Prompt γ-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 γ-rays from fission fragments using modern γ-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).

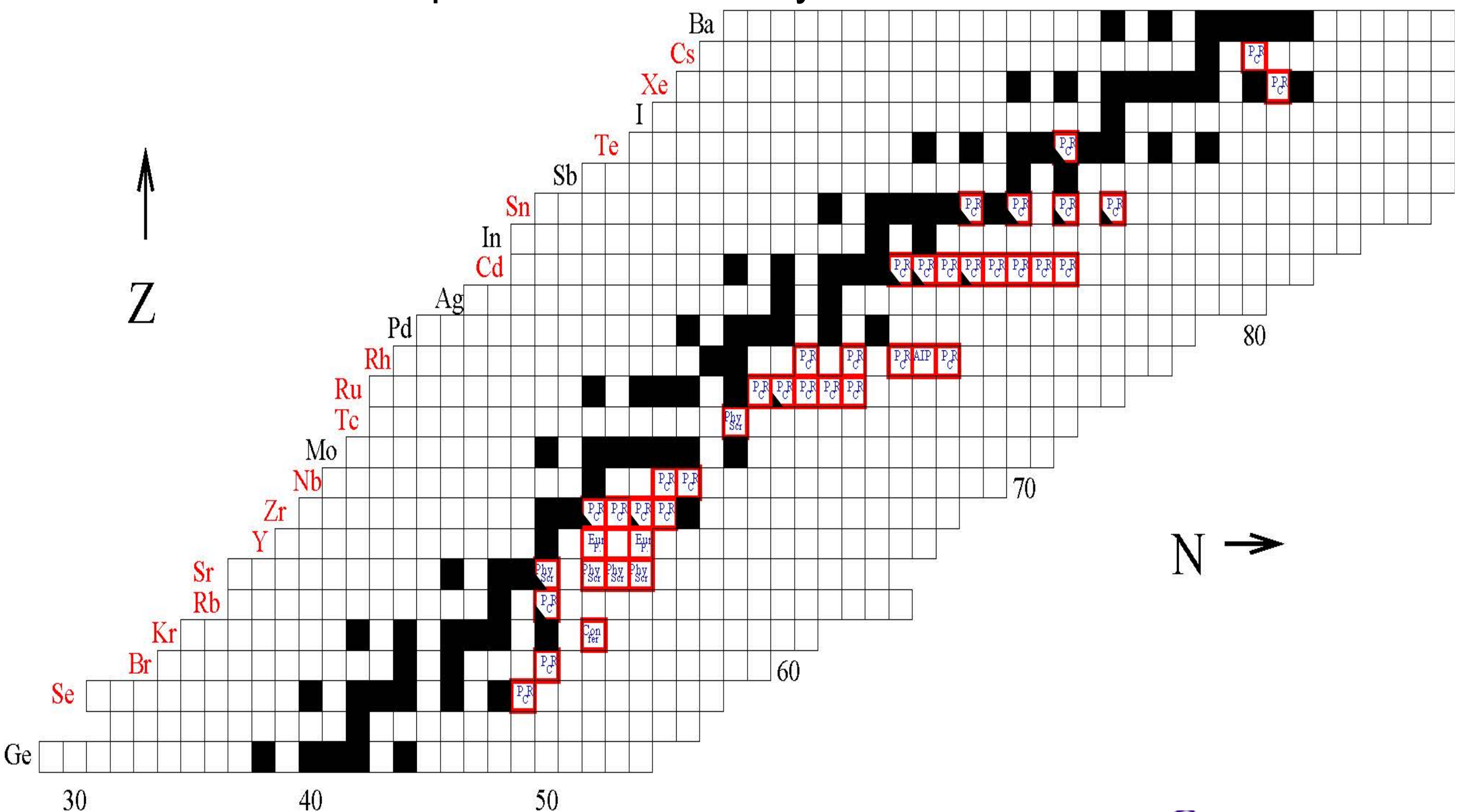
Neutron-rich nuclei: **fragments** from **spontaneous fission** sources or **light-ion or neutron-induced fission of actinide targets.**

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 **Target**

^{24}Mg (135MeV) + ^{173}Yb => ^{197}Pb* (Compound Nucleus)

+ ^{197}Au => ^{221}Pa* (CN) => Fragments + xn

Experiment II

^{23}Na (129MeV) + ^{176}Yb => ^{199}Tl* (CN)

+ ^{197}Au => ^{220}Th* (CN) => Fragments + xn

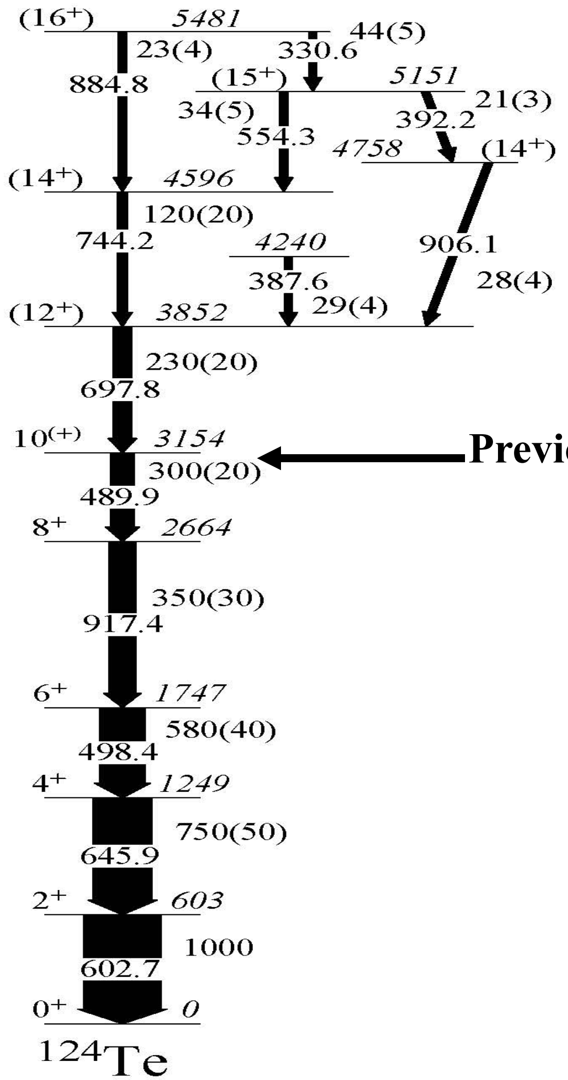
Experiment III

^{18}O (91MeV) + ^{208}Pb => ^{226}Th* (CN) => Fragments + xn

Fission Fragment publications

1) High-spin states in ^{124}Te. N Fotiades, *et al*., Phys. Rev. C 89 (2014) 017303
2) Medium-spin states in ^{135}Cs. N Fotiades, *et al*., Phys. Rev. C 88 (2013) 064315
3) States built on the $9/2^+$ isomers in ^{91,93}Y. N Fotiades, *et al*., Eur. Phys. J. A 48 (2012) 117
4) States built on the 10^+ isomers in ^{118,120,122,124}Sn. N Fotiades, *et al*., Phys. Rev. C 84 (2011) 054310
5) High-spin states in ^{96,97}Nb. N Fotiades, *et al*., Phys. Rev. C 82 (2010) 044306
6) High-spin states in ^{135}Xe. N Fotiades, *et al*., Phys. Rev. C 75 (2007) 054322
7) First observation of high-spin states in ^{83}Se N Fotiades, *et al*., Phys. Rev. C 74 (2006) 034308
8) High-spin states in N=50 ^{85}Br and ^{87}Rb nuclei. N Fotiades, *et al*., Phys. Rev. C 71 (2005) 064312
9) High-spin states in odd-odd ^{106,108,110,112}Rh. N Fotiades, *et al*., Phys. Rev. C 67 (2003) 064304
10) Enhanced production of neutron-deficient fission fragments in heavy-ion-induced fusion reactions. N Fotiades, *et al*., Phys. Rev. C 67 (2003) 034602
11) High-spin excitations in ^{92,93,94,95}Zr. N Fotiades, *et al*., Phys. Rev. C 65 (2002) 044303
12) Observation of $\nu\ h_{11/2}$ sequences in odd-A~110 nuclei. N Fotiades, *et al*., Phys. Rev. C 61 (2000) 064326
13) Intensity distributions of fragments from fission of the ^{197}Pb compound nucleus. N Fotiades, *et al*., Physica Scripta Vol. T88 (2000) 127
14) High-spin excitations in Ru nuclei near N= 60. N Fotiades, *et al*., Phys. Rev. C 58 (1998) 1997

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

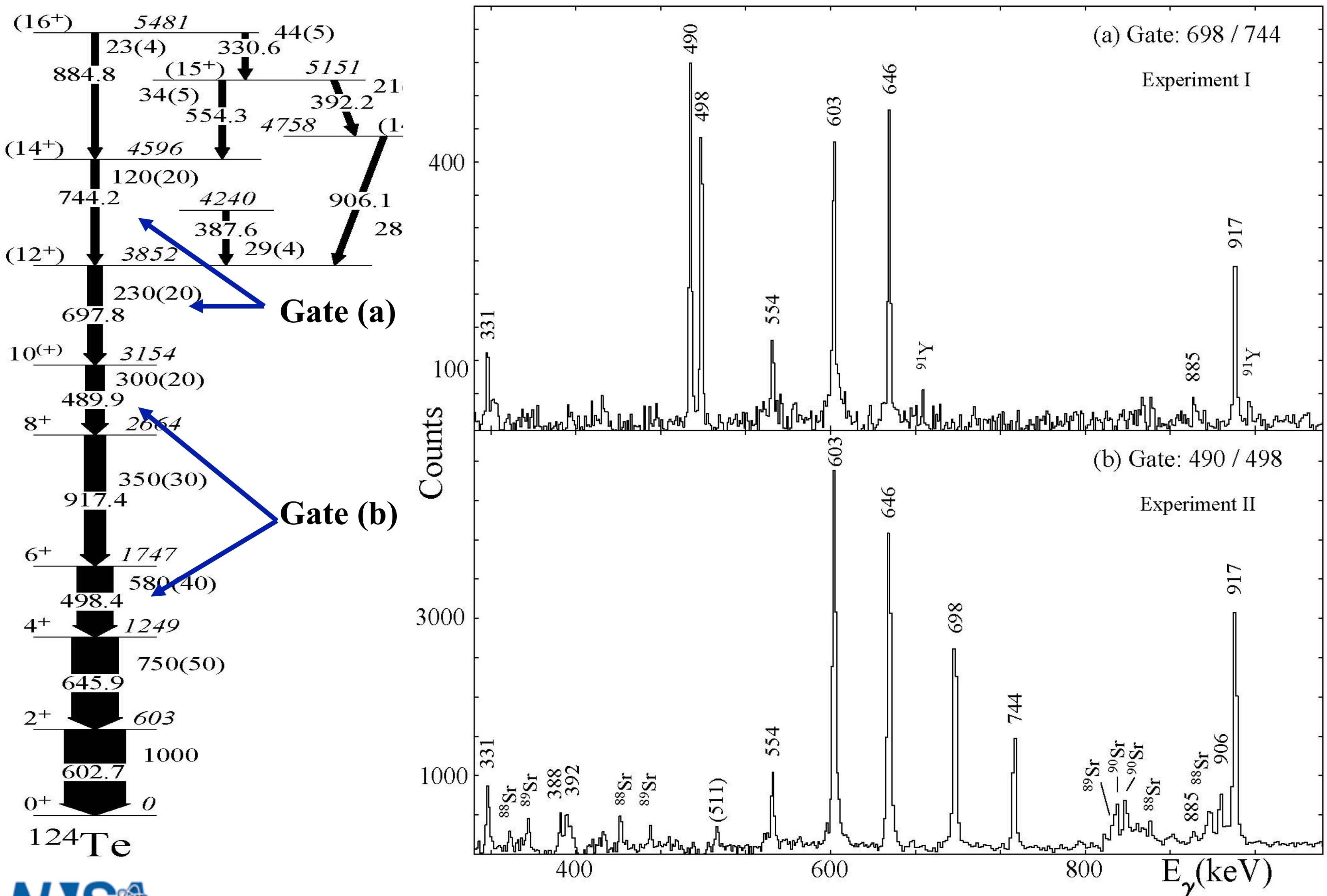


Previously established in (α, 2n) reactions.

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

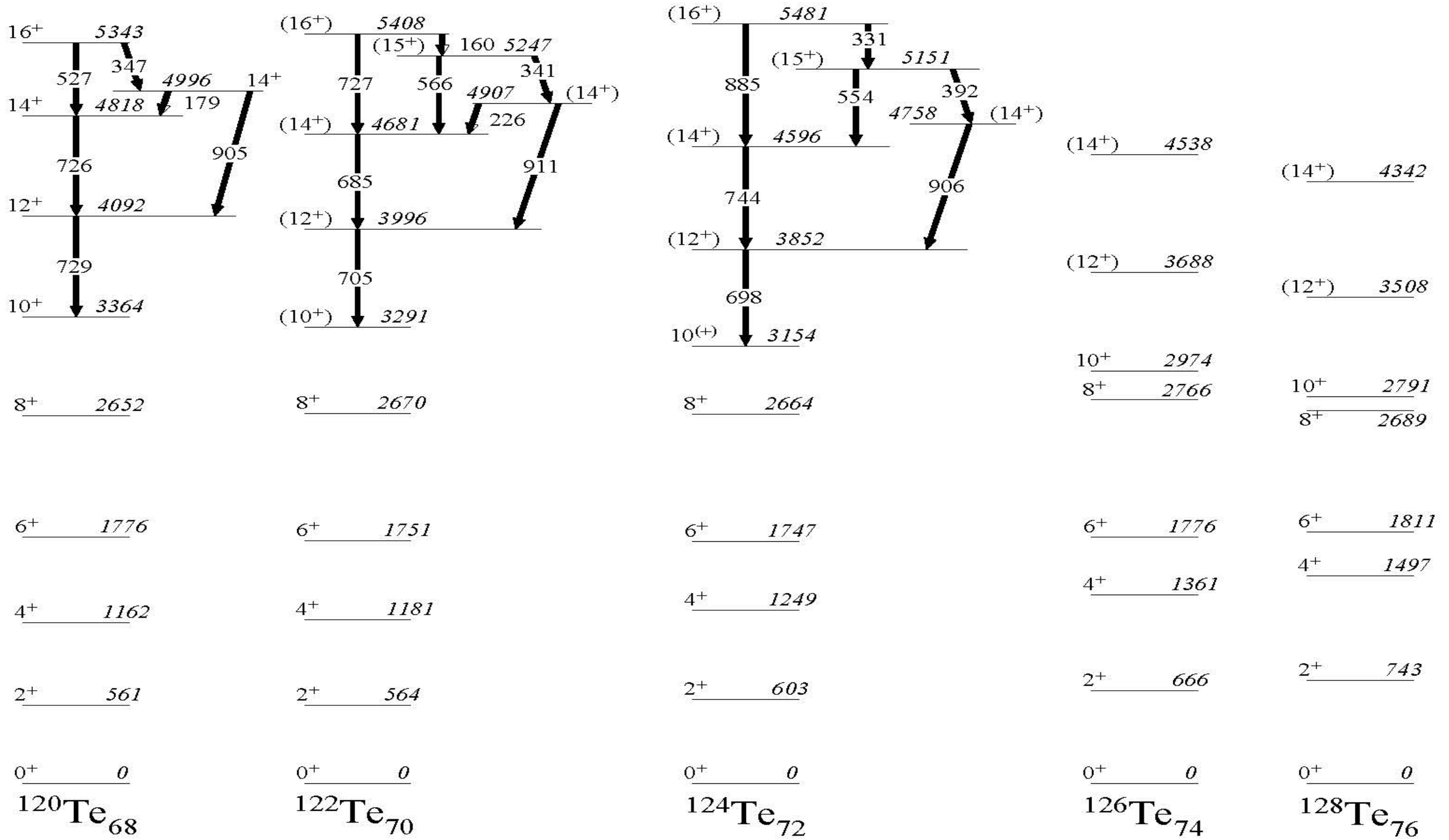
Yrast cascade extended from 3.1MeV to 5.5MeV excitation.

Examples of double gates in ^{124}Te.

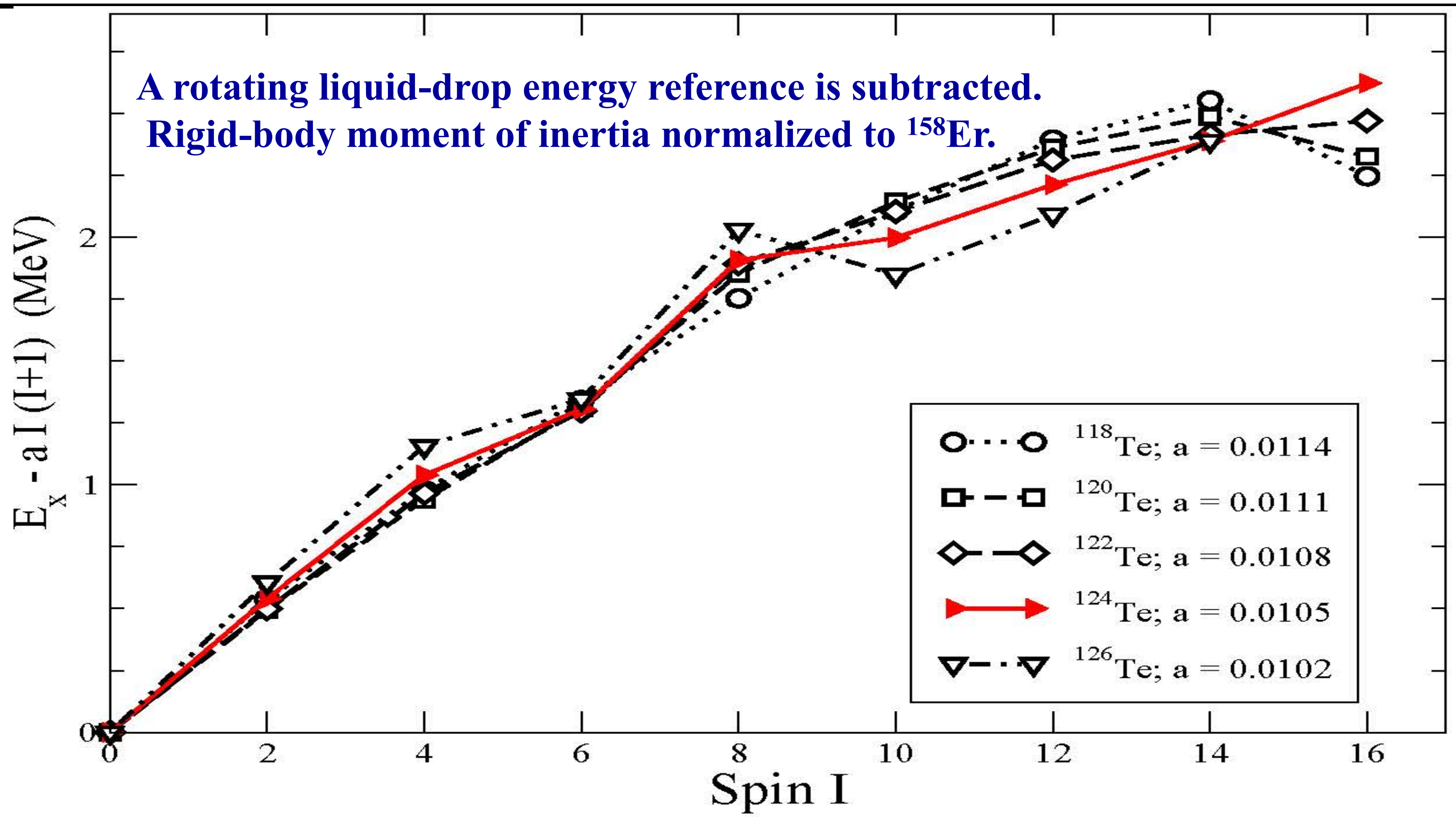


Systematics of main cascades in even-A Te isotopes.

In $^{114\text{-}122}$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.



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.

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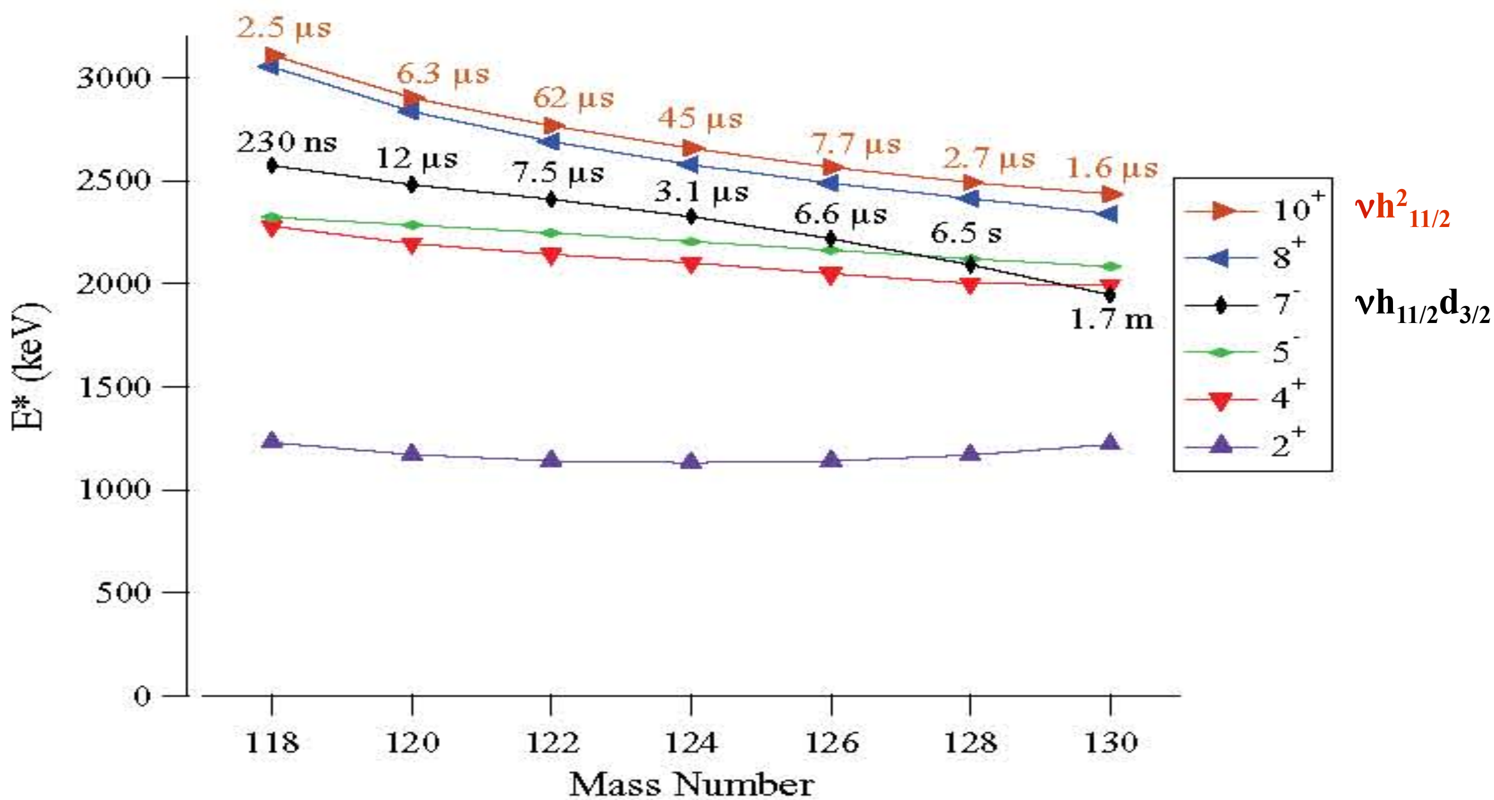
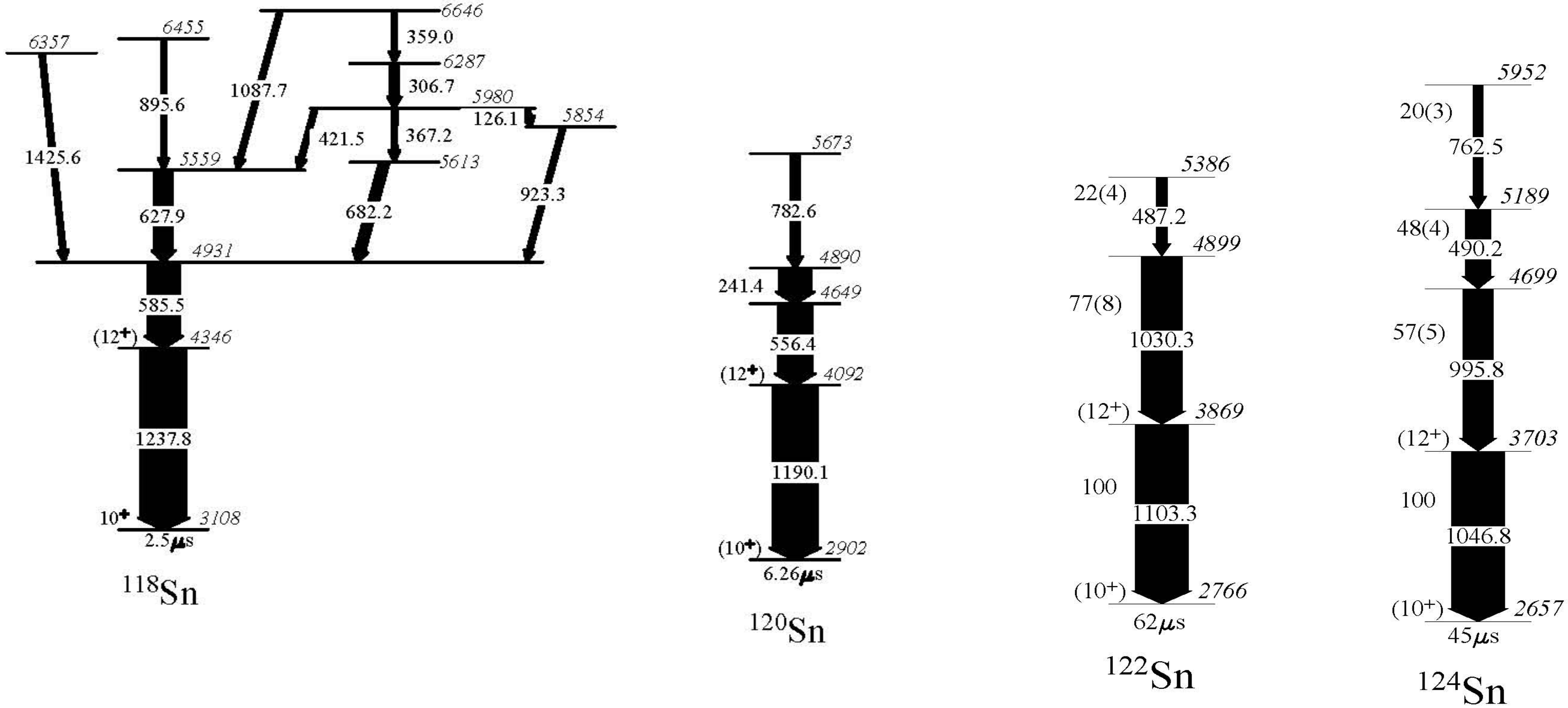
Systematics in even-A Sn isotopes



J. J. Ressler *et al.*, Phys. Rev. C 81, 014301 (2010)

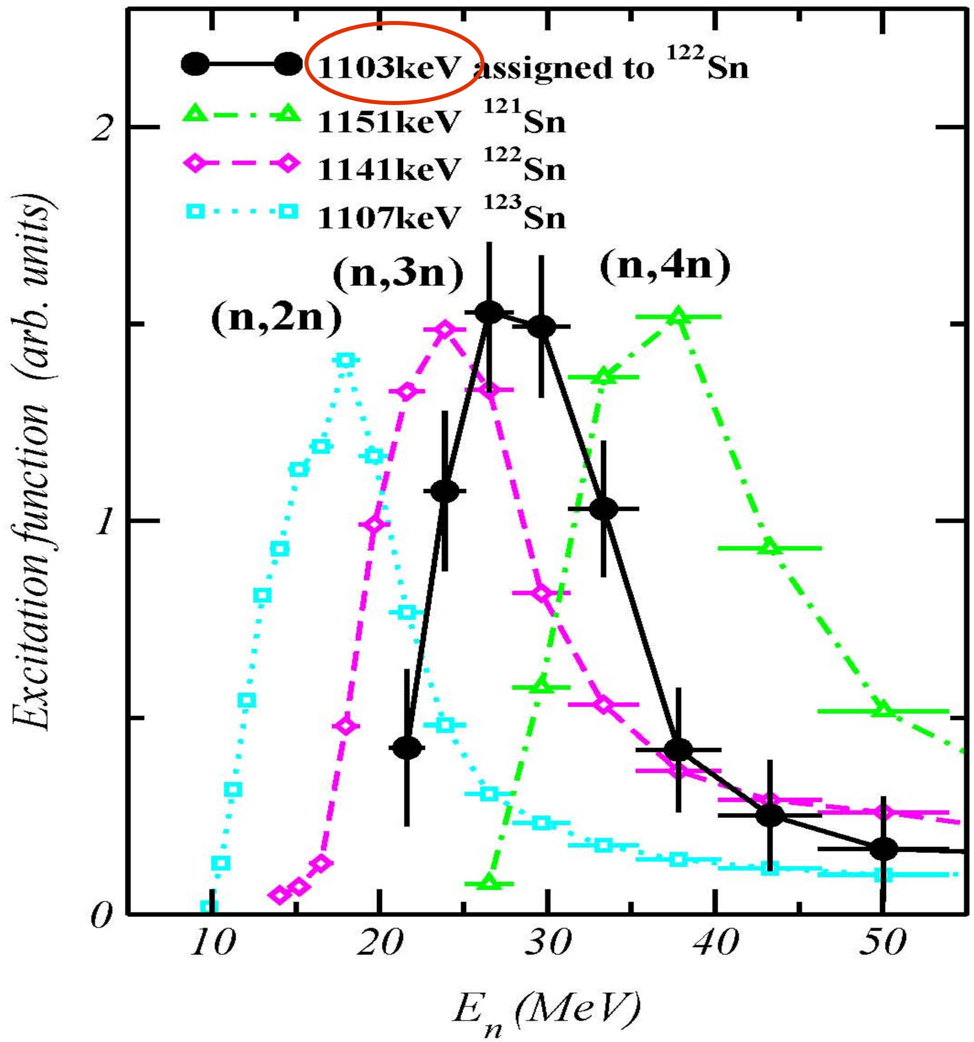
Transitions above the Sn 10^+ isomers

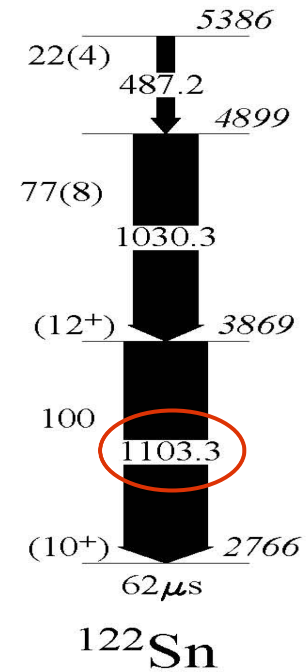
Gammasphere experiments populated Sn isotopes as fission fragments. Candidates for the $12^+ \rightarrow 10^+$ transitions in $^{118,120,122,124}Sn$ were observed and sequences in coincidence with these candidates were established.



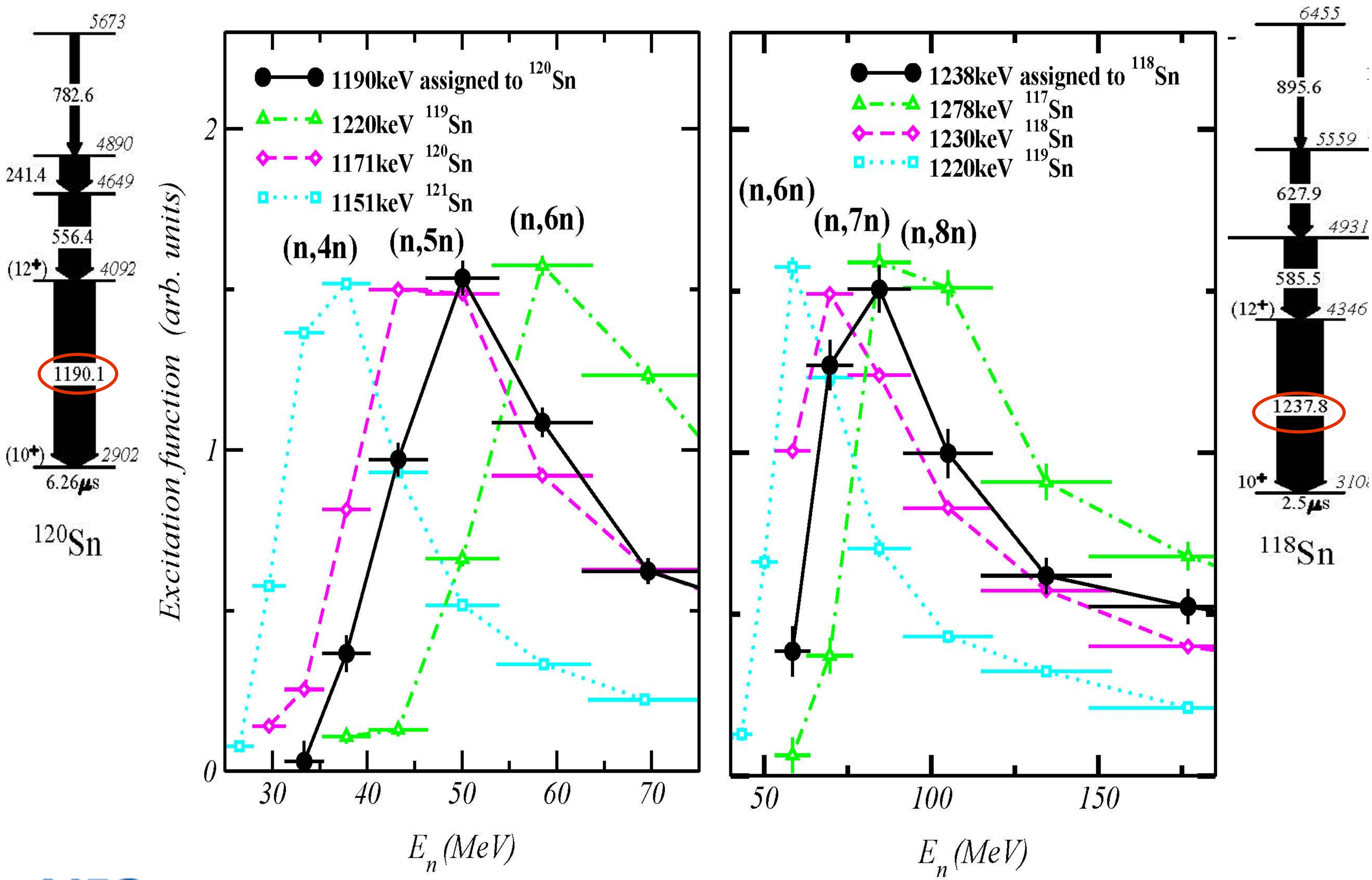
A GEANIE experiment, where Sn isotopes were populated in $^{124}Sn(n,xn\gamma)$ reactions, the assignment of the $12^+ \rightarrow 10^+$ transitions to $^{118,120,122}Sn$ was confirmed.

γ-ray excitation functions from $^{124}Sn(n,xn)$ GEANIE experiment

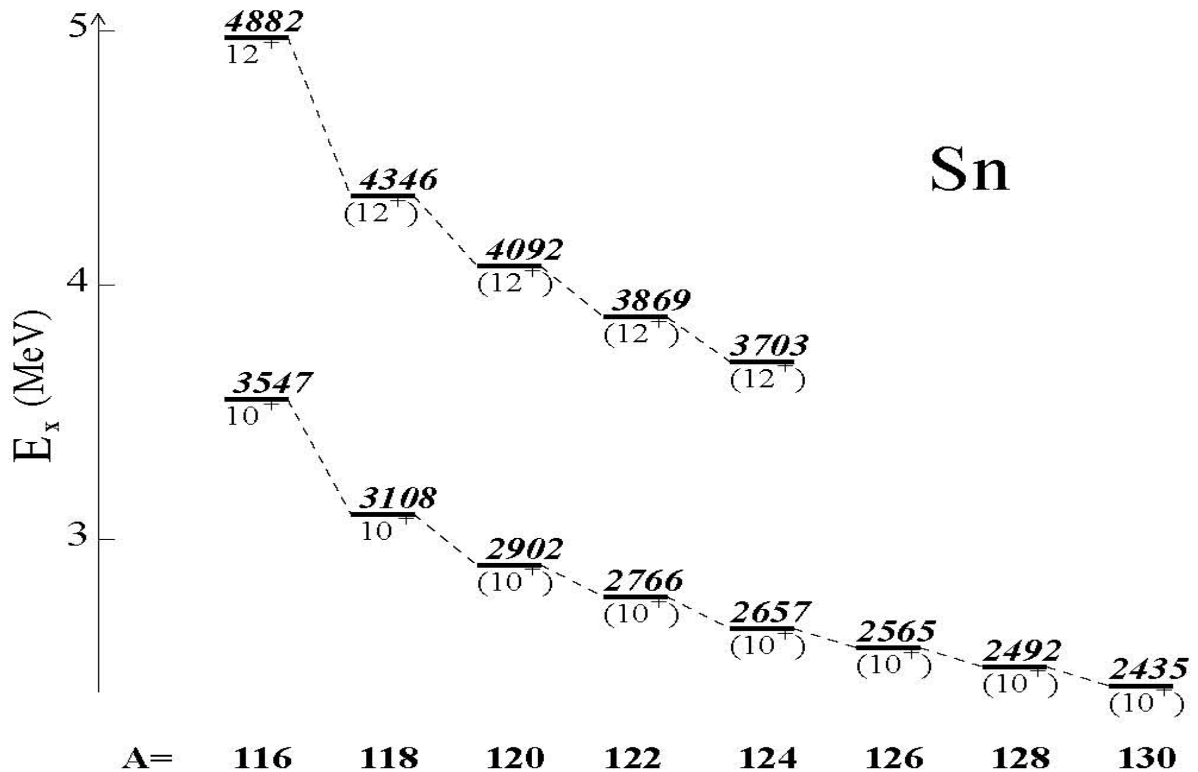




γ-ray excitation functions from $^{124}Sn(n,xn)$ GEANIE experiment



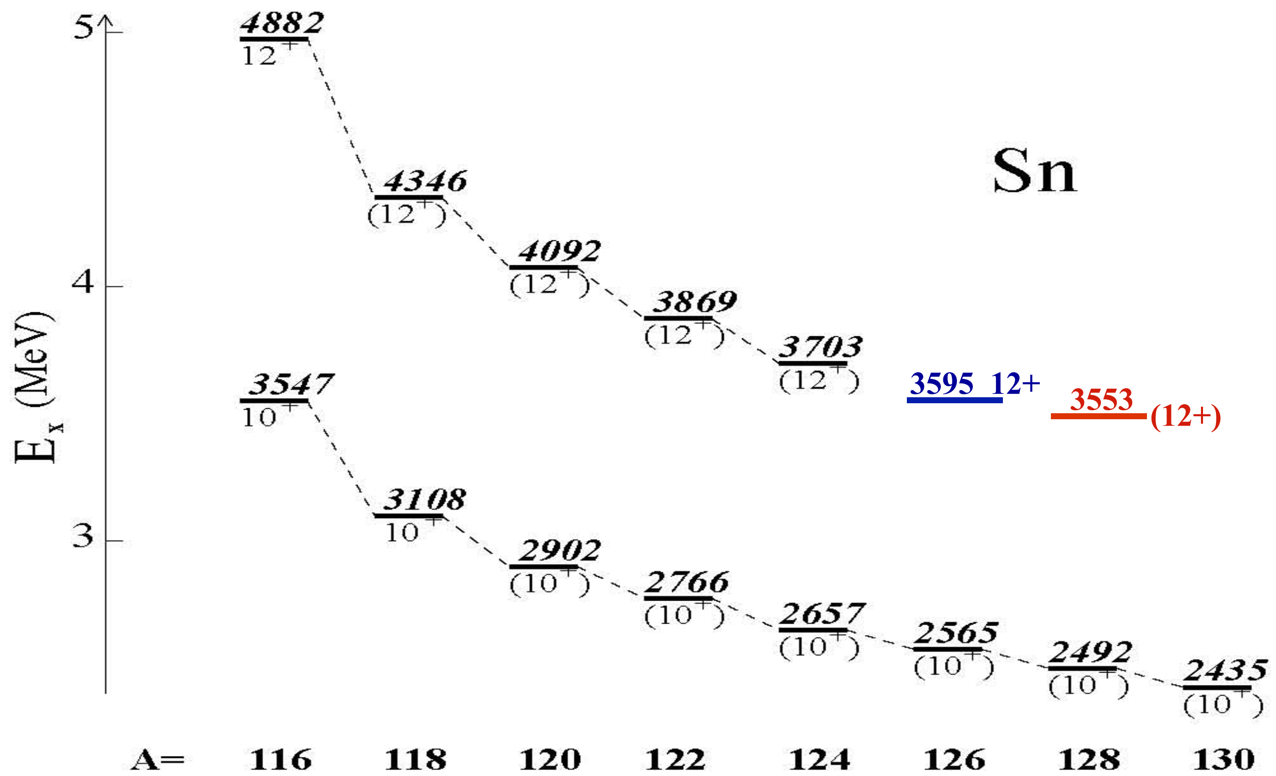
Systematics of the 12^+ states and shell-model comparison



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}Sn~ 4.8MeV, ^{118}Sn~ 4.3MeV, ^{120}Sn~ 4.05MeV, ^{122}Sn~ 3.88MeV, ^{124}Sn~ 3.75MeV

Systematics of the 12$^+$ states



A. Astier *et al.*, Phys. Rev. C 85, 054316 (2012)

S. Pietri *et al.*, Phys. Rev. C 83, 044328 (2011)
Ł. W. Iskra *et al.*, Phys. Rev. C 89, 044324 (2014)

CONCLUSIONS

Prompt γ-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

FIssion ExperimentS and Theoretical Advances

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Suggestion for next workshop? 2017?

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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?)

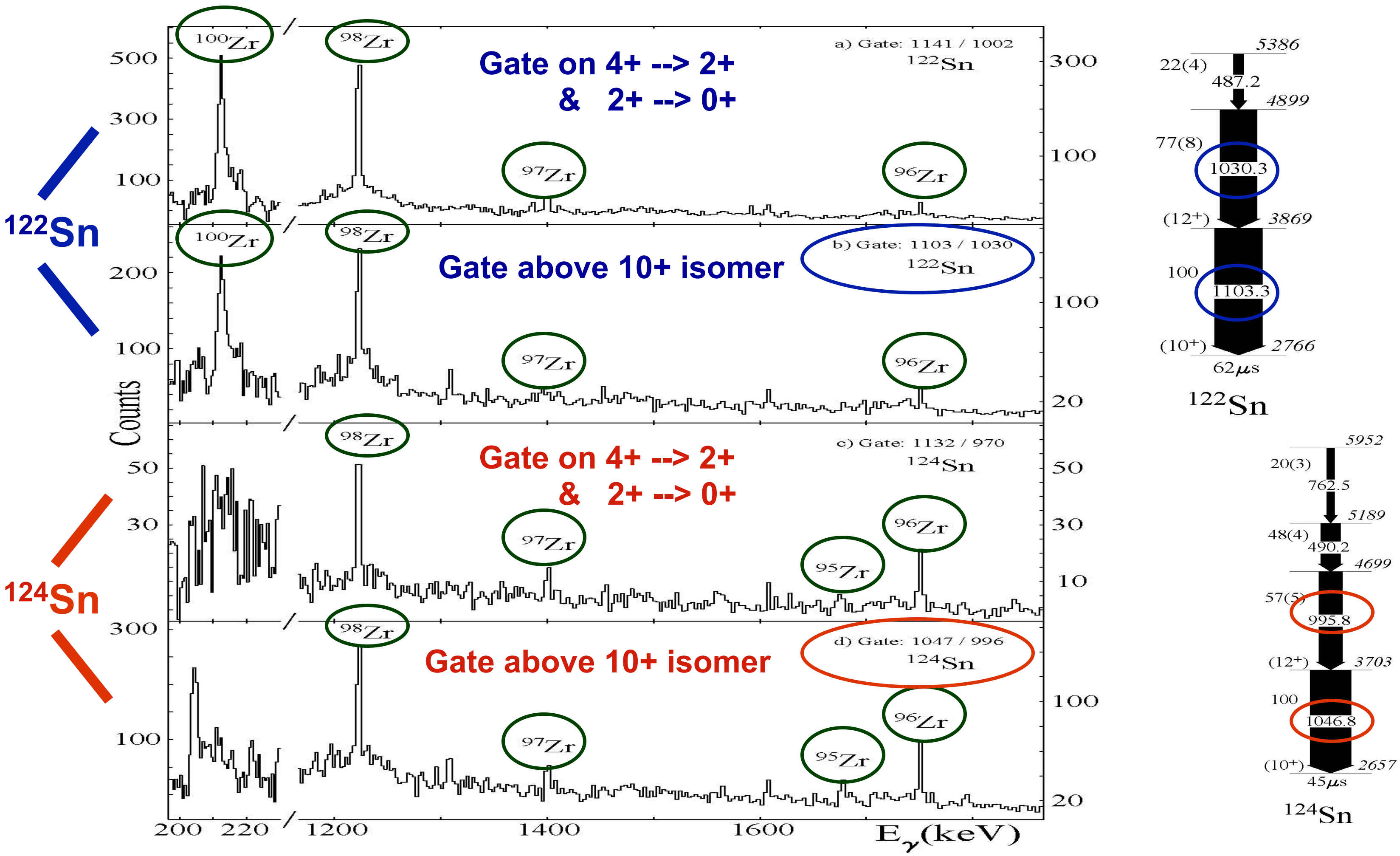
or

FETA (in Greece?)

Spectra from the Gammasphere experiment

^{18}O(91MeV) + ^{208}Pb -> ^{226}Th* -> ^{122}Sn + ^{96,97,98,100}Zr + 8,7,6,4n

-> ^{124}Sn + ^{95,96,97,98}Zr + 7,6,5,4n



Similar intensity patterns for the same complementary fragments!

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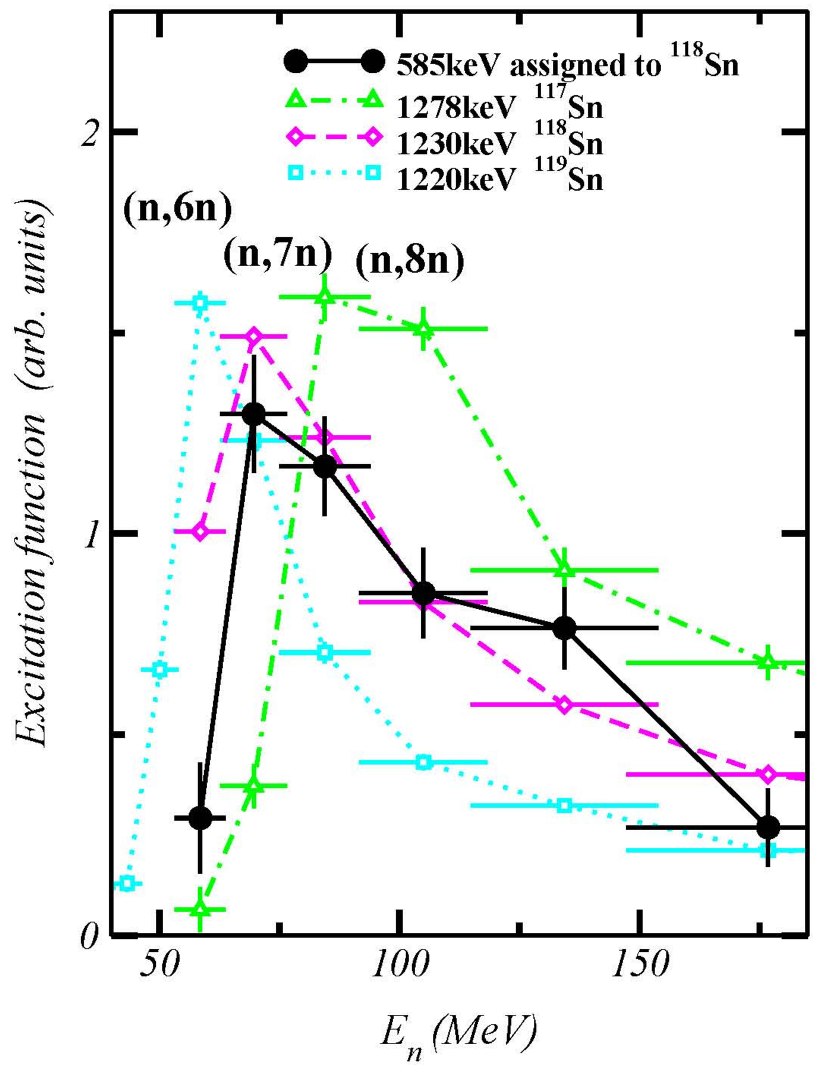
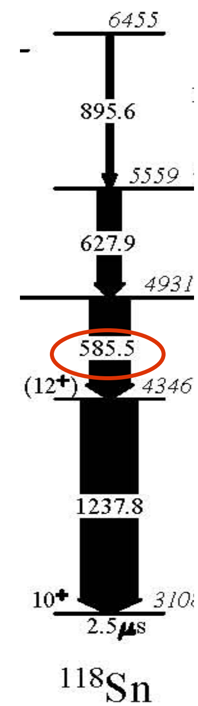
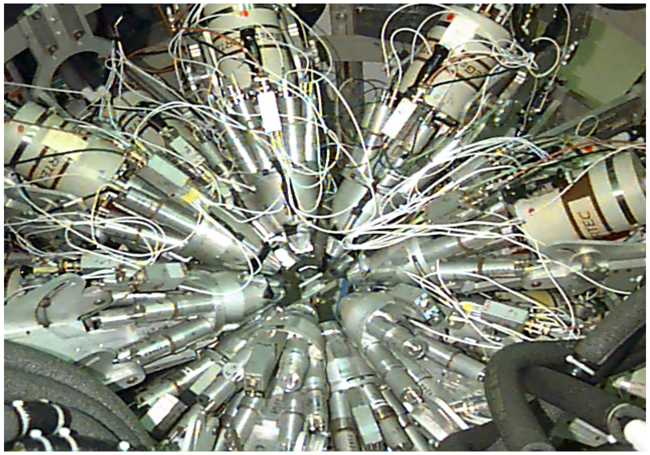
γ-ray excitation functions from $^{124}Sn(n,xn)$ GEANIE experiment

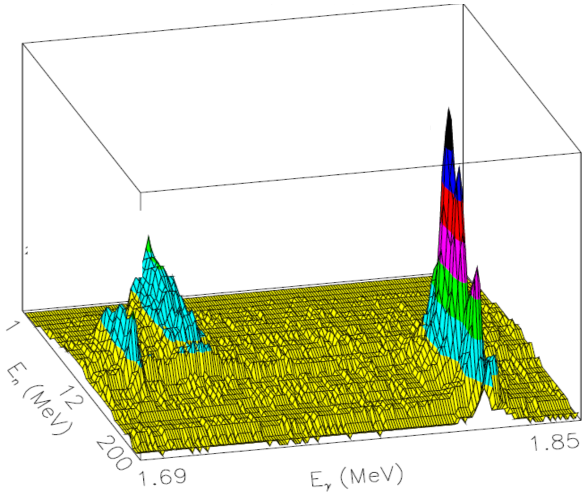




(n,xnγ) reactions with GEANIE at LANSCE

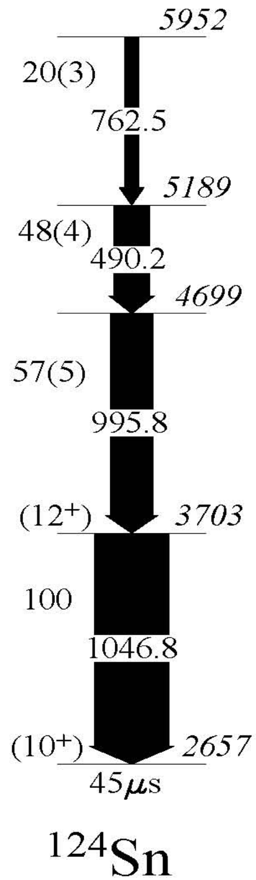
GEANIE (26 Ge detectors) used to determine excitation functions and cross sections for prompt γ rays in neutron induced reactions.

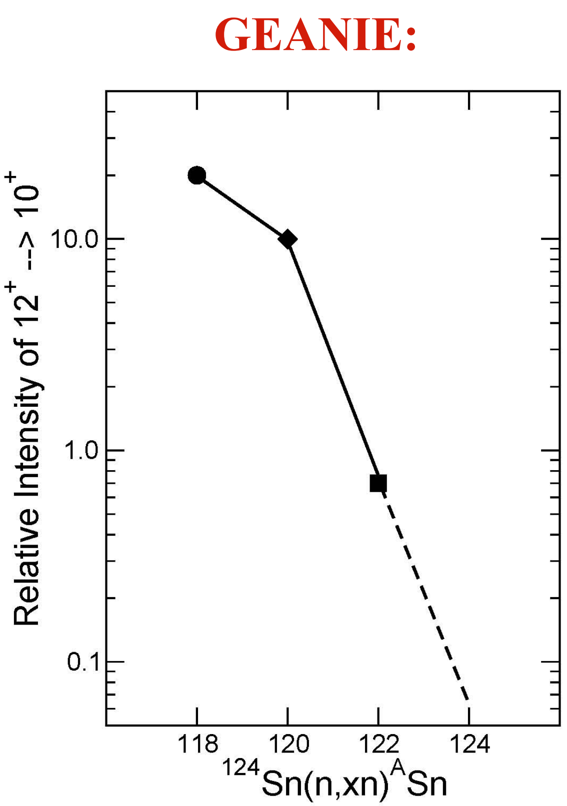




- Measure γ-ray pulse height (E_γ), neutron time of flight (E_n),
- Obtain γ-ray excitation functions, cross sections.

^{124}Sn 12^+ -> 10^+ transition not observed in the GEANIE experiment, as expected.





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