Fission-fragment studies using γ-ray spectroscopy

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INTRODUCTION

Long history of nuclear-structure and fragment-yield studies by identifying γ-rays from fission fragments using modern γ-ray detector arrays.

Neutron-rich fragments are populated from **spontaneous fission** sources or with **light-ion or neutron-induced fission of actinide targets.**

Fragments near stability are populated in fission of much heavier **compound nuclei** formed in **heavy-ion-induced fusion reactions;**

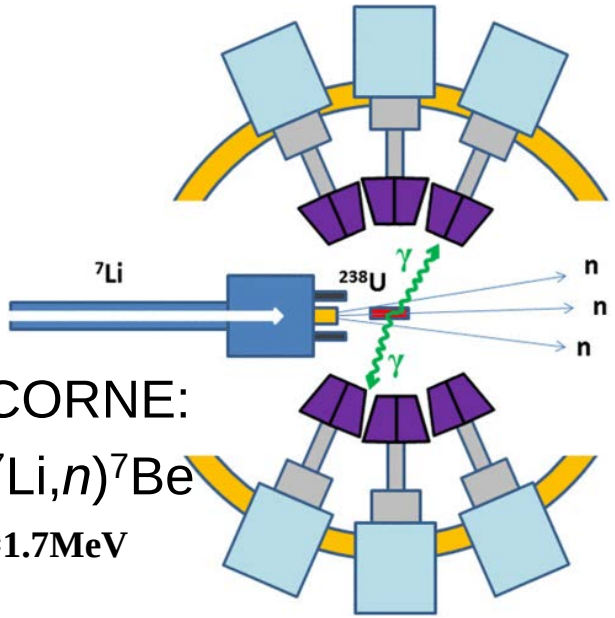
*Limitation***:** to uniquely identify fragment need additional data if no previous knowledge available (complementary fission fragment technique).

Two examples will be discussed: one about yields and one about structure.

1st example: Fission-fragment yields in ^{238}U(n,f)

J. N. Wilson *et al.*, Phys. Rev. Lett. 118, 222501, June 2017

MINIBALL: 24 Ge-dets, 33% 4π

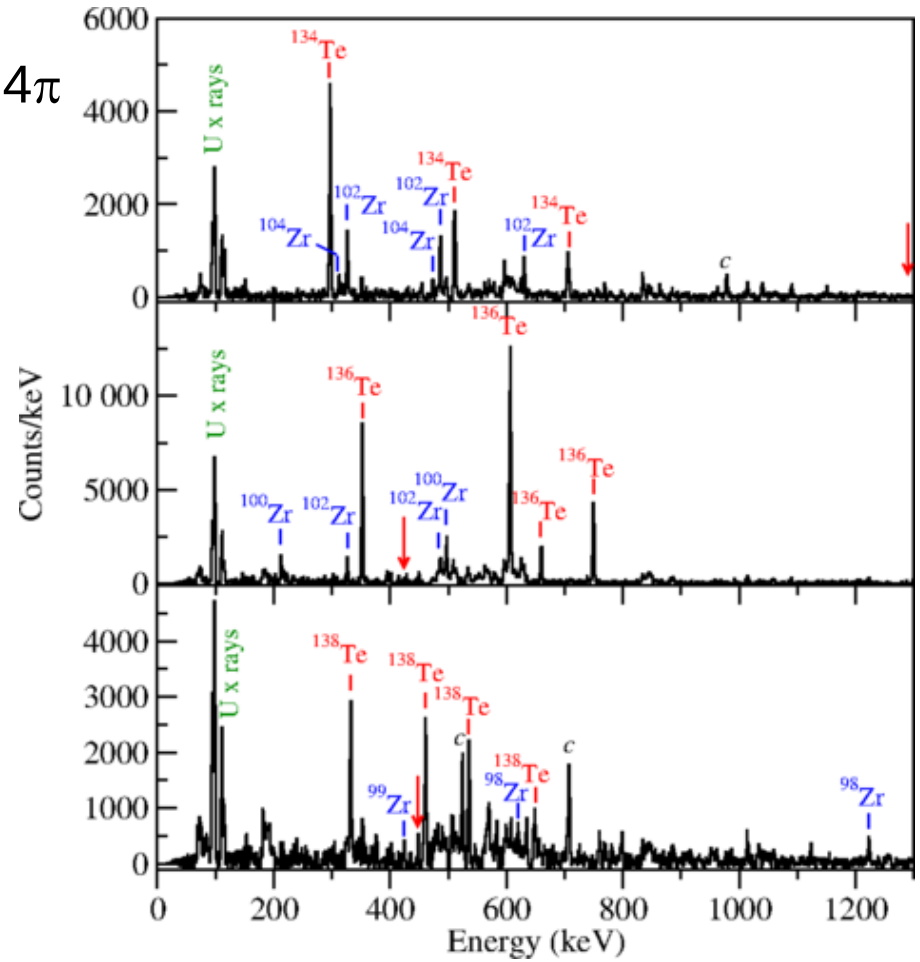


LICORNE:

$p(^{7}\mathrm{Li},n)^{7}\mathrm{Be}$

E_n=1.7MeV

@ IPN Orsay



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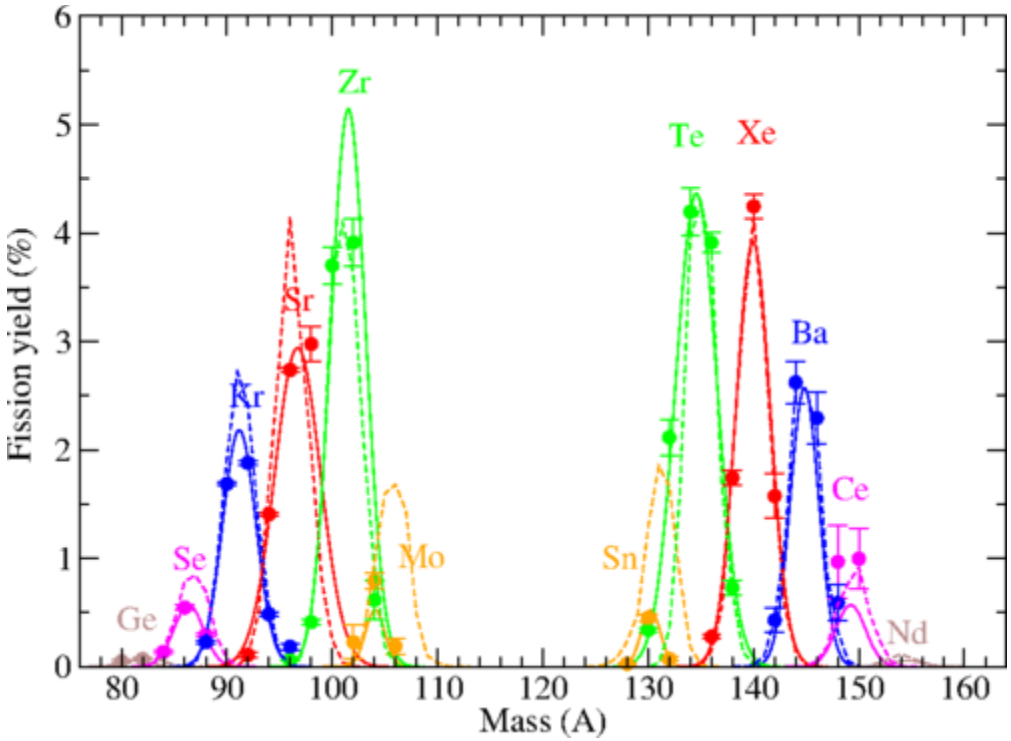
Yields of even-even fragments can be determined

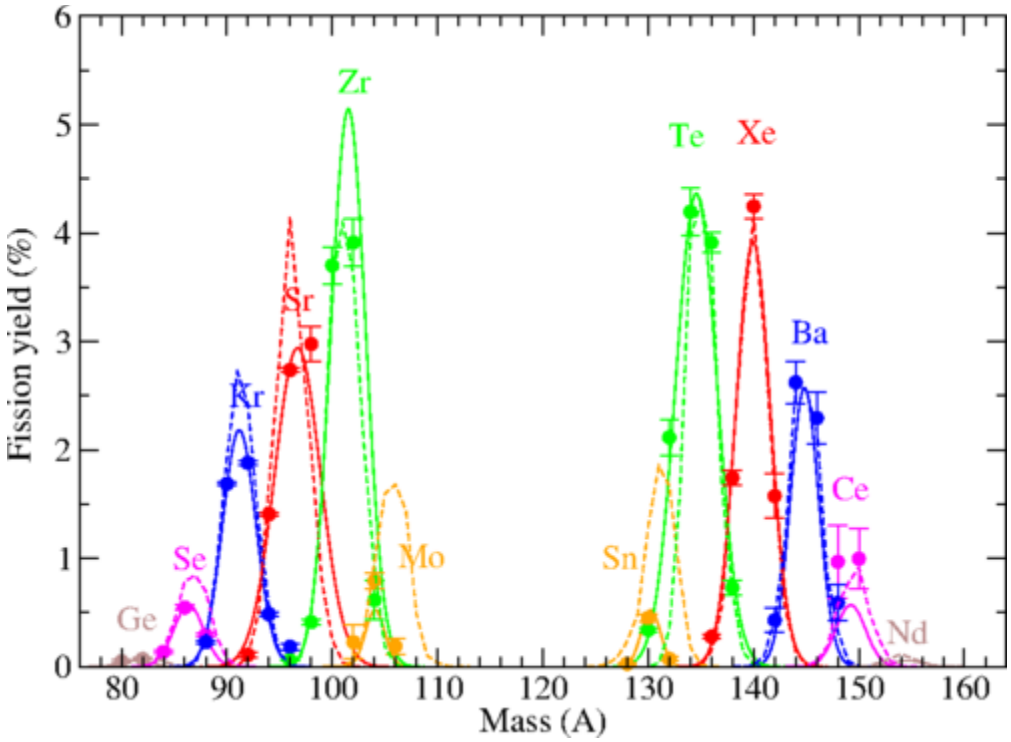
J. N. Wilson *et al.*, Phys. Rev. Lett. 118, 222501, 2017



Solid lines: fits; Dashed lines: predictions from JEFF3.1.1 based on a fission model. Contribution from isomers corrected by measuring intensities of delayed γ-rays between beam bursts.

In regions where the experimental data is sparse…

J. N. Wilson *et al.*, Phys. Rev. Lett. 118, 222501, 2017



…differences between experimental data and model predictions are observed. Predictions are accurate for well-measured systems, e.g. **$^{235}U(n_{th},f)$,** since model parameters are tuned to reproduce these data.

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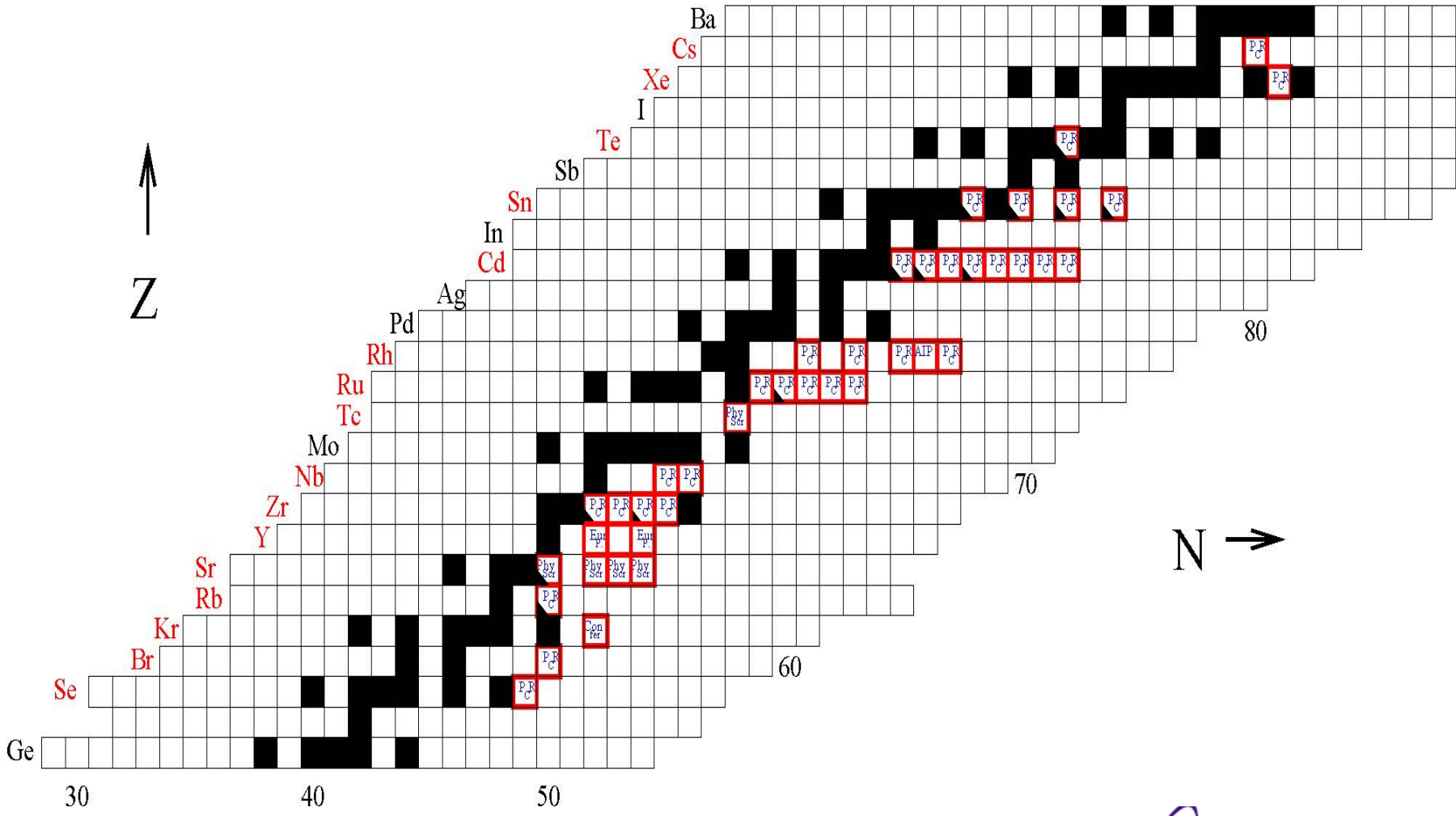
Isotopes we studied as fission fragments in heavy-ion-induced fusion reactions

Total of 42 isotopes studied in ~20 years.



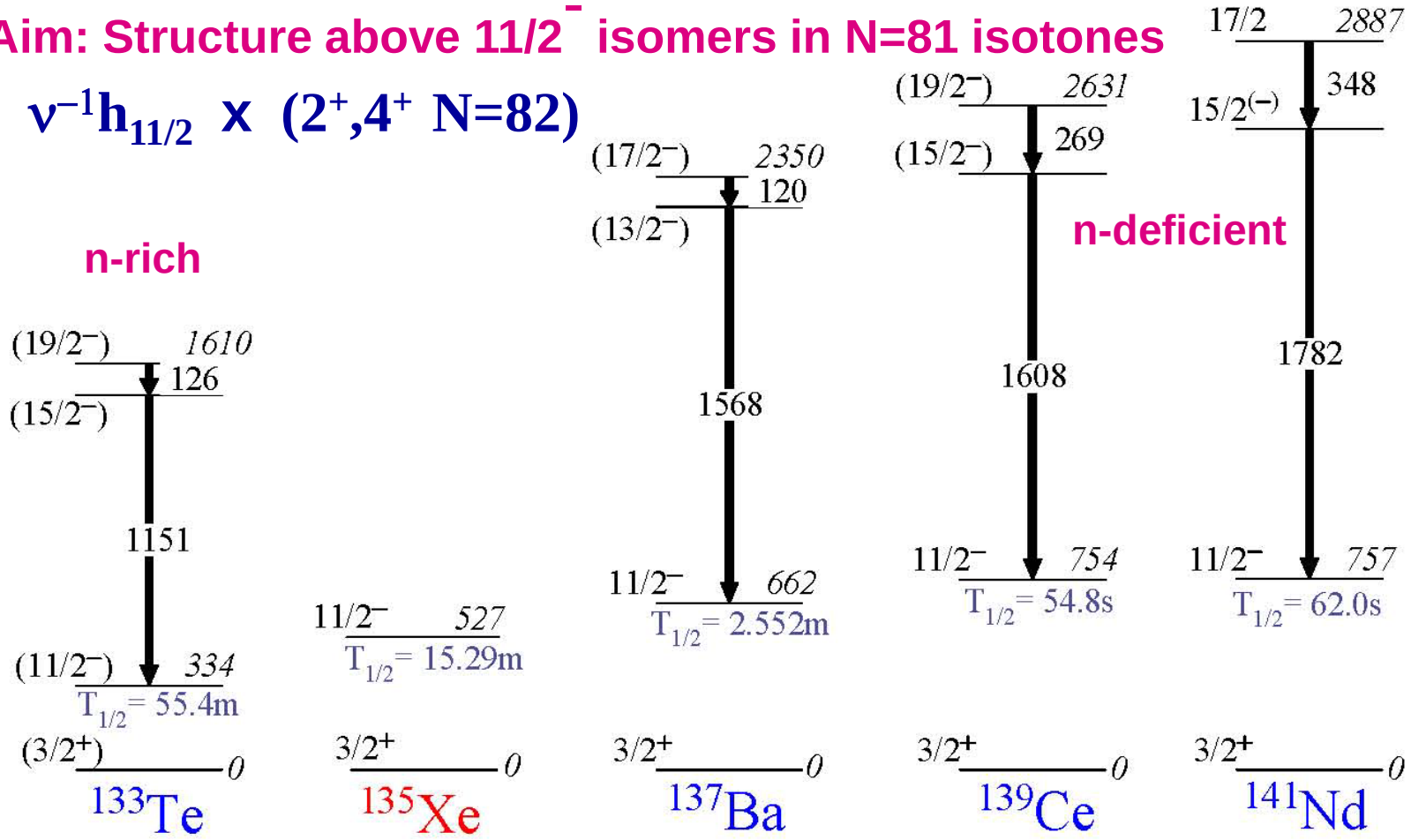
2nd example: Bridging nuclear structure gaps

Aim: Structure above $11/2^-$ isomers in N=81 isotones

$\nu^{-1}h_{11/2}$ x $(2^+,4^+$ N=82)

n-rich

n-deficient



^{252}Cf spontaneous fission: J.K. Hwang et al. PRC65,034319(02)

(α,3n):A.Kerek et al. NPA206,245(73)

(^{12}C,3n):D.Bucurescu et al. EPJA27,301(06)

(α,5n):J.Ludziejewski et al. ZPA281,287(77)

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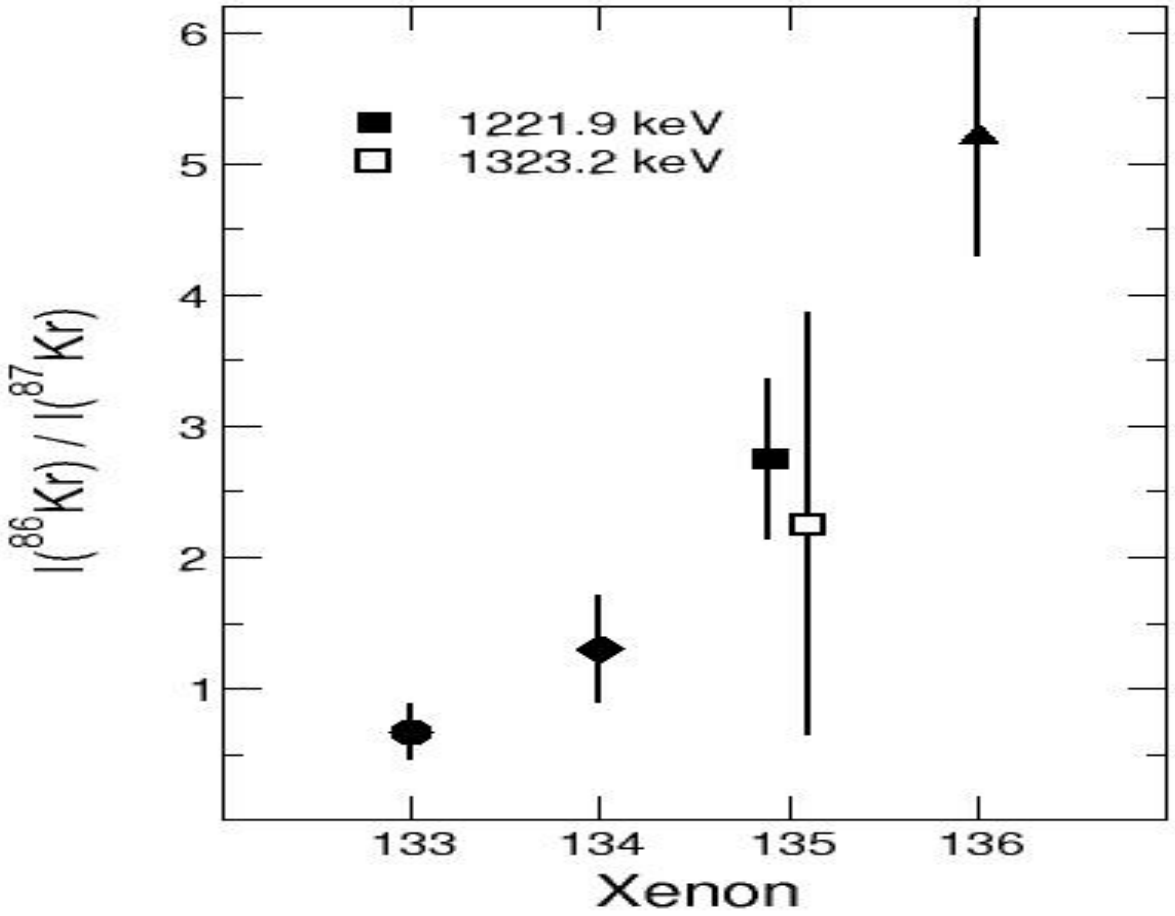
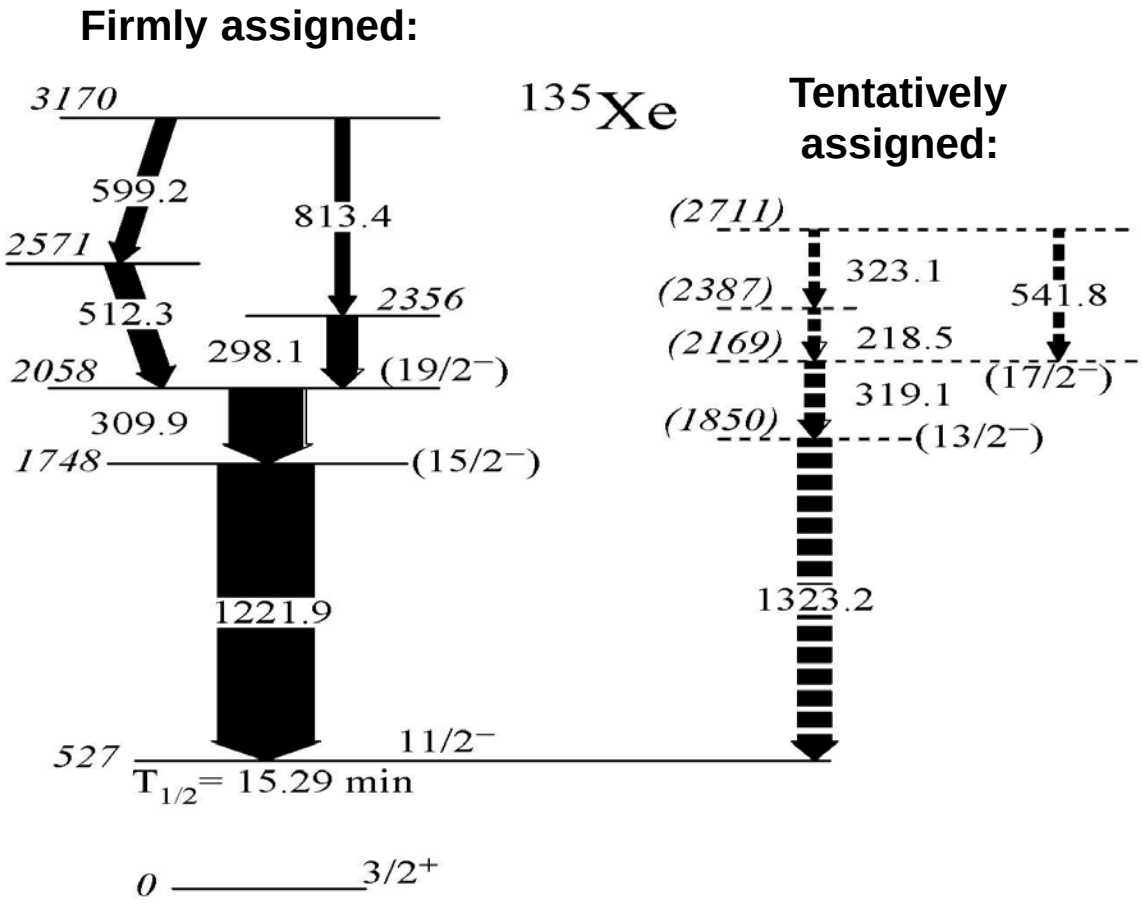
Intensity ratios of Xe lines in Kr-gated spectra

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



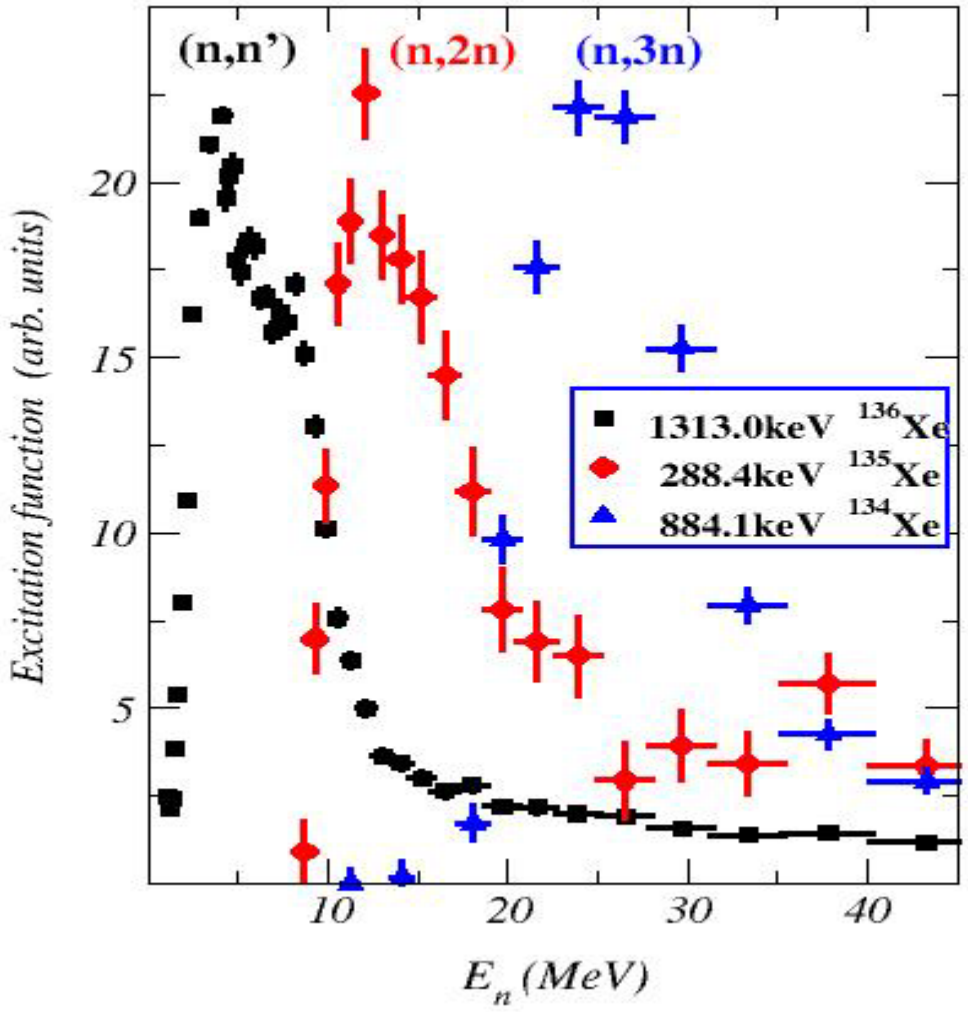
Always do the intensity check!

Resulting partial level scheme of ^{135}Xe

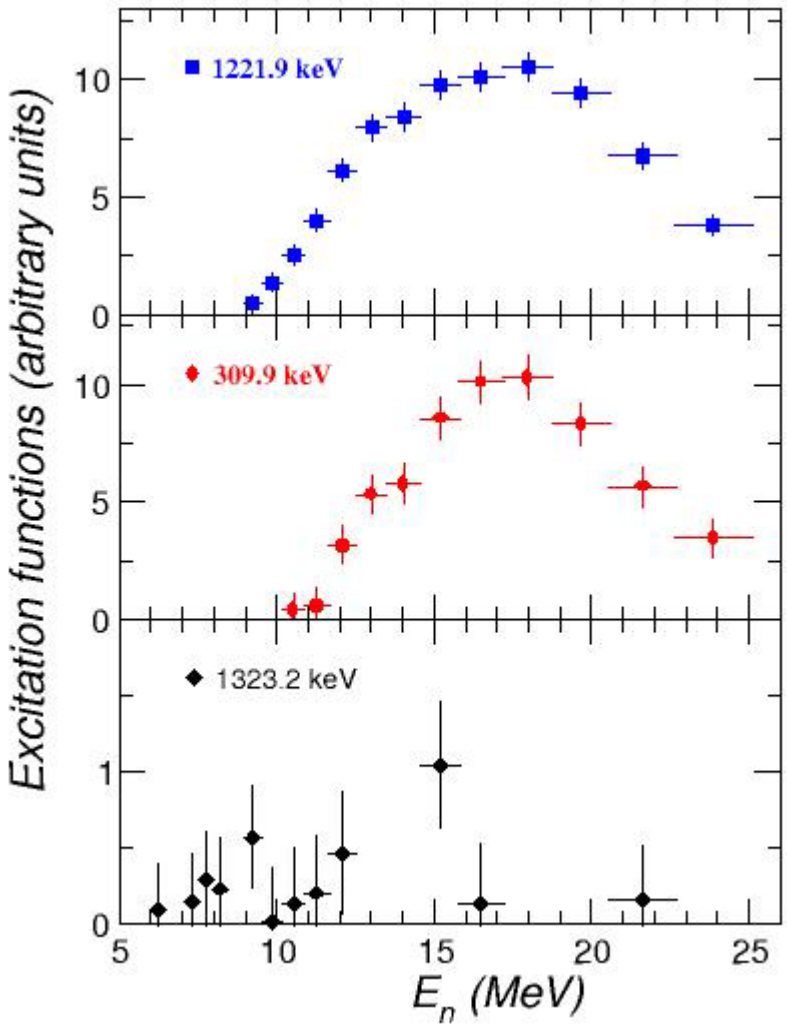


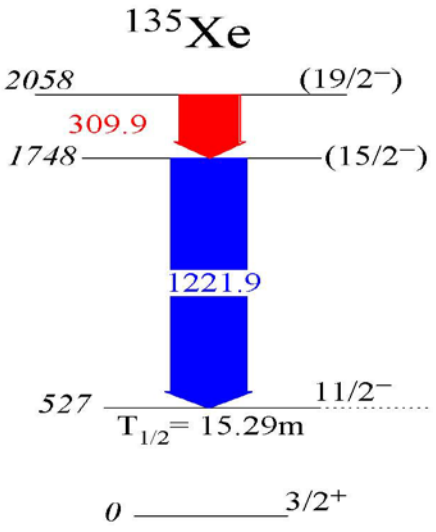
N. Fotiades et al., Phys. Rev. C 75, 054322, 2007

^{136}Xe(n,2n)^{135}Xe with GEANIE Ge-array at LANSCE



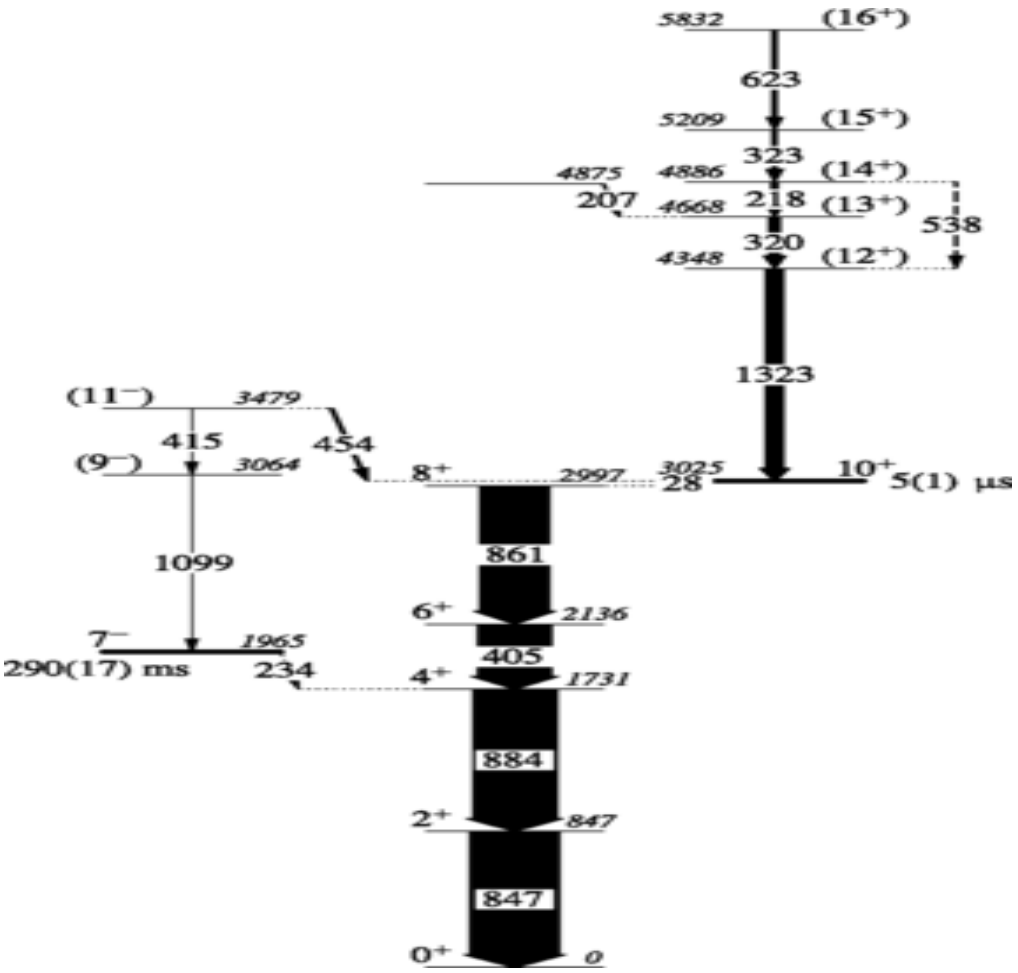
Excitation functions for new ^{135}Xe γ rays





The GEANIE experiment confirmed independently the assignment of two transitions from the strong sequence to ^{135}Xe. Assignment of the weak sequence remained tentative.

Partial level scheme of ^{134}Xe



^{136}Xe + ^{198}Pt

Gammasphere + CHICO

Firm assignment based on delayed-prompt γγ - coincindence spectra. Delayed time window: 45-780ns

A. Vogt *et al*., Phys. Rev. C 93, 054325, 2016

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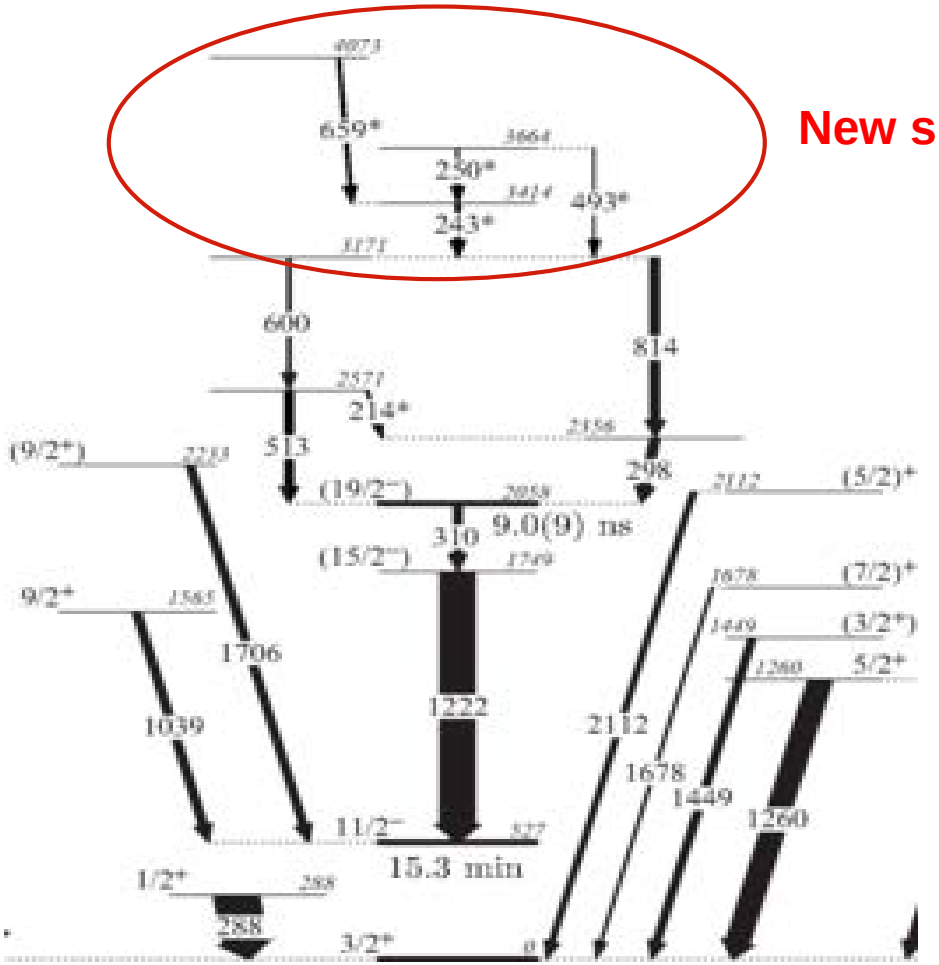
Partial level scheme of ^{135}Xe



New since earlier this year.

^{136}Xe + ^{198}Pt

Gammasphere + CHICO

A. Vogt et al., Phys. Rev. C 95, 024316, February 2017

Conclusions from the ^{135}Xe example

Nuclei near stability complementary techniques:

Deep-inelastic processes in heavy-ion multi-nucleon transfer reactions; *limitations*: relative small cross sections (typically <10mb) and to uniquely identify nucleus need additional data (particle detector) if no previous knowledge available.

Fragments in fission of compound nuclei in heavy-ion fusion reactions; *limitations*: cross sections vary and to uniquely identify nucleus need additional data (complementary fission fragment technique) if no previous knowledge available.

Especially for stable nuclei: Heavy-ion induced Coulomb excitation; *limitations*: stable species and excitations connected to ground state by strong matrix elements.

CONCLUSIONS

Prompt γ-ray spectroscopy of fission fragments useful for studying the structure of neutron-rich and nuclei near stability, and for obtaining information on fission-fragment yields.

For **neutron-rich** fragment studies **spontaneous fission** sources or **light-ion or neutron-induced fission of actinide targets** are usually more appropriate,

For **nuclei near stability** **fission of compound nuclei** formed in **heavy-ion- induced fusion reactions** is usually used to bridge the gaps 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

Requiem for GEANIE at LANSCE

1998 – 2015

In memoriam: GEANIE (26 “older” Ge detectors). Determined excitation functions and cross sections for prompt γ rays in neutron-induced reactions. Decommissioned in 2015.

Rests In several Pieces

Comment / Suggestion to organizers

FIssion ExperimentS and Theoretical Advances

Comment / Suggestion to organizers

FIssion ExperimentS and Theoretical Advances

Suggestion for next workshop? 2020?

Comment / Suggestion to organizers

FIssion ExperimentS and Theoretical Advances

Suggestion for next workshop? 2020?

Fission Experiments and Theoretical Advances

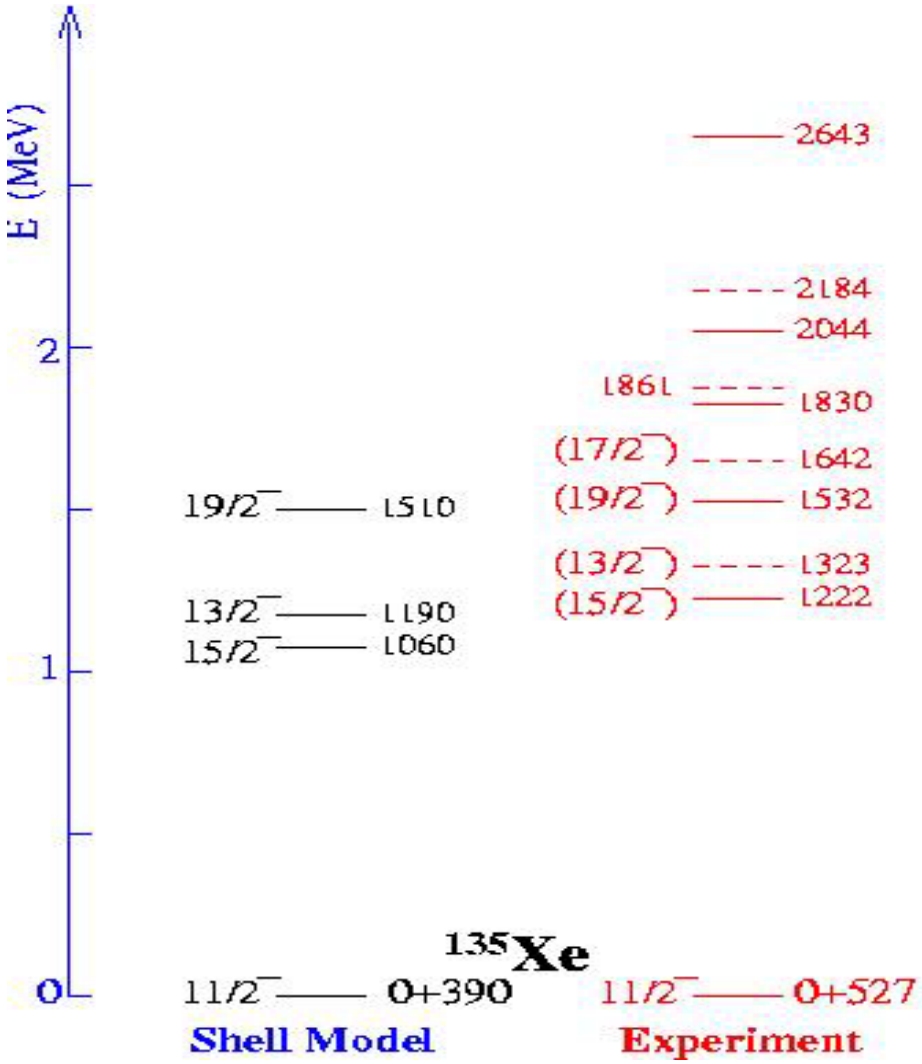
Hope to see everybody in the next

FIESTA (in New Mexico?)

or

FETA (in Greece?)

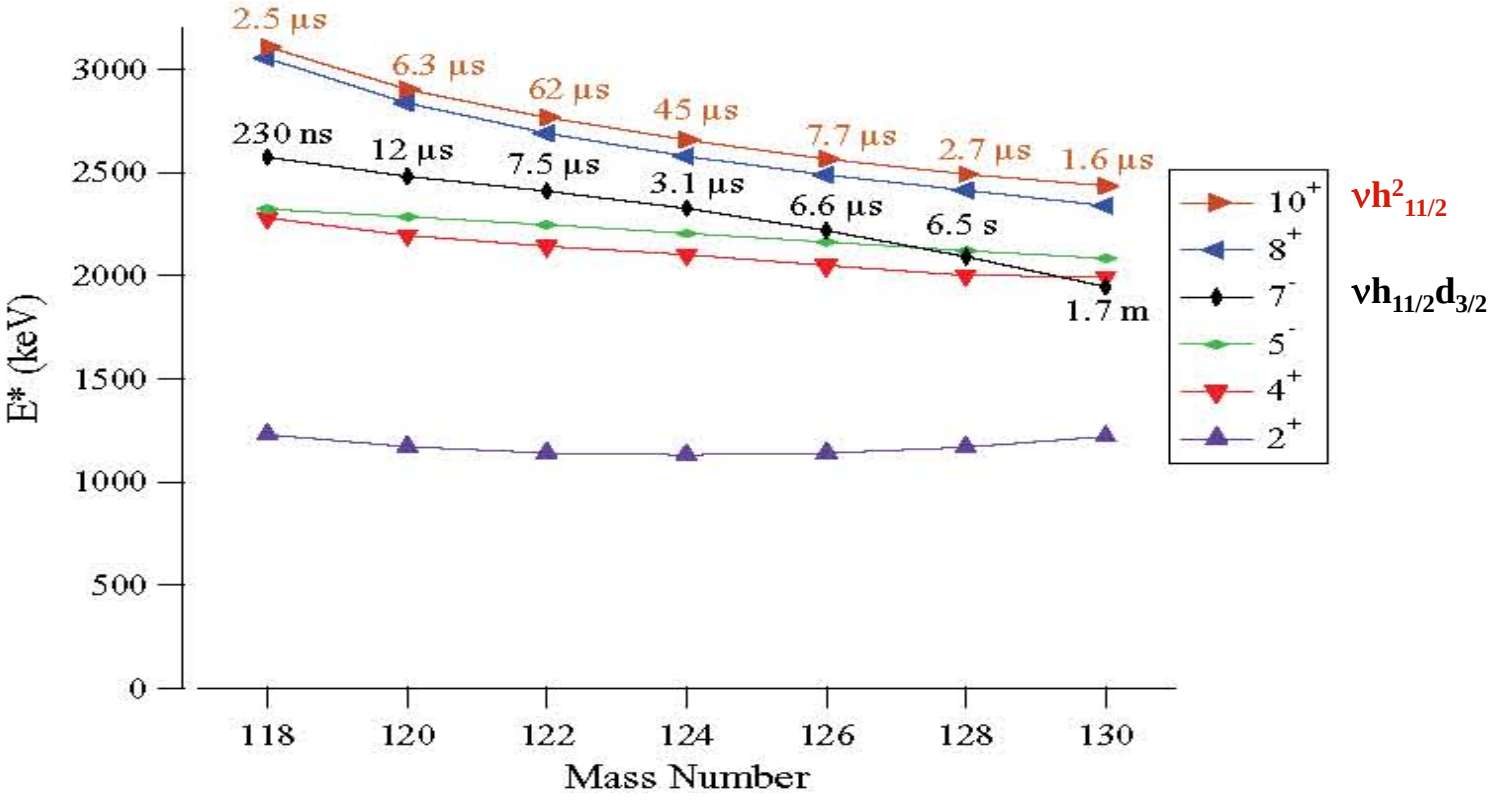
Comparison with shell-model predictions
from K. Higashiyama et al., PRC 65, 054317, 2002



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 ν $h_{11/2}$ 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

Systematics in even-A Sn isotopes



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

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