NEUTRON EMISSION ANISOTROPY IN FISSION

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Experimental neutron angular distributions are investigated in the spontaneous fission process of ^{252}Cf. The CORA experiment presented in this paper has the aim to study neutron angular correlations in order to elucidate the neutron emission mechanisms in the fission process. The experimental setup is composed by the CODIS fission chamber and the DEMON neutron multi-detector. The development of a simulation toolkit based on GEANT4 and ROOT adopted as a strategy to investigate the emission of the neutrons is described. Preliminary results on the sources of the anisotropy, scission neutron emission and/or dynamical anisotropy are shown.

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1. Introduction

In the fission process it is well known that the bulk of prompt neutrons is evaporated by the fully accelerated rotating fragments. The neutron evaporation theory [1] states that this emission is isotropic in the centre of mass (CM) of the moving fragments. Due to the velocity of the fission fragments (FF), when converting it from their CM to the laboratory system, the angular distributions of the neutrons present an enhancement at 0° and 180°, well known as the kinematical focusing (Fig.1 (a)). But when one compares the angular distributions with a pure isotropic evaporation, discrepancies appear in different works, experimental as well as theoretical ones. To understand the origin of these deviations a contribution has been introduced corresponding to neutrons ejected at an early stage of the fission process, at the scission point [2, 3]. But even by adding these scission neutrons (Fig.1 (b)) and taking into account the anisotropy effect due to the kinematical focusing, an excess of neutrons observed at small laboratory angles around heavy and light fragment remains. So it was assumed that an anisotropy appears also in the CM of the two fragments and this effect reinforces the kinematical anisotropy in the laboratory system as shown in (Fig.1 (c)) [4, 5]. There are theoretical arguments and calculations that claim that this anisotropy exists, but there isn't any direct observation because its contribution is acting in the same way as the kinematical focusing and it is very weak.

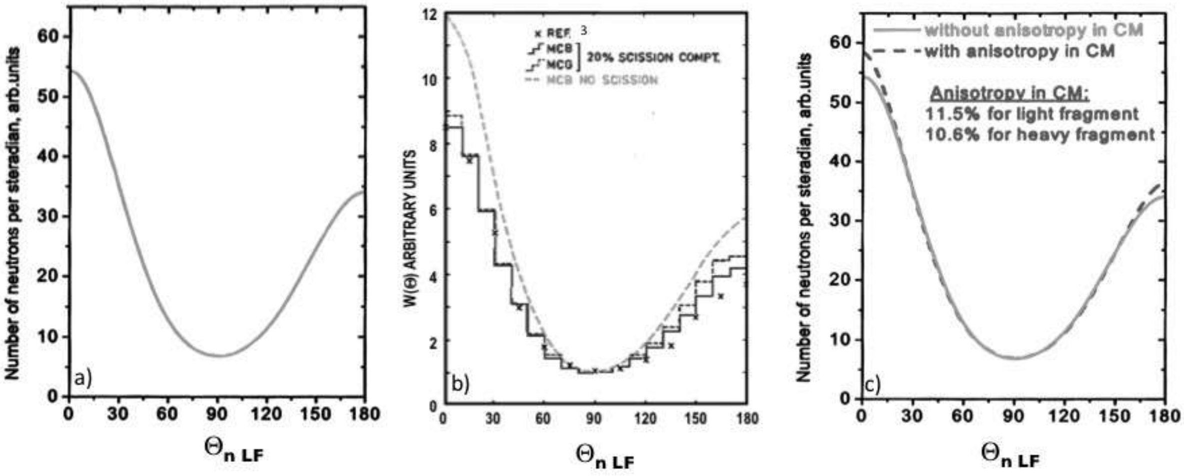


Fig. 1: Neutron angular distributions as a function of the angle between neutrons and the light fragment (LF). The kinematical focusing (a), the effect of the scission neutrons [3] (b, solid curve) and of the dynamical anisotropy [5] (c, dashed curve) are shown.

To highlight this dynamical anisotropy a new method has been developed by our collaboration. The CORA experiments were performed for this purpose [6]. All of them are measurements of triple coincidences between any fission fragment and two neutrons emitted in coincidence. In this way we can separate, in the laboratory system, the contribution of the predicted CM anisotropy from the anisotropy due to the kinematical focusing.

As we are looking for two effects, the dynamical anisotropy and the scission neutron emission, which may be of the same order of magnitude, the experimental biases had to be carefully addressed. The strategy pursued in this work has been to reproduce the detection system adopted in the experiment through the development of a simulation code that allows to assess the effect of all the experimental biases on the angular correlations between the neutrons. The simulation performed is based on GEANT4 [8], MENATE R [9, 10] to describe the neutron interaction in the DEMON detectors and ROOT [11].

2. CORA experimental setup

The experiment was performed at the IPHC laboratory in Strasbourg. The apparatus used for this experiment consists of the DEMON neutron multi-detectors (Fig. 2(a)) and the CODIS fission chamber (Fig. 2(b)).

The DEMON multi-detector consists of a hundred individual cylindrical cells with a depth $L = 20$cm and a diameter $D = 16$cm, each containing 4.4 liters of organic liquid NE213 rich in hydrogen ($^{1}H/^{12}C \sim 1.2$ on average). In the CORA experiments, only 60 modules were used and the DEMON geometrical configuration covered only 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 pulse shape analysis.

(a) (b) (c)

Fig. 2: CORA experiment setup: (a) DEMON which is close to a spherical configuration around the CODIS chamber; (b) CODIS detection system; (c) Determination of the fission axis from the CODIS cathode signals: the figure shows the first 4 sectors S_i [7].

The CODIS detection system is composed by a frisch-gridded 4π twin ionization chamber, filled with CH_4 at 0.75×10^5 Pa to perform the measurement of the fragments energies and their angles of emission. The two ionization chambers are assembled in a common cathode made of copper-plated teflon material, where the ^{252}Cf source is located in the centre. The angles determination is achieved by measuring the electron drift times from the cathode to the Frisch-grids, but also by means of the sectored, on each side, segmented cathode as shown in Fig. 2(c).

The outer signals of the sector depend on the orientation of the fission axis, i.e. θ and φ, and from the fragments kinetic energy, i.e. the height of the pulse S_i of the cathode section i (i=1,...,8). The quantities $q_{i,j}$ depending on the orientation (θ, φ) of the fission axis are calculated as

$$q_{ij} = \frac{S_i}{S_i + S_j}$$

where the sectors i and j lie on the same surface of the cathode, but opposite to each other; the other quantities are defined accordingly.

3. Features of the simulation toolkit

The simulation package allows to reproduce a ^{252}Cf fissioning system and the experimental neutron detection setup. In the simulation code FF which defines 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 the table of Fig.3.

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 the table of Fig.3 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:

$$\varphi(\eta) \sim \sqrt{\eta} e^{-\eta/T} \tag{3.1}$$

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.

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

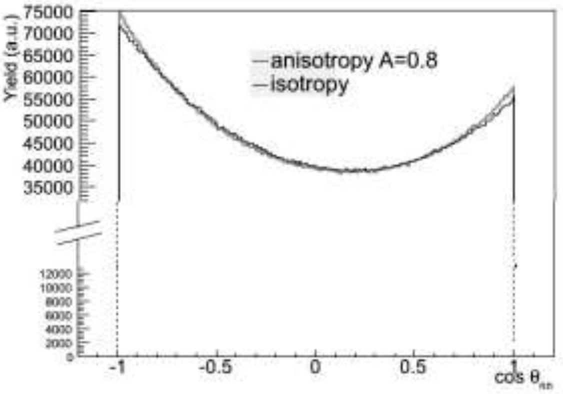


Fig. 3: In the table are shown the parameters adopted in the simulation [12]. LF and HF state respectively for the light and heavy fragments. The curves represent the theoretical neutron relative angular distribution θ_{nn} obtained by the simulation in two different cases: a pure isotropic emission (A=0, black curve), and an anisotropic emission (A=0.8, gray curve).

Then the kinematical focusing is obtained moving from the FF CMs to the laboratory system by adding the velocity of the fission fragments (table of Fig. 3) to the velocity of each neutron shot, obtained from 3.1.

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 momentum, $J \sim 8\hbar$, [13] 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 is well parameterized by:

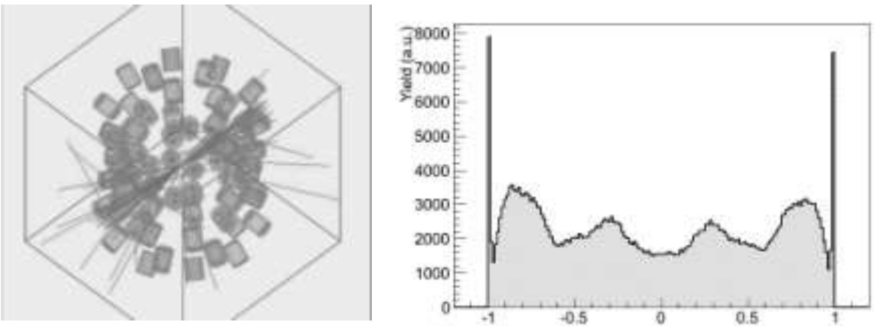
$$W(\theta_{CM}|_J) = 1 + A \sin^2 \theta_{CM}|_J, \qquad (3.2)$$

where $A = 0$ is the anisotropy parameter [5] and $\theta_{CM}|_J$ the angle relative to the angular momentum.

To complete the simulation the anisotropic neutron emission is added to the code according to formula 3.2 as shown in Fig. 3. The anisotropy effect appears very weak, in the neutron-neutron relative angular distribution, as one can observe figure Fig. 3. This observable is thus not the most adapted to investigate the dynamical anisotropy.

The simulation code allows to follow step by step the effect 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 as shown in Fig. 4(a). The simulation code reproduces the DEMON detector configuration to analyze the impact of the geometrical acceptance on the neutron angular distribution

(Fig.4(b)). At this stage, due to the two neutrons coincidences, only about 4% of the initially simulated counts remain.



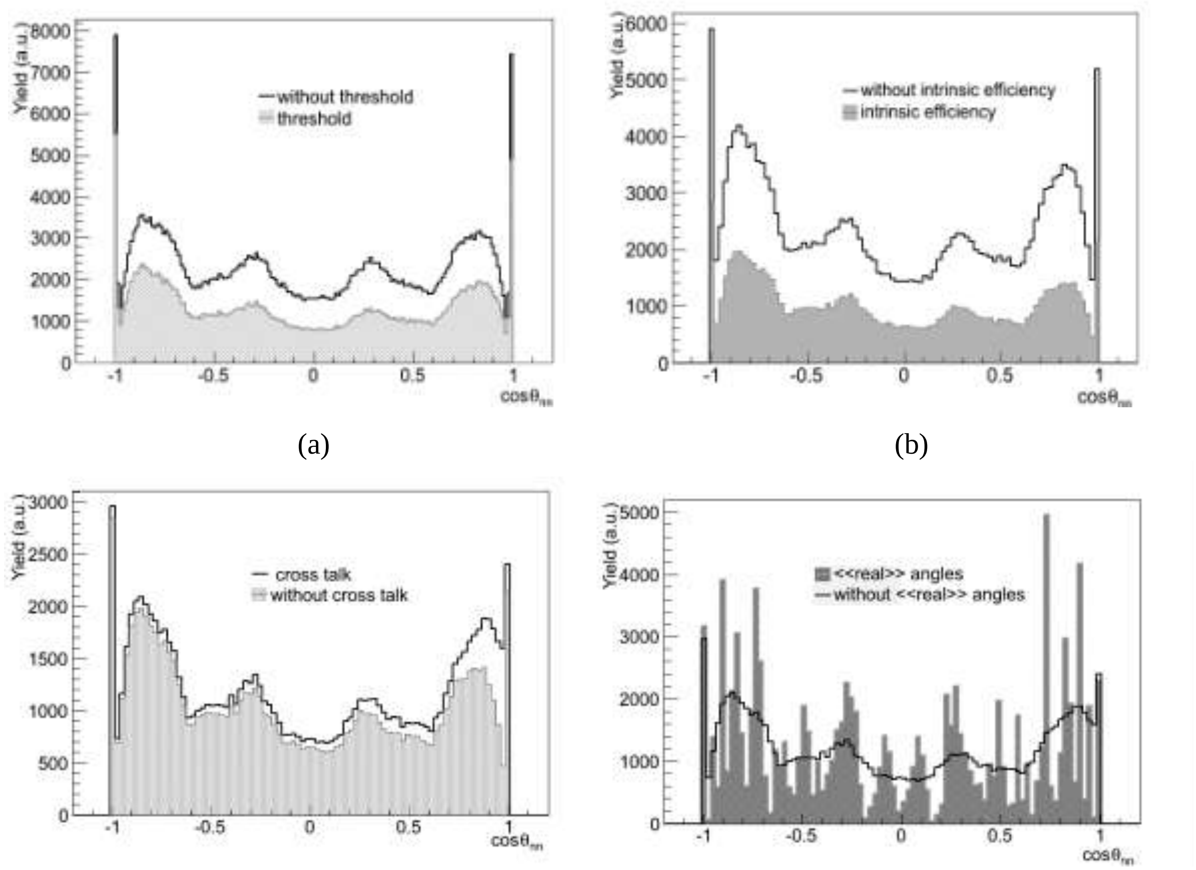
(a) (b)

Fig. 4: (a) The simulated DEMON geometrical configuration adopted in CORA experiments. (b) Filtered neutron relative angular distribution $\cos\theta_{nn}$: passing the DEMON geometrical configuration shown, the distribution is transformed in this shape.

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 [9, 10]. 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, $n + H \rightarrow n + p$, and the energy lost in this kind of interaction must be higher than the energy threshold of the detector. The effect of the intrinsic efficiency and of the energy threshold is evaluated in this way and the resulting effect in the angular distribution shown in Fig.5 (b). Another important effect is the cross talk: instead of one neutron signal the detection system detects few 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 as shown inFig.5(c).

4. Results and discussion

These simulations have the purpose to study all the effects of the experimental filter: geometrical acceptance, detection threshold of DEMON, intrinsic detection efficiency and cross talk on the angular distribution of neutrons. Starting from the theoretical distribution shown on Fig.6(a) one ends thus up with the distribution presented in Fig.6(b) (black histogram). At this point the filtered simulated distribution can be compared to the experimental one.

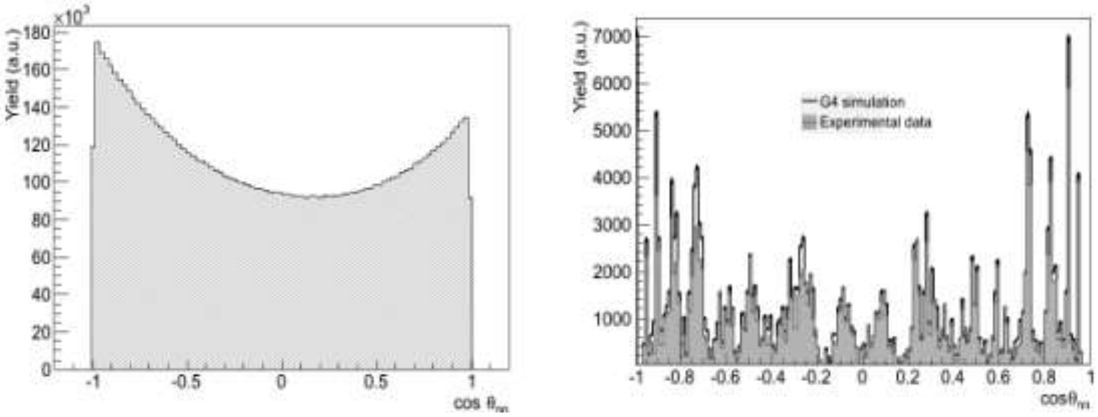


(a) (b)

(c) (d)

Fig. 5: Comparison of the effects on the neutron relative angular distribution cosθ_{nn} at each step of the introduction of the different biases into the simulation code:
(a): after geometrical acceptance introduction, before (black curve) and after (gray filled curve) threshold introduction.
(b): after geometrical acceptance and threshold introduction, before (black curve) and after (gray filled curve) intrinsic efficiency introduction. On average about 50% of counts are lost.
(c): after geometrical acceptance, threshold and intrinsic efficiency introduction, before (gray filled curve) and after (black curve) cross talk introduction. As expected the major contribution to the cross talk is at small relative angles.
(d): after geometrical acceptance, threshold, intrinsic efficiency and cross talk introduction, before (black curve) and after (gray filled curve) DEMON central angles introduction.

The comparison between the experimental results (gray filled histogram) of Fig.6(b) and the simulations (black histogram) is really encouraging. In Fig.6(b) the bumps of the two curves coincide very well. Moreover in the backward-forward direction there is a promising disagreement. Indeed this difference can be attributed to scission neutrons.



(a) (b)

Fig. 6: (a) Theoretical neutron relative angular distribution $\cos\theta_{nn}$ obtained by the simulation. (b) Comparison between the experimental distribution (gray filled curve) and the simulated one after the experimental filter (solid black curve).

5. Conclusion

The preliminary results indicate that the simulation works very well and the strategy to extract the correct parameters for the scission neutrons and the dynamical anisotropy from the CORA experiment using this code seems very promising. The next step is now to optimize the agreement between simulation and experiment by means of χ^2 minimizations, which will lead to the most probable combination (scission percentage, dynamical anisotropy strength) which are the two parameters intervening in the simulation. Another constraint on these two parameters will be obtained also by the angular distribution between the neutrons and the FFs. Independently, the anisotropy parameter will be fixed by the $\varphi_{12} = \varphi_2 - \varphi_1$ azimuth angular distribution method described in [6]. 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.

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