K X Rays from Cf^{252} Fission Fragments in Ternary Fission

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The yield and the energy distribution of the K x rays emitted by Cf^{252} fission fragments have been simultaneously measured for the cases of ternary and binary fission, with a cooled lithium-drifted silicon detector. The K x-ray yields in ternary fission are found to be greater than in binary fission by (25±6) and (14±6)% for fragments in the light and the heavy groups, respectively. It has been shown that a comparison of K x-ray yields and the energy spectra in binary and ternary fission can give information about the origin of the light charged particles emitted in ternary fission. From the analysis of the present results, it is inferred that these charged particles do not originate at the expense of nucleons exclusively from either of the fragment groups, but are liberated from the fissioning nucleus as a whole, implying emission just before or at the instant of scission.

1. INTRODUCTION

FROM earlier investigations[1–3] of the K x rays emitted in the spontaneous fission of Cf^{252}, it is known that these x rays are emitted as a result of internal conversion of certain low-energy transitions during the γ de-excitation of the fragments. The energy of these x rays gives information about the charge of the emitting fragment and, thereby, offers a physical means of studying the charge division in fission. The yield of these x rays contains information about the internal-conversion probability in the emitting fragment and, therefore, about the low-energy transitions of the fragment nucleus. On these considerations, it is expected that the study of K x rays emitted in ternary fission (fission accompanied by light charged particles) can be an effective probe to investigate the emission mechanism of these particles. In the present work, the energy spectra and the yield of the K x rays in ternary and binary fission of Cf^{252} have been simultaneously determined. These results have been analyzed with a view to understanding the origin of these light charged particles (LCP) emitted in fission.

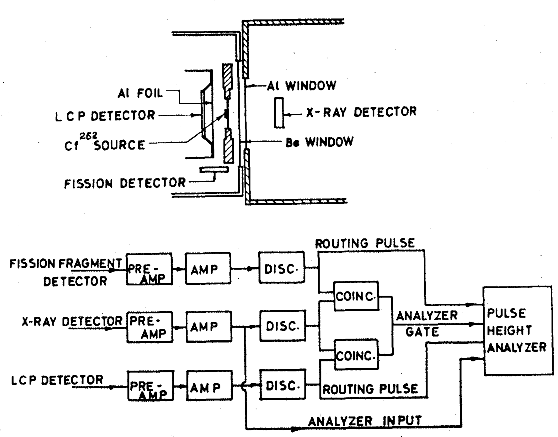

FIG. 1. Schematic diagram of experimental setup and electronic arrangement.

2. EXPERIMENTAL

The schematic diagram of the experimental arrangement used is shown in Fig. 1. A Cf^{252} source of strength 5×10^5 fissions per min deposited onto a thin nickel foil was used in the measurement. A surface-barrier detector with depletion depth of 400 μ was mounted at a distance of about 0.8 cm from the source to detect the LCP. This detector was covered with an aluminum foil of thickness 10 mg/cm^2 to stop completely all the natural α particles and the fission fragments emitted from the source. A semiconductor detector placed at right angles to the LCP detector was used to detect the fission fragments. The energies of the K x rays were measured with a cooled lithium-drifted silicon detector of 3 mm thickness, placed on the other side of the source foil at a distance of 1.6 cm from the source in line with the LCP detector. The pulse heights from the x-ray detector were calibrated into energies by using x-ray sources of Am^{241}, Co^{57}, Cs^{137}, Ba^{133}, and Gd^{153}. The energy resolution of the x-ray detector system, measured in terms of the full width at half-maximum of 59.57-keV line of Am^{241}, was about 2.4 keV.

The pulses from the fragment detector system were fed to a discriminator which was set to cut off natural α and pileup pulses. The pulses from the LCP detector system and the x-ray detector system were fed to two separate discriminators to cut off amplifier noise. The three discriminator outputs were fed to a coincidence unit which generated pulses corresponding to fragment-x-ray coincidences and LCP-x-ray coincidences. Since the pulses from the amplifier systems were slow, a coincidence resolution time of 1 μsec was used to ensure 100% coincidence efficiency. These coincidence pulses gated a pulse-height analyzer which stored the K x-ray spectra in coincidence with the LCP and the fission fragments in two separate quarters of its memory. In all, about 10^5 binary events and 8×10^3 ternary events were recorded. To ensure the stability of the x-ray

[1] L. E. Glendenin and J. P. Unik, Phys. Rev. **140**, 1301 (1965).
[2] S. S. Kapoor, H. R. Bowman, and S. G. Thompson, Phys. Rev. **140**, 1310 (1965).
[3] R. A. Atneosen, T. D. Thomas, W. M. Gibson, and M. L. Perlman, Phys. Rev. **148**, 1206 (1966).

detector system, the energy calibration was checked at regular intervals during the actual experimental runs.

3. RESULTS AND CORRECTIONS

The observed K x-ray spectra were corrected: (i) for the backgroud arising from the chance coincidences, measured by appropriately delaying the pulses from the LCP- and fragment-detector systems; and (ii) for the background arising from the true coincidences with the Compton scattered fission γ rays, measured by inserting a copper filter (570 mg/cm^2) in the path of the x rays. The detection efficiencies for x rays of different energies were calculated from the known photoelectric and total absorption cross sections in silicon, also taking into account a small attenuation of the x rays in one beryllium window of thickness 46 mg/cm^2 and one aluminum window of thickness 10 mg/cm^2. The observed number of the x rays of different energies per fission after correction for background and the detection efficiencies are shown in Fig. 2 for binary and ternary fission. The large statistical errors on the data points in the case of ternary fission is due to very small probability of ternary events as compared to binary.

To determine the absolute K x-ray yields per fission from the measured numbers shown in Fig. 2, it is necessary that the solid angles of x-ray detection be known in the two cases. A direct measurement of the solid angles using standard x-ray sources is not possible in this case since the x rays are known[1–3] to be emitted all along the fragment path. Moreover, a significant difference in the solid angles of detection in the cases of binary and ternary fission could arise since the directions of motion of the fragments were not exactly the same in the two cases, though to minimize this effect the fragment detector was placed at right angles to the LCP detector. The solid angles of x-ray detection for the binary and ternary fission were therefore determined for the geometry used by a simulation of the experiment in a CDC-3600 computer using the Monte Carlo method. In these calculations the x rays were assumed to be emitted exponentially with average

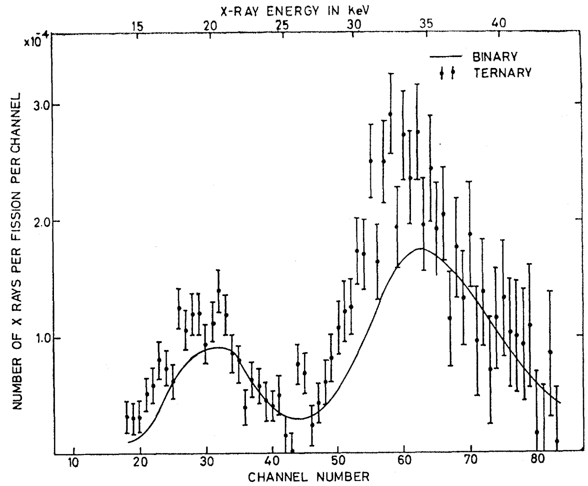

FIG. 2. Measured energy spectra of the K x rays emitted in binary and ternary fission, after correcting for the backgrounds and detection efficiencies.

half-lives of 0.68 and 0.5 nsec from fragments in the heavy and light groups, respectively.[2] These calculations took into account the stopping of the fragments in the beryllium window and shielding by the source holder of a fraction of the x rays emitted at considerable distances away from the source. Since the measured distances could be subject to slight uncertainties, these were adjusted to within 0.1 cm to give the known K x-ray yield of 0.57 per fission[2] in the binary case. In the case of ternary fission, the fission fragments were assumed to be emitted with respect to the direction of the LCP with the known[4] fragment-LCP angular correlation and the same average half-lives as known for the case of binary fission were used. However, it was found that for the present geometry the ratio of the x-ray solid angles in binary and ternary fission were not sensitively dependent on the assumed x-ray half-lives in the two cases. The calculated solid angles and the K x-ray yields per fission for binary and ternary fission are given in Table I. Also given in the table are the first moments $\langle E_L \rangle$ and $\langle E_H \rangle$ of the K x-ray energy

TABLE I. Summary of the results.

	Measured K x-ray yields[a] per 10^4 fissions		Solid angles[b] for K x-ray detection $\times 10^3$		K x-ray yields per fission		Ternary yield / Binary yield	
	Binary	Ternary	Binary	Ternary	Binary	Ternary	Expt	Calcu
Light	25.24±0.04	31.7±1.4	17.38±0.20	17.5±0.3	0.145±0.002	0.18±0.01	1.25±0.06	0.88[c]
Heavy	74.07±0.12	97.0±4.0	17.53±0.22	20.1±0.4	0.423±0.005	0.48±0.02	1.14±0.06	0.92[d]
Total	99.31±0.13	129.0±5.0			0.568±0.006	0.66±0.03	1.17±0.05	
	Binary	Ternary						
$\langle E_L \rangle$ (keV)	20.18±0.02	19.6±0.8						
$\langle E_H \rangle$ (keV)	35.35±0.05	34.5±1.4						

[a] Corrected for absolute detector efficiencies calculated from known cross section for silicon.
[b] Calculated by computer simulation of the experiment using Monte Carlo method.
[c] Assuming exclusive emission of LCP for the heavy group (see text).
[d] Assuming exclusive emission of LCP from the light group (see text).

[4] Z. Fraenkel, Phys. Rev. 156, 1283 (1967).

distributions for the light and the heavy groups, respectively.

4. DISCUSSION

Earlier, Schmitt *et al.*[5] measured simultaneously the mass distributions in ternary and binary fission of U^{235} induced by thermal neutrons. Treating emission of the LCP as a rapid two-step process, their results were consistent with LCP coming with a saw tooth-like probability as a function of fragment mass, but these results could be interpreted with the LCP originating either in the light fragments or in the heavy fragments or in both. However, on energy consideration, Feather[6] has proposed the hypothesis that these particles are emitted exclusively from those heavy fragments which are formed with proton numbers greater than the most probable values. In what follows, we will examine the validity of the following hypotheses concerning the emission of these particles on the basis of the K x-ray results: (i) The LCP are emitted exclusively from fragments in the light or in the heavy group and the emission probability P_α does not depend on the neutron-to-proton ratio; and (ii) the LCP are emitted exclusively from those heavy fragments that are less neutron rich than the normal binary fragments.[6]

On the basis of hypothesis (i), the fragment complementary to the emitting one is not perturbed with regard to its composition, excitation energy, number of neutrons emitted, and level structure of final fragment, and therefore the K x-ray yield from the complementary fragment should be the same in binary and ternary fission. It can then be shown[6] that charge yields Y and the x-rays yields X in the ternary and binary fission are related as

$$P_\alpha(Z \text{ or } \bar{A}) = Y^T(98-Z)/Y^B(98-Z) \qquad (1a)$$

$$= X^T(E)/X^B(E)\,, \qquad (1b)$$

where $\bar{A}$ is the most probable mass for charge Z in binary fission and E is the K x-ray energy corresponding to the nuclear charge (98-Z). Superscripts T and B refer to ternary and binary cases, respectively. The values of $P_\alpha(\bar{A})$ calculated from Eq. (1b) using the measured $X^T(E)$ and $X^B(E)$ (Fig. 2) are shown in Fig. 3 for the cases of the LCP emission exclusively from the light or the heavy group, taking the most probable charge versus mass from Ref. 2. This observed variation of P_α with mass appears remarkably similar to that derived[5] from mass-distribution measurements in binary and ternary fission for the case of thermal neutron-induced fission of U^{235}. But unlike the case of mass-distribution measurements, from the K x-ray measurements, it is also possible to infer whether the LCP are emitted from fragments in the heavy group or in the light group or from both. Suppose that the LCP are emitted from the fragments in the heavy group alone, then the ratio $(X^T/X^B)_L$ of the total K x-ray yields for the two cases from the light group is given by

$$\left(\frac{X^T}{X^B}\right)_L = \frac{\sum_L Y^B(A_L)P_\alpha(252-A_L)P_X{}^T(A_L)}{\sum_L Y^B(A_L)P_X{}^B(A_L)}\,, \qquad (2)$$

where $P_X(A)$ is the x-ray yield per fragment and $P_\alpha(252-A_L)$ is normalized so that

$$\sum_L Y^B(A_L)P_\alpha(252-A_L) = \sum_L Y^B(A_L)\,.$$

Since in this case fragments in the light group are not affected by LCP emission from the heavy group, we have $P_X{}^T(A_L) = P_X{}^B(A_L)$. Hence one can calculate the expected value of $(X^T/X^B)_L$ from known mass yields $Y^B(A)$ and the K x-ray yields[1,2] per fragment $P_X{}^B(A)$. Similarly, one can calculate the expected value of $(X^T/X^B)_H$ for the case when the LCP are emitted from the fragments in the light group alone. These calculated values are given in Table I. It can be seen that the measured values of X^T/X^B are significantly larger than those calculated either on the assumption of exclusive emission from the light group or the heavy group. The present results therefore do not favor hypothesis (i).

However, on the basis of the above arguments alone one cannot rule out the hypothesis (ii), suggested by Feather.[6] For in this case, the assumed selective emission of the particles from relatively less neutron-rich heavy fragments will lead to the detection of light fragments of different composition, and therefore the above analysis does not hold. In this mechanism, for

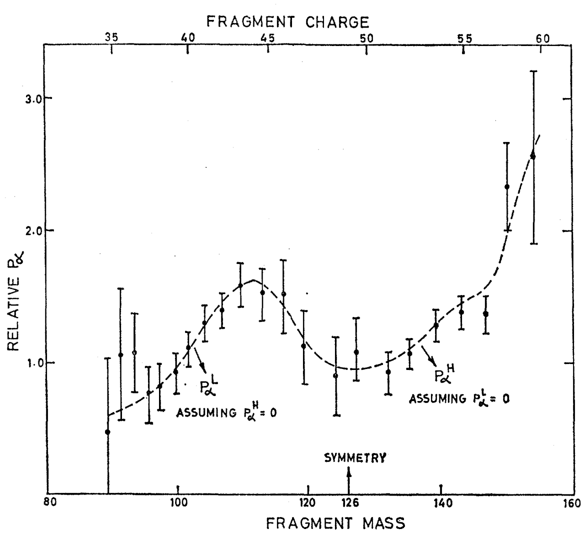

FIG. 3. Emission probabilities of LCP derived from the measured x-ray yields in binary and ternary fission. The dashed line shows the general trend of the variation.

[5] H. W. Schmitt and N. Feather, Phys. Rev. **134**, 565 (1964).
[6] N. Feather, *Physics and Chemistry of Fission* (International Atomic Energy Agency, Vienna, 1965), Vol. II, p. 387.

any specified mass in the light group, the most probable charge in ternary fission should be lower by at least one or two charge units as compared to that in binary fission, which can be tested by measuring the most probable charges for different masses in ternary and binary fission. Even from the present measurements of the x-ray energy distributions in binary and ternary fission some inference can be drawn about the validity of the hypothesis (ii). In the case when the emission probabilities of the LCP are assumed to be independent of the neutron-to-proton ratio of the heavy fragments, the yields $X(E_L)$ of K x rays of energy E_L from the light fragments of charge Z_L in the two cases are given by

$$X^B(E_L)=Y^B(Z_L)P_X{}^B(Z_L)dZ_L/dE_L\,, \tag{3a}$$

$$X^T(E_L)=Y^B(Z_L)P_\alpha(98-Z_L)P_X{}^B(Z_L)dZ_L/dE_L\,. \tag{3b}$$

The average K x-ray energy for the light group as calculated from Eqs. (3a) and (3b), using known binary-charge yields, K x-ray yields per fragment P_X, and the experimentally derived P_α, is found to be 0.5 keV less in ternary fission than in binary fission. Now if LCP were emitted from the relatively less neutron-rich heavy fragments [hypothesis (ii)], the average charge of the complementary light fragments will be further lowered by at least one to two charge units. It can therefore be expected that on the basis of hypothesis (ii), the average K x-ray energy of the light group will also be further decreased by at least 1 to 2 keV, barring the unlikely situation that the decrease may have been compensated by the change in $P_X{}^T$ due to the change in the composition of these fragments. Thus, in this case, the total decrease in the average K x-ray energy of the light group is expected to be at least about 1.5–2.5 keV, while the measured decrease is found to be 0.5 ± 0.8 keV only (Table I). Moreover, from an extrapolation of the known systematics of the low-lying states of even nuclei for fragments in the high-mass yield region, the transition energies are expected to decrease with increasing neutron number for the same value of Z. Since on the above mechanism the fragments of the heavy group in ternary fission have a lesser neutron-to-proton ratio than for the binary case, the K x-ray yield of the heavy group for the ternary case should have been lower than that for the binary case. This is also not found experimentally. Thus hypothesis (ii) is also not supported by the present results.

In general, therefore, the results of the present experiment do not seem to favor emission of these light charged particles exclusively from either of the fragment groups. If, however, these light charged particles were emitted at the expense of nucleons from both fragments, the ternary fragments in both groups will have greater neutron-to-proton ratio, giving rise to an increase in the K x-ray yield in both groups, as has been observed in the present experiment. Thus, it can be concluded that the light charged particles in ternary fission are liberated before or at the instant of scission at the expense of nucleons from the fissioning nucleus as a whole.

ACKNOWLEDGMENTS

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