MECHANISMS OF PROMPT RADIATION FROM FISSION FRAGMENTS

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The effect of the right-left asymmetry is considered in the angular distribution of gamma quanta from fission of ^{235}U by polarised thermal neutrons, which depends on the polarisation of the neutrons with respect to the gamma—fission plane. Electric dipole radiation from fission fragments arising due to the Strutinsky—Denisov induced polarisation mechanism may give rise to such an effect. A crucial experiment to give a more definite picture of the concrete mechanism would be determination of the energy of the quanta responsible for the asymmetry. Detection of the quanta with the energy of ~ 5 MeV descending from the GDR is needed in order to identify prompt gamma rays emitted at the stage of fissioning.

1 Introduction

First results of the current experiment on search for the angular correlation in the emission of gamma quanta from fission of ^{235}U induced by thermal polarised neutrons were surprising and of great interest [1]. Polarisation of the neutron beam defines the natural quantization axis z in the laboratory frame. In ref. [1] fission fragments and gammas were detected in the orthogonal geometry, that is in the $(x,\, y)$ plane, which is perpendicular to the neutron polarisation (Fig. 1). Let y be the fission axis. In [1], γ quanta were detected under the angle of ϑ_{exp} with respect to the fission axis, that is axis of y in the frame presented in Fig. 1. In the $(x,\, y)$ plane, angle ϑ_{exp} is complimentary to the azimuth angle ϕ in Fig. 1:

$$\vartheta_{exp} = \frac{\pi}{2} - \phi\,. \tag{1}$$

For this reason, we will refer the results to the angle ϑ_{exp}, using (1). There is obtained an evidence that the γ emission probability depends on the right or left neutron polarisation with respect to the $(x,\, y)$ plane. Furthermore, the asymmetry parameter, $R(\vartheta_{exp})$ has been obtained. That reads

$$R(\vartheta_{exp}) = \frac{N_\gamma^\uparrow(\vartheta_{exp}) - N_\gamma^\downarrow(\vartheta_{exp})}{N_\gamma^\uparrow(\vartheta_{exp}) + N_\gamma^\downarrow(\vartheta_{exp})}\,, \tag{2}$$

where $N_\gamma^\uparrow$, $(N_\gamma^\downarrow)$ is the number of gammas emitted at the given angle ϑ_{exp} with respect to the fission axis when the neutron polarisation is along (right) or counter (left) the quantization axis z, respectively. The experimental values reported in [1] with 90% longitudinally polarised thermal neutrons are

$R^{exp}(35°) = (1.5 \pm 0.4)\times 10^{-4}$,
$R^{exp}(57°) = (2.3 \pm 0.4)\times 10^{-4}$, and
$R^{exp}(90°) = (-0.2 \pm 0.6)\times 10^{-4}$.

Earlier, similar effect has been found in α or another light charged particle emission in ternary fission [2]. In that case, a simple though beautiful explanation of the effect was proposed by A.Gagarsky. The effect was attributed to the rotation of the fission axis after the light charged particles are ejected. It is needed that the alpha is emitted for the times of the order of 10^{-21} s, while the fragments do not separate on a large distance yet and the fission axis continues rotation primarily started by the fissile nucleus due to its spin. Therefore, this effect is of great interest because it sheds light on the dynamics of fission at a very early stage, also clarifying the fundamentals of quantum mechanics. As distinct from α's and other strongly interacting particles, γ emission mainly occurs from fully accelerated excited fragments, past the neutron evaporation (e.g. [7]), for characteristic times of 10^{-14} - 10^{-12} s, and therefore, cannot be explained as due to the same origin.

Our present purpose is further investigation of the Strutinsky—Denisov induced polarisation mechanism [3, 4]. In [5], this mechanism was proposed for explanation of the non-statistical part of the spectrum, observed in ref. [6]. We will show that these gamma rays will be characterized by left-right asymmetry, like that observed in ref. [1]. And though it seems to be early to relate the observed effect to the Strutinsky-Denisov mechanism, its study is useful to better understand the place of the effect [1], to realize its meaning. Moreover, it is shown that the polarisation of prompt gamma rays can be also studied and distinguished from the evaporative part of the spectrum through their left-right asymmetry. We show that their study will give a valuable information about this ingenious mechanism and dynamics of fission. In this mechanism, the radiation is emitted from fragments before the neutron emission due to snapping back the nuclear surface within a time interval τ_{dis} which is determined by dissipation of the collective energy. According to [7], $\tau_{dis} \lesssim 10^{-19}$ s. Therefore, study of this effect gives invaluable informa-

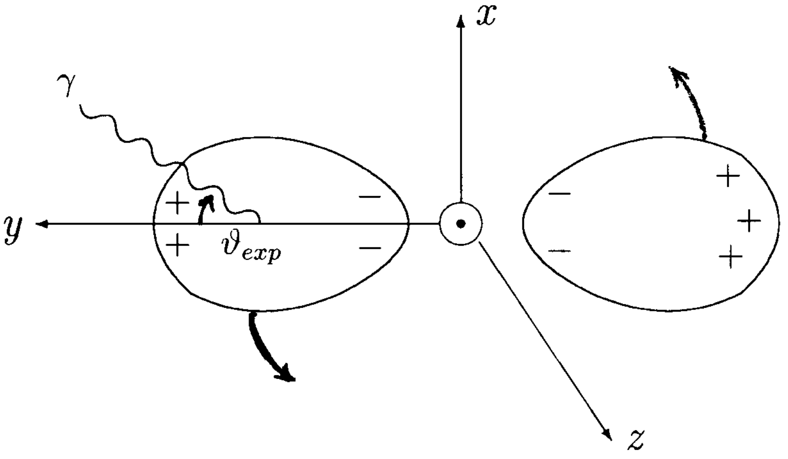

Figure 1: Scheme of study of the right-left asymmetry in radiation from fission of ^{235}U nucleus. Fission is induced by a capture of a thermal neutron (designated by an open circle at the origin) polarised along the z axis, as shown by the point in the middle. Pear-like fragments are polarised from the moment of birth. Signs '+' and '−' show redistribution of charge inside the fragments, which induces appearance of the electric dipole moments. Circular arrows show the direction of rotation of the fissile nucleus and nascent fragments caused by the polarisation of the fissile nucleus. The fragments separate in the direction of the y axis; γ quanta are registered in the (x, y) plane at the angle of ϑ_{exp} with respect to the y axis. The probability of γ emission at the given angle changes when the direction of rotation is reversed together with the neutron polarisation.

tion on the dynamics of this process, providing a direct confirmation of this phenomenon, which is of great interest, but very hardly observed. Previous evidence of this effect was obtained in the shaking muons emitted from the prompt fission fragments [8, 9, 10]. On the other side, at the present stage of investigation, our calculation suggests that the usual γ radiation from fragments can be expected to possess the same effect. However, even in this case, the value of the asymmetry parameter (2) depends on such a seemingly intrinsic and hardly observable property as the angular velocity of the spin rotation of the fragments, as well as dissipation of the nuclear matter, providing a unique information on these primordial features.

2 Physical premises

First premise is collective rotation of the polarised fissile nucleus due to its spin. Fission is facilitated by the rotation in the direction perpendicular to the rotation axis (that is the spin direction). Evidently, this rotation is transferred to the fragments, which thus remember the spin direction of the primary polarised neutron which induced fission. Experiment also shows that the fragments are formed partly aligned after scission in the plane perpendicular to the fission axis, with the average spin of $I = 7 - 8$. The effect of alignment was observed in the angular distribution of the emitted radiation [11] and conversion muons from the prompt fission fragments [12]. The spins of the fragments can be parallel or anti-parallel to each other. In the last case, their total spin is compensated by the large angular momentum of the relative motion of the fragments. Origin of this part of the fragment spins is probably due to statistics. The corresponding value of the spins is much more than the former one. However, this part of the spins is not related to the polarisation of the fissile nucleus and therefore, it is not relevant when speaking about the left-right asymmetry of the fragments. At the moment of scission, the nascent fragments have a pear-like form with the noses directed towards the point of the rupture.

The second premise comes from the shake effects brought about by the neck rupture. From mathematical view point, the rupture means break-down of the analyticity of the Hamiltonian with respect to time. At the moment of scission, the nascent fragments have a pear-like form with the noses directed towards the point of the rupture. The rupture starts the snapping-back of the nuclear surface [15], which goes over the oscillations of the surface smearing out in time. The lifetime of the oscillations is determined by dissipation. It can be evaluated as $\tau_{dis} \approx 10^{-19}$ s [7]. Sharpened shape of the fragments cause appearance of the induced electric dipole moment [3, 4]. The oscillations generate electromagnetic field in space, changing with time. That causes electromagnetic processes of internal conversion and γ radiation. Thus, muon shake in muon-induced prompt fission manifests itself in muonic conversion. The calculated probability agrees with the experiment [9, 10]. In ref. [5, 21], there was also calculated the probability of emission of γ quanta.

This radiation arises due to superposition of the quadrupole and octupole vibrations with the total energy $\hbar\omega_0 = \hbar(\omega_2 + \omega_3) = 5$ MeV with the probability

$$N_d = \int_0^\infty \frac{d\mathcal{E}_\omega}{\hbar\omega} \approx \frac{e^2 d_0^2 \omega_0^3}{6\gamma} = 0.014 \text{ fission}^{-1} , \qquad (3)$$

The differential harmonic is much less intense. This value is in qualitative agreement with experiment [6, 16], taking into account the uncertainties connected with the value of τ_{dis}.

On the other hand, we see that this contribution is proportional to τ_{dis}. Therefore, study of non-statistical γ rays from fission gives direct information about dissipation in large-amplitude collective motion represented by post-rupture oscillations in the fragments.

3 Transformation to the laboratory system

Let us start from consideration of classical radiation from a polarised dipole system in the intrinsic coordinate system. Then the angular distribution will be [17]

$$\chi(\theta') = |Y_{11}(\theta', \phi')|^2 \sim \sin^2(\theta') \ . \tag{4}$$

Distribution (4) is normalised to the emission of one dipole photon from the fragment. After the separation the axis of each fragment rotates in the (x, y) plane with the angular velocity ω (Fig. 1). The angle of the symmetry axis at the moment of emission against the flight direction y will be

$$\beta(t) = \omega t \ . \tag{5}$$

Transformation from the intrinsic to the laboratory frame can be done by means of two rotations at the Euler' s angles β against the axis z, and then at $\pi/2$ against the new axis y'. The spherical functions in (4) in the laboratory system can be expressed in terms of the generalised spherical Wigner functions as follows:

$$Y_{11}(\theta', \phi') = \sum_m \mathcal{D}^1_{m1}(\beta(t), \frac{\pi}{2}, 0) Y_{1m}(\theta, \phi) \ . \tag{6}$$

Inserting (6) into (4) and using formulae [18] for the $\mathcal{D}$ functions, one arrives at the angular distribution in the laboratory frame:

$$\mathrm{X}(\theta, \phi; \beta(t)) = \frac{3}{8\pi} \left[\sin^2\theta \cos^2(\phi - \beta) + \cos^2\theta\right] \ . \tag{7}$$

Integrating the last expression over time and taking into account the time of relaxation due to dissipation of the collective energy $\tau_{dis} \equiv 1/\gamma$, we arrive at the angular distribution in the laboratory system

$$\mathrm{X}(\theta, \phi) = \int_0^\infty \gamma e^{-\gamma t} \mathrm{X}(\theta, \phi; \beta(t)) \, dt = \frac{3}{16\pi} \left[1 + \cos^2\theta + \sin^2\theta \cos 2\delta \cos 2(\phi - \delta)\right] \ , \tag{8}$$

where

$$\cos 2\delta = \frac{\gamma}{\sqrt{\gamma^2 + 4\omega^2}}, \qquad \sin 2\delta = \frac{2\omega}{\sqrt{\gamma^2 + 4\omega^2}} \ . \tag{9}$$

Introducing the anisotropy parameter a, $|a| \ll 1$, we can put down instead of (8)

$$\mathrm{X}(\theta, \phi) = 1 + a \sin^2\theta \cos 2\delta \cos 2(\phi - \delta) \ . \tag{10}$$

Reversal of the polarisation of the incoming neutrons is equivalent to the reversal of the direction of the rotation of the fissile nucleus and the fragments. This leads to a replacement $\omega \to -\omega$, that is $\delta \to -\delta$. Therefore, we arrive by means of eq. (8) at the following expression for the asymmetry parameter (we omit $\sin^2\theta = 1$):

$$R(\theta,\phi) = a\cos 2\delta \sin 2\delta \sin 2\phi = \frac{1}{2} a \sin^2\theta \sin 4\delta \sin 2\phi \ . \tag{11}$$

Assuming the background radiation $\mathrm{X}_b(\theta,\phi)$ to be isotropic, we can normalise it to the total number of the emitted photons per fission N_γ and arrive at the following expression:

$$\mathrm{X}_b(\theta,\phi) = N_\gamma/4\pi \ . \tag{12}$$

Given the number of the dipole quanta per fission N_d, and allowing for (8), one can put down an expression for the total angular distribution as follows:

$$\mathrm{X}_b(\theta,\phi) + \mathrm{X}(\theta,\phi) = \frac{1}{4\pi} N_\gamma + \frac{3}{16\pi} N_d \sin^2\theta \ \cos 2\delta \ \cos 2(\phi-\delta) \ . \tag{13}$$

Comparing (13) with (10), we arrive at the following expression for the anisotropy parameter a:

$$a = \frac{3}{4}\frac{N_d}{N_\gamma} \ . \tag{14}$$

Note that (11) is anti-symmetric with respect to the value of $\phi = \pi/2$. The asymmetry parameter increases from zero to maximal value for $0 \le \phi < \pi/4$. Then it diminishes again to zero, changing the sign at $\phi = \pi/2$, and becomes negative for $\pi/2 < \phi < \pi$. Then it varies in the same manner in the open angle of $\pi \le \phi < 2\pi$. This behaviour is similar to the previously reported angular distribution which is characteristic to the ROT effect in ternary fission [2].

4 The results and discussion

First, we note that the experimental data [1] exhibit the angular dependence of the asymmetry parameter similar to (11): the experimental value changes the sign when ϑ_{exp} crosses $\pi/2$. Regarding the numerical values, simple solid-state estimation shows that with spin $I = 1$, the fragments revolve with $\omega \approx 2.1 \times 10^{19}$ s^{-1}. Therefore, with $\gamma \approx 10^{19}$ s^{-1} one obtains $\cos 2\delta \approx 0.24$.

Next task is evaluation of the anisotropy parameter a in (14). With the N_d value (3) in mind, let us consider the radiation background N_b. As a result of fission, deformed primary fragments are obtained with the excitation energy of around 12 MeV. The excitation energy is partly fallen down with the evaporated neutrons. Already the neutrons are emitted by the fully accelerated fragments, being kinematically shifted by the translation velocity of the fragments [7]. Only recently it was established that there is a certain fraction of prompt neutrons at the level of 10% which are emitted from the fission area before the fragments are accelerated. There is much less known about prompt gamma rays. The Nonstatistical part of the spectrum [6] can be of this kind. Brehmstrahlung gamma rays also can be emitted during acceleration of the fragments. Recently, brehmstrahlung was discovered in alpha decay (e.g. [19]). Angular distribution of the brehmstrahlung quanta would be the same as that in (4), and therefore, that would be accompanied by a related right-left effect due to rotation of the inter-fragment axis. However, fission fragments are much heavier than alphas, and moreover, the dipole moment of a pair of fragments is close to zero because of near constancy of the fragment Z/A ratio. For these reasons, one should not expect any essential manifestation of the brehmstrahlung. Experiments and calculations confirm this assumption [20, 21]. An estimate [21] shows for the number of brehmstrahlung quanta N_γ with the energy within a domain of 100 keV to 5 MeV

$$10^{-5}\ \mathrm{fission}^{-1} \leq N_\gamma \leq 2\cdot 10^{-4}\ \mathrm{fission}^{-1}\ . \tag{15}$$

As expected, these values are too low to produce a noticeable effect of right-left asymmetry.

According to the experimental spectrum [22], average number of quanta emitted per fission is $N_\gamma \approx 8$ fission^{-1}. Assuming the isotropic angular distribution of these quanta, and given the total probability of the electric dipole quanta of (3) with the angular distribution (4), we can estimate the parameter a to be $a \approx \frac{3}{4}\cdot 0.014/\ 8 \approx 0.0013$. By means of (11) we then get an estimation of the asymmetry parameter $R(\vartheta_{exp}) = 2.8\times 10^{-4}$ for the angles of $\vartheta_{exp} = 35°$ and $57°$, and $R(90°) = 0$. We note, that, generally speaking, these values are close to the experimental values [1] for these angles cited in Introduction. Note that for a slower rotation of the fragments, the value of $\cos 2\delta$ could be higher. The maximal value of the asymmetry parameter (11) could be by a factor of 2 higher. We however cannot still directly compare our theoretical results to data [1] until we discuss the energy dependence of the effect. In the above example, we retained only the resonant term in (3), corresponding to emission of the quanta with the total energy of approximately 5 MeV. From the experimental spectrum from fission [22] one can conclude that effect-to-background ratio would be much better in this domain. Thus, there is only ~ 0.3 quanta per fission with the energy $E_\gamma > 2.5$ MeV. With this background value, one arrives at the asymmetry parameter $a = \frac{3}{4}\cdot 0.014/0.3 = 0.035$, and the corresponding right-left effect R at the level of 10^{-2}.

It is worthy to draw analogy with the ROT effect. We note that the fragments rotate in the same plane with the fission axis, but with much larger angular velocity. Naturally, we mean ordered rotation related to the primary neutron polarisation. As a result, it follows from the above results that the fragments make more than 10^5 full revolutions before the evaporative γ quanta start to be emitted, while the fission axis rotates by less than one degree. Therefore, one should not expect any manifestations of effects due to rotation of the fission axis in the angular distribution of these γ quanta.

5 Emission of the prescission γ quanta?

Normal electromagnetic nuclear lifetimes $\lambda \sim 10^{-12}$ s. This is for gammas with energy ω of $\omega \lesssim 100$ keV. Let the energy be up to $\sim$1 MeV. Then one arrives at the electromagnetic lifetimes of $\sim 10^{-15}$ s. One can reinforce this estimate supposing a collective coherent process. Then one may multiply the probability by $Z \approx 100$, which gives an estimate $\lambda \sim 10^{-17}$ s. One can arrive at the same estimate from the upper energy of the giant dipole resonance (GDR), assuming its energy to be $\sim$10 MeV and supposing an $\sim$100% of the energy weighted sum rule (EWSR) is exhausted by the GDR. Then one obtains $\lambda_{GDR} \sim 10^{-20}$ s in the fissile nucleus. Assuming an attenuated mode due to nuclear deformation in fission with the energy within $\sim$1 MeV, we obtain again 10^{-17} s for its lifetime. This is a shortest reasonable value, which should be rather enlarged at least by an order of magnitude, taking into account an extreme character of such estimates. In principle, with the theoretical value of $R \sim \cos 2\delta \sim 0.24$ and the anisotropy parameter $a \approx 0.001$, we can then fit experimental data $R_{exp} \sim 10^{-4}$ with characteristic value of prefission lifetime $\tau_f \gtrsim 10^{-18}$ s, which, strictly speaking, appears to be quite a reasonable estimate. Then the number of the pre-scission gammas presents a time scale for the neutron-induced fission.

6 Conclusion

1. It is shown that the observed effect of right-left asymmetry in gamma radiation can be explained as due to emission from rotating fragments. The rotation is due to the primary polarisation of the fissile nucleus whose rotational moment partly transfers to the fragments after the scission. According to (3), this effect is predicted for the γ quanta of sufficiently high energy, descending from the giant dipole resonance. This is in accordance with the time scale, which is of the order of 10^{-19} s. For smaller energies, the emission probability is lower by orders of magnitude. The radiative lifetime is less than one period of rotation of a fragment. Therefore, study of the effect for such hard gammas presents an information about the process of fission at this early stage.

2. For further understanding, the energy dependence of the effect is highly needed to be measured in experiment. In the above example, we retained only the resonant term corresponding to emission of the quanta with the total energy of approximately 5 MeV. We neglected the other resonant term with the difference energy in (3) $\omega_{dif} = \omega_3 - \omega_2 = 0.6$ MeV, because in this case the expected emission probability is by three orders of magnitude less, being proportional to the cube of the energy. An important conclusion for experiment follows this result. In order to study early stages of fission, one should detect hard γ quanta with the energy in the region of giant dipole resonance (though reduced considerably by elongation of the fissile nucleus), as in refs. [6, 22].

The observed effect may be a fingerprint of the prescission gamma quanta. In this case, its value gives a time scale for the neutron-induced fission.

3. Study of the above effect gives information on the snapping back the nuclear surface on the born fragments. That is a direct confirmation of this phenomenon [15], which is of great interest, but very hardly observed. Previous evidence of this effect was obtained in the shaking muons emitted from the prompt fission fragments [8, 9, 10].

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