NEUTRON EMISSION ANISOTROPY IN FISSION*

A. Chietera[a,b], L. Stuttgé[a,b], F. Gönnenwein[c], Yu. Kopatch[d]
M. Mutterer[e], I. Guseva[f], A. Gagarski[f], E. Chernysheva[g]
O. Dorvaux[a,b], F.J. Hambsch[h], F. Hanappe[i], Z. Mezentsevah[d]
S. Telezhnikovch[d]

[a]IPHC, Université de Strasbourg, Strasbourg, France
[b]CNRS, UMR7178, 67087 Strasbourg, France
[c]Physikalisches Institut, Universität Tübingen, Germany
[d]Frank Laboratory of Neutron Physics, JINR, Dubna, Russia
[e]Institut für Kernphysik, Technische Universität, Darmstad, Germany
GSI Helmholtzzentrum für Schwerioneforschung, Darmstadt, Germany
[f]Petersburg Nuclear Physics Institute, Gatchina, Russia
[g]Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia
[h]EC-JRC-Institute for Reference Materials and Measurements, Geel, Belgium
[i]PNTPM, Université Libre de Bruxelles, Belgium

(Received March 3, 2015)

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 multidetector. The development of a simulation toolkit based on GEANT4 and ROOT adopted as 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.

DOI:10.5506/APhysPolB.46.569
PACS numbers: 25.85.–w, 25.85.Ca, 24.75.+i

1. Introduction

In the fission process, it is well known that the bulk of prompt neutrons is evaporated from the fully accelerated rotating fragments. The neutron evaporation theory [1] states that this emission is isotropic in the centre of mass of the moving fragments (CM). Due to the velocity of the fission

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 31–September 7, 2014.

fragments (FF), when converting it from their CM to the laboratory system, the angular distribution 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 is not any direct observation because its contribution is acting in the same way as the kinematical focusing and it is very weak.

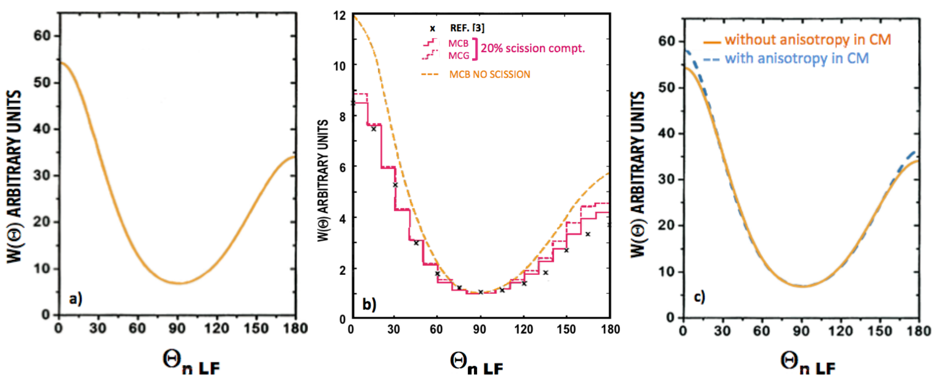

Fig. 1. Neutron angular distributions as a function of the angle between neutrons and the light fragment (LF). (a) The kinematical focusing, (b) the effect of the scission neutrons [3] (solid/pink line) and (c) of dynamical anisotropy [5] (dashed/blue line) are shown.

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 [7], MENATE_R [8, 9] to describe the neutron interaction in the DEMON detectors and ROOT [10].

2. Features of the simulation toolkit applied

The simulation package allows to reproduce a ^{252}Cf fissioning system and the experimental neutron detection setup. In the simulation code, FF 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 I.

TABLE I

Parameters adopted in the simulation [11]. LF and HF state the light and heavy fragments respectively.

Parameters	LF	HF
v [cm/ns]	1.37	1.04
T [MeV]	0.91	0.93
$\langle \nu \rangle$	1.37	1.04
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 shown in Table I and with a correlation value $\rho = -0.2$. In order to extract the neutron kinematical quantities in the CM coordinates system of the FF, neutron energies are randomly taken from a Maxwellian spectrum

$$\varphi(\eta) \sim \sqrt{\eta}\, e^{\frac{-\eta}{T}} , \tag{2.1}$$

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 emission in the centre of mass of the fragments is simulated. Then, the kinematical focusing is obtained moving from the FF CMs to the laboratory system by adding the velocity of the fission fragments (Table I) to the velocity of each neutron shot, obtained from equation (2.1).

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. Introducing kinematical focusing, the uniform distribution in the CM of the FFs becomes forward/backward asymmetric as expected.

By taking into account the assumption that the FFs have a large angular momentum, $J \sim 8\hbar$ [12] 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

$$W\left(\theta_{\mathrm{CM}\,|J}\right) \sim 1 + A\,\sin^2\theta_{\mathrm{CM}\,|J}\,, \tag{2.2}$$

where $A \neq 0$ is the anisotropical parameter [5] and $\theta_{\mathrm{CM}\,|J}$ the angle relative to the angular momentum. To complete the simulation, the anisotropical neutron emission is added according to formula (2.2). The simulation code is based on GEANT4 that allows to reconstruct the detection system employed in the CORA experiments.

The DEMON multidetector 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 ($^{1}\mathrm{H}/^{12}\mathrm{C} \sim 1.2$ on average). In the CORA experiments, only 60 modules were used and the DEMON geometrical configuration covered only a fraction of about 20% of 4π. The simulation code reproduces this detector configuration to analyze the impact of the geometrical acceptance on the neutron angular distribution. It also takes into account the interaction processes of the neutrons in a liquid scintillator containing xylene DEMON is consisted of. This code includes a model for the interaction of fast neutrons with the $^{12}\mathrm{C}$ and $^{1}\mathrm{H}$ [8, 9]. In the case of the neutrons, their detection is performed in two steps. It requires that first the 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, $n + H \rightharpoonup n + p$, 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. 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 neighboring DEMON module. For these reasons, the neutron–neutron angular distributions are mainly affected by this effect at small relative neutron angles.

3. 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 in Fig. 2 (a), one ends thus up with the distribution presented in Fig. 2 (b) (gray/green histogram). The comparison between the experimental results (black/blue histogram of Fig. 2 (b)) and the simulations is really encouraging. In Fig. 2 (b), we see that the bumps coincide very well. And in the backward–forward direction there is a promising difference. Indeed, this difference is probably due to the scission neutrons.

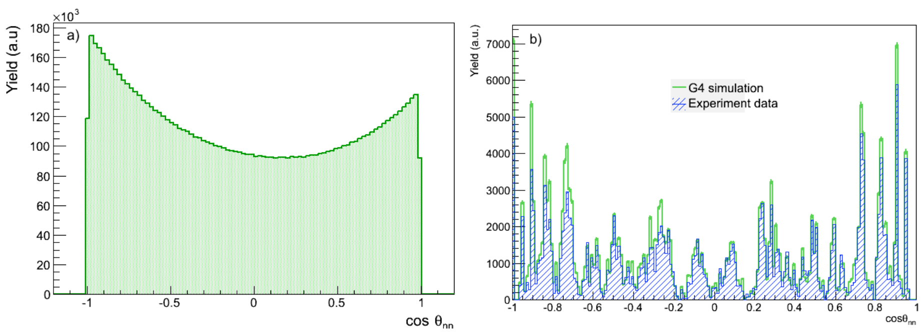

Fig. 2. (a) *Theoretical* neutron relative angular distribution θ_{nn} obtained by the simulation. (b) Comparison between the experimental distribution (black/blue) and the simulated one after the experimental filter (gray/green).

4. Conclusion

The preliminary results indicate that the simulation works very well, and the strategy to figure out the correct parameter for scission neutron and the anisotropy employing this code seems has been successful. 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, 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. The anisotropy parameter will be fixed independently by the $\phi_{12} = \phi_2 - \phi_1$ azimuthal angular distribution method described in [6]. The CORA experiment is probably the only one which may gives access simultaneously to the scission neutron and the CM neutron anisotropy from fragments in the fission process.

REFERENCES

[1] V.F. Weisskopf, *Phys. Rev.* **52**, 295 (1937).

[2] H.R. Bowman *et al.*, *Phys. Rev.* **126**, 2120 (1962).

[3] C.B. Franklyn *et al.*, *Phys. Lett.* **B78**, 564 (1978).

[4] A. Gavron, *Phys. Rev.* **C13**, 2562 (1976).

[5] V. Bunakov *et al.*, Proc. Int. Sem. ISINN-13 Dubna, Russia, p. 175, 2005.

[6] F. Gönnenwein *et al.*, in: Proc. of Seminar on Fission VI, (Eds.) C. Wagemans, J. Wagemans, P. D'hondt, World Scientific, 2007; L. Stuttgé *et al.*, in: Proc. of Seminar on Fission VII, (Eds.) C. Wagemans, J. Wagemans, P. D'hondt, World Scientific, 2010.

[7] J. Allison *et al.*, *IEEE Trans. Nucl. Sci.* **531**, 270 (2006).

[8] P. Désesquelles *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A307**, 366 (1991).

[9] B. Roeder, EURISOL Design Study, pp. 38–44, 2008.

[10] R. Brun, *Nucl. Instrum. Methods Phys. Res.* **A389**, 81 (1997).

[11] N.V. Kornilov *et al.*, *IAEA 2*, 61 (2001).

[12] J.B. Wilhelmy *et al.*, *Phys. Rev.* **C5**, 2041 (1972).