Total kinetic energy release in fission

W. Loveland
Oregon State University
Goals of Project

• Understanding the physics of the TKE release in fission and its variation with excitation energy of the fissioning system
• Relative role of Coulomb and dissipative forces in this large scale nuclear collective motion
• Practical applications
Vital statistics/deliverables

• **Date project started:** 07/01/2016

• **Individuals supported:**
  - J.S. Barrett, J. King, R. Yanez, L. Yao, V. Desai, K. McCaleb, A. Pica

• **Graduates (Lab employment):**
  - J.S. Barrett, (Ph.D., 2016, Senior Scientist, Fresenius Medical Care North America)
  - J. King (Ph. D., 2018, Program Manager, NNSA)
  - L. Yao (Ph. D., 2018, now at Oregon State University, [looking for a job](#))
  - K.McCaleb (M.S. 2017, Engineer, APTIM)
Deliverables/Papers


• 2. “Characterizing the mechanism(s) of heavy element synthesis reactions”, W. Loveland, EPJA Web of Conferences 131, 04003 (2016).


• 12. “Survival mediated capture and fusion cross sections for heavy element synthesis”

• 13. “Capture cross sections for the synthesis of new heavy nuclei using radioactive beams”,

• 14. “Measurement of the normalized $^{238}$U(n,f)/$^{235}$U(n,f) cross section ratio from threshold to 30 MeV with the fission Time Projection Chamber”,

• 15. “Sub-barrier fusion of $^{11}$Li with $^{208}$Pb”,
Deliverables/Papers (cont.)

Papers submitted for publication


- “The synthesis of new neutron-rich nuclei, W. Loveland, Frontiers in Physics, (submitted for publication)

- “PCN calculations for Z=111 to Z=118”, W. Loveland and L. Yao, CNR*18 Proceedings (submitted for publication)
Invited Talks

1. Survival Mediated Heavy Element Capture and Fission Processes, W. Loveland, FUSION17, Hobart Tasmania, February 2017
2. Total kinetic energy release and fission product mass distributions in the fast neutron induced fission of $^{232}$Th, $^{233}$U, $^{235}$U and $^{239}$Pu, W. Loveland, 253rd ACS National Meeting, San Francisco, CA, April, 2017.
3. Heavy elements, W. Loveland, The future of the 88 Inch cyclotron, LBNL, October, 2017
Honors and Awards

• Larry Yao—Outstanding poster in radiochemistry- SSAA 2018 meeting
• W. Loveland—Fellow of the AAAS-2016
• W. Loveland -Fellow of the ACS-2018
Experimental

- Expt. done at LANSCE using WNR “white” neutron spectrum

Neutron energies determined by time of flight with an uncertainty of 4.7%
Flight path geometry (15R)
Fission fragments detected by 4 pairs of 1 cm² Si PIN diode detectors positioned 2.1 cm from the target
Corrections applied to raw data

• Pulse Height Defect of Detectors (Schmitt calibration with $^{252}\text{Cf}$)
• Fragment energy loss in target and backing (Northcliffe-Schilling)
Benchmarking the data

• The same apparatus, detectors, targets etc were used at the OSU TRIGA reactor to measure the TKE release in the thermal neutron induced fission of $^{235}\text{U}$.

• The measured post neutron emission TKE was measured to be $169.8 \pm 0.4$ MeV in agreement with the known value of $169.1 \pm 0.5$ MeV.

• A similar comparison was done for $^{233}\text{U}(n_{th},f)$ and $^{239}\text{Pu}(n_{th},f)$.

• No normalizations of the data were made.
  • OUR MEASUREMENTS ARE ABSOLUTE MEASUREMENTS!!
Our results (TKE distributions)

$^{232}\text{Th}(n,f)$  $^{233}\text{U}(n,f)$
Our results (cont.)

\[ ^{235}\text{U}(n,f) \]

\[ ^{239}\text{Pu}(n,f) \]
Comparison to Other Data

![Graph showing comparison of TKE (MeV) to $E_n$ (MeV) for $235\text{U}(n,f)$, with various data points and fits from different sources including This expt., Fit, Duke, Madland, and Lestone and Strother.](image-url)
Comparison to Other Data

$^{239}\text{Pu(n,f)}$

- ▼ This work
- ○ Meierbachtol et al.
- Poly fit

TKE (MeV) vs. $E_n$ (MeV)
Where has all the energy gone?

- As $E_n$ increases by $\sim 85$ MeV, the TKE decreases by $\sim 7$ MeV.
- Answer: Into the excitation of the heavy fragment

\[ 237\text{Np}(n,f) \]
Unfortunately “theory” seems to disagree.
Variance of TKE distributions

$\sigma^2_{\text{TKE}}$ (MeV$^2$)

(a) $\sigma^2_{\text{TKE}}$ (MeV$^2$) vs $E_n$(MeV)

(b) $\sigma_{\text{f(b)}}$ vs $E_n$(MeV)

$^{235}\text{U}(n,f)$

$^{232}\text{Th}(n,f)$
232\text{Th}(n,f) - Mass Yields

- \( E_n = 3.2 \text{ MeV} \)
- \( E_n = 6.1 \text{ MeV} \)
- \( E_n = 10.0 \text{ MeV} \)
- \( E_n = 18.3 \text{ MeV} \)
- \( E_n = 28.1 \text{ MeV} \)
- \( E_n = 38.0 \text{ MeV} \)
- \( E_n = 49.1 \text{ MeV} \)
- \( E_n = 60.9 \text{ MeV} \)
- \( E_n = 74.8 \text{ MeV} \)
- \( E_n = 90.8 \text{ MeV} \)
$^{235}\text{U}(n,f)$
$^{233}\text{U}(n,f)$

$^{239}\text{Pu}(n,f)$
Comparison with predictive fission models

- **GEF** The GEF code calculates pre-neutron and post-neutron fission-fragment nuclide yields, angular-momentum distributions, isomeric yields, prompt-neutron yields and prompt-neutron spectra, prompt-gamma spectra and several other quantities for a wide range of fissioning nuclei from polonium to seaborgium in spontaneous fission and neutron-induced fission. K.-H. Schmidt and B. Jurado, NDS 131, 107 (2016)
- **GEF** will also allow one to convert the dependence of various quantities on $E_n$ to dependence on $E^*$ because it knows about multiple chance fission.
- **GEF** will also allow comparisons between (n,f) and (p,f) reactions
- **GEF** predictions shift with time !!
$^{235}\text{U}(n,f)$
$^{235}\text{U}(n,f)$

TKE$_{\text{post}}$ (MeV) vs. $E_n$ (MeV)

- **Expt**
- **GEF-2019**
$^\text{235}\text{U}(n,f)$

(b)

\begin{itemize}
  \item Expt.
  \item GEF (2017)
\end{itemize}

$\sigma_{\text{post}}^2 (\text{MeV}^2)$ vs. $E_n (\text{MeV})$
$^{235}\text{U}(n,f)$

$\sigma_{\text{post}}^2 (\text{MeV}^2)$

$E_n (\text{MeV})$

- Expt
- GEF-2019
A conversation on widths/variances

FIG. 18. Root-mean-square widths of the over-all total fragment kinetic energy distributions for $^{233}$U($p,f$), $^{235}$U($p,f$), and $^{238}$U($p,f$), as functions of compound-nucleus excitation energy.

Ferguson et al, PRC 7, 2510
Lessons Learned

• The TKE release in the fast neutron induced fission of $^{235}$U decreases $8.3 \pm 0.6$ MeV when $E_n$ varies from 0 to 90 MeV. (~4.9%). Most of the available energy of the incoming neutron does not go into collective motion in fission. The mean distance between the fragments at scission is nearly constant. A similar situation occurs for $^{232}$Th(n,f), $^{233}$U(n,f) and $^{239}$Pu(n,f).

• This modest decrease is not due solely to the increasing yield of symmetric fission events which have a lower TKE. The “missing” energy goes into the excitation of the heavy fragment.

• The variances of the TKE distributions reflect the onset of multiple chance fission and are constant for $E_n = 20$-90 MeV.

• “Theory” descriptions of the data are “woefully bad”, i.e., they don’t work at the 5% level.