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Prompt gamma ray multiplicity distributions in spontaneous fission of ^{252}Cf

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Abstract. The shape parameters of the multiplicity distribution of prompt gamma rays emitted in spontaneous fission of ^{252}Cf were obtained using the multiple coincidence technique. The multiplicity distribution is well represented by a Gaussian distribution. Assuming the average number of prompt gamma rays emitted per fission to be 10·3, the standard deviation of the multiplicity distribution was estimated to be $4 \cdot 2 \pm 0 \cdot 4$. The variation of the standard deviation of the multiplicity distribution has also been obtained as a function of kinetic energy of one of the fragments and was found to exhibit a strong zigzag dependence on the single fragment kinetic energy. The results have been discussed on the basis of the emission mechanism of prompt gamma rays in fission.

Keywords. Spontaneous fission of ^{252}Cf; prompt gamma ray emission; multiplicity distribution.

1. Introduction

When a nucleus undergoes fission, the primary fission fragments are always formed in a state of high excitation and de-excite by successive neutron and gamma ray emission. The de-excitation process of fission fragments has been a subject of many detailed investigations in the past (Nifenecker *et al* 1973, Vandenbosch and Huizenga 1973). Though the de-excitation of the fragments takes place long after the actual fissioning of the nucleus, it has been shown (Johansson 1964, Vandenbosch and Huizenga 1973) that a study of these de-excitation processes can give important information regarding the fission process itself. Detailed experimental investigations on various aspects of fission gamma rays such as the average multiplicity, energy distributions and angular distributions with respect to the fission fragment direction, have indicated that the gamma ray de-excitation is mainly statistical in nature and of quadrupole type coming from fragments having a spin of about 10–12$\hbar$ (Kapoor and Ramanna 1964, Johansson and Kleinheinz 1971). There also exist experimental evidences for some well defined rotational gamma ray cascades (Chiefetz *et al* 1971) which have been identified as belonging to different fragment isotopes. However, detailed information regarding the gamma ray emission mechanism and its dependence on the fragment properties is not known. In the present work we have carried out measurements of the second and third moments of the multiplicity distribution of fission gamma rays in the spontaneous fission of ^{252}Cf by means of multiple coincidence technique. These results are not presently available and as shown below can give valuable information regarding the de-excitation mechanism.

2. Experimental method and results

A schematic diagram of the experimental set up is shown in figure 1 *a*. The ^{252}Cf source was mounted inside a small ionisation chamber filled with xenon gas at a pressure of one atmosphere. Three NaI (Tl) detectors of 2″ × 2″ dimension were placed around the source making equal angles with each other. The coincidence rates between the fission pulse obtained from the ionisation chamber and from any one, two or all the three detectors were taken to give the single, double and triple coincidence rates of the gamma rays. The fission counts were monitored simultaneously. The second and third moments of the gamma ray multiplicity distribution were calculated from the above three coincidence rates by using the following equations. If Ω_1, Ω_2 and Ω_3 are the detection efficiencies including the solid angle factors of the three detectors respectively and $\bar{n}$, the average number of gamma rays per fission, then the following relations between the coincidence rates hold:

$$C_i = \bar{n}\, \Omega_i \quad i = 1, 2, 3 \tag{1}$$

$$C_{ij} = \langle n(n-1)\rangle\, \Omega_i\, \Omega_j, \; i, j = 1, 2, 3, \text{ and } i \neq j \tag{2}$$

$$C_{ijk} = \langle n(n-1)(n-2)\rangle\, \Omega_i\, \Omega_j\, \Omega_k, \quad i, j, k = 1, 2, 3 \text{ and } i \neq j \neq k \tag{3}$$

where C_i, C_{ij}, C_{ijk} are the single, double and triple coincidence rates per fission

The averages in equations (2) and (3) are taken over the whole multiplicity distribution $P(n)$, where $P(n)$ is the probability of emission of n gamma rays per fission. These relations are based on the assumption that the probability of more than one gamma ray entering the same detector in the same event is small

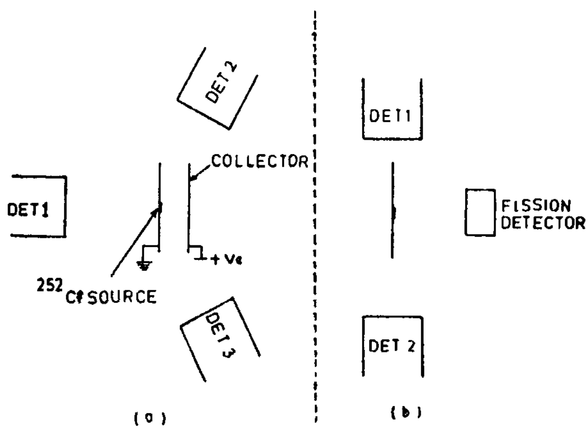

Figure 1. Schematic diagram of the experimental assembly.

and the detection efficiencies, Ω_1, Ω_2 and Ω_3 are the same in the events for single, double and triple coincidences. In the present geometry where the solid angles of the three NaI (Tl) detectors subtended at the fission source were small, the error due to the first assumption was calculated to be less than 1%. The validity of the second assumption was established by recording the gamma ray spectra in the cases of single, double and triple coincidence events which were found to be nearly the same. The contribution due to the fission neutrons to the count rates were also neglected because of the lesser number of neutrons per fission and also due to the small detection efficiency for neutrons in NaI (Tl) detector. This contribution was also estimated to be less than 1%.

A number of independent runs were carried out to find the average values of all the coincidence rates. The fission rate was approximately 800 per second. The typical fission-gamma coincidence rates per fission were as follows:

$$C_1 = 5\cdot 23 \times 10^{-2},\ C_2 = 6\cdot 35 \times 10^{-2},\ C_3 = 5\cdot 88 \times 10^{-2}$$

$$C_{12} = 3\cdot 5 \times 10^{-3},\ C_{23} = 4\cdot 1 \times 10^{-3},\ C_{31} = 3\cdot 3 \times 10^{-3}$$

$$C_{123} = 2\cdot 34 \times 10^{-4}.$$

Eliminating the unknown solid angle factors from eqs (1–3), using the experimentally determined value of $\bar{n} = 10\cdot 3$ per fission (Johansson and Kleinheinz 1966) the values of $\langle n^2\rangle$ and $\langle n^3\rangle$ were calculated to be

$$\langle n^2\rangle = 124\cdot 2 \pm 1\cdot 7$$

$$\langle n^3\rangle = 1659 \pm 20$$

The values of $\bar{n}$, $\langle n^2\rangle$ and $\langle n^3\rangle$ define the shape of the multiplicity distribution $P(n)$. In the case of a Gaussian distribution, $\bar{n}$, $\langle n^2\rangle$ and $\langle n^3\rangle$ are related through the following relations

$$\langle n^2\rangle = \bar{n}^2 + \sigma^2 \tag{4}$$

$$\langle n^3\rangle = \bar{n}^3 + 3\,\bar{n}\sigma^2 \tag{5}$$

where σ is the standard deviation of the Gaussian distribution. In the present case, if the multiplicity distribution is assumed to be of Gaussian form with $\bar{n} = 10\cdot 3$ and $\sigma^2 = (\langle n^2\rangle - \bar{n}^2) = 18\cdot 1 \pm 1\cdot 7$, then the value of n^3 as obtained from expression (5) is 1652 ± 52. This value of $\langle n^3\rangle$ compares well with the experimental value of $\langle n^3\rangle = 1659 \pm 20$. It can therefore be concluded that the multiplicity distribution of prompt gamma rays in fission can be very well represented by a Gaussian shape with the average at $10\cdot 3$ and a standard deviation of $4\cdot 2 \pm 0\cdot 4$.

The experiment was extended to determine the width of the gamma ray multiplicity distribution for different values of single fragment kinetic energy, by taking the fission fragment kinetic energy spectrum in coincidence with one and two NaI (Tl) detectors. The fission fragment kinetic energies were measured by means of a semiconductor detector (figure 1 *b*). Since the shape of the gamma ray multiplicity distribution was found to be Gaussian, only two gamma ray detectors were used to determine the second moment of the distribution. The fission fragment kinetic energy spectrum from the semiconductor detector was recorded in he first quarter of a 1024 channel analyser and was routed by the two single coincidence pulses ($\gamma_1 - F$) and ($\gamma_2 - F$) and double coincidence pulse ($\gamma_1 - \gamma_2 - F$) to the second, third and fourth quarters respectively, so that all the spectra were recorded under identical conditions. The fission fragment energies were obtained from the peak channels in the kinetic energy distribution. The equations for the double and triple coincidences can now be written as before for every window of the fission fragment kinetic energy. The value of $R = C_{12}/C_1C_2$ was calculated for each fragment kinetic energy. The ratio R is related to the second moment of the multiplicity distribution by [*see* eqs (1) and (2)].

$$\frac{\langle n^2 \rangle - \bar{n}}{\bar{n}^2} = R \tag{6}$$

$$\sigma^2 = \langle n^2 \rangle - \bar{n}^2 = (R - 1)\,\bar{n}^2 + \bar{n}. \tag{7}$$

The value of $\bar{n}$ for each window of single fragment kinetic energy was obtained by assuming the average value of $\bar{n}$ for all fission fragment energies to be 10·3. Figure 2 *a* shows the variation of $\bar{n}$ and σ with the single fragment kinetic energy. It is seen that the width of the multiplicity distribution shows a strong zigzag dependence on the single fragment kinetic energy. The width reduces almost by a factor of two when going from very low single fragment kinetic energy towards the valley where it has a sudden increase and again reduces for very large single fragment energy. The corresponding change in $\bar{n}$ is seen to be 10% over the entire kinetic energy range.

3. Discussion

An interpretation of the present results on the gamma ray multiplicity distributions can be carried out on the basis of the de-excitation mechanism of the fission fragments. It is known that the primary fragments on the average possess excitation energy to the extent of 10–15 MeV each (as indicated by the mean number of neutrons emitted per fission) and also significant spin of the order of 10–15 $\hbar$ (as indicated by the fragment — γ ray angular distribution measurements). These excited fragments release their excitation energy by means of neutron emission and subsequent gamma emission. It is also known that because of the high spin of the fragments, there might be appreciable neutron-gamma competition. Also because of high spin, apart from the statistical de-excitation process, there might be many gamma cascades through rotational states. Such cascades have been identified by means of high resolution fission gamma ray studies. One characteristic feature of these cascades is that the variance in the number of gamma rays in a given cascade with a specified initial spin is very small. This feature has been used in heavy ion reactions to estimate the spin distribution of the compound nucleus produced (Hagemann *et al* 1975). The observed width in the number of fission gamma rays is a net result of the width due to the statistical component and cascade decays. In figure 2 *a*, it is seen that the observed width shows a strong zigzag behaviour as a function of single fragment kinetic energy, whereas the mean number shows a change of only 10% over the entire region. It can therefore be concluded that the observed change in width arises due to different

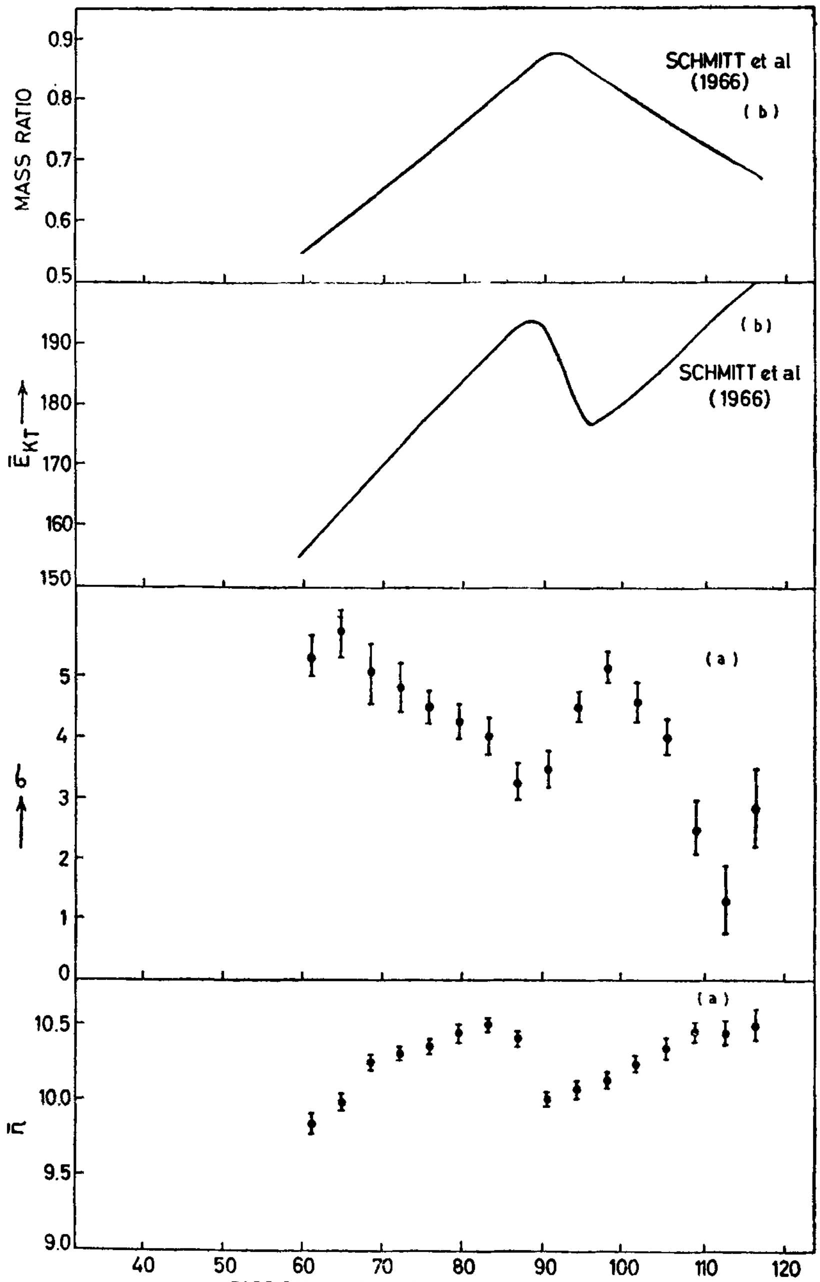

Figure 2. (*a*) Variation of $\bar{n}$ and σ of the gamma ray multiplicity distribution with the kinetic energy of one of the fission fragments. (note the false zero on the $\bar{n}$ axis).
(*b*) Variation of average mass ratio and average total kinetic energy with the kinetic energy of one of the fission fragments (Schmitt *et al* 1966).

fractions of gamma de-excitations through statistical and cascade decays—a decrease in the observed width can arise due to larger fraction of cascade gamma rays and *vice versa*. Further interpretation of these results in terms of fission mechanism is difficult since the present measurements have been carried out as a function of single fragment kinetic energy. However, it is known from double fragment energy measurements (Schmitt *et al* 1966) that the most probable mass ratio and the most probable total kinetic energy vary as a function of single fragment kinetic energy as shown in figure 2 *b*. A comparison of figures 2 *a* and 2 *b* shows that the observed width correlates well with the total kinetic energy rather than with the mass ratio. As the total kinetic energy increases, the width σ decreases indicating a higher fraction of cascade gamma rays. These results may suggest that fragment pairs with higher total kinetic energy also possess higher spin. In the present context, it is interesting to note that a classical calculation (Hoffman 1964) of fragment spins as a function of total kinetic energy assuming non-axial splitting of the fragments has led to similar results.

It can therefore be conjectured that the scission configuration is non-axial indicating the occurrence of appreciable bending and wriggling modes of oscillation of the fissioning nucleus during scission. However, more detailed investigations as a function of fragment mass and kinetic energy will be required for a quantitative study of the important features of scission.

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