Recent structure studies with proton-induced reactions

A. Obertelli, *CEA Saclay*

Direct Reactions with Exotic Beams Conference

July 11th-16th, 2016, Halifax, Canada

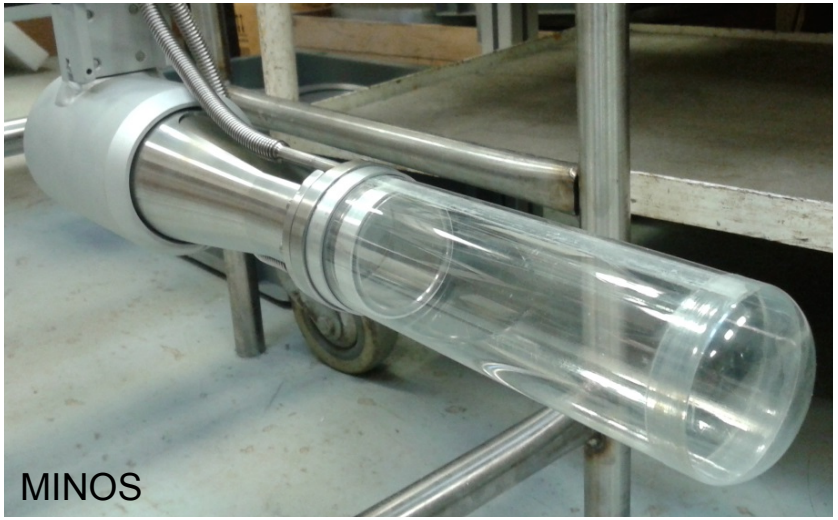
Outline

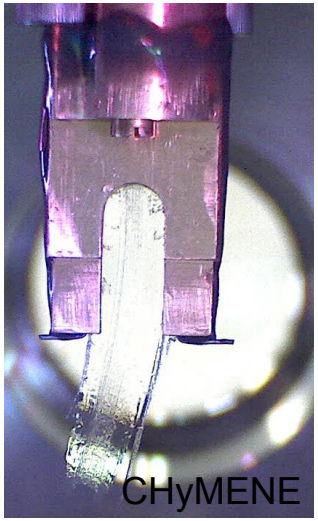
1- In-beam gamma spectroscopy at the RIBF with DALI2 and MINOS

- ^{66}Cr, ^{70,72}Fe (published in 2015)
- ^{78}Ni (unpublished, in preparation)
- ^{88,90,92,94}Se (unpublished, recently submitted)

2- Collectivity of neutron-deficient Sn isotopes: ^{104}Sn(p,p')

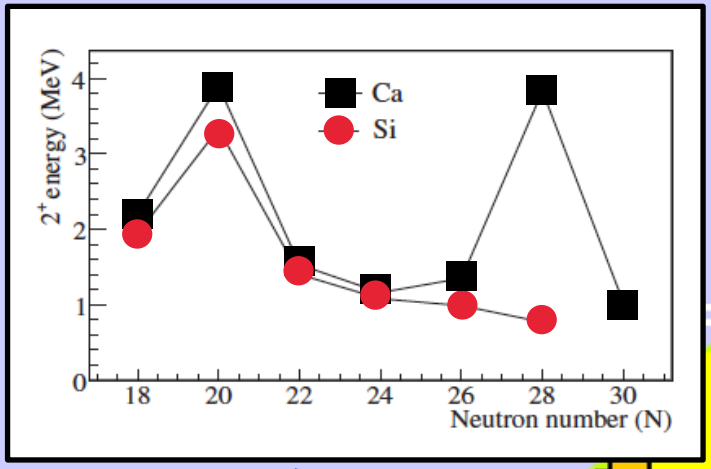
3- Status of the CHYMENE solid hydrogen target





Exploring nuclear structure far from stability

Adapted from B. Bastin *et al.*, PRL 99 (2007)



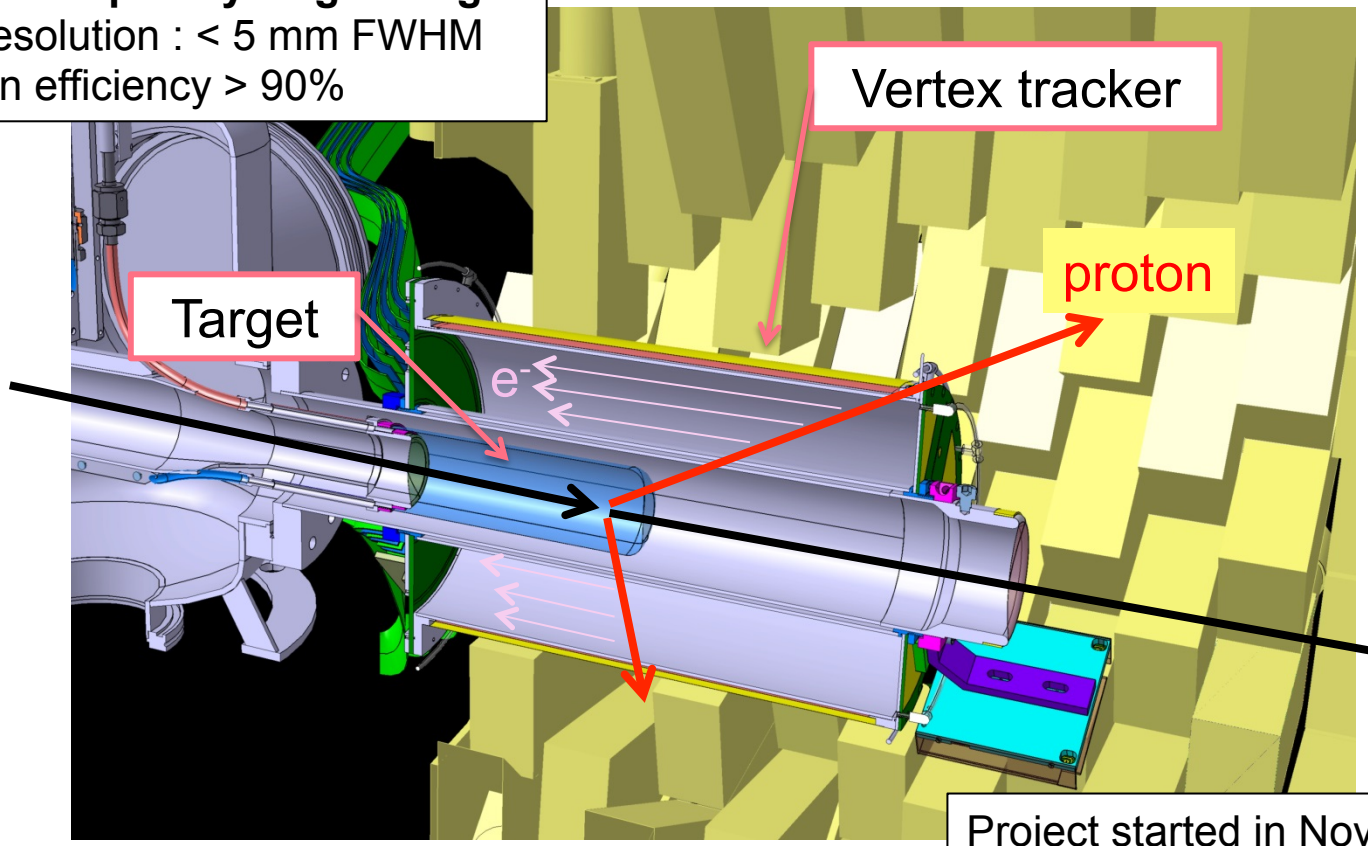
In-beam gamma:
One of the most powerful tools

RIBF leading facility today

MINOS at the RIBF

Program based on (p,2p), (p,pn), (p,3p)…

60-200 mm **liquid hydrogen target**
Vertex resolution : < 5 mm FWHM
Detection efficiency > 90%



Project started in November 2010
In use at the RIBF since 2014

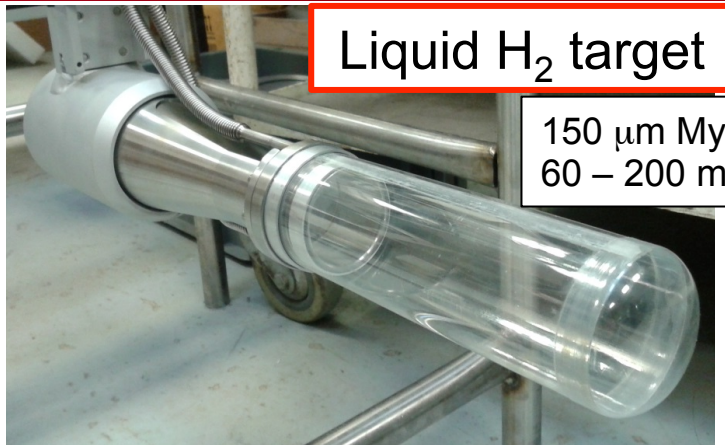
DALI2: S. Takeuchi et al., Nucl. Instr. Meth. A **763**, 596 (2014)
MINOS: A. Obertelli *et al.,* Eur. Phys. Jour. A **50**, 8 (2014)

MINOS at the RIBF

Features

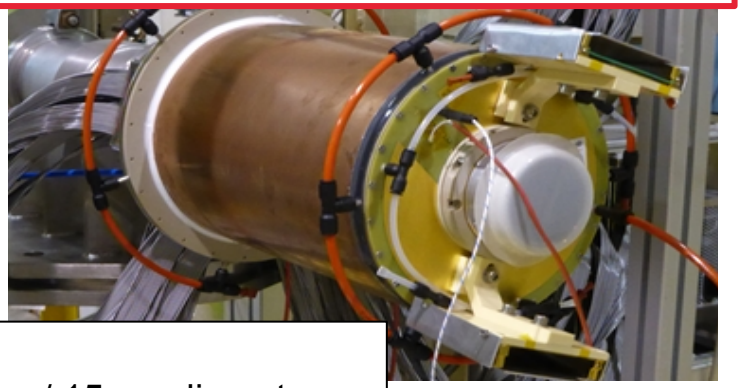
- Ar(85%)CF4(12%)iso(3%) gas
  drift velocity: 4.5 cm/μs
  dispersion: 200 μm × √cm
- AGET: digital, 512 time bin, 100 MHz
  individual discriminator / channel
  typical dead time of 100 μs / event

Liquid H_2 target

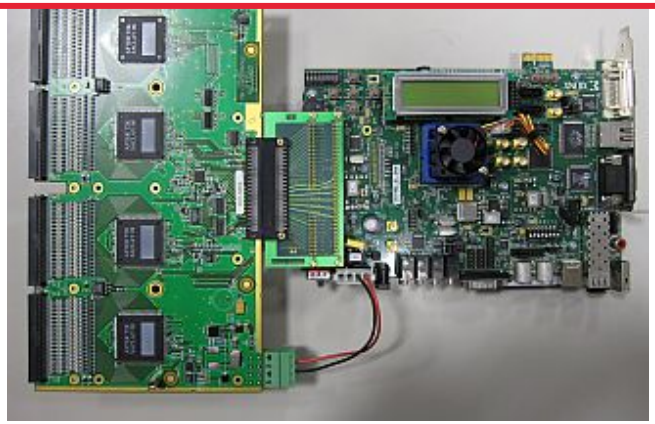


150 μm Mylar cell
60 – 200 mm long

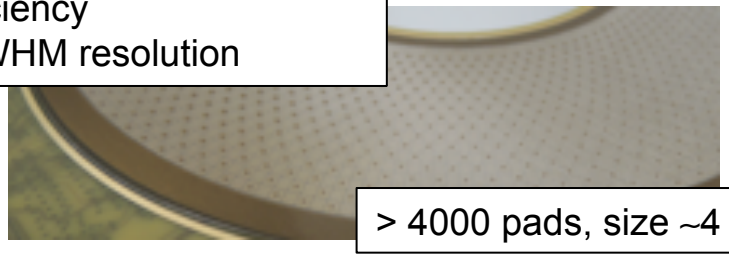
High granularity detector (TPC)



Specific electronics and Software



TPC
> 30 cm long / 15 cm diameter
> 90% efficiency
< 5 mm FWHM resolution

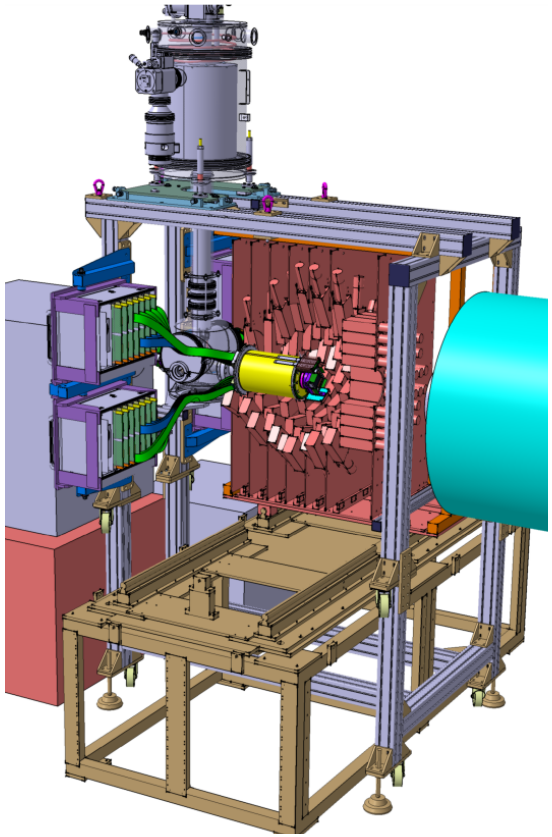


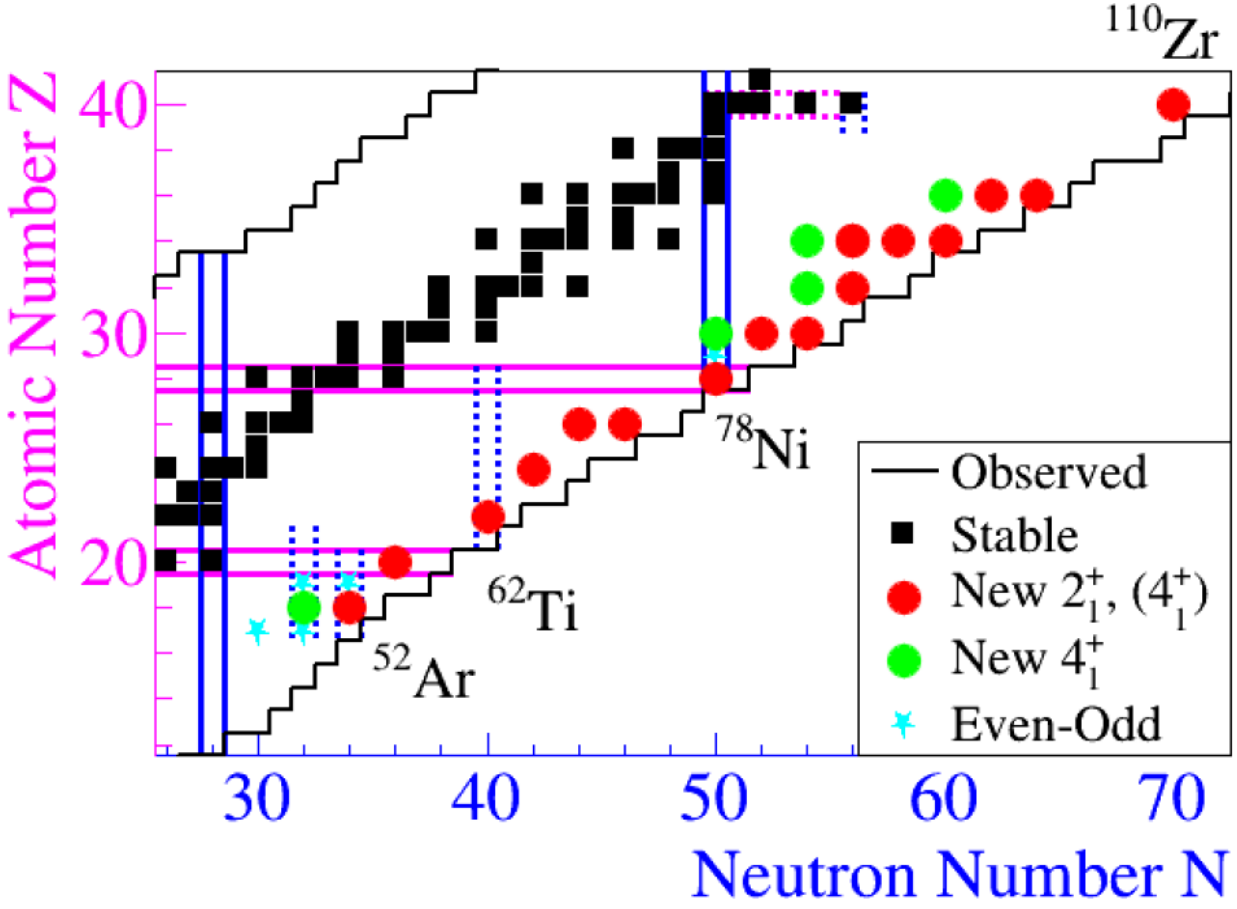
> 4000 pads, size ~4 mm^2

AGET chip from the GET project
(CEA, IN2P3, NSCL collaboration)

SEASTAR
Shell Evolution and Search for 2^+ Energies At the RIBF

Spokespersons: P. Doornenbal (RIKEN), AO (CEA)





http://www.nishina.riken.jp/collaboration/SUNFLOWER/experiment/seastar/index.html

SEASTAR
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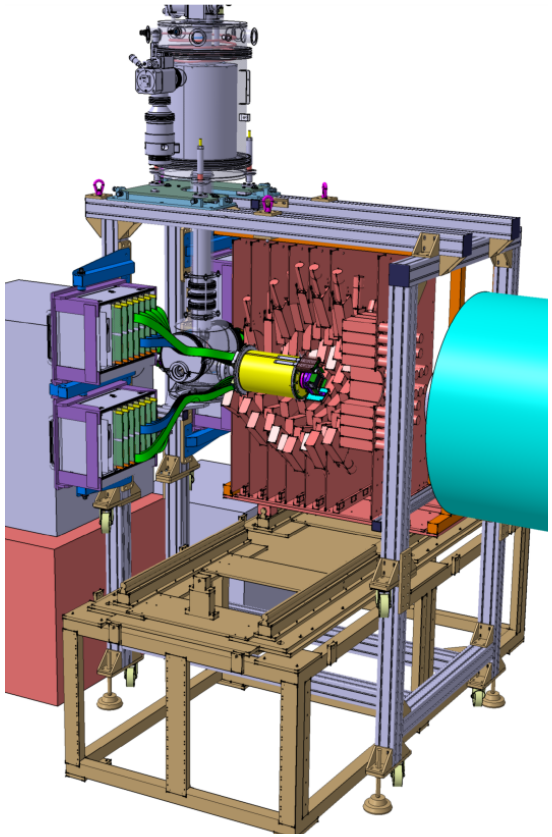
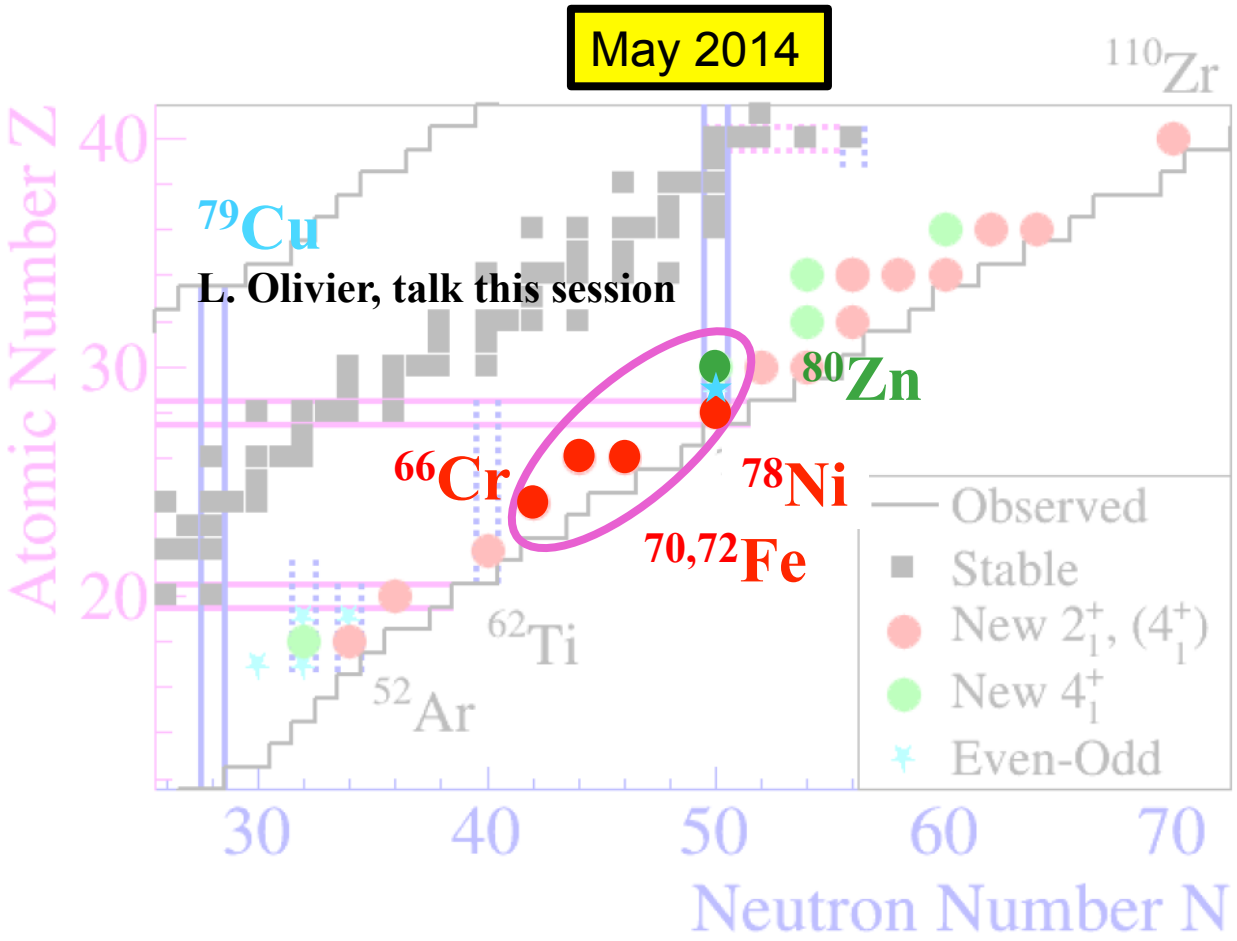
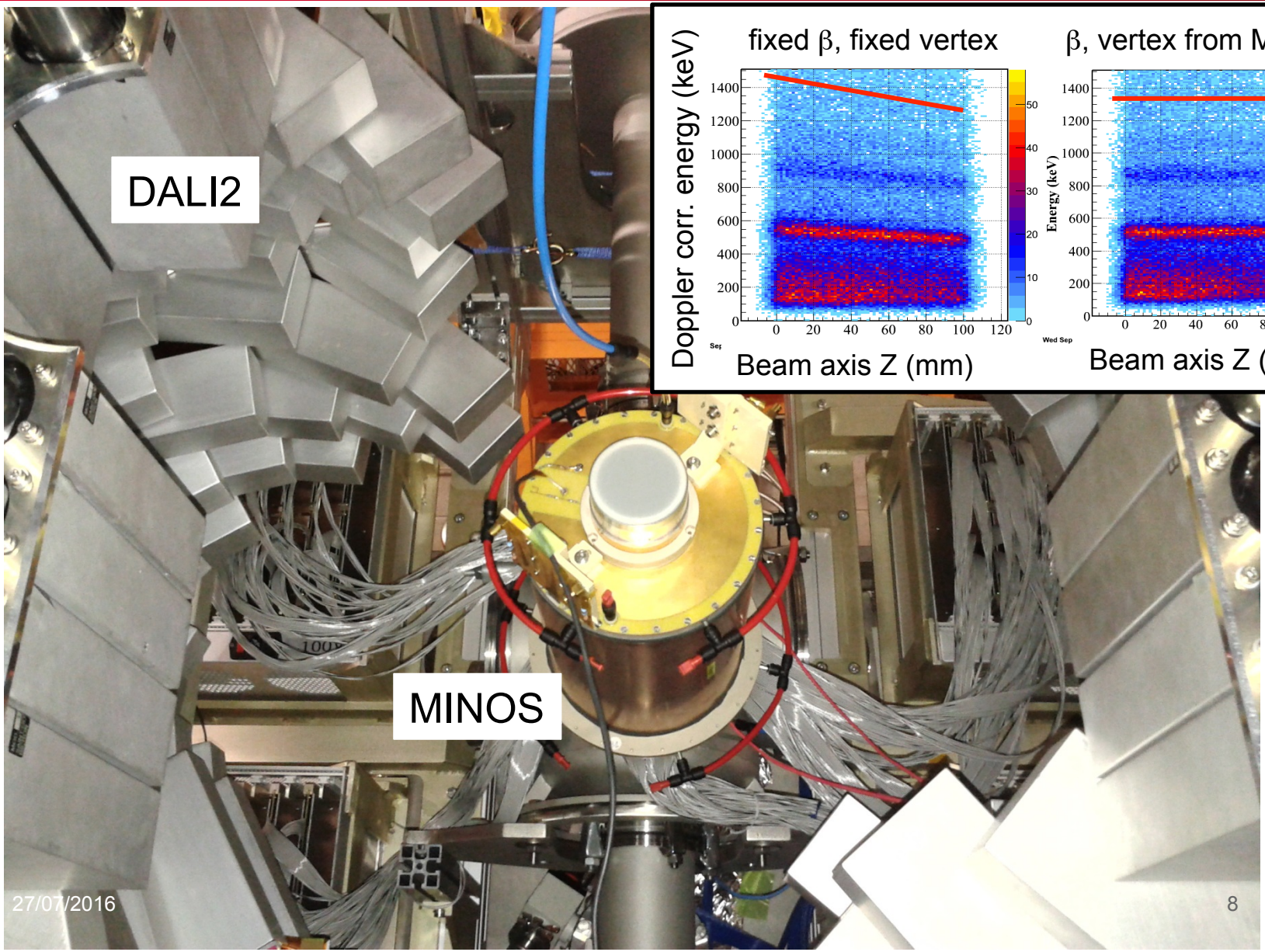




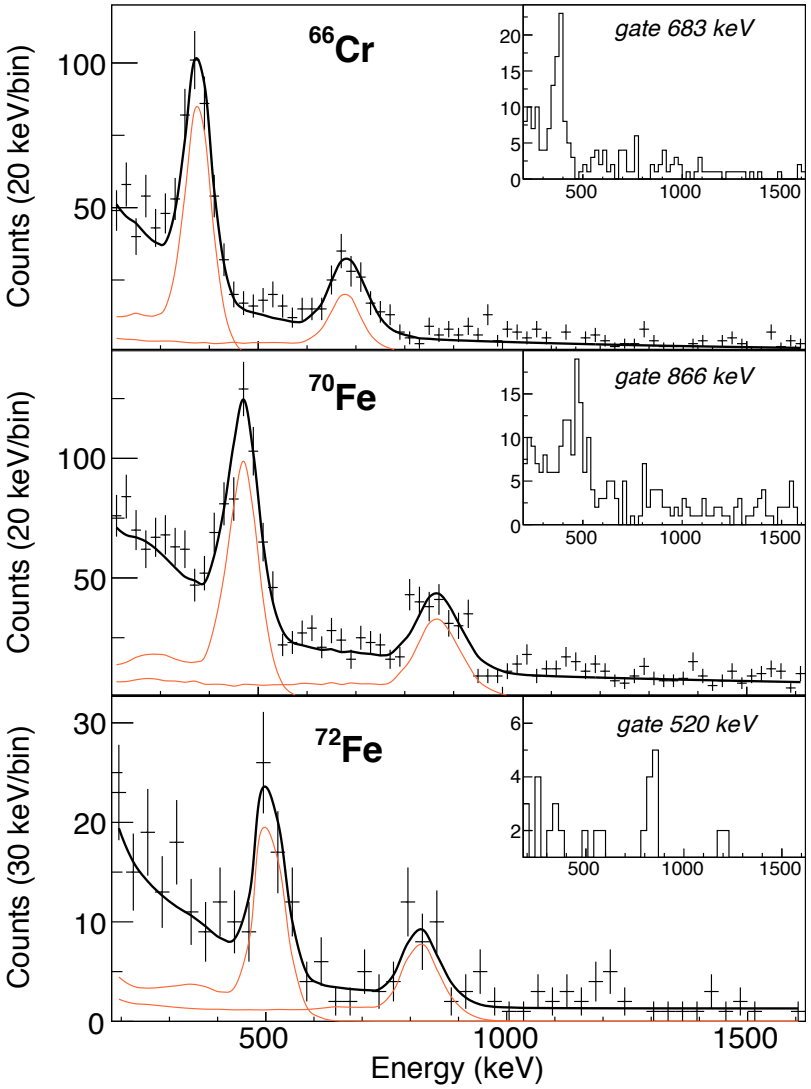
Primary beam ^{238}U at 345 MeV/nucleon, **mean intensity = 13 pnA**
Secondary beams at 250 MeV/nucleon, **100-mm target**, $\Delta\beta/\beta$ = 20%

DALI2-MINOS setup

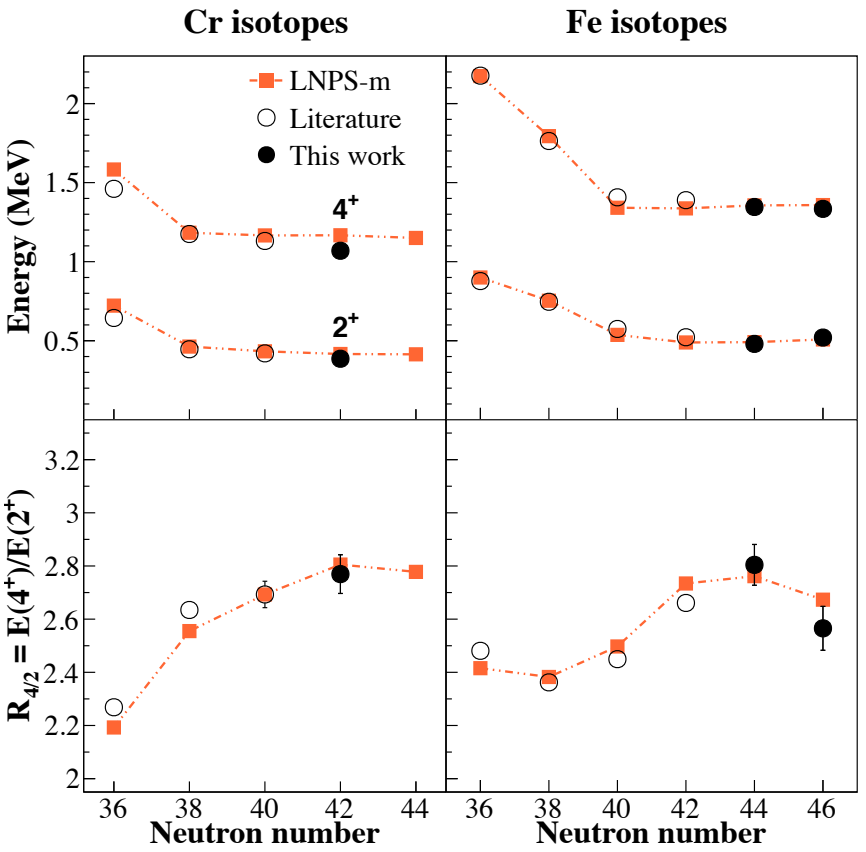


Collectivity beyond N=40 in Cr, Fe isotopes

Analysis by C. Santamaria (CEA) and C. Louchart (TU Darmstadt)



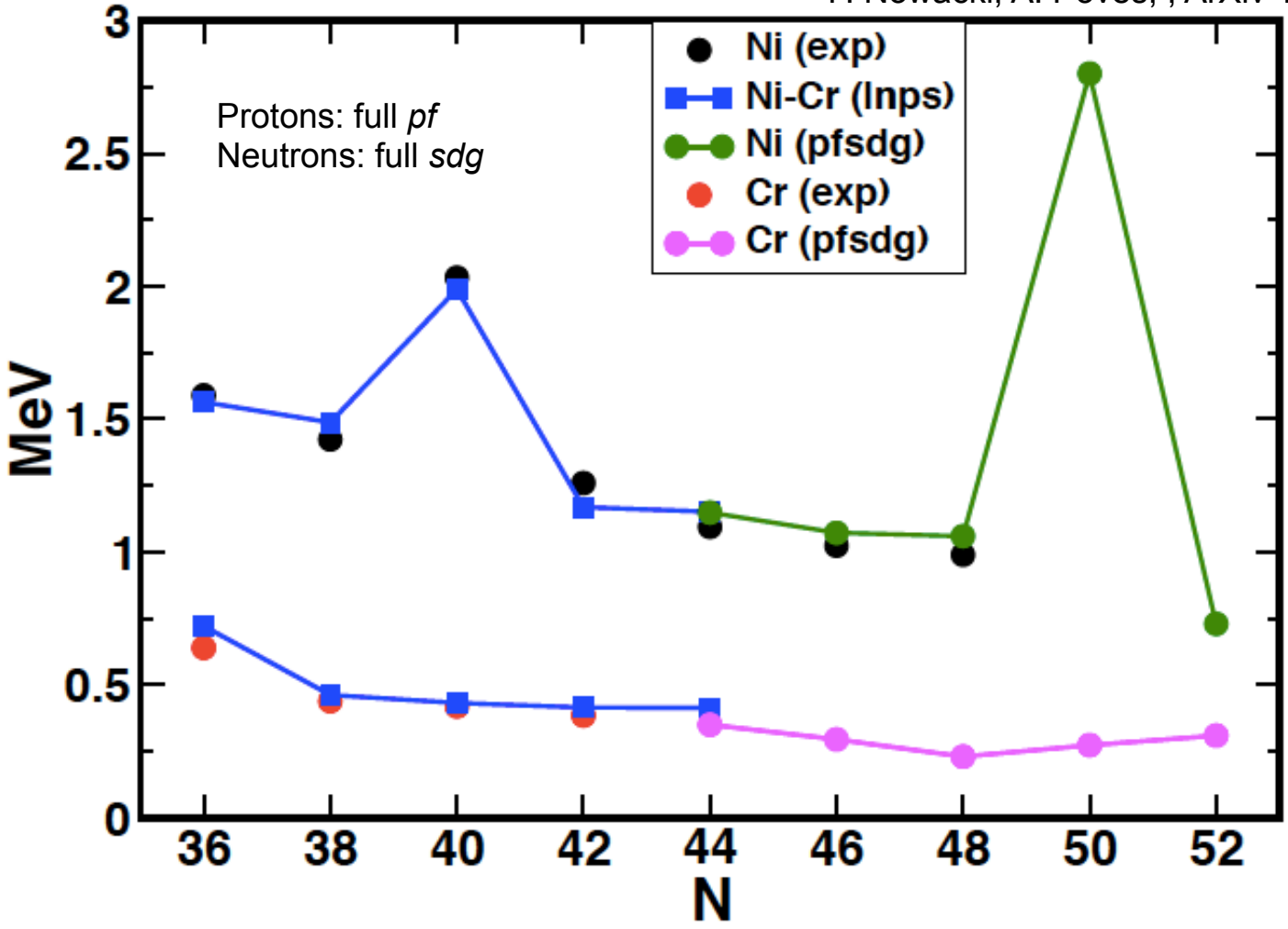
Second island of inversion



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

(non) magic character of N=50 at (below) ^{78}Ni

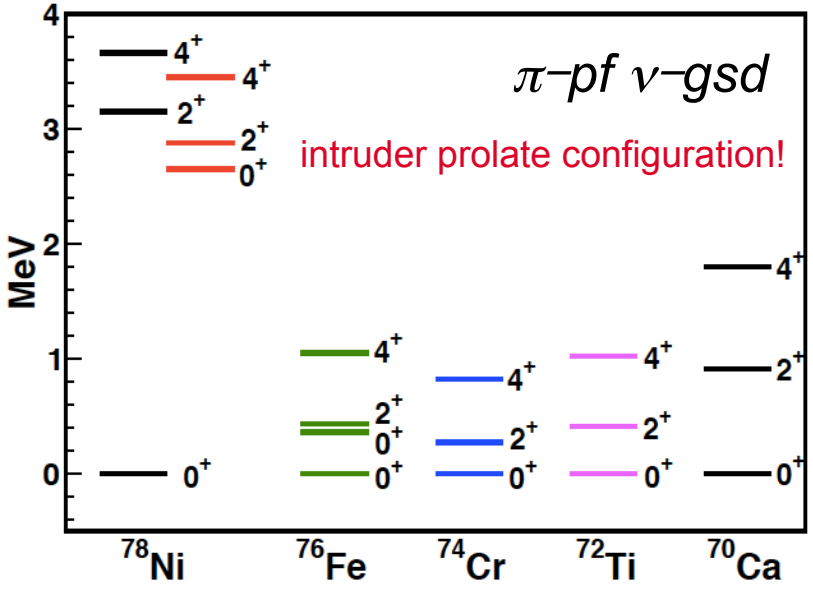
F. Nowacki, A. Poves, , ArXiv 1605.05103v1



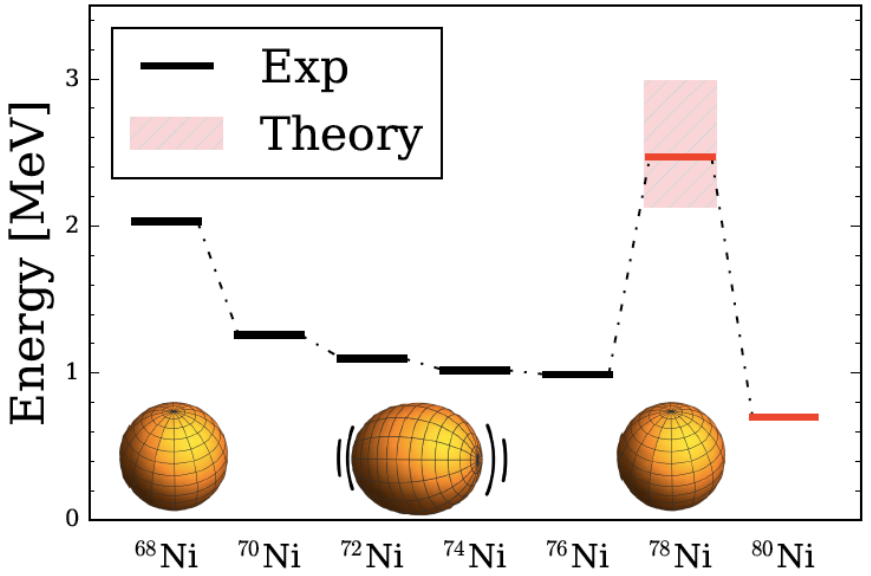
Similarity to the merging of the N=20 island of inversion and N=28 region of deformation

P. Doornenbal *et al.*, Phys. Rev. Lett. 111, 212502 (2013)

Recent predictions for the spectroscopy of ^{78}Ni



F. Nowacki and A. Poves, ArXiv 1605.05103v1



G. Hagen *et al.*, ArXiv 1605.01477v1

Large Scale Shell model calculations by Tsunoda, Otsuka (University of Tokyo), private comm.:

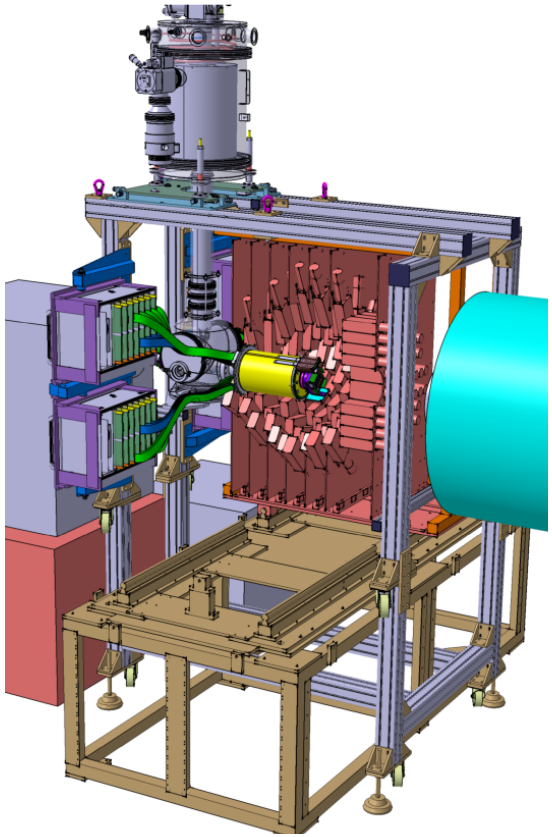
- full **pfg_9d_5 valence space**
- intruder configuration at high excitation energy

First spectroscopy of ^{78}Ni

Analysis by R. Taniuchi (University of Tokyo)

Ongoing collaboration with Ogata, Otsuka, Tsunoda, Schwenck *et al.* for interpretation

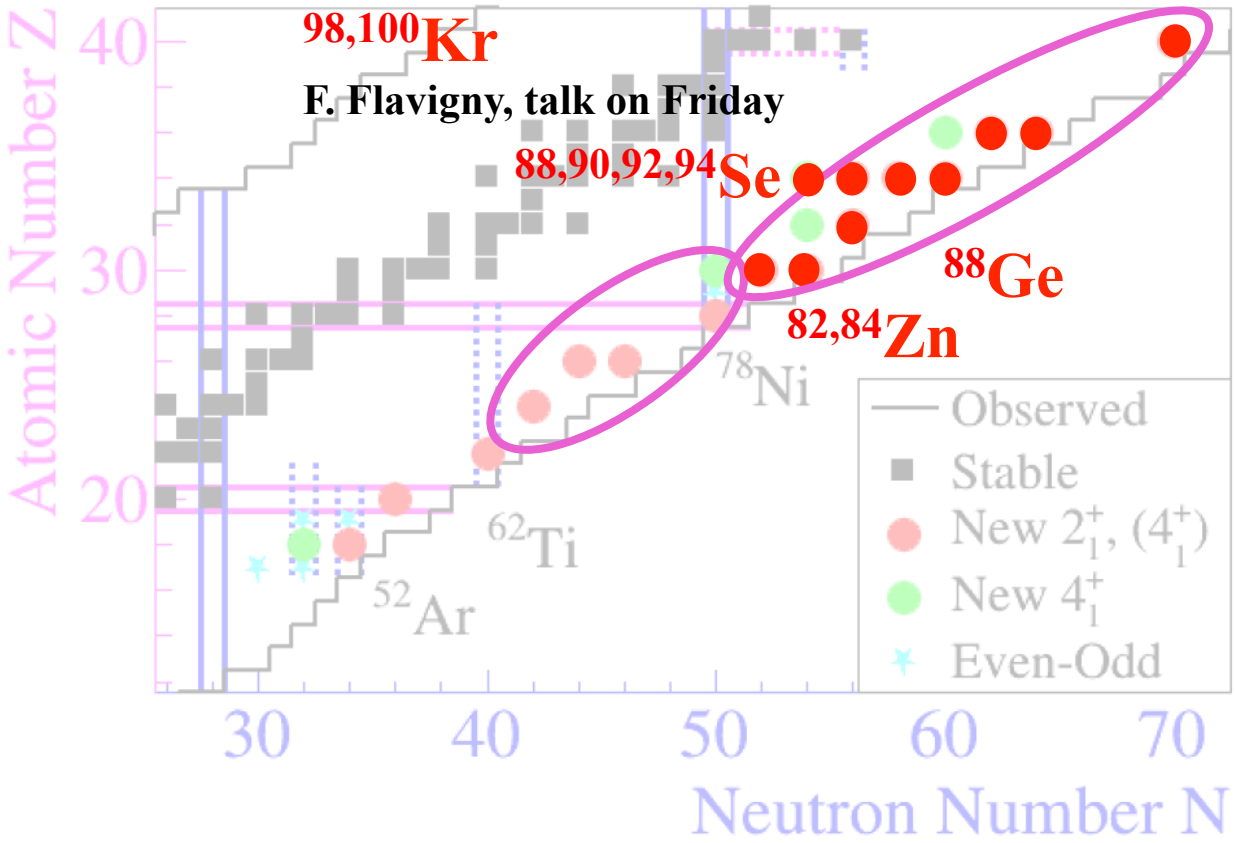
SEASTAR second campaign



May 2015

^{110}Zr

N. Paul, next talk



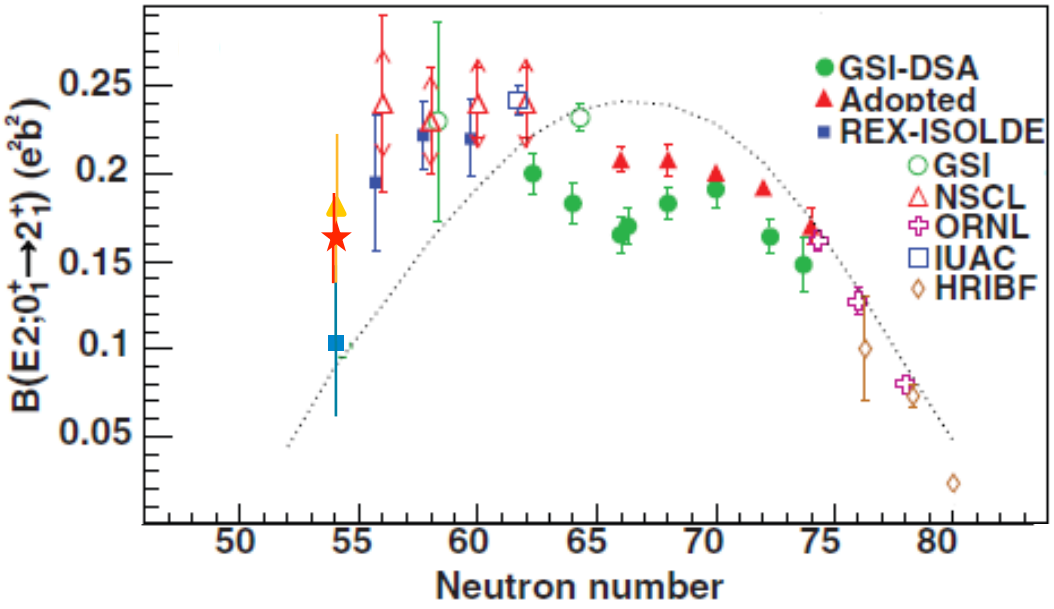
Primary beam ^{238}U at 345 MeV/nucleon, **mean intensity = 30 pnA!**
Secondary beams at 250 MeV/nucleon, 100-mm target, $\Delta\beta/\beta$ = 30%

Collectivity in neutron-deficient Sn isotopes

Experimental **B(E2) deviate from predictions** (SM, seniority scheme)

A. Banu, *et al.*, Phys. Rev. C 72, 061305 (2005).
J. Cederkall, *et al.*, Phys. Rev. Lett. 98, 172501 (2007).
P.Doornenbal *et al.*, Phys. Rev. C 78, 031303 (2008).
A. Ekstrom, *et al.*, Phys. Rev. Lett. 101, 012502 (2008).
C. Vaman, *et al.,* Phys. Rev. Lett. 99, 162501 (2007).
R.Kumar *et al.*, Phys Rev. C 81, 024306 (2010).

Adapted from V.Bader et al. PRC 88 051301(R) (2013)



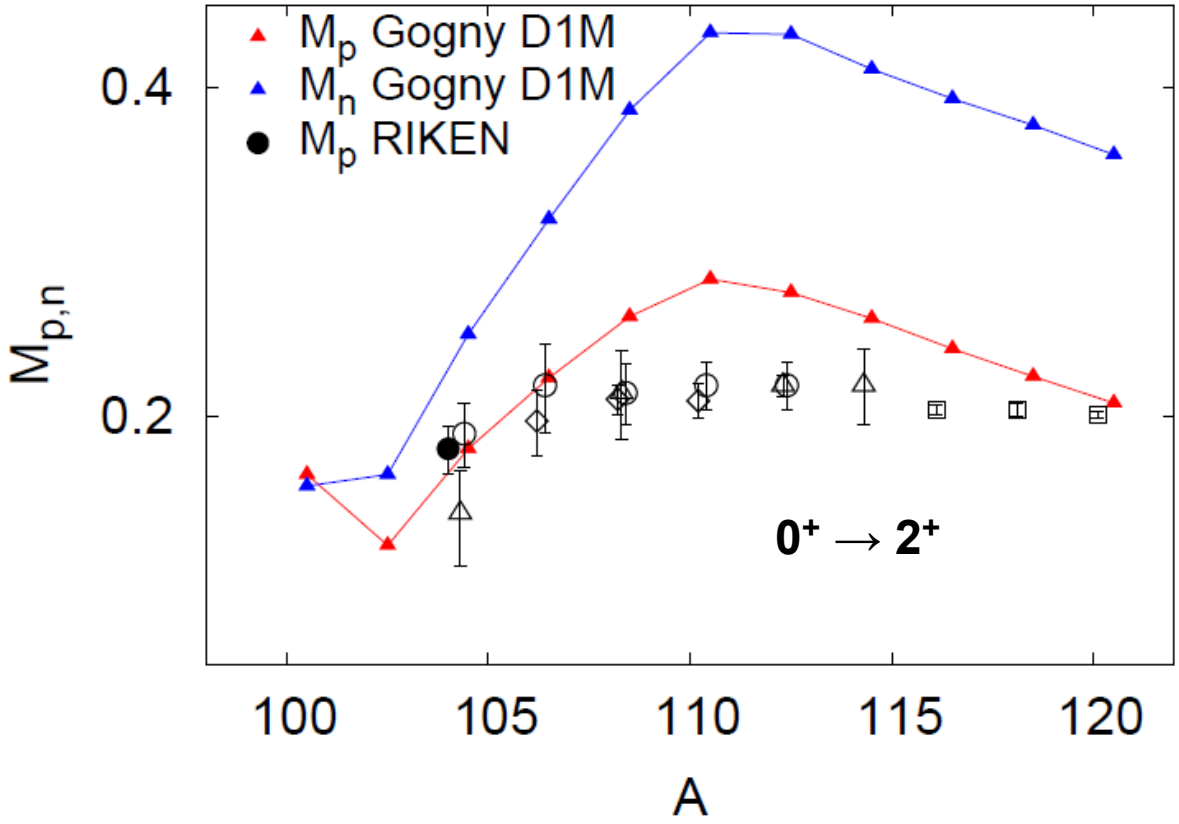
^{104}Sn

- GSI
  G.Guastalla *et al.*,
  PRL 110 172501 (2013)
  $B(E2)=0.10(4)e^2b^2$
- NSCL
  V.Bader *et al.*,
  PRC 88 051301(R) (2013)
  $B(E2)=0.180(37)e^2b^2$
- RIKEN
  P. Doornenbal *et al.*,
  PRC 90, 061302(R) (2014)
  $B(E2)=0.163(26)e^2b^2$

What is the origin of light Sn collectivity?

Neutron contribution from QRPA – Gogny D1M

HFB+QRPA with Gogny D1M interaction, no model space limitation
M.Martini, S.Péru and M.Dupuis, Phys. Rev. C 83, 034309 (2011).

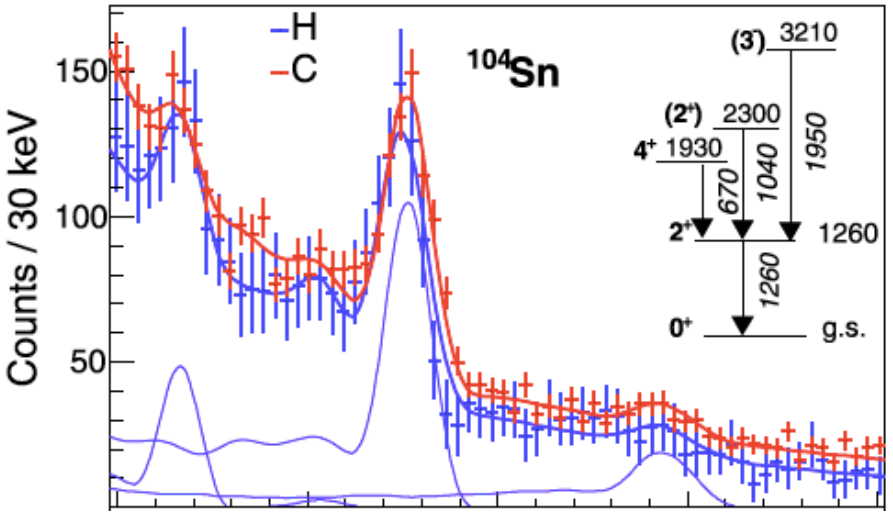


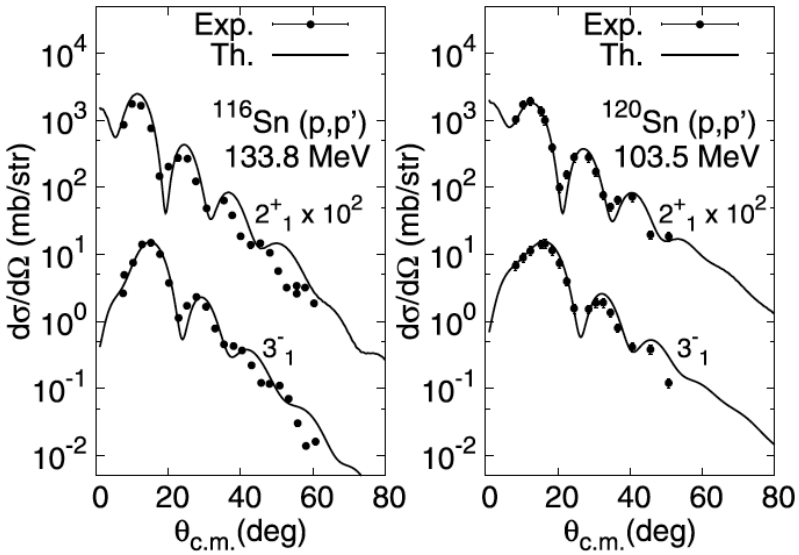
- **M_p shows a maximum at N=60** as in Ansari and Ring, PRC 74, 054313 (2006).
- **neutron contribution** dominant

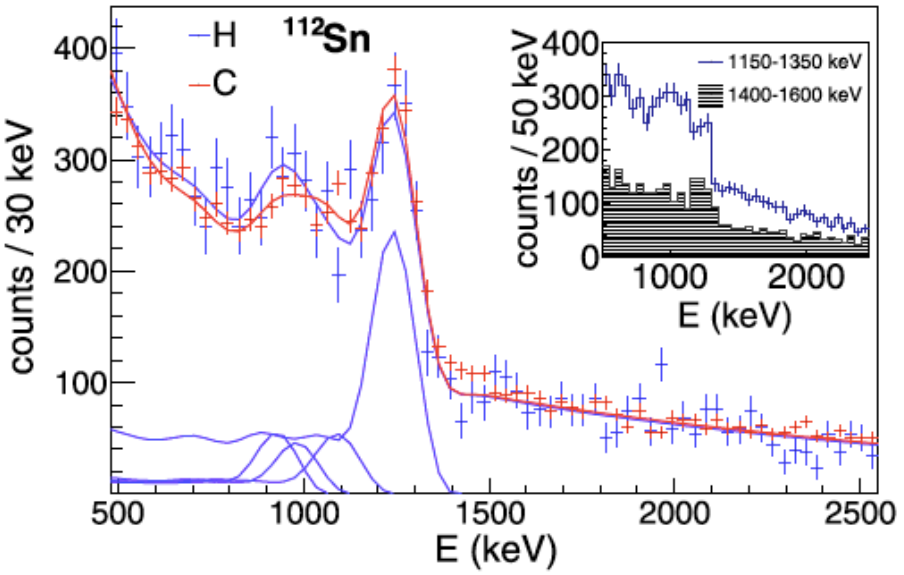
Proton inelastic scattering ^{104}Sn(p,p')

- 150 MeV/nucleon, RIBF
- inclusive gamma spectroscopy
- DALI2
- C + CH_2 targets

- ^{104}Sn and ^{112}Sn (benchmark)







Proton inelastic scattering ^{104}Sn(p,p')

^{112}Sn on H			
J^π	E_{ex} (keV)	σ_{exp} (mb)	σ_{th} (mb)
2_1^+	1245	9.1(38)	6.5(13)
0_2^+	2175	4.0(24)	< 0.1
4_1^+	2230	3.6(26)	1.8(4)
3_1^-	2335	4.6(20)	3.6(7)
^{104}Sn on H			
J^π	E_{ex} (keV)	σ_{exp} (mb)	σ_{th} (mb)
2_1^+	1260	5.4(24)	3.2(6)
4_1^+	1930	$4.2(8)(^{0}_{-10})$	0.7(1)
(2_2^+)	2300	1.8(9)	0.3(1)
(3_1^-)	3210	$3.8(14)(^{+10}_{0})$	3.0(6)

- predictions and experimental (p,p') cross section **consistent**
- no noticeable gap variations at Z=50 or N=50 predicted by Gogny D1M
- indication for **isoscalar** character of excitations predicted by QRPA

A. Corsi *et al.,* Phys. Lett. B 743, 451 (2015)

CHYMENE: hydrogen target for low-energy RI studies

Motivations

Thin target for high resolution measurements
Pure target for + statistics and - background

Objective

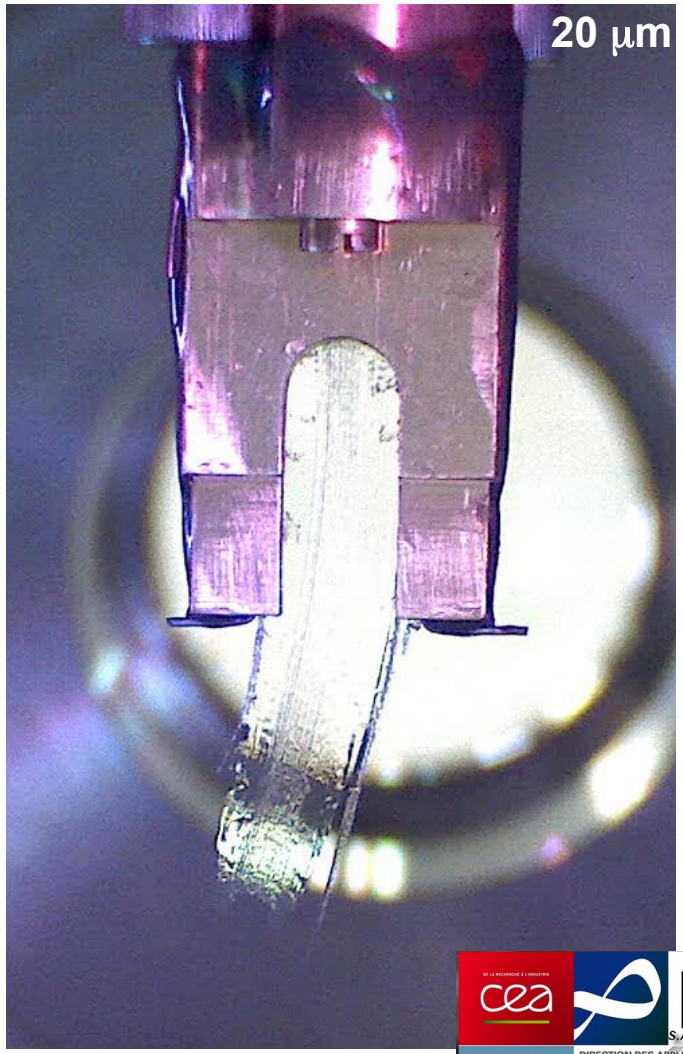
Solid H_2 or D_2 target from 20 to 200 µm
50 µm H2 = 350 µg.cm^{-2}
Windowless

Method

Extruded solid hydrogen

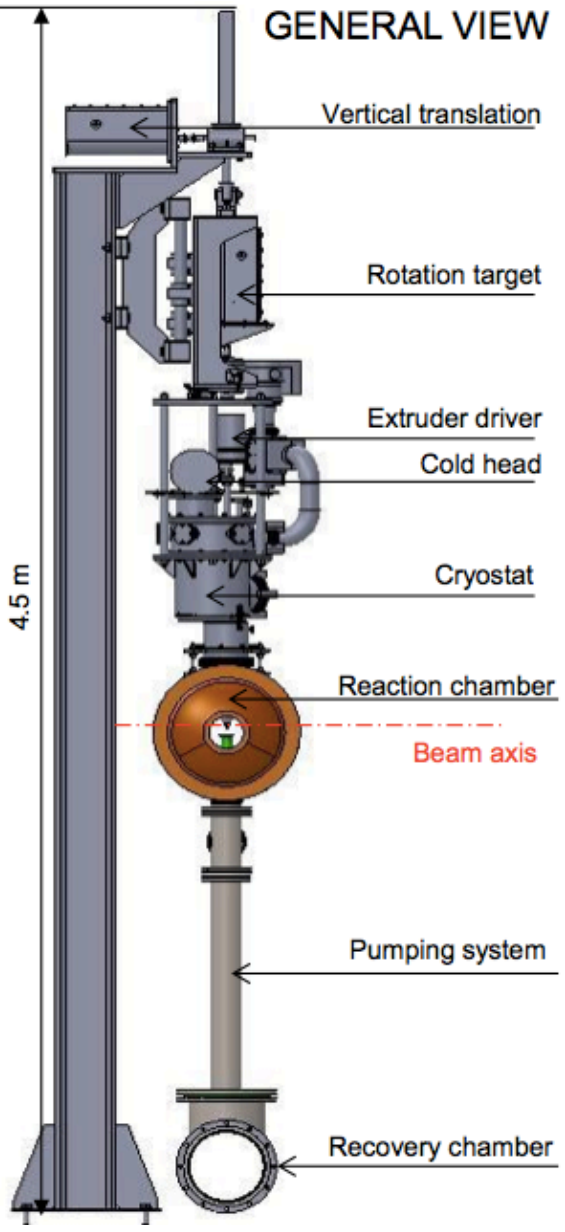
Present status

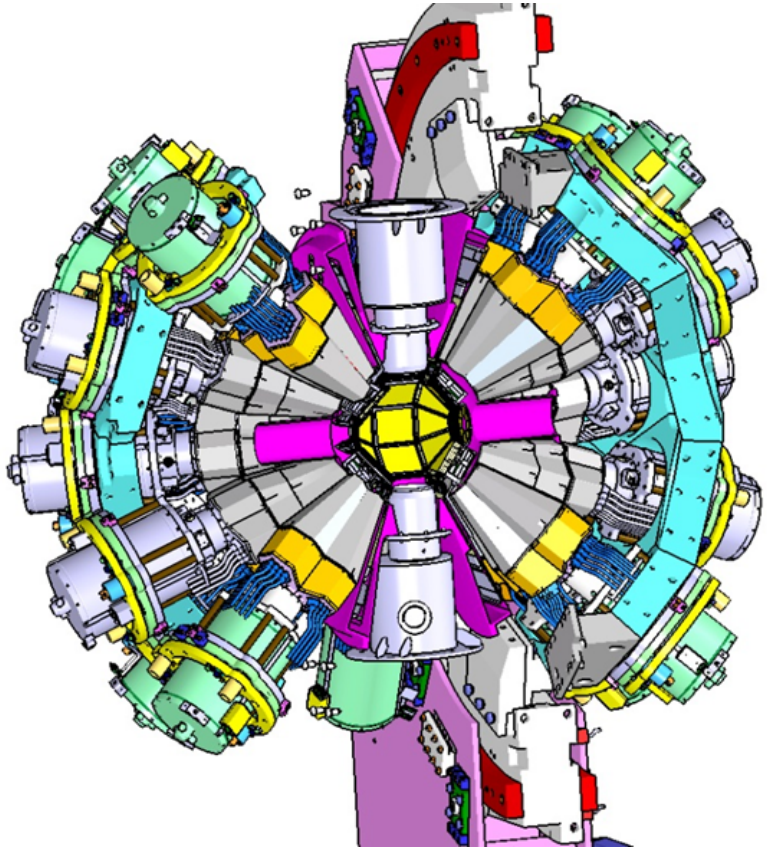
- Stable operation down to 50 µm (Ø 5 mm)
- Thickness homogeneity of 10-20%
- Continuous production **> 48 hours**
- 5.10^{-4} mbar
- Alpha source measurements



A. Gillibert *et al.*, EPJA **49** (2013).

CHYMENE: hydrogen target for low-energy RI studies





Ex. Gaspard-Trace + AGATA + CHyMENE
(D. Mengoni, Talk on Thursday)

Collaborators

Physics collaborations

N. Alamanos, G. de Angelis, N. Aoi, H. Baba, C. Barbieri, C. Bertulani, A. Corsi, F. Delaunay, Z. Dombradi, P. Doornenbal, T. Duguet, S. Franchoo, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, S. Grévy, J.D. Holt, E. Ideguchi, T. Isobe, A. Jungclaus, N. Kobayashi, T. Kobayashi, Y. Kondo, W. Korten, Y. Kubota, I. Kuti, V. Lapoux, S. Leblond, J. Lee, S. Lenzi, H. Liu, G. Lorusso, C. Louchart, R. Lozeva, F.M. Marques, I. Matea, K. Matsui, Y. Matsuda, M. Matsushita, J. Menendez, D. Mengoni, S. Michimasa, T. Miyazaki, S. Momiyama, P. Morfouace, T. Motobayashi, T. Nakamura, D. Napoli, F. Naqvi, M. Niikura, A. Obertelli, N. Orr, S. Ota, H. Otsu, T. Otsuka, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Potel, G. Randisi, F. Recchia, E. Sahin, H. Sakurai, C. Santamaria, M. Sasano, A. Schwenk, Y. Shiga, Y. Shimuzu, S. Shimoura, J. Simonis, P.A. Soderstrom, S. Sohler, V. Soma, I. Stefan, D. Steppenbeck, T. Sumikama, H. Suzuki, M. Tanaka, R. Taniuchi, K.N. Tuan, T. Uesaka, J. Valiente Dobon, Zs. Vajta, D. Verney, H. Wang, V. Werner, K. Wimmer, Zh. Xu, R. Yokoyama, K. Yoneda

Development and local teams

S. Anvar, L. Audirac, G. Authelet, H. Baba, B. Bruyneel, D. Calvet, F. Chateau, A. Corsi, A. Delbart, P. Doornenbal, A. Gillibert, J.-M. Gheller, A. Giganon, T. Isobe, Y. Kubota, C. Lahonde-Hamdoun, V. Lapoux, D. Leboeuf, D. Loiseau, M. Matsushita, A. Mohamed, J.-Ph. Mols, T. Motobayashi, M. Nishimura, S. Ota, H. Otsu, C. Péron, A. Peyaud, E.C. Pollacco, G. Prono, J.-Y. Rousse, H. Sakurai, C. Santamaria, M. Sasano, R. Taniuchi, S. Takeuchi, T. Uesaka, Y. Yanagisawa, K. Yoneda and the BigRIPS team

Theory

C.Bertulani, M. Dupuis, F. Nowacki, K. Ogata, T. Otsuka, S. Péru, A. Poves, T. Rodriguez-Gusman, A. Schwenck, Y. Tsunoda

Special thanks to

S. Chen, A. Corsi, P. Doornenbal, A. Gillibert, C. Santamaria, R. Taniuchi for their work and material

Summary

- A unique **physics program based on (p,2p) and (p,pn) reactions at the RIBF with DALI2 and MINOS** is ongoing

- **Shell evolution** and search for 2^+ states in neutron rich nuclei (SEASTAR)
  Two campaigns performed in **May 2014 and May 2015**
  ^{66}Cr, ^{70,72}Fe, ^{78}Ni,^{79}Cu, ^{82,84}Zn, ^{88}Ge, **^{88,90,92,94}Se**, **^{98,100}Kr**, ^{100}Sr, **^{110}Zr, ^{112}Mo**

  (**shown**, to be shown)

- Analysis / interpretation of cross sections under way – recent theory developments
- Systematics of more than 40 *(p,2p)*, *(p,pn)* and *(p,3p)* cross sections on the way

- Exciting perspectives expected in 2017: ^{52}Ar, ^{56}Ca, ^{62}Ti

- **Light Tin isotopes** investigated via inclusive proton inelastic scattering
  QRPA calculations, consistent with data, suggest **isoscalar excitations**

- **CHyMENE**: new windowless hydrogen thin (50 μm) target operational since 2016
  R&D still ongoing for thinner targets and better homogeneity