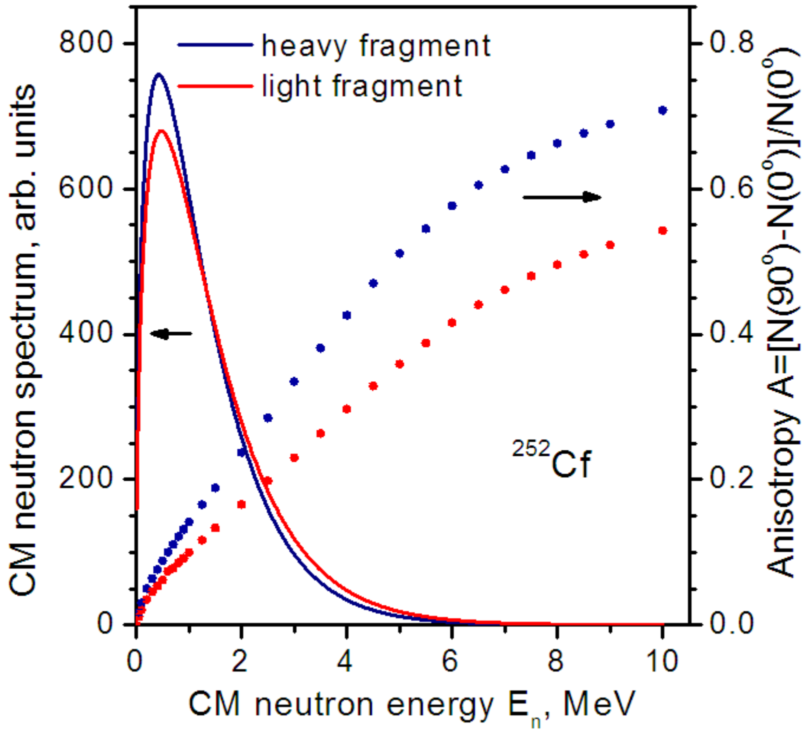
Theoretical calculations

Bunakov V.E., Guseva I.S., Kadmensky S.G., Petrov G.A., *Proc. Int. Seminar ISINN-13, Dubna, Russia*, p. 175 (2005).

Guseva, I., P *Proc. Int. Seminar ISINN-23, Dubna, Russia*, p. 80 (2016).



The angular distribution in the CMS with respect to the fission axis

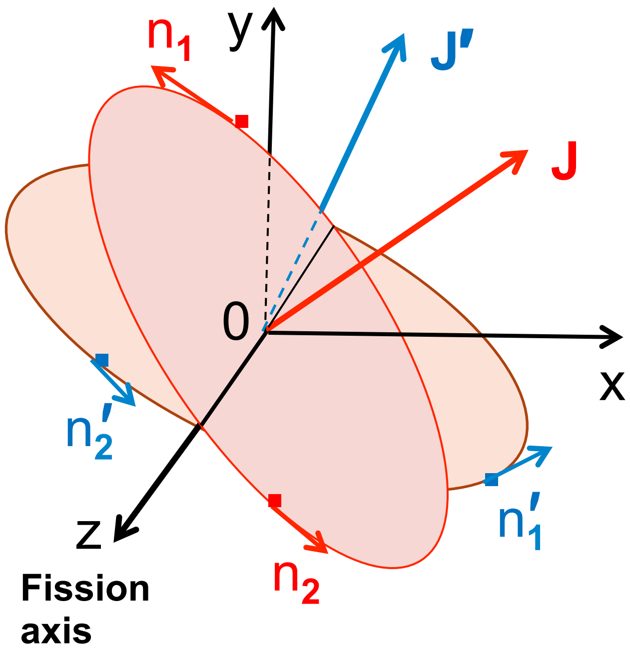


Anisotropy as a function of the CM neutron energy

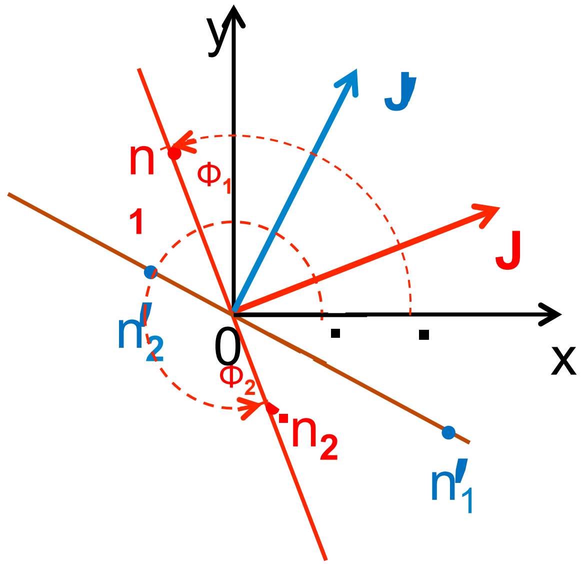
New method – triple FF-n-n correlations

F. Gönnenwein

Consider fission events from a source located at O with their fission axis pointing along a fixed z-axis in space.



Projection of neutron events on xy plane, perpendicular to the fission axis:

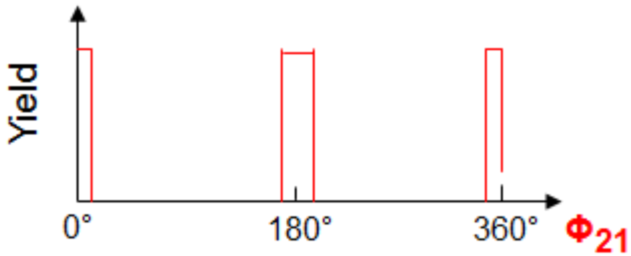


Azimuthal angle between two neutrons in a plane perpendicular to the fission axis

In the case of "perfect" alignment

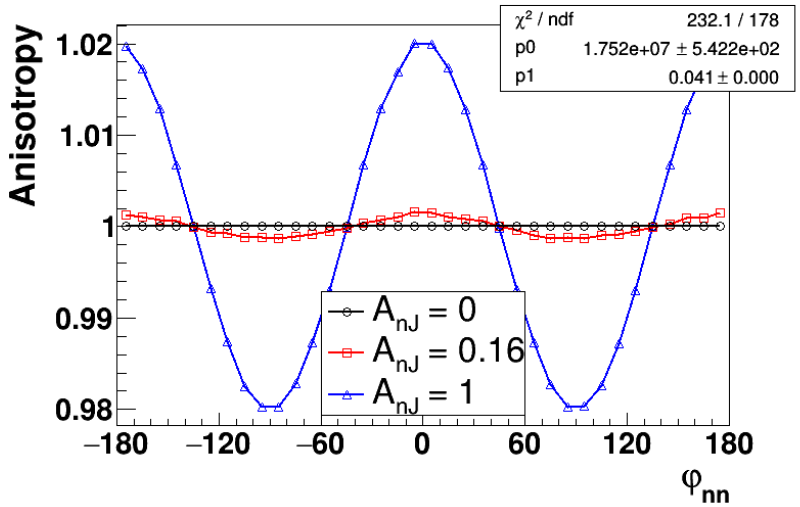
With all neutrons evaporated in a fission event being in the projection located on a straight line through the origin 0, the distribution of differences Φ_{21} of azimuth angles Φ_i is $\Phi_{21} = 0$ or $\Phi_{21} = \pi$.

$\Phi_{21} = \Phi_2 - \Phi_1$



By contrast, for isotropic neutron evaporation, the Φ_{21} distribution will be a constant.

In a realistic case

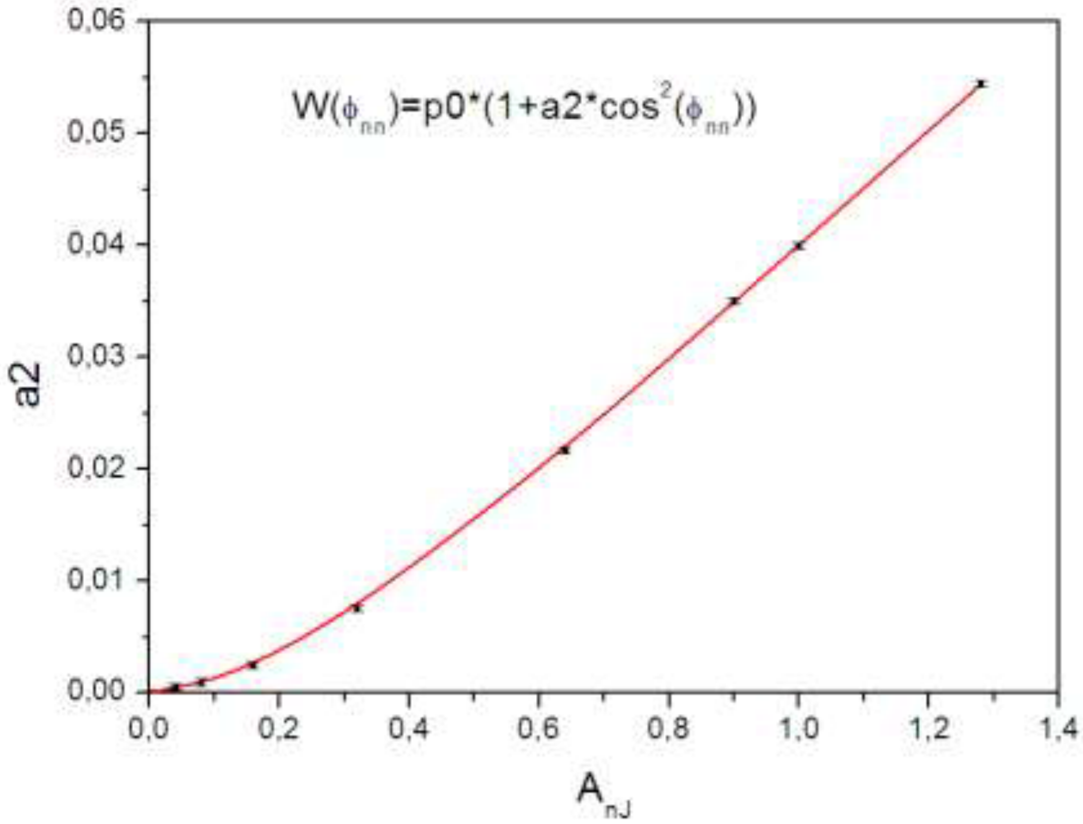


$$W(\varphi_{nn}) = p_0(1 + a_2 \cdot \cos^2(\varphi_{nn}))$$

Most important: $?_{nn}$ distribution is not affected by the kinematical focusing due to the moving fragments, as well as by the presence of the scission neutrons

The dependence of the parameter a2 on the average anisotropy A_{nJ} of neutron emission in the CM system of fragment.

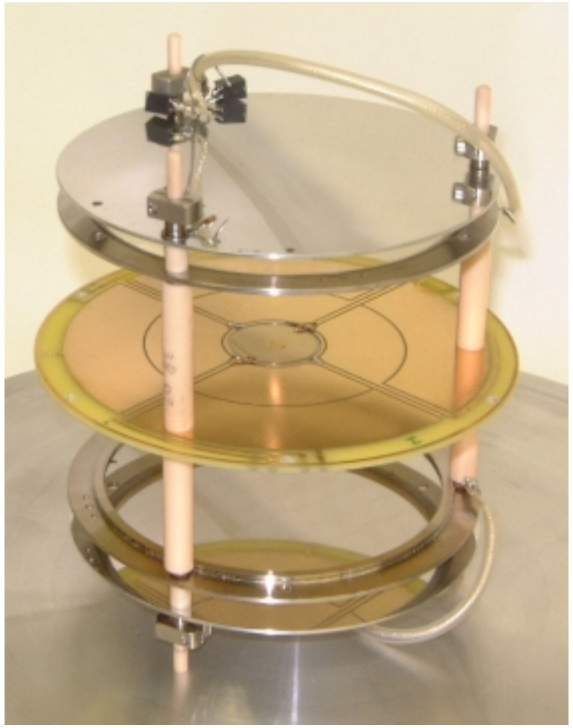
Guseva, I., P *Proc. Int. Seminar ISINN-23, Dubna, Russia*, p. 80 (2016).



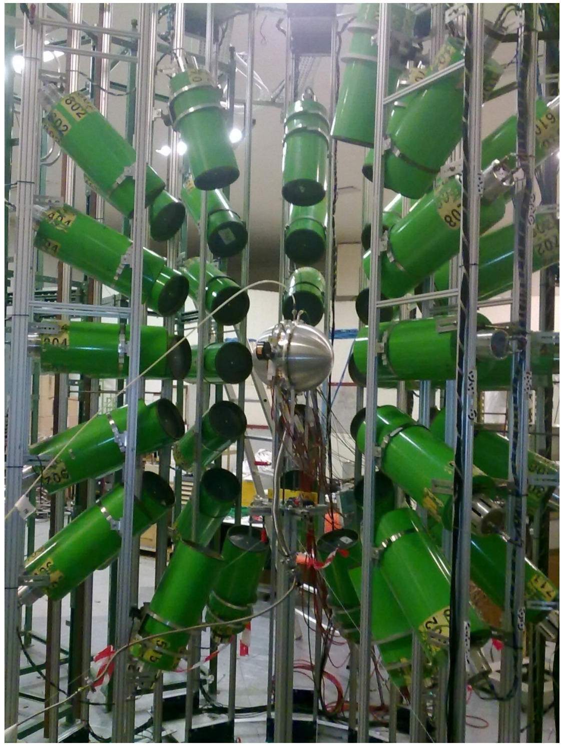
$A_{nJ} = 0.16 \Rightarrow a2$? 0.003

CORA experiment

CORrelation Angles

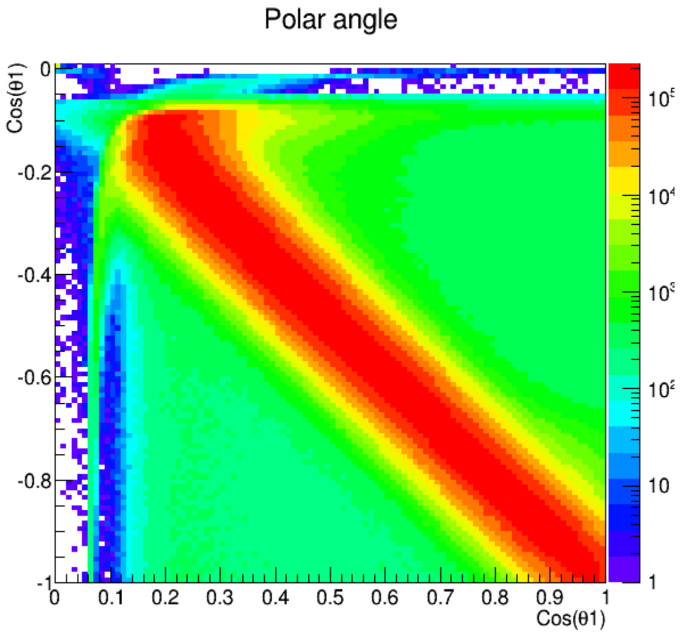


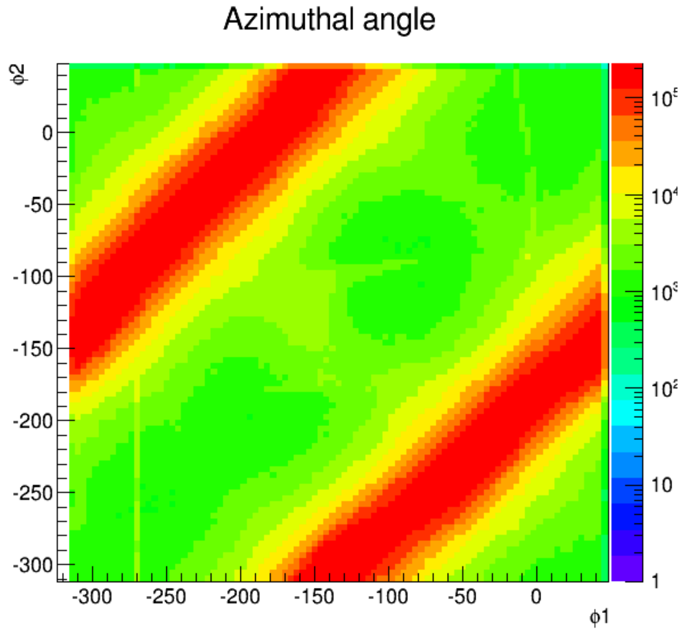
Angle-sensitive double ionization chamber CODIS

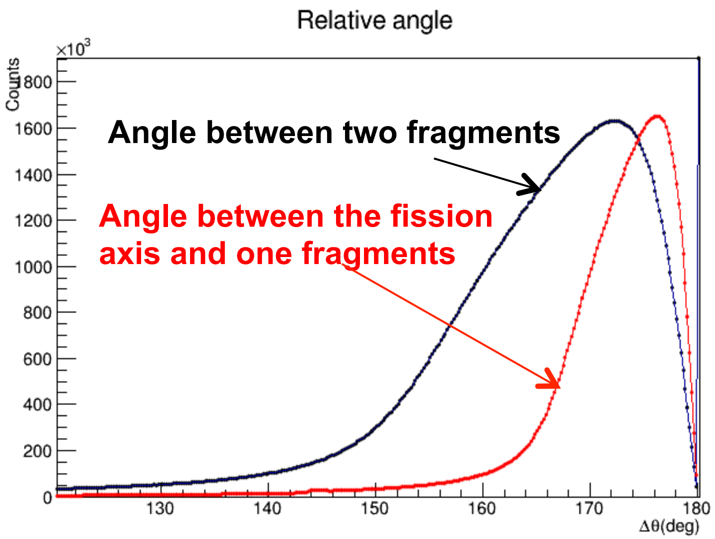


Set of large neutron detectors DEMON

Data Analysis – fragment angle determination



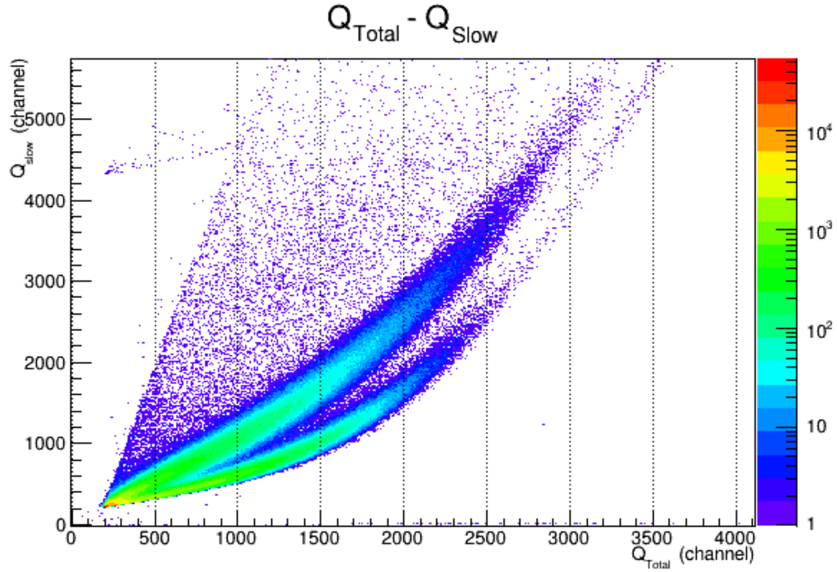




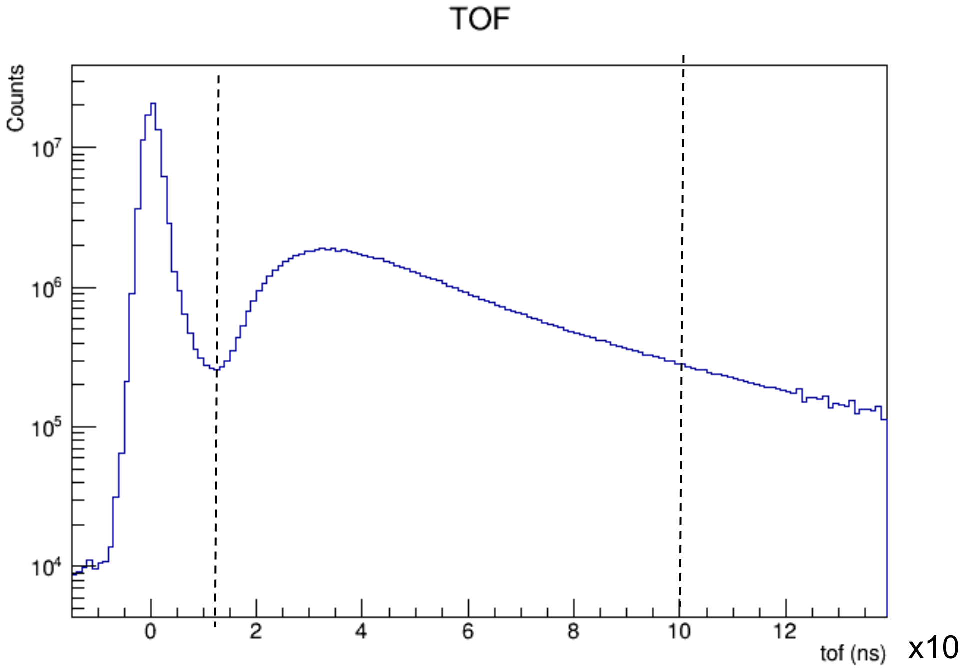
Fragment angular resolution ~ 10^0 (FWHM)

Demon opening angle ? 12^0

Data Analysis – DEMON



n-? separation



Monte Carlo simulations

Based on the GEANT4 simulation toolkit with MENATE-R physics list

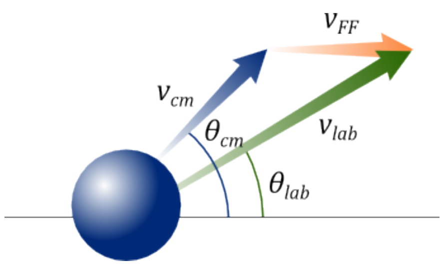
FFs attributes

- Type: heavy/light
- Random angle of emission
- Mean speed v_{FF}
- Nucleus temperature T
- *n* multiplicity n ⤏ 2D Gaussian with covariance $\rho=-0.2$

Parameters	LF	HF
v (cm/ns)	1.37	1.04
T (MeV)	0.91	0.93
$<\nu>$	2.06	1.71
σ	0.94	1.07

Neutron energy E_n in CMS: $$\varphi(\eta) \sim \sqrt{\eta} e^{-\eta/T}$$

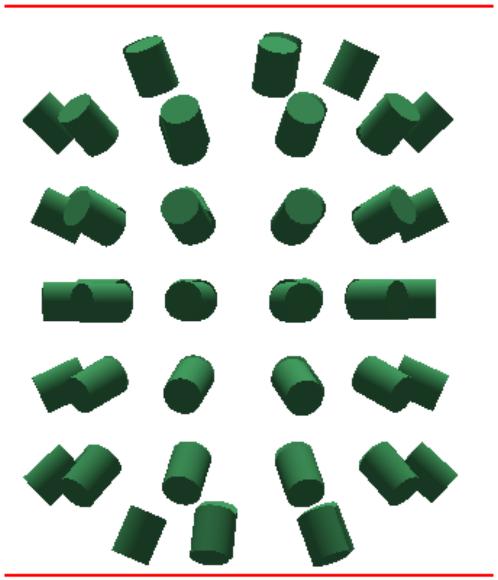
E_n in the lab. system: kinematical focusing



Neutron angular distribution in CMS:
- Isotropic or
- $$W(\theta_{nJ}) = 1 + A_{nJ} \sin^2 \theta_{nJ}$$

Monte Carlo simulations

DEMON geometry is reproduced as close as possible



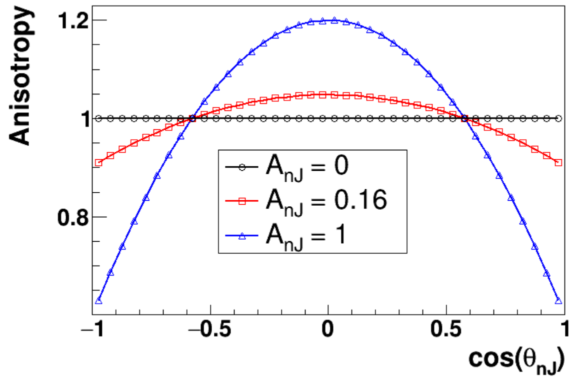
All experimentally measured distributions could be simulated and reproduced in the Monte Carlo code

The main purpose of the simulation is not to calculate and reproduce the geometrical and experimental efficiencies of the DEMON detection system and use it for the analysis of experimental data. It was used for developing and testing the analysis procedure for real experimental data.

Monte Carlo simulations

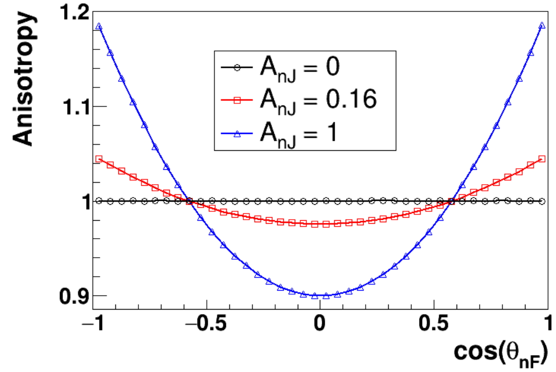
Original neuron anisotropy in the CMS:

$$W(\theta_{nJ}) = 1 + A_{nJ} \sin^2 \theta_{nJ}$$



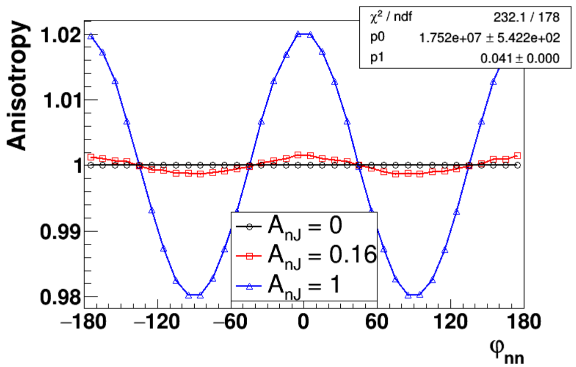
Neutron anisotropy relative to the fission axis the CMS:

$$W(\theta_{nF}) = 1 + A_{nF} \cos^2 \theta_{nF}$$



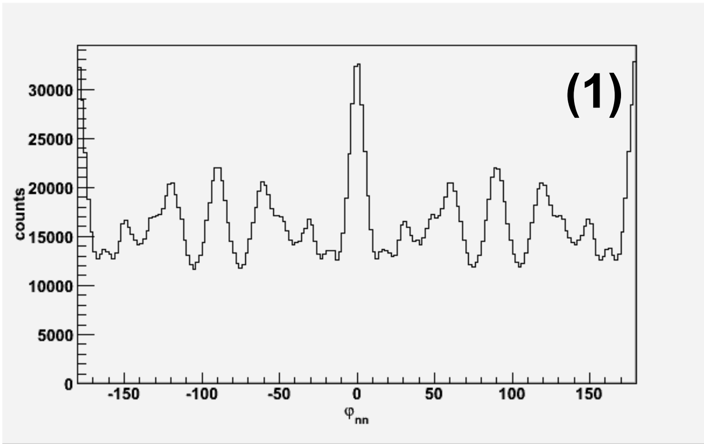
Projection of the neutron angular distribution onto the plane, perpendicular to the fission axis:

$$W(\varphi_{nn}) = p_0(1 + a_2 \cdot \cos^2(\varphi_{nn}))$$

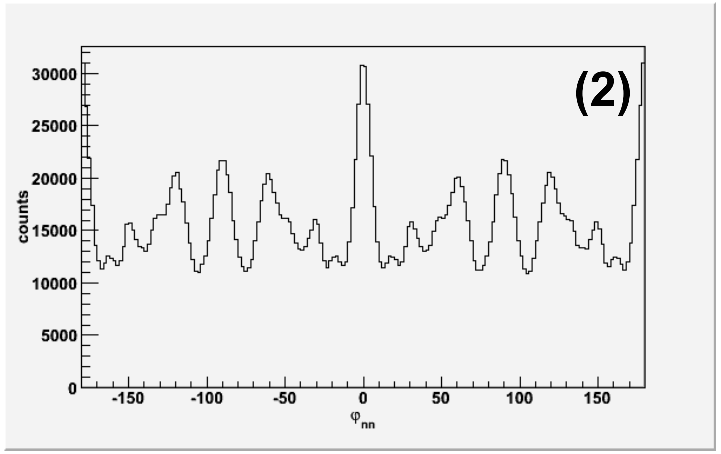


Note that this distribution is the same in the CMS and in the lab system

Monte Carlo simulations: mock experimental data

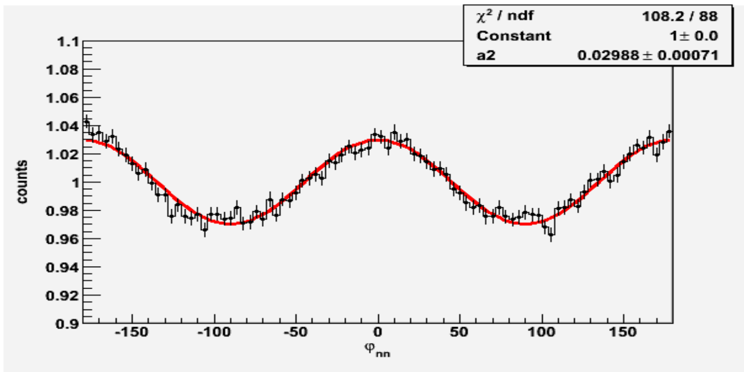


Distribution of angle ?$_{nn}$ detected by DEMONs, with anisotropy



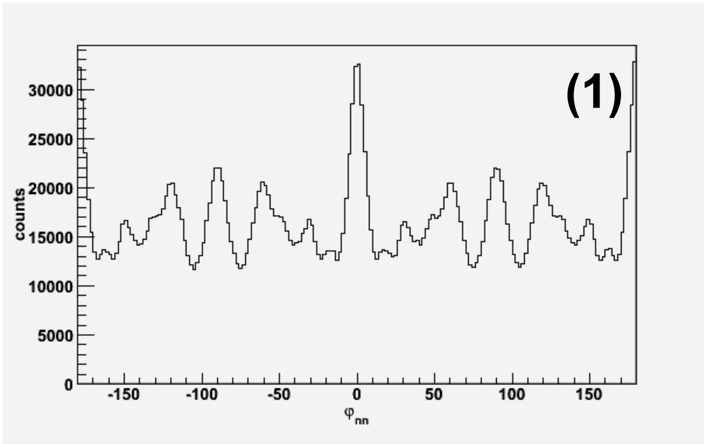
Distribution of angle ?$_{nn}$ for the isotropic emission.

The difference between two distributions is not visible, it can be only seen in the ratio:

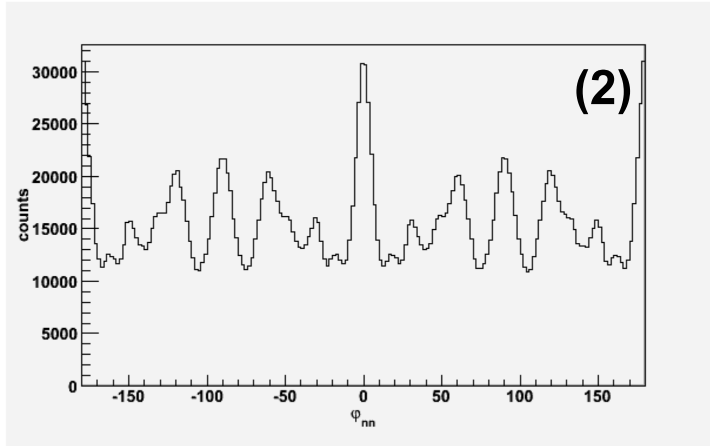


Normalized distribution (1)/(2)

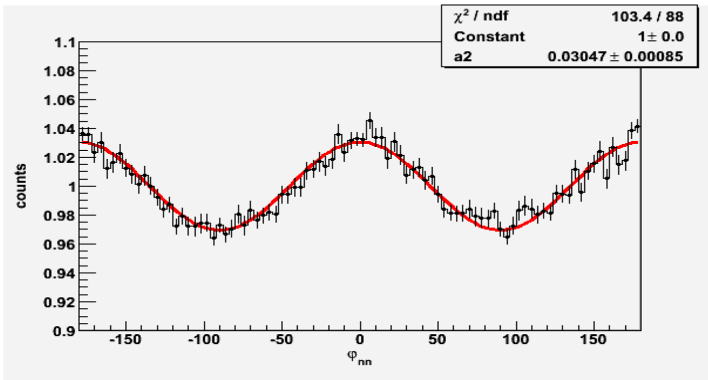
How to obtain the isotropic distribution in experiment?



Distribution of angle ?$_{nn}$ detected by DEMONs, with anisotropy



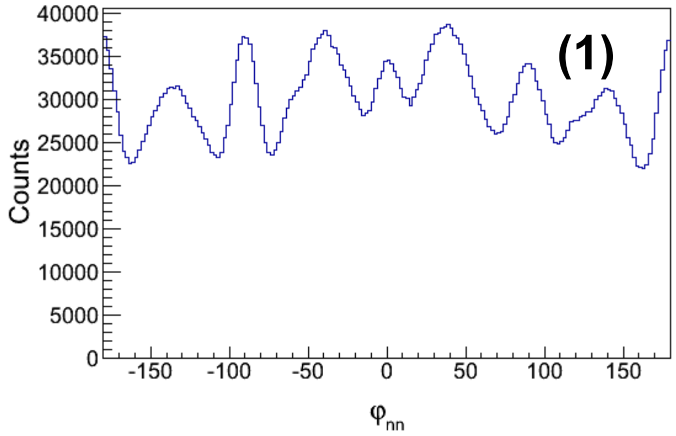
“Pseudo-isotropic” distribution, made from neutron couples, taken from different fission events



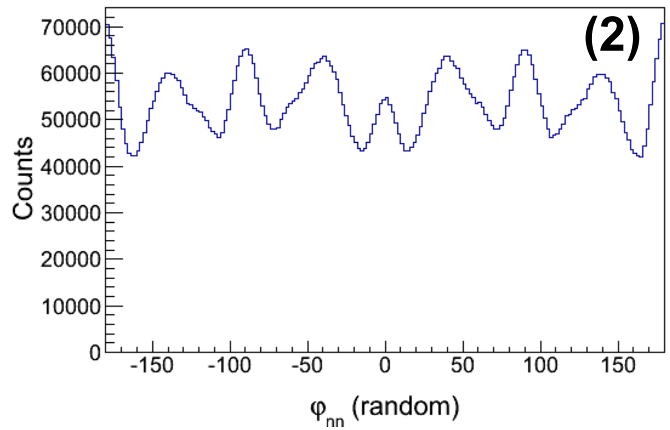
Normalized distribution (1)/(2)

MC simulations demonstrate that the statistics, obtained in the experiment should be sufficient to see the effect with theoretically predicted magnitude (a2 ~ 0.003)

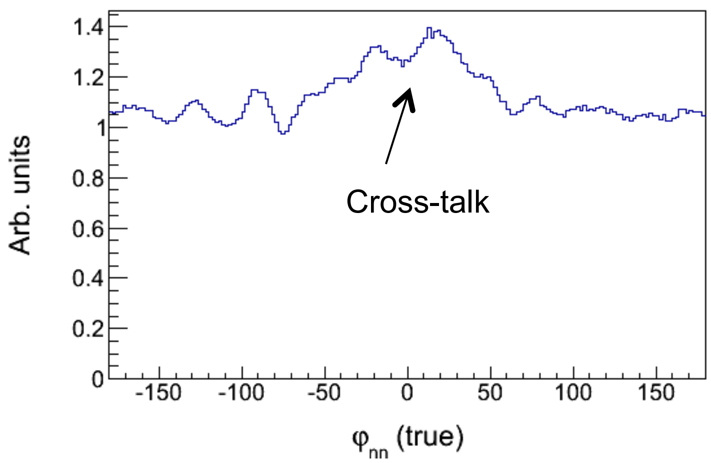
Experimental results



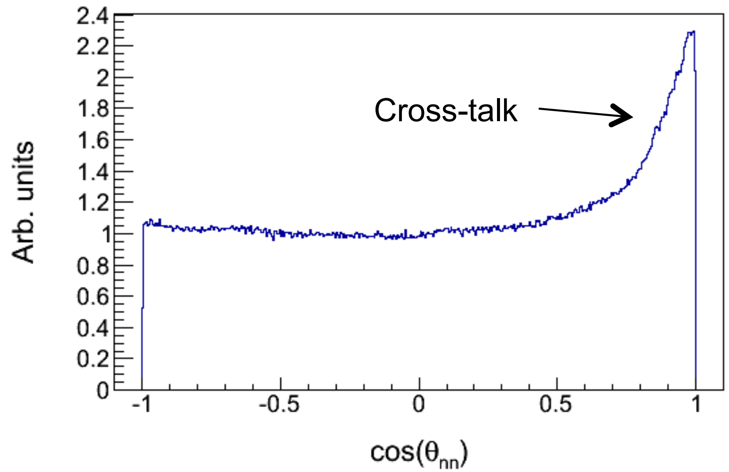
Distribution of angle $\boxed{?}_{nn}$ detected by DEMONs



Distribution of angle $\boxed{?}_{nn}$ from two different events.

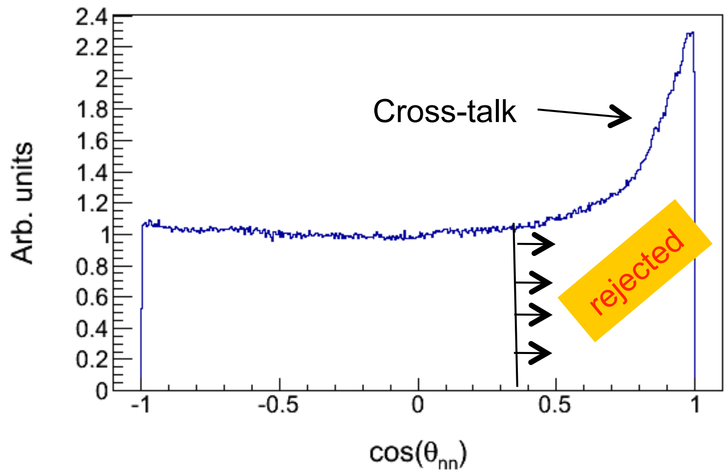


Normalized distribution (1)/(2)

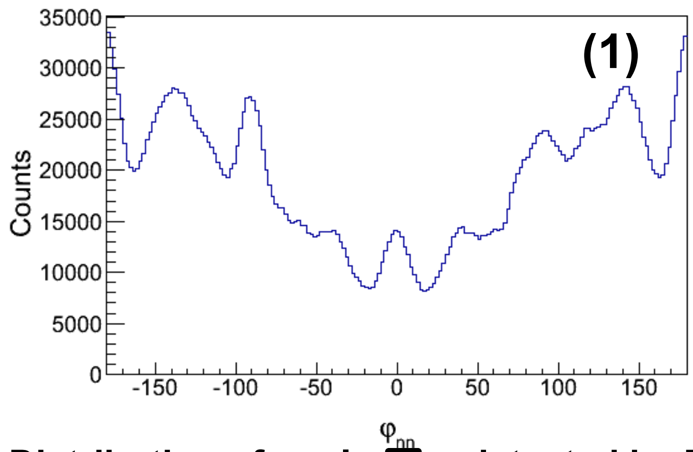


Normalized cosine of angle between two neutrons

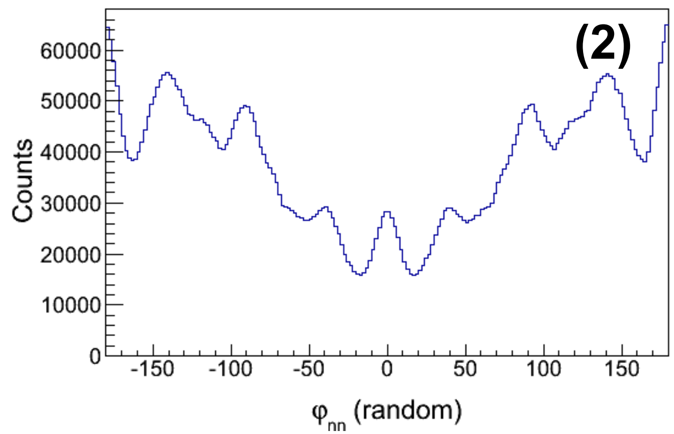
Experimental results – after elimination of the neutron “cross talk”



Cosine of angle between two neutrons



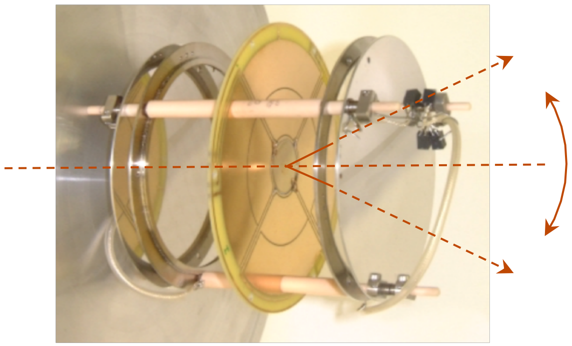
Distribution of angle ?$_{nn}$ detected by DEMONs



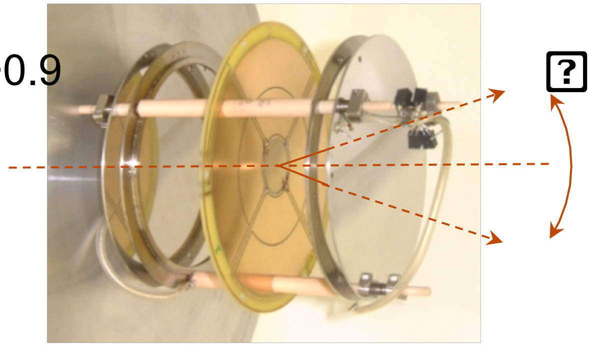
Distribution of angle ?$_{nn}$ from two different events.

Experimental results – normalized distributions

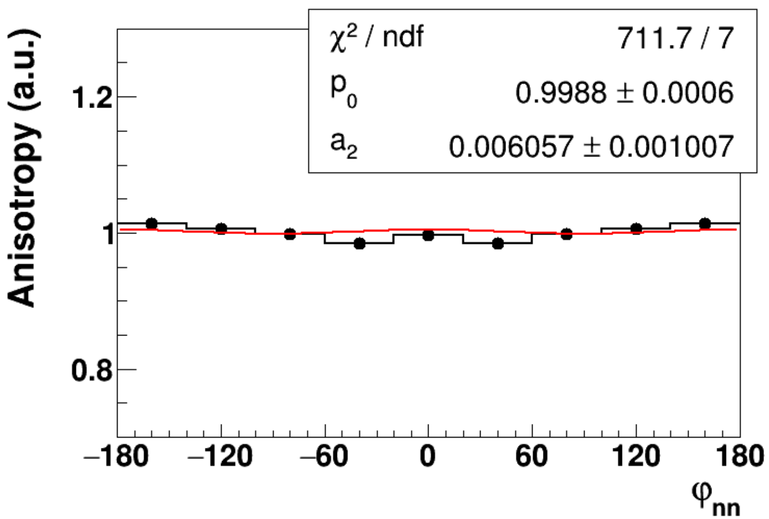
Only events with fragments emitted along the fission chamber axis are taken

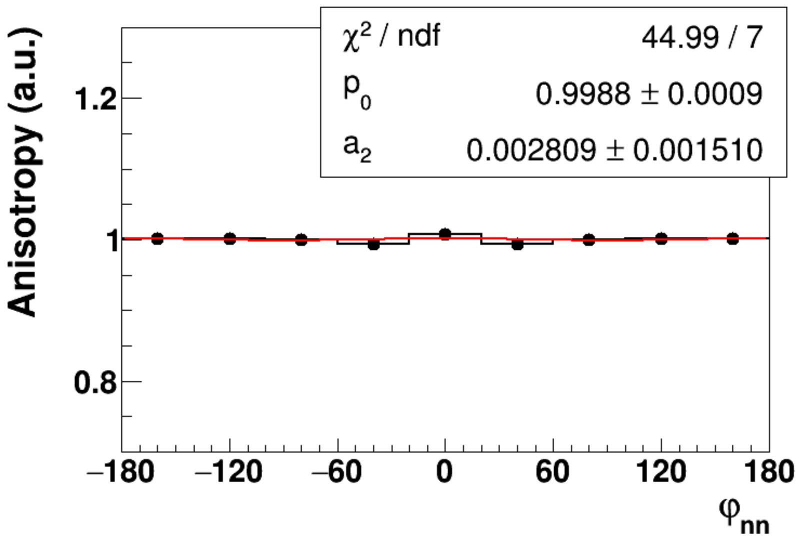


[?] 26^0: cos[?]>0.9



[?]18^0: cos[?]>0.95





Summary

- A new type of experiment has been performed, which allows to measure triple neutron-neutron-fission fragment correlations.
- A new type of data evaluation procedure is proposed, which allows to take into account rather precisely the geometrical and intrinsic efficiency of the DEMON detectors.
- Statistical accuracy is sufficient to detect the effect at the level of $\sim 10^{-4}$.
- The uncertainty of the obtained coefficient is mainly due to systematic errors caused by the "cross talk" between DEMON detectors and imperfectness of the geometry and efficiency correction procedure.

Thank you
for your attention!