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Studies of the Times of Emission and Multiplicities of *K* X Rays from Fission Fragments of Specified Atomic Numbers*

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The average emission times of *K* x rays emitted from U^{236} fission fragments and the multiplicities of *K* x rays from Cf^{252} fission fragments of specified atomic numbers have been determined. The average emission times of *K* x rays from U^{236} fragments were determined by detecting the x rays in the two cases of the emitting fragments moving towards and away from the x-ray detector in the time ranges of 110 and 1000 nsec after fission. The most striking delayed *K* x-ray emitter is found to be $_{52}$Te, wherein $(79 \pm 5)\%$ of the *K* x rays are emitted in the time interval 110–1000 nsec. Information about the cascade emission of *K* x rays from Cf^{252} fission fragments of specified atomic numbers was obtained by measuring the energy spectra of coincident *K* x rays with two Si(Li) x-ray detectors operated in coincidence with each other and with fission. From the analysis of these spectra the first and second moments of the x-ray emission distribution function were determined. A noteworthy feature of these results is that there exists a significantly large probability for a cascade emission of *K* x rays in several cases. The cascade emission is found to be, in general, more predominant in the heavy-fragment group as compared to the light-fragment group. In the heavy group, a strong odd-even effect is reflected on the cascade-emission probability. The observed effect on the average *K* x-ray yield per fragment, if only those events are selected in which the complementary fragment charge has emitted a *K* x ray, is also discussed.

I. INTRODUCTION

During the cascade γ deexcitation of the primary-fission fragments, quite often some of the transitions may be internally converted, leading to an electron vacancy in the *K* shell. Once such a vacancy is created, the atomic transitions, giving rise to *K* x rays, take place very quickly ($\sim 10^{-16}$ sec). Thus the times of emission of the *K* x rays following fission are determined by the average lifetimes of the nuclear transitions being converted. The yield of the *K* x rays from each fragment is determined by the average probability of creation of a vacancy in the *K* shell, which depends on the number of transitions involved and the energy and multipolarity of each of these transitions. Several investigations[1-10] on *K* x-ray emission have been carried out in the past for the cases of spontaneous fission of Cf^{252} and thermal-neutron fission of several heavy nuclei. In some of these studies, the yields and the times of emission of *K* x rays were determined as a function of fragment masses. Because of the effects of mass resolution, these results represent only a suitably weighted average over a number of neighboring nuclei. Detailed investigations of the *K* x rays originating from primary-fission fragments of specified atomic numbers have been made possible only recently with the development of high-resolution lithium-drifted silicon detectors, and in these studies[4,8-10] yields of *K* x rays as a function of fragment atomic numbers have been determined. With a high-resolution Si(Li)-detector x-ray spectrometer, we have studied the average emission times of the *K* x rays emitted from U^{236} fragment nuclei of specified atomic numbers, and this forms part of the work reported herein.

The other part of the work is aimed at studying the multiplicity of *K* x-ray emission from fragments of specified atomic number. After neutron emission, the fission fragments of a specified atomic number *Z* can be formed with a distribution of other variables such as the fragment mass number, excitation energy, and angular momentum. Therefore the measured[4,8-10] *K* x-ray yield per fragment refers to a weighted average over these other variables. Although for most of the fragment nuclei the x-ray yield per fragment is found to be appreciably less than 1, it is possible that for certain combinations of the other variables, more than one *K* x ray is emitted in a cascade. We can, therefore, define an x-ray emission distribution function $f_z(n)$, where $f_z(n)$ represents the fraction of events in which n x rays are emitted in a cascade from fragments of atomic number *Z*. The average value of *K* x-ray yield per fragment is then equal to the first moment ($\bar{n}$) of the distribution function. For a proper interpretation of the data on the x-ray yields, it is further necessary to investigate the shape of the distribution function $f_z(n)$. In the present work, both the first moment $(\bar{n})$ and the second moment $(\overline{n^2})$ of the distribution function $f_z(n)$ have been determined. The experiments have also given information regarding the effect on the normal average K x-ray yield per fragment, if one selects only those events in which the complementary fragment charge also emits a K x ray.

II. EXPERIMENT, ANALYSIS, AND RESULTS

A. Studies of *K* X-Ray Emission Times

1. *Outline of the Method*

The experimental arrangement is shown schematically in Fig. 1. The experiment consisted of determining the numbers $N_x^1(Z)$ and $N_x^2(Z)$ of the x rays detected per fission in the cases of the emitting fragments of specified atomic number Z, moving towards and away from the x-ray detector, respectively. From the ratio N_x^1/N_x^2, the average half-life for x-ray emission was determined assuming a single decay constant in the following manner: The solid angles Ω_1 and Ω_2 of the x-ray detection in the two cases were calculated for the present geometry, as a function of the average half-life and fragment velocity, with a Monte Carlo program by a simulation of the experiment on the computer CDC 3600. The average emission times for x-ray emission from fragments of specified atomic numbers were then deduced by a comparison of the experimental values of N_x^1/N_x^2 and the calculated values of Ω_1/Ω_2. In addition, information regarding the presence of any significantly delayed components in the heavy-fragment K x rays was obtained by recording separately the spectra of heavy-fragment K x rays emitted in coincidence with fission within 110 and 1000 nsec, respectively. These experiments for determining the emission times of the K x rays were carried out for the case of U^{236} fission.

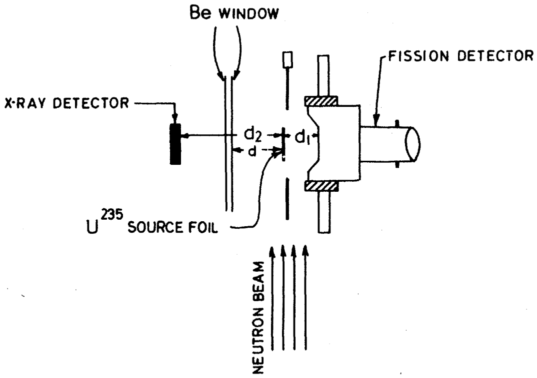

FIG. 1. Schematic diagram of the experimental setup for the measurement of the K x-ray emission times.

2. *Experimental*

A source of U^{235} of thickness 200 μg/cm^2 coated on to VYNS film and a surface-barrier detector were mounted in a chamber having a beryllium window, such that the source foil, the fragment detector, and the beryllium window were parallel to each other and in line (Fig. 1). The fragment detector and the beryllium window were at distances of 1 and 1.5 cm, respectively, from the foil. The x-ray detector was a 1.1-cm^2×0.3-cm Si(Li) detector (with an energy resolution of 0.8 keV for the 26.25-keV line of Am^{241}) which was placed parrallel to the source foil at a distance of 3.0 cm and at right angles to the collimated neutron beam from the CIRUS reactor. To reduce the fast-neutron and γ-ray content of the beam, the beam from the reactor core passed through 15.0 cm of quartz, 25.4 cm of Bismuth, and finally, through a steel collimator which reduced the beam size to 1.2 cm. The vacuum chamber housing the foil-detector assembly had very thin entrance and exit windows of aluminum to minimize beam scattering and thus the background field in the vicinity of the x-ray detector.

The pulses from the x-ray detector system and the fragment detector system were fed to a slow-fast coincidence setup, which gave two independent outputs corresponding to fission x-ray coincidences within 110 and 1000 nsec. The slow-coincidence output gated a multiparameter data-acquisition system, which recorded, event by event, the x-ray and the fission pulse heights. A flag pulse was also registered in the third analog-to-digital converter (ADC), if the coincidence was achieved within 110 nsec. The pulses from a high-precision pulser were fed at the input of the x-ray detector which was initially calibrated into energies using the electromagnetic radiations from a Am^{241} source. A careful channel vs energy calibration was obtained at the start and end of each run. The energy calibration and the system stability were further monitored during each run by simultaneously recording a fixed pulser output.

The singles fission count rate was about 27/sec. The fragment x-ray coincidence rate was about 8 and 11/min in the resolving times of 110 and 1000 nsec, respectively. During the experiment about 2.5×10^5 events of the fragment x-ray coincidence were recorded.

3. *Analysis of Data and Deduction of K X-Ray Emission Times*

The recorded data were sorted out with a CDC-3600 computer. As the peak-to-valley ratio in the fragment pulse-height distribution was about 10 to 1, the identification of the fragments into the light and the heavy group could be carried out without any significant intermixing. Figure 2 shows the observed spectra of the K x rays in the time interval of 0–110 nsec after fission for the cases of the (i) light fragments and (ii) heavy fragments, moving towards the x-ray detector, respectively. Also shown in the same figure is the observed spectrum for the heavy-fragment group for the time interval of 110–1000 nsec. Each of these spectra was analyzed using a least-squares-fitting procedure[10] to determine the yield of the K x rays per fission from fragments of specified atomic number Z. The standard deviation σ of the x-ray energy resolution function was varied to arrive at the best fit (minimum χ^2). In the time range of 0–110 nsec, a fraction of the x rays detected are Doppler-shifted resulting in an increased value of σ. The values of σ for the minimum χ^2 were found to correspond to a full width at half maximum (FWHM) of 1.1 and 1.6 keV, respectively, for the light- and heavy-fragment groups. This shows significant broadening of the resolution function due to mixing of the unshifted and Doppler-shifted spectra. In the time range of 110 to 1000 nsec, for the heavy-fragment x-ray spectra, the minimum χ^2 was obtained for the values of σ corresponding to a FWHM of 0.90 keV. The results obtained from the least-squares analysis of the x-ray spectra are shown in Fig. 3(a). Here the intensities N_x^1 and N_x^2 of the K x rays detected per fission in the time interval of 0–110 nsec for the cases of the emitting fragments moving towards and away from the x-ray detector, respectively, are plotted against Z.

From a comparison of the observed values of N_x^1/N_x^2 for fragments of specified atomic numbers and the computed ratios Ω_1/Ω_2 for the corresponding average fragment velocity, the average K x-ray emission times were deduced and these are shown in Fig. 3(b). In order to provide a check on the accuracy of the geometry used in the computation of the solid angles, the solid angle of the x-

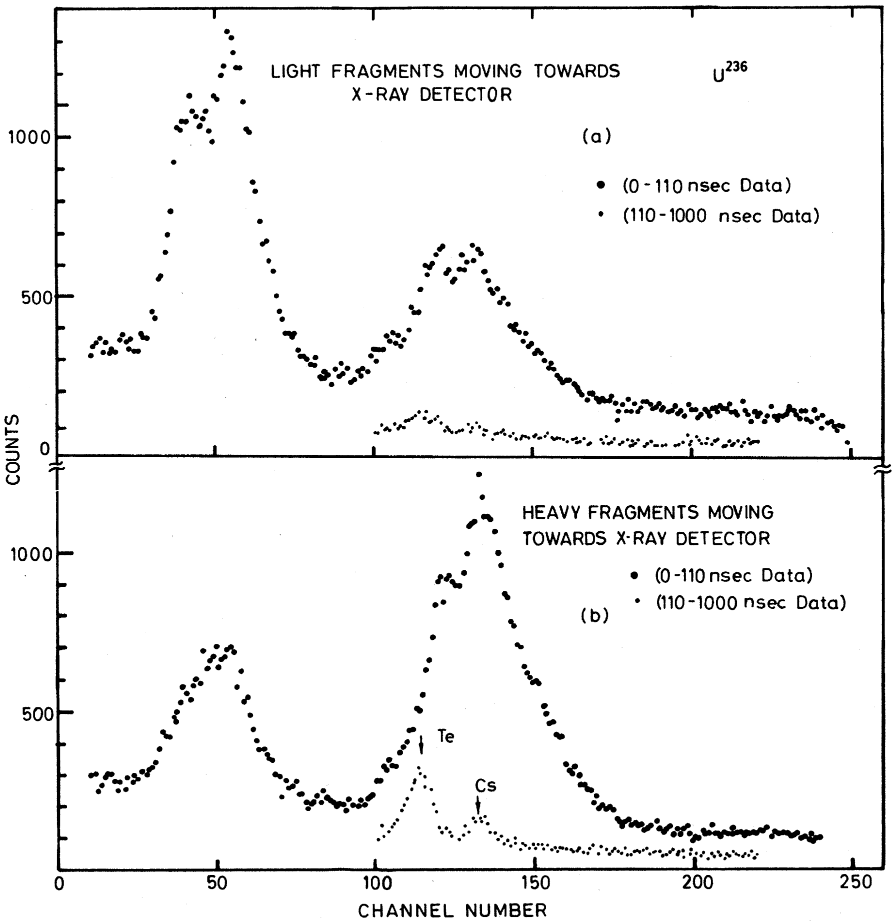

FIG. 2. Pulse-height spectrum of the K x rays detected in the Si(Li) detector in the time intervals of 0–110 and 110–1000 nsec for the two cases of (a) light fragments moving towards, and (b) heavy fragments moving towards the x-ray detector.

ray detection was also determined experimentally by measuring the L x rays of Th^{230} in coincidence with the natural α particles emitted in the decay of the U^{234} isotope which is present in traces in the source foil. The solid angle determined by α-x-ray coincidence data using the measured value[11] of 0.48 for the average L florescence yield was found to agree within 2% with the computed solid angle for zero half-life. From the data of Figs. 3(a) and 3(b), the observed intensities in 110–1000-nsec interval, and from the computed solid angles corresponding to the respective emission times and fragment velocities, the intensities of K x rays emitted per fission were determined for the time interval of 0–1000 nsec. These results are shown in Fig. 4(a) along with the results of an earlier measurement[10] where the K x rays were observed by stopping the fragments in a very short distance in order to avoid the dependence of the solid angle on x-ray half-lives. The observed good agreement between the two independent measurements shows the validity of the present method of determining the x-ray emission times. The fragment-charge yield curve estimated by Wahl *et al.*[12] is also shown in Fig. 4(a). The K x-ray yield per fragment obtained from the present data on K x-ray yield per fission and the above charge-yield curve are shown in Fig. 4(b). After appropriate solid-angle corrections, the fractions of the K x rays emitted in the time region 110–1000 nsec, from fragments of different atomic numbers in the heavy group, were deduced from the observed x-ray intensities in the two time intervals. For the case of emission from $_{52}\text{Te}$ and $_{55}\text{Cs}$ this fraction was found to be $(79\pm5)\%$ and $(6\pm2)\%$, respectively. For all other fragments in the heavy group this fraction was found to be less than 3%.

B. Studies of K X-Ray Multiplicities from Cf^{252} Fission Fragments

1. *Experimental Setup and Method*

A schematic diagram of the experimental arrangement is shown in Fig. 5. The experimental arrangement consisted of two independent high-resolution x-ray detectors which were operated in coincidence with one another and with a fission detector to record the energies of the coincident x rays. The fission fragments from the Cf^{252} source were detected in 2π geometry by a parallel plate ionization chamber having a cathode-anode separation of 0.1 cm and filled with pure argon gas. A Cf^{252} source, of strength 5×10^5 fissions per minute, coated on a thin nickel backing formed the cathode of the ionization chamber. The walls of the fission chamber facing the x-ray detectors were made very thin to reduce the attenuation of x rays. The energies of the x rays were measured by two cooled Si(Li) detectors A and B, each of size $1.0\ \text{cm}^2\times0.3$ cm, placed on either side of the fission chamber at a distance of about 2 cm from the source foil. Each of these detectors, coupled to a cooled field-effect transistor (FET) preamplifier, was housed in a cryostat with a 10-mil beryllium window. The energy resolution of the x-ray spectrometers A and B, in terms of FWHM of 26.25-keV line of Am^{241}, were 0.8 and 1.0 keV, respectively.

The pulse outputs from the fission chamber and the x-ray detectors were suitably amplified and fed to fast discriminators to cut off noise pulses. The output of the discriminators was fed to a pair of double-coincidence units, each of 1-μsec resolving time, one for taking coincidences between fission and x rays detected in system A and the other for coincidences between fission and x rays detected in system B. The output of the discriminators was also fed to a triple-coincidence unit, where the fission pulse and the pulses from systems A and B were required to be in coincidence within 1 μsec to generate an output. The double-coincidence output after being scaled down by a factor of 128 and the triple-coincidence output were fed to an OR gate, the output of which gated a multiparameter data-recording system. The amplifier outputs from the fission chamber and the two x-ray detectors were fed to three ADC's of the recording system. In this way, whenever there was a double- or triple-coincidence event, the respective pulse heights were recorded event by event on the data-acquisition system coupled to a paper punch. During the experiment the number of fission events was also being monitored continuously. Initially the two x-ray detectors were energy calibrated, using an Am^{241} source and during the experiment, this was checked by means of an energy-calibrated precision mercury pulser. The online check of the energy calibration of the x-ray detectors was made by setting the pulser at 50 keV which gave a peak due to chance coincidences with fissions and by the presence of a K x-ray peak originating from the nickel backing of the Cf^{252} source. About 3×10^5 x-ray–x-ray coincidence events were recorded in several runs.

2. *Data Analysis*

The recorded data were sorted out on the computer CDC 3600 to obtain the following spectra for the total number of fission events: (i) independent energy spectra $N_A(E)$ and $N_B(E)$ of K x rays detected in the A and B systems, respectively; (ii) energy spectra $N_A^L(E)$, $N_A^H(E)$, and $N_A^C(E)$ of the K

x rays detected in the system A for the triple-coincidence events of those cases in which the photons detected in system B belonged to the energy regions of (a) light-fragment *K* x rays (10–24 keV), (b) heavy-fragment *K* x rays (25–50 keV), and (c) Compton-scattered γ rays (50–60 keV), respectively. The observed independent energy spectrum $N_A(E)$ and the x-ray–x-ray coincidence spectrum $N_A^H(E)$ in a typical run are shown in Figs. 6 and 7, respectively. From each of the measured *K* x-ray spectra the x-ray yield from fragments of specified atomic numbers was determined using the least-squares-fitting procedure,[10] which took into account the transmission through the beryllium windows, the x-ray detection efficiencies, and the corrections for the background counts which arise mainly from the true coincidences between the fission and the Compton-scattered fission γ rays giving pulses in the *K* x-ray energy region. With the recorded numbers N_B^L, N_B^H, and N_B^C of the double coincidence between fission and x rays detected in the system B in the energy regions of 10–24, 25–50, and 50–60 keV, respectively, and the results of the least-squares analysis of the different *K* x-ray spectra, the numbers $Y_x^L(Z)$, $Y_x^H(Z)$, and $Y_x^C(Z)$ were obtained. These numbers represent *K* x-ray yields detected per fission in the system A, for those selected events in which another photon with its energy in the region of light-fragment x rays, heavy-fragment x rays, and Compton-scattered γ rays, respectively, have also been detected in system B. The numbers $Y_x^L(Z)$ and $Y_x^H(Z)$ thus obtained include events where x rays of system A are in coincidence with the x rays as well as Compton-scattered γ rays detected in system B. The number $Y_x^{Lx}(Z)$ $[Y_x^{Hx}(Z)]$ of the *K* x rays detected per fission in the system A, in those selected events in which a light-fragment (heavy-fragment) *K* x ray is detected in system B, was estimated from the relations

$$Y_x^{Lx}(Z)=[Y_x^L(Z)-f_B^L Y_x^C(Z)]/(1-f_B^L) \qquad (1)$$

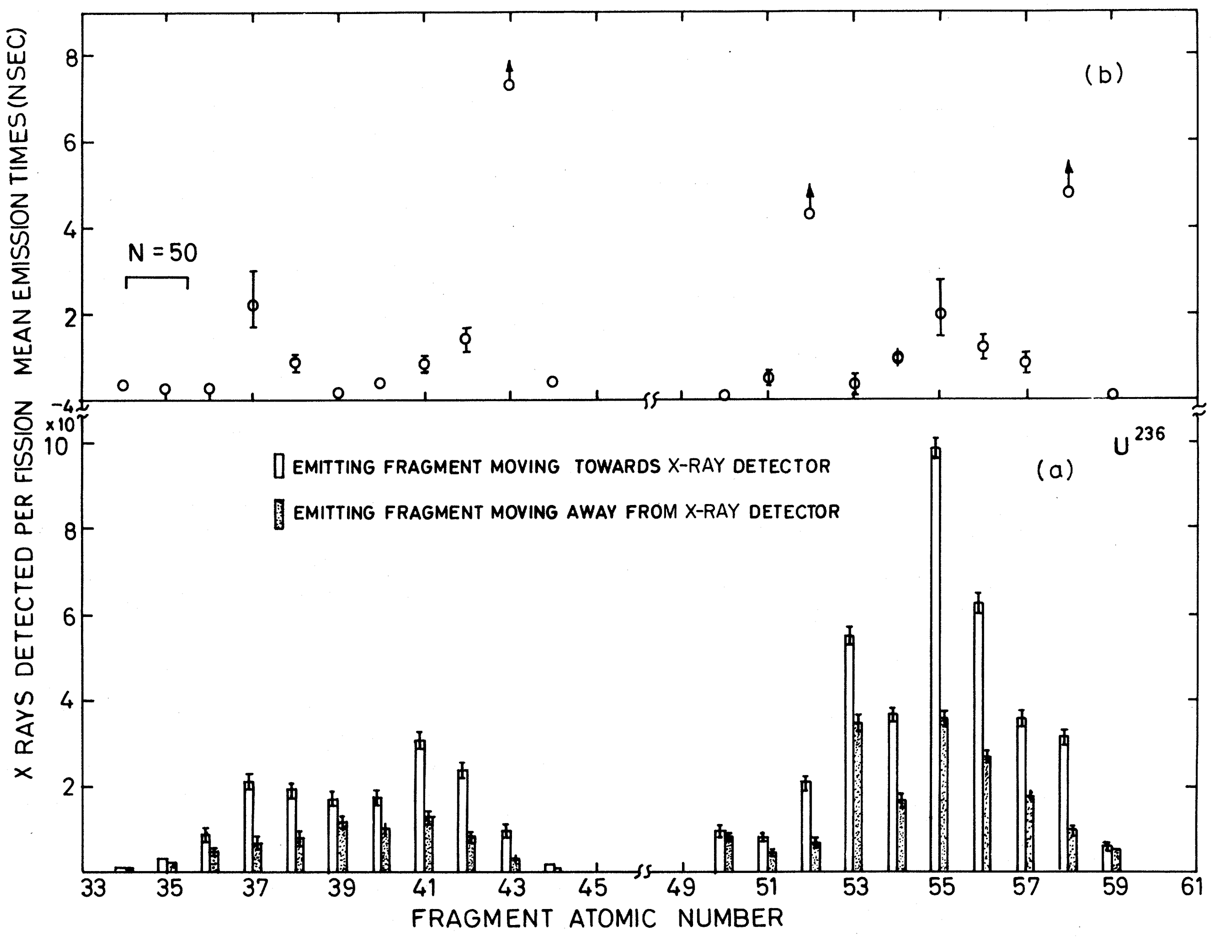

FIG. 3. (a) Measured *K* x-ray yields per fission as a function of the fragment atomic number in the time interval 0–110 nsec for the two cases of the emitting fragment moving towards and away from the x-ray detector. (b) The mean *K* x-ray emission times for fragments of different atomic numbers deduced from the results of (a).

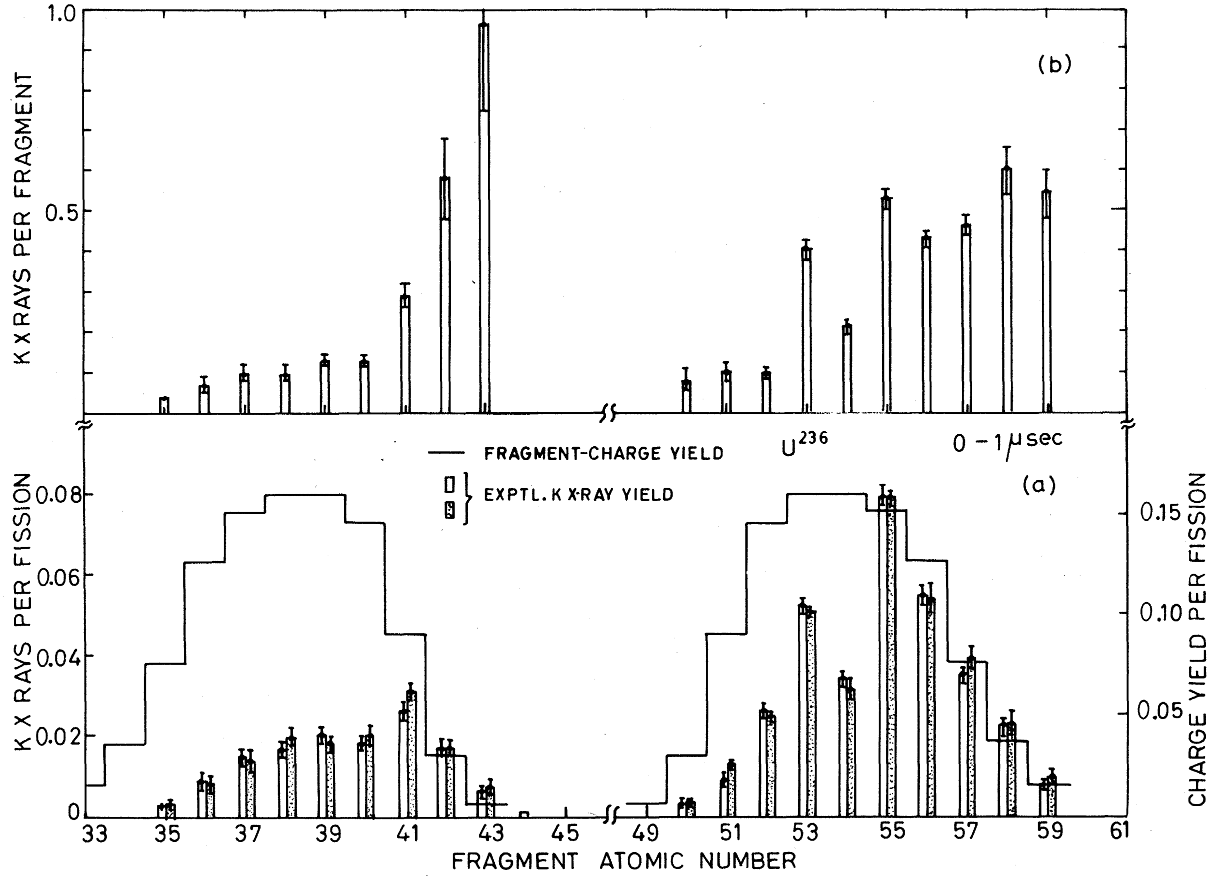

FIG. 4. (a) Average K x-ray yield per fission in the time interval 0–1000 nsec from fragments of different atomic numbers. The dotted bars refer to the results of Ref. 10. The fragment-charge yield curve from Ref. 12 is also shown in the figure. (b) Average K x-ray yield per fragment calculated from the data in (a).

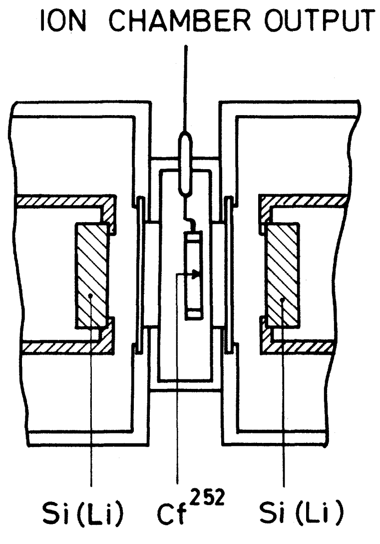

FIG. 5. A schematic diagram of the experimental set-up for the investigation of the K x-ray multiplicities.

and

$$Y_x^{Hx}(Z)=[Y_x^H(Z)-f_B^H Y_x^C(Z)]/(1-f_B^H), \tag{2}$$

where f_B^L and f_B^H denote the fractions of the background counts under the light and heavy x-ray peaks, respectively, in the spectrum $N_B(E)$. The unbiased K x-ray yields per fission $Y_x(Z)$ detected in the system A were also obtained using the total number of fission events.

Let Ω_1 and Ω_2 be the solid angles of x-ray detection for the systems A and B, respectively. The solid angle Ω_1 was determined by normalizing the measured total x-ray yield per fission, in the time interval 0–110 nsec, to a value of 0.57 as obtained in earlier work.[2,4] If $Y(Z)$ is the fragment-charge yield per fission and $f_Z(n)$ is the fraction of the fragments of atomic number Z that emit n number of K x rays in a cascade, it follows that

$$Y_x(Z)=\Omega_1 Y(Z)\overline{n}(Z), \tag{3}$$

where

$$\overline{n}(Z)=\sum_n n f_Z(n)\ . \tag{4}$$

Here $f_Z(n)$ is a weighted average of the corresponding quantity over the various isotopes, i.e.,

$$f_Z(n)=\sum_A f_{Z,A}(n)\,\omega(Z,A),$$

where $\omega(Z,A)$ is the fractional yield of the different isotopes of atomic number Z.

(i) Heavy-heavy or light-light fragment x-ray coincidence data. The triple-coincidence x-ray yields per fission $Y_x^{Hx}(Z_H)$ corresponding to the cases when both the systems A and B detect x rays from the same heavy fragment of atomic number Z_H, is given by

$$Y_x^{Hx}(Z_H)=\frac{Y(Z_H)\Omega_1\Omega_2\eta(Z_H)[\sum_n n(n-1)f_{Z_H}(n)]}{N_B^H}, \tag{5}$$

where $\eta(Z_H)$ is the efficiency of detection, in system B, of the x rays emitted from charge Z_H including x-ray absorption in the nickel backing and beryllium windows. Here N_B^H is equal to the average number of K x rays detected per fission by the heavy-fragment group and is given by

$$N_B^H=\sum_{Z_H} Y(Z_H)\eta(Z_H)\bar{n}(Z_H)\Omega_2 \;. \tag{6}$$

From Eqs. (3), (5), and (6) it follows that

$$R^{Hx}(Z_H)\equiv\frac{Y_x^{Hx}(Z_H)}{Y_x(Z_H)}=\frac{\sum_n n(n-1)f_{Z_H}(n)\eta(Z_H)}{\sum_n nf_{Z_H}(n)\nu_{xH}}, \tag{7}$$

where

$$\nu_{xH}=\sum_{Z_H} Y(Z_H)\eta(Z_H)\bar{n}(Z_H)=\frac{N_B^H}{\Omega_2}.$$

Hence, the average number $\overline{n^*}(Z_H)$ of K x rays per fragment from fragments of atomic number Z_H when one x ray from the same fragment is known to have been emitted, is given by

$$\overline{n^*}(Z_H)\equiv\frac{\sum_n n(n-1)f_{Z_H}(n)}{\sum_n nf_{Z_H}(n)}=\frac{\nu_{xH}R^{Hx}}{\eta(Z_H)} \;. \tag{8}$$

The second moment $\overline{n^2}(Z_H)$ of the distribution function is given by

$$\overline{n^2}(Z_H)=\sum_n n^2 f_{Z_H}(n)=\bar{n}(Z_H)\left[\frac{\nu_{xH}R^{Hx}(Z_H)}{\eta(Z_H)}+1\right]. \tag{9}$$

Similarly, for the light fragments, one gets

$$\overline{n^2}(Z_L)=\sum_n n^2 f_{Z_L}(n)=\bar{n}(Z_L)\left[\frac{\nu_{xL}R^{Lx}(Z_L)}{\eta(Z_L)}+1\right]. \tag{10}$$

From the measured values of R and $\bar{n}$, the values of $\overline{n^*}$ and the second moment $\overline{n^2}$ of the distribution function $f_Z(n)$ can therefore be determined from the Eqs. (8)–(10).

The values $\overline{n^*}(Z)$ deduced in this manner are shown in Fig. 8. For comparison, we have also shown in the same figure, the normal values $\bar{n}(Z)$ of the first moment obtained from Eq. (3) with the

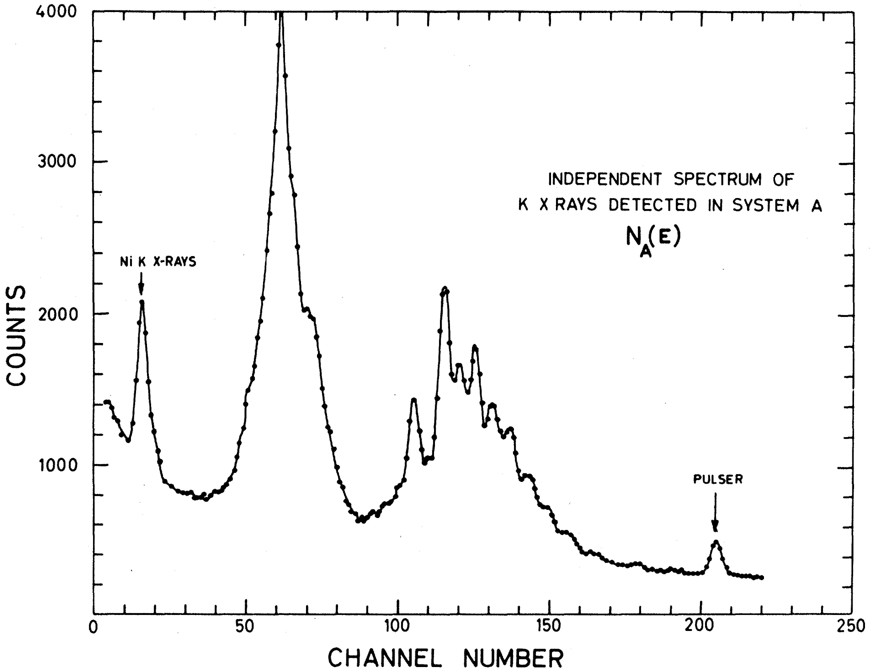

FIG. 6. Pulse-height spectrum of the K x rays detected in detector A.

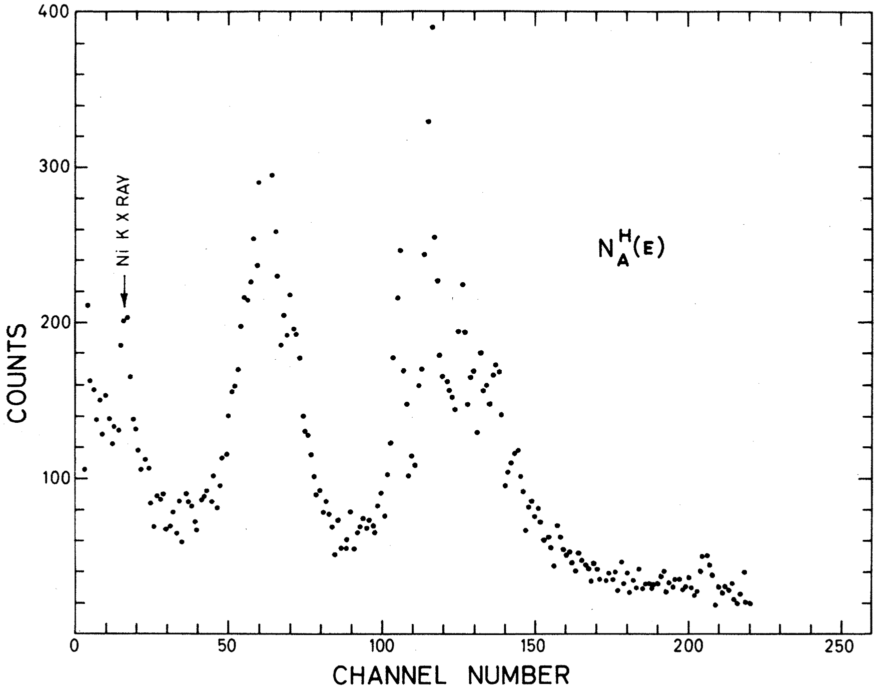

FIG. 7. Pulse-height spectrum of *K* x rays detected in system A for those cases in which a heavy-fragment *K* x ray has been detected in system B for a typical run.

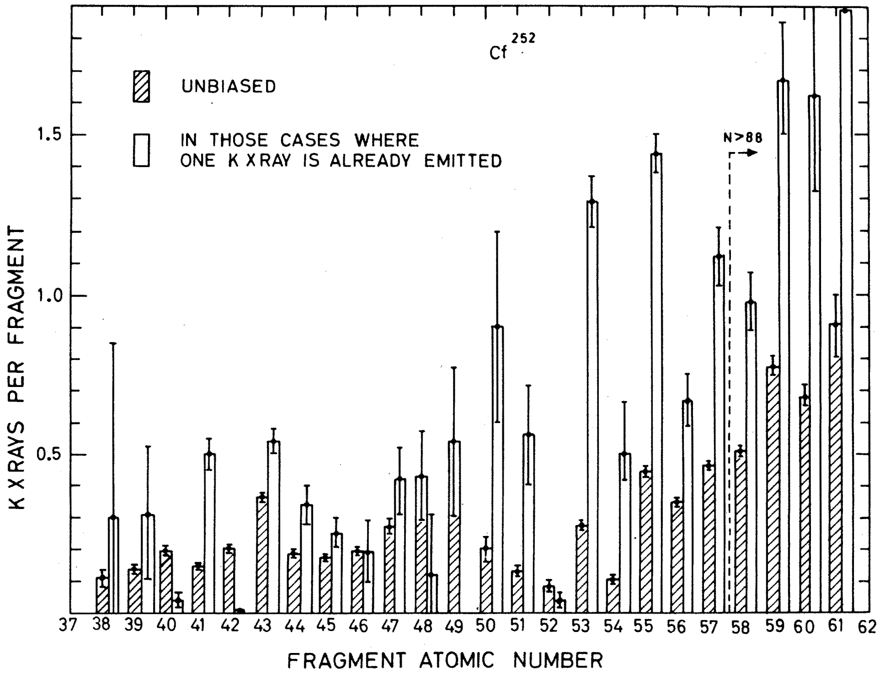

FIG. 8. The unbiased average *K* x-ray yield per fragment is compared with the yield of the additional *K* x rays per fragment when one *K* x ray is known to have been already emitted from fragments of specified atomic numbers.

measured values of $Y_x(Z)$ and the calculated[4] charge yield $Y(Z)$. The results of $\overline{n^*}(Z)$ can also be represented in terms of the second moment $\overline{n^2}(Z)$ of the distribution function $f_Z(n)$, and these are shown in Fig. 9.

(ii) Light-heavy x-ray coincidence data. This analysis of the data was carried out to infer whether the normal value of $\bar{n}(Z)$ is altered if one selects only those fission events in which the complementary fragment charge also emits a K x ray. Suppose the x-ray yield from light fragments Z_L gets altered by a factor $K^H(Z_L)$, if only those events are considered in which the complementary heavy fragments Z_H also emit a K x ray. The average K x-ray yield per fission $Y_x^{Hx}(Z_L)$ from fragments of atomic number Z_L, selecting only those events in which an x ray has also been emitted from any of the fragments in the heavy group, is given by

$$Y^{Hx}(Z_L)=K^H(Z_L)\bar{n}(Z_L)[Y(Z_L)\bar{n}(Z_H)\eta(Z_H)]\Omega_1\Omega_2/N_B^H, \tag{11}$$

where

$$N_B^H=\nu_{xH}\Omega_2 .$$

The normal K x-ray yield per fission $Y_x(Z)$ is given by

$$Y_x(Z_L)=Y(Z_L)\bar{n}(Z_L)\Omega_1 . \tag{12}$$

From Eqs. (11) and (12), one has

$$K^H(Z_L)=\frac{Y_x^{Hx}(Z_L)}{Y_x(Z_L)}\,\frac{\nu_{xH}}{\bar{n}(Z_H)\eta(Z_H)} . \tag{13}$$

Similarly, one can write

$$K^L(Z_H)=\frac{Y_x^{Lx}(Z_H)}{Y_x(Z_H)}\,\frac{\nu_{xL}}{\bar{n}(Z_L)\eta(Z_L)} , \tag{14}$$

where all the notations have their usual meanings.

The values of $K^H(Z_L)$ and $K^L(Z_H)$ can therefore be determined from the measured $Y_x^{Hx}(Z_L)$, $Y_x^{Lx}(Z_H)$, $Y_x(Z_H)$, and $Y_x(Z_L)$ from Eqs. (13) and (14), and these results are shown in Fig. 10.

III. DISCUSSION

A. K X-Ray Emission Times

The observed features about the x-ray emission times are, broadly speaking, as follows: (i) small x-ray emission times of the order of 0.1 nsec in the region of $N=50$ in the light-fragment group (the very small x-ray emission times and the x-ray yields in this region can be attributed to the presence of wide level spacings there, giving rise to faster decay and low internal conversion); (ii) comparatively large values for the average emission times from ${}_{43}$Tc, ${}_{52}$Te, and ${}_{58}$Ce; for the case of ${}_{52}$Te, a significantly large fraction of about 80% of K x-ray intensity is observed in the time interval 110–1000 nsec showing the presence of a predominantly delayed component. This result is consistent with that of a recent study of isomeric transitions from Cf^{252} fragments by John, Guy, and Wesolowski[13] showing the presence of a 162-nsec cascade of transitions from ${}_{52}$Te^{134} and further brings out a specific example where x-ray

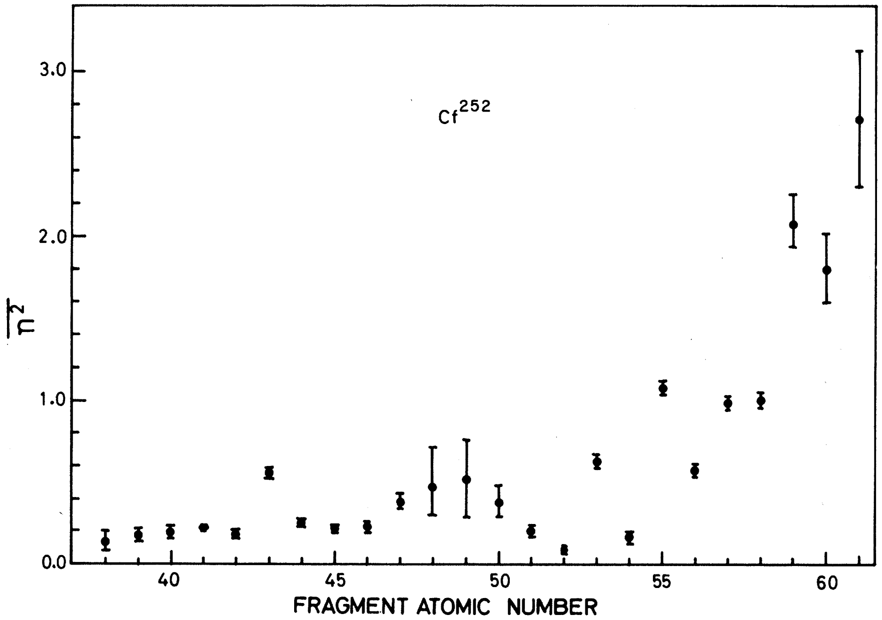

FIG. 9. The second moment $\overline{n^2}$ of the x-ray emission distribution function $f(n)$ for fragments of different atomic numbers.

yield from one element is dominated by a single transition from one isotope. For the case of fragment nuclei ${}_{43}$Tc and ${}_{58}$Ce, no significant x-ray yield in the 110–1000-nsec time interval is observed above the background thereby implying that the long life component is either of very small intensity or the average emission time is less than about 100 nsec. For the case of ${}_{55}$Cs, a noticeable x-ray yield above the background is observed in the time region of 110–1000 nsec and on this basis the 197.3-keV transition with a 2.8-μsec half-life observed by John, Guy, and Wesolowski[13] can be assigned to ${}_{55}$Cs^{137}, as sufficiently delayed transitions from any other mass in the range 136–148 were not observed. (iii) For the remaining fragment nuclei, the average emission times are found to be in the region of 1 nsec, showing the absence of any intense isomeric transition of long half-life in these nuclei.

B. *K* X-Ray Yields and Multiplicities

The broad features of the x-ray yields from fission fragments are very much similar in both U^{236} and Cf^{252} fission, as seen from Figs. 4(b) and (8). These features are the observed increase in the x-ray yields as one moves away from the closed-shell regions of $N=50$, $Z=50$, and $N=82$, a relatively large x-ray yield from odd-Z nuclei in the heavy-fragment group in the region $Z=51$ to 57 (a feature more predominant for Cf^{252} fission), and an increasing x-ray yield for the region of $N\gtrsim 88$. These observations on the relative probability of internal-conversion process in different fragment nuclei have been earlier qualitatively correlated with the expected properties of the low-lying transitions in these neutron-rich nuclei.

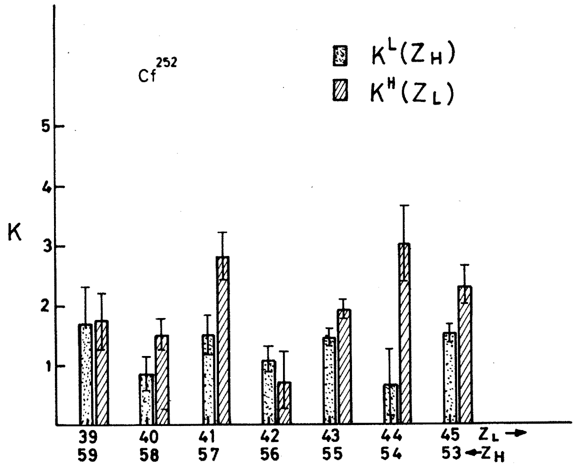

FIG. 10. Plot of the x-ray correlation factors $K^L(Z_H)$ and $K^H(Z_L)$ for various fragment pairs of complementary atomic numbers.

The present measurements of the K x-ray yield per fragment from fragments of specified atomic number, when it is known to have already emitted one K x ray, show certain striking features. It can be seen from Fig. 8 that for almost all fragment atomic numbers, the second x-ray emission probability is significantly large which shows that x-ray emission is, in general, a cascade process. Another noteworthy feature is that the additional yield of K x rays per fragment in those cases when it is known to have already emitted one K x ray is, in general, higher than the average unbiased K x-ray yield per fragment from the same fragment. In view of the fact that the average K x-ray yield per fragment, $\bar{n}(Z)$, is less than unity and there exists a significantly large probability for multiple (or cascade) x-ray emission in some cases, one can conclude that a very significant fraction of fission events does not emit any x rays. Furthermore, the multiple x-ray emission probability is considerably larger for the heavy fragments than for the light fragments, and also shows odd-even effect in the heavy-fragment region similar to that observed for $\bar{n}(Z)$. It is seen that for fragments of atomic number $Z=53$, 55, 57, 59, 60, and 61, the second x-ray emission yield is greater than unity indicating a fairly large probability of emission of more than two K x rays per fragment in some of the events in these cases. These results on multiple x-ray emission have been represented in terms of the second moment $\overline{n^2}$ of x-ray emission distribution function $f_z(n)$ in Fig. 9. The values of $\overline{n^2}$ are found to be nearly constant for all light fragments except for $Z=43$ which has a larger $\overline{n^2}$ value showing a larger probability of multiple x-ray emission in this case as compared to neighboring fragment charges. In the heavy-fragment region the width $\overline{n^2}$ of the x-ray emission distribution function, shows a strong dependence on the odd-even nature of the fragment atomic number and also there is a large increase in $\overline{n^2}$ for fragment nuclei in the deformed region ($N\gtrsim 88$) showing an increased cascade x-ray emission in these cases.

The enhancement (or decrease) in the observed average K x-ray yield $\bar{n}(Z)$ due to the selection of only those events in which the fragments of complementary atomic number $(98-Z)$ have also emitted an x ray, is shown in Fig. 10 in terms of the factors $K^H(Z_L)$ and $K^L(Z_H)$ defined by Eqs. (13) and (14). Although for the fragment pairs 40-58 and 42-56 the values of K lie close to unity within the experimental errors, for other cases the values of K are , in general, greater than unity. It is possible that the observed deviations from unity in the values of K arise from an intrinsic correlation in the x-ray yields of complementary fragment pairs due to some common condition existing at scission, such as the fragment spins which are expected to be correlated. However, it is also possible to conceive of some secondary effects resulting in the observed correlation. For example, a selection of events in which heavy fragments of specified atomic number Z_H must emit a K x ray can lead to a preferential selection of neutron-rich isotopes as, in an average way, K x-ray yields are expected to increase going away from the 82-neutron shell. Since the neutron-rich isotopes can be preferentially populated in the high total kinetic-energy events due to the emission of a lesser number of neutrons in these cases, by detecting K x rays one may be preferentially selecting events with higher total kinetic energies. This can consequently also lead to a preferential population of neutron-rich isotopes in the complementary light fragments Z_L and therefore to a higher K x-ray yield due to the effect of the 50-neutron shell in this case. Further investigations will be required to isolate the extent of these secondary effects and to infer quantitatively any intrinsic correlation that may exist in the K x-ray emission from fragment pairs.

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