THE EMISSION OF K-X-RAYS IN SLOW NEUTRON FISSION
OF $^{233}$U, $^{235}$U, AND $^{239}$Pu*

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Present techniques admit the possibility of studying the character of fission fragments with spectroscopic identification of pairs of fragments. The simultaneous measurement of the masses and atomic numbers of fission fragments has been demonstrated in studies of the fission of $^{252}$Cf (1). The atomic number is determined by detection of a characteristic x-ray, most often a K-x-ray, emitted by one of the fragments. These x-rays arise from atomic electron vacancies produced by internal conversion in the deexcitation of the fragments (2). Not surprisingly, there is considerable structure in yield as a function of the masses of the fragments (1) and of their atomic numbers (3).

The work reported in this letter sought to determine the feasibility of studies of slow neutron induced fission by multi-parameter measurements which include K-x-ray identification of atomic number. Such measurements require an appreciable yield of K-x-rays from the fragments, but, more importantly, this method of identification must not introduce an unknown bias in the selection. It is clear that the structure in yields implies that a considerable bias is introduced by requiring the emission of a

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K-x-ray, but the degree to which this bias depends on features of the fission process, other than the Z and A distributions of the fragments, is not known. Eismont and Yurgenson (4) have discussed the rationale for a universal dependence of x-ray emission probability on the Z and A of the secondary (post-neutron-emission) fragments. They measured the K-x-ray yields in the fission of \(^{235}\text{U}\) and found results which are incompatible with an extrapolation, based on a universal dependence, from published values for K-x-ray yields in \(^{252}\text{Cf}\) fission. However, the poor agreement among reported K-x-ray yields in neutron-induced fission (see Table I) prevents a clear conclusion regarding such a universal dependence.

**Experimental Methods**

We have employed an experimental arrangement similar to that previously used for \(^{252}\text{Cf}\) (2,3) in order to facilitate direct comparisons between the results for the different fissioning systems. Targets of fissionable material were placed in a collimated beam of neutrons (8x10^6 n cm\(^{-2}\) sec\(^{-1}\), Cd ratio for Au of 28). Each target consisted of about 0.5 mg of material spread over an area of 1 cm\(^2\) on a backing of Al foil (7 mg cm\(^{-2}\)). Fission fragments were detected in a surface-barrier semiconductor detector, which was placed 1 cm from the target. X-rays were detected in a thin NaI(Tl) detector placed on the opposite side of the target and at a distance of 7 cm from the target (solid angle of x-ray detector about 1.3% of 4\(\pi\)). Fragments were selected by a single channel analyzer with a lower level set above pulses corresponding to twice the energy of the \(\alpha\) particles emitted by the target. (This criterion prevented contamination of the fission K-x-ray spectrum with L-x-rays which are emitted following \(\alpha\) decay of the target.) Coincidences between the two detectors were selected by
a time overlap circuit with a total resolving time of 0.4 microseconds. Valid events were recorded in a coincidence-gated multichannel analyzer, which processed the signals from the NaI(Tl) detector.

Net K-x-ray distributions were obtained both by graphically estimating the height of the continuum produced by neutrons and γ rays, and by subtracting the spectrum obtained through a graded Cu-Al absorber. (The absorber removes some of the γ rays which contribute to the continuum, and the correction is slightly insufficient.) Although these corrections amount to less than 40% of the net x-ray contributions from either the light or the heavy group of fission fragments, they are rather uncertain and are the major source of error in the final yields.

The x-ray detection efficiencies were determined with a set of x-ray standards consisting of radioactive samples which decay by electron capture. Efficiency corrections were made in two ways. First, the efficiency versus x-ray energy was assumed to imply a corresponding scale of efficiency versus channel number. This efficiency scale was applied directly to the net counts per channel, and these corrected counts were summed to give light and heavy group yields. This method introduces errors due to the curvature of efficiency versus energy over an energy range related to the resolution of the detector. Such errors are small because the extremes in efficiency differ by less than 30%. Second, trial yields, as a function of Z, were multiplied by the efficiency versus Z, and these results were compared with the net x-ray spectrum. Final yields were obtained by summing suitable trial functions. The two methods gave essentially the same results.

Results

Our results are summarized in Table I, which includes other
TABLE I

Yields of K-X-Rays from Light and Heavy Fragments

<table>
<thead>
<tr>
<th>Target Group</th>
<th>Measured</th>
<th>Predicted</th>
<th>Other values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{233}$U light</td>
<td>$11^{+2}_{-2}$</td>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$13^{+2}_{-2}$</td>
<td>14</td>
<td>$10^{+3}<em>{-2}$ (5a), 8 (5b), $17^{+2}</em>{-2}$ (5c), $12^{+3}<em>{-2}$ (5d), $18^{+4}</em>{-2}$ (4), $8^{+1}_{-1}$ (5e).</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>$18^{+3}_{-3}$</td>
<td>18</td>
<td>$15^{+2}_{-2}$ (5c).</td>
</tr>
<tr>
<td>$^{233}$U heavy</td>
<td>$19^{+3}_{-3}$</td>
<td>19</td>
<td>--</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$21^{+3}_{-3}$</td>
<td>20</td>
<td>$42^{+12}<em>{-2}$ (5a), 12 (5b), $43^{+4}</em>{-2}$ (5c), $20^{+5}<em>{-2}$ (5d), $34^{+7}</em>{-2}$ (4), $30^{+3}_{-2}$ (5e).</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>$21^{+3}_{-3}$</td>
<td>19</td>
<td>$26^{+3}_{-3}$ (5c).</td>
</tr>
</tbody>
</table>

Values reported for K-x-ray yields. Although the same time intervals were not used in the several studies, the differences are negligible in terms of the errors in the measurements and the known time dependence of K-x-ray emission in the fission of $^{252}$Cf (2). Measurements for time intervals of about 1 nanosecond give significantly lower yields and have been omitted from the summary. The predicted yields given in the table were obtained by assuming a mass dependence of emission probabilities and applying this dependence to the experimental mass distributions (6) for the three fissioning systems. This mass dependence was based on the results of Kapoor, Bowman, and Thompson (1) and an extrapolation to masses below $A=95$ with a dependence proportional to that given by Reisdorf (7) for a 1 nanosecond interval following fission of $^{235}$U.

The good agreement between our results and the predicted yields supports the hypothesis that K-x-ray emission is largely independent of details of the fission process. This support is strongest in terms of the relative yields and their relation to...
shifts in the mass yield distributions. A better measure of the
trends in x-ray emission could be obtained by the use of a high-
resolution detector, such as that used by Watson, Bowman, and
Thompson (3). Preparations are being made for such a measurement.

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References

1. L. E. GLENDENIN and J. P. UNIK, Phys. Rev. 140, B1301 (1965);
   140, B1310 (1965).
   1169 (1967).
4. V. P. EISMONT and V. A. YURGENSON, Sov. J. Nucl. Phys. 5,
   852 (1967).
5. a) V. V. SKLYAREVSKII, E. F. STEPANOV, and B. A. MEDVEDOV,
   Soviet Phys. JETP 9, 225 (1959); b) H. HOHMANN, Zeit. fur
   Phys. 172, 143 (1963); c) L. BRIDWELL, M. E. WYMAN, and
   B. W. WEHRING, Phys. Rev. 145, 963 (1966); d) B. W. WEHRING and
   M. E. WYMAN, Phys. Rev. 157, 1083 (1967); e) S. S. KAPOOR,