

SHAPE EVOLUTION OF NEUTRON-RICH NUCLEI IN THE VICINITY OF ^{110}Zr

Toshiyuki Sumikama
RIKEN

Contents

1. Introduction:
 - i. Isomeric state in even-even nucleus ^{108}Zr
 - ii. Shape evolution of neutron-rich Zr and Mo isotopes
2. Decay spectroscopy using EURICA and $\text{LaBr}_3(\text{Ce})$ at RIBF
3. Results
 - i. Search for new isomeric state in even-even nuclei
 - ii. Life-time measurement of 2_1^+ state in $^{104,106}\text{Zr}$

Collaboration

RIKEN/Tohoku University

SUMIKAMA, Toshiyuki
NISHIZUKA, Ippei
CHIGA, Nobuyuki

University of Brighton

BROWNE, Frank
ROBERTS, Oliver
BRUCE, Alison

Seoul National University

HA, Jeongsu
CHOI, Seonho

Beihang University/RIKEN

WATANABE, Hiroshi

University of Surrey

PATEL, Zena
RICE, Simon
REGAN, Patrick
PODOLYAK, Zsolt
CARROLL, Robert

Department of physics, University of Tokyo

XU, Zhengyu

Grenoble CNRS/IN2P3

SIMPSON, Gary

RIKEN Nishina Center

NISHIMURA, Shunji
DOORNENBAL, Pieter
LORUSSO, Giuseppe
SOEDERSTROEM, P.-A.

WU, Jin

BABA, Hidetaka
FUKUDA, Naoki
INABE, Naohito
ISOBE, Tadaaki
KAMEDA, Daisuke
KUBO, Toshiyuki
SAKURAI, Hiroshi
SUZUKI, Hiroshi
TAKEDA, Hiroyuki

Osaka University

DAIDO, Rie
YAGI, Ayumi
FANG, Yifan
ODAHARA, Atsuko
IDEGUCHI, Eiji
TANAKA, Mana
NISHIBATA, Hiroki

Consejo Superior de Investigaciones Cientificas

TAPROGGE, Jan

University of York

SINCLAIR, Laura

Institut Pluridisciplinaire Hubert Curien

DIDIERJEAN, Francois
LOZEVA, Radomira

Milano

WIELAND, Oliver

Universit´ Joseph Fourier Grenoble

GEY, Guillaume

Sofia University

LALKOVSKI, Stefan

Yale University

WERNER, Volker

Peking University

LI, Zhihuan

GSI Helmholtzzentrum f´ ur Schwerionenforschung mbH

KOJOUHAROV, Ivan
KURZ, Nikolaus
SCHAFFNER, Henning

Collaboration

RIKEN/Tohoku University

SUMIKAMA, Toshiyuki
NISHIZUKA, Ippei
CHIGA, Nobuyuki

RIKEN Nishina Center

NISHIMURA, Shunji
DOORNENBAL, Pieter
LORUSSO, Giuseppe
SOEDERSTROEM, P-A

Institut Pluridisciplinaire Hubert Curien

DIDIERJEAN, Francois
LOZEVA, Radomira

University of Bristol

BROWNE, Frank
ROBERTS, Oliver
BRUCE, Alison

Seoul National University

HA, Jeongsu
CHOI, Seonho

Beihang University

WATANABE, Hiroshi

University of Sussex

PATEL, Zena
RICE, Simon
REGAN, Patrick
PODOLYAK, Zsolt
CARROLL, Robert

Department of physics, University of Tokyo

XU, Zhengyu

Grenoble CNRS/IN2P3

SIMPSON, Gary

Consejo Superior de Investigaciones Cientificas

TAPROGGE, Jan

University of York

SINCLAIR, Laura



University of Bonn

LAND, Oliver

University of Joseph Fourier Grenoble

Guillaume

University of Vienna

KOVSKI, Stefan

University of Jyväskylä

KÄNÄR, Volker

University of Jinan

Zhihuan

Helmholtzzentrum für Energieforschung mbH

DOUHAROV, Ivan

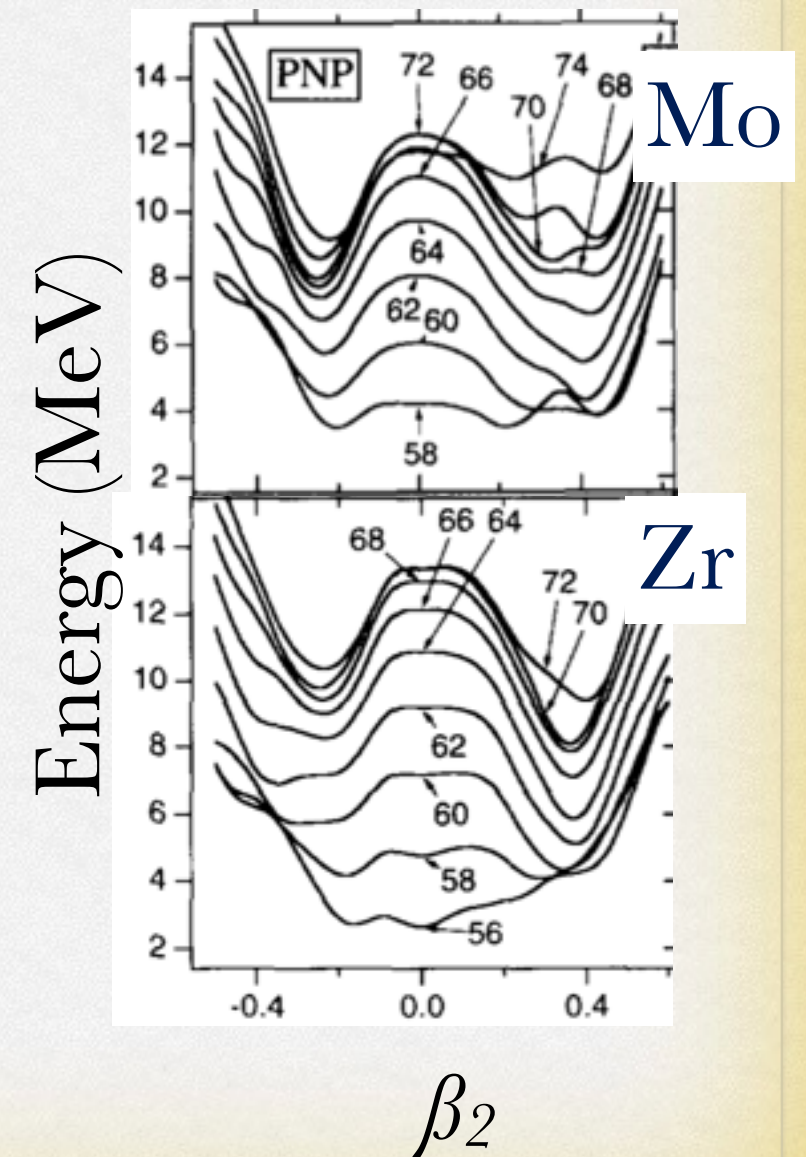
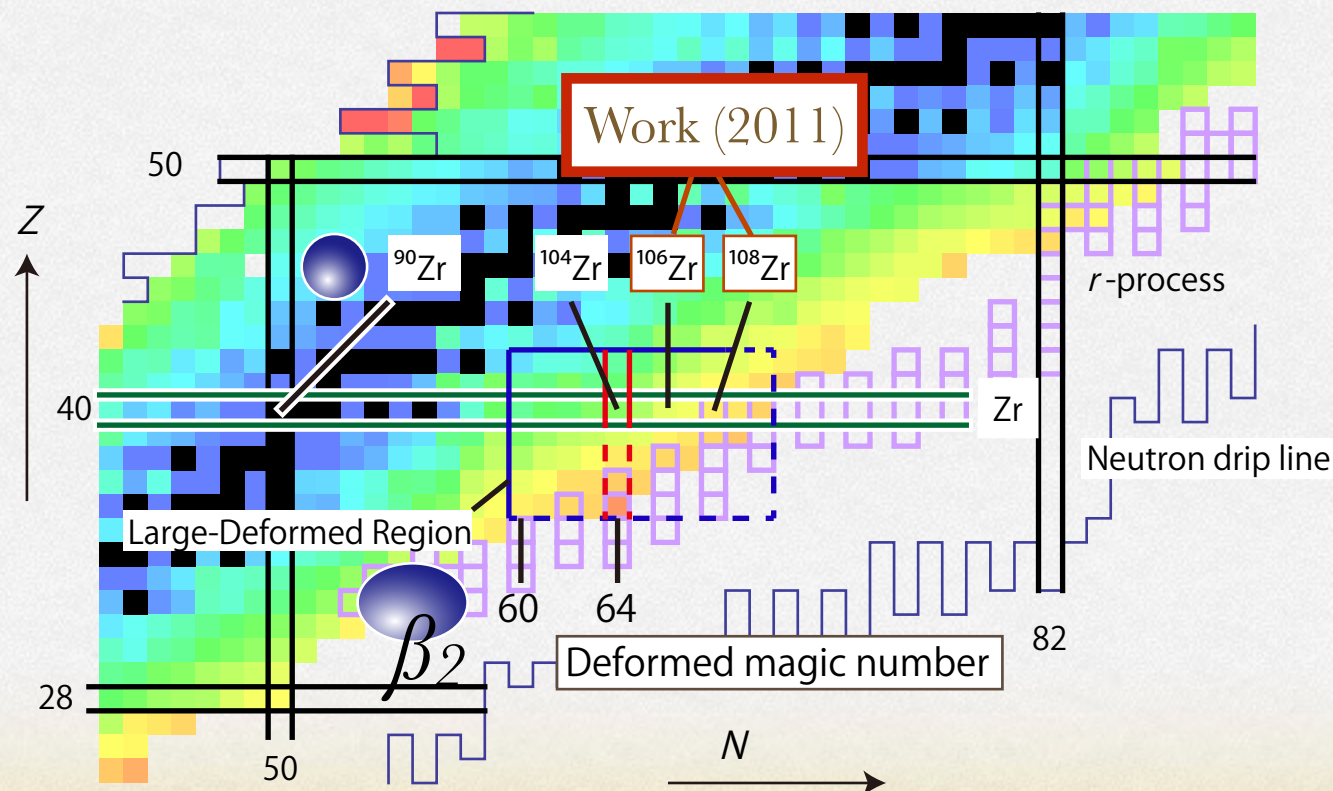
KURZ, Nikolaus

SCHAFFNER, Henning

NEUTRON-RICH ZR ISOTOPES

- ✱ Shape transition at $N = 60$ from spherical to prolate
- ✱ Coexistence of deformed shape: Theoretical prediction
 - ✱ Prolate (Zr, deep minimum)
 - ✱ Oblate
 - ✱ Triaxial
 - ✱ Tetrahedral at $Z = 40, N = 70$

Skalski et al., NPA617, 282 (1997)



SHAPE EVOLUTION OF Zr, Mo & Ru ISOTOPES

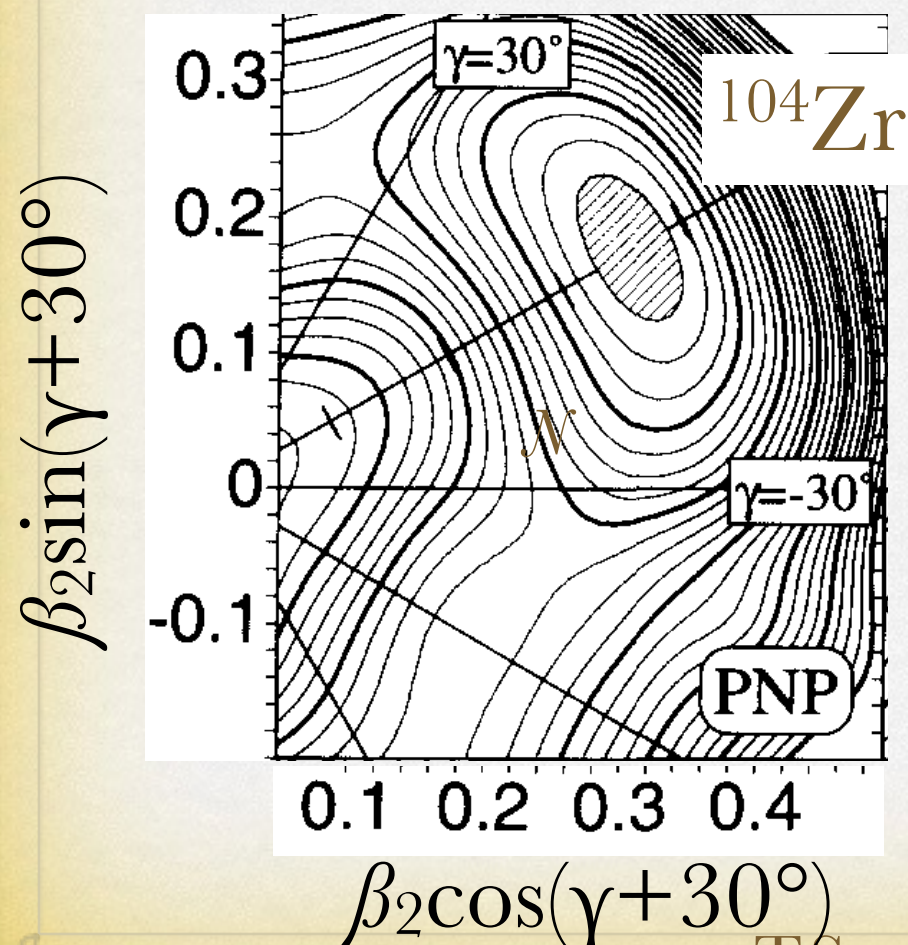
- * Shape evolution beyond $N = 60$
 - * Zr isotopes: prolate shape with axial symmetry
 - * Mo & Ru isotopes: triaxial deformation or γ soft
- * Aim

* β_2 : $\tau(2_1^+)$, $E(2_2^+)$: γ softness,

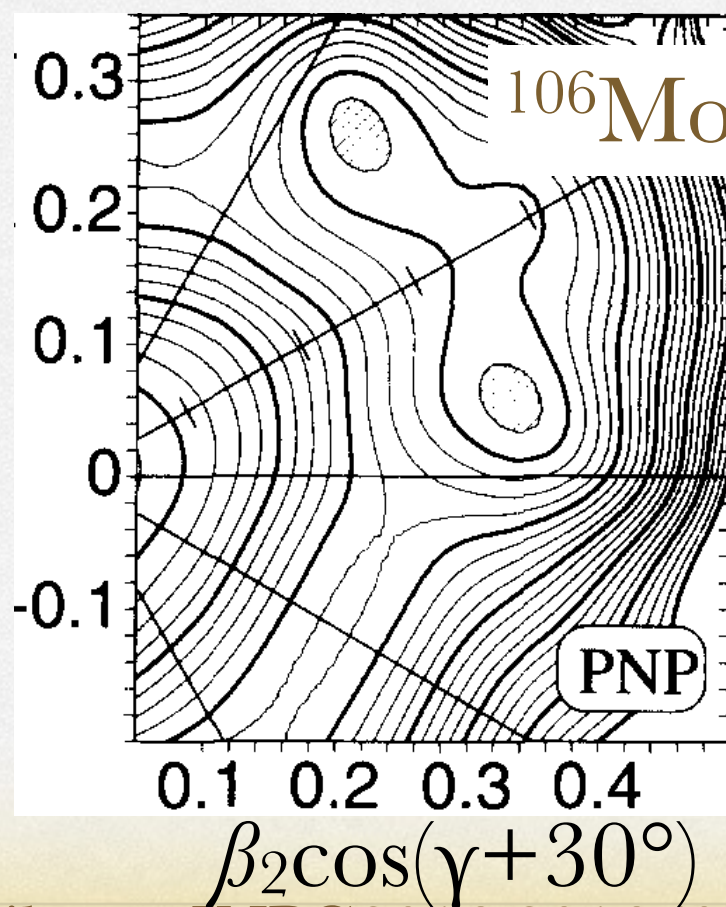
$N = 64$

Skalski et al., NPA617, 282 (1997)

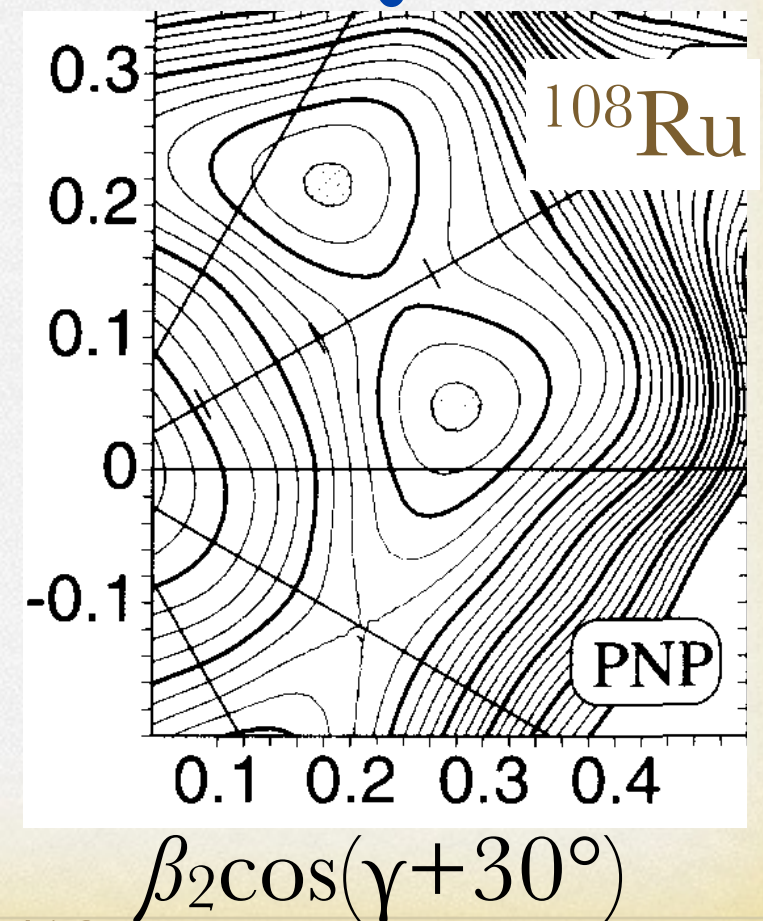
$Z = 40$



$Z = 42$



$Z = 44$



SHAPE EVOLUTION OF Zr, Mo & Ru ISOTOPES

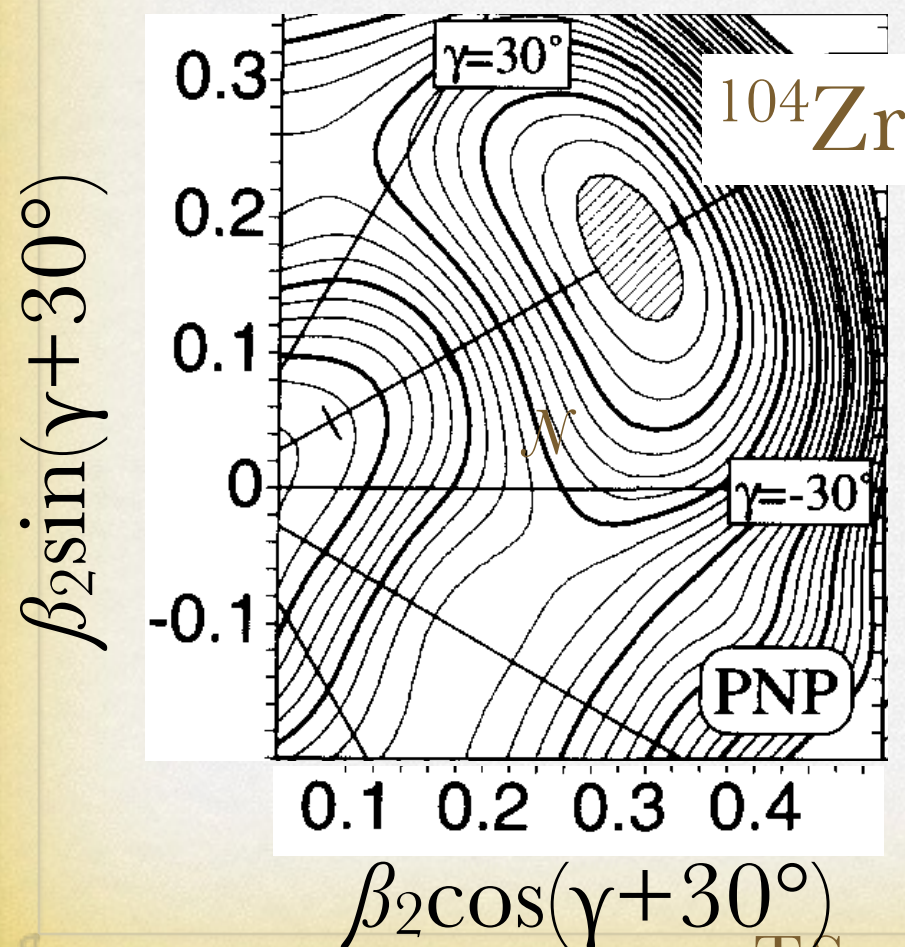
- * Shape evolution beyond $N = 60$
- * Zr isotopes: prolate shape with axial symmetry
- * Mo & Ru isotopes: triaxial deformation or γ soft
- * Aim

* β_2 : $\tau(2_1^+)$, $E(2_2^+)$: γ softness,

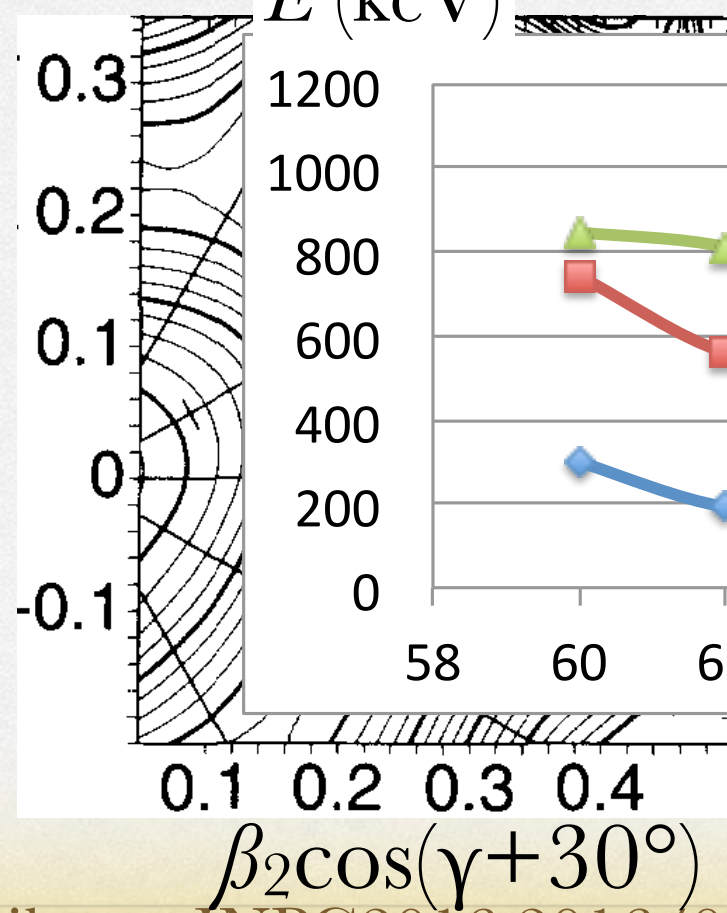
$N = 64$

Skalski et al., NPA617, 282 (1997)

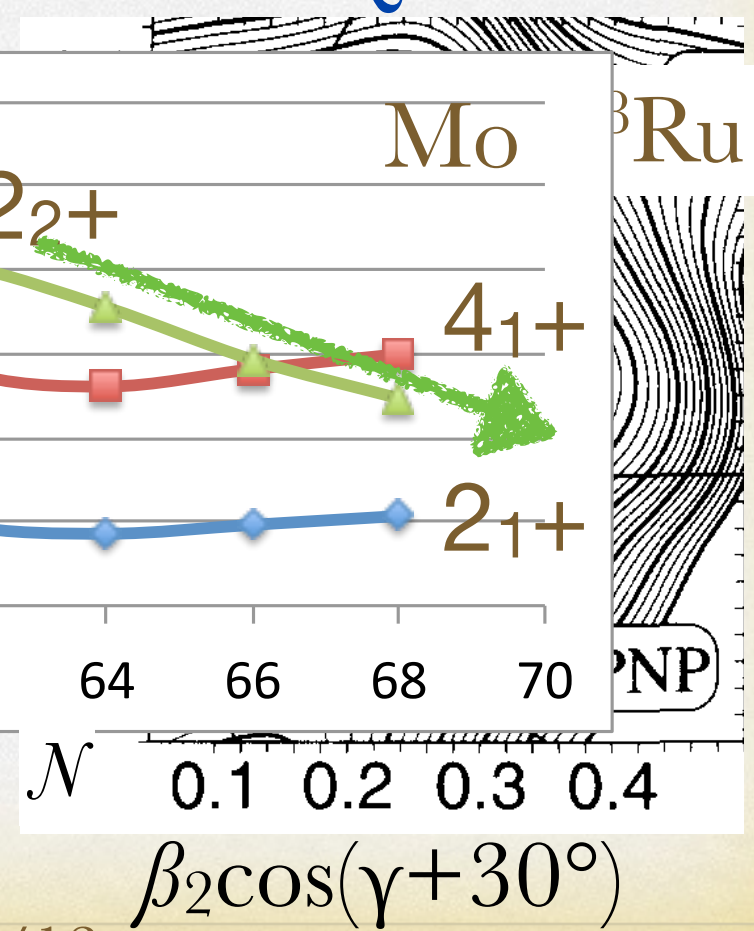
$Z = 40$



$Z = 42$



$Z = 44$



ISOMER SEARCH AROUND ^{108}Zr

✱ Previous

Long-lived isomer in even-even nucleus (620 ± 150 ns)

Energy > 1 MeV, Spin > 4

1. Tetrahedral shape isomer
magic at $Z = 40, N = 70$

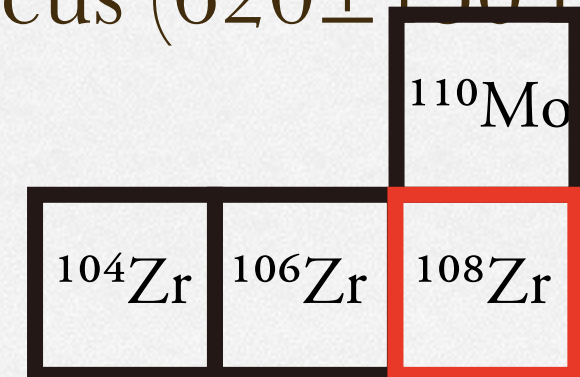
2. K isomer



2 quasiparticle states

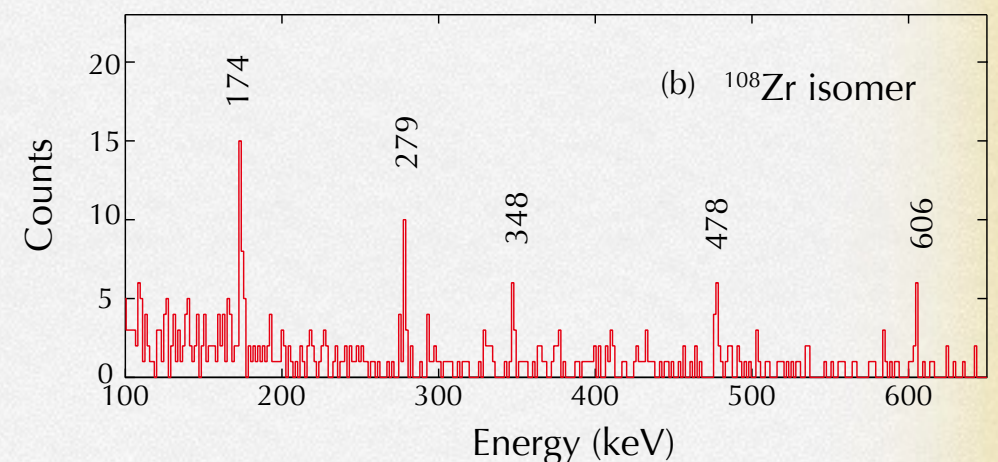
Aim

Level scheme of ^{108}Zr

Search for isomer in even-even nuclei



 Isomer was observed
 No isomer was observed



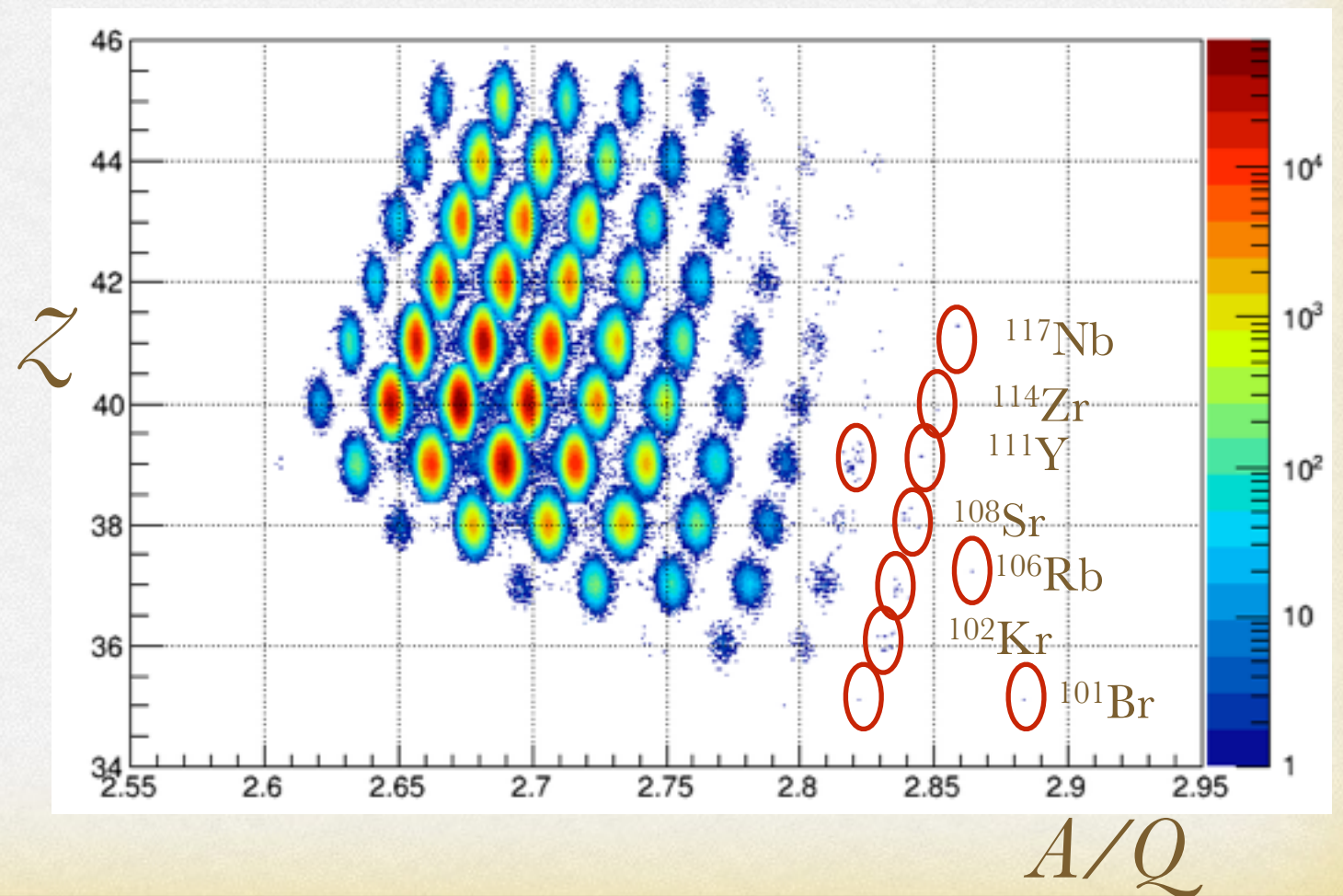
T. S et al.,
PRL 106, 202501 (2011).

Decay spectroscopy using EURICA and $\text{LaBr}_3(\text{Ce})$ at RIBF

SECONDARY BEAM PRODUCTION



Isomeric state: produced by in-flight fission reaction

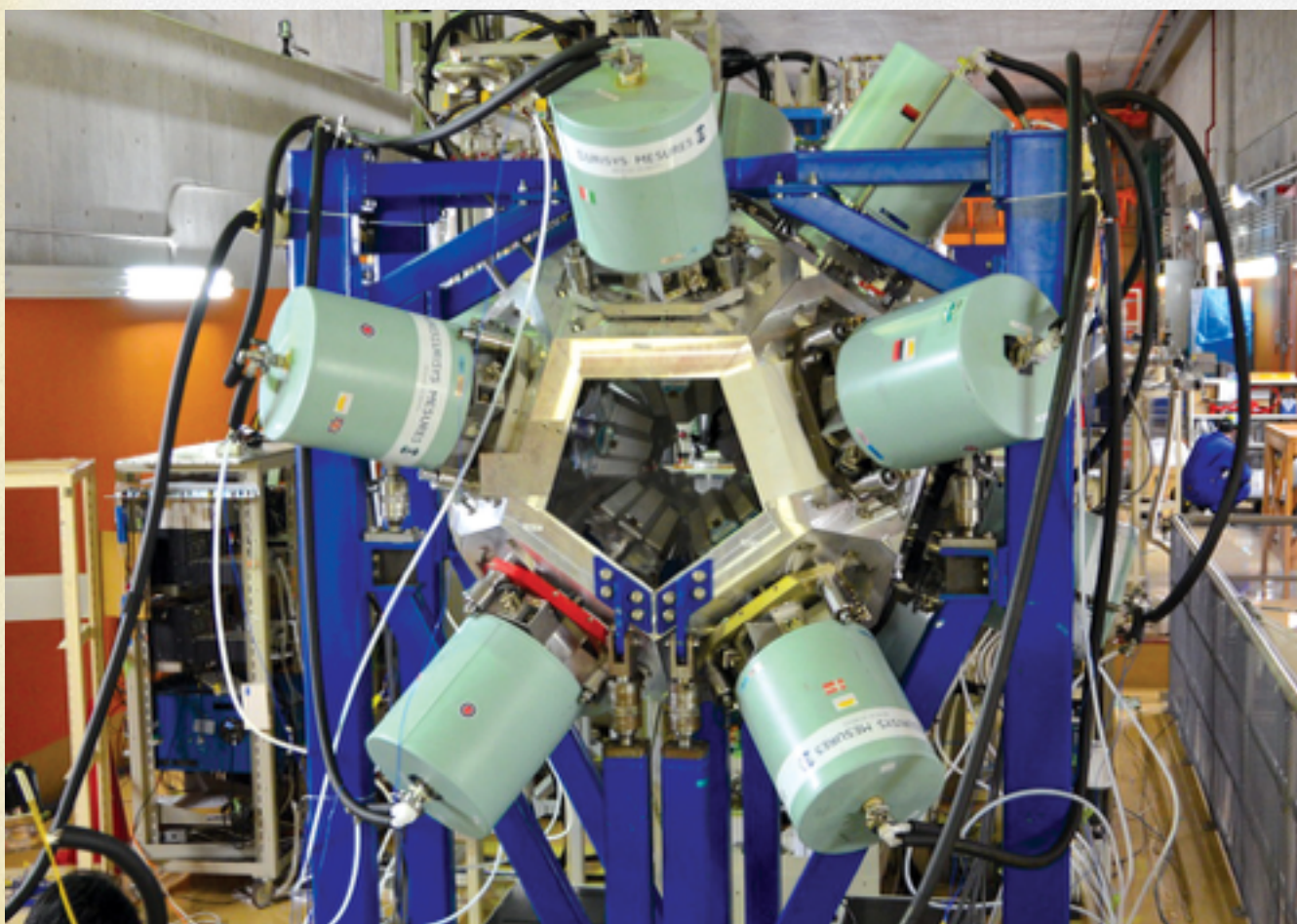


EURICA

✱ EUROBALL Array (γ ray detection)

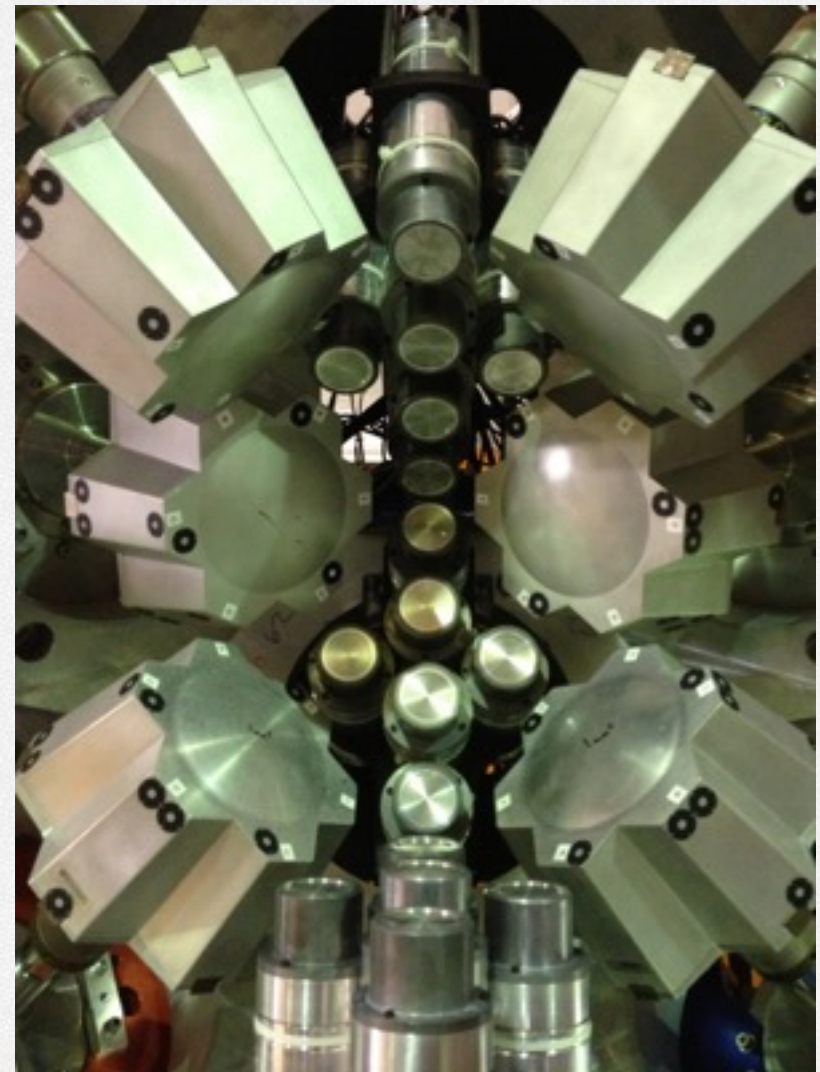
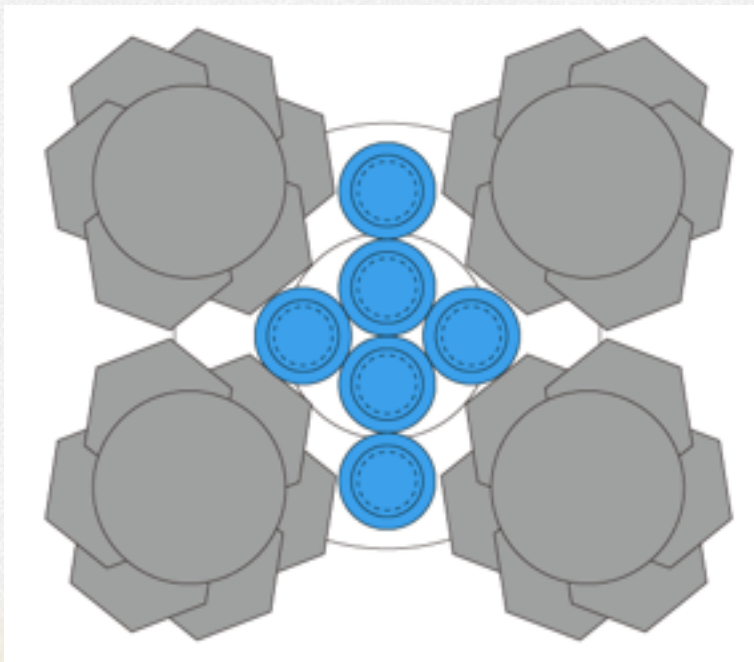
✱ WAS3ABi (Implantation Si array)

5 DSSDs (60x40x1 mm)
2 Plastic Sci. (2mm)



FAST TIMING ARRAY

- ✱ 12 Clusters + 18 LaBr₃ (Ce)
- ✱ LaBr₃(Ce) from UK (Surrey & Brighton)
- ✱ 1.5''x2'' size
- ✱ Deformed even-even nucleus
 - ✱ Lifetime of 1st 2⁺ state
 - ✱ longest case: 3 ns around ¹⁰⁴Zr



Lifetime measurements of 2_1^+ in $^{104,106}\text{Zr}$

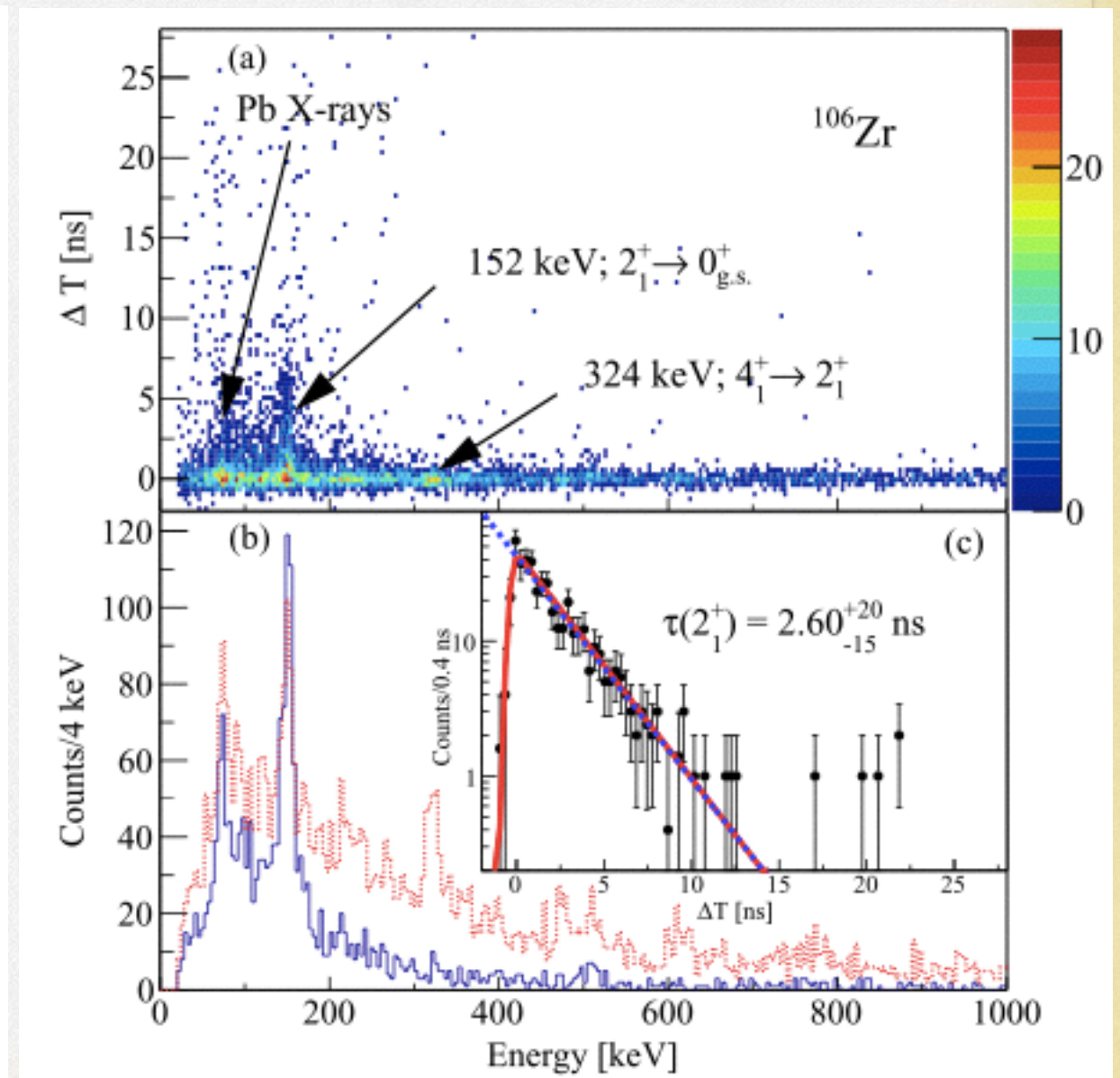
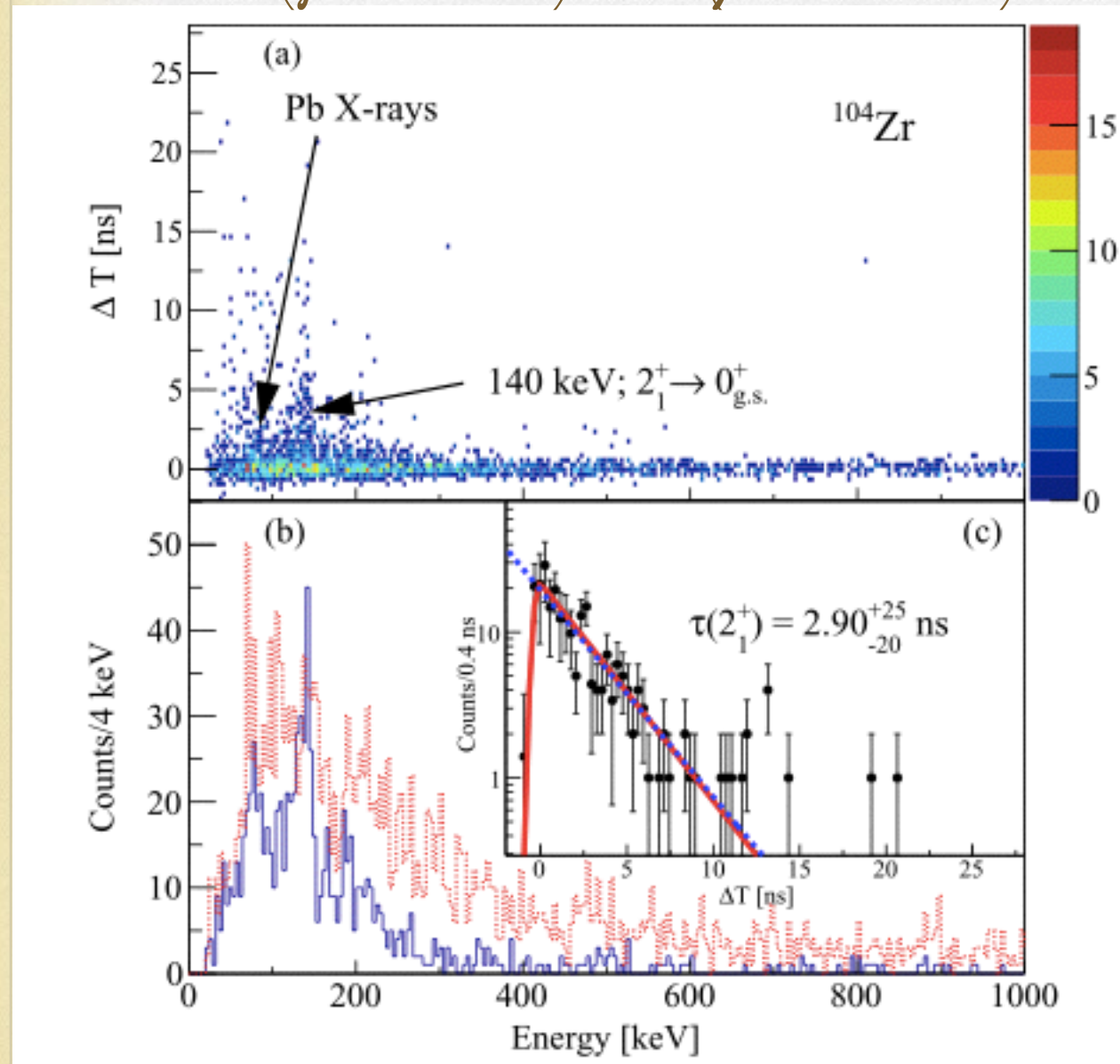
F. Browne, A.M. Bruce, T.S. et al., PLB 750, 448 (2015)

Life-time measurement of 2^+ states in $^{104,106}\text{Zr}$

✿ γ -ray spectra using LaBr₃ detector for $^{104,106}\text{Zr}$

$$\Delta T = T(\gamma:\text{LaBr}_3) - T(\beta:\text{Plastic})$$

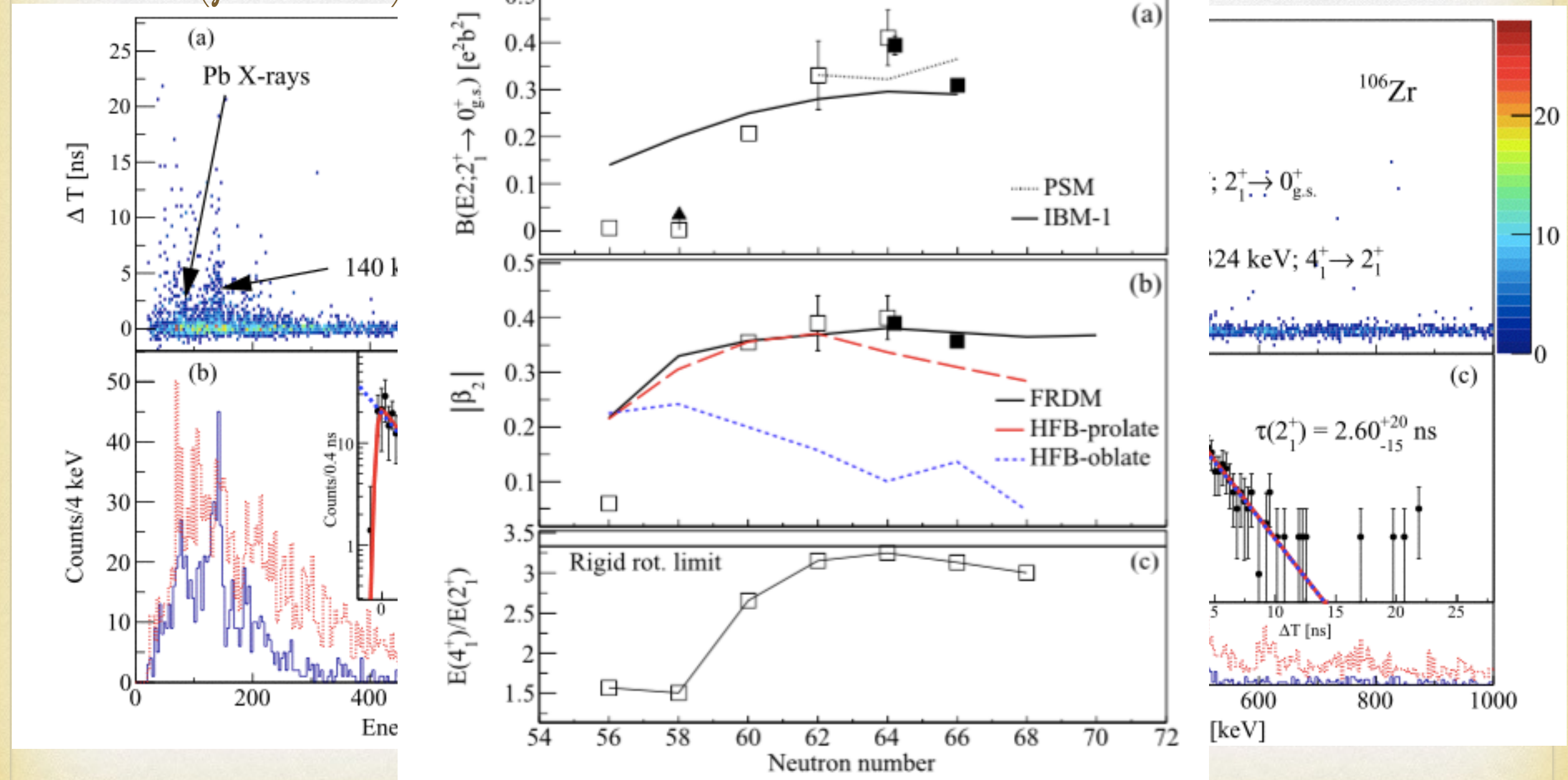
Browne et al., PLB 750, 448 (2015)



Life-time measurement of 2^+ states in $^{104,106}\text{Zr}$

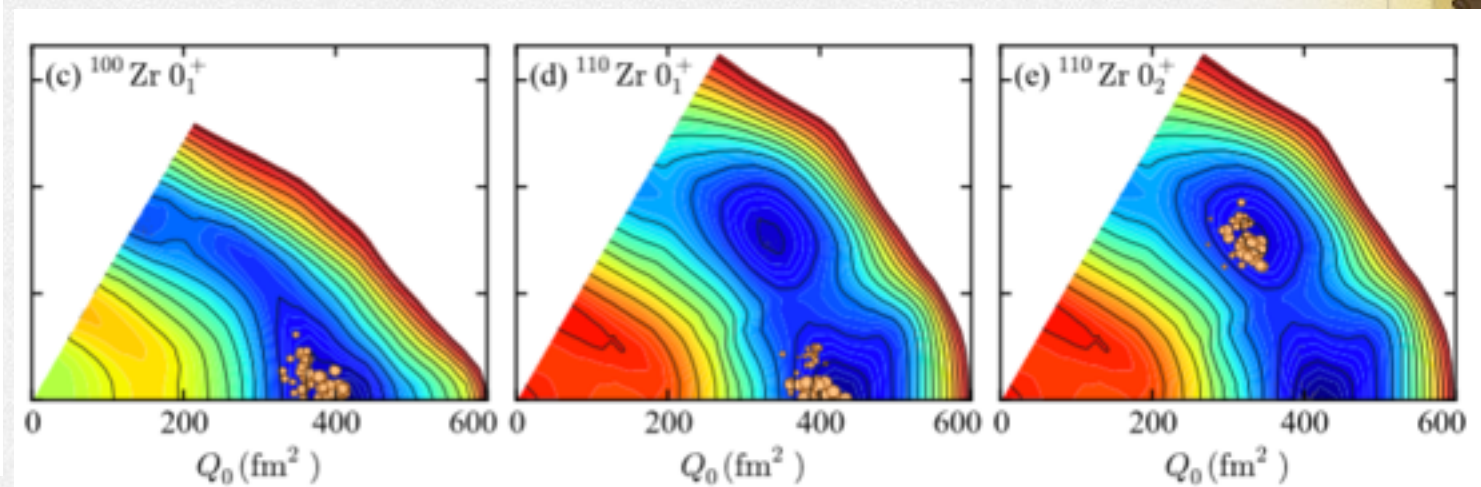
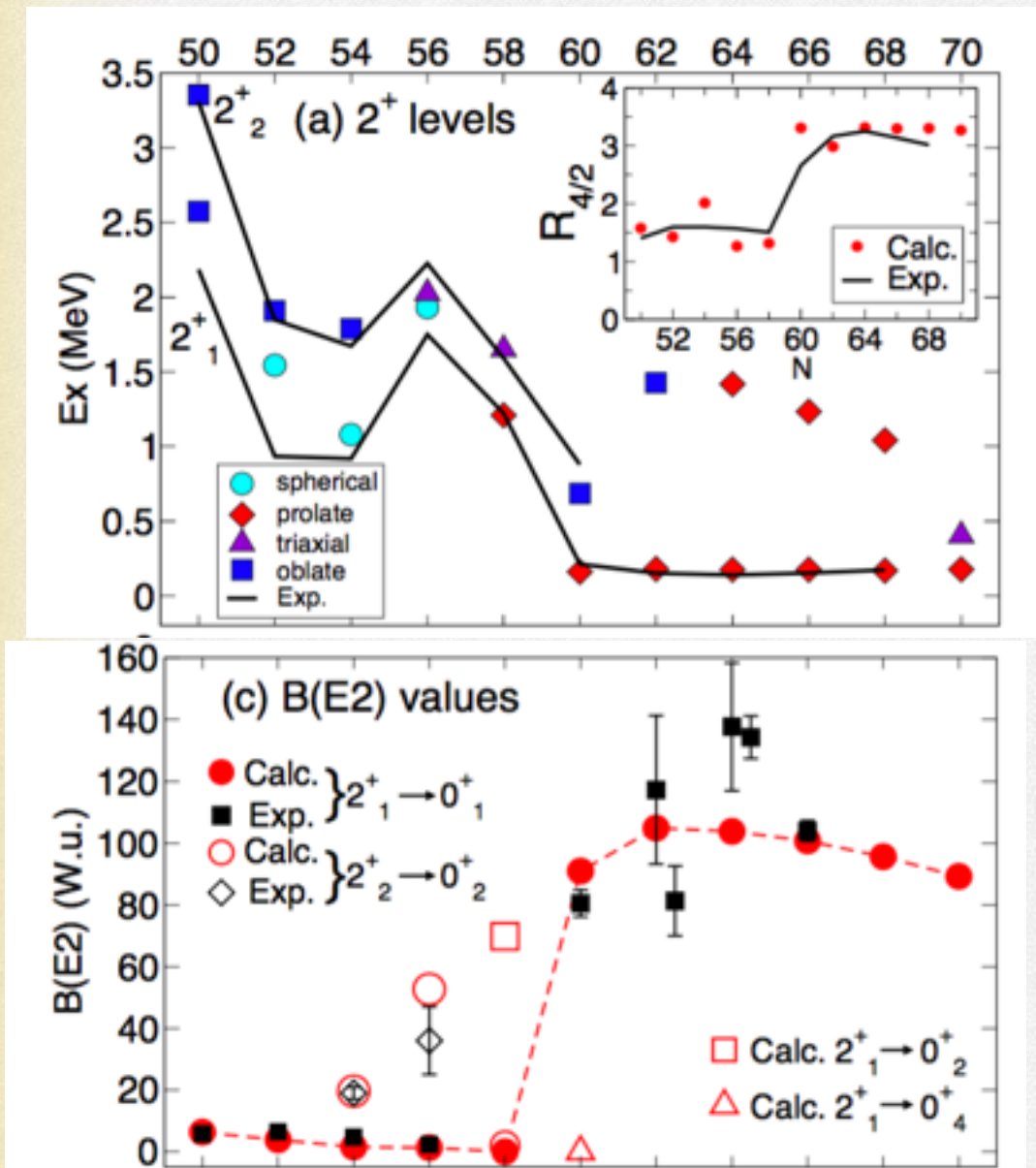
✱ γ -ray spectra using LaBr₃ detector for $^{104,106}\text{Zr}$

$$\Delta T = T(\gamma:\text{LaBr}_3) - T(\gamma:\text{Pb X-rays}) \quad \text{PRL 750, 448 (2015)}$$



SHELL MODEL CALCULATION

✿ Shape transition of Zr isotopes at $N = 60$



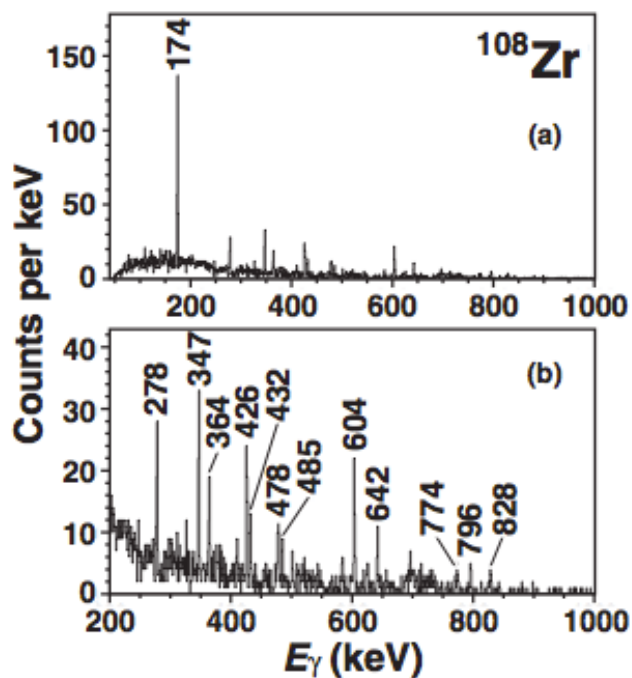
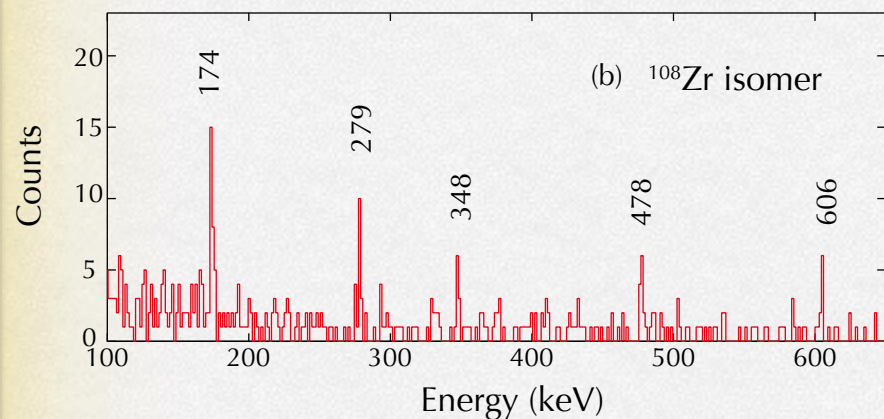
Togashi, Tsunoda, Otsuka, Shimizu, PRL approved.
arXiv:1606.09056v2 [nucl-th]

Isomer search for even-even nuclei in the vicinity of ^{108}Zr

^{108}Zr ISOMER

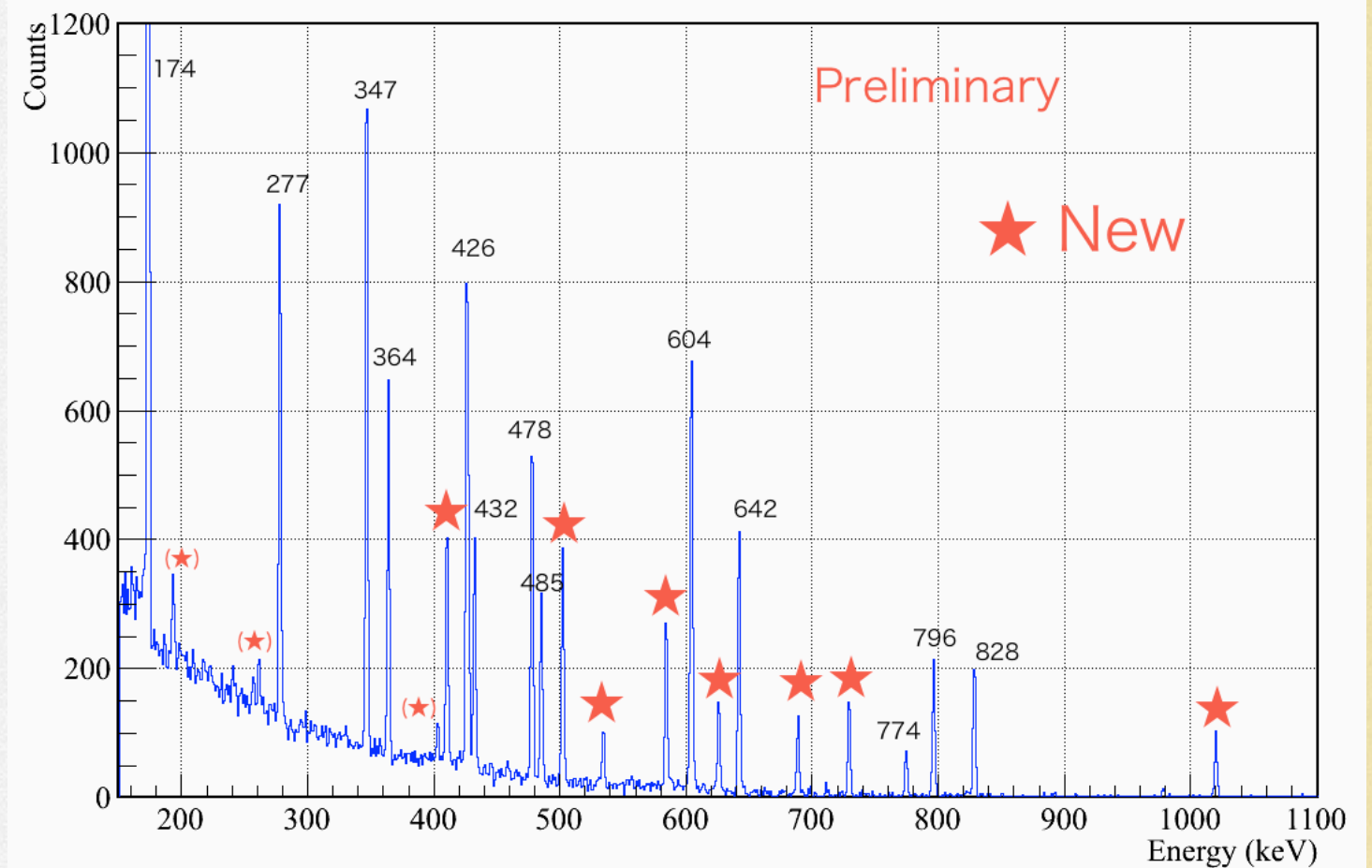
✿ New gamma rays were observed.

✿ Small peaks??



Sumikama et al.,
PRL 106 052502
(2011)

Kameda et al.
PRC 86, 054319(2012)

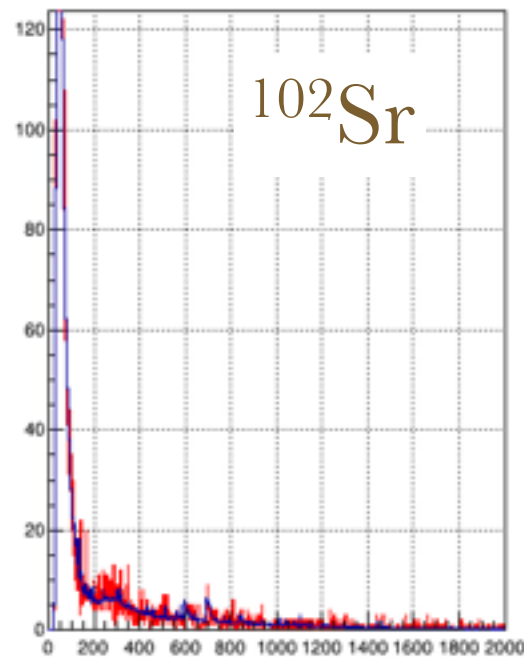


ISOMER SEARCH

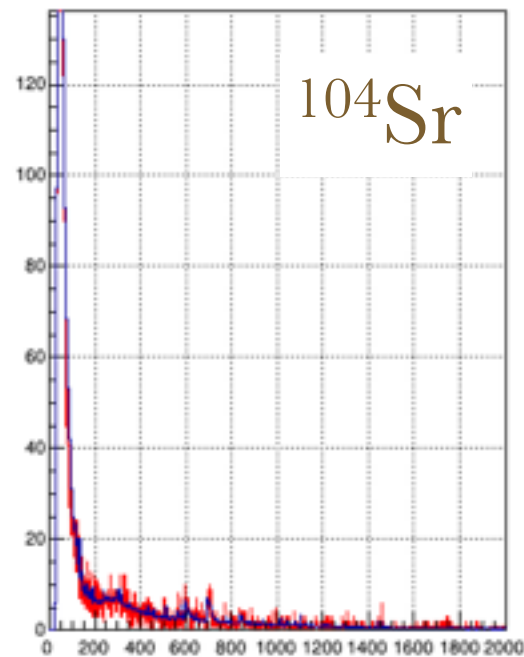
✿ Isomer search for even-even nucleus (up to $10\mu\text{s}$)

		^{110}Mo	^{112}Mo	^{114}Mo
	^{106}Zr	^{108}Zr	^{110}Zr	
^{102}Sr	^{104}Sr			

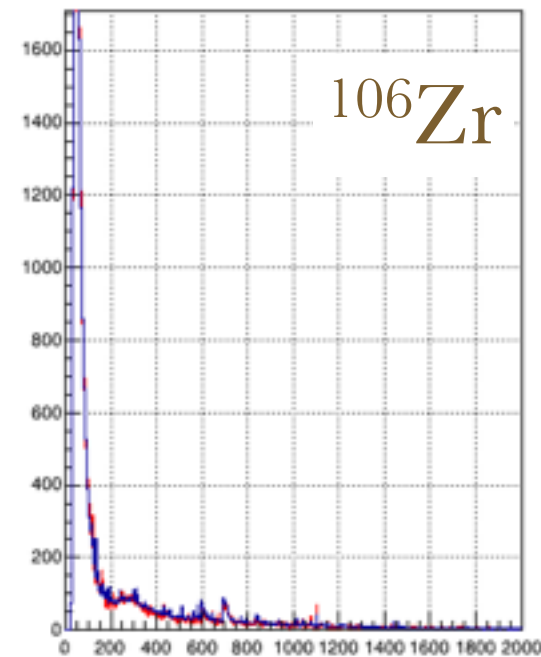
^{102}Sr isomer search



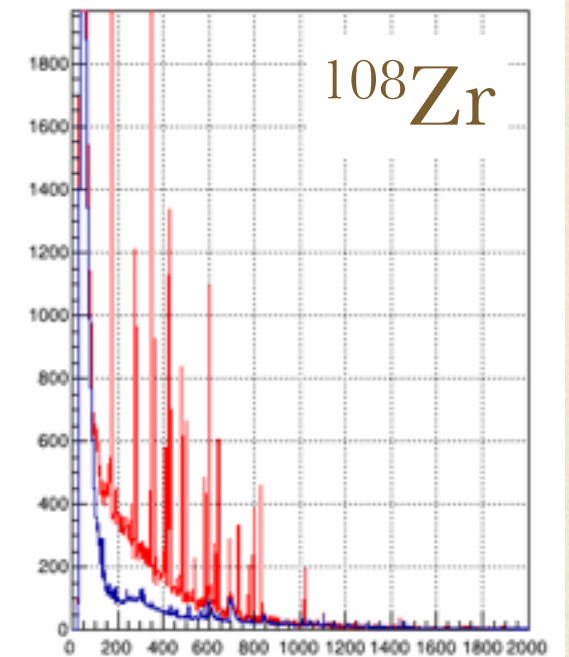
^{104}Sr isomer



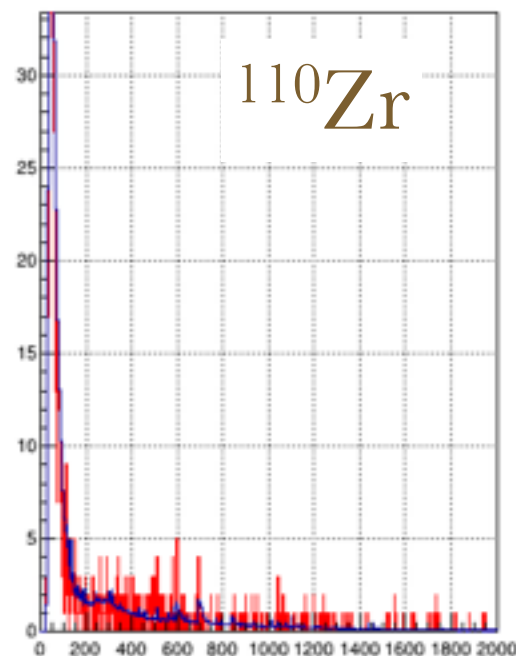
^{106}Zr isomer search



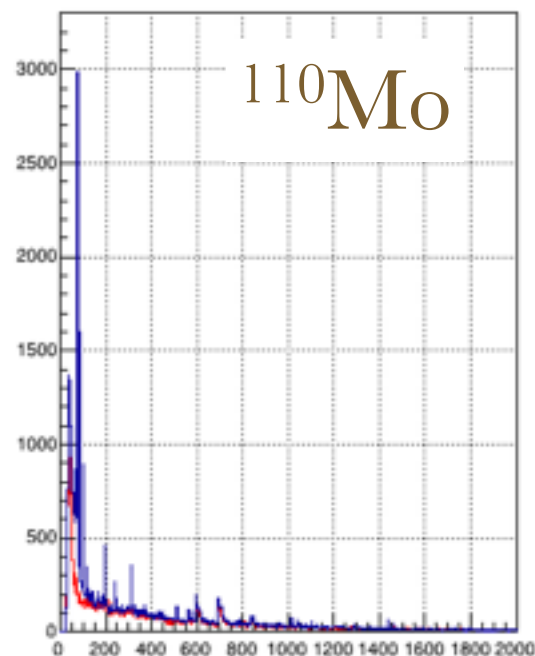
^{108}Zr isomer



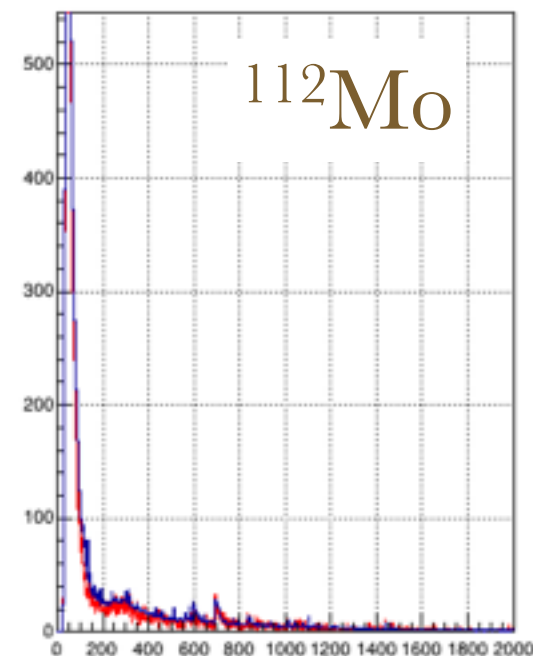
^{110}Zr isomer search



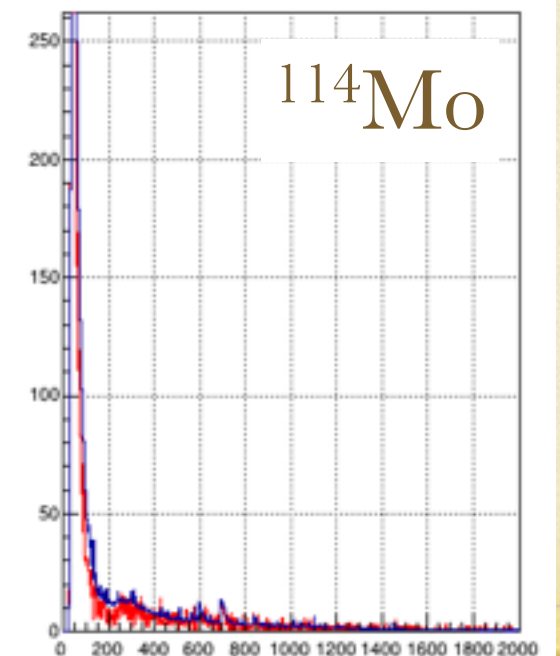
^{110}Mo isomer search



^{112}Mo isomer search

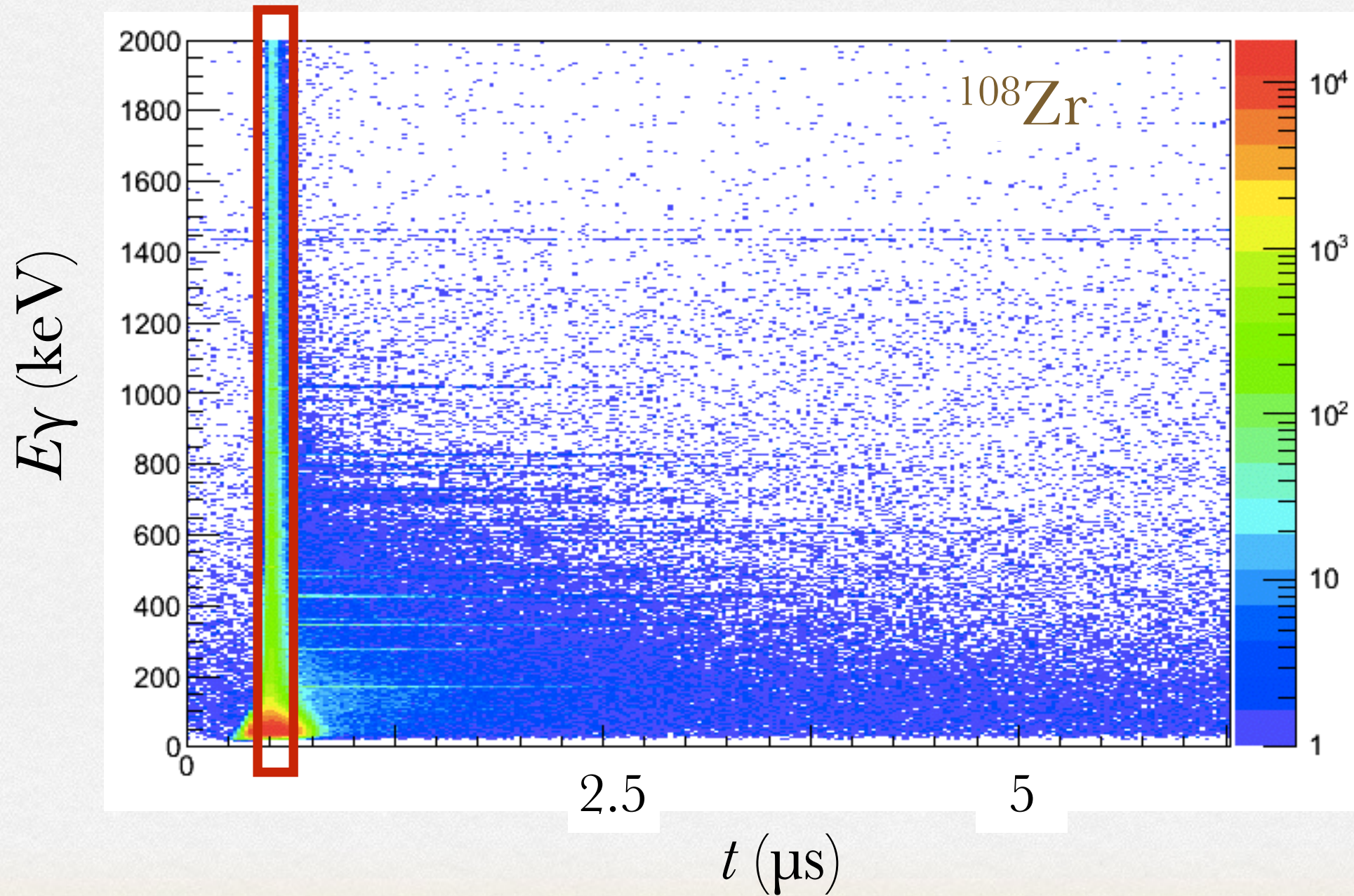


^{114}Mo isomer search



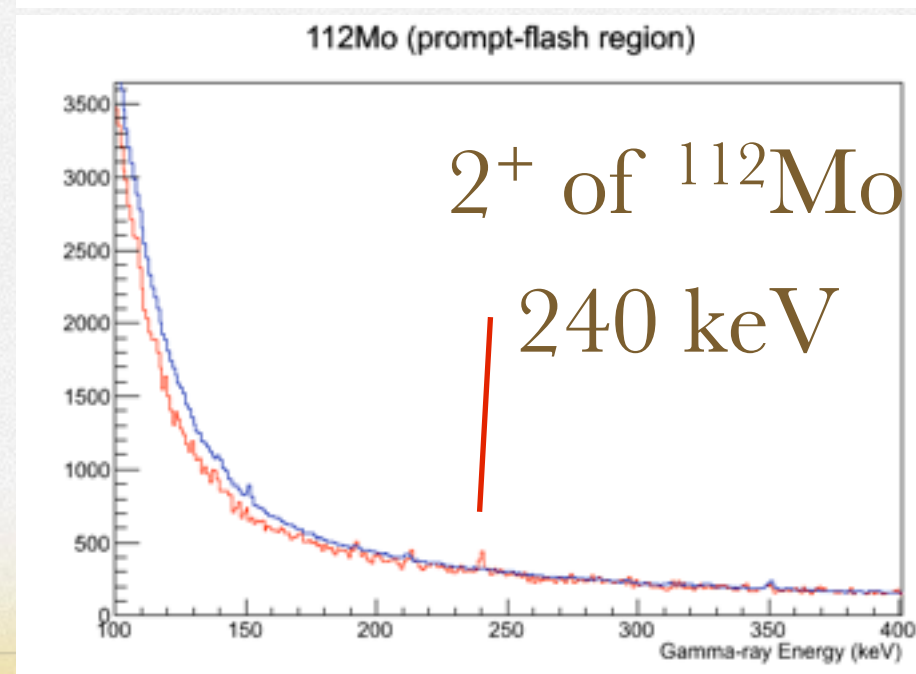
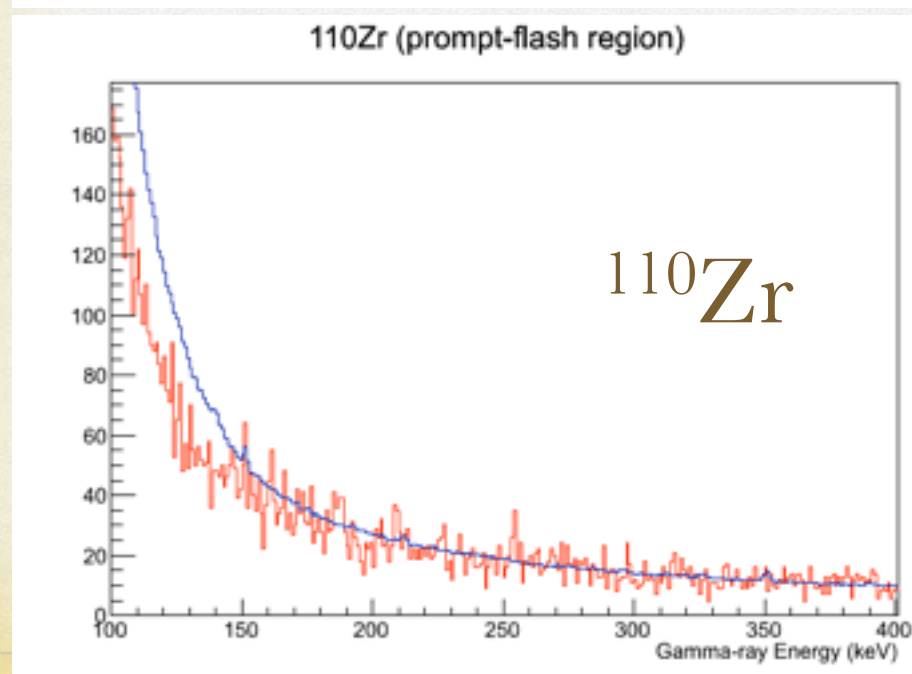
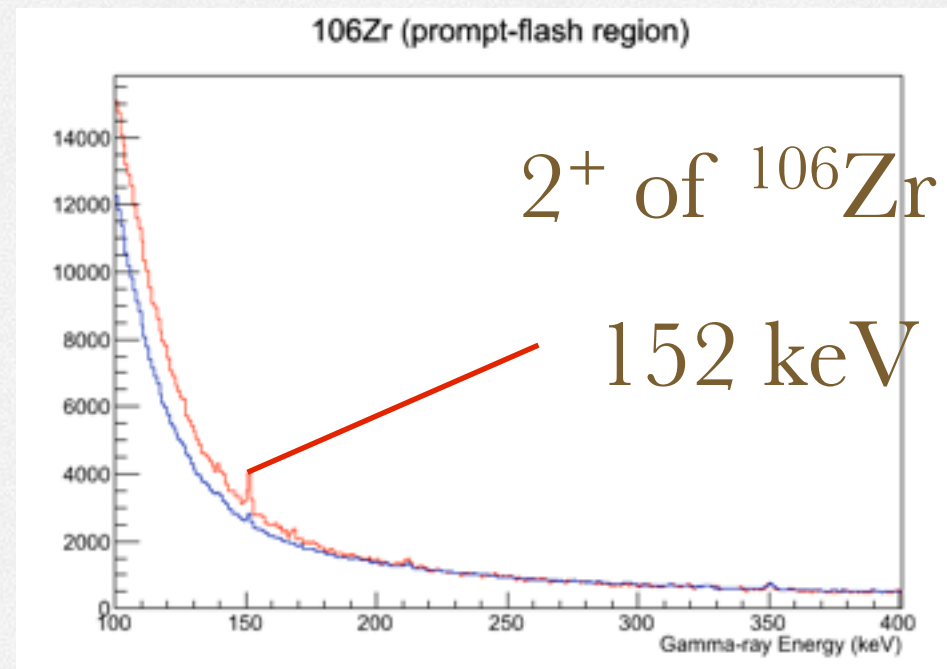
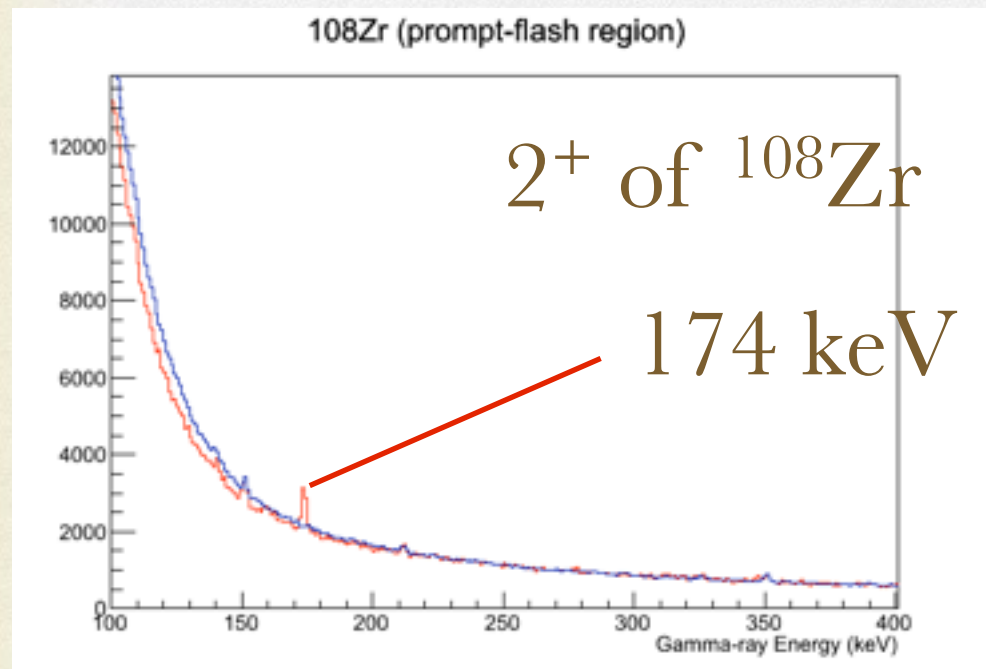
SHORT LIFE?

✱ How about prompt-flash region



PROMPT FLASH REGION

- ✿ Gamma-ray spectra in prompt-flash region
- ✿ Blue: background



SUMMARY

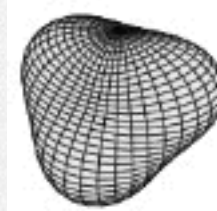
- ✱ Decay spectroscopy in the neutron-rich Zr region with EURICA:
Statistics was much improved by a factor of more than 100.
- ✱ Lifetime of $^{104,106}\text{Zr}$ was measured and shows the maximum deformation at $N=64$.
- ✱ Search for isomeric state in even-even nuclei. But no isomer was found.
- ✱ Future results from EURICA data
Isomer structure of ^{108}Zr
 β Decay spectroscopy of even-even Zr and Mo isotopes
Odd nuclei etc.

Backups

TETRAHEDRAL SHAPE IN ^{110}Zr

✿ Doubly magic for the tetrahedral shape.

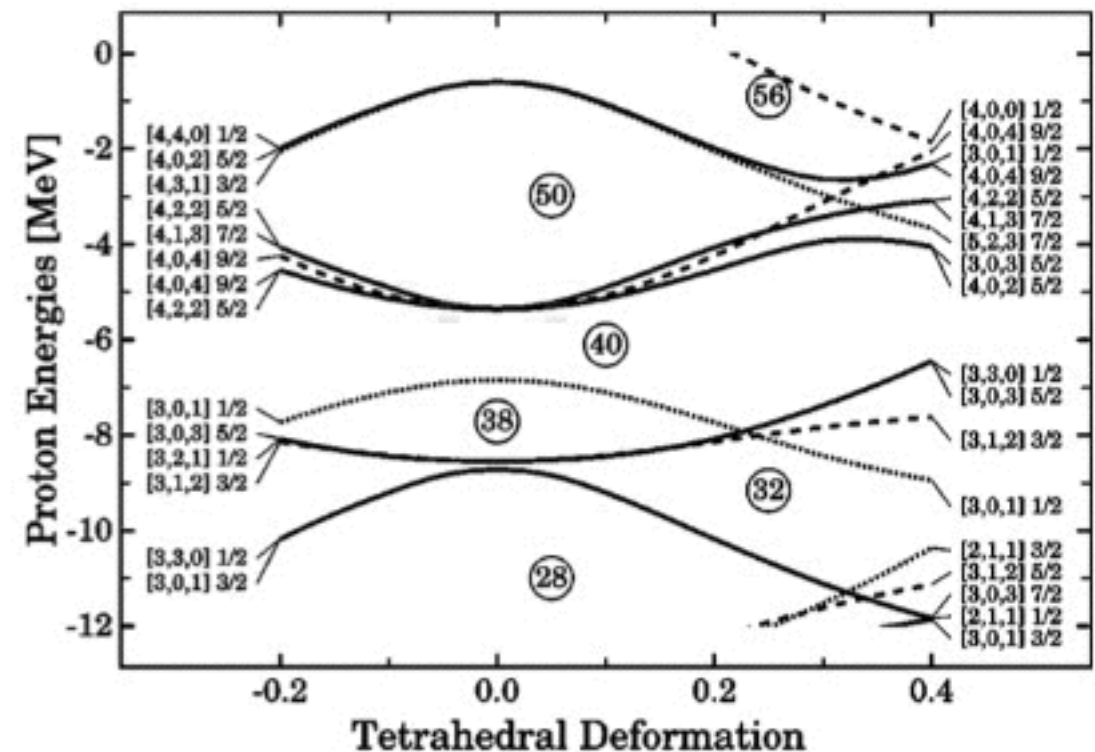
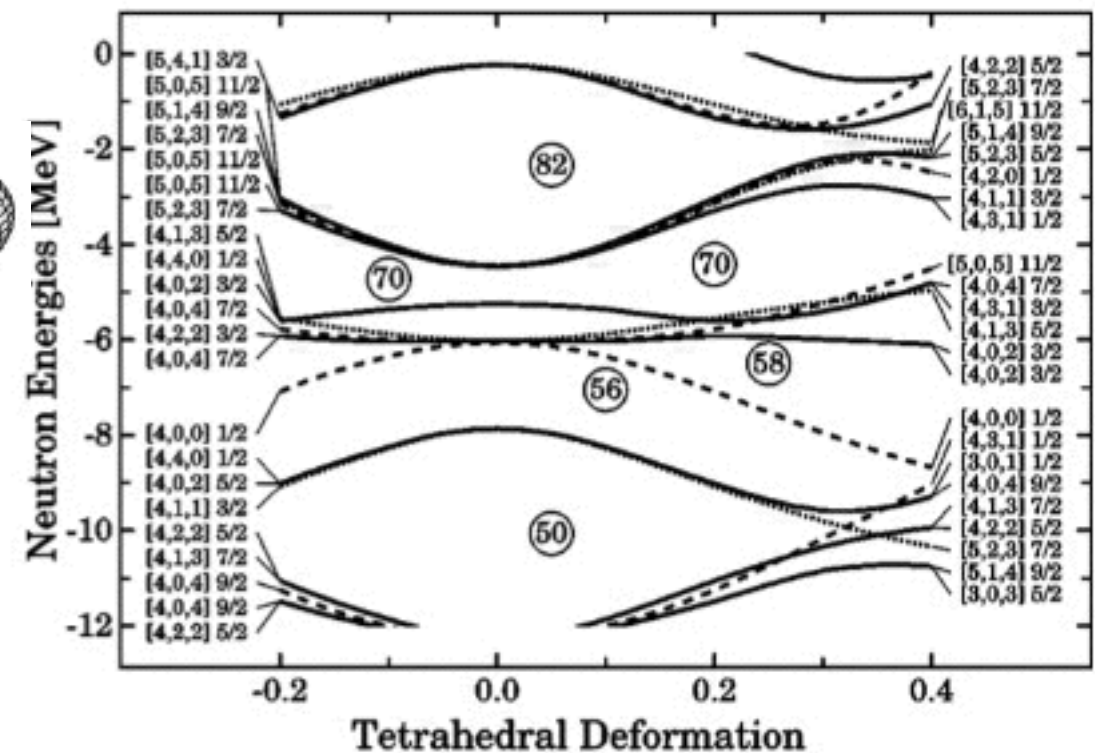
✿ $Z = 40, N = 70$



J. Dudek et al., PRL 88, 252502 ('02).

N. Schunck et al., PRC 69, 061305(R) ('04).

✿ Competition among other shapes:
Spherical shape,
Prolate & Oblate



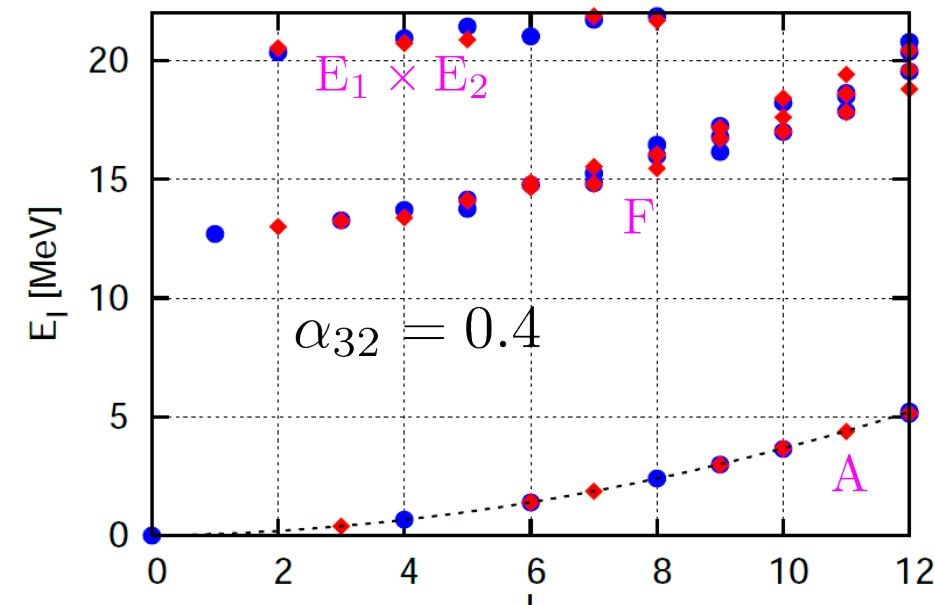
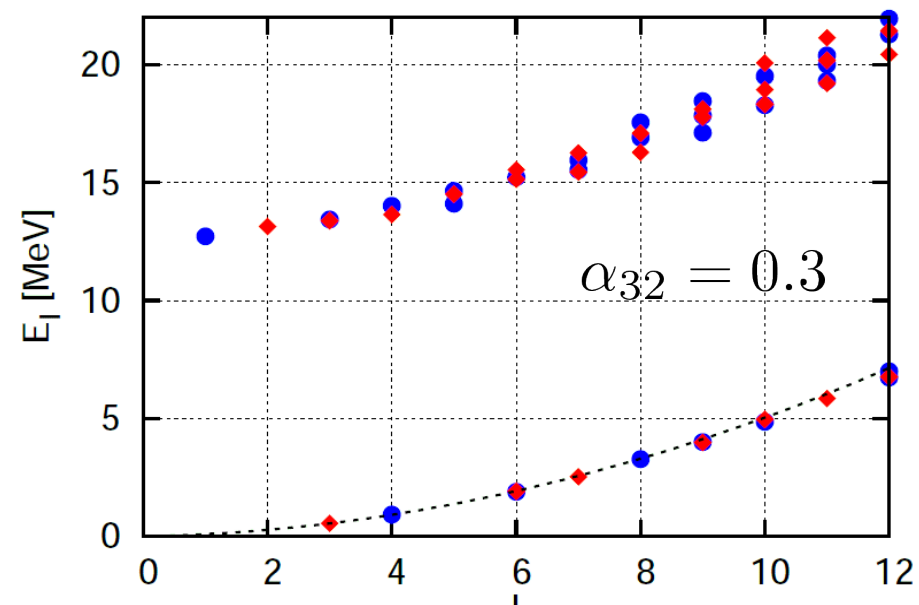
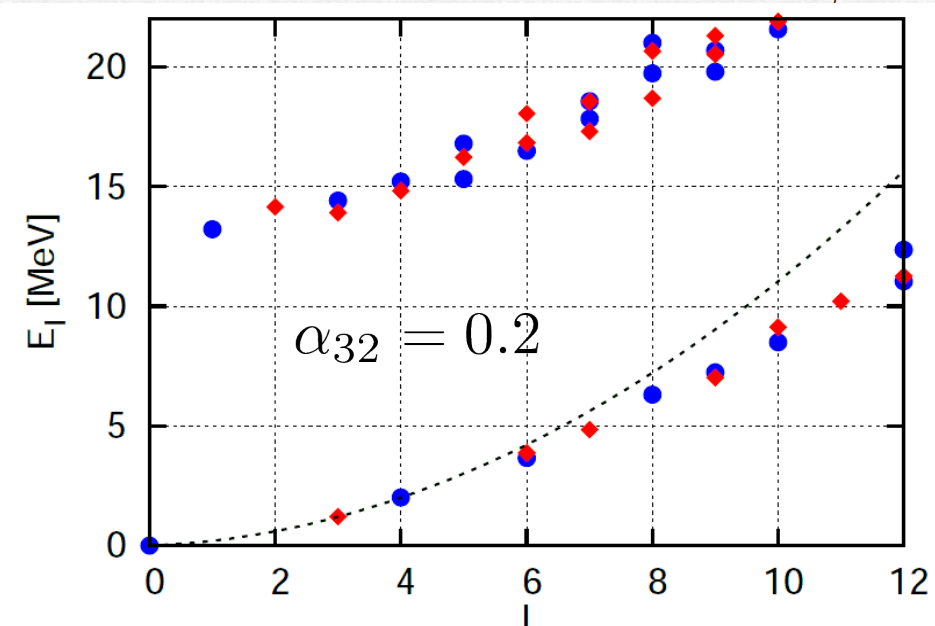
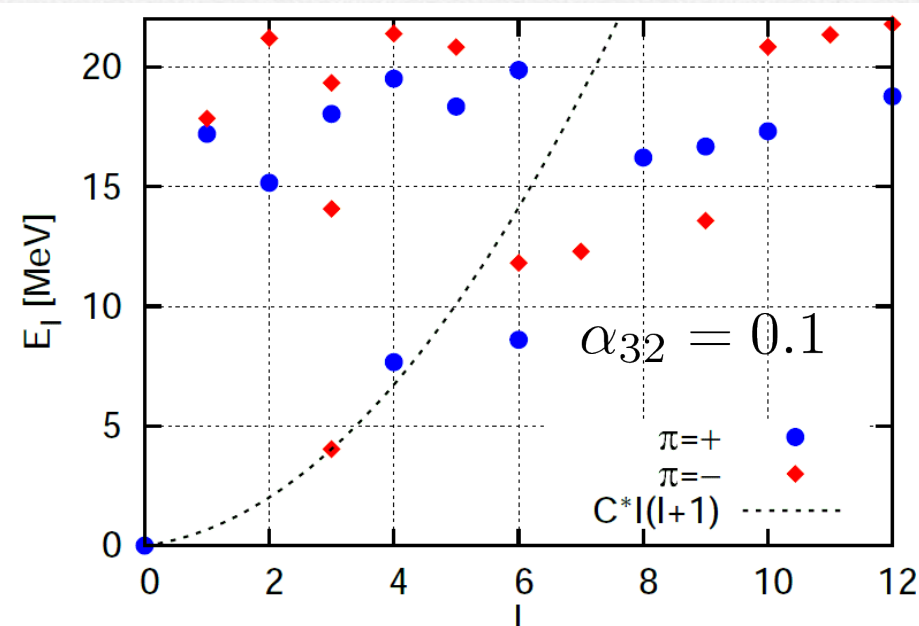
LEVELS OF TETRAHEDRAL SHAPE

✿ Case of ^{110}Zr

S. Tagami, Y.R. Shimizu,
J. Dudek

PTP Supl 196 334 (2012)

PRC 87, 054306 (2013).

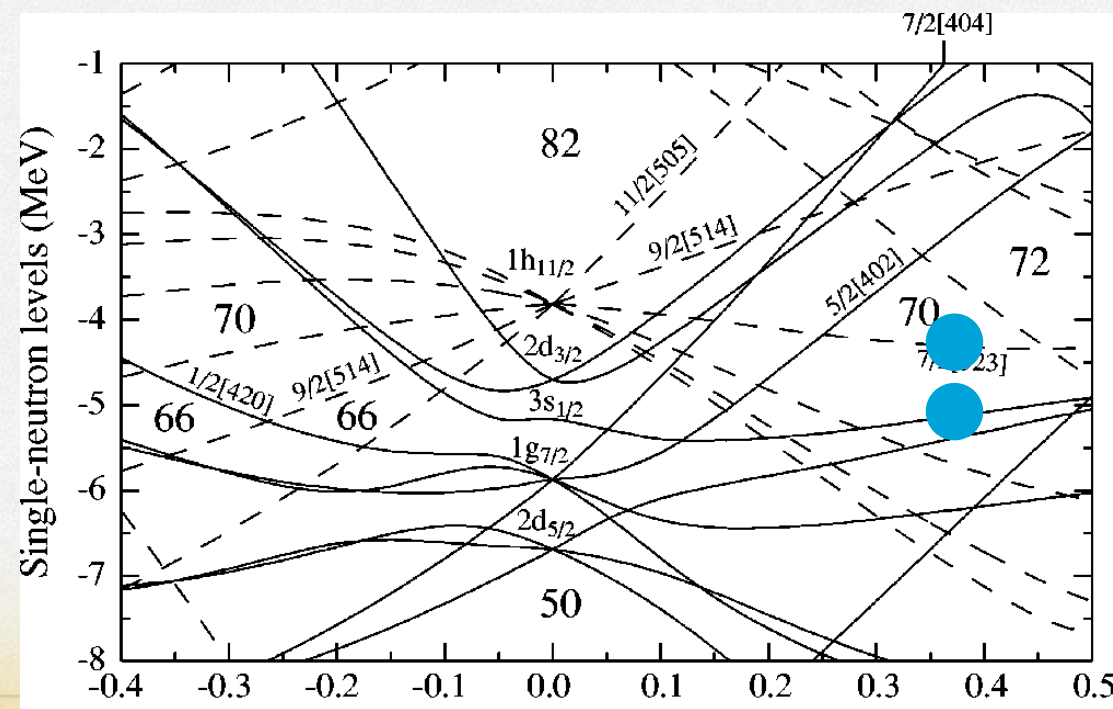


HIGH K ISOMER?

✿ Example

Nuclide	K^π	Configuration	β_2	γ°	β_4	E (MeV)
^{108}Zr	0^+	vacuum	0.353	1.0	-0.03	0.0
	4^-	$\nu \frac{7}{2}^- [523] \otimes \frac{1}{2}^+ [411]$	0.357	1.5	-0.03	1.414
	6^+	$\nu \frac{7}{2}^- [523] \otimes \frac{5}{2}^- [532]$	0.333	0.0	-0.04	1.997
	3^+	$\nu \frac{5}{2}^+ [402] \otimes \frac{1}{2}^+ [411]$	0.327	5.6	-0.02	2.165
	5^-	$\nu \frac{5}{2}^+ [402] \otimes \frac{5}{2}^- [532]$	0.309	0.1	-0.03	2.561
	4^-	$\pi \frac{3}{2}^- [301] \otimes \frac{5}{2}^+ [422]$	0.322	0.0	-0.03	2.326
	5^-	$\pi \frac{5}{2}^- [303] \otimes \frac{5}{2}^+ [422]$	0.313	1.2	-0.02	2.726
	3^-	$\pi \frac{3}{2}^- [301] \otimes \frac{3}{2}^+ [431]$	0.307	0.3	-0.03	3.421

Shi et al.,
PRC 85, 027307 (2012).



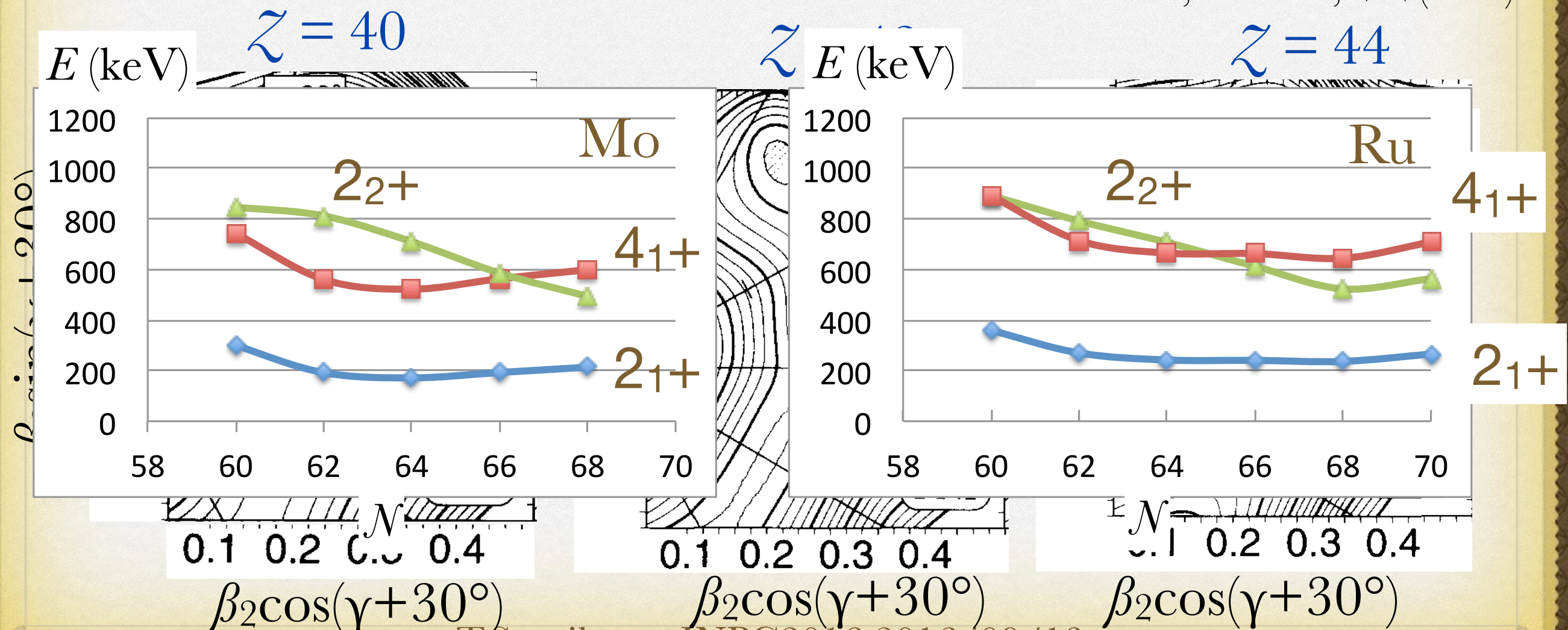
Xu et al.,
PRC 65, 021303 (2002).

SHAPE EVOLUTION OF ZR, MO & RU ISOTOPES

- * Shape evolution beyond $N = 60$
- * Zr isotopes: prolate shape with axial symmetry
- * Mo & Ru isotopes: triaxial deformation or γ soft

$N = 64$

Skalski et al., NPA617, 282 (1997)



EVOLUTION OF 2ND 2+ STATE IN ZR ISOTOPES

✱ ^{106}Zr case

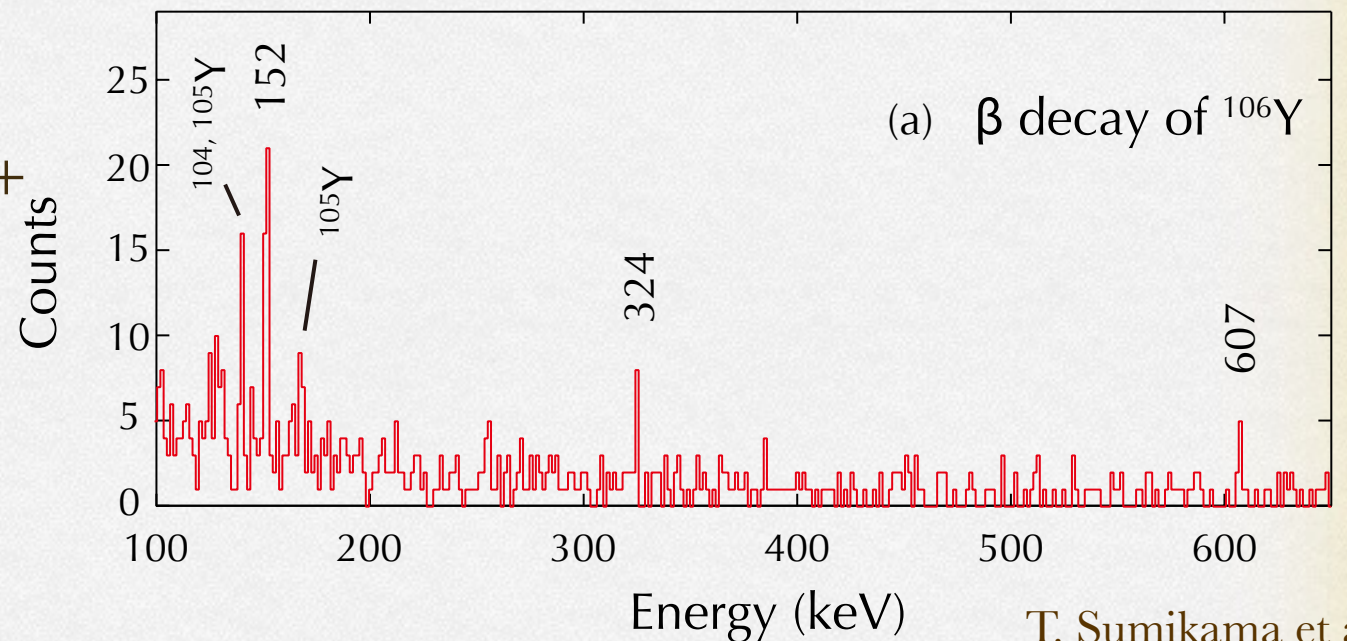
✱ 607 keV: $2_2^+ \rightarrow 0_1^+$

✱ Prediction (IBM)

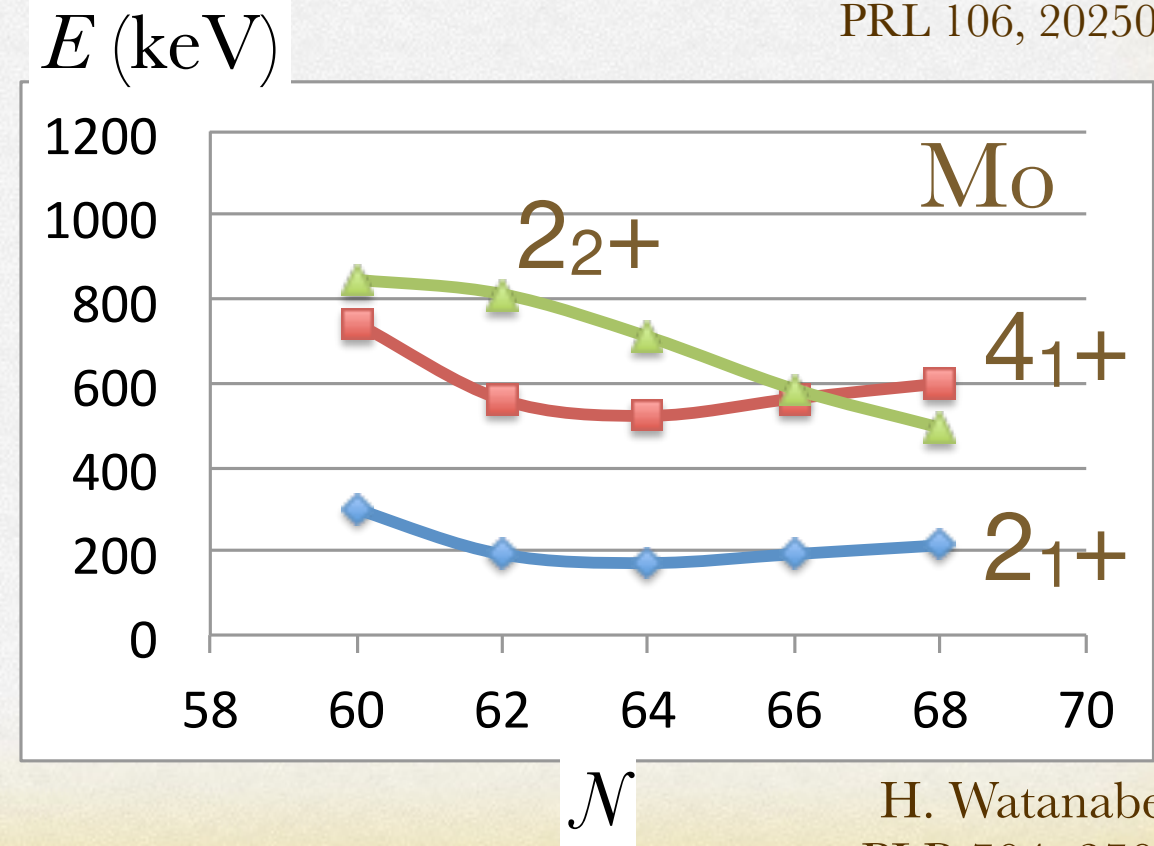
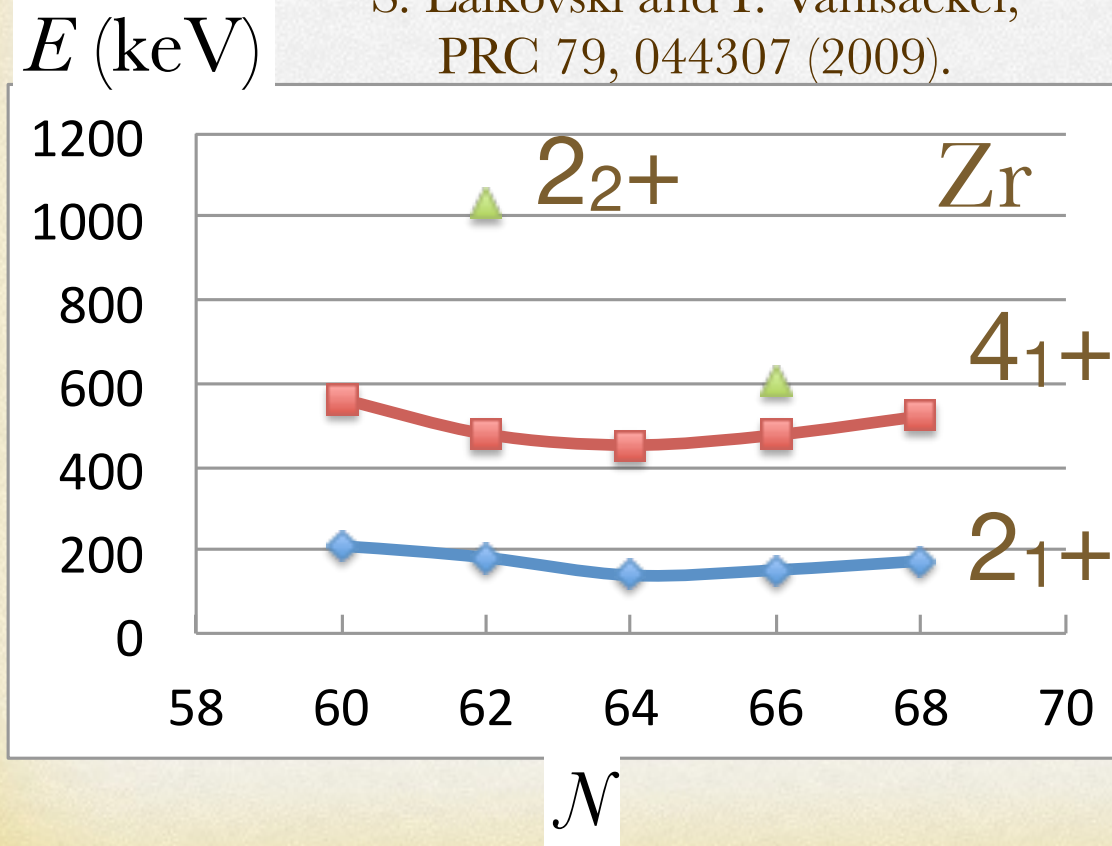
$$E(4_1^+) = 455 \text{ keV}$$

$$E(2_2^+) = 618 \text{ keV}$$

S. Lalkovski and P. Vanlsacker,
PRC 79, 044307 (2009).



T. Sumikama et al.,
PRL 106, 202501 (2011).



H. Watanabe et al.,
PLB 704, 270 (2011).

EVOLUTION OF 2ND 2+ STATE IN ZR ISOTOPES

✱ ^{106}Zr case

✱ 607 keV:

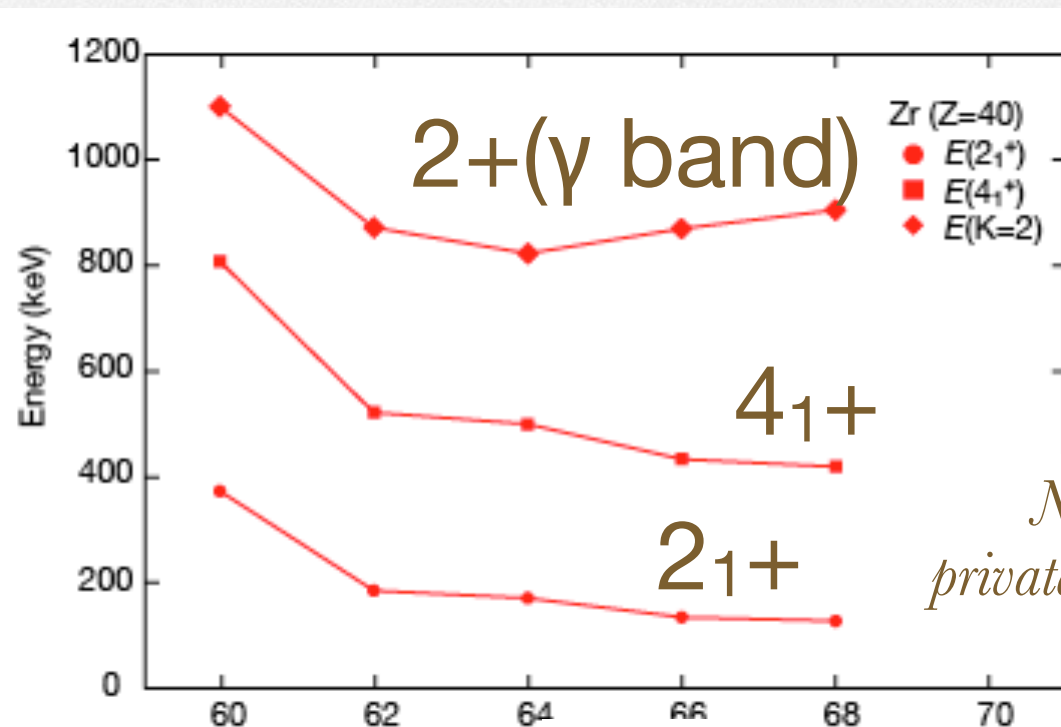
✱ Prediction (

$$E(4_1^+) = 455$$

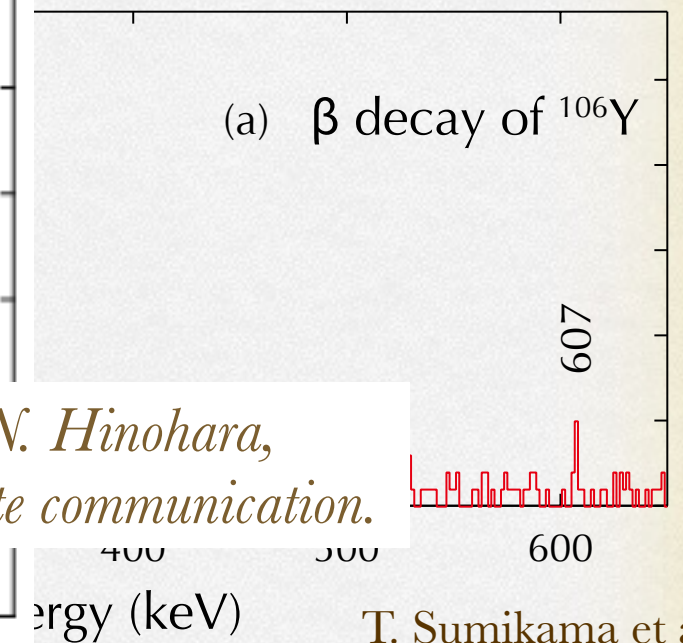
$$E(2_2^+) = 618$$

S. Lalkovski et al.

PRC 79, 011307 (2009).

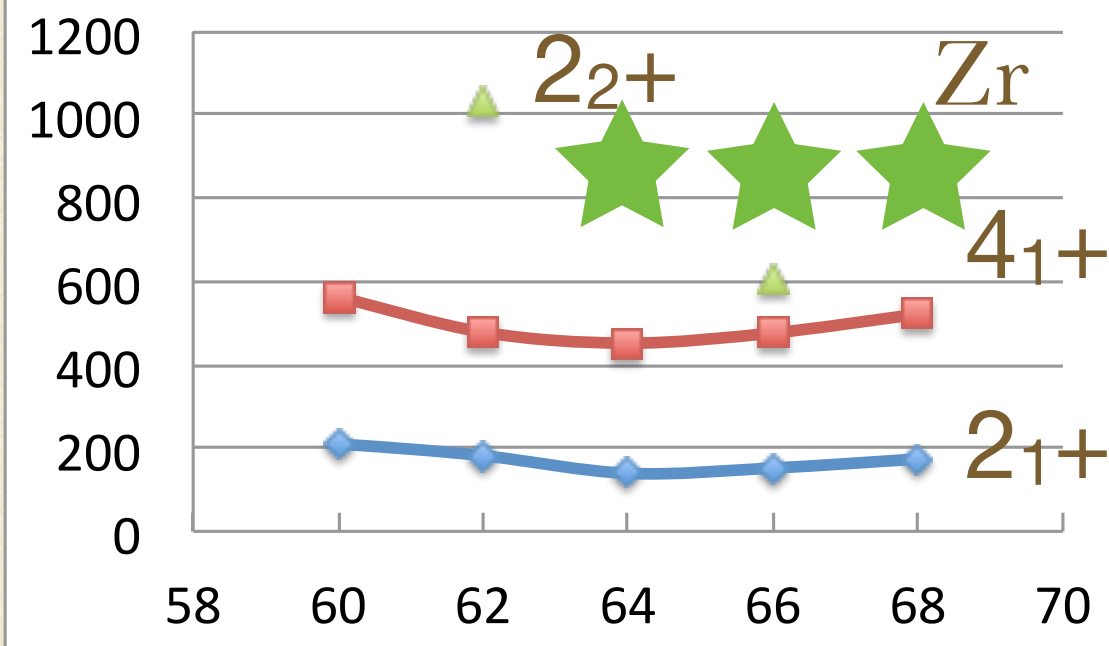


N. Hinohara,
private communication.



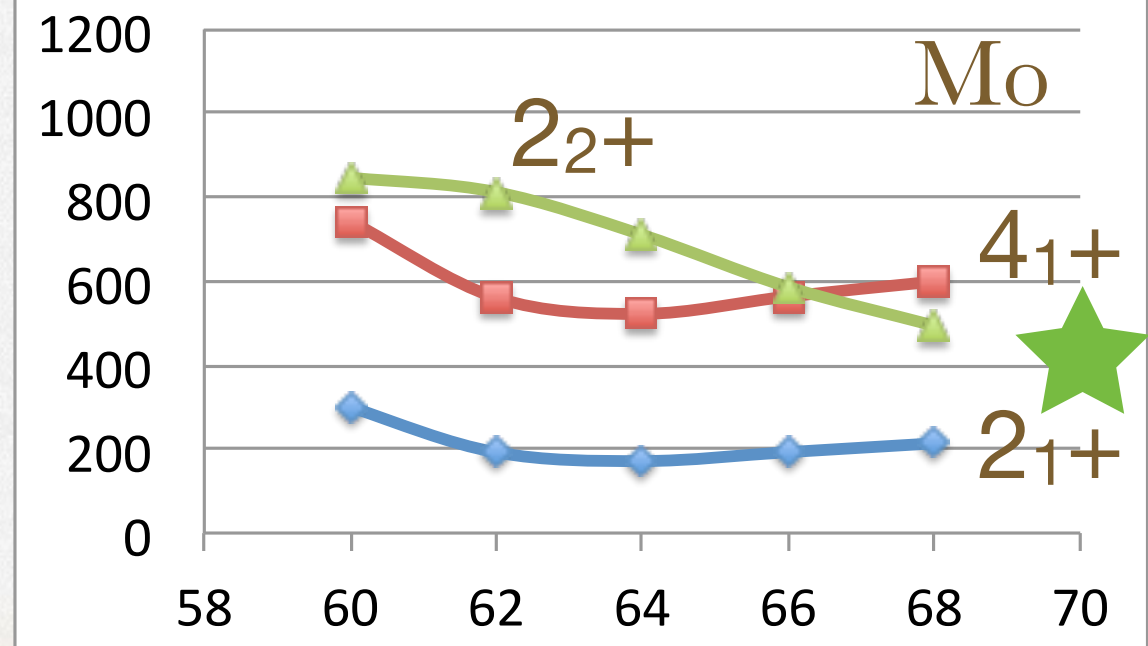
T. Sumikama et al.,
PRL 106, 202501 (2011).

E (keV)



N

E (keV)



N

H. Watanabe et al.,
PLB 704, 270 (2011).