Angular correlations in the prompt neutron emission of spontaneous fission of $^{252}$Cf

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Received: 25 July 2017 / Revised: 7 May 2018
Published online: 18 June 2018
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Communicated by A. Gade

Abstract. Neutron angular distributions in spontaneous fission of $^{252}$Cf are investigated. The CORA experiment, performed at IPHC Strasbourg, aims at elucidating neutron emission mechanisms in the fission process. The experimental setup is composed of the angle-sensitive twin ionisation chamber CODIS for the detection of fission fragments and the DEMON neutron detector assembly. The development of a simulation toolkit based on GEANT4 and MENATEHR is described, adapted as a strategy to investigate the influence of experimental conditions on the observed properties of neutrons emitted. Besides the kinematic neutron anisotropy in the laboratory system due to neutron evaporation from moving fragments, two additional effects are discussed which may have an influence on the angular distributions of neutrons: scission neutrons and dynamic neutron emission anisotropy in the CM system of fragments due to the spin carried by fragments. A new analysis method is presented to disentangle the dynamic anisotropy from the other effects in an independent way. For the dynamic anisotropy only an upper limit could be found. Results for the angular correlation $(n,n)$ between two evaporated neutrons and the correlation $(n,LF)$ between an evaporated neutron and the Light Fragment direction of flight are reported.

1 Motivation

It is well known that in the fission process the bulk of prompt neutrons is evaporated by the fully accelerated fragments. The neutron cascade emission is assumed to follow Weisskopf's evaporation theory [1]: the neutrons are emitted isotropically in each fragment. In the laboratory system a sizeable anisotropy appears due to the high velocity of the fission fragments (FF) at the moment of neutron emission: when the isotropic neutron distributions are transformed from the CMs of the FFs to the laboratory system they produce an enhancement at $0^\circ$ and $180^\circ$ in the neutron angular distribution relative to FF motion. But

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the laboratory system, a ratio of the distributions around 1 is obtained as shown in fig. 1 (right), except for the extreme points around 0° and 180°. Bowman et al. gave an indication to explain the deviation at these two angles invoking some dynamic anisotropy in the CMs of the FFs. They claimed also that the disagreement in the data at backward angles in fig. 1 (right), corresponding to the direction of flight of the heavy fragment (HF), can be improved by varying the neutron multiplicity of the HF.

Other authors also observed similar deviations and explained them either by scission neutron emission or by some dynamic anisotropy due to the angular momentum of the fission fragments [3–7].

In 1978, Franklyn et al. [3] performed simulations to compare with data measured in thermal neutron induced fission of $^{235}$U by Skarsvåg and Bergheim [7] on the angular distribution of prompt neutrons as a function of the angle $\theta_{nLF}$ between neutrons and the light fragment (LF). Similar to Bowman et al., they had to add 20% of scission neutrons to obtain a good agreement with the data, as shown in fig. 2 (left). The remaining excess of neutrons observed particularly at wide angles led them also to the conclusion that some anisotropy in the CMs of the FFs might occur. There are theoretical arguments and calculations claiming that this anisotropy is linked to FF spin, but there is no direct observation because its contribution is acting in the same way as the kinematic focusing. It is very weak and acts the opposite way the scission neutron contribution does, as can be observed in fig. 2.

More recently, Bunakov and Guseva et al. [5, 6] have calculated following Gavron [4] the influence of fragment angular momentum on neutron evaporation. A statistical model of neutron evaporation was applied. In the fragment centre of mass system the angular distribution of evaporated neutrons relative to the fission axis was described by a sum over spherical harmonics: $W(\theta) = \left| \Sigma_l m P_{lm} \gamma_{lm}(\theta, \varphi) \right|^2$. The angular distribution was followed by a Monte Carlo procedure where the probability $P_{lm}$ of emitting a neutron with given orbital angular momentum $l$ and its projection $m$ is proportional to the sum over all values of final fragment spin $J_F$ that can couple to initial spin $J_i$ for the given $l$ value. It was assumed that the initial angular momentum of fission fragments is aligned perpendicular to the fission axis and hence its projection on this axis equals zero. Upon averaging over all spin directions in the plane perpendicular to the fission axis an anisotropy of neutron emission relative to the fission axis appears. The angular distribution can be well approximated by

$$W_{CM}(\theta_n) \propto 1 + A_{nF} \cos^2 \theta_n$$

where $\theta_n$ is the angle between neutron motion and fission axis $A_{nF}$ the anisotropy parameter.

The angular anisotropy in the CM system of fragments relative to the fission axis allows the description of neutron-fragment correlation data. However, this coordinate system with the $z$-axis along the fission axis is not appropriate for experiments where $(n, n)$ or $(n, n, F)$ correlations are studied. In these cases it is necessary to use as $z$-axis of reference the fragment spin $J$ at scission. Calculations of angular distributions of evaporated neutrons similar to [4–6] but relative to fragment spin were performed in [8]. The angular distribution of neutrons $W(\theta_{nJ})$ relative to fragment spin $J$ is well approximated by

$$W_{CM}(\theta_{nJ}) \propto 1 + A_{nJ} \sin^2 \theta_{nJ}$$

where $\theta_{nJ}$ is the angle between neutron motion and fragment spin $J$ and $A_{nJ} > 0$ the parameter of dynamic anisotropy. This is the basic notion that for dynamic anisotropy neutrons are preferentially evaporated in a plane perpendicular to fragment spin.

It can be shown analytically that the anisotropy parameter $A_{nJ}$ in eq. (2) is twice as large as the parameter $A_{nF}$ in eq. (1): $A_{nJ} = 2A_{nF}$.

In a recent study of neutron emission in the $^{235}$U ($n_{th}, f$) reaction, Vorobyev et al. [9] repeated the experiment by Skarsvåg and Bergheim [7]. The neutron yield at neutron - Light Fragment angles $\theta_{nLF}$ was measured. The $(n, LF)$ correlation observed by Vorobyev was analysed.
taking into account the calculated dynamic anisotropy of neutron emission in the CM system of fragments. The fit is nearly perfect and, which is remarkable, leaves only room for about 3% of scission neutrons.

The impact of dynamic anisotropy on the prediction of the contributions by scission neutrons is studied in the present paper. More detailed insight into the interplay between these two physical phenomena working in opposite direction in the \((n, nF)\) correlation is evidently required (see fig. 2). The importance is stressed of including in all discussions on neutron emission in fission the influence of the dynamic anisotropy on neutron energy spectra, neutron angular distributions and neutron correlations \((n, n)\) and \((n, nF)\). The idea that neutron evaporation in the CMs may not be perfectly isotropic is attributed to the presence of quite large fragment spins after scission. As already stated the quantum-mechanical theory of neutron evaporation from fragments carrying angular momentum was worked out by Bunakov et al. \cite{Bunakov2000, Bunakov2002} and adapted to neutron observables in fission by Guseva \cite{Guseva2001}. Though the evaporation theory appears to be reliable it is necessary to corroborate theory by experiment. A new experimental method to analyse dynamic anisotropy was devised. So far only an upper limit for the dynamical anisotropy \(A_{nJ}\) could be found. But the experiment has allowed to assess besides dynamic anisotropy the \((n, n)\) and \((n, nF)\) correlations. Results are discussed taking dynamic anisotropy from theory into account.

2 Method of triple coincidences

The purpose of the present paper is to investigate in experiment the suggestion that for fragments carrying angular momentum the evaporation of neutrons can no longer be isotropic. This dynamic anisotropy in the CMs should lead to observable effects also in the laboratory.

Fragments are known to carry large angular momenta up to \(J = 8h\) which are aligned perpendicular to the fission axis. Neutrons should then be preferentially emitted in a plane perpendicular to angular momentum. Following Gavron \cite{Gavron1991}, Bunakov et al. \cite{Bunakov2000, Bunakov2002} and Guseva \cite{Guseva2001} worked out the theory of neutron emission in a statistical model. It was shown that the anisotropy may be parameterised by eq. (2). For spontaneous fission of \(^{252}\text{Cf}\) the dynamic anisotropy parameter \(A_{nJ}\) was determined to be \(A_{nJ} = 0.16\) in \cite{Guseva2001}. In the transition from the CMs to the laboratory, the dynamic CMs anisotropy of eq. (2) is boosted by the kinematic focusing of neutrons in the direction of flight of fragments. Note that the dynamic CMs anisotropy is a minor contribution to the anisotropy observed in the laboratory.

To study dynamic anisotropy a new method was introduced \cite{Bunakov1997, Bunakov2002}. It is proposed to measure triple coincidences of a fission fragment and two prompt fission neutrons. For the evaluation, the neutron angular distributions are projected onto a plane perpendicular to the fission axis. In this way one can separate, in the laboratory system, the contribution of the predicted CM anisotropy from the anisotropy due to kinematic focusing. Kinematic focusing and the emission pattern of scission neutrons which is supposed to be symmetric around the fission axis will not give rise to anisotropies in the projection plane.

The principle is best explained for the case of extreme anisotropy. Here, as shown in fig. 3:

- all neutrons are emitted in a plane perpendicular to the fragment spin \(J\);
- the spin \(J\) is perpendicular to the fission axis.

As sketched in fig. 3, a coordinate system is introduced where the fission axis defines the \(z\)-axis. The projection plane \((x, y)\) is perpendicular to the \(z\)-axis. The spin \(J\) is then, for example, pointing along the \(y\)-axis. In the projection plane:

- all neutron angles will occur along the \(x\)-axis;
- the projections of neutron angles will follow the spin orientation as shown in fig. 4 (centre).

In experiment the orientation of fragment spin cannot be fixed, only the fission axis is accessible. As the fragment spins are supposed to be perfectly aligned perpendicular to the fission axis, they will lie in the plane perpendicular to the fission axis. For any inclination of the spin \(J\) in the \((x, y)\) plane, the neutrons projected on a line will then follow the inclination of the spin. For any orientation of spin direction there will be a corresponding neutron projection line. The fragment spins are distributed isotropically in the \((x, y)\) plane. Their orientation in this plane cannot be determined. Neutrons emitted from both fission fragments will lie on the same projection line, as it is commonly accepted that the spins of complementary fragments are antiparallel. Hence all neutrons are emitted in the same plane \((x, z)\).

For each triple (or more) \((n_1, n_2, \text{FF})\) event the azimuthal angles \(\varphi_1\) and \(\varphi_2\) relative to the \(x\)-axis are determined. The crucial parameter is the difference of these two angles

\[\varphi_{nnF} \equiv \varphi_{21} = \varphi_2 - \varphi_1.\]  

Thus in case of extreme anisotropy all \(\varphi_{21}\) angles between any two neutrons are expected to be at \(0^\circ\), \(180^\circ\) or \(360^\circ\) depending on the sign of the \(x\)-coordinate. In fig. 4 this extreme anisotropic case is compared to an isotropic emission where the neutrons are randomly spread over the \((x, y)\) plane. This case will lead to a flat \(\varphi_{21}\) distribution.
Fig. 4. (Color online) Model description of correlated neutron angular distributions. The cases of extreme CM anisotropy (left) and perfect CM isotropy (right) are compared. Top: for extreme anisotropy all neutrons lie on the x-axis whereas for perfect isotropy they are randomly spread over the whole (x, y) plane. Centre: for extreme anisotropy the projection lines follow the fragment spin J orientation. Bottom: distributions for the difference $\varphi_{21}$ of azimuthal neutron angles in the two cases.

The realistic shape of the $\varphi_{21}$ angular distribution was calculated using a Monte Carlo method. The fission axis in the CM system of fragments was directed along the z-axis and the initial spin J was randomly distributed in the (x, y) plane with polar angle $\theta_J = 90^\circ$ and azimuthal angle $\varphi_J$ randomly distributed in the [0:360°] range. In this system a pair of neutrons was generated with polar angle $\theta_{nJ}$ for each neutron being randomly distributed according to eq. (2) and with the $\varphi_{nJ}$ angle having a flat distribution in the [0:360°] range. Finally the distributions in the CM system had to be transformed to the laboratory system. For each neutron in the CM system the polar coordinates ($\theta$, $\varphi$) in the laboratory coordinate system were determined. The $\theta$ angle coincides with the $\theta_{nF}$ angle in eq. (1) and the $\varphi$ angle is the azimuthal angle in the projection perpendicular to the fission axis. The projection of the relative angle between two neutrons is the difference angle $\varphi_{21}$ in eq. (3) called in the following $\varphi_{nnF}$. The distribution of the $\varphi_{nnF}$ angles turned out to be well described by

$$W_{CM}(\varphi_{nnF}) \propto 1 + a_2 \cos^2 \varphi_{nnF}. \quad (4)$$

Fig. 5. (Color online) Simulated neutron angular distributions in the CM system of fragments for various anisotropies $A_{nJ}$. The distributions are normalised to the same number of simulated counts integrated over the angles. Top: distribution of the cosine of the angle $\theta_{nJ}$ between neutron and fragment spin (eq. (2)). Centre: distribution of the cosine of the angle $\theta_{nF}$ between neutron and fission axis (eq. (1)). Bottom: distribution of the projected neutron-neutron angle $\varphi_{nnF}$ in the plane perpendicular to the fission axis.

The distributions of $\cos \theta_{nJ}, \cos \theta_{nF}$ and $\varphi_{nnF}$ in the CM system are plotted in fig. 5 for three different values of the anisotropy coefficient $A_{nJ}$ chosen as input parameters. For each $A_{nJ}$ value the anisotropy coefficients $A_{nF}$ were determined by fitting the distribution of the $\theta_{nF}$ angle by eq. (1) and the distribution of the $\varphi_{nnF}$ angle by eq. (4). Note that these distributions are calculated in the CM system of fragments. The distributions $W(\theta_{nJ})$ and $W(\theta_{nF})$ cannot be observed in the laboratory system LS,
while the distribution $W(\varphi_{nnF})$ in the LS system is the same as in the CM system of fragments.

The dependence of the $a_2$ coefficient in the $\varphi_{nnF}$ distribution on the basic $A_{nJ}$ coefficient of dynamic anisotropy was determined from a set of calculations with various input $A_{nJ}$ parameters. It is plotted in fig. 6.

In case the distribution $W(\varphi_{nnF})$ deviates from isotropy the coefficient $a_2$ in eq. (4) is $a_2 \neq 0$. It serves as a marker for the presence of a dynamic anisotropy $A_{nJ} \neq 0$ in eq. (2). Adopting in the figure $A_{nJ} = 1$ yields $a_2 \approx 0.04$ for the anisotropy in the $\varphi_{nnF}$ distribution. This is about 6 times larger than $A_{nJ} = 0.16$ expected from theory. For $A_{nJ} = 0.16$ theory predicts $a_2 \approx 0.003$ in the $W(\varphi_{nnF})$ angular distribution of eq. (4). To determine this small deviation from isotropy is a challenge for experiment.

Note that the $a_2$ parameter is conveniently evaluated in the $W(\varphi_{nnF})$ distribution from experiment as the ratio

$$a_2 = \frac{W(0^\circ) - W(90^\circ)}{W(90^\circ)}. \quad (5)$$

The distributions which are accessible to experiment in the laboratory system are the neutron-fragment and the neutron-neutron angular correlations. In the present simulations they were also evaluated using average fragment velocities taken from known literature data on $^{252}$Cf. They are shown in fig. 7. From the simulations it is quite obvious that in the laboratory system the dynamic anisotropy is overwhelmed by the kinematic anisotropy and barely visible. By contrast, in the new type of experiments proposed in the present work, measuring neutron-neutron-fragment events and projecting them on a plane perpendicular to the fission axis, the dynamic anisotropy $A_{nJ} \neq 0$ is identified in the projection by a structure in the distribution of relative angles $\varphi_{nnF}$ in eq. (4) (see fig. 5 (bottom)).

The distributions shown in fig. 7 are not aimed for a comparison with the experimental data. No energy threshold for neutrons has been taken into account. Thus the effect of anisotropy is lower than in the case where a neutron energy threshold is set as will be shown below.

### 3 CORA experiment

The CORA experiment was performed at the IPHC laboratory in Strasbourg. The setup shown in fig. 8 (top) combines the neutron detector array DEMON [12] and the fission chamber CODIS [13] in its centre.

Fission fragment energies and their emission angles were measured with the CODIS detector. CODIS is a back-to-back Frisch-gridded 4r twin ionisation chamber, operated with CF$_4$ gas at a working pressure of $2.64 \times 10^4$ Pa. As shown in fig. 8 (bottom) the two ionisation chambers have a small common central cathode carrying the $^{252}$Cf source and providing the master trigger for the data acquisition and start for neutron time of flight (TOF). It is surrounded by two separate fourfold sectored cathodes in each of the two chambers, which are insulated from each other. Fragment emission angles with respect to the chamber axis were deduced, on the one hand, from
Fig. 8. (Color online) CORA setup. Top: 60 DEMON cells are arranged on a near spherical configuration around the CODIS fission chamber. Bottom: view of the open CODIS chamber with the $^{252}\text{Cf}$ source in the centre of two back-to-back segmented cathodes.

With both chambers only fragment emission angles up to 66° relative to the chamber axis were analysed since fission events emitted at flatter angles from the source, deposited on a 0.25 μm thick self-supporting Ni foil, suffer from poorer energy resolution. Also the angle assessment by the split cathodes becomes inferior at flat fragment emission angles.

The DEMON detector array shown in fig. 8 (top) is an array consisting of up to one hundred individual cylindrical cells with a depth $L = 20$ cm and a diameter $D$ of 16 cm, each containing 4.4 litres of organic scintillating liquid NE213 rich in hydrogen. In the CORA experiment, only 60 modules were used, mounted on support rails in a fairly regular manner with respect to detector spacing and neutron TOF path. The distance between modules was about 35 cm and distances of all modules to the central Cf source varied between 60 and 95 cm. All detector modules were placed using a laser with a geometrical accuracy of ±1 mm. The chosen near spherical DEMON geometrical configuration covered a fraction of about 20% of 4π.

In a five-month experiment, with a $^{252}\text{Cf}$ source with about 2000 fissions/s, about $10^8$ triple or higher coincidences between any FF and two or more associated neutrons have been collected. This is the statistics before taking into account all constraints set by neutron energy threshold and angular acceptance of FFs.

4 Monte Carlo simulation

In the present work general properties of fission are not simulated but taken from experiment. Simulation codes like FREYA are unfortunately not suited in our case, even in the recent version of FREYA with inclusion of fragment spin [14]. Based on the Bunakov-Guseva theory [5,6] for neutron evaporation from fragments carrying spin, we take into account both, anisotropy of neutron evaporation and emission of scission neutrons. The combination of these two effects is not discussed in current simulation models.

We start from the generally accepted fact that the bulk of fission neutrons is evaporated from the fully accelerated fragments. Occasionally further neutrons, so-called scission neutrons, may be emitted right at the moment of nucleus rupture. The average number of all emitted neutrons per fission is for $^{252}\text{Cf}$ $\nu_{\text{tot}} = 3.766$ [15]. The total number of neutrons emitted from the light and heavy fragments is $\nu_L = 2.056$ and $\nu_H = 1.710$ [15]. The relative share of scission neutrons $\omega_{\text{sci}} = \nu_{\text{sci}}/\nu_{\text{tot}}$ is a fitting parameter of the calculation and is adjusted in order to obtain the best agreement between calculated and experimental neutron angular distributions. It is taken into account that the angular and energy distributions of evaporated and scission neutrons are different. In consequence also (n,n) correlations for the two emission mechanisms are different. Comparing experimental and simulated (n,n) correlations a reliable value for the fraction of scission neutrons

$$\omega_{\text{sci}} = \nu_{\text{sci}}/\nu_{\text{tot}}$$ (6)
should be obtained.

The so-called model of two fragments is used. This means that all fragments belonging to one of the two groups, light or heavy, have one and the same velocity imparted by Coulomb repulsion. These average velocities have been calculated using the fact that the multiplicity of evaporated neutrons depends on fragment mass (weighted values) [16]. All integral characteristics of the calculation for the fission neutron quantities, not only partial neutron multiplicities, but also their dispersions and covariance, were traced to coincide with the parameters known from experiment [17].

The fission fragments which define the fission axis are supposed to be isotropically distributed in space. The physical parameters necessary to simulate the neutron emission from the fragments of 252Cf fission are shown in table 1.

The FF velocities \( v \) are deduced from the FF energies per nucleon corrected for neutron emission [16]. The temperature parameters \( T \) in the CMs of the FFs are deduced from the measured neutron energies. The neutron multiplicity \( \nu \) 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 covariance \( \rho = -0.2 \) between LF and HF neutron multiplicities [18]. In order to extract the neutron kinematic quantities in the FF CMs, neutron energies \( \epsilon \) are randomly taken from Maxwellian distributions

\[
\varphi(\epsilon) \propto \sqrt{\epsilon} e^{-\epsilon/T},
\]

where \( T \) is the mean temperature parameter of the FF given in table 1 and \( \epsilon \) represents the neutron energy in the CM of the corresponding FF. The shape of the energy spectra of neutrons in the CM of the fragments is assumed to be Maxwellian as expected for a cascade evaporation [19], with fixed temperatures \( T \) for the light and heavy fragment groups, respectively.

With neutrons being evaporated by fragments in flight, an assumed isotropic angular distribution in the CMs becomes anisotropic in the laboratory system LS. Any dynamic anisotropy in the CMs of fragments from eq. (2) will further increase the anisotropy in the LS. The kinematic focusing is evaluated by adding the fragment velocity from table 1 to the velocity of the neutron sampled with eq. (7). For each simulated fission event one computes the relative angle in the LS between emitted neutrons \( \theta_{\text{ne}L,F} \) as well as the angle \( \theta_{\text{ne}L,F} \) between the neutrons and the LF.

For the scission neutron component, it is assumed that they are emitted isotropically by a stationary source in the laboratory frame LS [1]. The simulation provides at maximum a single scission neutron with a certain occurrence \( \omega_{\text{sci}} \) relative to the total multiplicity. The scission neutron energies are therefore sampled from a Weisskopf evaporation spectrum for single neutron evaporation of the form

\[
\varphi(E_{\text{sci}}) \sim E_{\text{sci}} e^{-E_{\text{sci}}/T_{\text{sci}}},
\]

where \( T_{\text{sci}} \) is the thermodynamic temperature of the nucleus at the scission point. To compute distributions of scission neutron energy the temperature \( T_{\text{sci}} = 1.2 \pm 0.1 \) MeV was taken from a fit to neutron-neutron correlations measured by Gagarski et al. [18]. This value is close to the one adopted in the work of Pringle and Brooks [20], \( T_{\text{sci}} = 1.3 \) MeV, to describe neutron-neutron correlations. Besides the scission emission probability \( \omega_{\text{sci}} \) the temperature \( T_{\text{sci}} \) is the second fitting parameter of the calculation. The choice of an isotropic angular distribution for scission neutrons is by default.

In the Monte Carlo simulation the experimental data corresponding to averaged total and partial neutron multiplicities, their dispersions and covariance, neutron energy spectra in the reference frame of fragment centre of mass CMs are randomly inspected in each fission event. All possible observables of neutron correlations are thus accessible in these simulations.

In order to develop and test the procedure of the data analysis and estimate possible systematic errors of the experiment, particular Monte Carlo simulations were performed, based on the GEANT4 simulation toolkit [21] with the MENATE_R physics list [22]. For the simulation of fission and neutron emission, the same formalism introduced by Guseva and described in sects. 2 and 3 was adopted.

This simulation allowed also to trace step by step various effects of the experimental biases related to DEMON: geometrical acceptance, energy threshold, intrinsic efficiency, cross talk, etc. Thus, the GEANT4 code permits to simulate experimental details of the complex detection system in the CORA experiment. For example, the impact of the geometrical acceptance of the DEMON detector configuration on the neutron angular distributions is reproduced. At this stage, due to the coincidence request between at least two neutrons, only about 4% of the initially simulated counts remain, which is consistent with the 20% angular acceptance of DEMON for a single neutron detection. The simulation also takes into account the interaction processes of the neutrons in a liquid scintillator containing like in DEMON xylene. The code includes a model for the interaction of fast neutrons with \(^1\)H and \(^{12}\)C [22]. Another important effect is the cross talk: instead of a single neutron signal per incoming neutron, the detection system may register two or more hits. This occurs when a neutron interacts in a DEMON module and is scattered into another cell, most probably into a neigh-

| Parameter | LF | HF |
|-----------|----|----|
| \( v \) (cm/ns) | 1.355 | 1.022 |
| \( T \) (MeV) | 0.91 | 0.93 |
| \( \nu \) | 2.056 | 1.710 |
| \( \sigma \) | 0.94 | 1.07 |
| \( \rho \) | -0.2 |
bouring one. For this reason, the neutron-neutron angular distributions are mainly affected by this effect at small relative neutron angles. In the CORA geometry, the spacing between neighbouring detectors was chosen so that the cross talk probability of about $10^{-3}$ [12,23] is quite low. But as the effect of interest is also very weak, it may impact the result. The cross talk has thus been considered very carefully in the simulation although its perfect evaluation couldn’t be achieved. The MENATE_R code has been adapted by its authors for the DEMON detector array. It is well suited to trace the trajectories of neutrons inside the detector. In the analysis a common neutron threshold on the proton recoil energy in all DEMON cells were set to 0.9 MeV. The same threshold was also put on the neutron energies deduced from the measured times of flight. This quite high value corresponds to the threshold of the worst detector. The threshold does not influence the study of the dynamic anisotropy since one has to keep in mind that the anisotropy concerns virtually only neutron energies above 1 MeV. By contrast, the $(n,n)$ correlations depend strongly on the neutron energy threshold [24]. As a side effect, the high threshold reduces cross talk.

All details of the simulation are described in reference [25].

5 Analysis and results

The data from the triple correlation $(n,n,F)$ experiment CORA allow to inspect in parallel the simpler correlation $(n,n)$ [18,20] between two neutrons from the same fission event and the correlation $(n,LF)$ [3,9] between a neutron and the light fragment. These correlations have been discussed again in recent times [26]. The question is whether they are suited to study the dynamic anisotropy. In our simulation the influence of dynamic anisotropy $A_{nJ}$ and the contribution of scission neutrons $\omega_{\text{sci}}$ on these correlations was calculated for the distributions in the laboratory system. The correlations depend also strongly on the energy threshold of the neutrons [24]. In the present calculations a neutron energy threshold of 0.5 MeV has been applied. In fig. 9 an unrealistic large anisotropy parameter $A_{nJ} = 0.8$ and a strong scission neutron emission probability of $\omega_{\text{sci}} = 20\%$ have been introduced into the simulation to emphasize the effects and separate the curves. The results demonstrate that the two effects act in opposite directions, both for the $\theta_{nn}$ and $\theta_{nLF}$ correlations. Without a precise knowledge of the anisotropy $A_{nJ}$ the scission neutron contribution $\omega_{\text{sci}}$ can hence not be determined. Therefore these observables are not suited to investigate in experiment the dynamic anisotropy and the existence of scission neutrons.

By contrast, the triple coincidence $(n,n,F)$ method is uniquely sensitive to dynamic CM anisotropy and not disturbed by the much larger kinematic anisotropy nor the presence of scission neutrons. However, as repeatedly stressed, the anticipated size of this anisotropy is very small and therefore difficult to assess reliably.

![Fig. 9.](Color online) Simulated $\theta_{nn}$ (top) and $\theta_{nLF}$ (bottom) distributions in the laboratory for an isotropic emission (green solid), an unrealistic anisotropy parameter $A_{nJ} = 0.8$ (red dashed), a strong scission neutron emission probability of $\omega_{\text{sci}} = 20\%$ (blue dotted) and the combination of both (purple dash-dotted). All curves have been normalised at 90° to bring about shape differences. A neutron energy threshold of 0.5 MeV has been applied.

The main problem in the $(n,n,F)$ analysis is to clean the data from structures due to the arrangement of detectors in the array of DEMON. To this purpose, we developed a procedure to determine from experimental data the geometrical response of the setup. The procedure was tested in simulations and proved to be satisfactory. It consists in evaluating correlated and uncorrelated $(n,n,F)$ yields as a function of the angle $\varphi_{nnF}$ in the plane perpendicular to the fission axis (see fig. 4). Uncorrelated yields were obtained with neutrons originating from two independent fission events. The distribution from uncorrelated events is a realistic measure of the efficiency of the DEMON configuration. By taking the ratio of correlated to uncorrelated distributions, normalised to the same number of events, we obtain to good approximation the $(n,n,F)$ distributions we are looking for which are free from geometrical effects and are corrected for the intrinsic efficiency of the neutron detectors.
The mathematical background of this procedure is the following. The number of registered events in the laboratory having the relative angle between two neutrons \( \delta_{nn} \) for the neutrons emitted from the same fission event (correlated yield) can be specified by

\[
Y_{cor}(\delta_{nn}) = N_{cor} \cdot P_{cor}(\delta_{nn}) \cdot W_{cor}(\delta_{nn}).
\]

(9)

Here \( \delta_{nn} \) can be the relative polar angle \( \theta_{nn} \) or the relative azimuthal angle \( \varphi_{nn} \) in the plane perpendicular to the fission axis; \( W_{cor}(\delta_{nn}) \) is the angular correlation function \( W_{cor}(\delta_{nn}) \) in fig. 7 (top) and \( W_{cor}(\varphi_{nn}) \) in fig. 5 (bottom); \( N_{cor} \) is the number of two-neutron correlated events emitted from the source; \( P_{cor}(\delta_{nn}) \) is the probability to detect both neutrons in the DEMON detection system at a given angle \( \delta_{nn} \). This probability can be regarded as an overall detection efficiency, which includes DEMON geometrical and intrinsic efficiencies as well as the probability to detect scattered/false neutron events, integrated over all possible fragment emission angles.

For the uncorrelated yield (two neutrons from different fission events) the number of registered events is given by

\[
Y_{ucor}(\delta_{nn}) = N_{ucor} \cdot P_{ucor}(\delta_{1}) \cdot P_{ucor}(\delta_{2}) \cdot W_{ucor}(\delta_{nn}).
\]

(10)

Here \( N_{ucor} \) is the number of two-neutron uncorrelated events (note that this number is artificial and can be chosen arbitrarily); \( P_{ucor}(\delta_{1}) \), \( P_{ucor}(\delta_{2}) \) are the probabilities to detect first and second neutrons in the detection system at angles \( \delta_{1} \) and \( \delta_{2} \) having relative angle \( \delta_{nn} \); \( W_{ucor}(\delta_{nn}) \) is the angular correlation function for uncorrelated events.

The ratio between these two distributions then is

\[
R(\delta_{nn}) = \frac{Y_{cor}(\delta_{nn})}{N_{cor} \cdot P_{cor}/P_{ucor}} = \frac{W_{cor}(\delta_{nn})}{W_{ucor}}.
\]

(11)

Obviously, the \( N_{cor}/N_{ucor} \) term can be set to 1 by choosing the proper number of events in the uncorrelated case. For the second term, \( P_{cor}/(P_{cor1} \cdot P_{cor2}) \), the numerator is \( P_{cor} = P_{cor1} \cdot P_{cor2} \cdot (1 + P_{cross}) \), where \( P_{cor1} \) and \( P_{cor2} \) are the probabilities for neutron 1 and neutron 2, emitted as two correlated neutrons, to be detected in the DEMON array at relative angle \( \delta_{nn} \) while \( P_{cross} \) is the probability to detect a cross talk neutron due to a single neutron detected in one DEMON detector and after scattering detected in a neighboring one, producing a false two-neutron coincidence event.

It is obvious and was proved by Monte Carlo simulations that \( P_{cor1} = P_{cor1} = P_{cor2} = P_{cor2} \) with high accuracy, provided that correlated and uncorrelated neutron are taken from the same set of events. The probability for a neutron to be detected depends only on the geometrical and physical properties of the detector system. If it has been already emitted, it is not important whether it was the first or the second neutron, whether it was correlated or uncorrelated. So the second term in eq. (11) is \( P_{cor}/(P_{cor1} \cdot P_{cor2}) = 1 + P_{cross} \) and only the cross talk term remains.

In the last term \( W_{cor}/W_{ucor} \) there will be no correlation between 2 neutrons from uncorrelated fission events. The correlation function \( W_{cor} \) therefore reads \( W_{cor} = 1 \). Hence for the neutron-neutron angle in space \( \theta_{nn} \) the ratio in eq. (11) becomes

\[
R(\theta_{nn}) = (1 + P_{cross}) \cdot W(\theta_{nn}).
\]

(12)

For the triple correlation \((n,n,F)\) with the fission axis fixed in space by the chamber axis of CODIS, the ratio in eq. (11) becomes

\[
R(\varphi_{nnF}) = (1 + P_{cross}) \cdot W(\varphi_{nnF}).
\]

(13)

The only effect which may have a large influence on the resulting ratio distributions is not surprisingly the cross talk which has to be minimised in experiment and analysis. In the analysis therefore only two neutron events \((n,n)\) with angles in space larger than 53° were considered. This measure reduces effectively cross talk.

The different steps of the analysis using the uncorrelated normalisation method are on display in fig. 10. The correlated and uncorrelated \( \varphi_{nnF} \) distributions are shown on top and at the centre, respectively. The uncorrelated distribution was normalised to the same number of events as the correlated one. Both distributions are built using the same set of fission events emitted in a cone along the CODIS chamber axis with opening angle < 18°. For the neutrons the condition was introduced that the angle in space \( \theta_{nn} \) between two neutrons is \( \theta_{nn} > 53° \). This condition was imposed to eliminate the cross talk effect \( P_{cross} \) in eq. (13). The two distributions look very similar. The expected anisotropy effect being very small this is not surprising. The ratio of the two normalised distributions is the experimental distribution \( W(\varphi_{nnF}) \) depending on the dynamic anisotropy provided that the \( P_{cross} \) term is sufficiently small. It is shown at the bottom of fig. 10. These data were grouped in rather large bins of 40°, still small enough to observe the expected structure having a period of 180°.

The distribution \( W(\varphi_{nnF}) \) was fitted according to eq. (4). For a total of \( 5.2 \times 10^6 \) analysed events the anisotropy coefficient \( a_2 \) in the distribution \( W(\varphi_{nnF}) \) turned out to be \( a_2 = (2.8 \pm 1.5) \times 10^{-3} \). As shown in fig. 6, the anisotropy \( a_2 \) is a marker for the dynamic anisotropy \( A_{n,f} \) of eq. (2) at issue. The value quoted for the anisotropy \( a_2 \) is consistent with the value \( A_{n,f} = 0.16 \) for the dynamic anisotropy predicted by Guseva [8]. However, as seen in the insert of fig. 10 (bottom), the reduced \( \chi^2 \) value of the fit is rather large indicating that beyond the statistical error there is still a sizeable systematic one. The total error was estimated by adding in quadrature for each data point an estimated systematic uncertainty to the statistical error. The size of the systematic error was found from the requirement that for the total error the reduced \( \chi^2 \) becomes \( \chi^2/\text{ndf} = 1 \). The experimental result for the anisotropy coefficient \( a_2 \) is \( a_2 = (2.8 \pm 1.5 \pm 3.8) \times 10^{-3} \). It only allows to give an upper limit for the \( a_2 \) coefficient of \( a_2 < 7 \times 10^{-3} \). With reference to fig. 6 this corresponds to a dynamic anisotropy coefficient \( A_{n,f} < 0.3 \) with a confidence level of 68%. 
The \((n, n)\) correlation was inspected next. The detector array of DEMON allows the observation of two neutrons only for specific angles between them. This leads to a pronounced structure in the \((n, n)\) angular correlation \(\theta_{nn}\) on display in fig. 11. Narrow structures appear in the experimental distribution plotted on top. This is different from the distribution of \(\varphi_{nnF}\) angles projected on a plane perpendicular to the fission axis in fig. 10. The simulated distribution of \(\theta_{nn}\) is given at the centre of fig. 11. It was obtained under the same constraints as to neutron threshold, geometrical acceptance etc. as the experimental one, but in addition a dynamic anisotropy \(A_{nJ} = 0.16\) and a scission neutron contribution \(\omega_{scii} = 8\%\) as average from several experiments was introduced \([9, 18, 24]\). Also in this case the method of uncorrelated neutron events could be applied to both, the experimental and simulated \(\theta_{nn}\) distributions. The resulting distributions are compared in the bottom of fig. 11. The agreement between experiment and simulation is good. The reduced \(\chi^2\) evaluated from these two curves in the range 53° < \(\theta_{nn}\) < 180° is 1.33, which corroborates the choice of the parameters \(A_{nJ}\) and \(\omega_{scii}\).

Finally the \((n, LF)\) correlation was analysed. For this correlation FFs were not confined in a narrow cone along the chamber axis. Instead, all fission events detected in the
CODIS chamber in a wide opening angle up to 66° were accepted. Fragment angles were determined with the θ and ϕ angles of both fragments to find accurately the fission axis. Measured and simulated distributions of neutron angles relative to the light fragment θ_{n,LF} are compared in fig. 12. Both in experiment and simulation no significant structures appeared in the distribution of angles θ_{n,LF} of neutron emission relative to the light fragment LF. This is in contrast to the distribution of angles θ_{nn} between two neutrons as shown in fig. 11. The difference is due to the wide opening cone of acceptance for fission fragments in the (n, LF) data. Many more angles θ_{n,LF} become accessible and the distribution of angles observed becomes densely and virtually continuously spaced taking into account the angular width of acceptance for any detector. There is therefore no need to correct for the response function depending on the structures in the angular acceptance of neutrons in the detector array of DEMON.

The simulated distribution was calculated under the same conditions as the experimental one. The same pairs of parameters A_{nJ} and ω_{sci} as in the simulation of the (n, n) correlation in fig. 11 were used. All distributions are normalised at 90° to get a better perception of the differences in the shapes of the curves. The agreement between experiment and simulation is good as indicated by the reduced χ² = 1.45 for the W(θ_{nLF}) distribution of eq. (1) transformed into the laboratory system as W(θ_{n,LF}). The ratio between the curves with (purple) and without (green) scission emission and dynamic anisotropy is of the same magnitude as that of fig. 9 although the scission emission and anisotropy parameters are different. This is due to the different neutron energy thresholds used for fig. 9 (0.5 MeV) and fig. 12 (0.9 MeV) which, as already mentioned, affects the shapes of the curves. The same is valid for fig. 11.

6 Conclusion

Due to the presence of fragment spin J at scission, evaporation theory of neutron emission predicts that a dynamic anisotropy of emission in the CMs of fragments should exist. Neutron emission perpendicular to fragment spin is favoured: W(θ_{nJ}) ∝ 1 + A_{nJ} sin² θ_{nJ} with θ_{nJ} the angle between neutron emission direction and fragment spin. From theory the size of the dynamic anisotropy A_{nJ} in the fragment CM system is A_{nJ} = 0.16 for 252Cf(sf). A novel method uniquely sensitive to this dynamic anisotropy is proposed. For a fission axis fixed in space, the angular correlation (n, n, F) between two neutrons projected on a plane perpendicular to the fission axis was measured for the reaction 252Cf(sf). The distribution W(ϕ_{nn,F}) of the angular difference between the two neutrons is W(ϕ_{nn,F}) ∝ 1 + a₂ cos² ϕ_{nn,F}. For A_{nJ} = 0.16 a Monte Carlo simulation yields the value a₂ = 2.5 × 10⁻³ for the anisotropy coefficient a₂. Due to large systematic errors in the present experiment, only an upper limit for the dynamical anisotropy of a₂ < 7 × 10⁻³ can be given.

The data collected in the CORA experiment for the triple correlation (n, n, F) allowed moreover to study the (n, n) correlation between two neutrons and the correlation (n, LF) for neutron emission relative to the light fragment direction of flight. These latter correlations have been studied by several authors in the past. The correlations (n, n) and (n, LF) are described taking into account dynamic neutron anisotropy A_{nJ} in the CMs of fragments and a non-zero contribution of neutrons ejected isotropically in the lab system ω_{sci}. Quantitative figures for A_{nJ} and ω_{sci} for the two phenomena can be found in the literature. The present experimental findings were compared to simulations with parameters A_{nJ} = 0.16 from theory and ω_{sci} = 8% as average of experimental results for 252Cf(sf).

Our experiments agree rather well with these simulations. However, according to recent theoretical considerations the emission of scission neutrons is neither an evaporation process nor is the emission isotropic [27] as generally accepted. These new ideas are speculative and have so far not found general acceptance.

Remarkably the anisotropy and the emission of scission neutrons both influence the (n, n) and the (n, LF) correlations, however in opposite directions. This is an interesting result from simulations on display in fig. 9. In a sense the two effects compensate each other. This makes the fact that when dynamic anisotropy is not taken into account the mere existence of scission neutrons is put in jeopardy understandable. This is the result of a re-analysis of (n, LF) data from Vorobyev [9] and (n, n) data from Gagarski [18] by Lestone [26].

It appears important to continue with experiments like CORA only sensitive to dynamic anisotropy but not to scission neutrons. This should fix the size of the dynamic anisotropy and with simulations of the fission process help establishing the existence of scission neutrons. Further work is needed to confirm the present preliminary results. In particular, higher statistics and a better control of the cross talk are mandatory.
This work was partially supported by the JINR-IN2P3 agreement for which the authors are grateful.

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