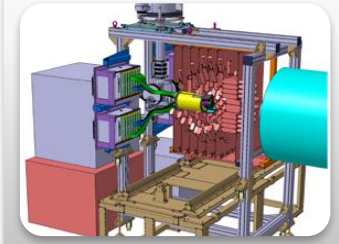
FROM RESEARCH TO INDUSTRY

Latest SEASTAR Results with MINOS+DALI2 in the ^{110}Zr region

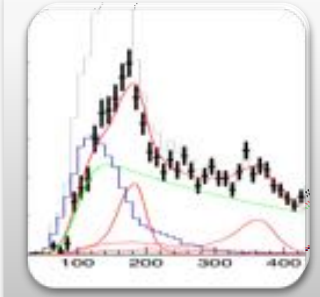
NUSTAR Annual Meeting, March 2017
Nancy Paul
CEA Saclay—Université Paris-Saclay

Overview



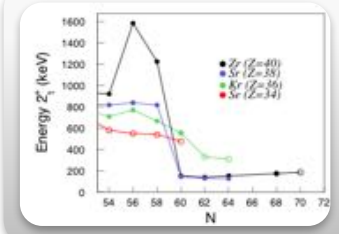
Motivation and Setup

- E_2^+ as a probe of structure evolution
- The SEASTAR Campaign
- MINOS+DALI2 @ RIKEN



Physics Cases—What happens beyond N=60?

- $^{88\text{-}94}$Se—shape coexistence?
- $^{98\text{-}100}$Kr—quantum phase transition?
- ^{110}Zr—tetrahedral? harmonic oscillator?



Summary

- The emerging picture of 60<N<70 structure evolution

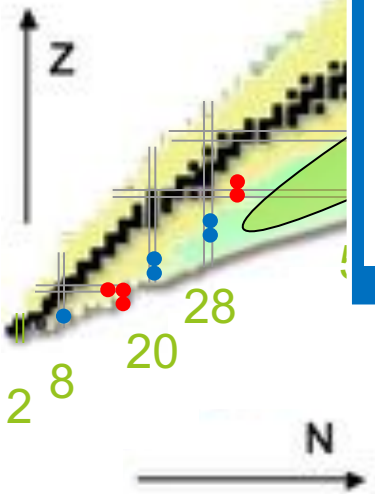
Motivation: Understanding Structure Evolution

Evolution of nuclear structure with N/Z not fully understood

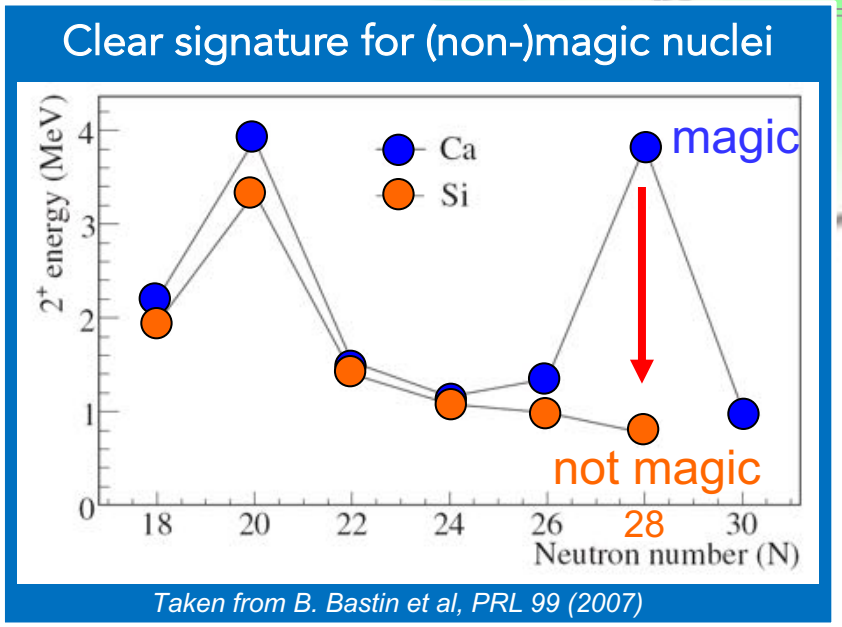
- Disappearance of known magic numbers
- Appearance of new magic numbers

Probes of structure evolution

- First 2+ excited states (this work)
- Masses, radii, transition probabilities,…….

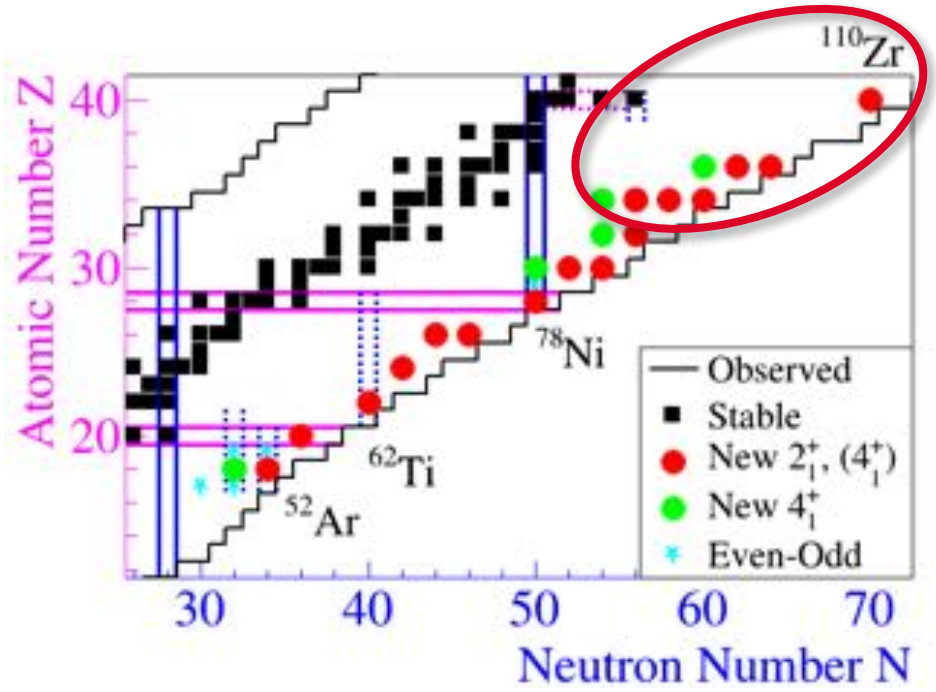


- new magic
- not magic



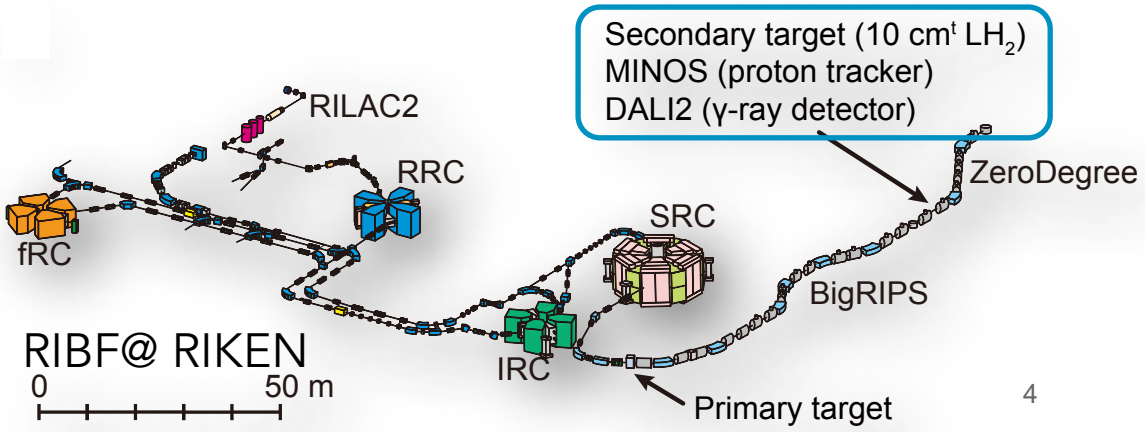
- stable nuclei
- known nuclei
- unknown nuclei (prediction)

Experiment: The SEASTAR Campaign

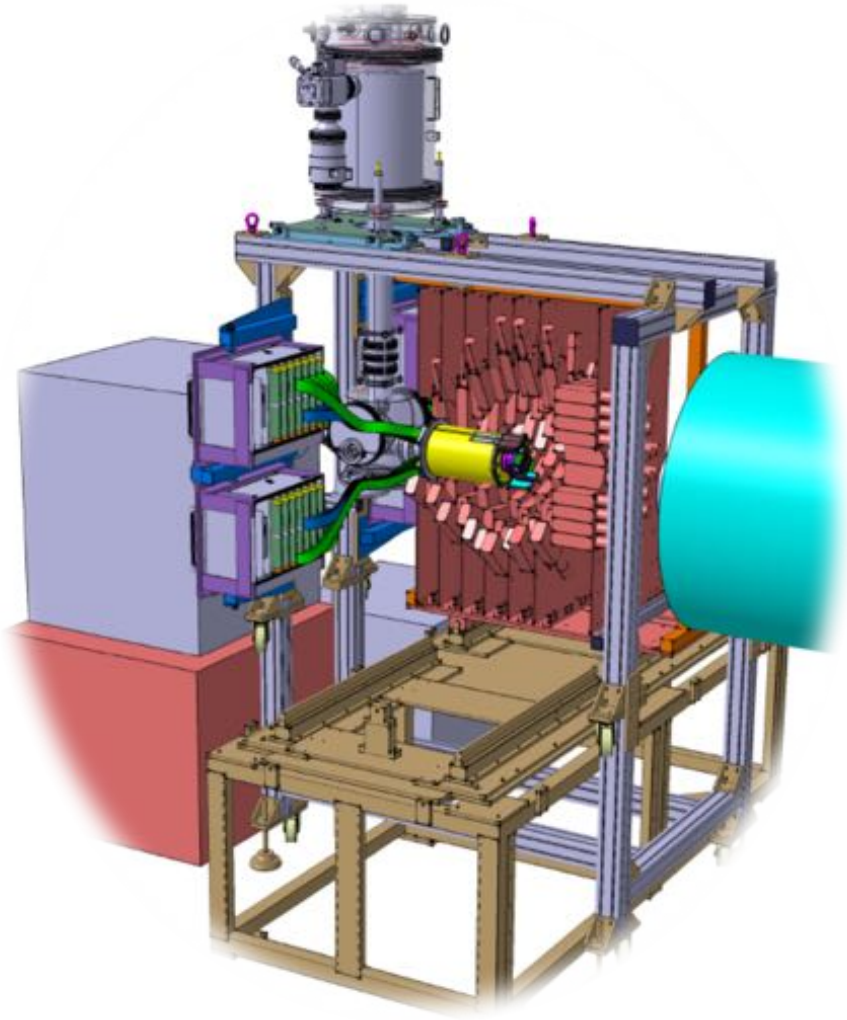


- **Goal:** First E_2^+, E_4^+ measurements of selected most exotic nuclei through (p,2p) reaction
- **Innovation:** MINOS+DALI2 detectors
- **Spokespersons:** P. Doornenbal and A. Obertelli
- Multiyear campaign:
  - 2014 ~^{78}Ni
  - 2015 ~^{110}Zr and south
  - 2017 ~^{52}Ar, ^{62}Ti

Primary beam: ^{238}U
Energy: 345 MeV/U,
Intensity: 30 pnA
β @ MINOS: 0.6c



DALI2+MINOS detectors



DALI2

- 182 NaI(Tl) scintillators
- 35% efficiency @ 500kev
- 9% resolution (FWHM) @ 662 kev
- ~15-160° angular coverage

Takeuchi et al, NIM A 763 (2014)

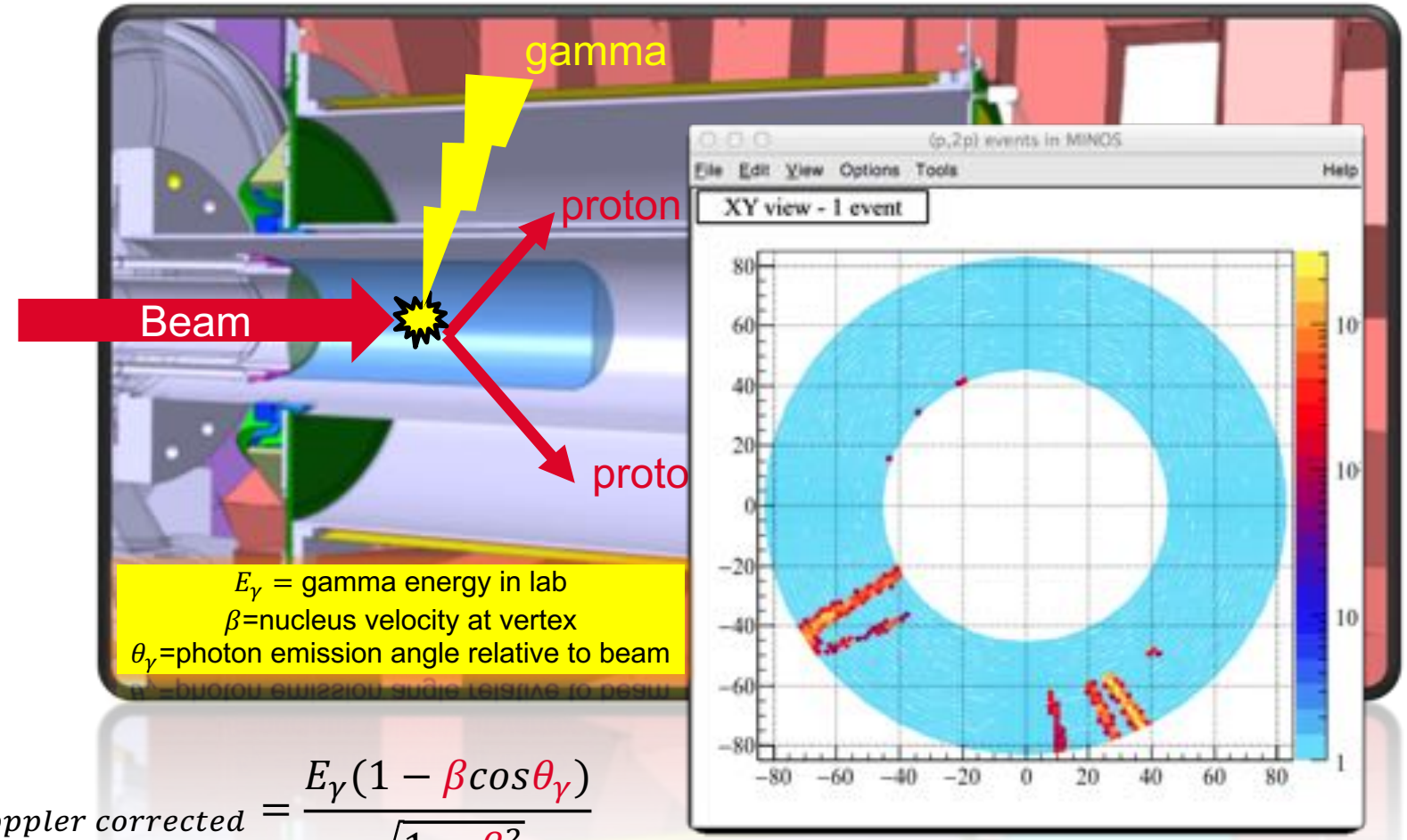
MINOS

- LH2 target +TPC
- Thick target → high luminosity
- Reaction vertex → Doppler correction
- >95% 1p detection efficiency

Obertelli et al, EPJA 50 (2014)

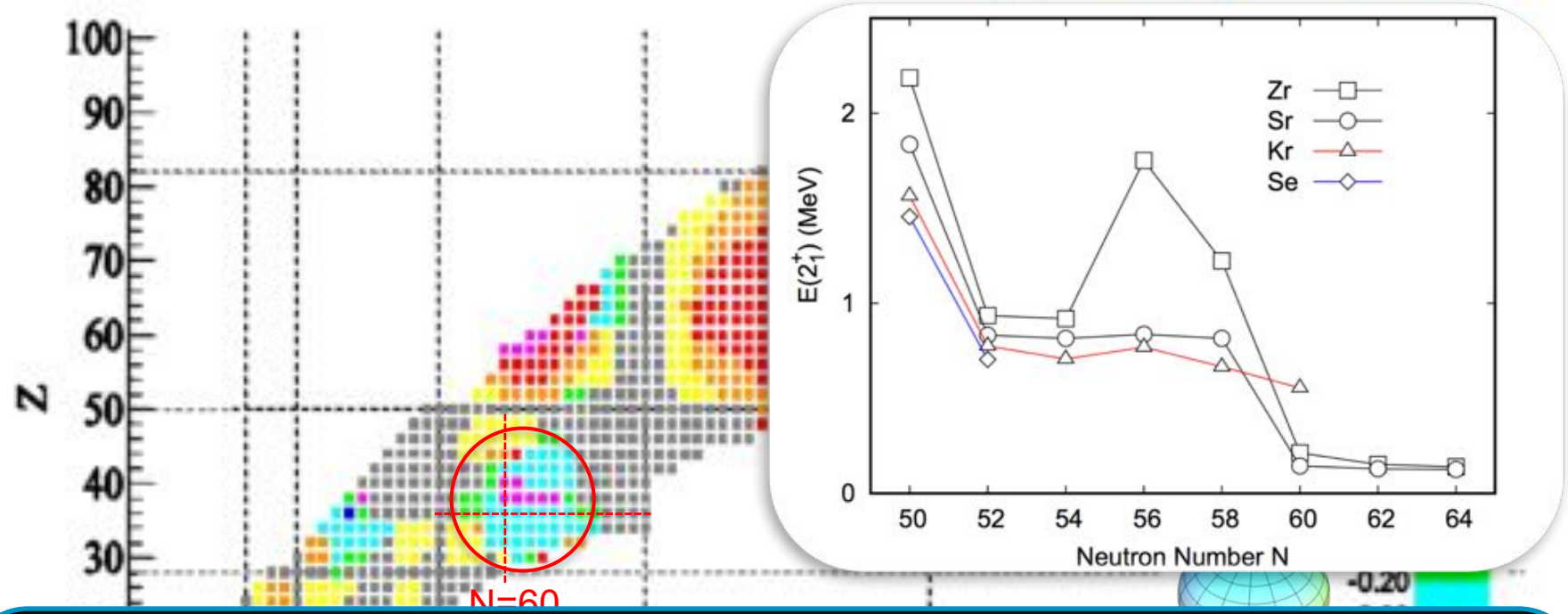
→ (p,2p) knockout reactions

MINOS



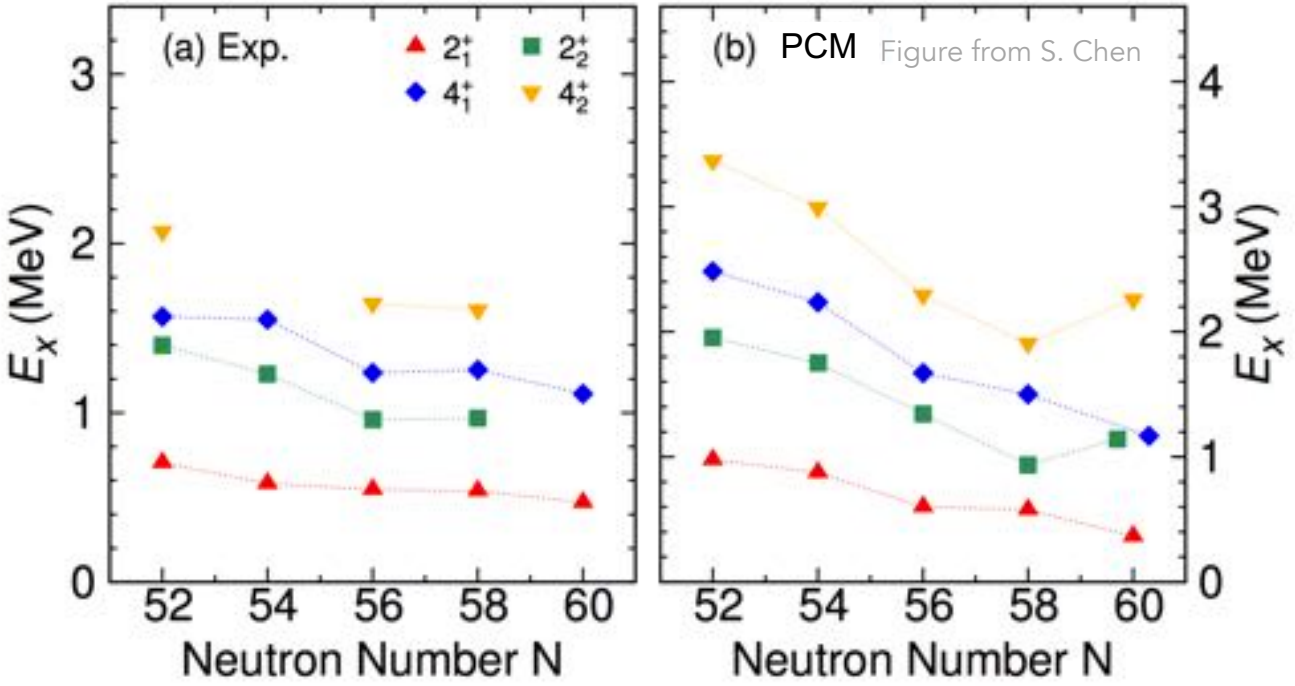
$$E_{doppler\ corrected} = \frac{E_\gamma(1-\beta cos\theta_\gamma)}{\sqrt{1-\beta^2}}$$

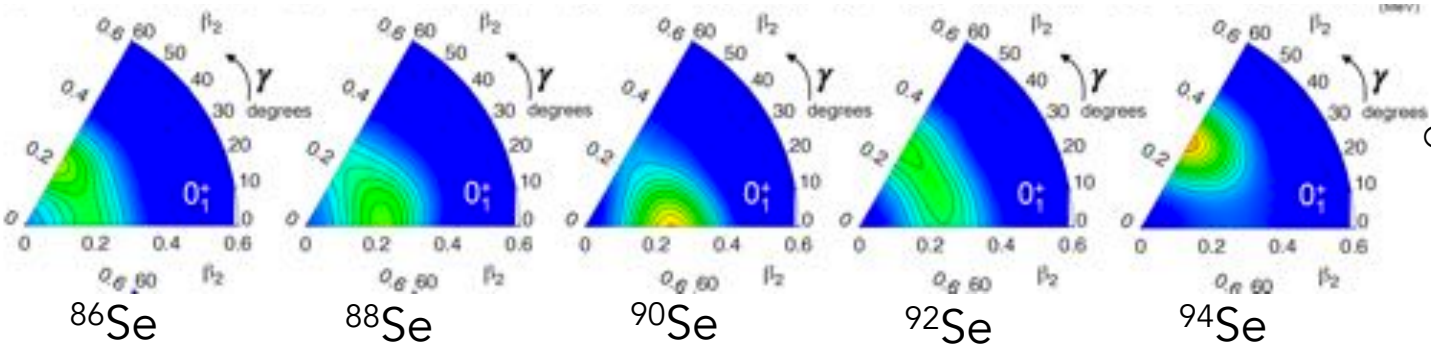
Motivation: What Happens Beyond N=60?



- Rapid onset of deformation @ N=60 in Zr chain—competing prolate configuration, interacting p-n orbitals (Federman-Pittel mechanism, type II shell evolution of Otsuka)
- Same effect when removing protons?
- Complicated shape coexistence—rich testing ground for structure models
- New effects at N=70?

Results: Se Isotopes And SCCM Calculations



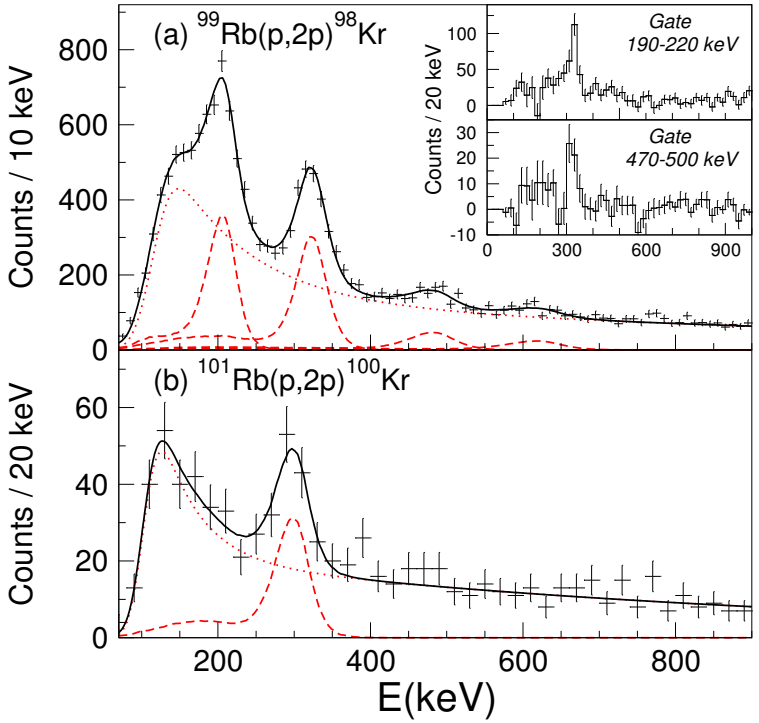


^{86}Se ^{88}Se ^{90}Se ^{92}Se ^{94}Se

- Measurement consistent with D1S+PCM calculations from Tomas Rodriguez
- Calculations show oblate-prolate transition at N=56, *then* sharp prolate-oblate transition at N=58.
- No indication of N=56 subshell closure (^{90}Se)

Figures from S. Chen and T.R. Rodriguez

Results: ^{98,100}Kr (courtesy of F. Flavigny)

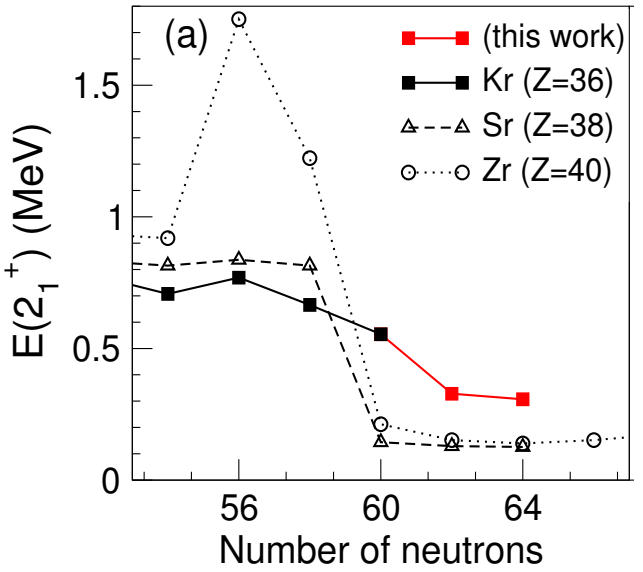


$E(2_1^+)$ evolution:

- Overall progressive decrease for Kr
- Not as brutal as Zr and Sr, but present
- Stabilization at N=64

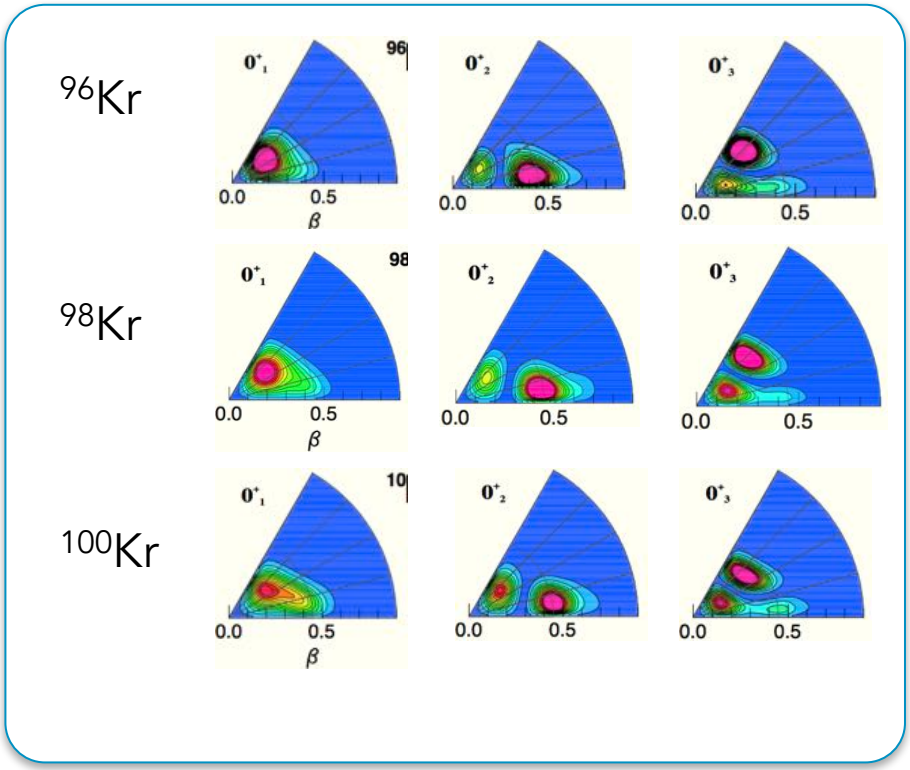
Intruder configuration:

- First evidence in neutron rich Kr isotopes



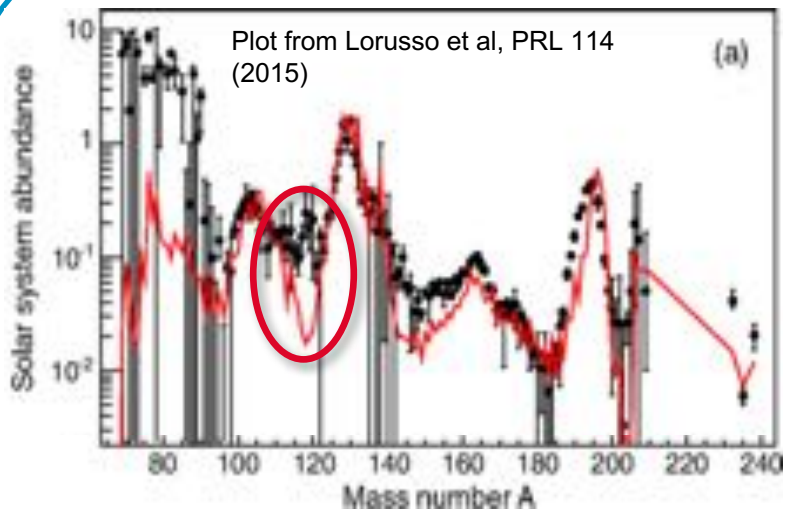
Results: ^{98,100}Kr (courtesy of F. Flavigny)

- Coexistence of prolate and oblate shapes
- Prolate intruder state competing at low energy
- Origin of drop at N=62? Unclear from theory



Motivation: ^{110}Zr (Z=40, N=70)

- Conflicting theoretical predictions
  - Weakening of spin-orbit splitting, shell gap at N=70?
  - Tetrahedral symmetry?
    - 40,70, both tetrahedral magic numbers
      - *Dudek et al, PRL 88 (2002); Dudek et al, PRC 69 (2004);*
  - Deformed, shape coexistent?
    - *Delaroche et al, PRC 81 (2010); Geng et al, PTP 110 (2003); Kortelainen et al, PRC 82 (2010); Skalski et al, NPA 808 (2008); Xu et al, PRC 65 (2002); Petrovici et al, J. Phys. Conf. Ser., Sorgunlu and Van Isacker; Bender et al. PRC 2009.*
- Important benchmark for theory

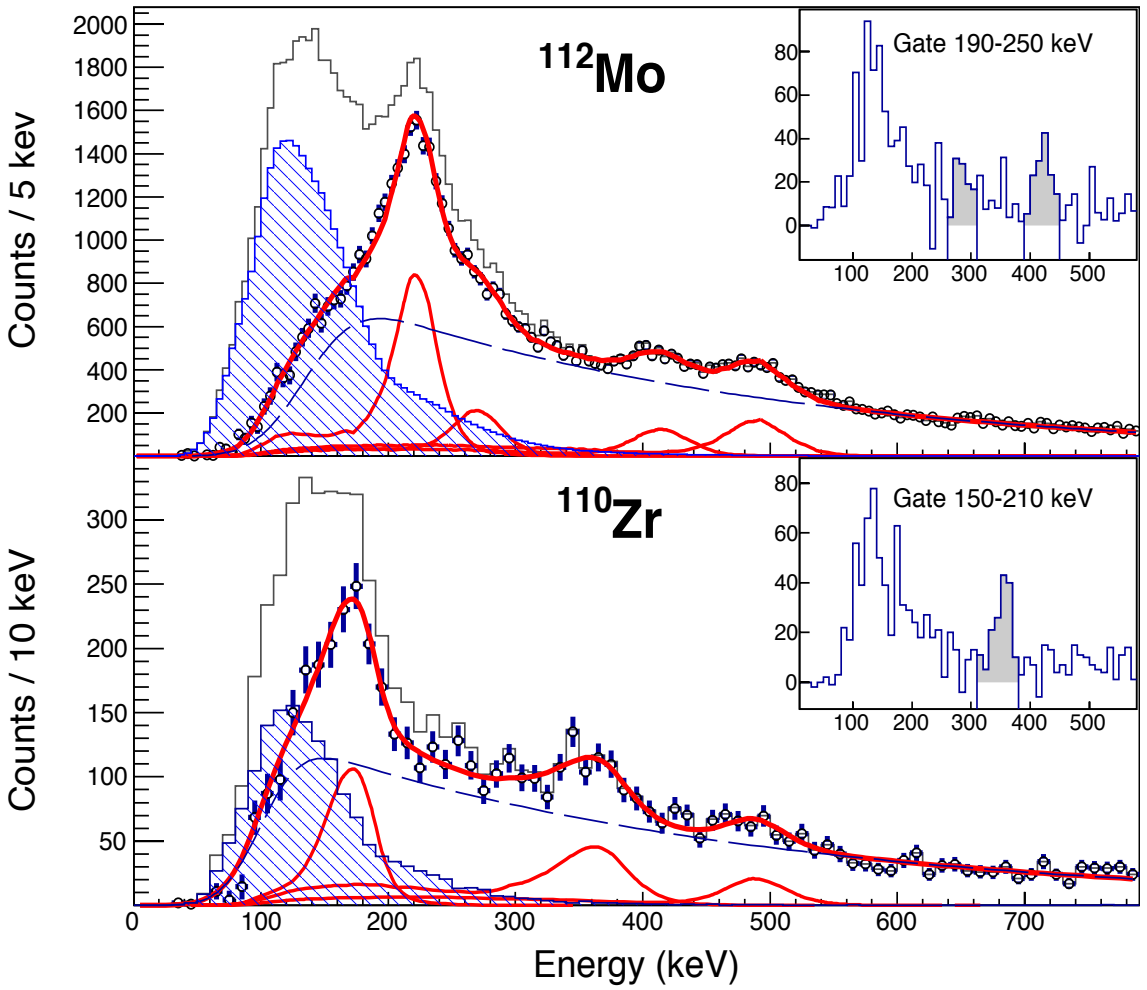


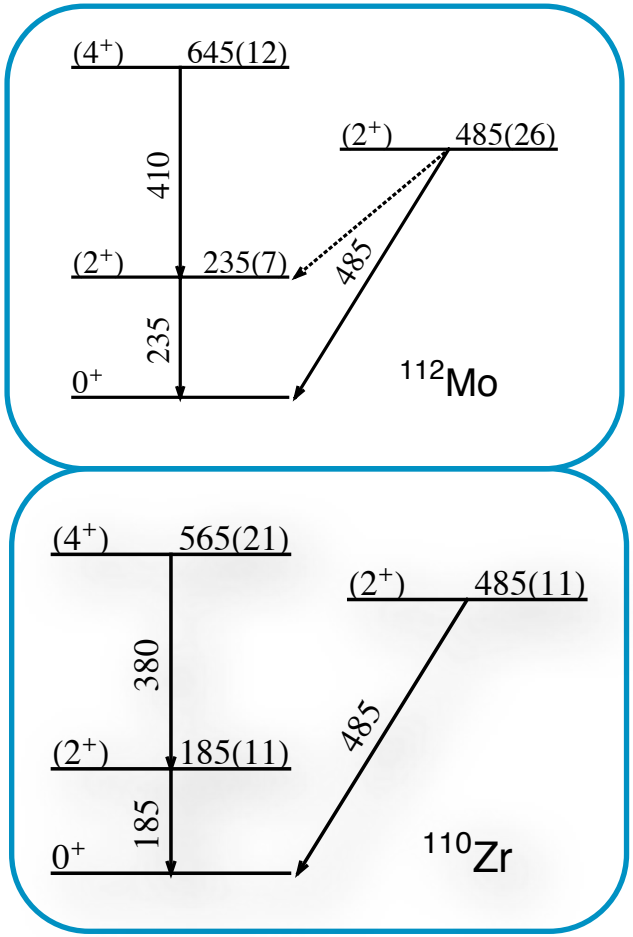
Astrophysical interest:

- Shell-stabilized ^{110}Zr potential explanation for r-process model discrepancies before A=130 peak?

No existing evidence of stabilized ^{110}Zr
(published spectroscopy of ^{108}Zr, beta decay lifetime of $^{110\text{-}112}$Zr)
Still missing direct structure measurement!

Results: ^{112}Mo and ^{110}Zr





Results: ^{110}Zr Theory Comparison

Tetrahedral predictions
Tagami et al, PRC 87 (2013)

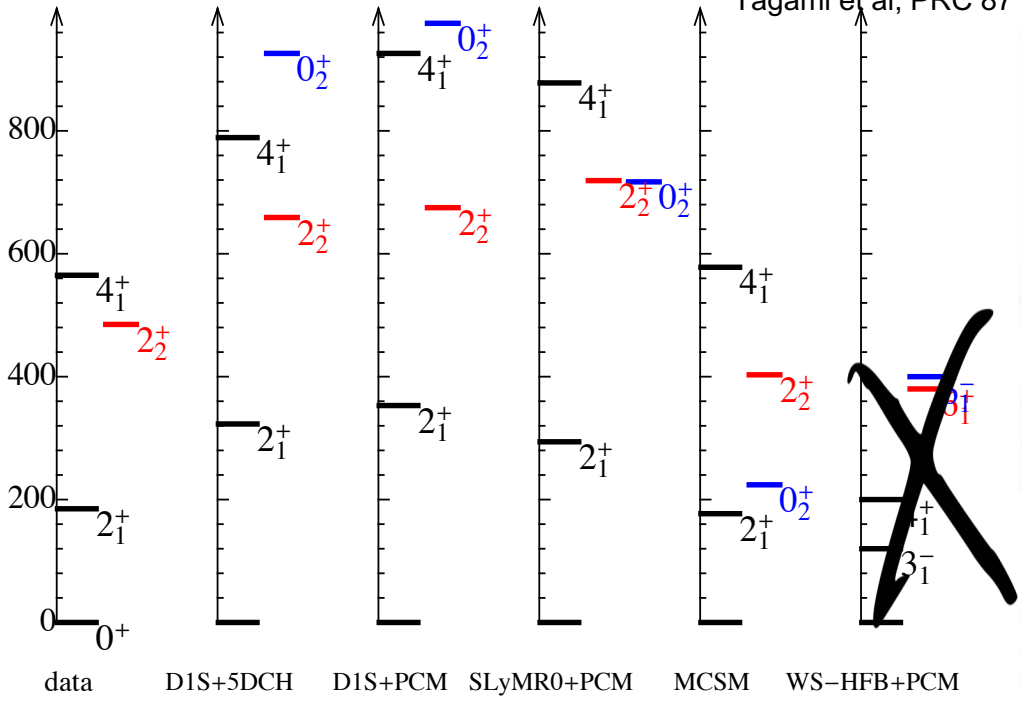
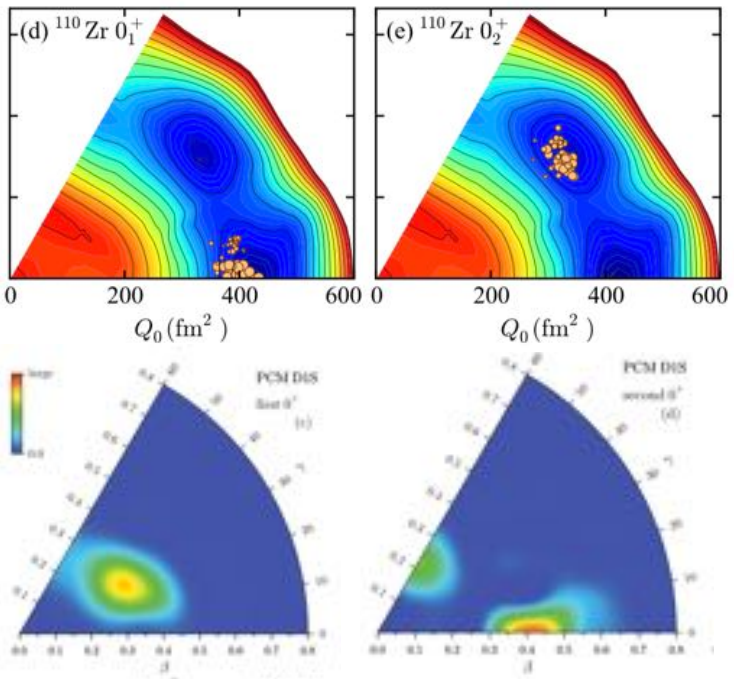
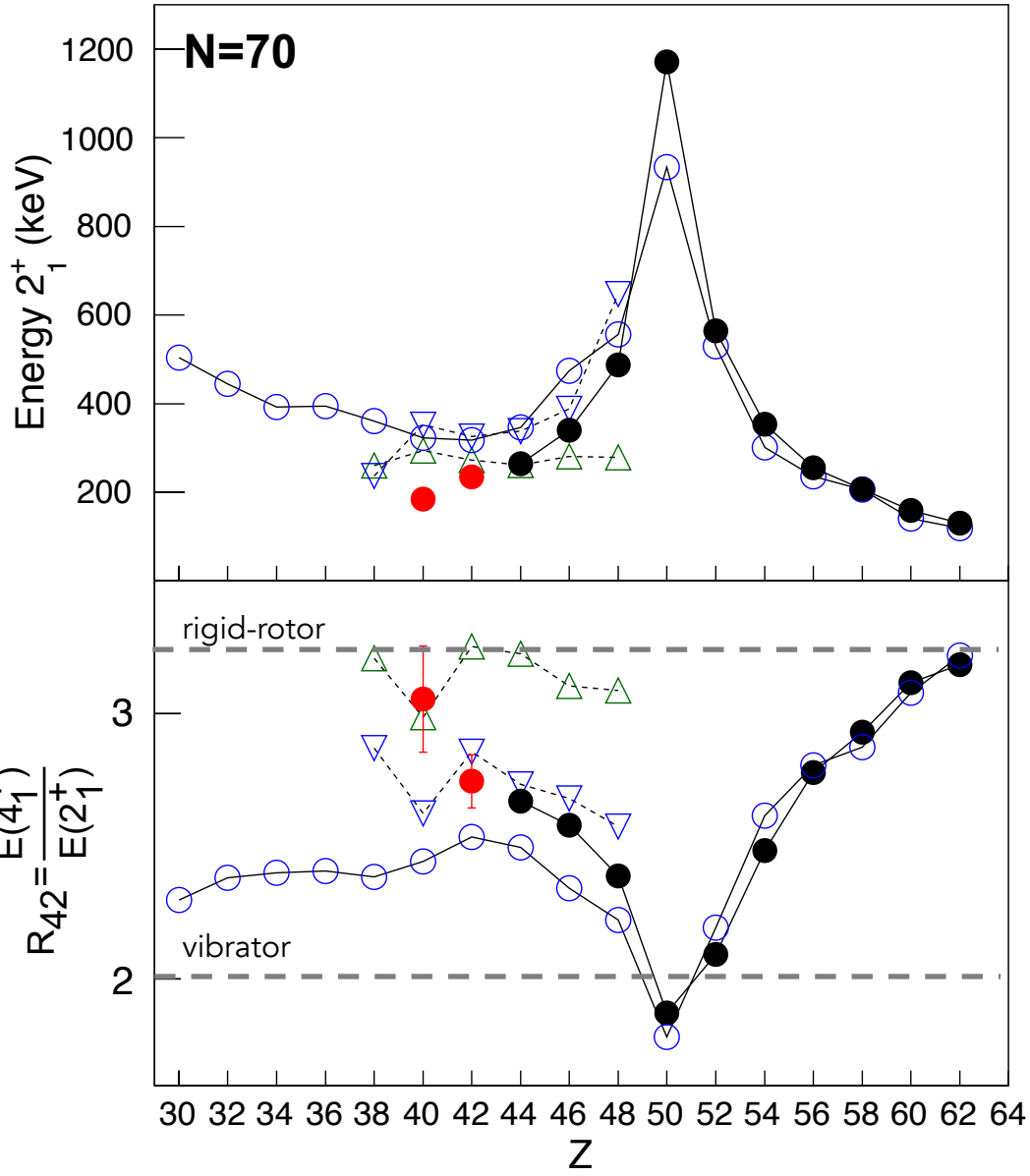


Figure from Togashi et al, 2016

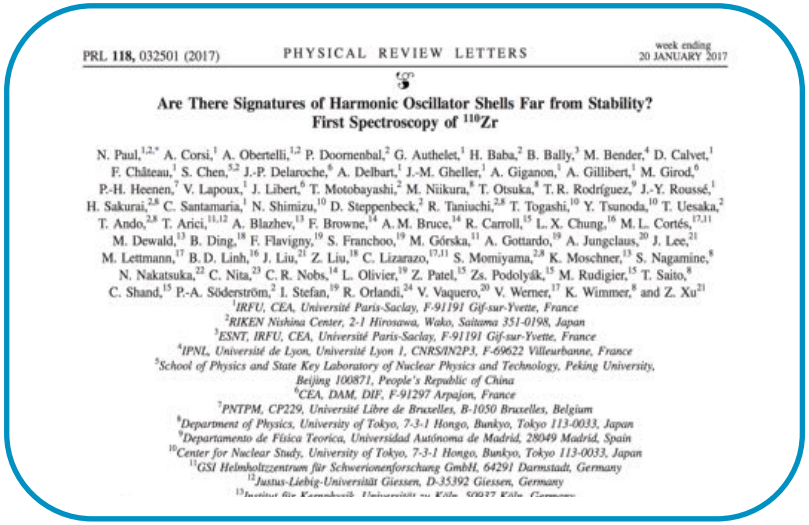


- Best agreement with MCSM calculations→ prolate deformation in ground state
  Togashi et al, PRL 117 (2016)
- Qualitative agreement with Gogny and Skyrme calculations
- Exclude tetrahedral symmetry in ground state of ^{110}Zr
- ^{110}Zr→ Well deformed, rotational nucleus

Results: N=70 Theory Comparison



- NNDC-evaluated data
- This work
- D1S+5DCH
  Delaroche, Girod, Libert (CEA)
- D1S+PCM
  Rodriguez (Madrid)
- SLyMR0+PCM
  Bally (CEA), Bender (IPNL), Heenen (Bruxelles)



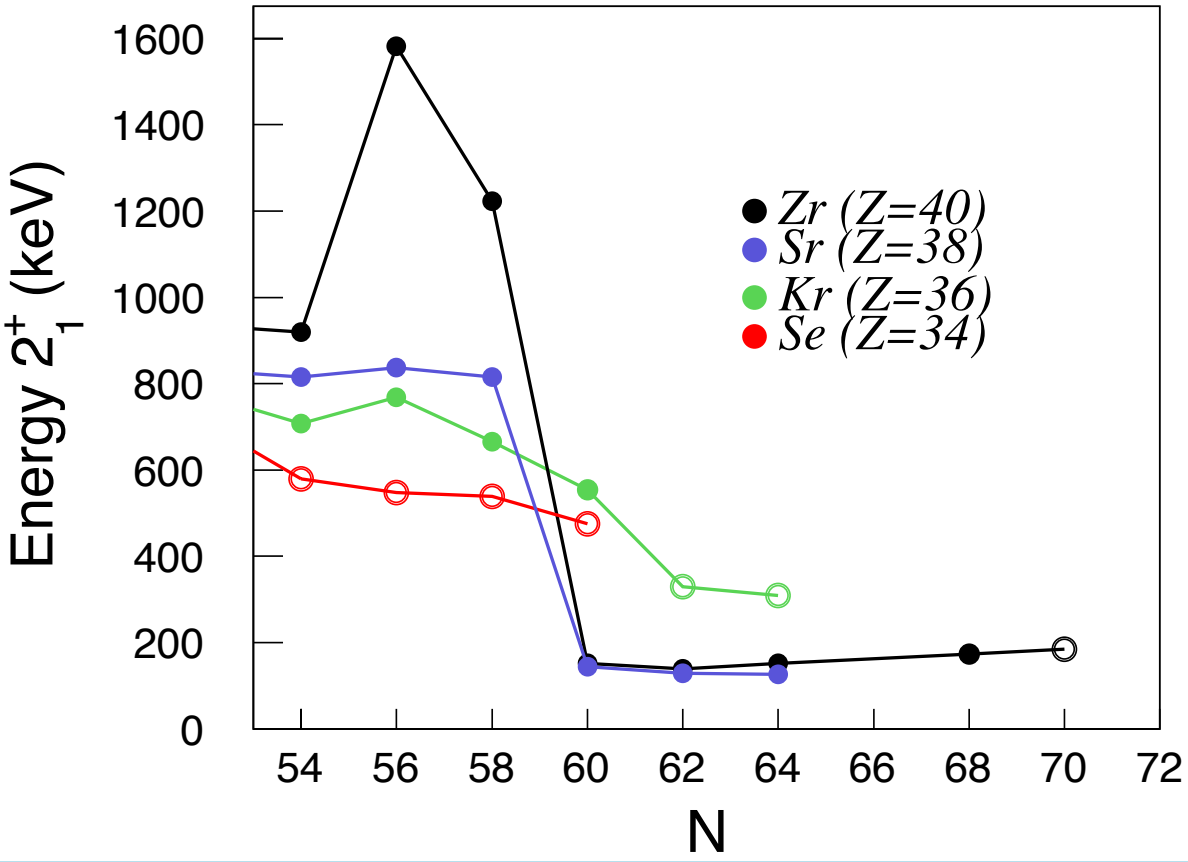
PRL 118, 032501 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Are There Signatures of Harmonic Oscillator Shells Far from Stability? First Spectroscopy of ^{110}Zr

N. Paul,[1,2,*] A. Corsi,[1] A. Obertelli,[1,2] P. Doornenbal,[2] G. Authelet,[1] H. Baba,[2] B. Bally,[3] M. Bender,[4] D. Calvet,[1] F. Château,[1] S. Chen,[3,2] J.-P. Delaroche,[6] A. Delbart,[1] J.-M. Gheller,[1] A. Giganon,[1] A. Gillibert,[1] M. Girod,[6] P.-H. Heenen,[7] V. Lapoux,[1] J. Libert,[6] T. Motobayashi,[2] M. Niikura,[8] T. Otsuka,[8] T. R. Rodríguez,[9] J.-Y. Roussé,[1] H. Sakurai,[2,8] C. Santamaria,[1] N. Shimizu,[10] D. Steppenbeck,[2] R. Taniuchi,[2,8] T. Togashi,[10] Y. Tsunoda,[10] T. Uesaka,[2] T. Ando,[2,8] T. Arici,[11,12] A. Blazhev,[13] F. Browne,[14] A. M. Bruce,[14] R. Carroll,[15] L. X. Chung,[16] M. L. Cortés,[17,11] M. Dewald,[13] B. Ding,[18] F. Flavigny,[19] S. Franchoo,[19] M. Górska,[11] A. Gottardo,[19] A. Jungclaus,[20] J. Lee,[21] M. Lettmann,[17] B. D. Linh,[16] J. Liu,[21] Z. Liu,[18] C. Lizarazo,[17,11] S. Momiyama,[2,8] K. Moschner,[13] S. Nagamine,[8] N. Nakatsuka,[22] C. Nita,[23] C. R. Nobs,[14] L. Olivier,[19] Z. Patel,[15] Zs. Podolyák,[15] M. Rudigier,[15] T. Saito,[8] C. Shand,[15] P.-A. Söderström,[2] I. Stefan,[19] R. Orlandi,[24] V. Vaquero,[20] V. Werner,[17] K. Wimmer,[8] and Z. Xu[21]

[1]*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[2]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*ESNT, IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[4]*IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne, France*
[5]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China*
[6]*CEA, DAM, DIF, F-91297 Arpajon, France*
[7]*PNTPM, CP229, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium*
[8]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[9]*Departamento de Física Teorica, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
[10]*Center for Nuclear Study, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[11]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[12]*Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany*

The New Picture Beyond N=60



- ✓ Smooth behavior in Se consistent with shape coexistence
- ✓ Evidence for shape coexistence and rise in deformation at @ N=62
- ✓ ^{110}Zr—well deformed, no magicity nor tetrahedral symmetry, shape coexistence

Thank you!

A. Corsi, A. Obertelli, G. Authelet, F. Chateau, A. Delbart, J.-M. Gheller, A. Giganon, A. Gillibert, V. Lapoux, J-Y. Roussé, C. Santamaria, J.-P. Delaroche, J. Libert, M. Girod, B. Bally

P. Doornenbal, H. Baba, S. Chen, T. Motobayashi, D. Steppenbeck, T. Uesaka

T. Ando, S. Momiyama, R. Taniuchi, M. Niikura, H. Sakurai, T. Saito, K. Wimmer, S. Nagamine, T. Otsuka

F. Flavigny, L. Olivier, S. Franchoo, A. Gottardo

R. Caroll, Z. Patel, Z. Podolyak, M. Rudigier, C. Shand

J. Liu, Z. Xu

L.X. Chung, B. Linh

A. Jungclaus, V. Vaquero

N. Nakatsuka

R. Orlandi

L. Cortes, V. Werner

P.-H. Heenen

M. Bender

A. Blazhev, M. Dewald,K. Moschner,

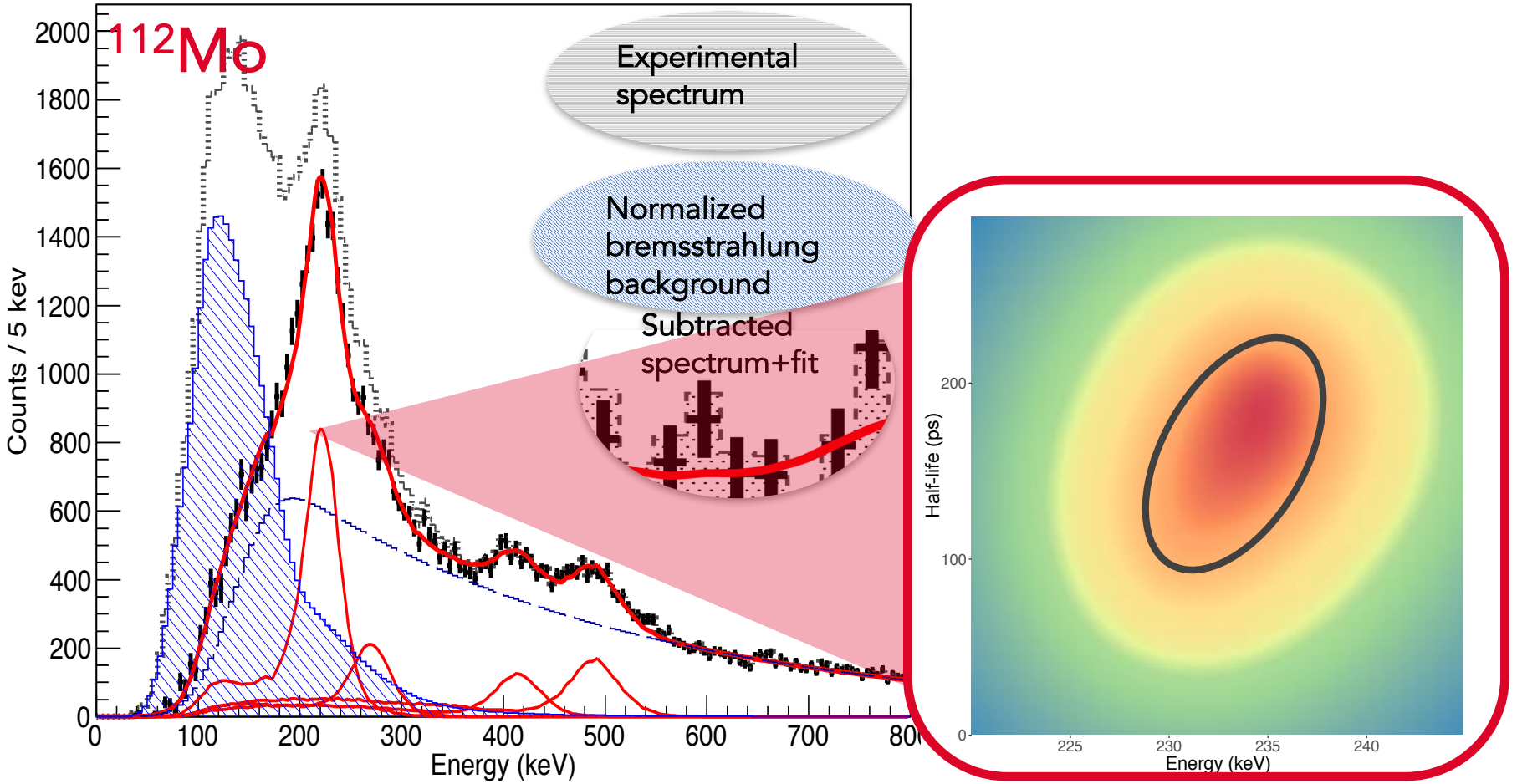
T. Arici, M. Górska, C. Lizarazo

T.R. Rodriguez

F. Browne, A. Bruce, C. Nobs

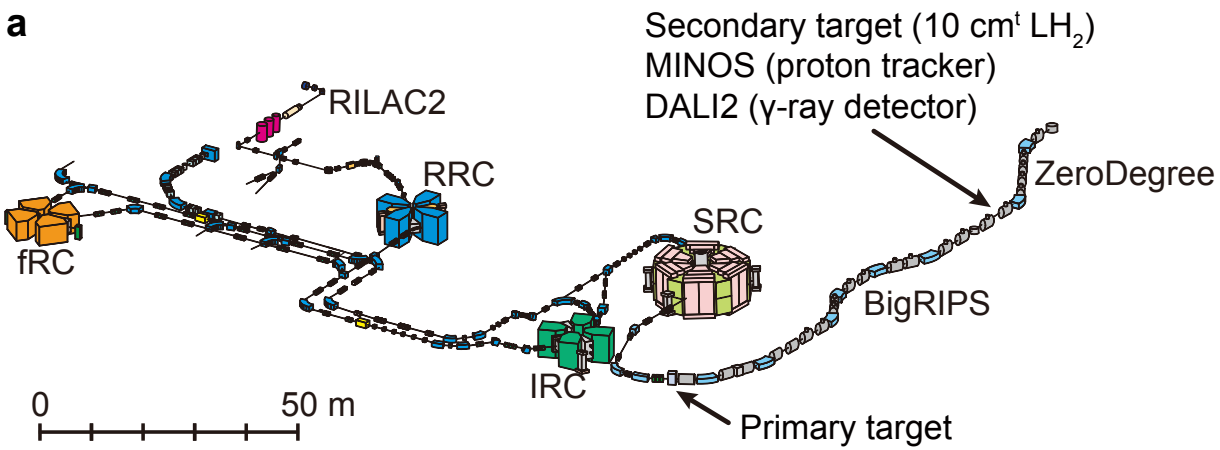
Backup Slides

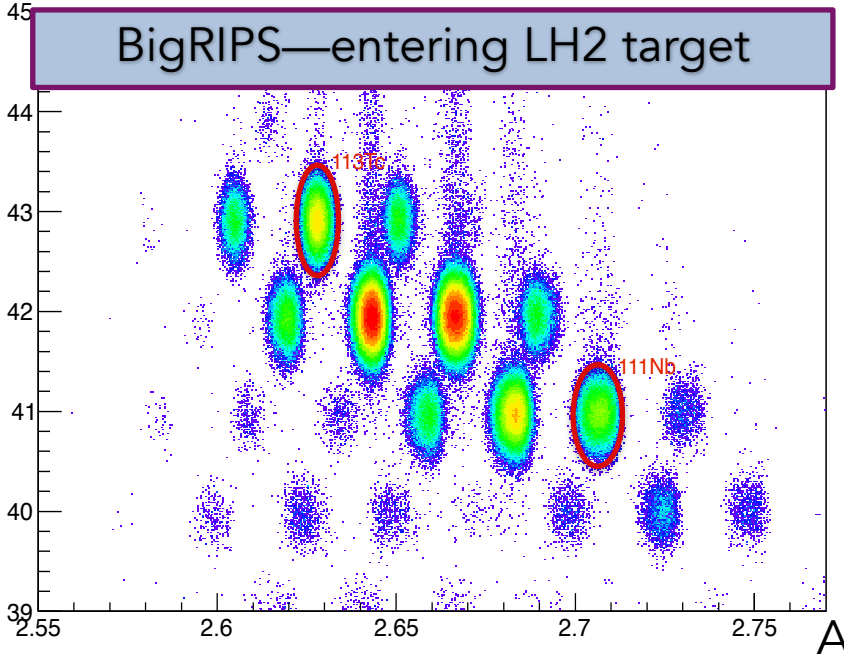
Backup: ^{112}Mo—high stats case

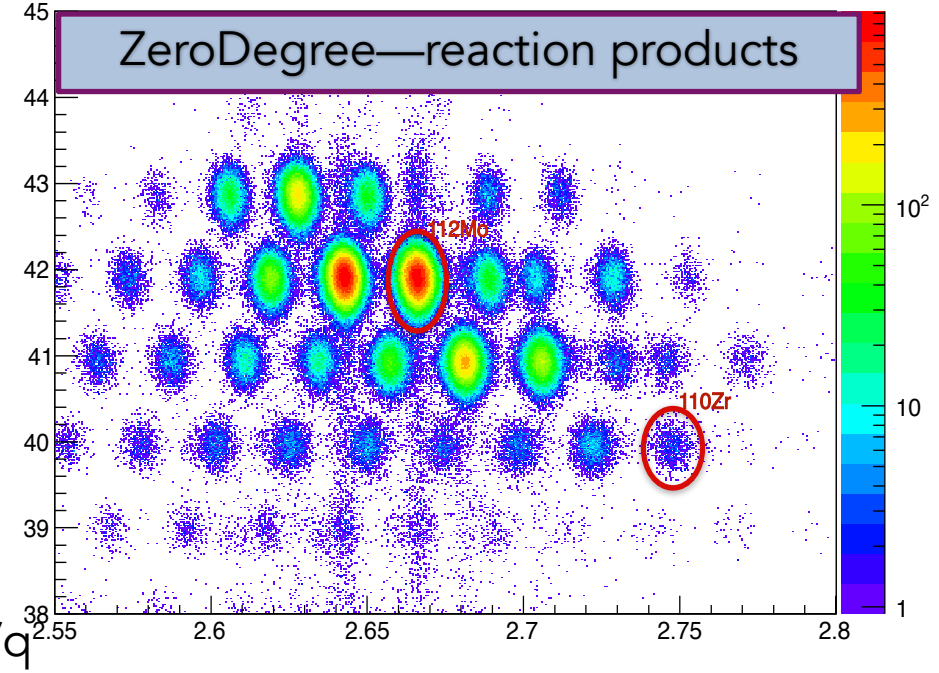


Backup: Experimental setup @ RIKEN

Primary beam: ^{238}U
Energy: 345 MeV/U,
Intensity: 30 pnA
β @ MINOS: 0.6c

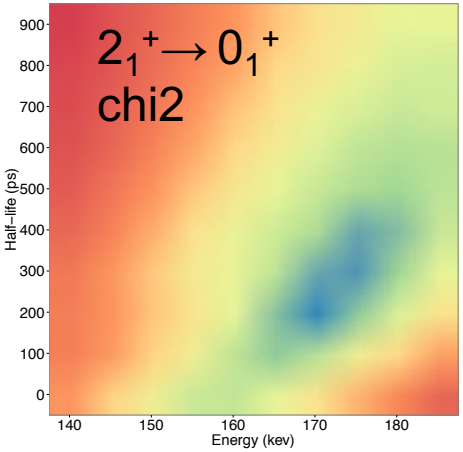


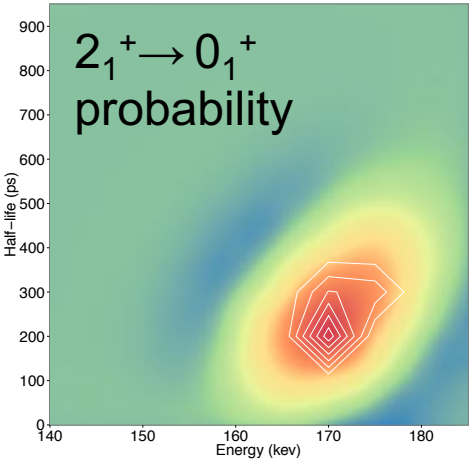


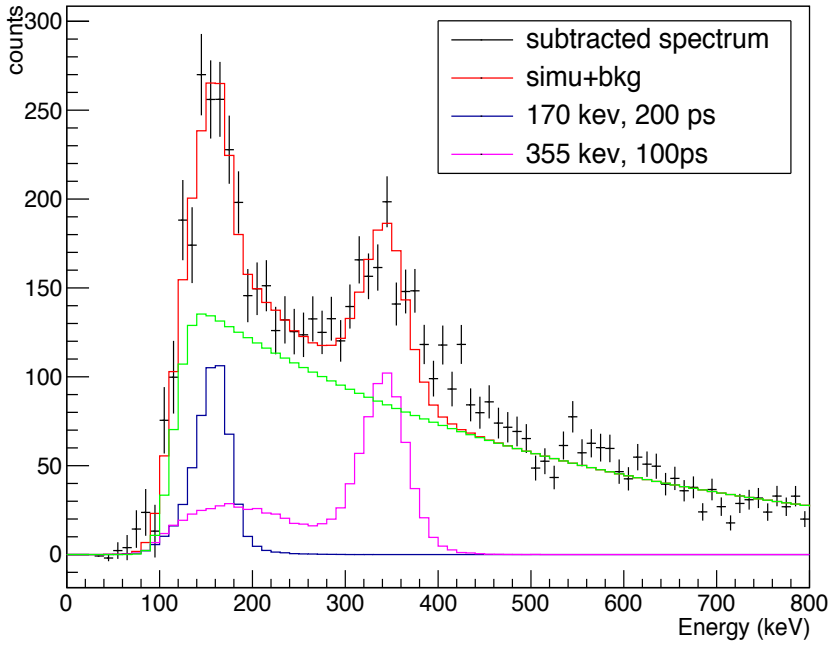


A/q

Proof of principle: ^{108}Zr—two peak fit







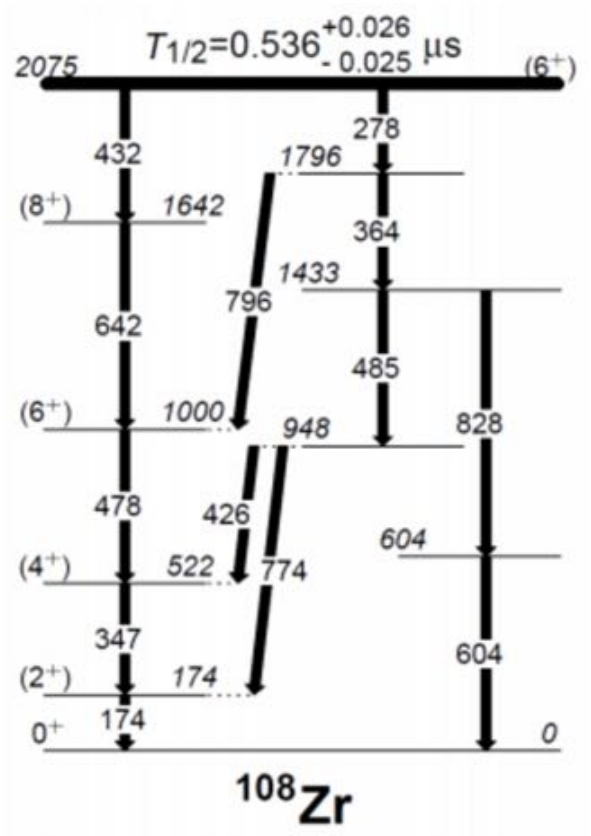
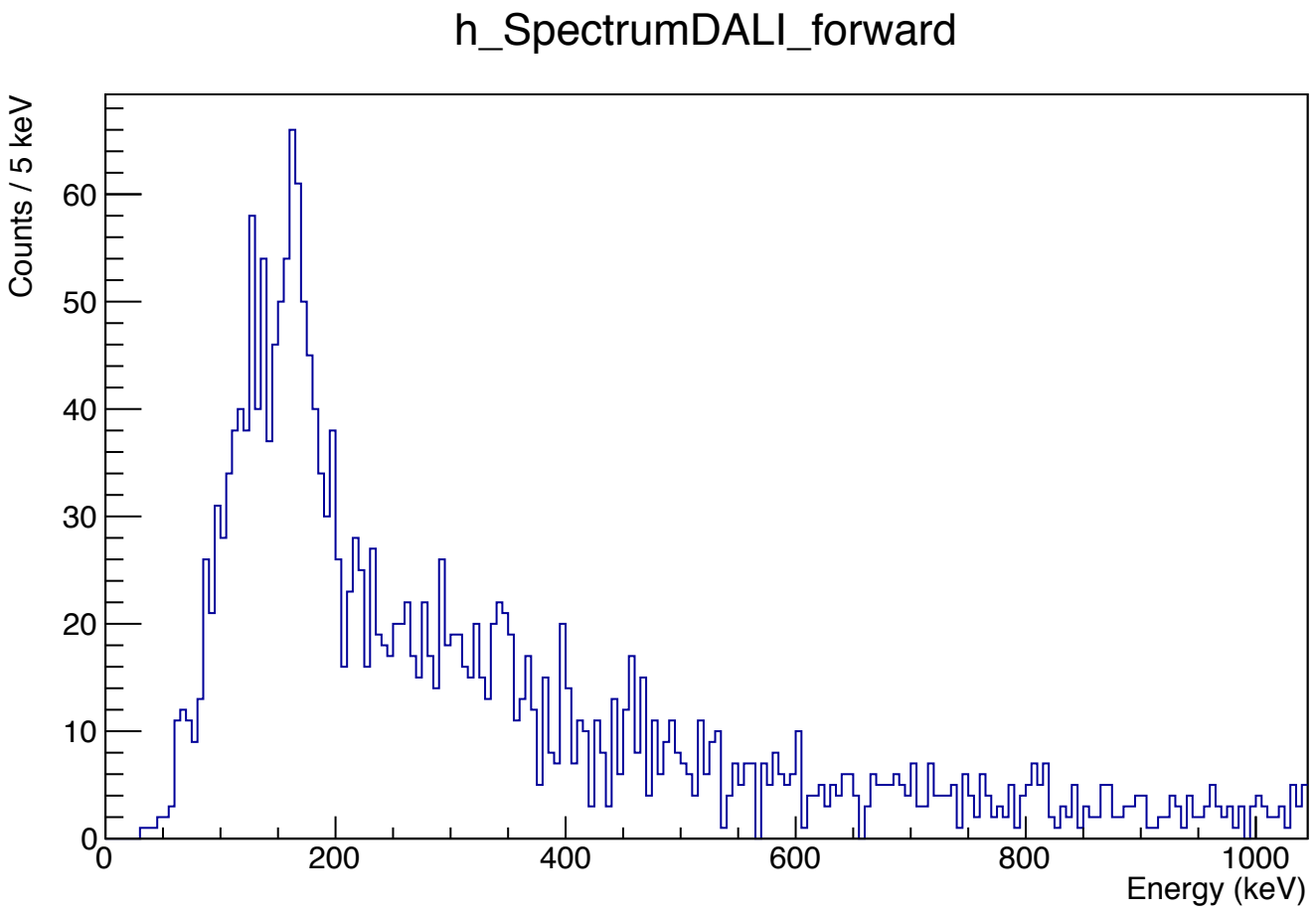


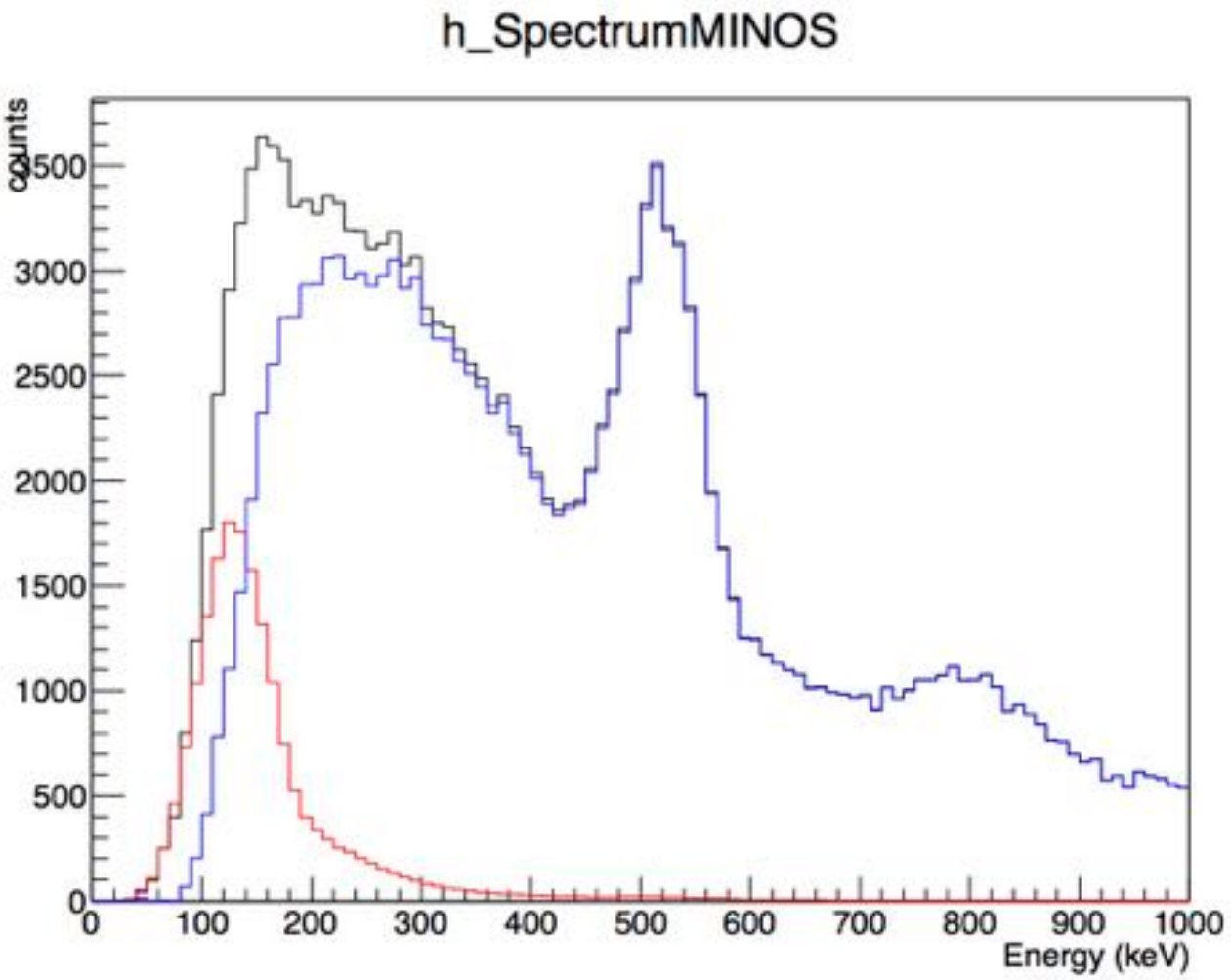
FIG. 14. Proposed level scheme of $^{108}Zr^m$.

From Kameda et al 2012

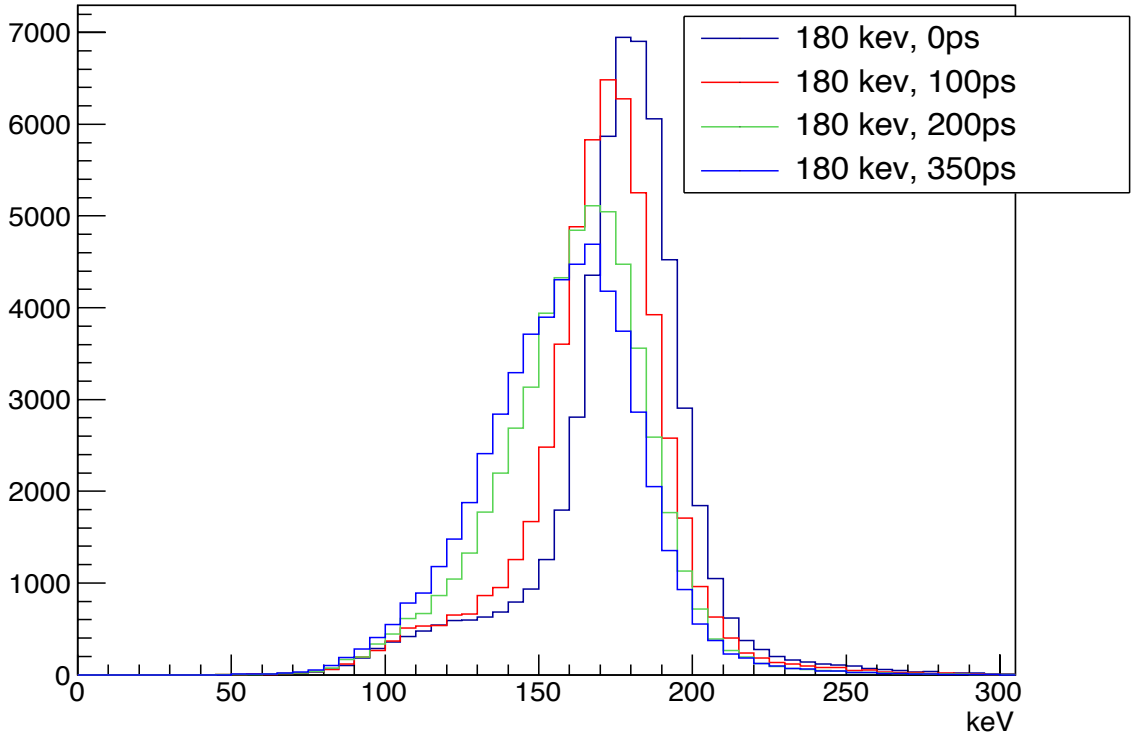
^{110}Zr—Forward Angles



Proof of principle: Background subtraction-^{86}Ge



Lifetime effects



Half-life (ps)	Centroid (keV)
0	180
100	173
200	167
350	159