Prompt $\gamma$-ray spectroscopy of fission fragments

N. Fotiades

LANSCE-NS & P-27,
LANL

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INTRODUCTION

Long history of nuclear structure studies by identifying prompt $\gamma$-rays from fission fragments using modern $\gamma$-ray detector arrays; especially for neutron-rich and nuclei near stability (cannot study as evaporation residues in heavy-ion fusion reactions as is customary for neutron-deficient nuclei).

**Neutron-rich nuclei**: fragments from spontaneous fission sources or light-ion or neutron-induced fission of actinide targets.

**Nuclei near stability**: fragments in fission of compound nuclei in heavy-ion-induced fusion reactions;

*Limitation*: to uniquely identify nucleus need additional data if no previous knowledge available (complementary fission fragment technique).
Isotopes we studied as fission fragments in heavy-ion-induced fusion reactions

Total of 42 isotopes studied in ~16 years.
Heavy-ion-induced experiments with Gammasphere

**Experiment I**

**Beam** \( ^{24}\text{Mg} \ (135\text{MeV}) \) + \( ^{173}\text{Yb} \)  
\( \Rightarrow \) \( ^{197}\text{Pb}^* \) (Compound Nucleus)  
\( + \ ^{197}\text{Au} \Rightarrow ^{221}\text{Pa}^* \) (CN) \( \Rightarrow \) Fragments + \( xn \) 

**Experiment II**

**Beam** \( ^{23}\text{Na} \ (129\text{MeV}) \) + \( ^{176}\text{Yb} \)  
\( \Rightarrow \) \( ^{199}\text{Tl}^* \) (CN)  
\( + \ ^{197}\text{Au} \Rightarrow ^{220}\text{Th}^* \) (CN) \( \Rightarrow \) Fragments + \( xn \) 

**Experiment III**

**Beam** \( ^{18}\text{O} \ (91\text{MeV}) \) + \( ^{208}\text{Pb} \)  
\( \Rightarrow \) \( ^{226}\text{Th}^* \) (CN) \( \Rightarrow \) Fragments + \( xn \)
Fission Fragment publications

States in $^{124}$Te above the $10^{(+)}$ yrast level.

Previously established in $(\alpha, 2n)$ reactions.

We established new states (6) above the $10^{(+)}$ yrast level in $^{124}$Te.

Yrast cascade extended from 3.1MeV to 5.5MeV excitation.
Examples of double gates in $^{124}$Te.
Systematics of main cascades in even-A Te isotopes.

In $^{114-122}$Te the yrast 16$^+$ states were interpreted as favored non-collective oblate states involving a fully aligned $\nu [(h_{11/2})^2]_{10^+}$ configuration.
Rigid-rotor plots for yrast states in even-A $^{118-126}$Te isotopes.

A rotating liquid-drop energy reference is subtracted. Rigid-body moment of inertia normalized to $^{158}$Er.

Cranking TRS calculations in $^{114-120}$Te predict an oblate minimum at 16$^+$ from the fully aligned $\pi [(g_{7/2})^2]_6 + \nu [(h_{11/2})^2]_{10}^+$ configuration. Change of pattern in $^{124}$Te suggests that this interpretation is no longer valid in this isotope. 16$^+$ state in $^{124}$Te is part of weakly deformed collective structure.
Systematics in even-A Sn isotopes

Transitions above the Sn 10\(^+\) isomers

**Gammasphere** experiments populated Sn isotopes as fission fragments. Candidates for the 12\(^+\) -> 10\(^+\) transitions in \(^{118,120,122,124}\)Sn were observed and sequences in coincidence with these candidates were established.

A **GEANIE** experiment, where Sn isotopes were populated in \(^{124}\)Sn(n,xn\(\gamma\)) reactions, the assignment of the 12\(^+\) -> 10\(^+\) transitions to \(^{118,120,122}\)Sn was confirmed.
\( \gamma \)-ray excitation functions from \(^{124}\text{Sn}(n,xn)\) GEANIE experiment
γ-ray excitation functions from $^{124}\text{Sn}(n,xn)$ GEANIE experiment
Systematics of the $12^+$ states and shell-model comparison

Excitation energies of the candidate $12^+$ states in good agreement with shell model predictions from A. Insolia et al., Nucl. Phys. A 550, 34 (1992): $^{116}\text{Sn}\sim 4.8\text{MeV}$, $^{118}\text{Sn}\sim 4.3\text{MeV}$, $^{120}\text{Sn}\sim 4.05\text{MeV}$, $^{122}\text{Sn}\sim 3.88\text{MeV}$, $^{124}\text{Sn}\sim 3.75\text{MeV}$
Systematics of the $12^+$ states

CONCLUSIONS

Prompt $\gamma$-ray spectroscopy of fission fragments especially useful for studying neutron-rich and nuclei near stability.

For **neutron-rich nuclei** fragment-study with **spontaneous fission** sources or **light-ion or neutron-induced fission of actinide targets** is usually more appropriate,

For **nuclei near stability** fission of compound nuclei in **heavy-ion-induced fusion reactions** is usually used to bridge the gap between neutron-rich and neutron-deficient nuclei.
Collaborators in the experiments

M. Devlin, R. O. Nelson
LANSCE

J. A. Becker, L. A. Bernstein, D. P. McNabb, W. Younes
Lawrence Livermore National Laboratory

R. Krucken
TRIUMF

R. M. Clark, P. Fallon, I. Y. Lee, A. O. Macchiavelli
Lawrence Berkeley National Laboratory
Comment / Suggestion to organizers

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Comment / Suggestion to organizers

Fission Experiments and Theoretical Advances

Suggestion for next workshop? 2017?
Comment / Suggestion to organizers

**Fission Experiments and Theoretical Advances**

Suggestion for next workshop? 2017?

**Fission Experiments and Theoretical Advances**
Wish

Hope to see everybody in the next

FIESTA (in New Mexico?)
or
FETA (in Greece?)
Spectra from the Gammasphere experiment

\[ ^{18}_{\text{O}}(91\text{MeV}) + ^{208}_{\text{Pb}} \rightarrow ^{226}_{\text{Th}}^* \rightarrow ^{122}_{\text{Sn}} + ^{96,97,98,100}_{\text{Zr}} + 8,7,6,4n \]

\[ \rightarrow ^{124}_{\text{Sn}} + ^{95,96,97,98}_{\text{Zr}} + 7,6,5,4n \]

Similar intensity patterns for the same complementary fragments!
$\gamma$-ray excitation functions from $^{124}\text{Sn}(n,xn)$ GEANIE experiment

![Graph showing excitation functions for different reactions:](image)

- $E_n$ (MeV) vs. Excitation function (arb. units)
- Reactions: $(n,6n)$, $(n,7n)$, $(n,8n)$
- Energy levels: $1237.8$, $310.9$, $2.5$, $585.5$, $493.1$, $627.9$, $555.9$, $645.5$
- ISOLDE, CERN
(n,xnγ) reactions with GEANIE at LANSCE

GEANIE (26 Ge detectors) used to determine excitation functions and cross sections for prompt γ rays in neutron induced reactions.

- Measure γ-ray pulse height ($E_\gamma$), neutron time of flight ($E_n$),
- Obtain γ-ray excitation functions, cross sections.
$^{124}\text{Sn}$ $12^+ \rightarrow 10^+$ transition not observed in the GEANIE experiment, as expected.

Sn isotopes were populated in $^{124}\text{Sn}(n,xn\gamma)$ reactions. $^{124}\text{Sn}(n,n')$ $^{124}\text{Sn}$ doesn’t bring enough angular momentum to populate the $12^+$ state.