Large Gamma Anisotropy Observed in the ^{252}Cf Spontaneous-Fission Process

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The energy spectrum and the angular dependence relative to the fission direction of photons in the energy region between 2 and 40 MeV have been measured for the spontaneous fission of ^{252}Cf. A large anisotropy was found in the energy region 8 to 12 MeV implying that photons in this region are emitted from a nuclear system which is highly elongated along the fission axis.

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Nuclear fission is a phenomenon which addresses widely different aspects in physics and chemistry. After more than fifty years of continuous investigations [1,2] a number of interesting questions are still unanswered. Among these, the dynamical aspects of fission are the least understood. A particular dynamical feature is the dissipation of energy during the massive rearrangement of nucleons from the ground state of a spontaneously fissioning nucleus to the scission point [3-8]. For many years measurements addressing the fission process have concentrated on particle emissions from fissioning nuclei [1,9]. Only a few experiments have been performed on the high-energy part of the γ spectrum coming from spontaneously fissioning nuclei [10-15], although it has been suggested to contain specific information on the dynamical features of fission (see, e.g., Ref. [16]).

Here we report on an extensive investigation of photon emission accompanying the spontaneous fission of ^{252}Cf. For the first time the angular correlation of gamma rays, emitted parallel and perpendicular to the fission direction, has been measured. An unexpected large anisotropy is observed in the energy region between 8 and 12 MeV, the giant dipole resonance (GDR) region. The measured anisotropy requires emission of gamma rays from a nuclear system which is highly elongated along the fission axis, consistent with shapes predicted close to the scission point [8]. Neither the anisotropy nor the total photon spectrum can be described using a statistical code incorporating the GDR strength function to model the γ emission from the excited daughter nuclei.

The experimental setup is shown in Fig. 1. Two large-volume (2.6 liter) BaF_2 detectors and a 25 cm diameter×35 cm cylindrical NaI spectrometer with a plastic anticoincidence shield were used to detect high-energy gamma rays in the range of 2 to 40 MeV, with a total absolute efficiency of 1.4% for $E_\gamma > 6$ MeV. Eight ($35 \times 35 \times 60$ mm^3) BaF_2 γ detectors, four below and four above the reaction plane and placed inside the vacuum chamber as close as possible to the ^{252}Cf source, were used to determine the start signal for each event. Time-of-flight measurements distinguish prompt gamma rays from neutrons for the large-volume gamma detectors. Four low-pressure position-sensitive avalanche detectors (PSAD) were placed around the source within the vacuum chamber, in such a way that for each event in which a high-energy gamma is detected, fission could be observed either along or perpendicular to the direction of the gamma ray emitted. The position of the emitted fission fragments could be determined with an accuracy of 1.5×10^{-4} sr. One ninth of all fission decays were detected. A californium source of 1.2×10^4 (fission decays)/sec was used during a total of 26 days of effective data taking. One million events were recorded in which fission was accompanied with the emission of a photon with an energy larger than 5 MeV. The measured gamma spectrum and the anisotropy with respect to the fission direction are shown in Fig. 2. This spectrum has been obtained after adequate gating in the time spectrum on prompt gamma emission and after subtraction of background random coincidences. The γ background due to cosmic radiation is efficiently suppressed by measuring coincidences with the fission fragments. For the NaI detector further reduction is obtained by the plastic anticoincidence shielding.

The γ spectrum measured in coincidence with fission

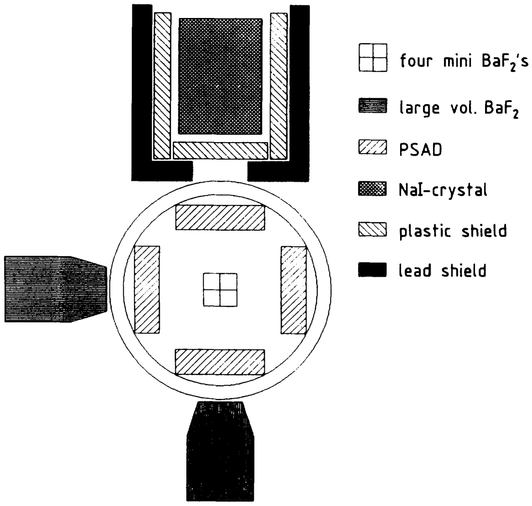

FIG. 1. Schematic diagram of the top view of the experimental setup.

was assumed to be composed of three components. The first component from about 3 to 6 MeV is due to statistical γ emission from the excited fission fragments. Several measurements indicate that this statistical γ emission is isotropic [11,17,18] for $E_\gamma < 3.5$ MeV in the rest frame of each fission fragment, which implies that in the laboratory system there will be an anisotropy due to the Doppler shift. As will be shown below, the measured anisotropy cannot be explained by this first component: A second component is necessary to explain the measured anisotropy in the region between 8 and 12 MeV. A possible third component (20–40 MeV) is depicted as a high-energy tail [13,14]. As indicated in Fig. 2 this component can be described by an exponentially decreasing curve. Upper limits for this third component were obtained using only the NaI detector with its efficient cosmic-ray background suppression. The upper limits are 5.7×10^{-7} and 2.0×10^{-8} γ/(fission MeV) in the regions between 20–30 and 30–40 MeV, respectively. The latter cross section is in disagreement with the value measured by Kasagi *et al.* [13], but not with the one of Luke, Gossett, and Vandenbosch [14]. Within the poor statistics obtained, this component is assumed to be isotropic. In calculating the anisotropy and γ emission this component has been extrapolated to lower energies.

In order to calculate the γ spectrum and anisotropy due to the statistical decay of the fission fragments, the statistical code CASCADE [19] was used. This code was modified in such a way that the initial treatment of the Hauser-Feshbach formalism started from a matrix representing the initial population probability of excited states of a nucleus with a given A and Z. The probability $\mathcal{P}(A_1,Z_1,E_1^*,I_1,A_2,Z_2,E_2^*,I_2)$ of populating a given pair of daughter nuclei with particular values of excitation energy E^* (collective and noncollective) and angular momentum I was calculated analytically. The measured mass distribution and the calculated charge distribution [20] were taken into account. The total energy available $(E^*_{\rm tot} = E_1^* + E_2^*)$ was estimated from the Q value of the channel under consideration and the measured kinetic energy of both fragments [21]. This energy was then allowed to vary as a representative parameter influencing the statistical decay process. An amount of about 10 MeV, corresponding to the currently accepted average prefission noncollective excitation energy [22] was divided among the two daughter nuclei on the basis of equal temperature. The remaining energy was then divided among the two daughter nuclei on the basis of a detailed model, which has proven to be successful in predicting the mass-dependent prompt-neutron multiplicities for the spontaneous fission of ^{252}Cf [23]. The collective rotational energy is calculated from the angular momentum of the two daughter nuclei. These were estimated from the measured average gamma multiplicities for this fission decay

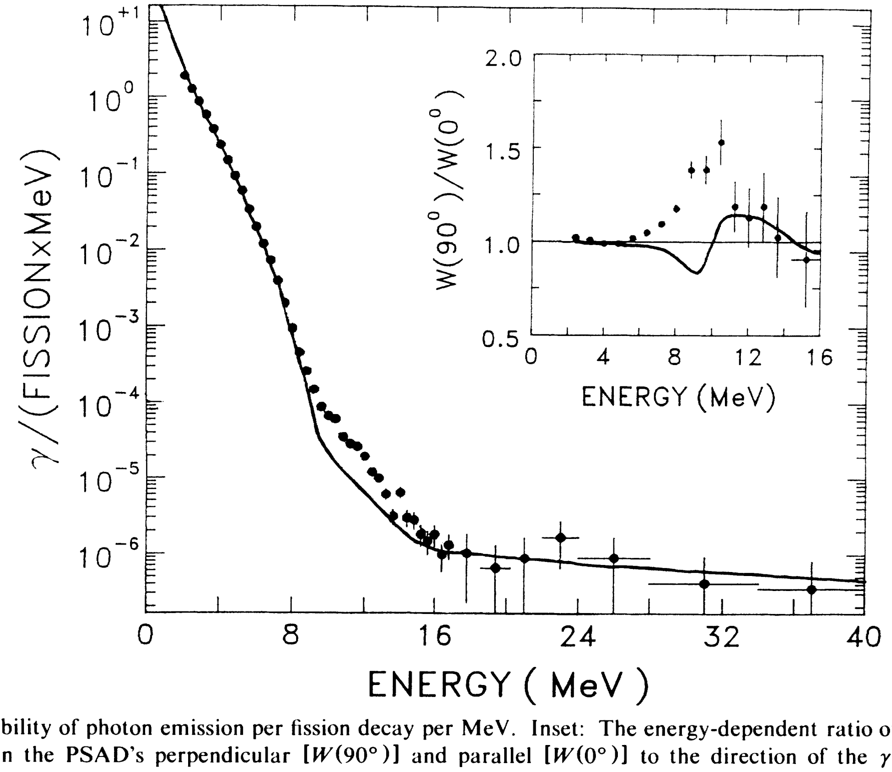

FIG. 2. The probability of photon emission per fission decay per MeV. Inset: The energy-dependent ratio of the number of fission fragments observed in the PSAD's perpendicular [$W(90°)$] and parallel [$W(0°)$] to the direction of the γ rays. The error bars shown are 1σ. The solid line represents the calculated γ emission and its anisotropy, due to the statistical γ decay from the excited daughter nuclei, and an exponential high-energy tail discussed in the text.

[15], and the assumption of a bending mechanism [17,24] for the coupling between the two angular momenta. The calculated photon spectrum is then corrected for the Doppler shift, since these photons are emitted after the fragments have obtained full speed. All calculations are folded with the response function of the gamma detectors. The fact that the photon spectrum in the energy region up to 8 MeV does not follow an exponential decay curve (see Fig. 2) is fully reproduced by the present calculation. It seems to be the result of the limited amount of excitation energy and the mass distribution of the fission fragments.

A quantitative estimate of the post-scission high-energy γ emission ($E_\gamma > 8$ MeV) is obtained by incorporating in the CASCADE calculations a GDR strength function for prolate deformed nuclei. This will enhance the photon multiplicity in the region of the GDR centroid energies. The photon spectrum originating from the decay of the GDR has an angular dependence relative to the spin axis of the fission fragments [25], which due to the bending mechanism will be perpendicular to the fission direction. In addition to this anisotropy there is an extra contribution, affecting the entire photon energy spectrum, resulting from the Doppler correction needed to calculate the observed γ emission in the laboratory frame. In Fig. 2 both the calculated gamma spectrum and total anisotropy are shown for fission fragments with an average deformation of $\beta = 0.2$ (solid lines). This fit was obtained with an effective excitation energy parameter of $E^*_{\text{tot}} - 10$ MeV. Different average deformations of the fission fragments could not explain the behavior of the measured γ spectrum and anisotropy. Also at higher deformations the excitation energy available for GDR decay becomes inadequate. We conclude that describing the current measurement of both the γ-ray energy and anisotropy by considering only post-scission gamma emission is not possible.

In order to explain the measured γ-ray multiplicity and its anisotropy one needs to consider, therefore, another source of γ emission. Whether this γ emission takes place prior to or just after the scission point is not possible to determine from the present data. However, the observed anisotropy requires the photon emission to occur from charge displacements oriented along the fission axis. It is tempting to associate this γ emission with the dynamical buildup, and subsequent collapse, of the highly elongated shapes encountered close to the scission point. In a recent work [16], based on a nuclear transport theory, specifically giant vibrations were coupled to the shape relaxation of fission fragments. It would be interesting to extend this model to pre-scission shape dynamics.

In summary, we measured the energy spectrum and angular dependence with respect to the fission direction of gamma radiation accompanying the spontaneous fission of ^{252}Cf. We found a strong anisotropy for $8 < E_\gamma < 12$ MeV suggesting that in the fissioning system γ radiation occurs from processes leading to, or as a consequence of, the nuclear scission. A measurement of the correlation between gamma emission, in this energy region, and the mass distribution of the fission fragments could give further insight into the dynamics of fission.

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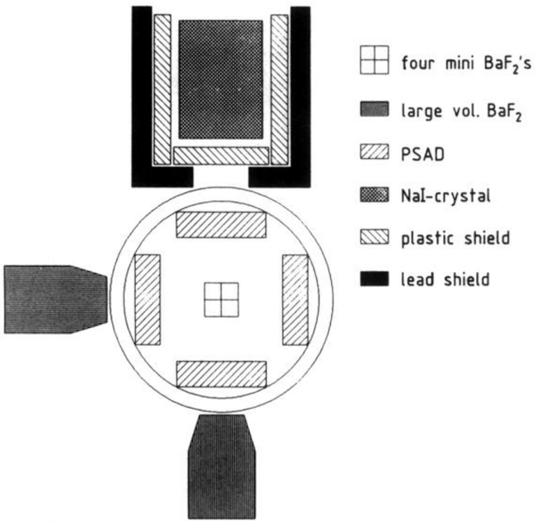

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