Prompt X-Rays from Fast-Neutron-Induced Fission of $^{238}\text{U}$

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Fission X-Rays a Very Brief History

• 1960-70’s - Reisdorf, Griffin, Wilhelmy - measurements for spontaneous fission and thermal neutron induced fission only
  – 1965 Glendinin and Griffin calculated K x-ray yields

• Internal Conversion – not fission acceleration ionization!

• Produced by levels with strong internal conversion means odd mass and odd-Z-odd-N nuclei favored

• Provide Z identification

• Complements gamma-ray studies that are most sensitive to even-even nuclei via 2+ – 0+ observations

• LANSCE – with CEA-Bruyeres, first measurements on $^{238}\text{U}(n,f)$ with fast neutrons
Overview of the LANSCE/WNR Facility Showing the Beam Structure and Neutron Flux

WNR Spallation Neutron Source

- Intense high-energy “white” neutron source
- $0.1 < E_n < 400$ MeV
- Time-of-flight for efficient excitation function acquisition

Typical WNR Proton Beam Parameters

- Energy = 800 MeV
- Average Current < 5 μA
- Protons/Micropulse < $7 \times 10^8$

WNR Typical Proton Beam Parameters

- 8.3 ms
- 725 μs
- 1.8 μs
- ~300 ps

Typical WNR 60R Flux at 20m in 10% neutron energy bins
GEANIE – Germanium Array for Neutron-Induced Excitations at LANSCE

- Located at the WNR spallation neutron source – driven by the 800 MeV LANSCE proton linac
- Neutron energy is determined by time-of-flight on a 20 meter flight path
- Typical neutron energy range is
  - $1 < E_n < 200$ MeV
- Both 25% coaxial HPGe detectors and low-energy planar HPGe detectors are used.
- Typical gamma-ray energy range $15$ keV $< E_{\gamma} < 4$ MeV
- Built on the former HERA array from Lawrence Berkeley National Laboratory
Multiple Solar Cell Fission Fragment Detectors Were Used with $^{238}$U Deposited by Mass Separator (CEA)

- 11 low energy photon spectrometers for x-ray detection
- 15 coaxial Ge detectors for $\gamma$ ray detection
- 8 $^{238}$U deposits on thin solar cells in the WNR neutron beam as an active target
- Fission-photon coincidences required to eliminate high backgrounds at $E_{\gamma}<50$ keV
X-Ray Spectra for Lighter-Mass Fission Fragments

Due to Ag backing on solar cells

X-Ray Spectra for Higher-Mass Fission Fragments

Due to Ag backing on solar cells

Fission Fragment K X-Ray Decay Properties

- For our data, measured on 100 ns time scale, mainly E2, M1 transitions contribute significantly to the observed K-shell x-ray yields.

- Internal conversion rate is small for E1 transitions.

- Decay time is much longer for higher multipoles and conversion is much less for higher gamma energies.

- Odd-even staggering is observed, especially for heavier fragments.
$^{238}\text{U}(n,f)$ Mass Yield Distributions vs $E_n$ (for Iodine)
Provide a View into Different Masses with changing $E_n$

Wahl Fission Fragment Systematics Compared with GEANIE Gamma-Ray Yield Data for $^{238}$U(n,f) vs $E_n$

https://www-nds.iaea.org/publications/tecdocs/sti-pub-1286/
Measured K X-Ray Yields vs Atomic Number for Five Incident Neutron Energy Bins from 3 to 180 MeV
Calculations of X-Ray Yields from Energy Levels, Fission Yield Systematics, and other data

• Calculated K Yield = Sum over all known (NUDAT) IC levels \((\alpha/(1+\alpha))\) weighted by systematic (Wahl) mass yields \(*\) branching \(*\) lifetime factor \(*\) fluorescent yield

• Consider the case of a single low-lying state with large internal conversion coefficient
  – Typically have large feeding from higher levels
  – For ease of calculations assume 100% population
  – But, may be less due to isomers, feeding patterns
  – Multiple x-ray emission is possible

• Estimated uncertainties in calculations include only IC coefficient and mass yield uncertainties
E_n=3 MeV Measured and Calculated K X-Ray Yields

- Data greater than calculation – missing IC levels
- Data less than calculation – 100% feeding not true
$E_n = 8$ MeV Measured and Calculated K X-Ray Yields

238$^\text{U}$ 8 MeV

- Wahl -Nudat 238U 8 MeV
- GEANIE 8 MeV

$K$ x-ray/Fission

$Z$
$E_n=14$ MeV Measured and Calculated K X-Ray Yields

![Graph showing $^{238}$U 14 MeV x-ray/fission yields for Wahl-Nudat and GEANIE calculations.](image)
E_n=32 MeV Measured and Calculated K X-Ray Yields

![Graph showing measured and calculated K X-ray yields for 238U at 32 MeV, comparing Wahl-Nudat and GEANIE data.]
$E_n=180\ \text{MeV}$ Measured and Calculated K X-Ray Yields

![Graph showing K x-ray/fission yield for $^{238}\text{U}$ at 180 MeV](image)
Reisdorf $^{252}\text{Cf}$ Spontaneous Fission K Yields
K X-ray yields for thermal fission of $^{233,235}\text{U}$, $^{239}\text{Pu}$, & spontaneous fission of $^{252}\text{Cf}$

Fig. Top: Mean K X-ray emission probabilities per fragment of charge Z ($K(Z)$) obtained by Reisdorf et al. [4] for $^{252}\text{Cf}$ spontaneous fission (circles), $^{235}\text{U(n,f)}$ (squares), $^{233}\text{U(n,f)}$ (triangles) and $^{239}\text{Pu(n,f)}$ (diamonds). Bottom: Ratio of $K(Z)$ in $^{252}\text{Cf}$ spontaneous fission (circles), $^{233}\text{U(n,f)}$ (triangles) and $^{239}\text{Pu(n,f)}$ (diamonds) to $K(Z)$ for $^{235}\text{U}$ (data from ref. [4]).

Charge yields inferred from K X-ray yields
Inferred charge yields for 180 MeV

Fig. Charge distributions determined from the X-ray yield measurements (symbols). Top: threshold–6 MeV, $\langle E_n \rangle \simeq 3$ MeV. Bottom: 6–11 MeV, $\langle E_n \rangle \simeq 8$ MeV. Solid error bars correspond to propagated fit errors, dotted error bars correspond to the sum in quadrature of the fit error and the 50% relative uncertainty associated with $K(Z)$. Dashed curve is the result of the GEF code by Schmidt-Jurado [43] (see text). Solid curve within hatched area corresponds to Wahl systematics and associated uncertainty obtained for the corresponding energy ranges.

Future

- High-energy neutron-induced fission of actinides provides a window for spectroscopy of a range of neutron-rich nuclei
- X-ray – gamma-ray coincidences can provide new information on energy levels of specific neutron rich nuclei
- Fission X-ray-gamma-ray coincidence experiments have been proposed using increased actinide mass in a fission counter to enable x-ray-gamma-ray coincidence studies with sufficient statistics
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