SEASTAR

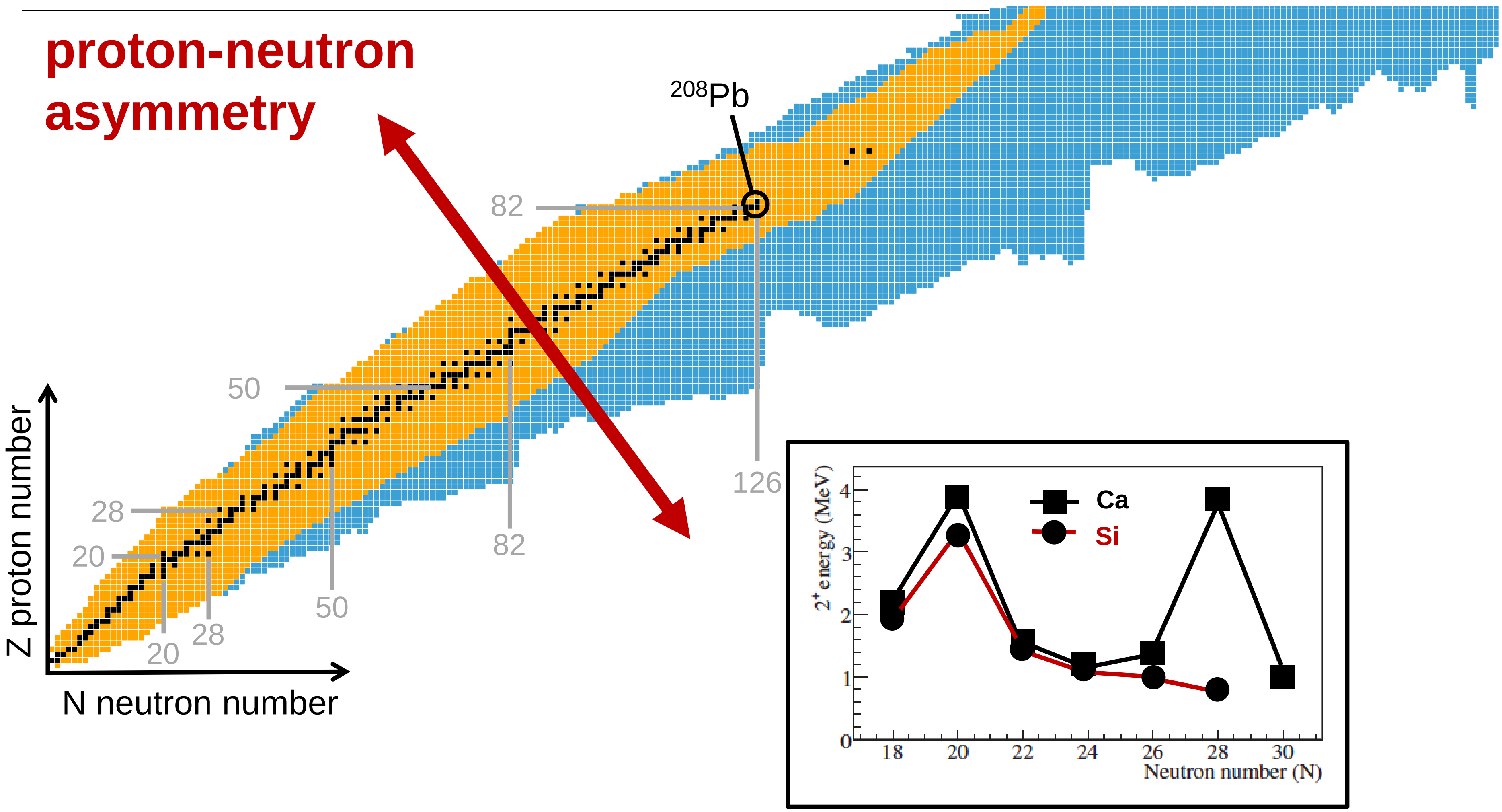
Spectroscopy of neutron-rich nuclei at the RIBF

Alexandre Obertelli, TU Darmstadt

SFB1245 workshop, Mainz
October 4th – 6th, 2017

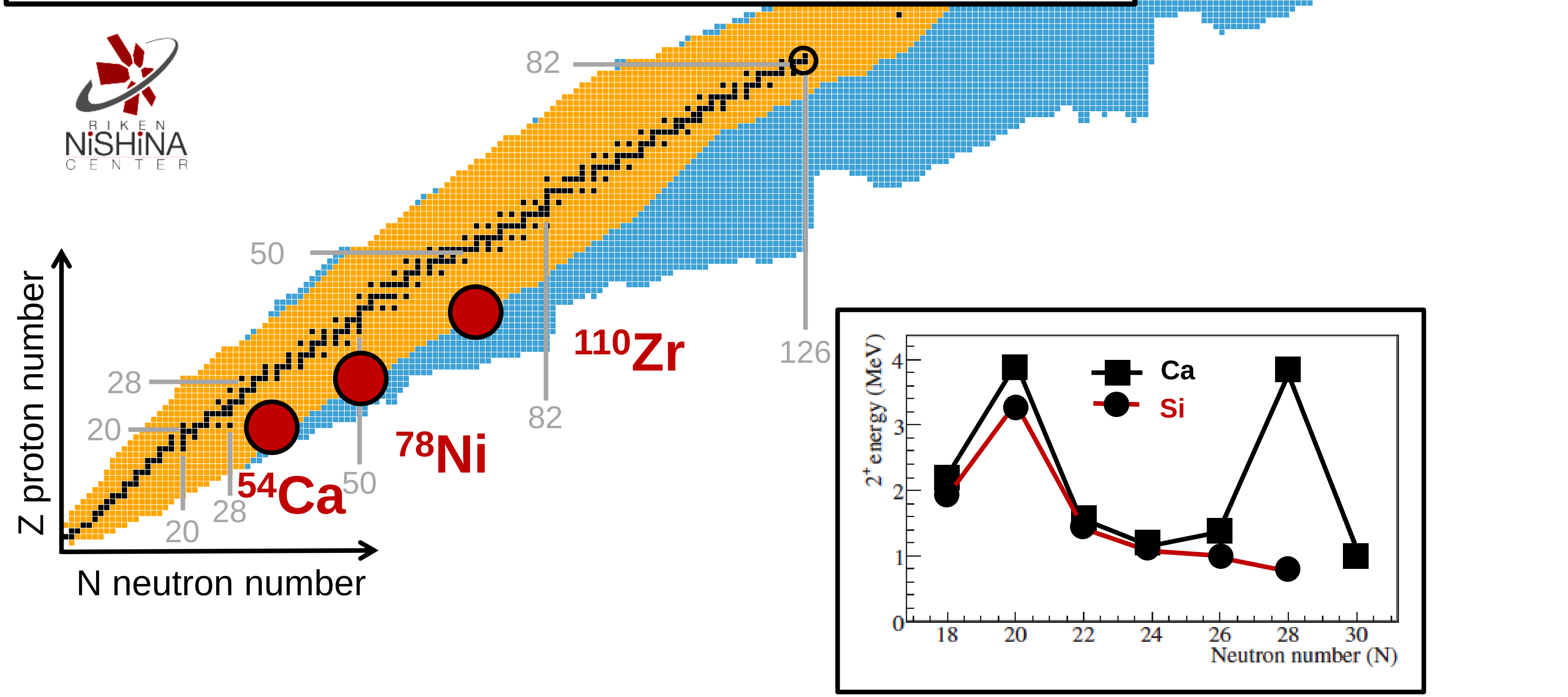
Radioactive isotopes

proton-neutron asymmetry



The Radioactive Isotope Beam Factory

RIBF (Japan) leading facility today to produce very exotic nuclei
Opened new opportunities in the recent years



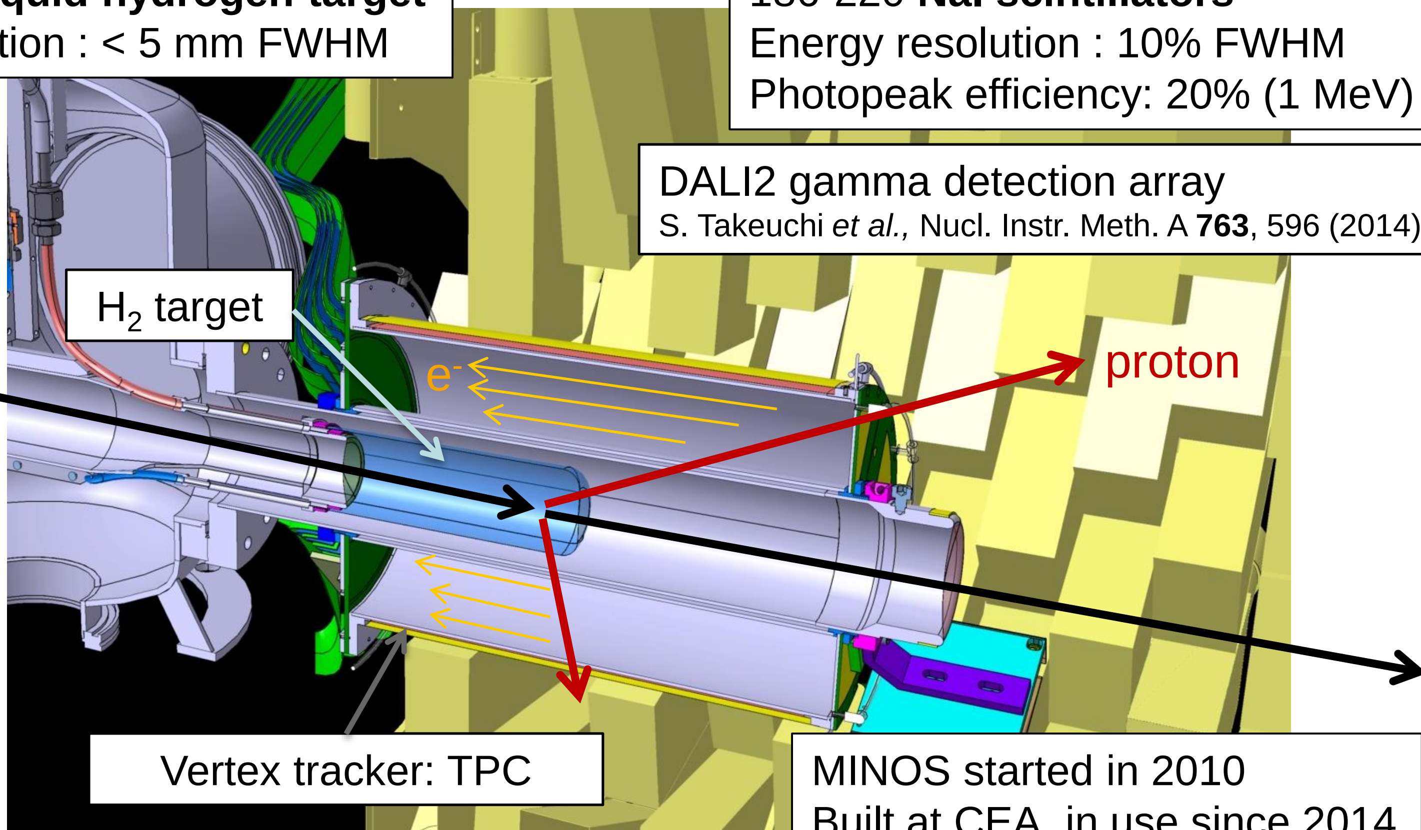
DALI2 and MINOS at the RIBF

TECHNISCHE UNIVERSITÄT DARMSTADT

50-150 mm **liquid hydrogen target**
Vertex resolution : < 5 mm FWHM

186-220 **NaI scintillators**
Energy resolution : 10% FWHM
Photopeak efficiency: 20% (1 MeV)

DALI2 gamma detection array
S. Takeuchi *et al.*, Nucl. Instr. Meth. A **763**, 596 (2014)



H_2 target

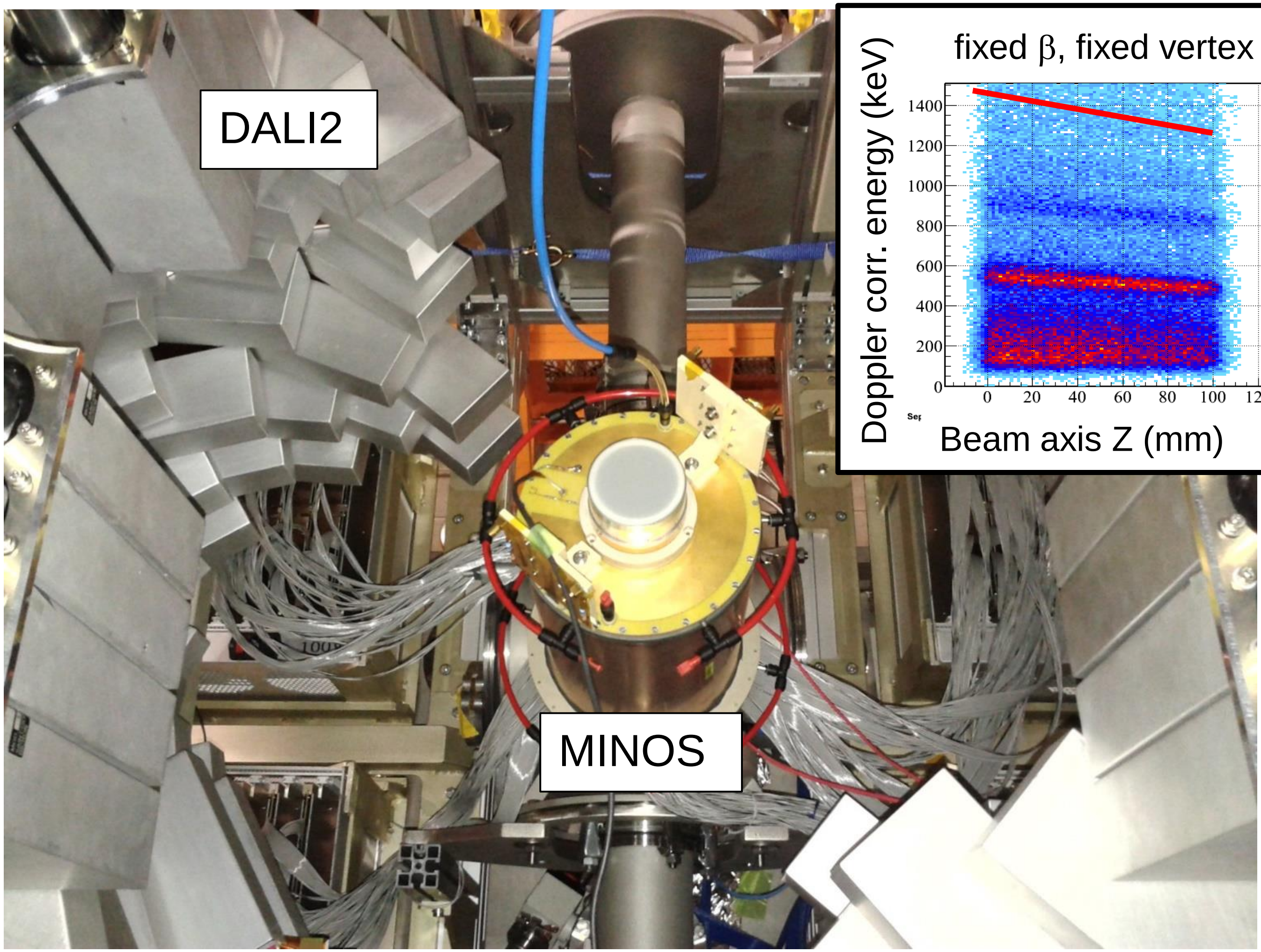
Vertex tracker: TPC

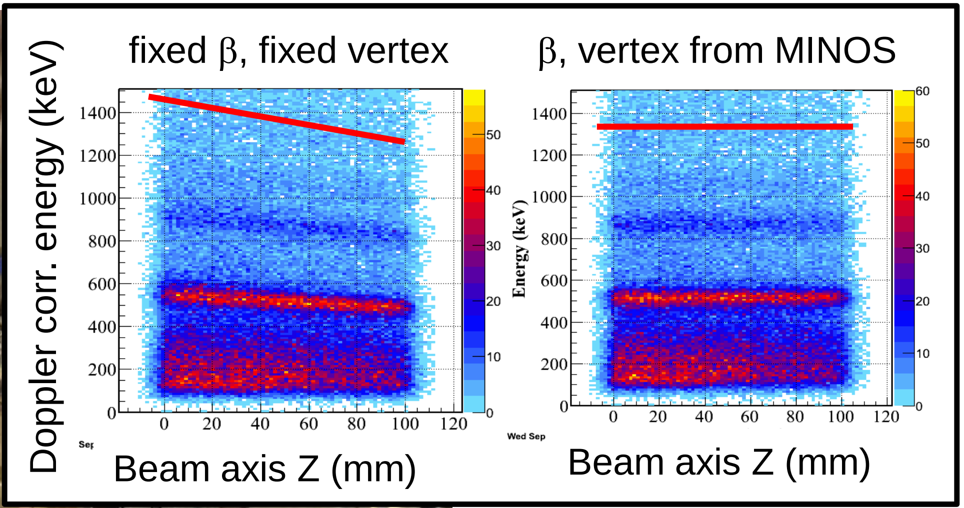
MINOS started in 2010
Built at CEA, in use since 2014

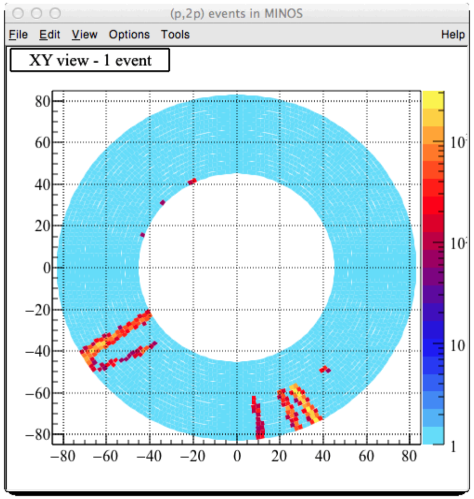
A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

MINOS working principle

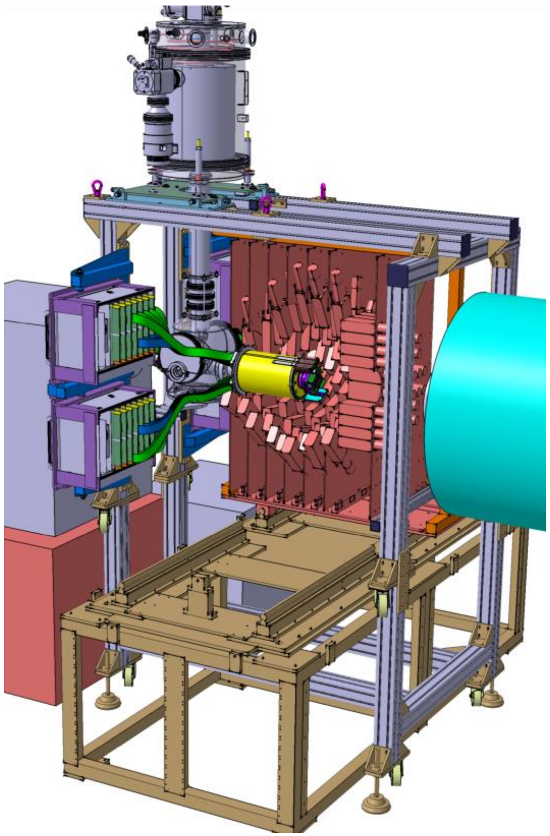
TECHNISCHE
UNIVERSITÄT
DARMSTADT

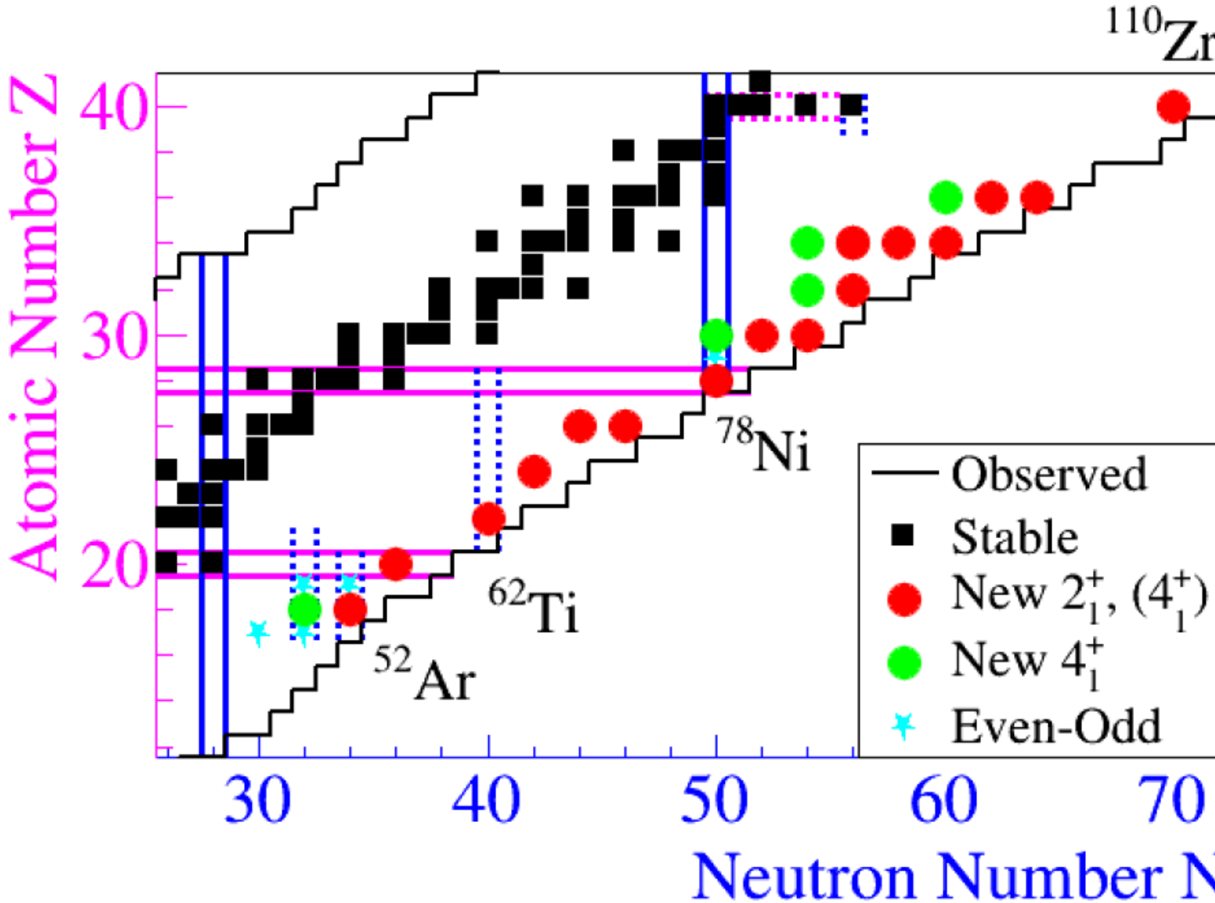






SEASTAR physics program: 2014 - 2017





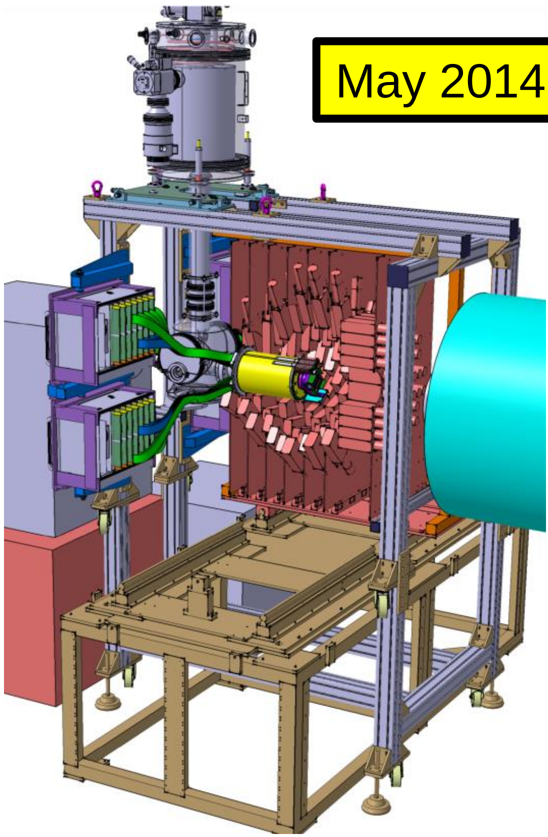
SEASTAR spokespersons: P. Doornenbal (RIKEN), AO

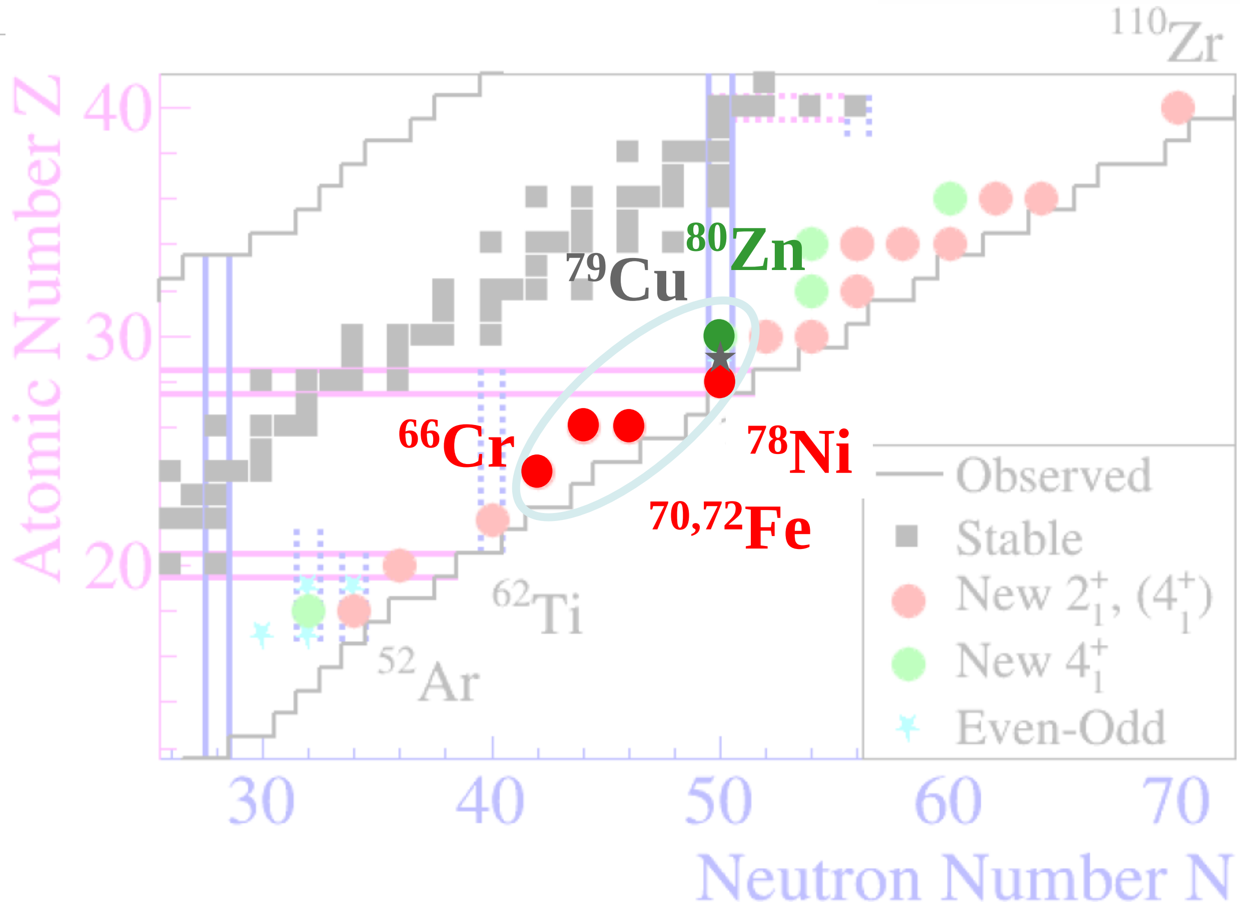
SEASTAR collaboration (expt)

TECHNISCHE UNIVERSITÄT DARMSTADT

L. Achouri, O. Aktas, G. de Angelis, N. Aoi, T. Aumann, H. Baba, F. Brown, D. Calvet, S. Chen, N. Chiga, L. Chung, M.L. Cortes, A. Corsi, F. Delaunay, A. Delbart, Z. Dombradi, P. Doornenbal, F. Flavigny, S. Franchoo, I. Gasparic, R.-B. Gerst, J.-M. Gheller, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, K. Hahn, C. Hilaire, A. Jungclaus, D. Kim, N. Kobayashi, T. Kobayashi, T. Koiwai, Y. Kondo, W. Korten, P. Koseglou, Y. Kubota, V. Lapoux, J. Lee, B.D. Linh, H. Liu, T. Lokotko, G. Lorusso, C. Louchart, R. Lozeva, M. Marques, M. Mc Cormick, K. Matsui, Y. Matsuda, M. Matsushita, S. Michimasa, T. Miyazaki, S. Momiyama, K. Moschner, I. Murray, D. Napoli, F. Naqvi, M. Niikura, A. Obertelli, , N. Orr, S. Ota, H. Otsu, V. Panin, S.-Y. Park, N. Paul, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Randisi, F. Recchia, W. Rodriguez, E. Sahin, M. Sasano, Y. Shiga, Y. Shimuzu, P.-A. Soderstrom, D. Sohler, I. Stefan, D. Steppenbeck, L. Stuhl, Y. Sun, M. Tanaka, R. Taniuchi, S. Takeuchi, Y. Togano, V. Vaquero, H. Wang, S. Wang, V. Werner, K. Wimmer, Z. Xu, H. Yamada, D. Yan, M. Yasuda, K. Yoneda, Y. Zaihong

First campaign: exploring the region of ^{78}Ni



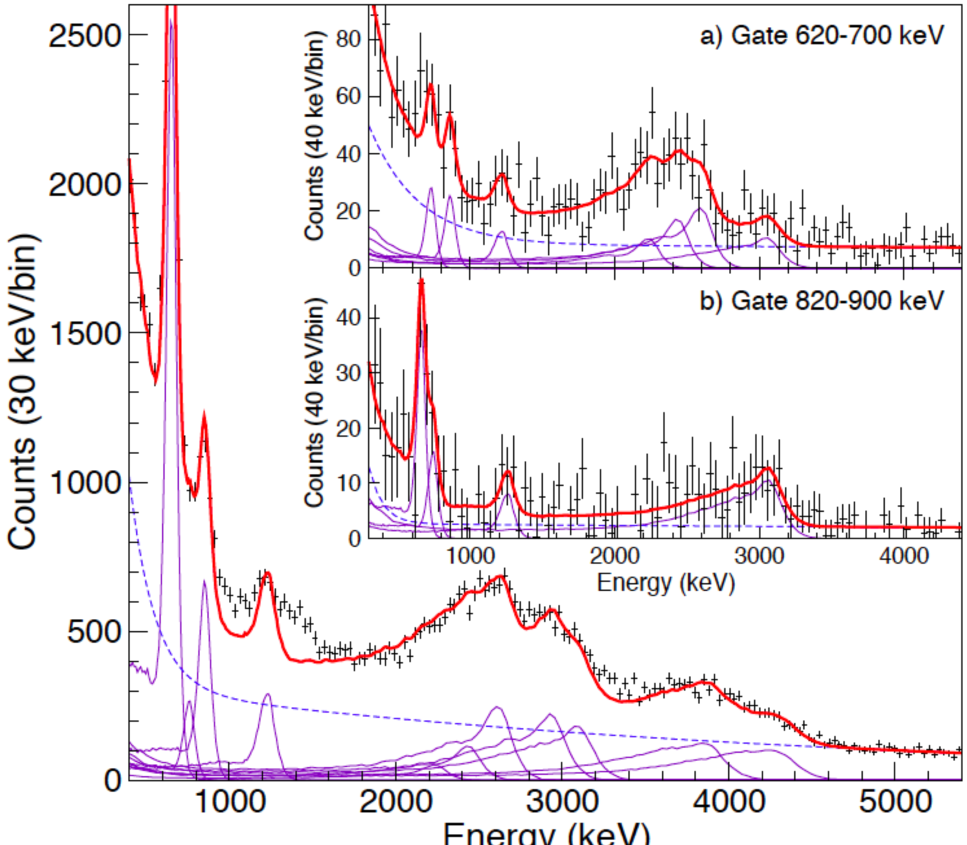


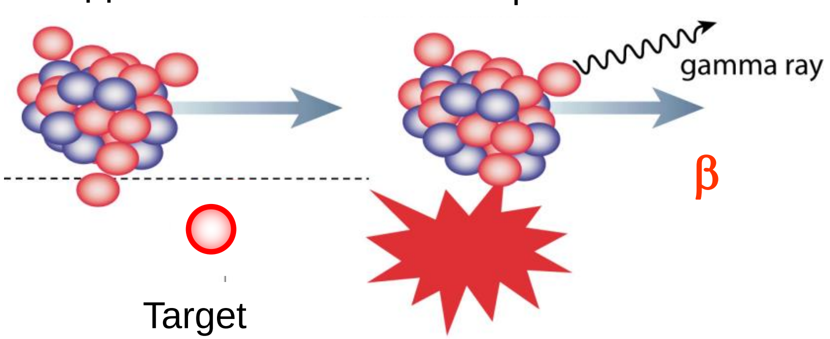
- Primary beam ^{238}U at 345 MeV/nucleon, **mean intensity = 13 pnA**
- Secondary beams at 250 MeV/nucleon, 100-mm target, $\Delta\beta/\beta$ = 20%

Is ^{78}Ni doubly magic? Spectroscopy of ^{79}Cu

TECHNISCHE UNIVERSITÄT DARMSTADT

Gamma spectrum after Doppler correction

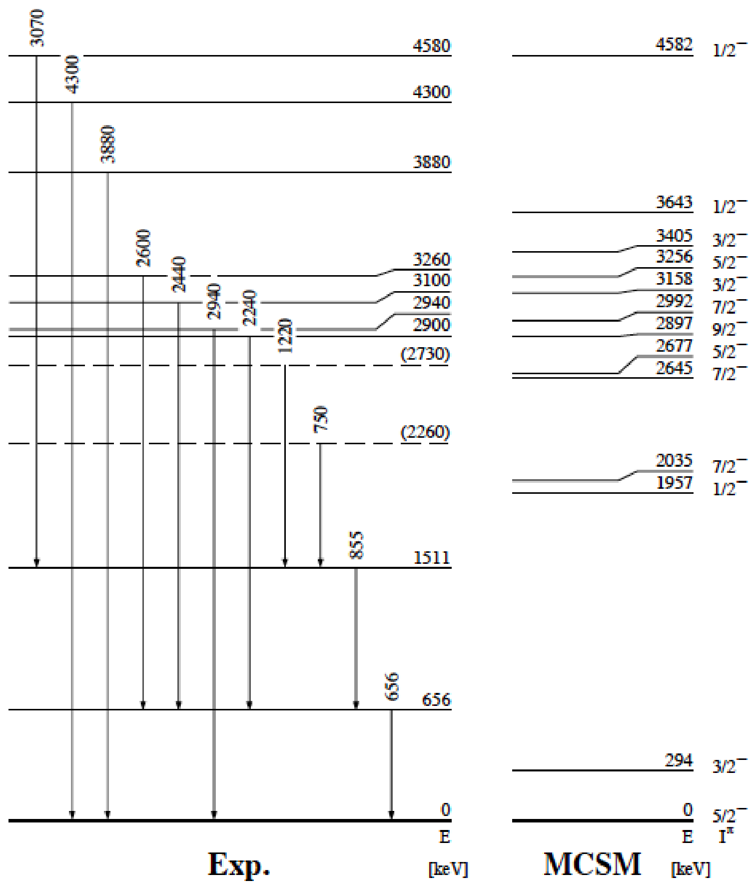




L. Olivier *et al.*, Phys. Rev. Lett., in press (2017)

Is ^{78}Ni doubly magic? Spectroscopy of ^{79}Cu

TECHNISCHE UNIVERSITÄT DARMSTADT



- ❑ no significant $f_{7/2}$ knockout feeding to states below 2.2 MeV
- ❑ mulitplet of states between 2.7 and 3.3 MeV interpreted as ^{78}Ni(2^{+}) coupled to proton in f5/2 or p3/2

Consistent with (shell model):

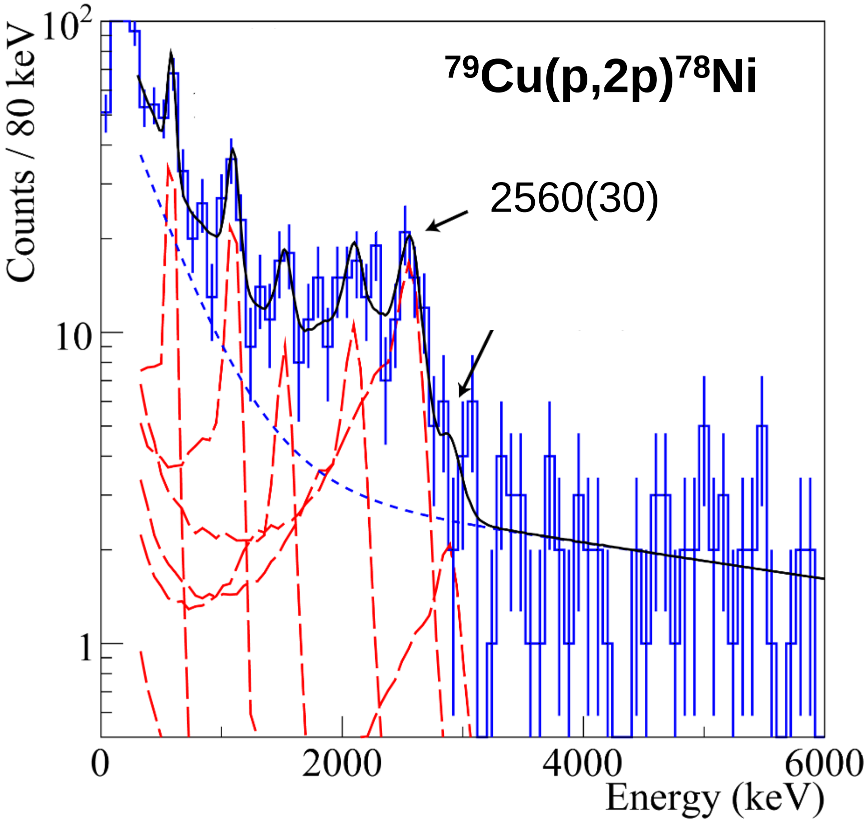
- ❑ a sizeable Z=28 shell gap
- ❑ ^{80}Zn(gs) = two protons + ^{78}Ni magic core

- ❑ Indirect proof of magicity of ^{78}Ni

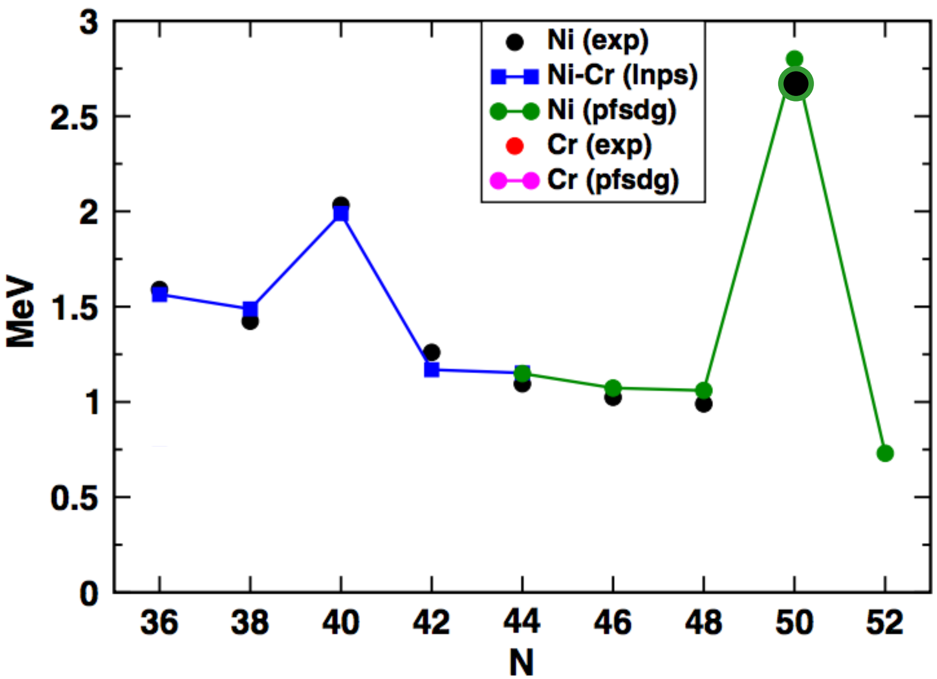
L. Olivier *et al.*, Phys. Rev. Lett., in press (2017)

Spectroscopy of ^{78}Ni

R. Taniuchi *et al.*, in preparation (2017)



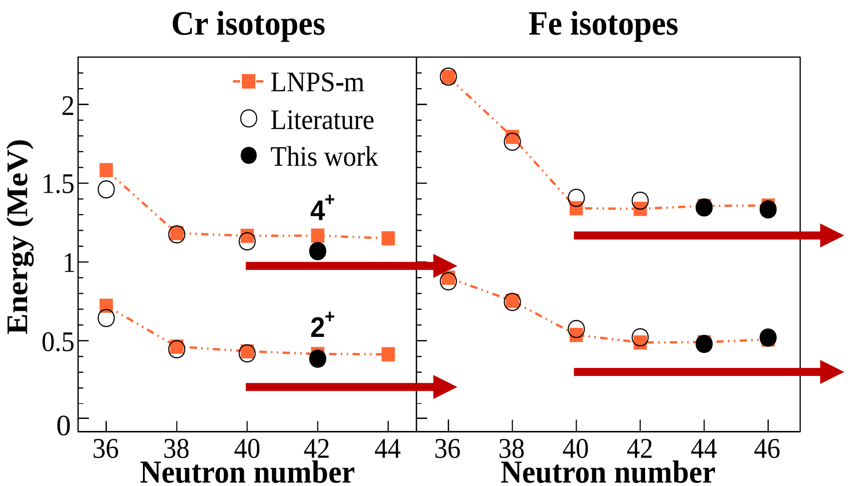
F. Nowacki *et al.*, Phys. Rev. Lett. **117**, 272501 (2016)

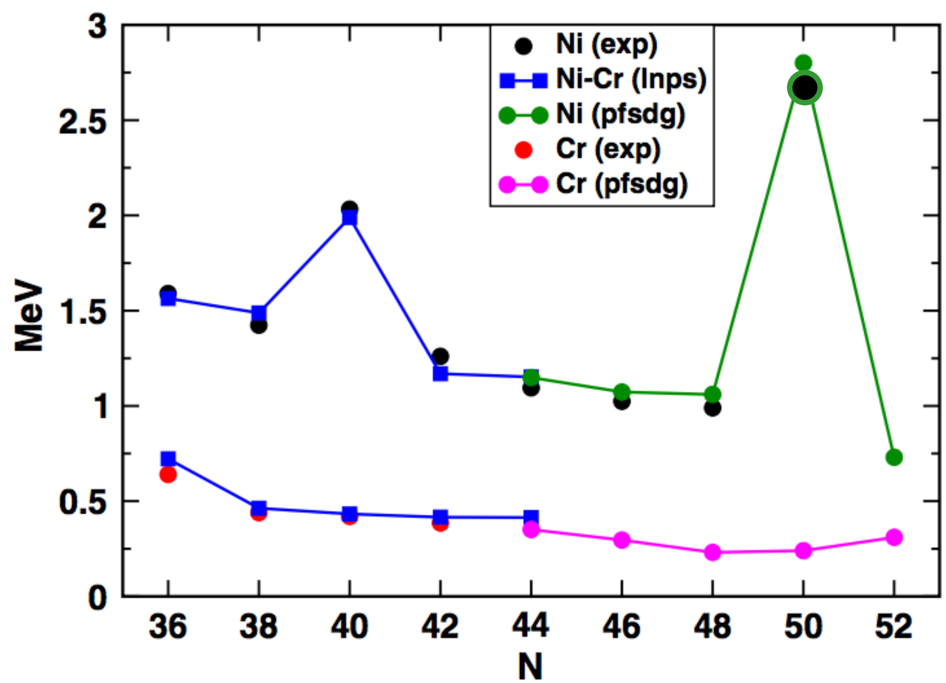


In agreement with several theories:
Coupled Cluster, QRPA+D1S, Tokyo MCSM

Extension of Island of Inversion towards N=50

F. Nowacki *et al.*, Phys. Rev. Lett. **117**, 272501 (2016)



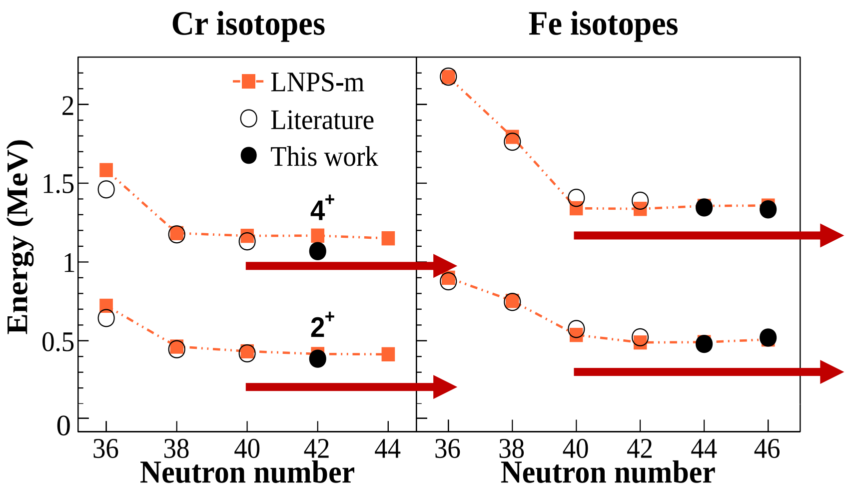


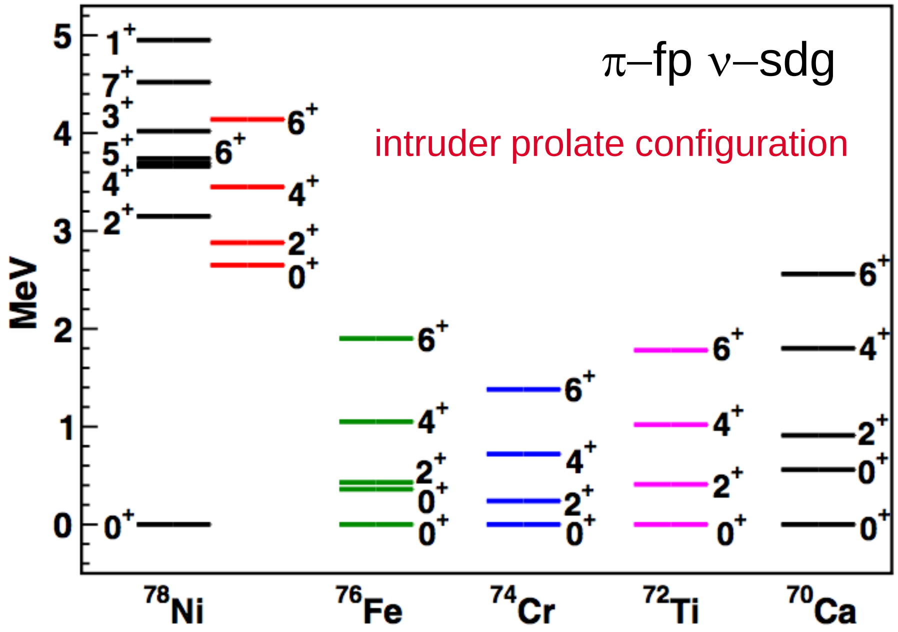
Does the island of deformation extends to N=50?

C. Santamaria, C. Louchart *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)

Extension of Island of Inversion towards N=50

F. Nowacki *et al.*, Phys. Rev. Lett. **117**, 272501 (2016)

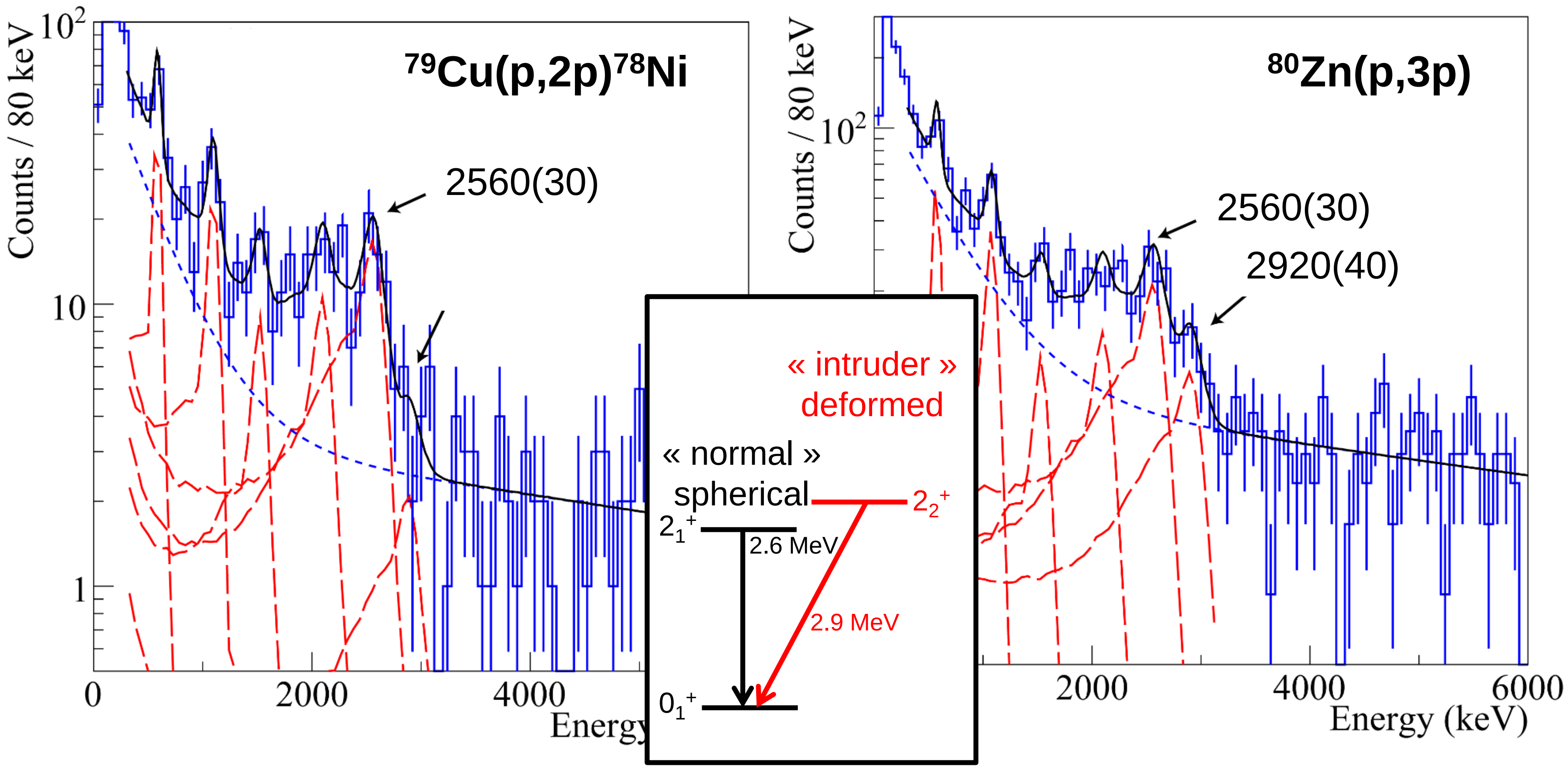




Does the island of deformation extends to N=50?

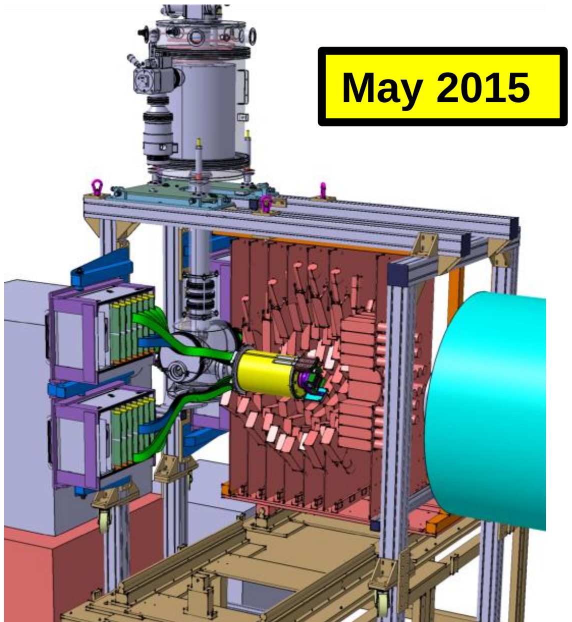
C. Santamaria, C. Louchart *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)

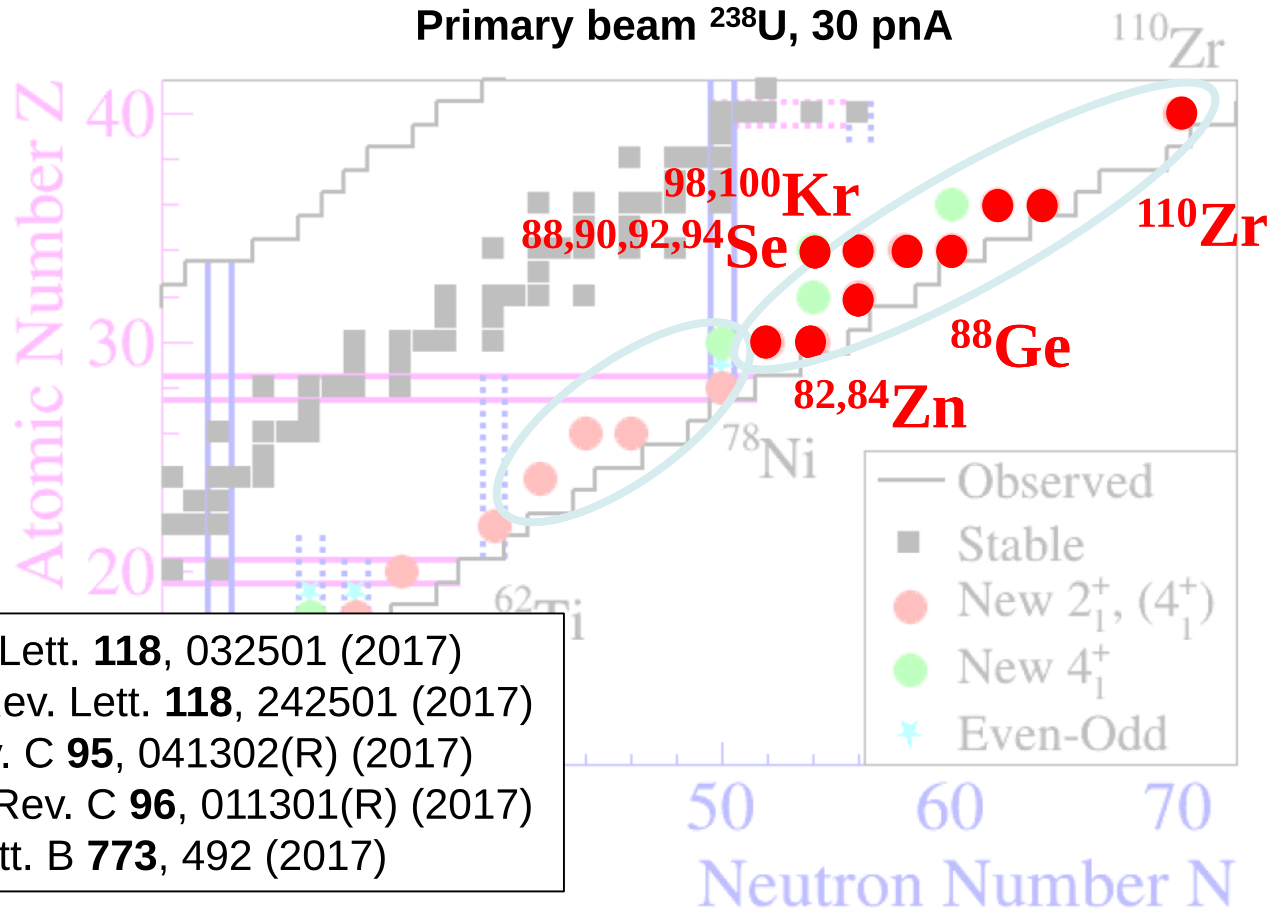
First indication of low-lying intruders in ^{78}Ni



R. Taniuchi *et al.*, in preparation (2017)

Second campaign: deformation in medium-mass nuclei at Z=32-40

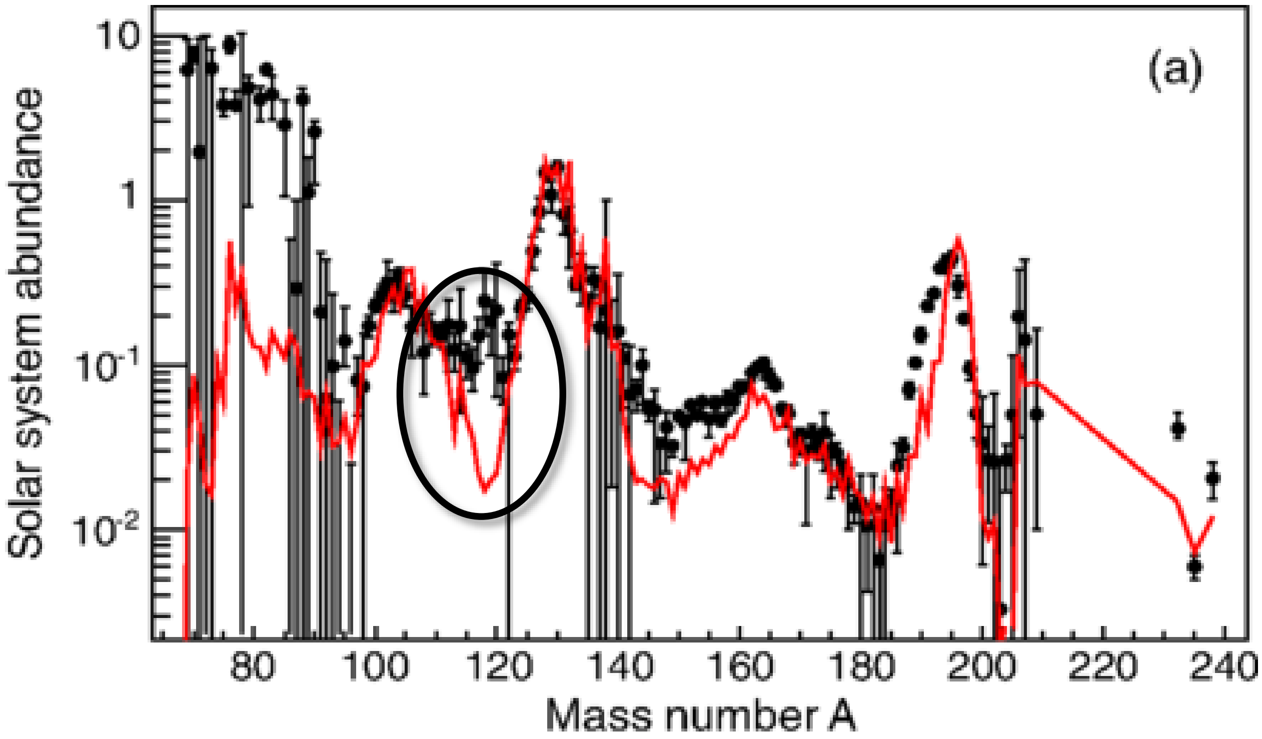




Zr: N. Paul *et al.*, Phys. Rev. Lett. **118**, 032501 (2017)
Kr: F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)
Se: S. Chen *et al.*, Phys. Rev. C **95**, 041302(R) (2017)
Ge: M. Lettman *et al.,* Phys. Rev. C **96**, 011301(R) (2017)
Zn: C. Shand et *al.,* Phys. Lett. B **773**, 492 (2017)

What is the structure of ^{110}Zr?

Figure from G. Lorusso *et al.*, Phys. Rev. Lett. 1**14** (2015)



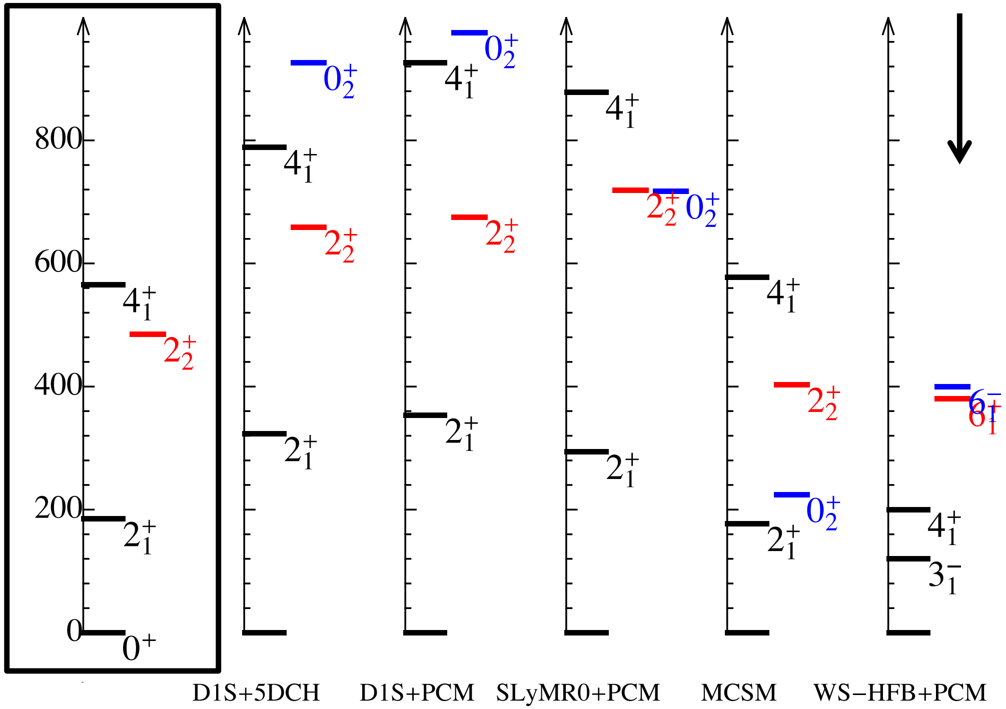
- ❑ **Various theoretical predictions**
  - **Shell gap at N=70? Tetrahedral** symmetry? **Axially deformed**?
- ❑ Important **benchmark for theory**

Spectroscopy of ^{110}Zr

data

Ellipsoidal predictions

Tetrahedral prediction
Tagami *et al.*, PRC 87 (2013)



Spectroscopy of ^{110}Zr

TECHNISCHE UNIVERSITÄT DARMSTADT

data

Ellipsoidal predictions

Tetrahedral prediction
Tagami *et al.*, PRC 87 (2013)

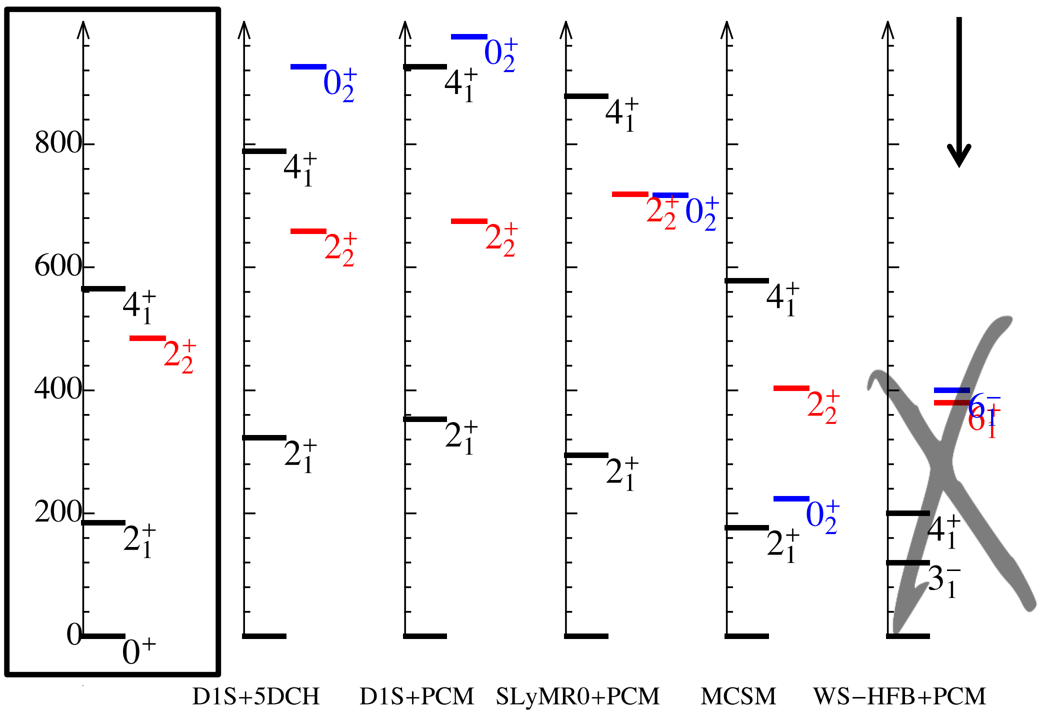
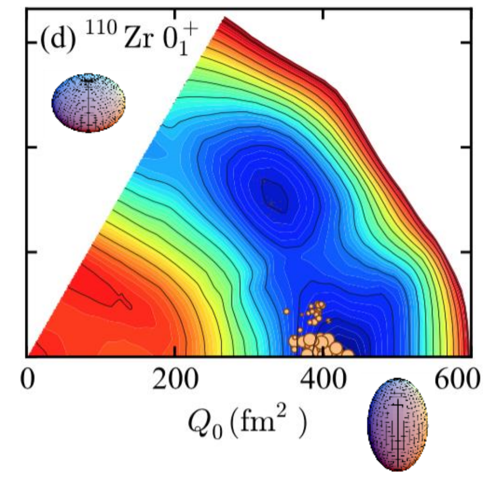


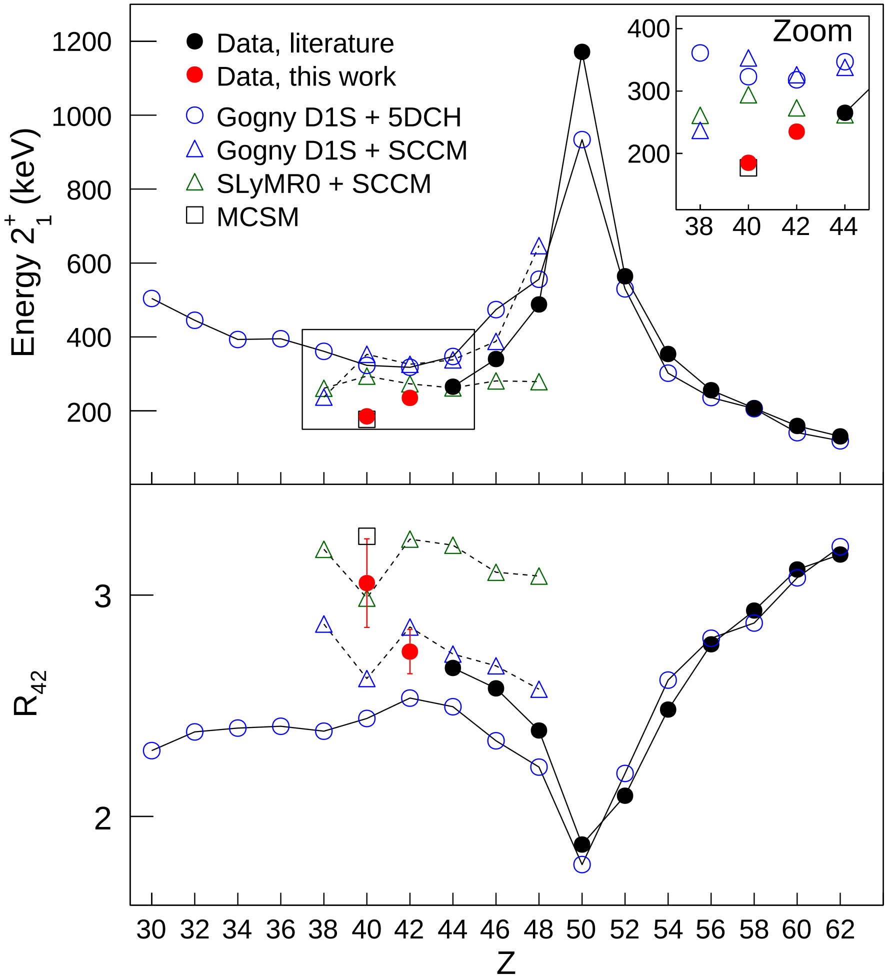
Figure from Togashi *et al.*, 2016



^{110}Zr well deformed, prolate nucleus

N. Paul *et al.*, Phys. Rev. Lett. **118**, 032501 (2017)

Spectroscopy of ^{110}Zr: comparison to theory

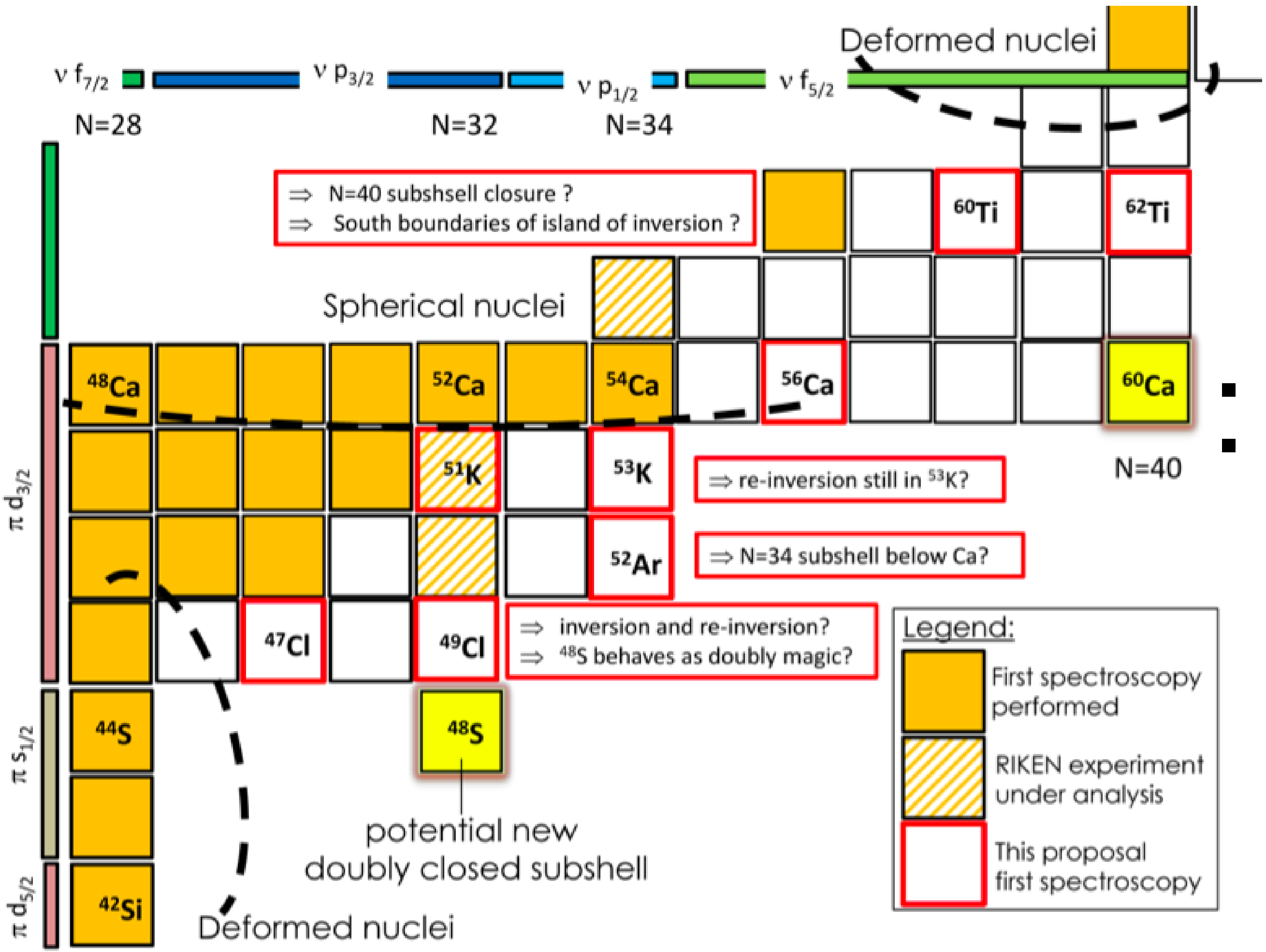


N=70 isotones

N. Paul *et al*., Phys. Rev. Lett. **118**, 032501 (2017)

Third campaign: shell evolution in the *fp* shell

TECHNISCHE UNIVERSITÄT DARMSTADT



May 2017

- SAMURAI spectrometer
- NeuLAND + NEBULA

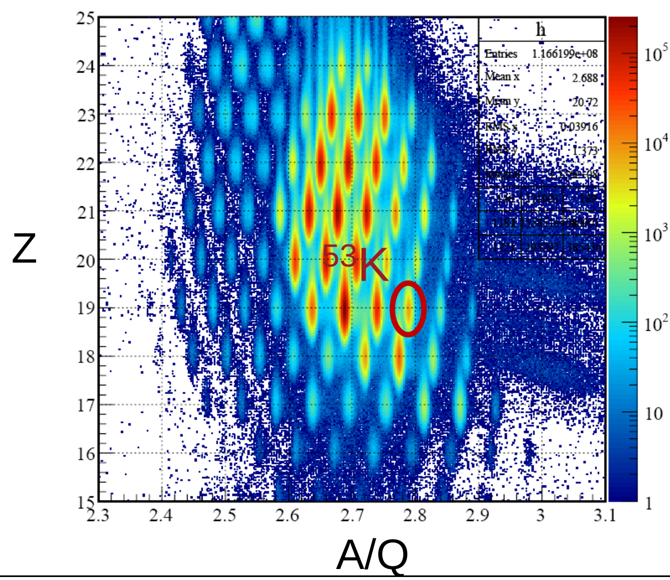
Experimental details

- ^{70}Zn primary beam, 350 MeV/nucleon, 200-250 pnA
- Secondary beam at about **240 MeV/nucleon** (entrance of secondary target)
- 150 mm thick hydrogen tqrget

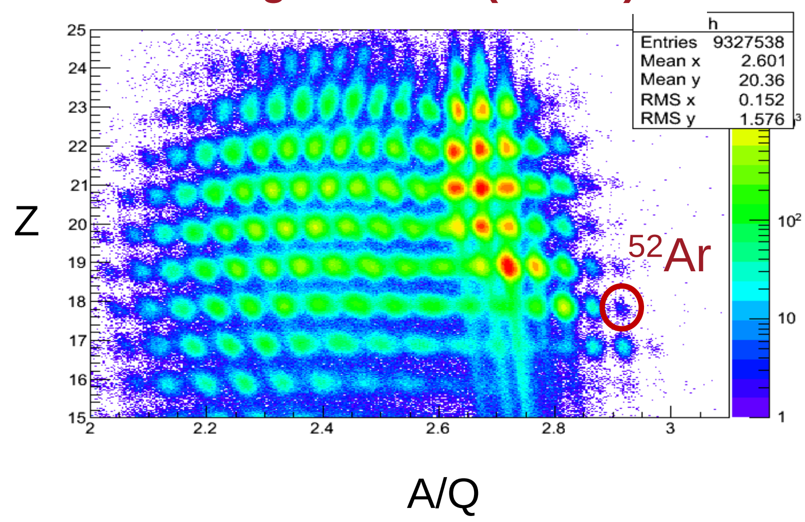
- **ONE unique setting**

- Total beam intensity: 200 pps; **^{53}K: 0.8 pps, ^{57}Sc: 13 pps, ^{63}V: 3 pps**

Beam PID (online)



Fragment PID (online)

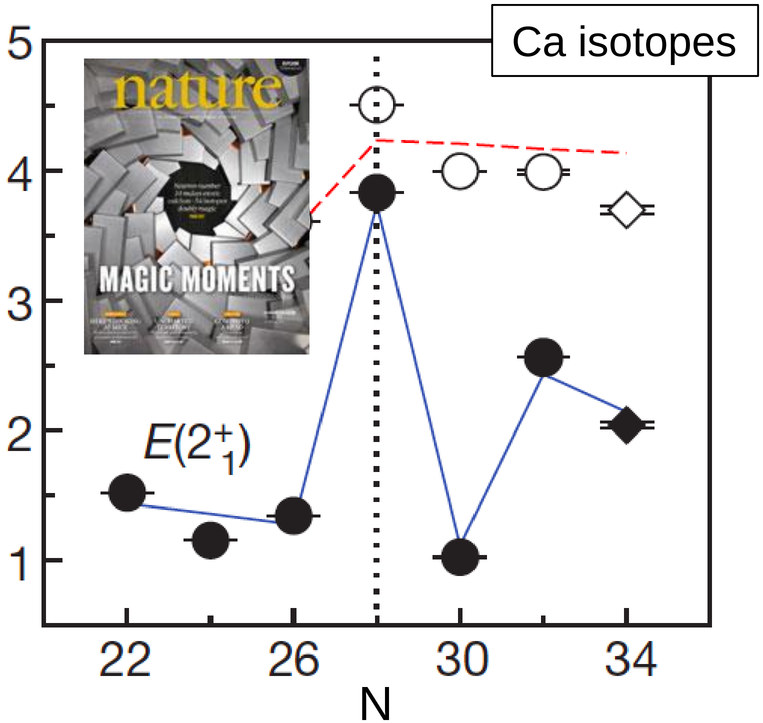


Is N=34 a (new) shell closure?

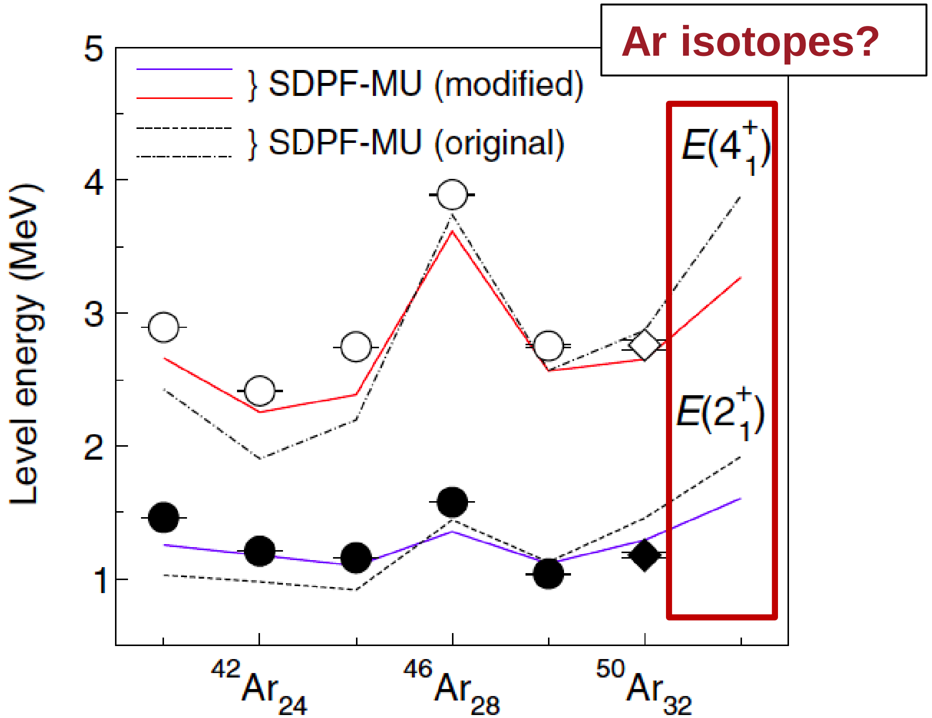
TECHNISCHE UNIVERSITÄT DARMSTADT

Two mechanisms into play to explain the N=34 shell gap:

- ❑ Three-body forces
- ❑ Tensor term of the effective two-body NN interaction



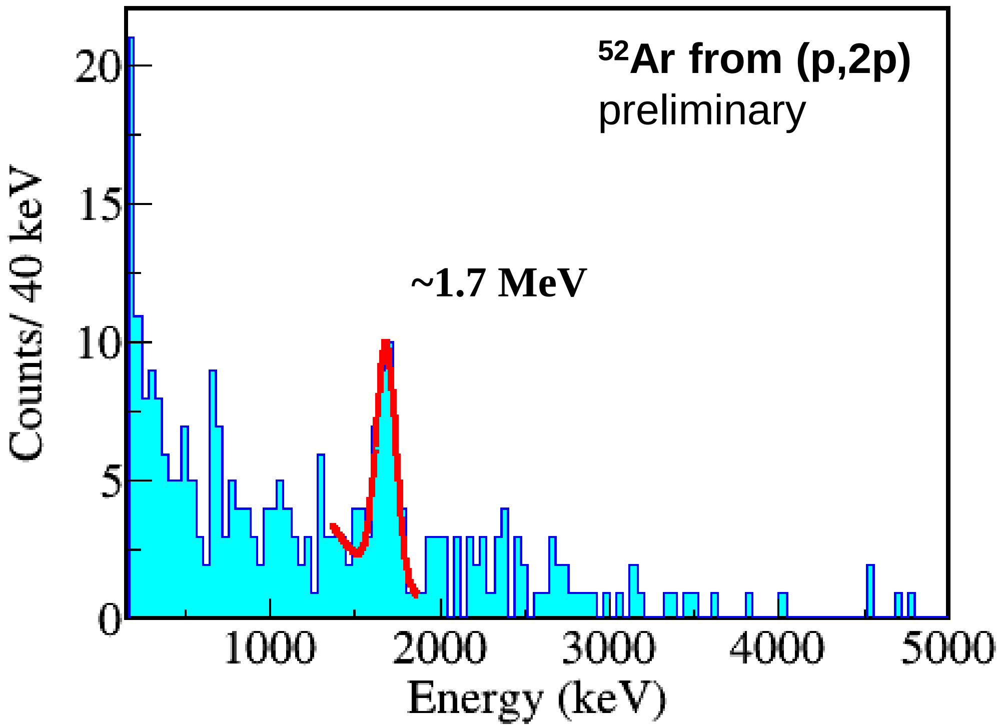
D .Steppenbeck *et al.*, Nature **502** (2013)



D. Steppenbeck *et al.*, PRL **114**, 252501 (2015)

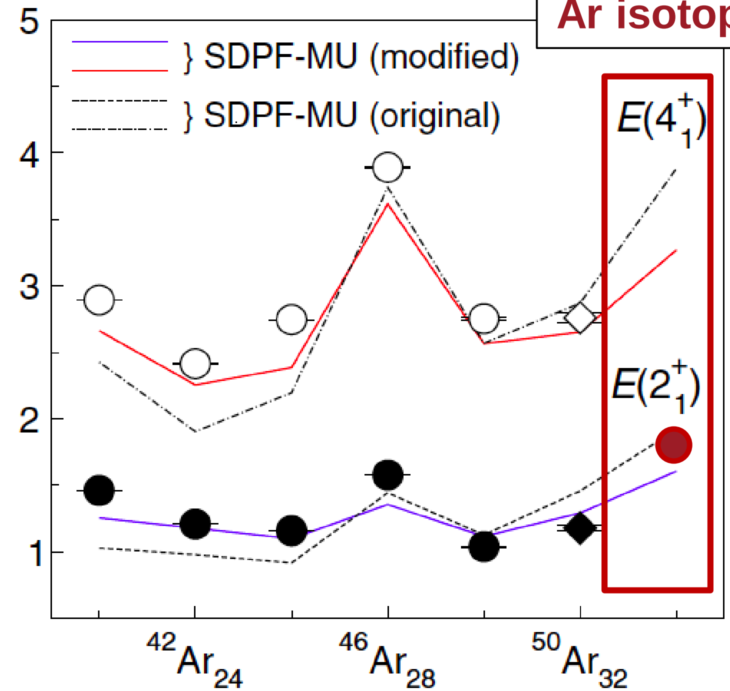
Is N=34 a (new) shell closure?

S_n (^{52}Ar) = 3.1 MeV from systematics (NNDC)



Analysis by H. Liu, CEA

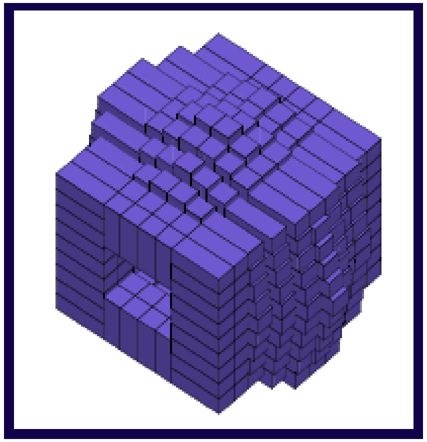
Ar isotopes?



D. Steppenbeck *et al.*, PRL **114**, 252501 (2015)

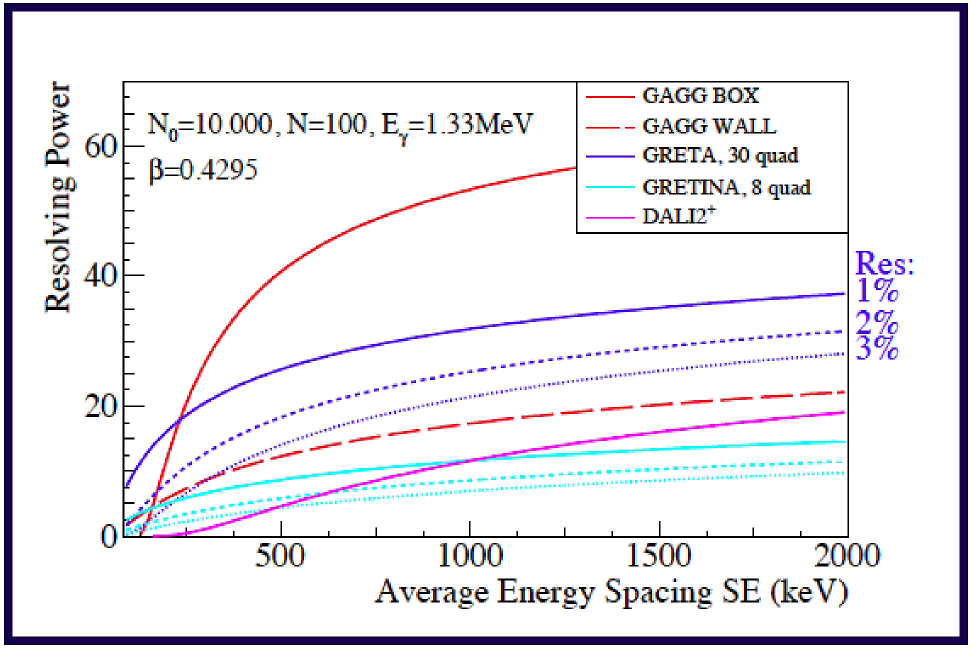
Upgrade: a new scintillator array at the RIBF

GAGG: Gadolinium Aluminium Gallium Garnet



- 500 rectangular detectors of $35\times35\times100$ mm^3
- WALL configuration
  - Place all 500 mm downstream
- BOX configuration
  - Cover 4π
- $25\times25\times76$ mm^3 prototypes deliverd in April 2017
  - $<$ 4% resolution (FWHM) achieved @ 1332 keV
  - Wrapped in single layer of ESR
  - Single S8664-1010 APD

Estimated gain of **X5** in sensitivity

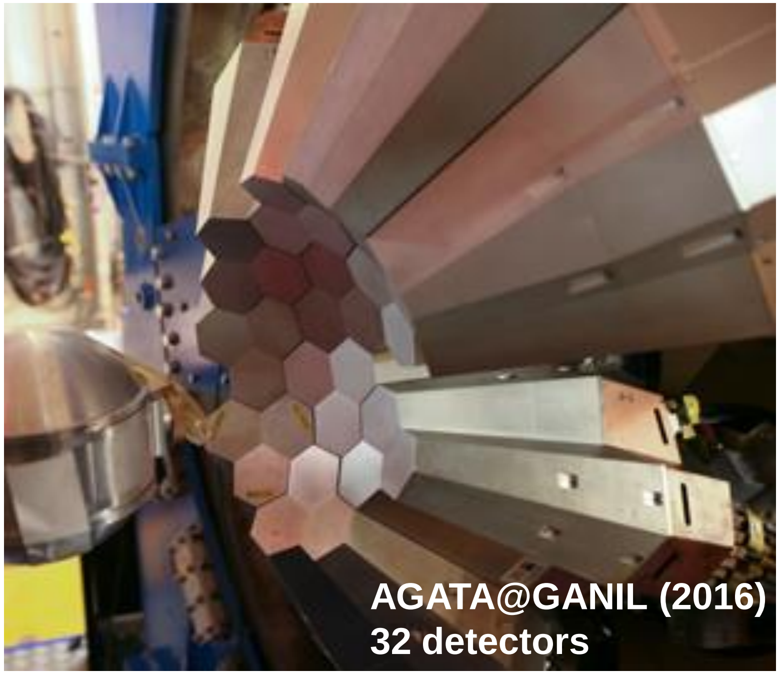


Resolving power as defined in:
M.A. Deleplanque *et al.*, NIMA 430, 292 (1999)

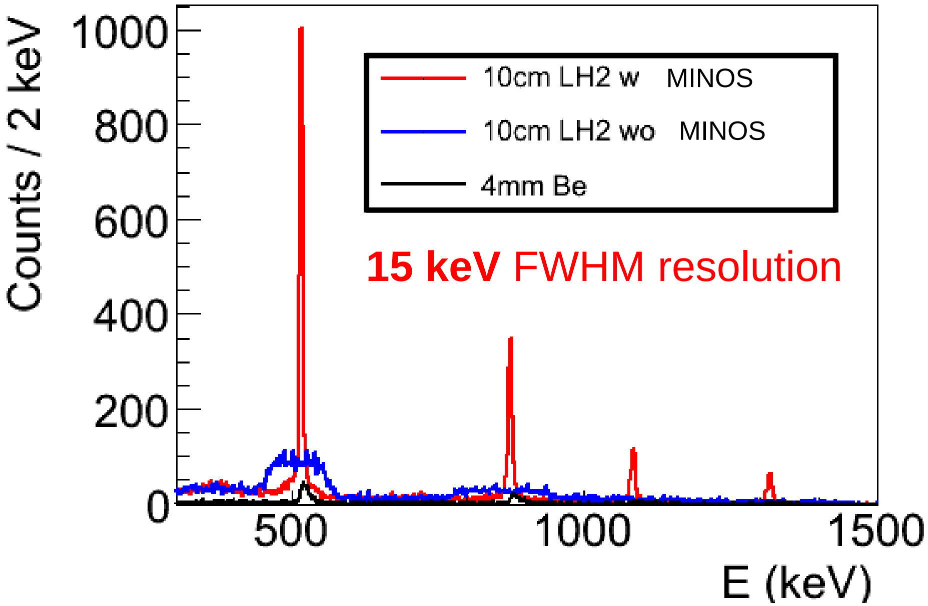
Courtesy P. Doornenbal, RIKEN

Future: high-resolution spectroscopy

- A high-resolution Ge tracking arrays would open new opportunities
- GRETINA and AGATA at the RIBF: to be forgotten for the coming years
- promising future at FAIR, NUSTAR/HISPEC: AGATA + MINOS-like system



$^{69}Co(p,2p)^{68}Fe$ at 200 MeV/nucleon



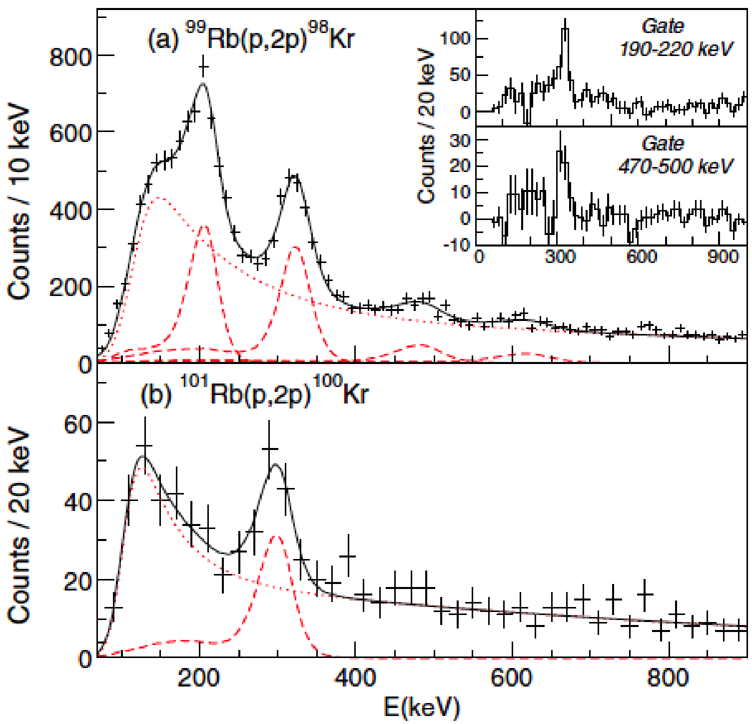
AGATA@FAIR simulation, 30 detectors

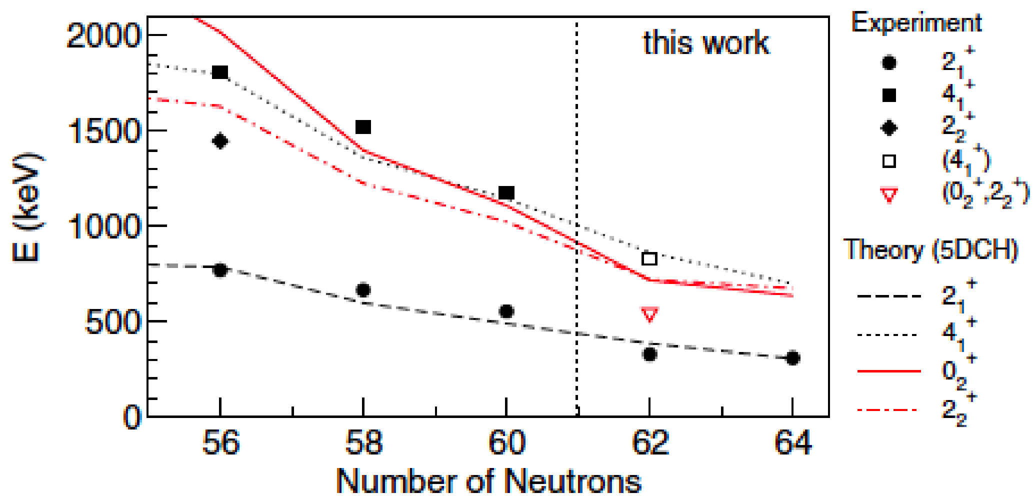
Summary

- **SEASTAR**: spectroscopy of the **neutron-rich nuclei** with **DALI2** and **MINOS** at the **RIBF**
- SEASTAR experiments (2014, 2015, 2017) **successfully finished**
- Several **new results** on shell evolution and deformation in medium-mass nuclei
  - ^{78}Ni doubly magic
  - hint for an onset of deformation at N=50 below ^{78}Ni
  - ^{110}Zr strongly deformed
  - Shape coexistence beyond N=60 in Kr isotopes
  - hint for shape transition at N=60 in heavy Se isotopes
  - triaxial deformation in ^{86}Ge
  - "magic character" of N=34 in ^{52}Ar chain seems to be confirmed (analysis ongoing)
- Others to come: **>30 analysis ongoing** (core and side channels)

Annexes

Shapes in heavy krypton isotopes



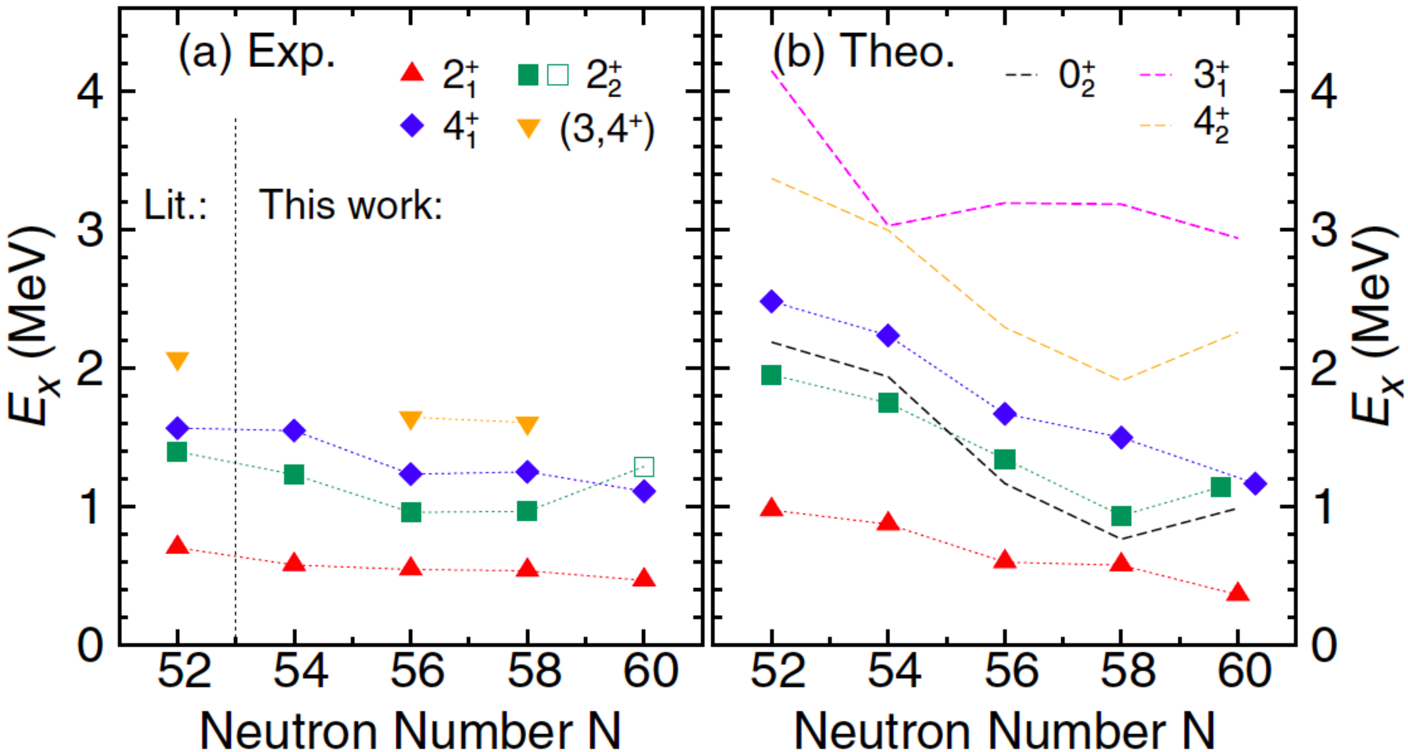


- ❑ Smoother onset of collectivity than in Zr, Sr
- ❑ Shape transition predicted beyond N=60 (^{100}Kr): ground state from prolate to oblate
- ❑ Low-lying (2^+_2) state in agreement with shape competition at low energy

F. Flavigny *et al.*, Phys. Rev. Lett. **118**, 242501 (2017)

Shapes in heavy selenium isotopes

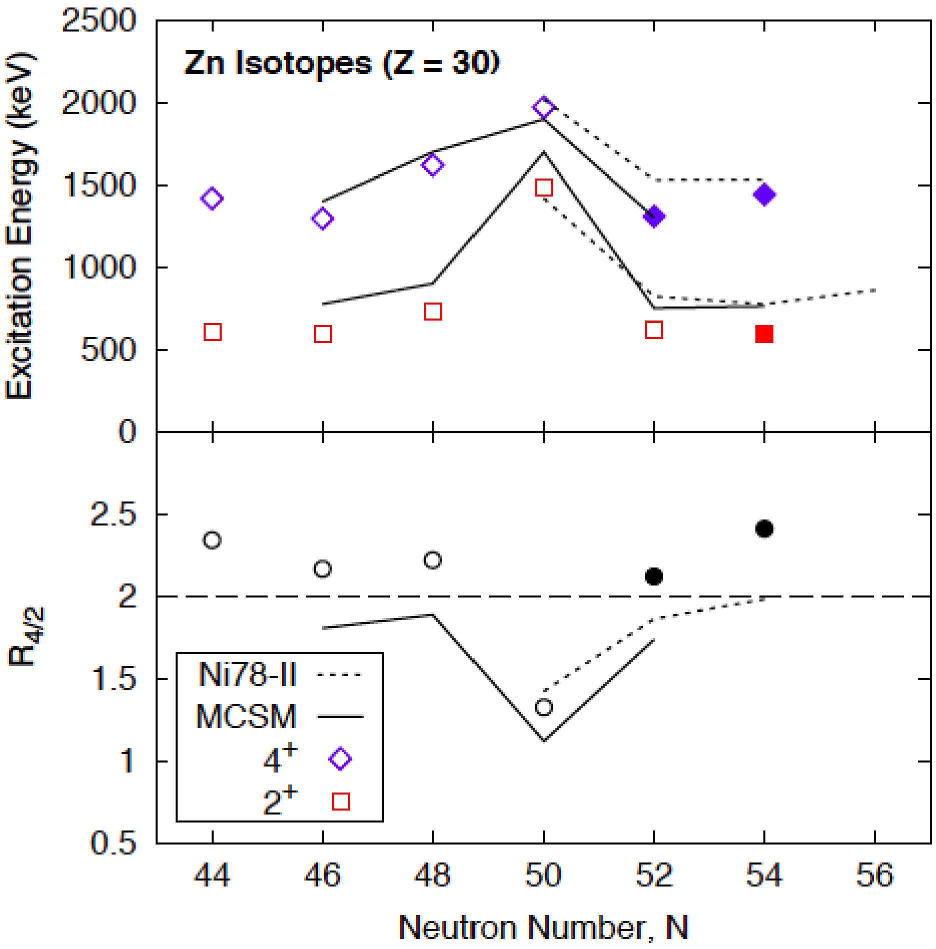
D1S Gogny interaction; Calculations by Tomas R. Rodriguez, University of Madrid



- ❑ Predicted oblate – prolate shape coexistence
- ❑ shape transition at N=60 (94Se): ground state from prolate to oblate

S. Chen *et al.*, Phys. Rev. C **95**, 041302(R) (2017)

Spectroscopy of heavy zinc isotopes



- ❑ new states observed in ^{81,82,83,84}Zn
- ❑ low-lying spectroscopy interpreted within the shell-model framework
- ❑ Ni78-II: ^{78}Ni core, Z=28-50, N=50-82 orbitals
- ❑ MCSM: ^{40}Ca core, pf shell + g9/2-d5/2
- ❑ in the SM and used interactions, both the breaking of the Z=28 and N=50 improve the agreement with data

C. Shand *et al.*, Phys. Lett. B **773**, 429 (2017)