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Nucleus-Nucleus Bremsstrahlung Observed in the Spontaneous Fission of ^{252}Cf

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High energy γ rays from the spontaneous fission of ^{252}Cf have been measured with energies from 5 to 160 MeV. The obtained spectrum clearly exhibits the existence of the γ rays up to more than 100 MeV, and is roughly proportional to $1/E_\gamma$ for E_γ > 20 MeV. Calculations of the nucleus-nucleus bremsstrahlung for the Coulomb acceleration of the fragments as well as the sudden acceleration have been performed. The results show that the high energy γ rays are essentially explained as the bremsstrahlung which accompanies the creation of rapid moving nuclei caused by the fission.

§ 1. Introduction

Bremsstrahlung is a continuous energy electromagnetic radiation which accompanies any interaction of charged particles. Recently, much attention has been paid to explain hard photons observed in heavy-ion reactions. Various bremsstrahlung mechanisms, ranging from nucleon-nucleon single collisions[1)] to fully collective processes[2)], have been proposed. Among them, the incoherent nucleon-nucleon bremsstrahlung picture is mostly accepted to explain the inclusive γ-ray spectra observed in the reactions with incident energies of several tens MeV/nucleon. Into the category of the fully collective processes falls the coherent nucleus-nucleus bremsstrahlung (here, we call this simply "nucleus-nucleus bremsstrahlung"), where the change in the relative motion of the two nuclei causes the radiation. It is very difficult, however, to observe the nucleus-nucleus bremsstrahlung in the reactions, since the reaction products are usually highly excited and emit much more γ rays as the statistical decay[3)] than those originated from the nucleus-nucleus bremsstrahlung. Thus, up to now, no definite observation of the hard photons produced by the nucleus-nucleus bremsstrahlung mechanism has been reported.

A fissioning system is very suitable to investigate the nucleus-nucleus bremsstrahlung. The change in the relative motion of the two nuclei is the largest. In addition, the amount of the kinetic energy released is much larger than that of intrinsic excitation energies of the fragments.

We have measured high energy γ rays from the spontaneous fission of ^{252}Cf. Althogh the γ rays from ^{252}Cf have been already reported by several authors, the maximum measured energy is only 18 MeV. We have extended the measurements of the γ rays for the energies up to 160 MeV.

§ 2. Experiment

In the present work, γ-γ coincidence measurements were carried out. The basic experimental arrangement employed a ^{252}Cf source placed next to an NE213 detector and 60 cm from a BaF_2 detector surrounded by 10 cm-thick plastic veto counters. The ^{252}Cf source of 3.9×10^4 fissions/sec, commercially obtained from Amersham as a neutron source, was capsulized in a standard capsule (type X.2). The NE213 detector (12.5 cm$\phi\times$5 cm^t) detected γ rays emitted from the fission fragments, and provided a zero-time reference for the fission events. Neutron-induced events in the NE213 detector were almost completely rejected by using a pulse shape discriminator. A threshold level of a constant fraction discriminator (CFD) for the NE213 detector was set just above the noise level and detection efficiency of 36 % of the total fission events was obtained with the experimental arrangement. The γ-ray spectra were measured by the BaF_2 detector which consisted of seven hexagonal crystals (37 cm$^2\times$20 cm) optically separated. Calibrated light pulses from an LED irradiating the BaF_2 crystals and cosmic rays were used for the energy calibration of each element. Anode outputs from photomultipliers were fed separately into CAMAC ADCs and the total energy deposit in the BaF_2 detector was calculated for each event by a front-end processor J11. Time signals were provided by CFDs and were fed into TDCs. The measurement run was carried out for about 140 hours with the source and the background was measured for about 50 hours without the source.

§ 3. Result

In Fig. 1 shown is the γ-ray spectrum observed with the source (histogram) and the background spectrum measured without the source (solid dots). The vertical scale of the background spectrum is normalized to the other with the correction of the dead time of the counting system. The insert of the figure shows a typical time spectrum obtained with the center element of the BaF_2 detector and the NE213 detector. A narrow gate of 2.9 ns in width set arround the prompt γ-ray peak in each time spectrum serves to reject the events induced by neutrons with energies up to 55 MeV and to reduce random coincidence events to be less than 0.3 %, which have been subtracted in the γ-ray spectrum. Although the shapes above 20 MeV of the two spectra are quite similar to each other, the yields measured with the source are about 2.5 times larger than those of the background. Only cosmic rays can contribute to the background events, which are very energetic and are observed in the coincidence measurement. The time spectrum of the background run has shown a sharp peak at exactly the same position as the one measured with the source.

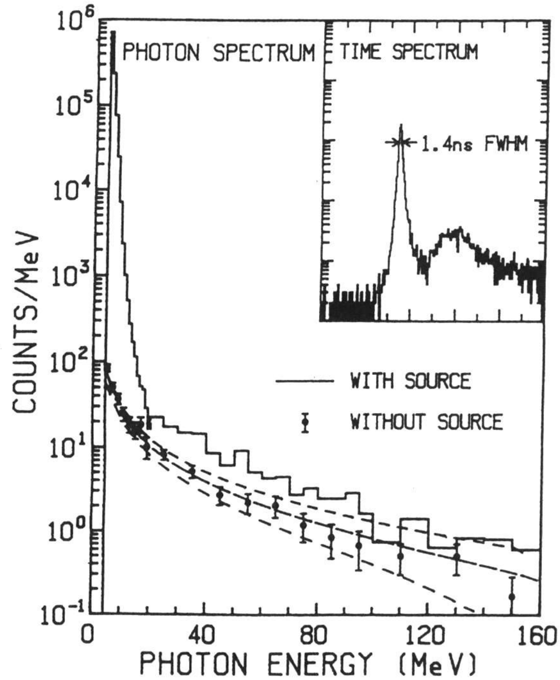

Fig.1. The γ-ray spectra obtained in the present experiment. The histogram plot is the one measured with ^{252}Cf source, and the dots show the background yield measured without the source. The insert shows a typical TOF specrum.

This fact suggests that the background events are due to the bremsstrahlung induced by high energy charged particles punching through or stopping in the NE213 detector. In order to estimate the yields of the background especially in the high energy region, we have fitted the spectrum with the following function which approximates the photon spectrum emitted by fast electrons[4),

$$Y(E_\gamma) = A/E_\gamma \ \log(B/E_\gamma)$$

Here, A and B are treated as adjustable parameters and are determined so as to reproduce the background spectrum. A long dashed curve in the figure corresponds to the most probable background yields and dashed curves show the uncertainties within which the background events are believed to be established.

Fig. 2 shows the γ-ray spectrum from the ^{252}Cf source, in which the background defined above has been subtracted. The spectral shape as well as the absolute intensity is in good agreement with the previously reported one[5) at low energies where the yields fall off very rapidly as expected from the statistical decay of the excited fragments. In addition, the obtained spectrum clearly reveals the existence of γ rays in the higher energy region, for the first time. As can be seen, the slope of the spectral shape suddenly changes at arround 20 MeV and the spectrum falls off less rapidly with increasing energy above 20 MeV.

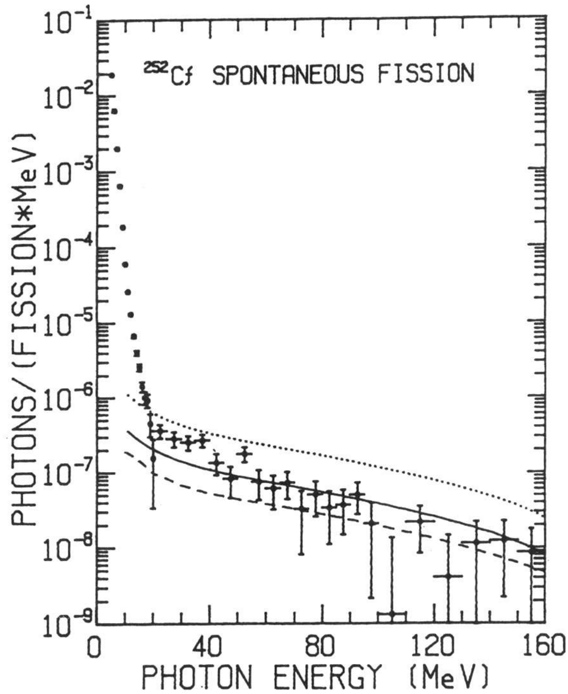

Fig. 2. The γ-ray spectrum from the 252Cf fission. The dotted line is the calculated value of the sudden acceleration model and the dashed line is that of the Coulomb acceleration model.

Although the uncertainties of the data which are mainly determined by the accuracy of the background yield are very large for $E_\gamma > 100$ MeV, the yield continues up to more than 100 MeV. Possible sources of spurious events in the high energy region have been examined, for pile up events, events induced by neutrons with $E_n \geqq 55$ MeV and events induced by (n, γ) reactions on the materials nearby the fission source. However, these spurious events are turned out not to affect the spectrum at all. For example for the worst case, the yields of the events induced by (n, γ) reactions are only $\sim 10^{-9}$ photons/(fission · MeV) in the region of 20 MeV. The effect of the radiation caused by the fission fragment during the deceleration in the material has been estimated according to ref. 6). Although so-called nuclear bremsstrahlung process can contribute to create hard photons, the estimated yield is about 10^{-16} photons/(fission · MeV) at $E_\gamma \sim 20$ MeV. Therefore, we conclude that the γ-rays with energies above 20 MeV are the internal bremsstrahlung of the spontaneous fission of ^{252}Cf.

§4. Bremsstrahlung Calculations

We have considered the bremsstrahlung which occurs when a nucleus fissions into two nuclei. We have performed a quantum mechanical calculation as well as classical mechanical calculations. The model of the quantum mechanical calculation is a pure kinematical one, and is described in ref.7). For the classical calculations, we have calculated the bremsstrahlung probability for two extreme cases. In one case, the two fragments instantaneously obtain their final velocities (we call this sudden acceleration model). In the other case, the fragments are accelerated by the Coulomb force (Coulomb acceleration model).

For the sudden acceleration model, the bremsstrahlung probability per fission can be obtained analytically and is found out to be exactly same as the result of the quantum mechanical kinematical model calculation. It is described for the fragment with mass number A_1, atomic number Z_1 and kinetic energy E_1 as

$$dP = 8/3 \cdot e^2/(\pi \hbar c) \cdot (F_1+F_2) \cdot A_1 \cdot E_1/(M_n c^2) \cdot E_\gamma^{-1}\, dE_\gamma ,$$

where $F_1 = (Z_1/A_1 - Z_2/A_2)^2$,

and $F_2 = 2A_1/5 \cdot (Z_1/A_1{}^2 + Z_2/A_2{}^2)^2 \cdot E_1/M_n c^2$.

A_2 and Z_2 are, respectively, mass and atomic number of the other fragment and M_n is nucleon mass. F_1 term corresponds to the dipole radiation and F_2 term to the quadrupole radiation.

For the Coulomb acceleration model, the bremsstrahlung probability has been calculated numerically for a given pair of the fragments with masses A_1 and A_2, and atomic numbers Z_1 and Z_2.

In order to compare the calculation with the experimental data of ^{252}Cf, the calculated probabilities have been summed over all pairs of the fission fragments after being multiplied by the weight for each pair. The experimental mass distribution from the ^{252}Cf fission[8)] has been used to obtain the weight, together with the Gaussian distribution as a Z-distribution for a given mass number. The centroid of the Z-distribution has been assumed in such a way that the Z/A value is equal to that of ^{252}Cf, and experimentally determined width of the distribution[9)] has been employed. The value of the kinetic energy required for the calculations has been deduced from the average kinetic energy reported in ref. 8).

The calculated spectra have been folded by the response function of the BaF_2 detector and are plotted in Fig. 2. A dotted line in the figure shows the result of the sudden acceleration model (also the quantum mechanical kinematical model) and a dashed line is the Coulomb acceleration model. As shown, both calculations have a $1/E_\gamma$ dependence and explain the general trend of the data. However, the sudden acceleration model overestimates the magnitude of the probability by a factor of $\sim$3. On the other hand, the Coulomb acceleration model underestimates the magnitude a factor of 2.5. The solid line shows the predicted yield of the sudden acceleration model multiplied by a factor of 0.33, which reproduces the data for E_γ > 40 MeV.

§5. Conclusion

The present results clearly indicate that the spontaneous fission is necessarily accompanied by the simultaneous production of hard photons. The bremsstrahlung calculations for the two extreme cases presented here can reproduce the general trend of the experimental data. However, the experimental values of the bremsstrahlung probability are lying just between those of the calculations. Therefore it is highly desirable to develop more sophisticated model calculations which include the dynamics of the fission process. Disagreement between the experiment and the present calculations is to be explained by such calculations.

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