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Detailed study of the angular correlations in the prompt neutron emission in spontaneous fission of ^{252}Cf

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Abstract

An experiment has been performed at IPHC Strasbourg, aimed at the detailed investigation of angular correlations in the neutron emission from spontaneous fission of ^{252}Cf. Fission fragments were measured by the angle-sensitive double ionization chamber CODIS while neutrons were detected by a set of 60 DEMON scintillator counters. The main aim of the experiment is the observation of the correlation between the fragment spins and neutron emission anisotropy. Preliminary results, based on the Monte-Carlo simulations, as well as the preliminary analysis of the experimental data are shown.

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Keywords: Spontaneous fission; Prompt neutrons; Scission neutrons; Angular correlations

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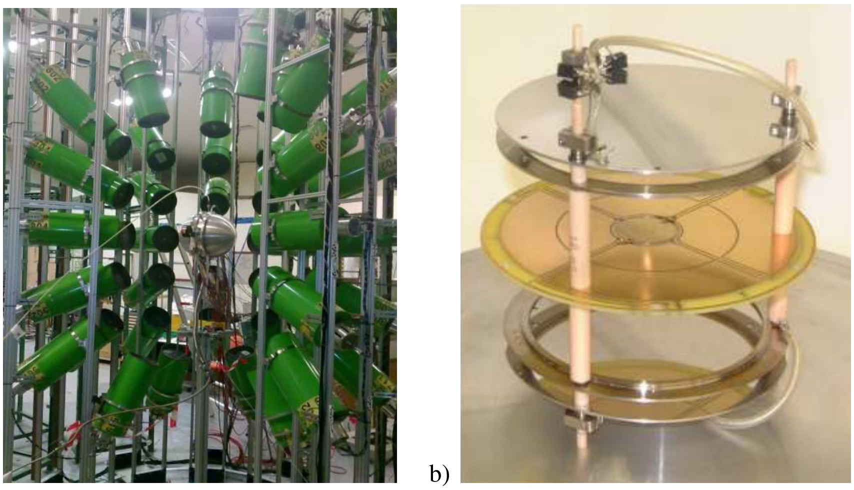
1. Introduction

It is well known since many decades that neutron emission from fragments is anisotropic relative to the fission axis (Bowman et al, 1962, Skarsvag at al, 1963). The statistical model of neutron evaporation assumes that neutron emission is isotropic in the center of mass system (cms) of fragments. The model explains reasonably well the anisotropy observed in the laboratory system by kinematical focusing caused by neutron evaporation from moving fragment. However, there are small discrepancies between the calculations and experimental data, which could not be explained by the kinematical focusing alone. Two model assumptions were put forward to explain these discrepancies: a) there exist scission neutrons which are emitted mostly isotropically in the laboratory system, and b) neutrons are emitted anisotropically in the cms of the fragments due to a correlation between neutrons and fragment angular momenta (Gavron, 1976, Bunakov at al, 2005). A similar anisotropy due to fragment spins is well known for gamma-ray emission (Kopach et al, 1999). For neutrons, in the latter assumption, it is expected that they are emitted preferentially in a plane perpendicular to fragment spin. For s-neutrons ($l = 0$) the distribution of evaporation angles is isotropic. But for non-zero l-values an anisotropy of neutron emission is anticipated (Gavron, 1976, Bunakov at al, 2005). Theoretical calculations predict that the anisotropy from spin is rather small compared to the kinematical anisotropy and it is rather difficult to separate the two sources of neutron anisotropy. To study neutron anisotropy triple neutron-neutron-fragment correlations have been investigated. In case the above mentioned anisotropy due to fragment spin exists, it will exhibit itself as a correlation of a prompt neutron with respect to another prompt neutron from the same fission event. To get rid of the known pronounced fragment-neutron angular anisotropy, the search for neutron-neutron correlations is performed in a plane perpendicular to the fission axis, where the anisotropy in the cms is not masked by the kinematical focusing.

2. Experiment

The experiment was performed at the IPHC laboratory in Strasbourg. The experimental setup consists of a 4π detector for fission fragments CODIS (Kopatch et al, 2002), surrounded by a set of 60 DEMON cells (Tilquin, 1995) for measuring prompt fission neutrons.

The kinematic spectrometer CODIS is a Frisch-gridded 4π twin ionization chamber, filled with CH4 at 0.75×10^5 Pa to perform the measurement of the fragments energies/masses and their angles of emission. The common cathode of the twin ionization chamber is made of copper-plated teflon material, with the ^{252}Cf source located in the centre. The polar θ angle is determined by measuring the electron drift times from the cathode to the Frisch-grids, while the azimuthal φ angle can be determined by means of the sectored cathode, segmented on both sides.



a) b)

Fig. 1. The experimental setup: (a) DEMON detectors surrounding the CODIS chamber; (b) CODIS detection system with sectored cathode.

The neutron multi-detector spectrometer DEMON consists of 60 NE213 liquid scintillator cells of 20 cm length and 16 cm diameter, optically coupled to XP4512B photomultiplier tubes. The DEMON detectors were disposed in a quasi-cylindrical geometry around the CODIS chamber with the minimal and maximal distance to the source of about 60 cm and 90 cm, respectively. The neutron detectors covered a fraction of about 20% of the 4π, with an angular acceptance of the different modules in this configuration between $2.2° < \Delta\theta < 5.8°$. The neutron energy is determined by the time-of-flight technique and the discrimination from γ-rays is archived a by a combination of pulse shape analysis and time-of-flight. The time resolution of DEMON is about 1.5 ns.

We applied a new method for the analysis of the influence of fragment angular momentum (spin) on neutron emission from the fragments. It is well known that the initial angular momenta of fragments are aligned, i.e. oriented preferentially perpendicular to the fission axis. All events are analyzed in a coordinate system, in which the Z axis coincides with the flight direction of the light fission fragment, while the most probable orientation of the fragment spin I is in the XY plane (see Fig. 2). Two neutrons, emitted from the same fragment (or from different fragments, but from one fission event) with azimuthal angles φ_1 and φ_2 in the lab system, respectively, are considered. In case the first neutron is correlated with fragment spin, i.e. emitted preferentially perpendicular to the spin direction, the same correlation should be observed for the second neutron, and both neutrons should hence be correlated with each other. So one should observe a non-isotropic distribution of the relative angle $\varphi_{21} = (\varphi_1 - \varphi_2)$.

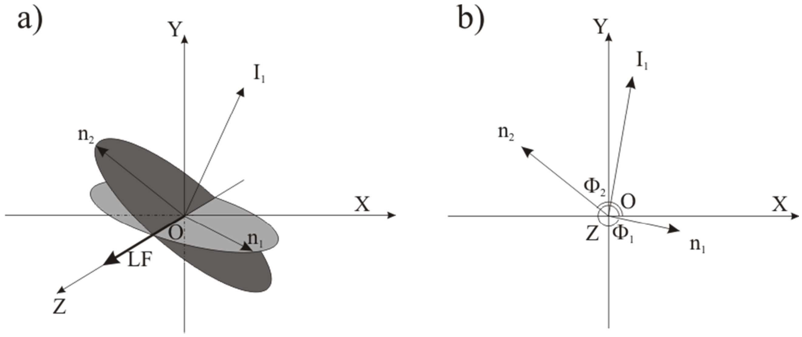


Fig. 2. Evaluation scheme for the search of nn-anisotropy. a) Light fragment (LF) direction coincides with the Z axis; spin (I) of the fragment lies in the XOY plane; $\mathbf{n_1}$ and $\mathbf{n_2}$ are neutron velocities in the lab system. b) the projections of neutron velocity vectors on the XOY plane.

3. Monte Carlo simulations

The Monte Carlo simulations were performed, based on the GEANT4 simulation toolkit (Agostinelli, 2003) with MENATE-R physics list (Desesquelles et al, 1991, Roeder, 2008), in order to develop and test the procedure of the data analysis and estimate possible systematic errors of the experiment. In the simulation code fission fragments which define the fission axis are isotropically distributed in the 3D-space. The physical parameters necessary to simulate the neutron emission from the fragments of ^{252}Cf are shown in table 1.

Table 1. Parameters of the simulation. LF and HF stand for the light fragment and heavy fragment, respectively.

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

The neutron multiplicity ν for each fragment is computed by a random sampling from a 2D-normal distribution defined with the physical quantities also shown in table 1 and with a correlation value $\rho = -0.2$. In order to extract the neutron kinematical quantities in the CM system of the FF, neutron energies are randomly taken from a Maxwellian distribution:

$$\varphi(\eta) \sim \sqrt{\eta}e^{-\eta/T} \tag{1}$$

where T is the temperature of the daughter nucleus and η represents the neutron energy in the CM of the corresponding FF.

First, the isotropic neutron emission in the centre of mass of the fragments is simulated. Then the kinematical focusing is applied by adding the velocity of the fission fragments (see table 1) to the velocity of each neutron shot, obtained from (1). For each simulated fission event, the relative angle between the emitted neutrons is computed. To obtain the angular correlations at least two neutrons per fission are needed. Taking into account the kinematical focusing, the uniform distribution in the CM of the FFs becomes forward/backward asymmetric as expected. The dynamical anisotropy is introduced by taking into account the assumption that the FFs have a large angular momenta, J~8ħ, (Wilhelmy et al, 1972) which are aligned perpendicularly to the fission axis. Neutrons evaporated from a rotating nucleus will preferentially be emitted in the plane perpendicular to the fission axis. This anisotropy can be parameterized by:

$$W(\theta_{nI}) = 1 + A\sin^2\theta_{nI} \tag{2}$$

where $A \neq 0$ is the anisotropy parameter (Bunakov at al, 2005) and θ_{nI} is the angle of a neutron relative to the angular momentum of the fission fragment. To complete the simulation the anisotropic neutron emission is added to the code according to formula (2) as shown in Fig. 3. The anisotropy effect appears very weak, in the neutron-neutron relative angular distribution, as one can observe figure in Fig. 3. This observable is thus not the most adapted to investigate the dynamical anisotropy.

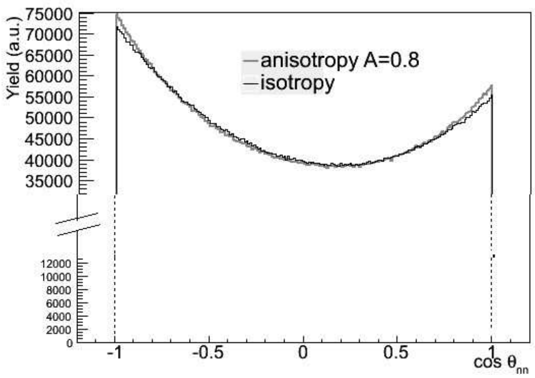


Fig. 3. Calculated neutron relative angular distribution θ_{nn} obtained by the simulation in two different cases: a pure isotropic emission (A=0, black curve), and an anisotropic emission (A=0.8, gray curve).

The simulation code allows to trace step by step various effects of the experimental biases related to DEMON: geometrical acceptance, energy threshold, intrinsic efficiency, cross talk and central angles instead of the real angles. It is based on GEANT4 that allows to reconstruct the detection system used in the CORA experiments. The simulation code reproduces the DEMON detector configuration to analyze the impact of the geometrical acceptance on the neutron angular distribution. At this stage, due to the two neutrons coincidences, only about 4% of the initially simulated counts remain. It also takes into account the interaction processes of the neutrons in a liquid scintillator containing xylene as DEMON is consisted of. This code includes a model for the interaction of fast neutrons with ^{1}H and ^{12}C (Desesquelles et al, 1991, Roeder, 2008). In the case of the neutrons, their detection is performed in two steps. First a neutron transfers all or part of its kinetic energy to the charged particles of the medium. A neutron arriving in a DEMON cell interacts mainly with hydrogen atoms, n + H → n + p, and the energy lost in this kind of interaction must be higher than the energy threshold of the detector. Another important effect is the cross talk: instead of one neutron signal the detection system detects two or more. It occurs when a neutron interacts in a DEMON volume and is scattered into another cell, most probably in a neighbouring DEMON module. For these reasons the neutron-neutron angular distributions are mainly affected by this effect at small relative neutron angles.

Figure 4 shows the simulated projection of the neutron-neutron angular distribution onto the XY plane (see Fig.2) with the anisotropy coefficient A=1 in eq. (2), which is about factor of 10 larger than expected from the theory (Bunakov, 2005). In this simulation the cross-talk between different neutron detectors was not considered. Apparently, the distribution in Fig.4 doesn't depend on the fragment velocities and is not affected by the kinematical focusing, as it is built in the plane perpendicular to the direction of motion of the fragments.

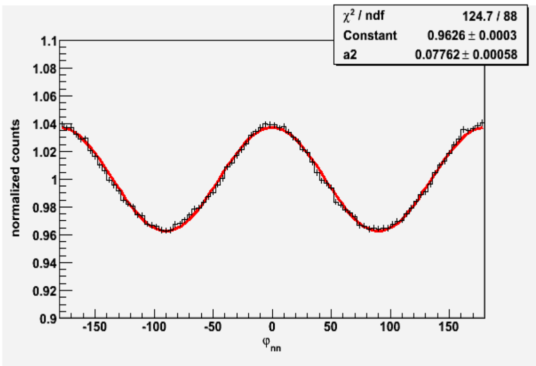
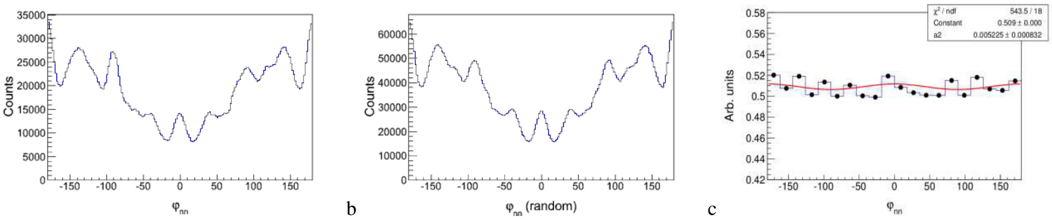


Fig. 4. Calculated projection of the n-n angular distribution onto the XY plane (perpendicular to the fission axis).

4. Analysis and results

The main problem in the analysis of the data from the experiment with many detectors, each of them having its own geometrical and intrinsic efficiency, is how to take into account different detector efficiencies in the most accurate way. We developed a procedure of self-normalization of the neutron-neutron angular distributions. The procedure was tested in the simulations and proved to be accurate enough. It consists in building "pseudo-random" neutron-neutron angular distributions with two neutrons originated from different fission events. This can be either the distribution of the relative angle between two neutrons (as shown in Fig. 3) or the projection of the angular distribution onto the XY plane (see Fig. 4). In all cases the geometrical and intrinsic efficiencies of the neutron detectors are considered, but the actual correlation between two neutrons is missing. So making such a "pseudo-random" angular distribution is practically equivalent to the simulation of the neutron-neutron angular distributions with zero correlation, but with very accurate detector response, taken from the experimental data. By normalizing the measured neutron-neutron angular distribution to such a "pseudo-random" one, we obtain the distribution, which is free of the geometrical effects. One problem, which still remains not fully solved after such normalization, is the cross-talk between different detectors. If the cross-talk is large enough, it may distort the resulting distribution.

In order to minimize the effect of the cross-talk and possible systematic effects connected with the averaging of the events with very different angles of emission in the laboratory system, we selected only those events, for which the fission fragments were emitted along the chamber axis ($\cos\theta > 0.9$) and the angle between two neutrons were larger than 65^0.



a b c

Fig. 5. Different steps of analysis of the projection of the n-n angular distribution onto the XY plane: a) measured n-n distribution; b) "pseudo-random" n-n distribution (neutrons from different fission events); c) normalized n-n distribution.

Figure 5 shows different steps of analysis using the "pseudo-random" normalization method. The measured (a) and "pseudo-random" (b) distributions are almost identical, as the expected effect is very small. The resulting normalized distribution is shown in Fig 5(c) together with a fit by the formula $W(\varphi) = D\cdot(1+\mathbf{a2}\cdot cos(2\varphi))$. The parameter $\mathbf{a2} = (5 \pm 3)\cdot 10^{-3}$ (the uncertainty had to be increased because of the large χ^2) is correlated with the parameter A in eq. (2) and approximately corresponds to the expected value of A=0.08.

5. Conclusion

The preliminary analysis of the data, as well as the Monte Carlo simulations indicate that the searched correlation should exist, and its magnitude is not far from the one which is predicted by the theory. Further improvement of the simulations and the analysis, by taking into account fission events with all emission angles, and by dealing with the cross-talk properly may also shed light on the long standing question of the existence of the so-called scission neutrons in fission. The CORA experiment is probably the only one which may give access simultaneously to the scission neutrons and the CM neutron dynamical anisotropic emission by the fragments in the fission process.

Acknowledgements

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