Improved Prompt and Delayed Decay Spectra for Advanced Fuels

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Goal & Approach

• **Characterize Radiation from Fission for Different Reactor Fuels**
  – Prompt gammas & neutrons
  – Delayed gammas & neutrons
  – Betas & Antineutrinos
  – Charged particles

• **Applications**:
  – Stockpile Stewardship
  – Criticality Safety
  – Decay heat
  – Safeguards
  – Non-proliferation
  – Waste Management
  – Materials Damage
  – Fundamental Science

The project is a joint experimental-theoretical attack on the problem
Sources of Radiation & Time scales

Burning fuel

Fission

Prompt $\gamma$-rays and neutrons

$10^{-19}$ sec to micro-second

Delayed $\gamma$, n, $\beta$, $\nu$

milliseconds- to years
Theory and Simulations
Radiation Involves \( n, \alpha, \beta, \nu, \gamma \)
Depends on the fuel composition, irradiation history, and neutron flux

- Run reactor burn simulations using CINDER
- Track 3400 nuclides & isomers
- Calculate time- and energy-dependent decay spectra using ENDFB-VI and ENDFB-VII decay libraries
- Compare with macroscopic –microscopic model of Moller and Nix
- Examine implications for nuclear astrophysics, reactor monitoring, etc.

Simulation for WIPP
Weapons grade Pu
As Burn Proceeds Different Combination of Isotopes Fission

PWR, lightly enriched uranium

MOX Pu: UO₂ + 5.3% PuO₂
Aggregate Fission Beta and Antineutrino Spectra

Important for reactor monitoring, reactor heat, and neutrino oscillations

\[ S_k(E) = \sum_{FF} Y_{FF}(Z,Z,m)S(E,Z,A,m); \quad S(E,A,Z,m) = \sum_i B^i S(E,Z,A,m,E_0^i) \]

Sum over hundreds of fission fragments and thousands of end-point energies

*Equilibrium aggregate beta spectra for thermal fission on U and Pu*

Cumulative fission yields from England & Rider (LA-UR-94-3106 ENDF-349)

Individual spectra from ENDFB-VI, both continuous and discrete data
Implications for Reactor Antineutrino Monitoring

- Number of antineutrinos/fission *decrease* with burn of LEU
- Number of antineutrinos/fission *increase* with burn for MOX Pu

Antineutrino monitoring could verify burning of MOX Pu with independent knowledge of thermal power
Comparison with Moller-Nix

- Average end-point energy predicted by Moller-Nix ~ 300 keV smaller than ENDF
- Moller-Nix predicts decay to excited states considerably more often than ENDF
- Consequently, more high-energy $\beta$-delayed gamma-rays emitted
- Implications for neutron star crust heating calculations from EC gammas
Prompt Spectra
Prompt Gammas measured for $^{239}\text{Pu}, ^{241}\text{Pu}, ^{233}\text{U}, ^{235}\text{U}, ^{242}\text{Am}$

- Highly enriched samples used to prepare targets
- DANCE + high neutron flux
  => measurements possible on ~ 50 $\mu$g samples
- Gamma-ray multiplicity and energy measured
- Unfolding analysis used to extract the true multiplicity from the data
- Fission fragment detector used to identify prompt fission gamma-rays
- Delayed gammas also measurable
Example: $^{242}\text{mAm}$

- LLNL recovered available $^{242}\text{mAm}$ and prepared 44$\mu$g enriched target (electroplated onto a 0.5 mil beryllium substrate)
- $^{242}\text{mAm}$ installed at DANCE with fission fragment detector
- Collected data for 14 days

*Measured $^{242}\text{mAm}(n,f)$ cross section*
Prompt Gamma-ray Energy and Multiplicity from Fission of $^{242m}$Am, $En=6$ eV – 0.5 MeV

Currently analyzing data to unfold the true multiplicity from the exp data
Students and Postdoc Training

- **LANL**: Y.H. Lee (PD), Jainwei Hu (GS→PD), N. Jarrett (UGS), G. Wilburn (UGS), I. Wisher (UGS→GS)
- **LLNL**: A. Chyzh (PD), E. Kwan (PD), J. Gositic (PD)

Budget:
- **LANL**: Original $1098K, Remaining: $290K
- **LLNL**: $592K, $80K
Status of Deliverables

1. Data analysis for prompt $\gamma$-ray energy and multiplicity data for $^{233,235}$U and $^{242}$Am
   Completed

2. Fabricate $^{241}$Pu target  Completed

3. Beta and antineutrino spectra for all Pu and U isotopes up to 15 MeV  Completed

4. Finalize measured prompt spectra for $^{233,235}$U, $^{239}$Pu, $^{242}$Am  Completed

5. Beta and antineutrino spectra for all neutron-induced fissioning systems On-going

6. Detailed report on prompt and delayed decay data for $^{233,235}$U, $^{239}$Pu, $^{242}$Am and $^{241}$Pu (preliminary) On-going
Future Directions

Nuclear Physics
• Detailed measurements of delayed gamma spectra
• Accurate determination of antineutrino spectra for neutrino oscillations
• Implications for microscopic nuclear structure models (e.g., Moller-Nix)

Applied Physics Spin-offs:
• Antineutrino reactor monitoring (NA-22), with LLNL, SNL, MIT, and Chalk River
• Monitoring Plutonium Reprocessing Activities using Fission gases (NA-22), with Chalk River
• Improved prompt gamma diagnostics for Stockpile Stewardship (NNSA, C1), current LLNL and LANL team