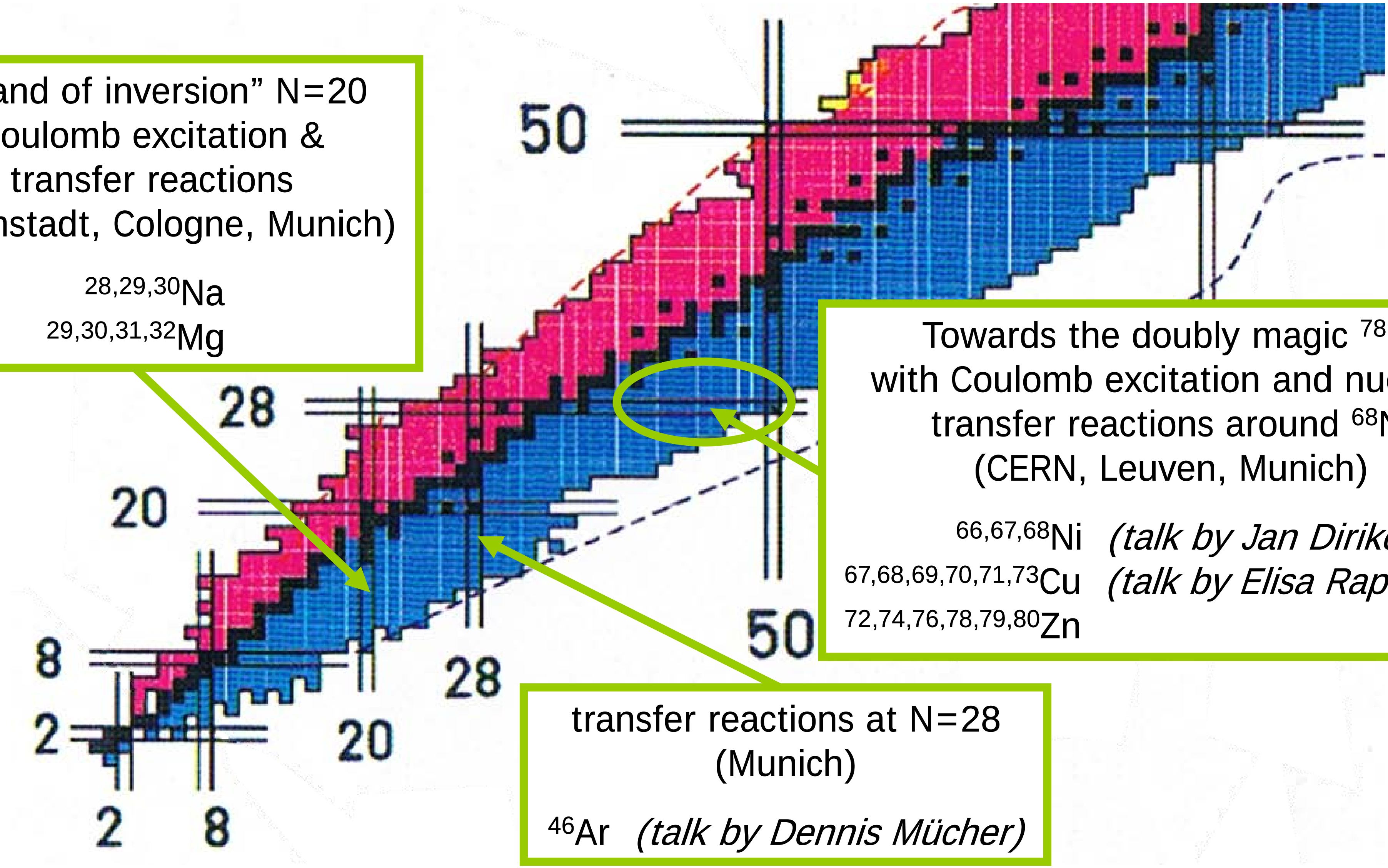
γ-ray spectroscopy far from stability with MINIBALL

- Overview Physics Case
- MINIBALL @ REX-ISOLDE
- News from the ‚Island of Inversion‘
- Perspectives

Peter Reiter
IKP, University of Cologne
for the MINIBALL collaboration

EGAN 2011 workshop
Padova, 27-30 June 2011

Shell Model Physics with MINIBALL@REX-ISOLDE



"Island of inversion" N=20
Coulomb excitation &
transfer reactions
(Darmstadt, Cologne, Munich)

^{28,29,30}Na
^{29,30,31,32}Mg

Towards the doubly magic ^{78}Ni
with Coulomb excitation and nucleon
transfer reactions around ^{68}Ni
(CERN, Leuven, Munich)

^{66,67,68}Ni *(talk by Jan Diriken)*
^{67,68,69,70,71,73}Cu *(talk by Elisa Rapisarda)*
^{72,74,76,78,79,80}Zn

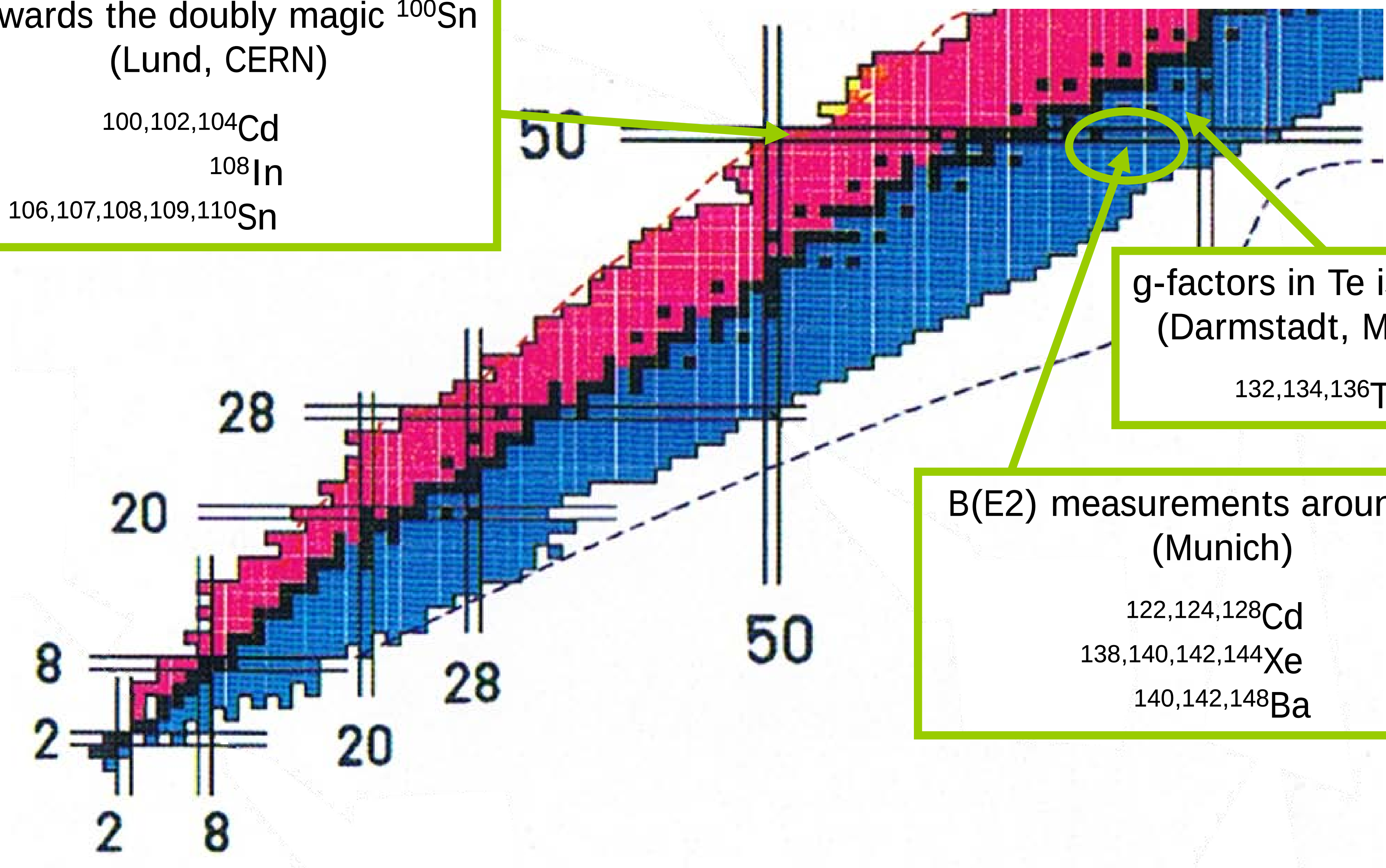
transfer reactions at N=28
(Munich)

^{46}Ar *(talk by Dennis Mücher)*

Shell Model Physics with MINIBALL@REX-ISOLDE

Towards the doubly magic ^{100}Sn
(Lund, CERN)

$^{100,102,104}Cd$
^{108}In
$^{106,107,108,109,110}Sn$



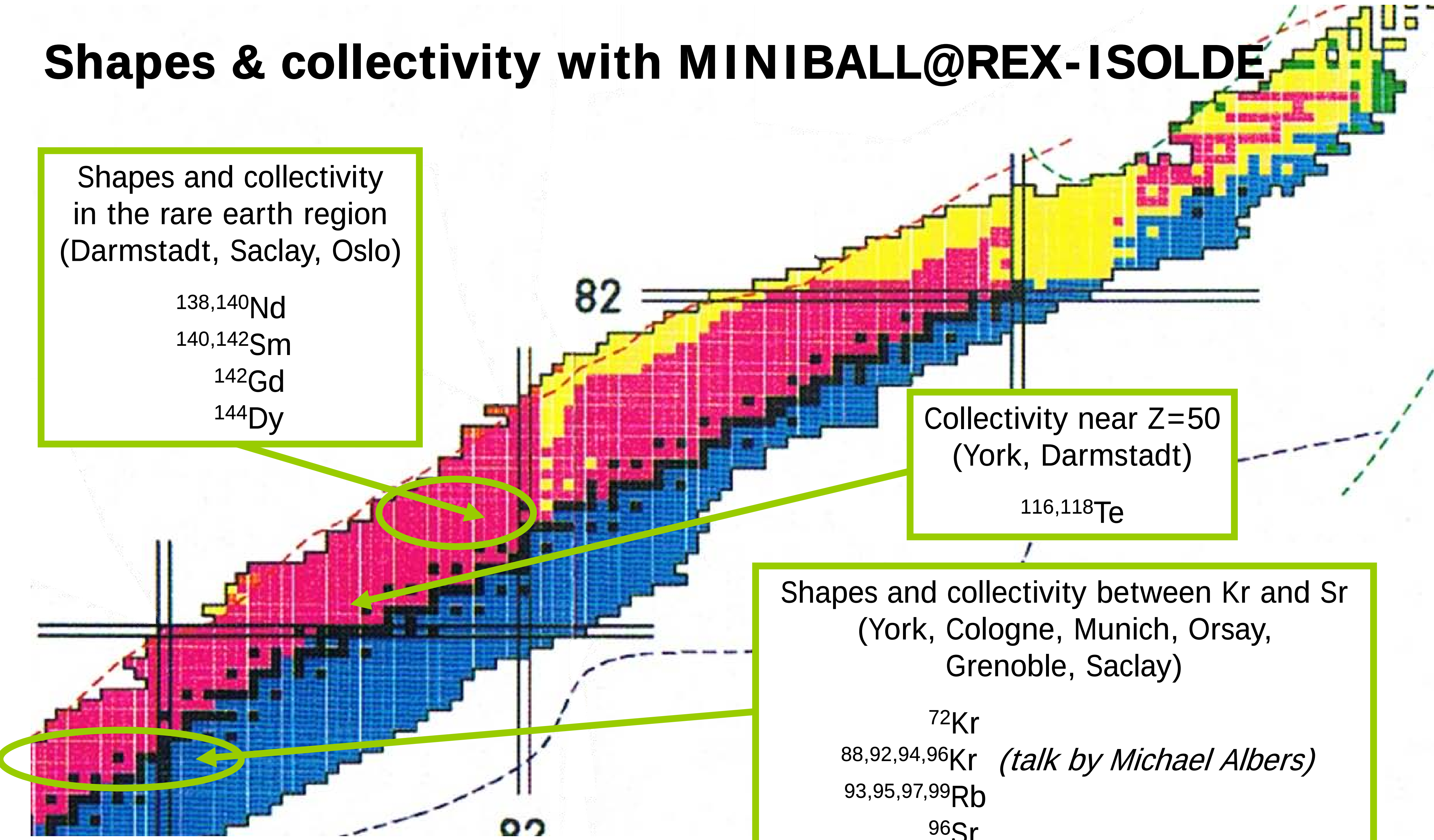
g-factors in Te isotopes
(Darmstadt, Madrid)

$^{132,134,136}Te$

B(E2) measurements around ^{132}Sn
(Munich)

$^{122,124,128}Cd$
$^{138,140,142,144}Xe$
$^{140,142,148}Ba$

Shapes & collectivity with MINIBALL@REX-ISOLDE



Shapes and collectivity
in the rare earth region
(Darmstadt, Saclay, Oslo)

^{138,140}Nd
^{140,142}Sm
^{142}Gd
^{144}Dy

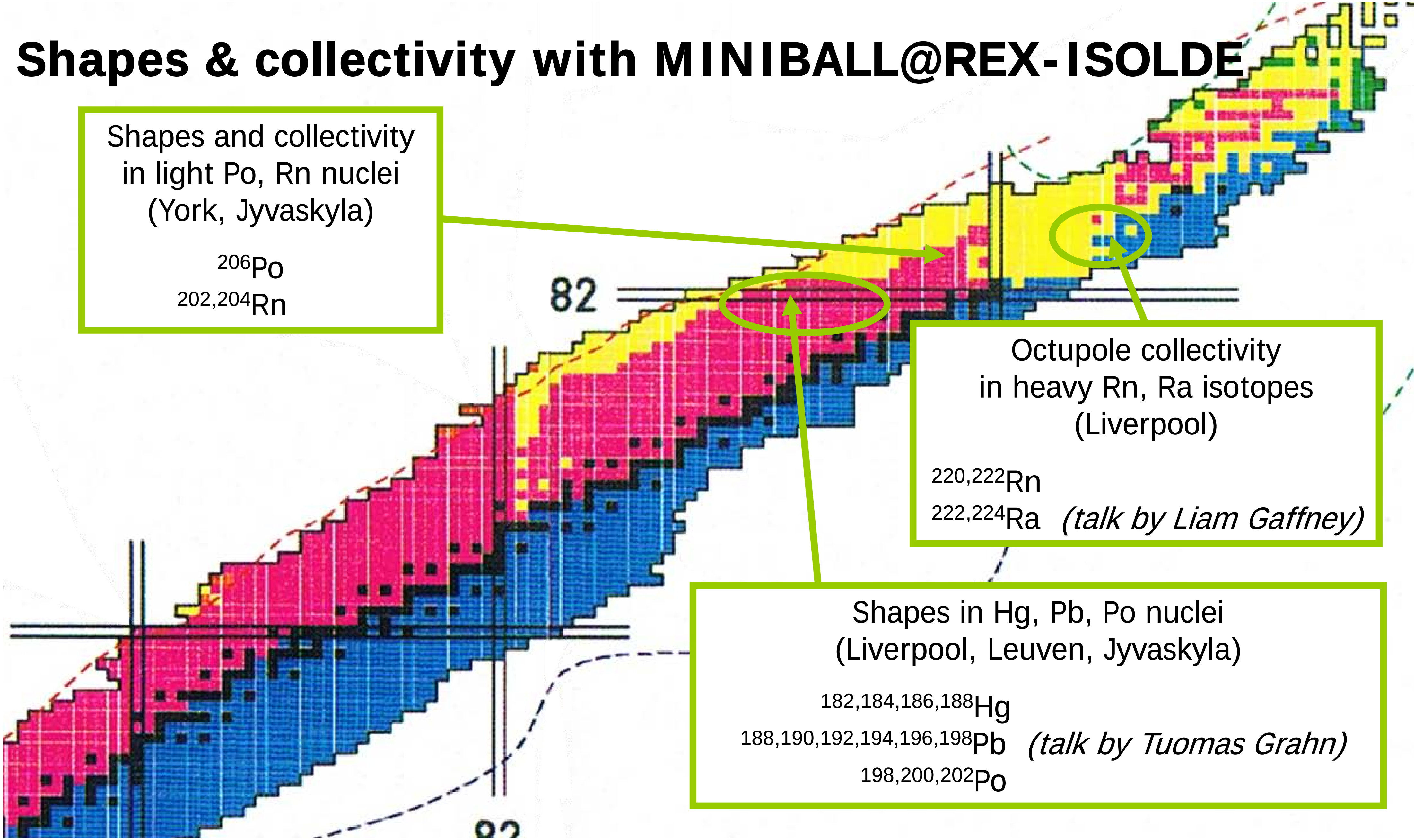
Collectivity near Z=50
(York, Darmstadt)

^{116,118}Te

Shapes and collectivity between Kr and Sr
(York, Cologne, Munich, Orsay,
Grenoble, Saclay)

^{72}Kr
^{88,92,94,96}Kr *(talk by Michael Albers)*
^{93,95,97,99}Rb
^{96}Sr

Shapes & collectivity with MINIBALL@REX-ISOLDE



Shapes and collectivity
in light Po, Rn nuclei
(York, Jyvaskyla)

^{206}Po
^{202,204}Rn

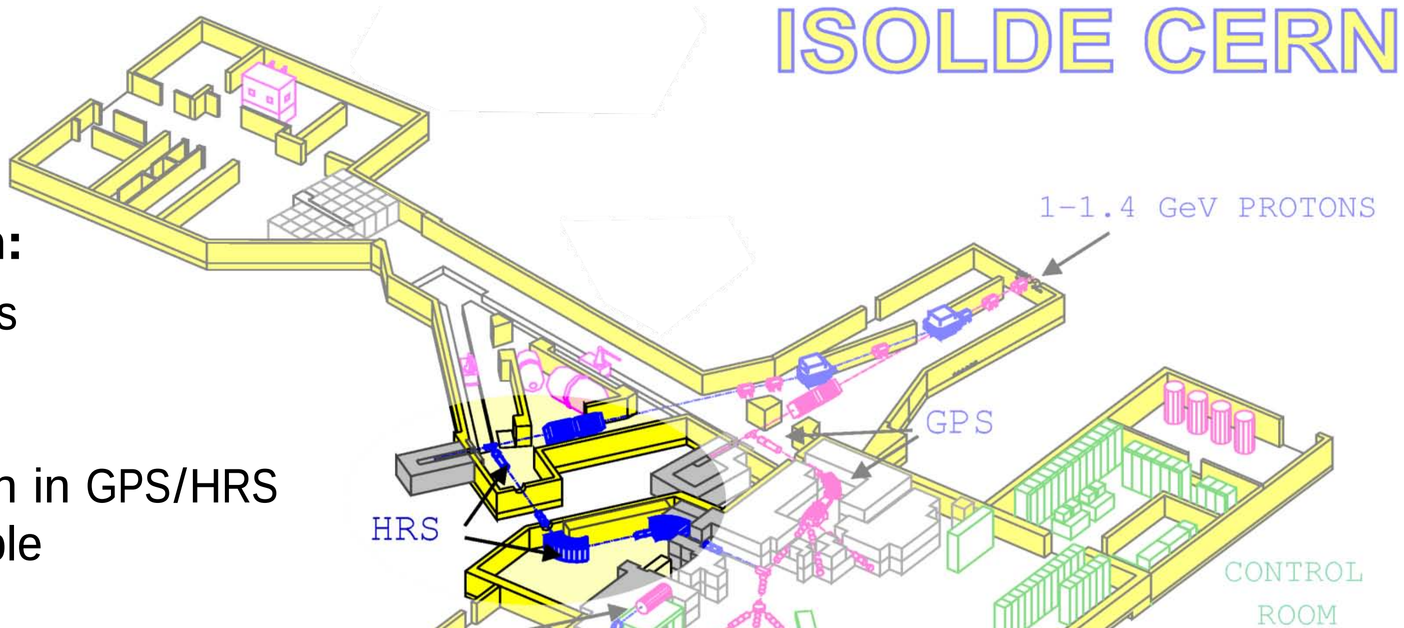
Octupole collectivity
in heavy Rn, Ra isotopes
(Liverpool)

^{220,222}Rn
^{222,224}Ra *(talk by Liam Gaffney)*

Shapes in Hg, Pb, Po nuclei
(Liverpool, Leuven, Jyvaskyla)

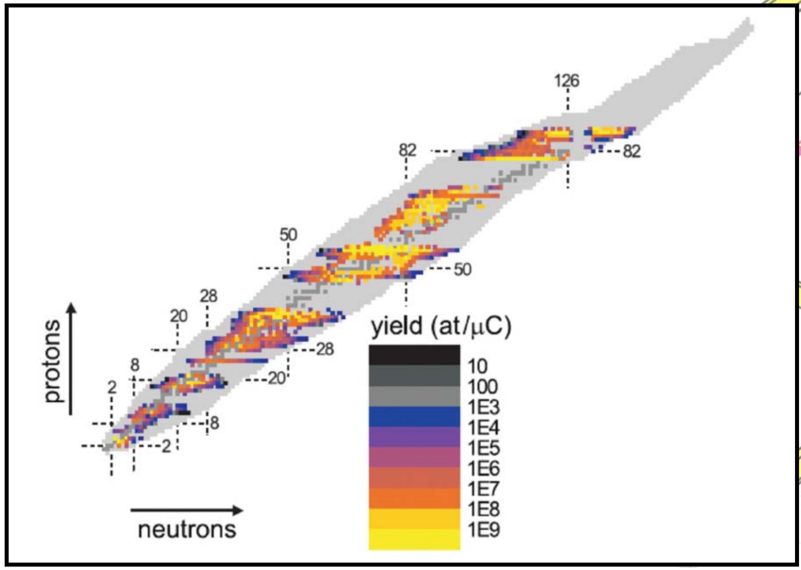
^{182,184,186,188}Hg
^{188,190,192,194,196,198}Pb *(talk by Tuomas Grahn)*
^{198,200,202}Po

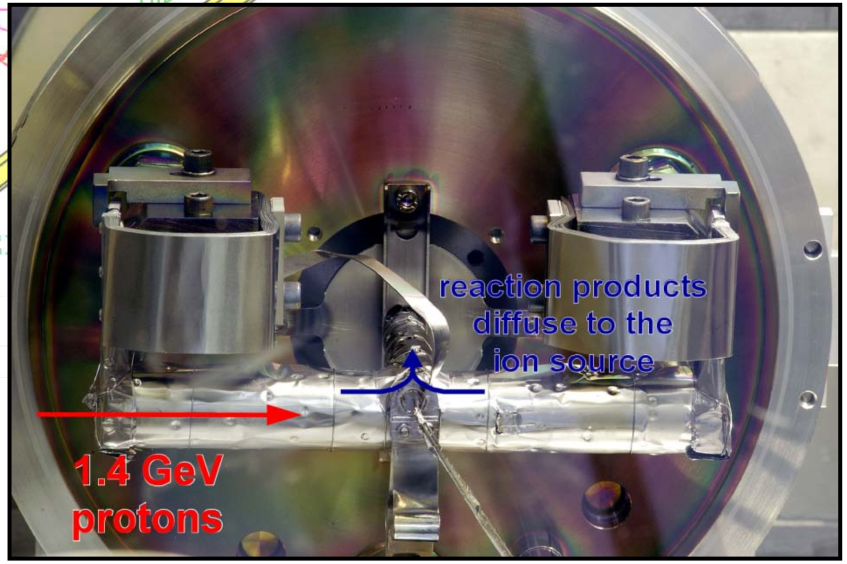
RIB production at ISOLDE



RIB Production:

- 1,4 GeV protons
- various targets
- ionization
- mass separation in GPS/HRS
- 800 RIB available

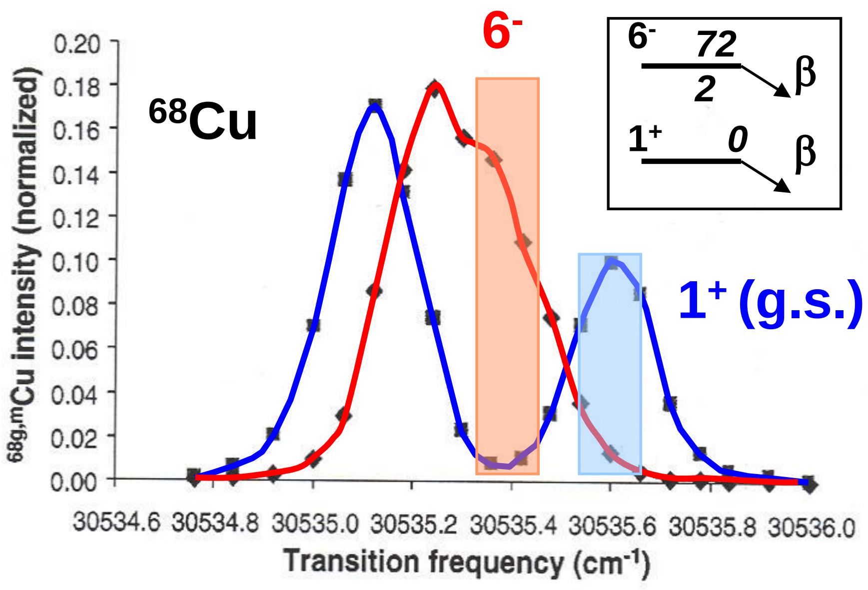


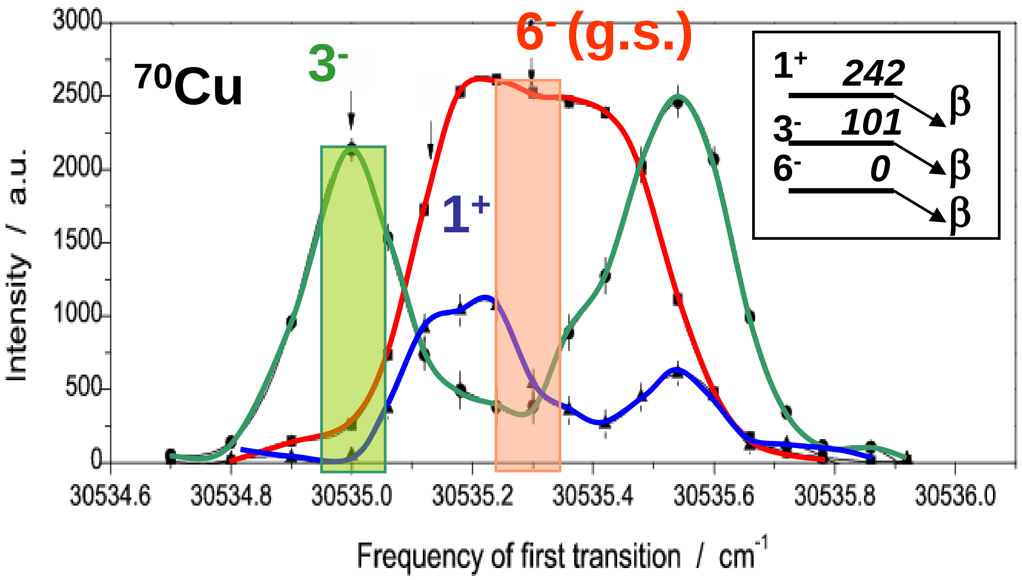


Isomeric beams @ ISOLDE

- technique based on in-source laser spectroscopy
  (U. Köster et al., NIM B160, 528 (2000), L. Weissman et al., PRC 65, 024315 (2000))

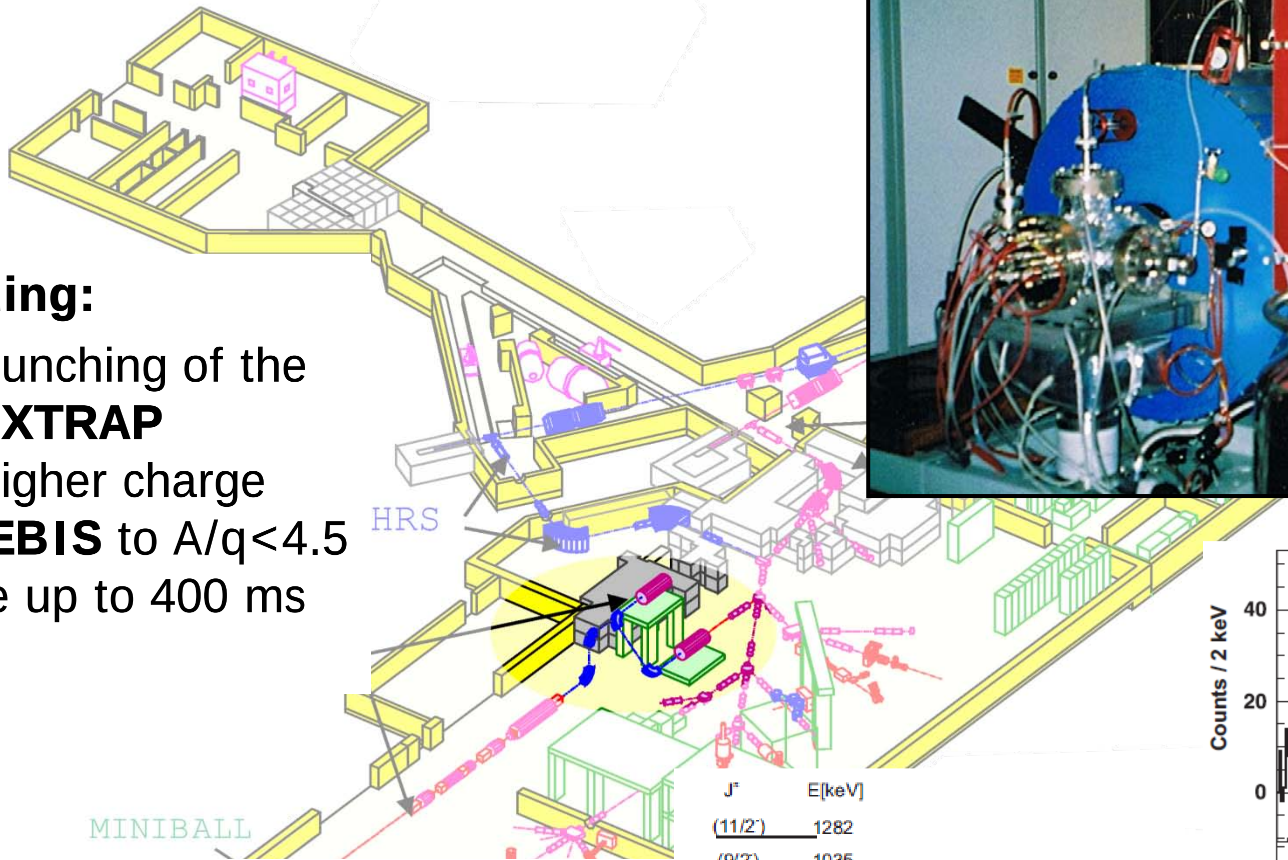
- set the laser frequency to select and maximize the production of the isomer of interest

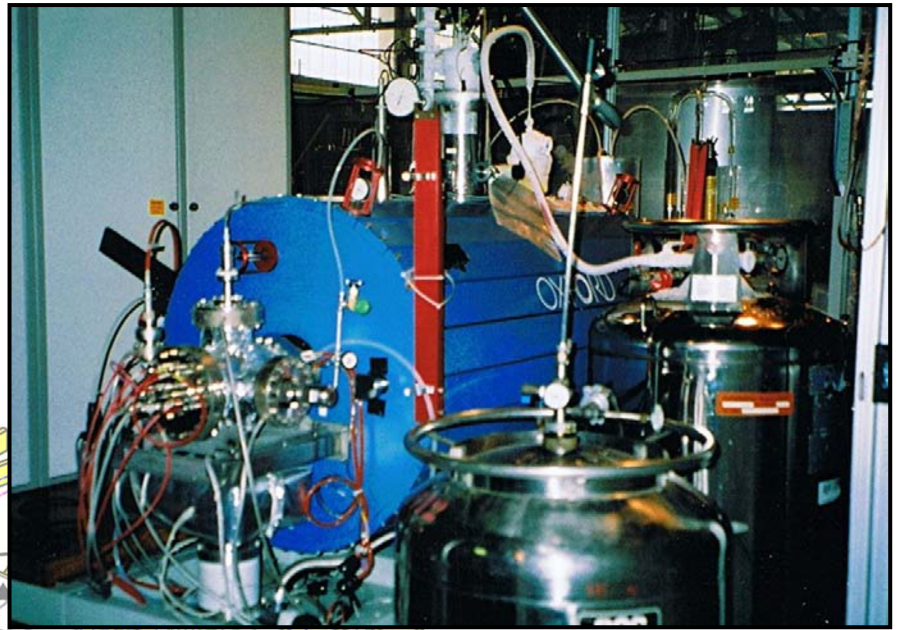




Spectroscopy with Cu isomer beams I. Stefanescu et al. PRL **98**, 122701 (2007) talk by E. Rapisarda

RIB preparation @ REX-ISOLDE



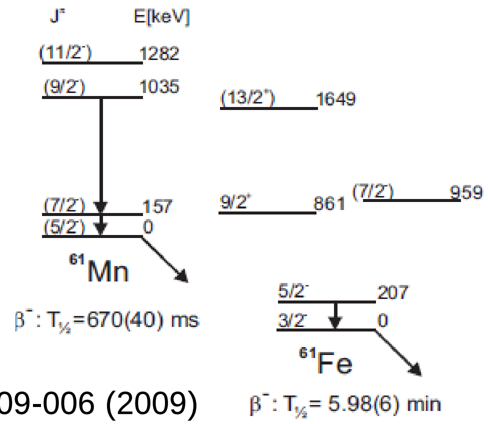


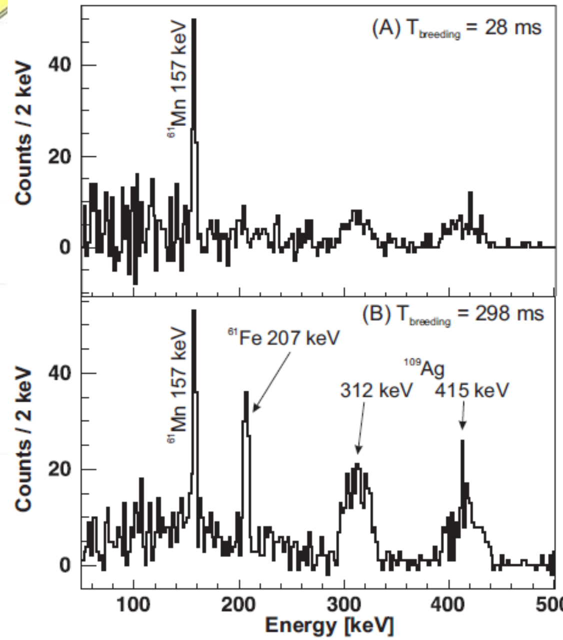
Charge breeding:

- cooling and bunching of the RIB in the **REXTRAP**
- breeding to higher charge states in the **EBIS** to A/q<4.5
- breeding time up to 400 ms
- A/q selection

Possibility of in-trap decay during charge breeding:

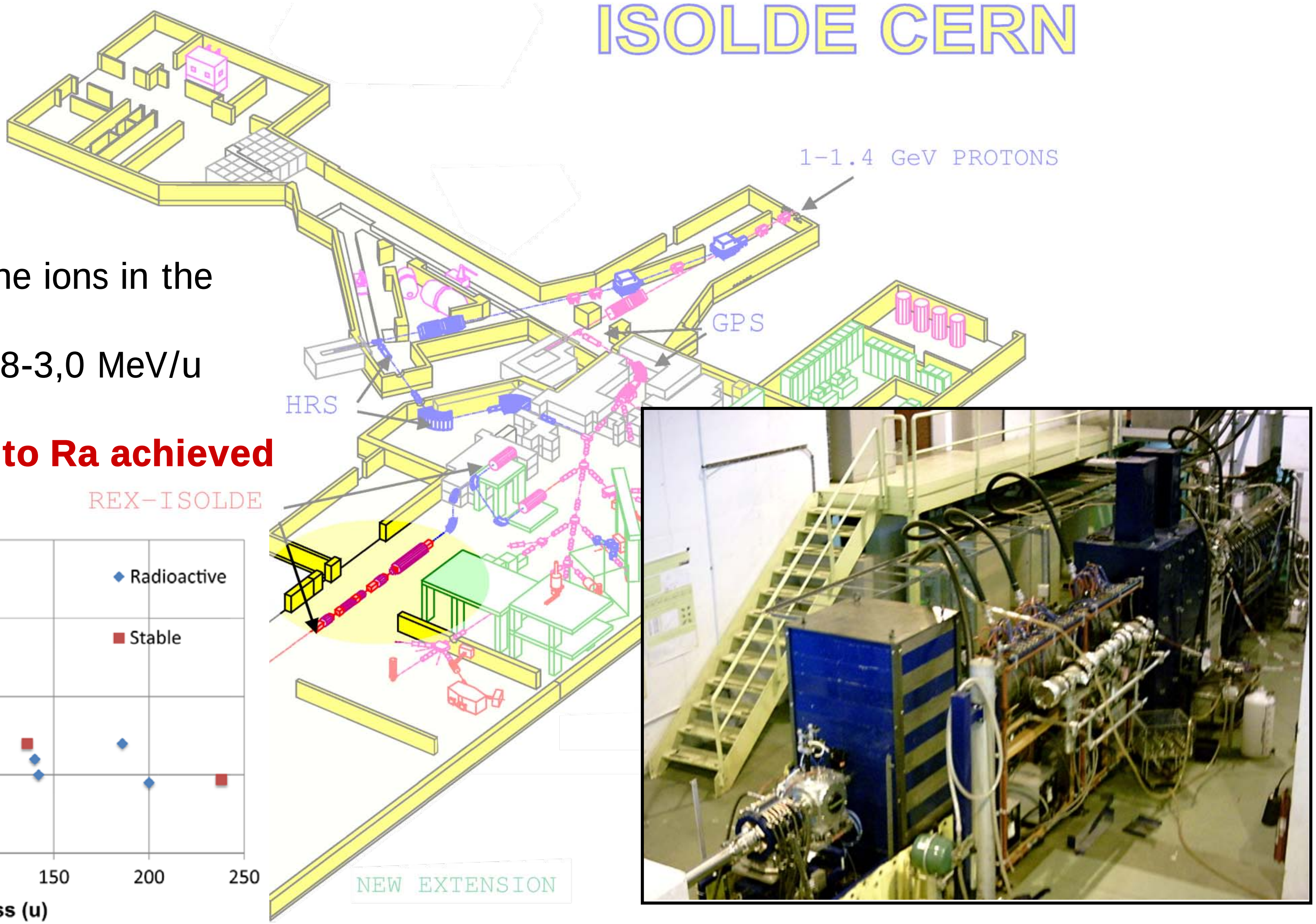
$^{61}Mn \rightarrow {}^{61}Fe$





J. Van de Walle et al., CERN-INTC-2009-006 (2009)

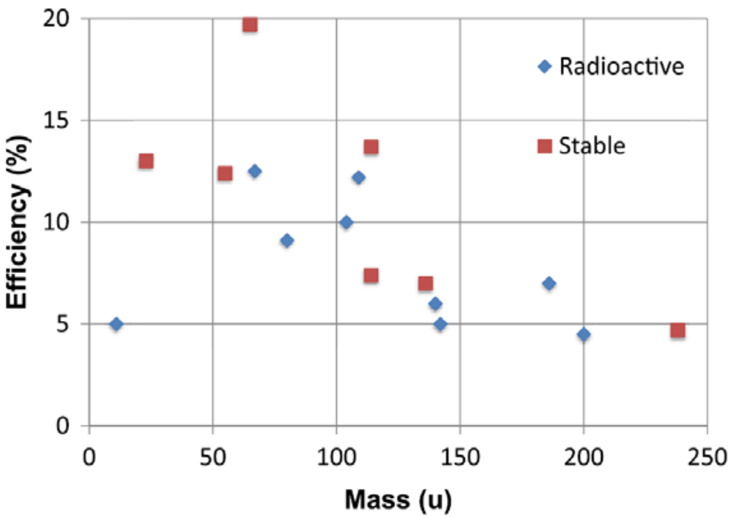
RIB preparation @ REX-ISOLDE



Re-acceleration

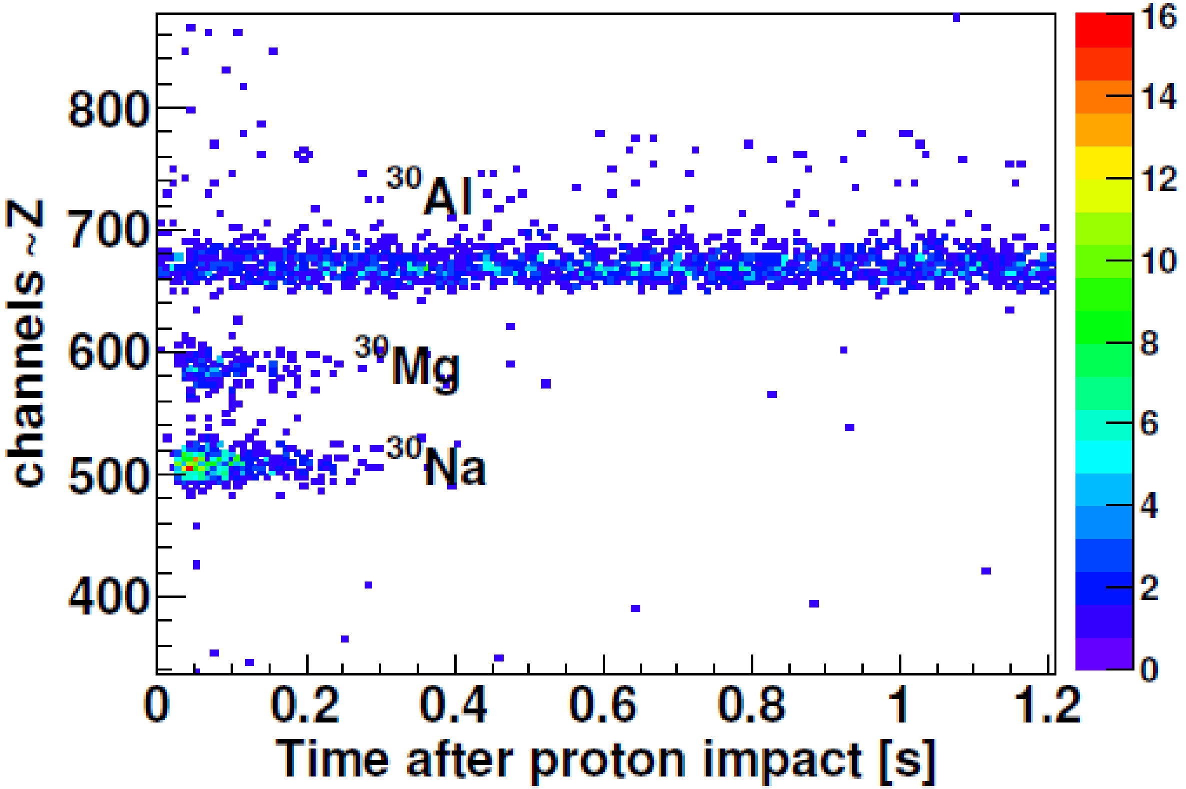
- acceleration of the ions in the REX-LINAC
- beam energy: 0,8-3,0 MeV/u

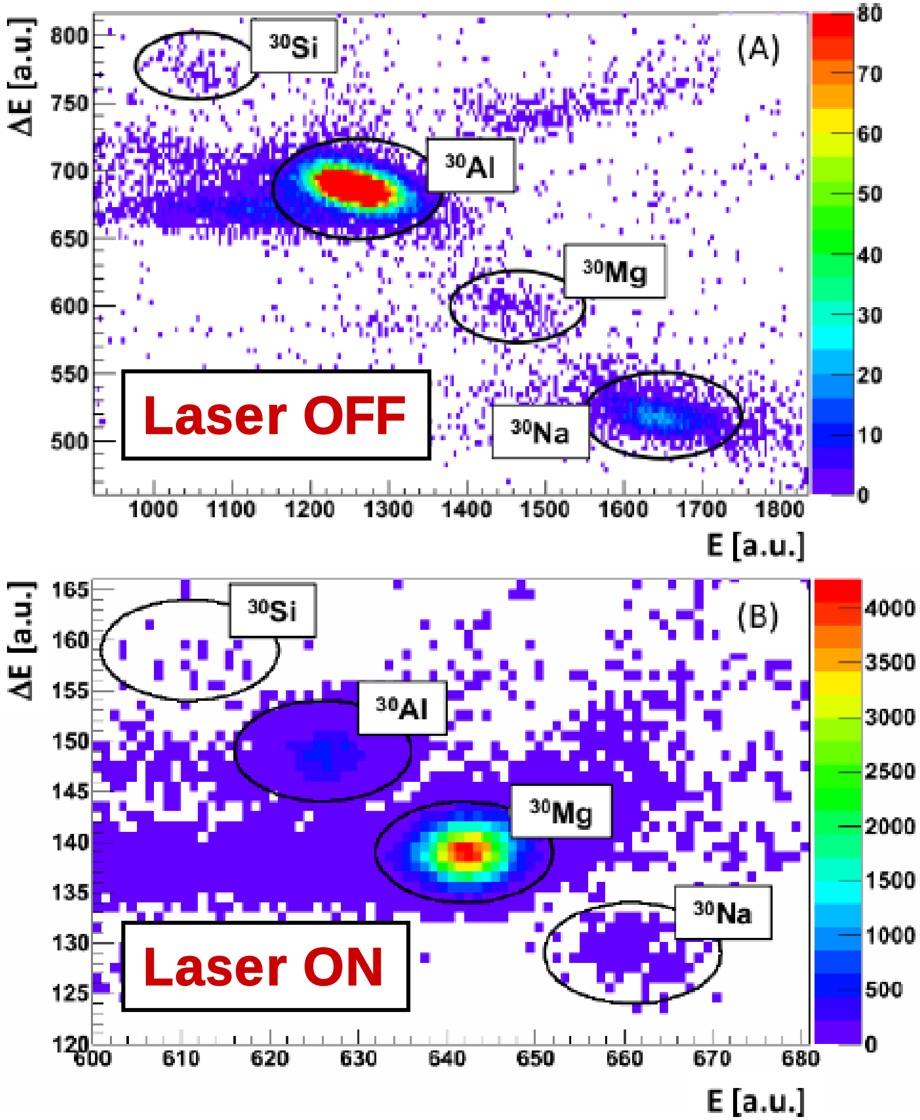
Acceleration up to Ra achieved



Beam quality, monitoring, quantitative composition

Measured with ionization chamber (ΔE-E_{rest}) at the MINIBALL beam dump position

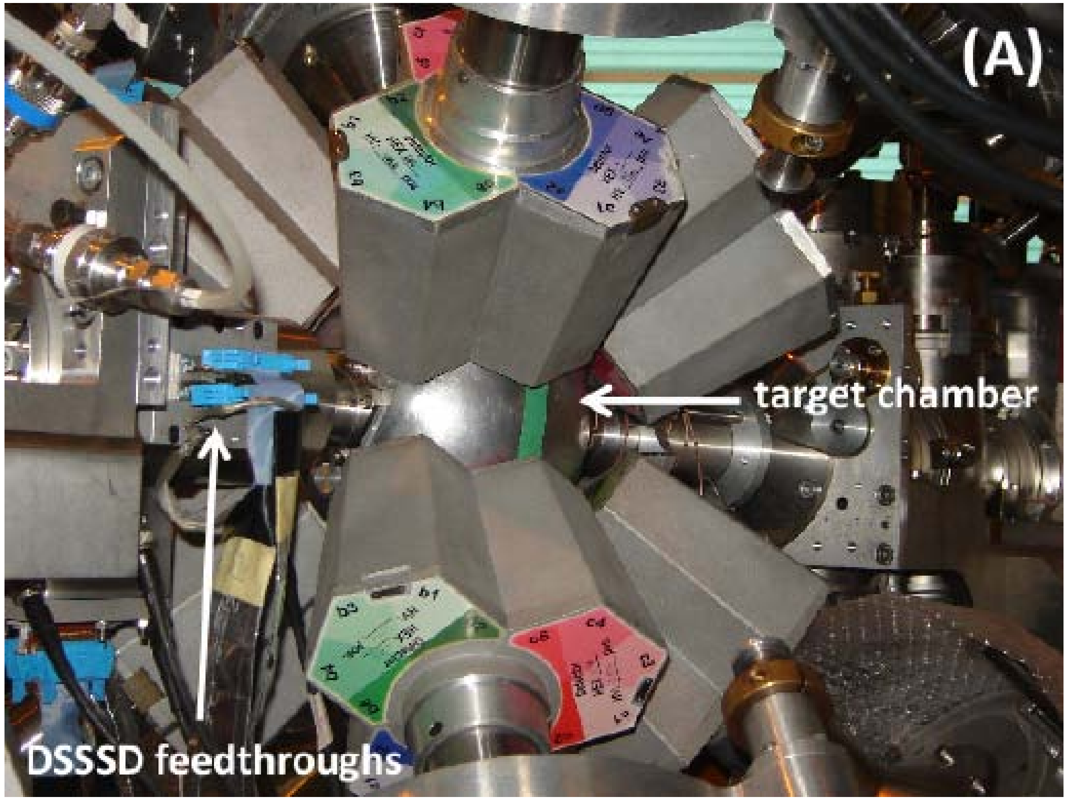


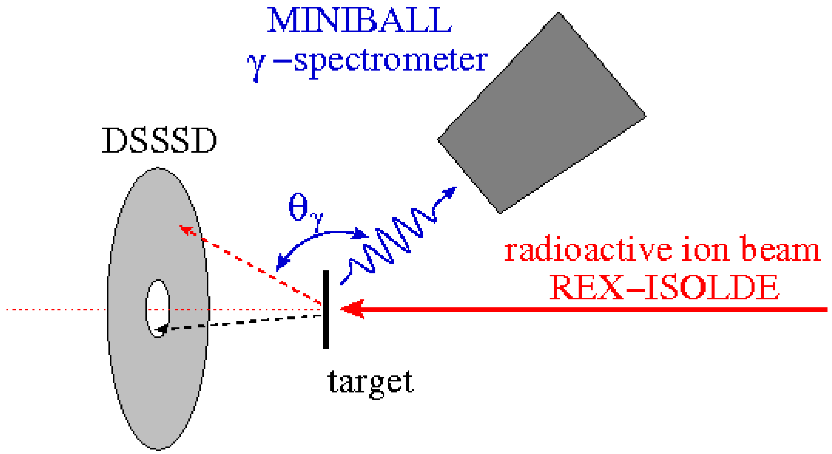


The MINIBALL Coulomb excitation setup

segmented Si detector for particle detection (DSSSD)

- 16 rings (front side)
- 96 strips (back side)
- angle coverage: θ_{lab} = 16-55°
- ΔE-E measurement possible (pad)





The T-REX setup

Talks by J. Diriken, D. Mücher

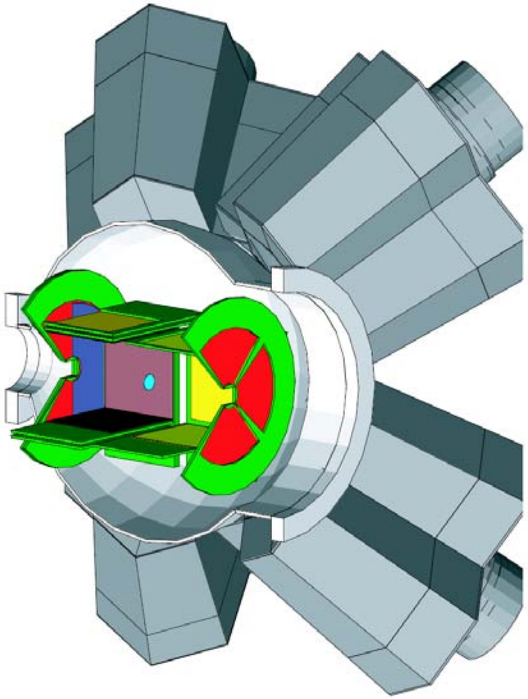
T-REX: Si detector array for Transfer experiments at REX-ISOLDE

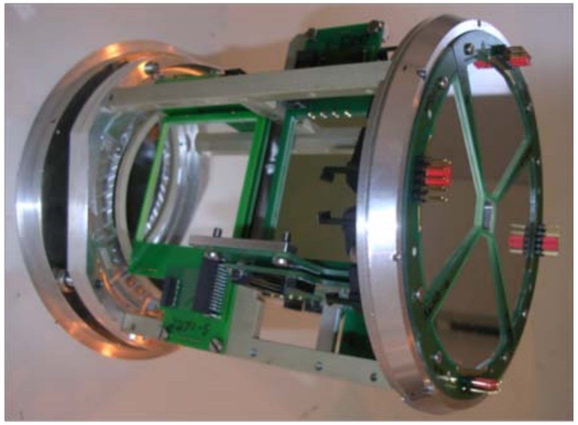
- large solid angle (58% of 4π)
- position sensitive
- PID (ΔE-E): p, d, t, α,
  ... and e^- from β-decay (!)

Technical details:

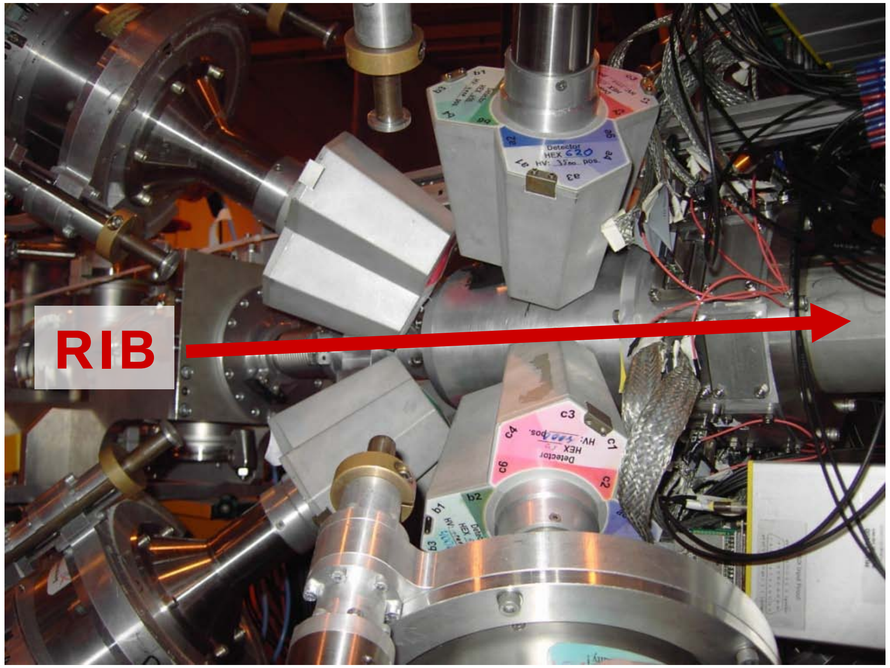
Barrel: 140 mm ΔE / 16 resistive strips
1000 mm E / pad

Backward CD: 500 mm ΔE / DSSSD
500 mm E / pad





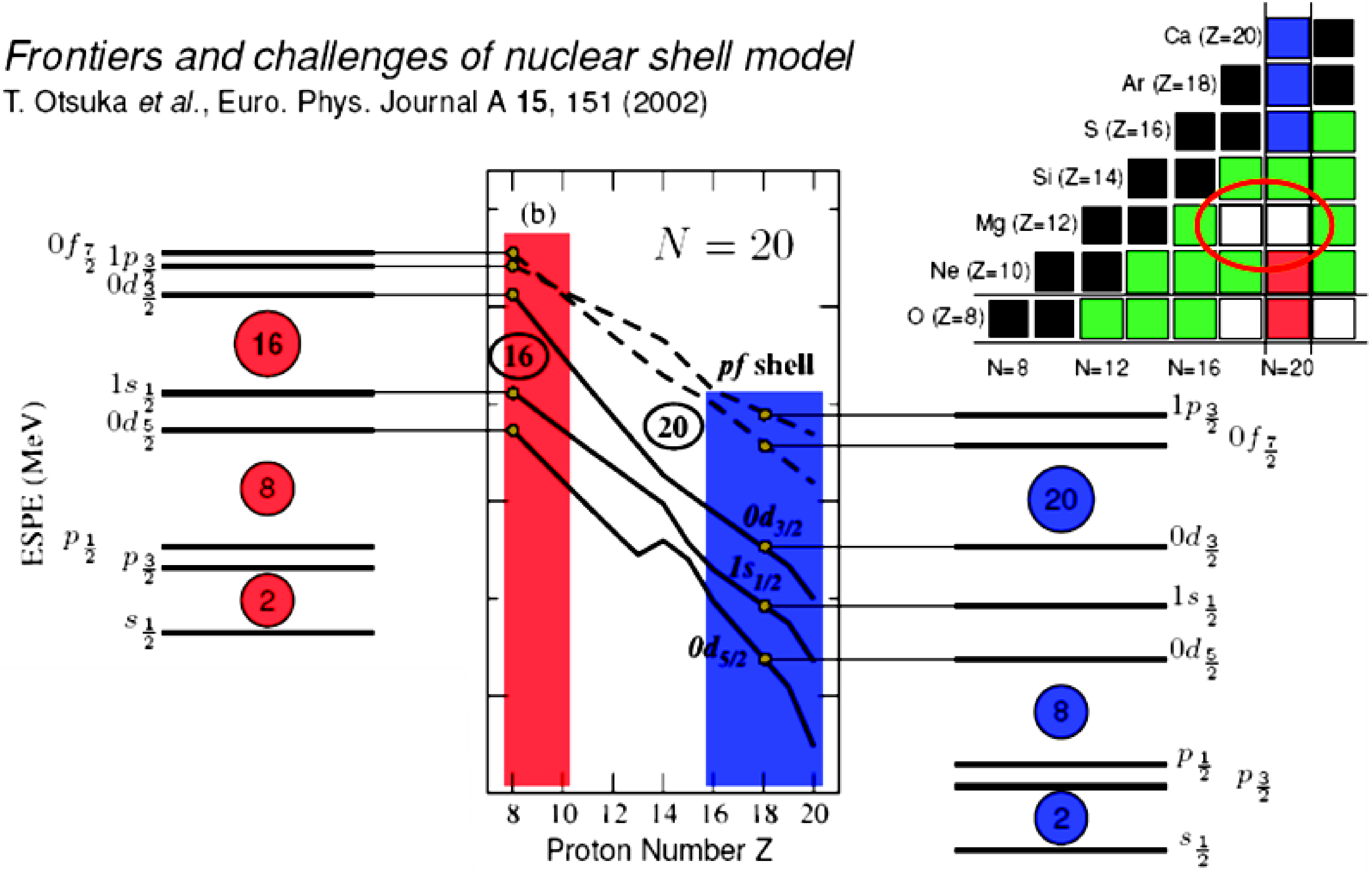
V. Bildstein, K. Wimmer,
Th. Kröll, R. Gernhäuser et al.
(funded by TU München,
KU Leuven, U Edinburgh, CSNSM Orsay, TU Darmstadt)



Deviations from classical shell model

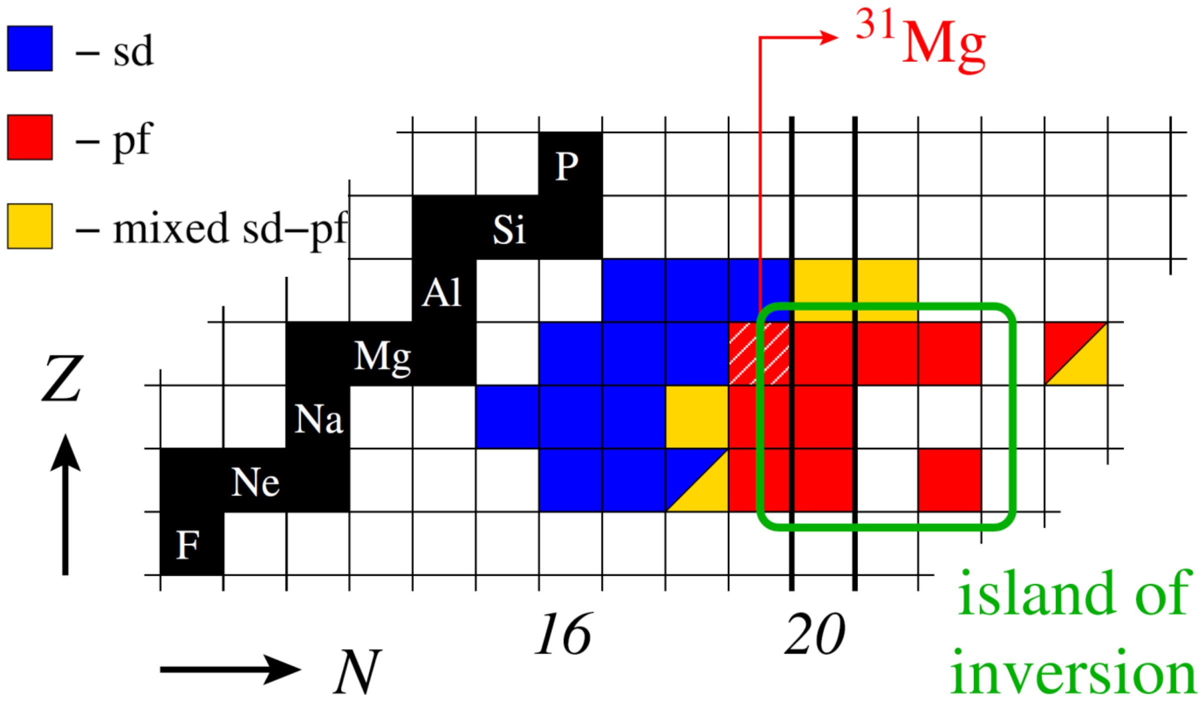
Frontiers and challenges of nuclear shell model

T. Otsuka *et al.*, Euro. Phys. Journal A **15**, 151 (2002)



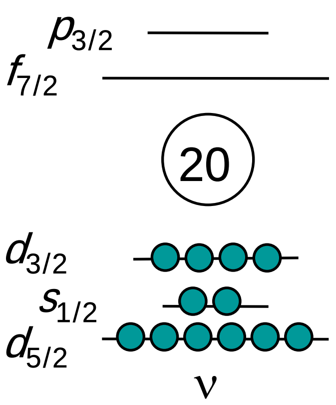
„Island of Inversion“

1975, ISOLDE: C. Thibault *et al.*:
Masses show considerable deviations for nuclei around Z=11, N=20.
⇒ additional binding energy

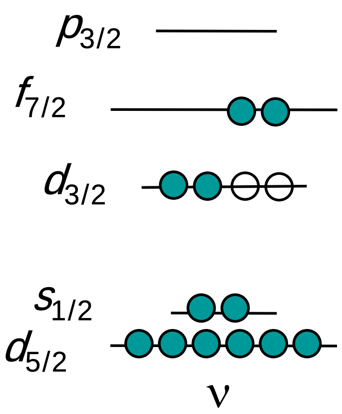


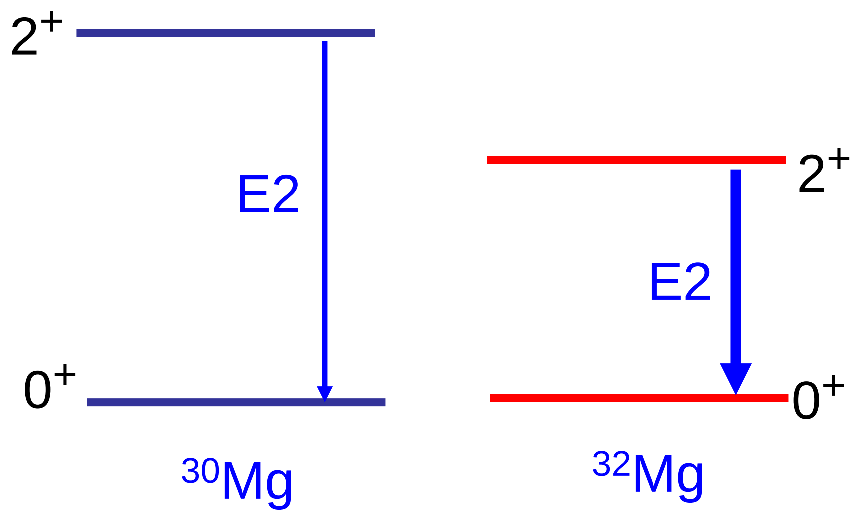
Normal *sd*-shell configuration

0p0h, spherical



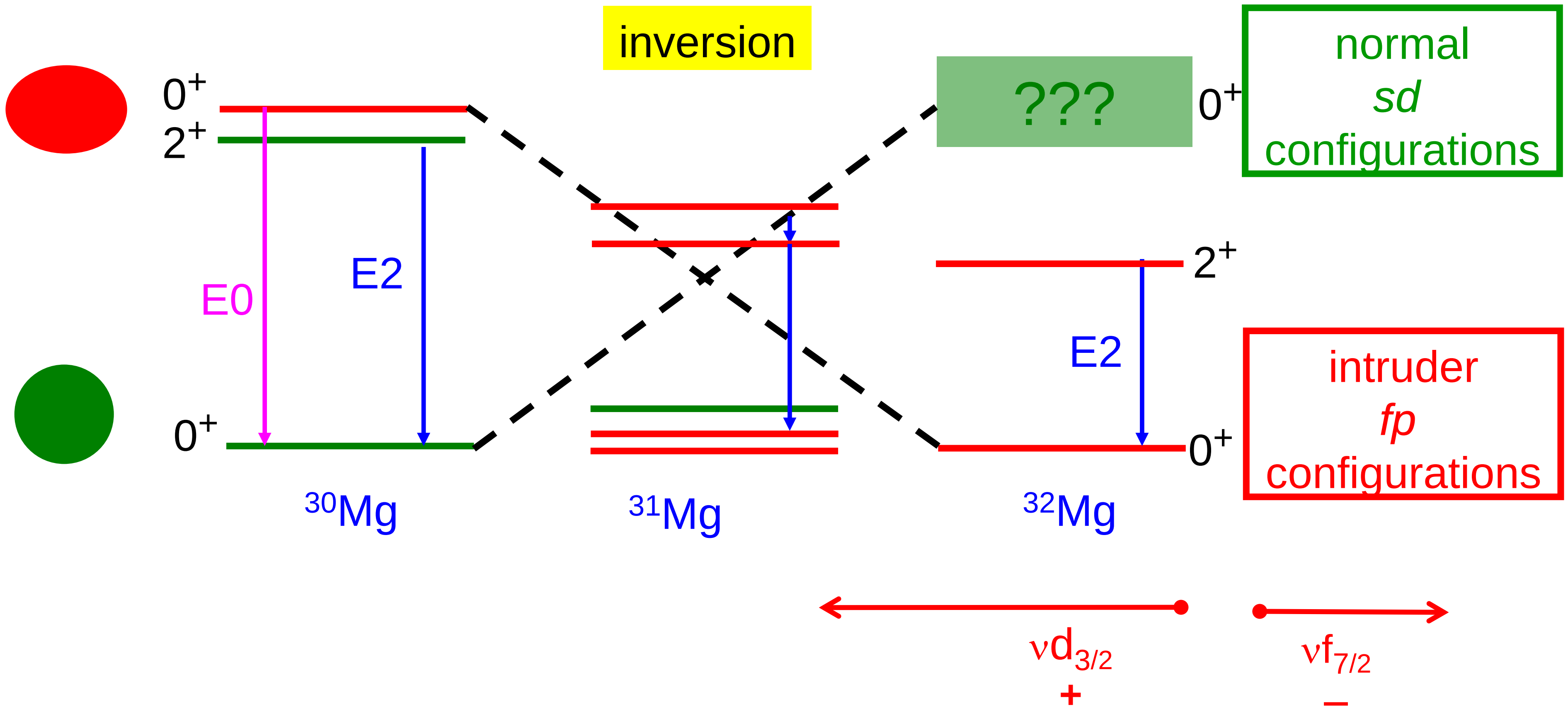
2p2h (intruder), deformed





E.K. Warburton, J. A. Becker and B. A. Brown, PRC **41** (1990) 1147.

T. Motobayashi, et al.; PLB **346** (1995) 9

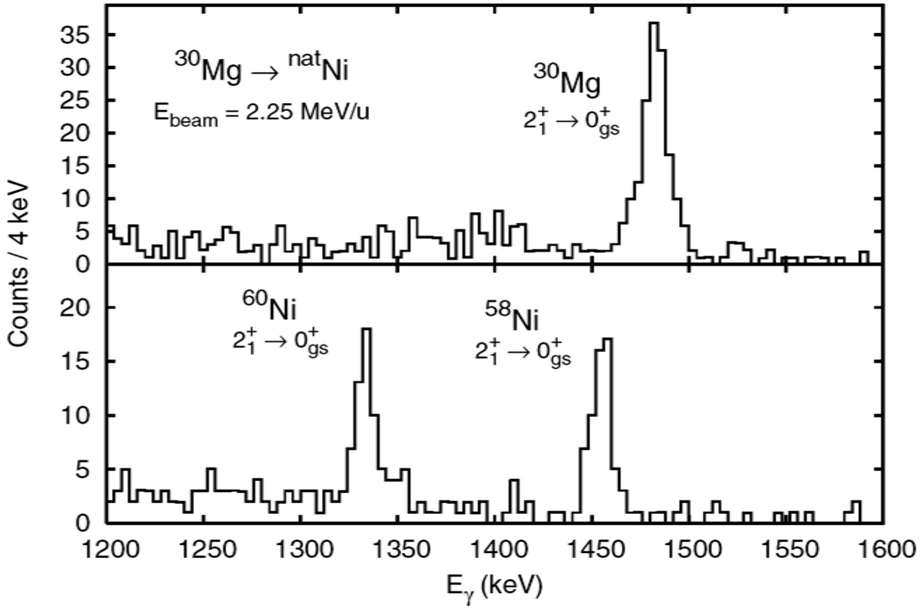


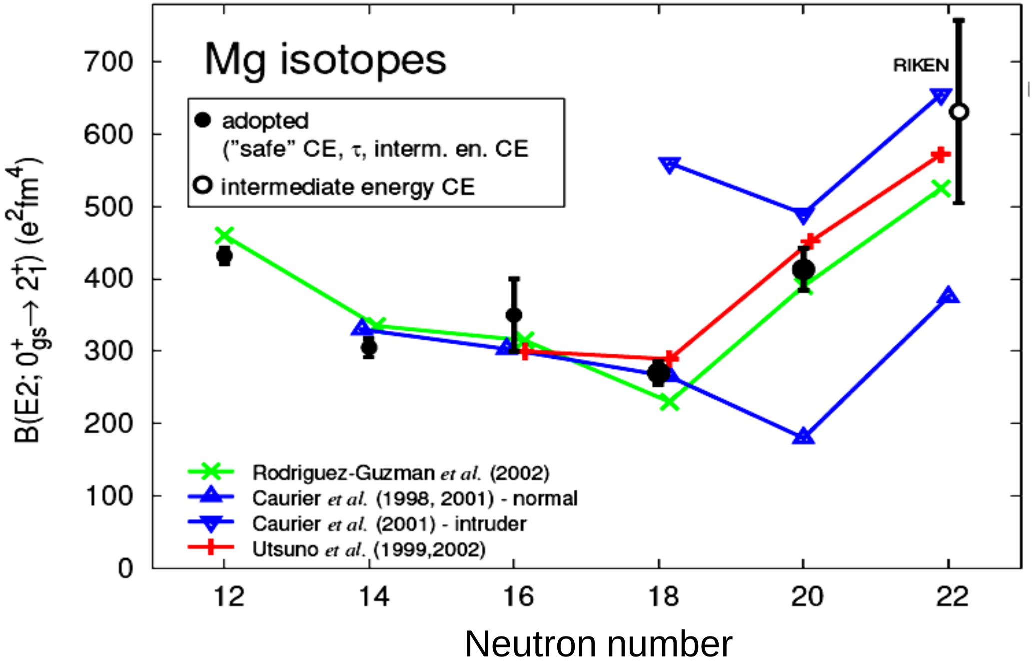
Where are the borders?

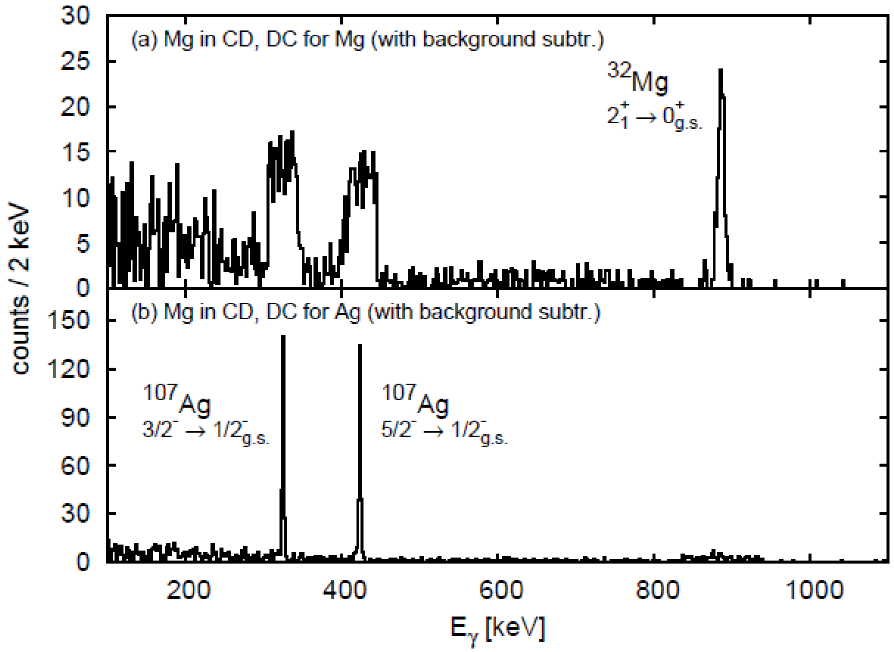
How does transition into island of inversion occur ?

Does picture of shape coexistence hold?

Coulomb excitation of ^{30,32}Mg





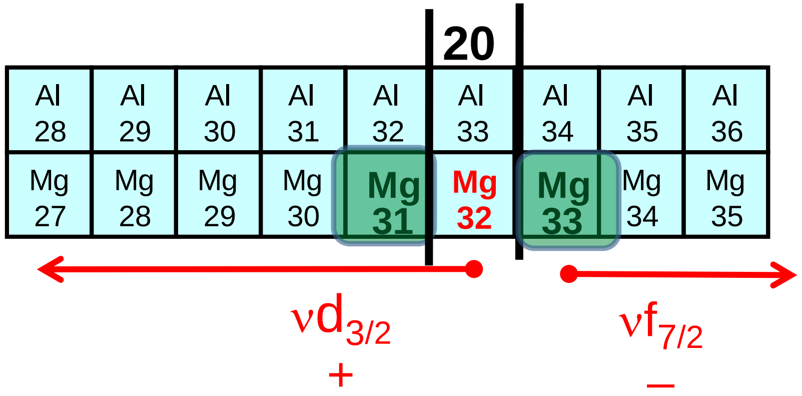


‚Safe' energy Coulomb excitation at 2.25 MeV/u

MINIBALL measures with small uncertainty B(E2) values from first excited 2^+ states to ground state in ^{30,32}Mg

O. Niedermeier, *et al.,* Phys. Rev. Lett. **94**, 172501 (2005)

g-factor and spin of the ^{31,33}Mg ground state



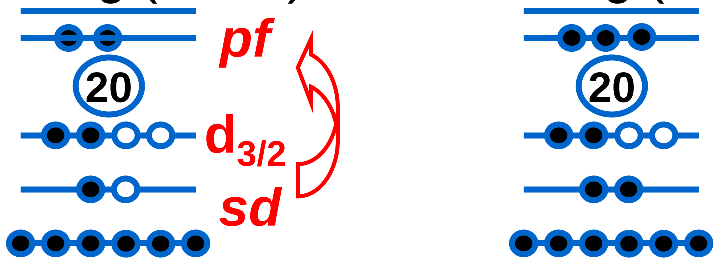
laser spectroscopy and β-NMR
g-factor and spin for ^{31}Mg and ^{33}Mg
from sign of g-factor → parity

^{31}Mg, $I^\pi = 1/2^+$ $\nu(sd)^{-3}(fp)^2$
^{33}Mg, $I^\pi = 3/2^-$ $\nu(sd)^{-2}(fp)^3$

→ pure 2p-2h intruder ground states !

Intruder ground state configurations:

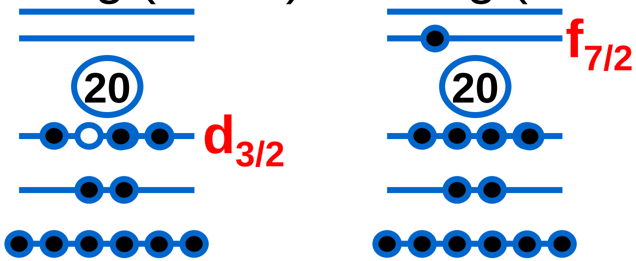
^{31}Mg (N=19) ^{33}Mg (N=21)



$I^\pi=1/2^+$ $I^\pi=3/2^-$

Normal ground state configurations:

^{31}Mg (N=19) ^{33}Mg (N=21)



$I^\pi=3/2^+$ $I^\pi=7/2^-$

G. Neyens et al., PRL 94, 022501 (2005)
D. Yordanov et al., PRL 99, 212501 (2007)

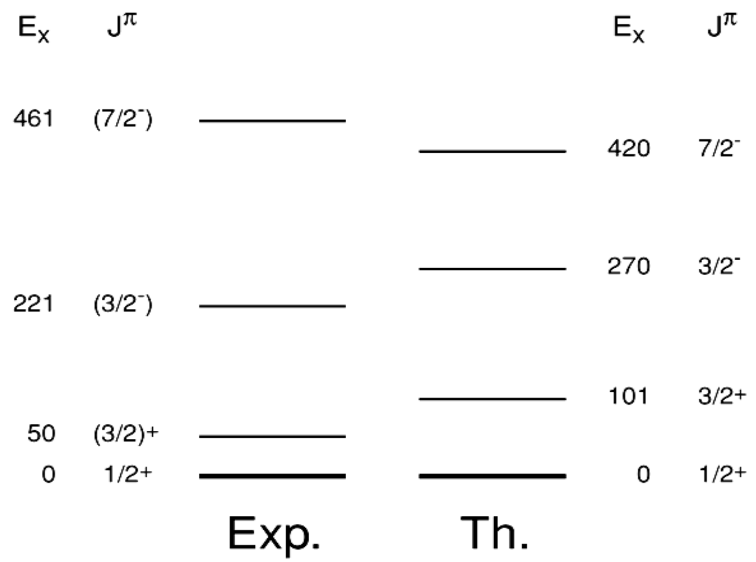
Renewed β-decay studies

^{31}Mg F. Maréchal et al., PRC 72, 044314 (2005)
^{33}Mg V. Tripathi et al., PRL 101, 142504 (2008)

collective properties of ^{31}Mg

– β-decay studies of ^{31}Mg at GANIL

- shell model calculation *sd-fp* valence space
  ANTOINE code, effective interaction SDPF-NR

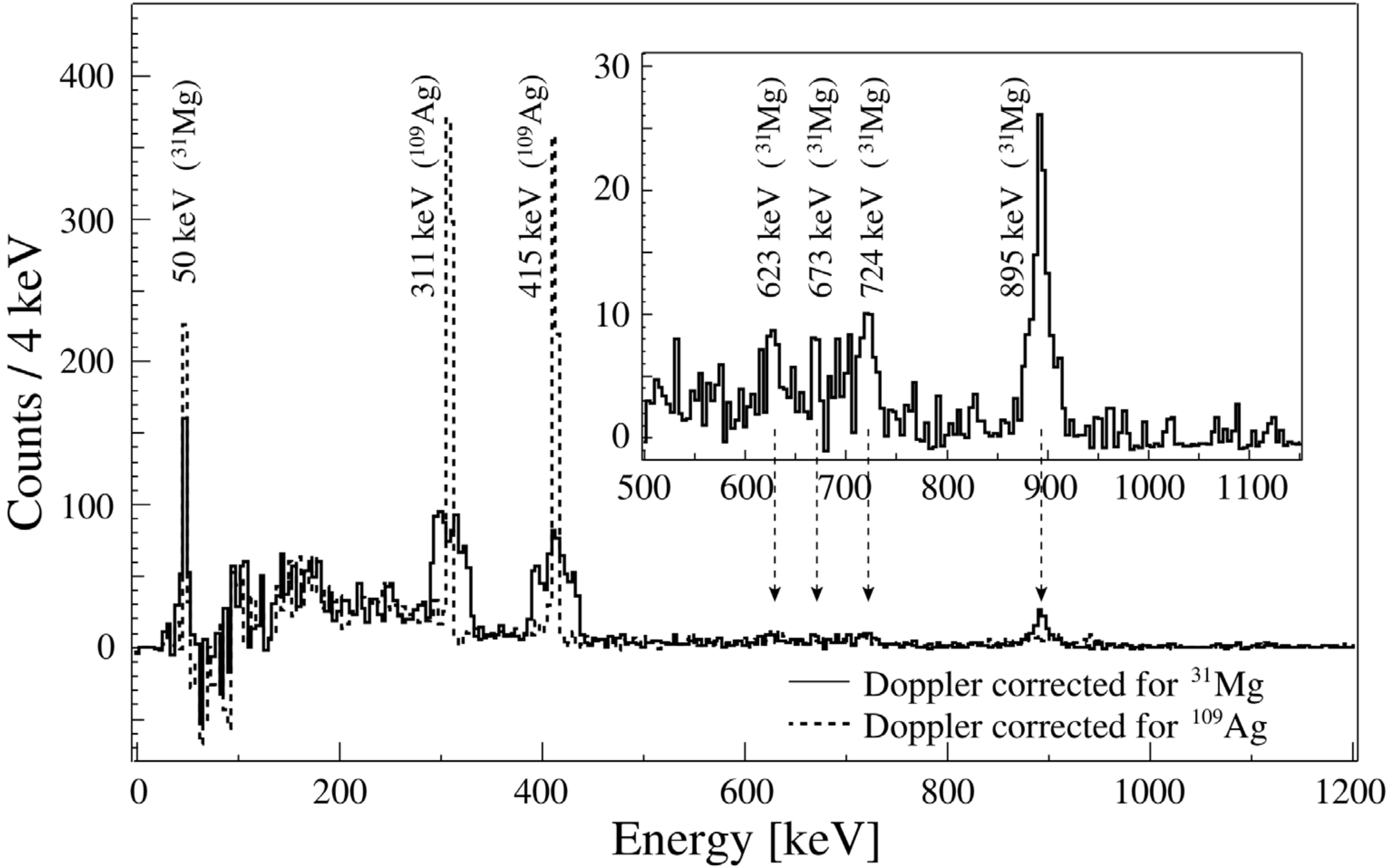


collective properties of positive K=1/2 rotational band of ^{31}Mg:
excitation energy, quadrupole moment Q, B(E2), magnetic moment μ, B(M1)

J	E_x	$n^{\nu}_{d_{5/2}}$	$n^{\nu}_{d_{3/2}}$	$n^{\nu}_{s_{1/2}}$	Q_s/Q_0	$B(E2)$	μ	$B(M1)$
1/2	0	5.62	1.99	1.33			−0.98	
3/2	101	5.63	1.77	1.56	−17/84	106	+0.56	0.06
5/2	988	5.60	2.02	1.31	−17/59	127	−0.30	0.38
7/2	1236	5.63	1.68	1.64	−25/75	151	+0.94	0.04
$K = 1/2^+$		5.75	1.52	1.73				

F. Maréchal *et al.*, Phys. Rev. C **72**, 044314 (2005)
M. Kimura, Phys. Rev. C **75**, 041302(R) (2007)

Coulomb excitation ^{31}Mg



GOSIA Coulex calculation

Results:

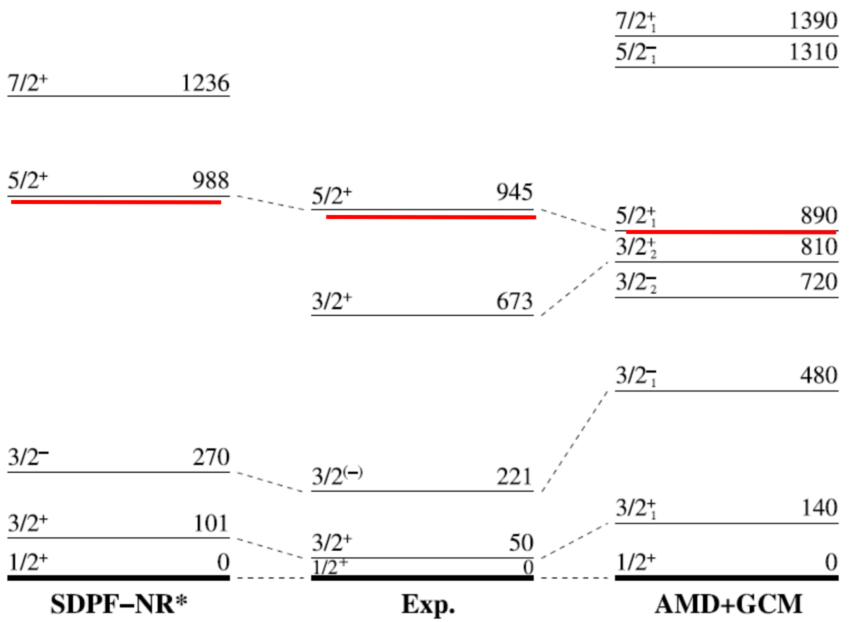
- one step E2 excitation

$B(E2, 1/2^+ \rightarrow 5/2^+) = 182\ e^2fm^4$

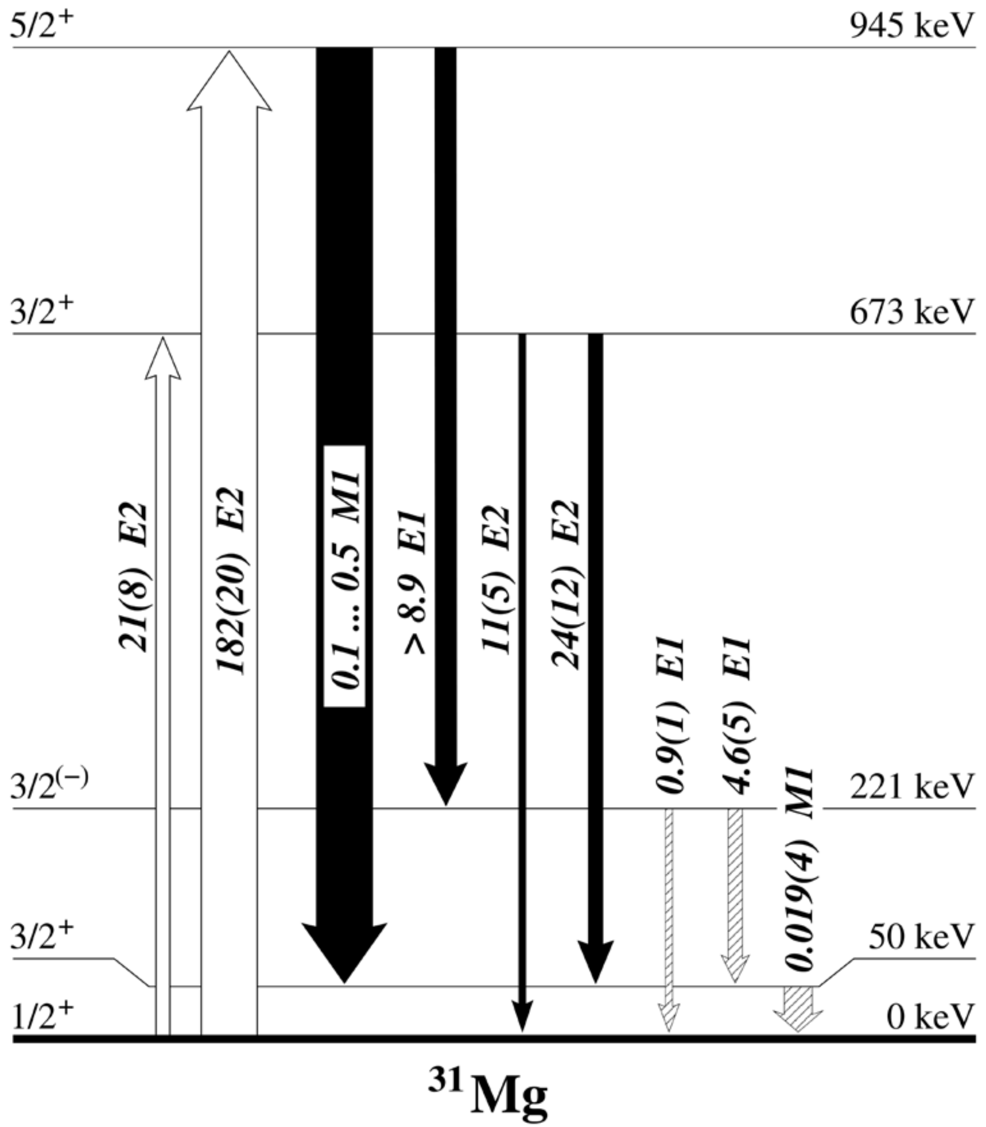
- decay of (5/2+,3/2+) level via M1 transition

$B(M1, 5/2^+ \rightarrow 3/2^+) = 0.1 – 0.5\ \mu_n^2$

- results confirms strong collective excitation
- rotational sequence: $1/2^+ \rightarrow 3/2^+ \rightarrow 5/2^+$

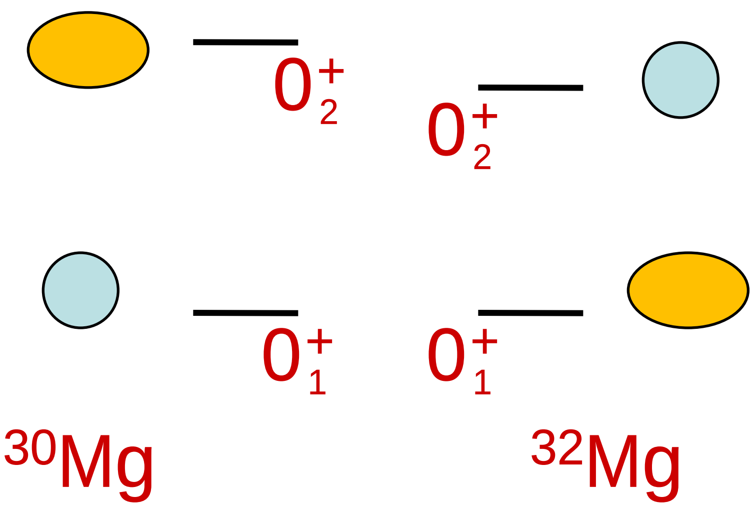


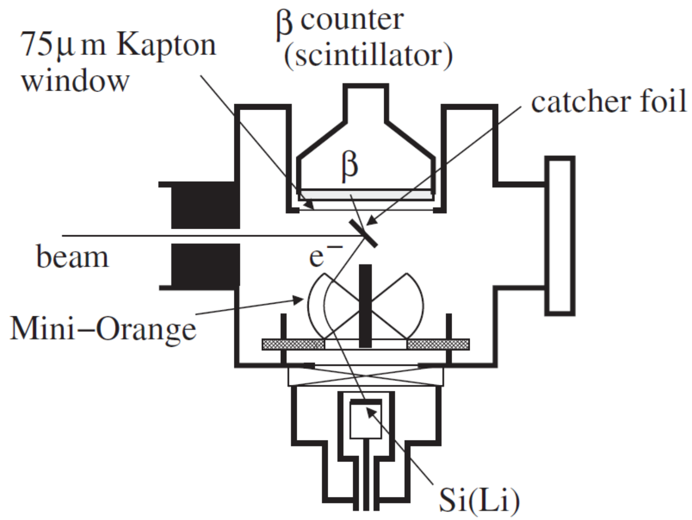
M. Kimura, Phys. Rev. C **75**, 041302(R) (2007)



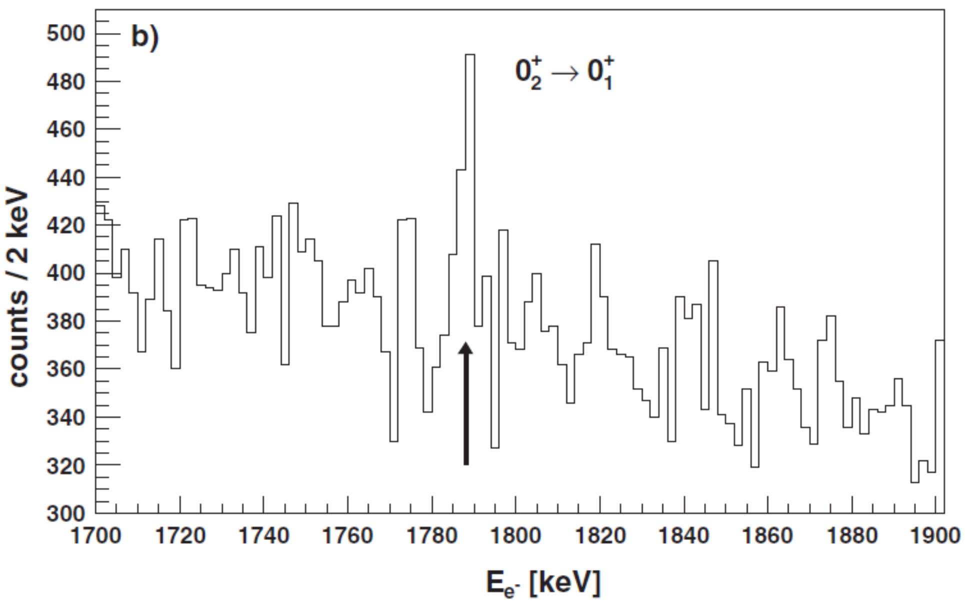
M. Seidlitz et al; PLB 700 (2011) 181

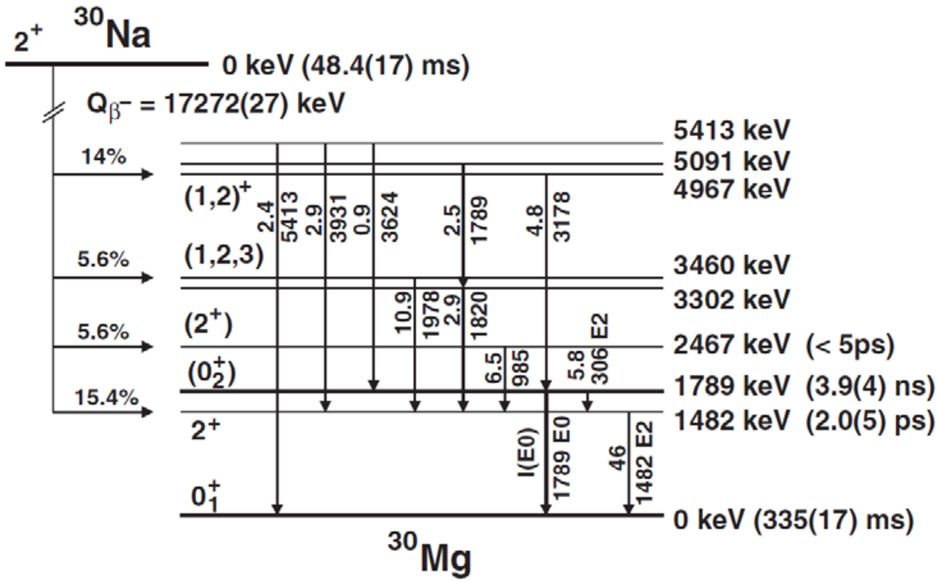
Shape coexistence ?





- electron spectroscopy after β-decay at ISOLDE
- first excited 0^+ state at 1789 keV in ^{30}Mg





W. Schwerdtfeger, et al; PRL 103, 012501 (2009)

Shape coexistence in ^{30}Mg

electric monopole (E0) transition to ground state:
$\rho^2(E0) = (26.2\ (7.5)) \times 10^{-3}$

beyond-mean-field calculations with Gogny force:
- two competing configurations, small mixing
- largely different intrinsic quadrupole deformation
- ground state: $1d_{3/2}$ neutrons
- first excited 0^+ state: $1f_{7/2}$ neutrons

predictions for ^{32}Mg

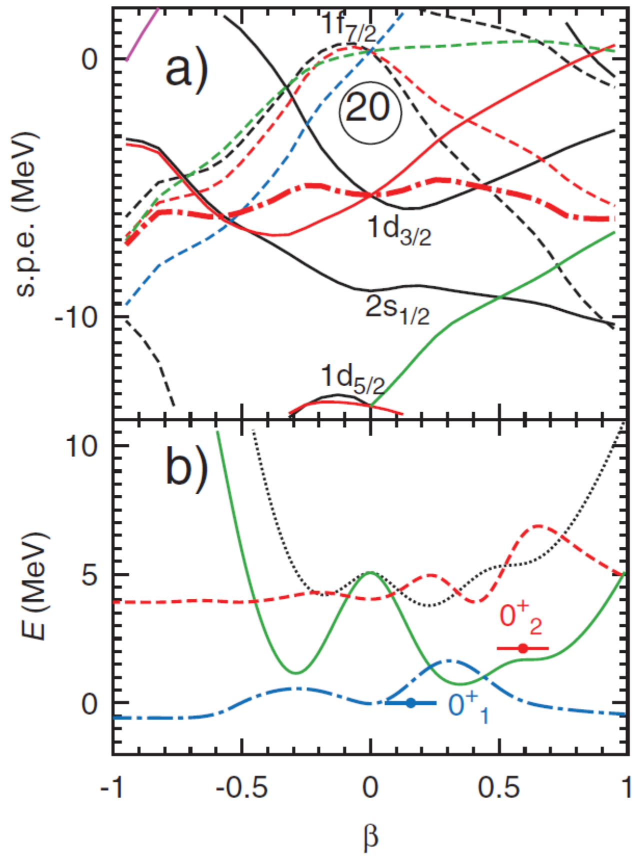


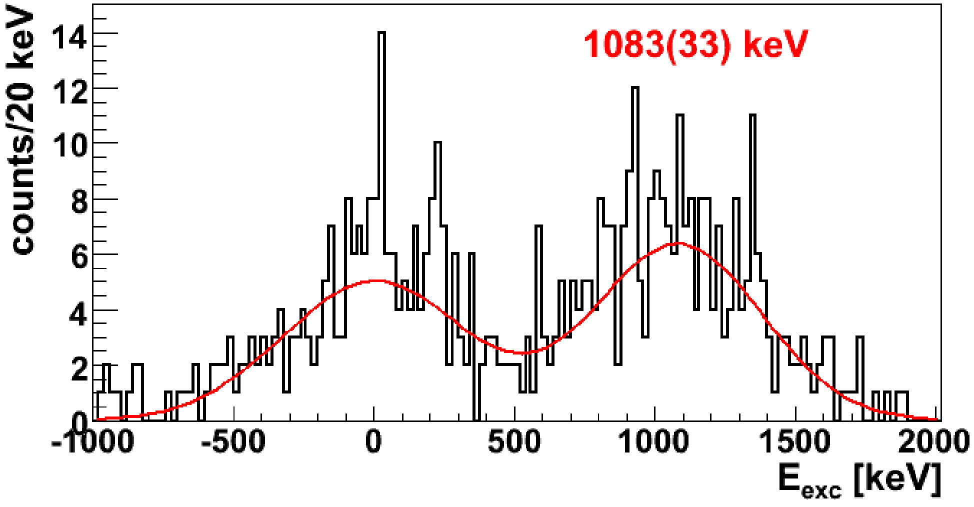
TABLE I. Results from beyond-mean-field calculations with Gogny force for ^{30}Mg and ^{32}Mg (indicated as "T") compared to experimental values ("E").

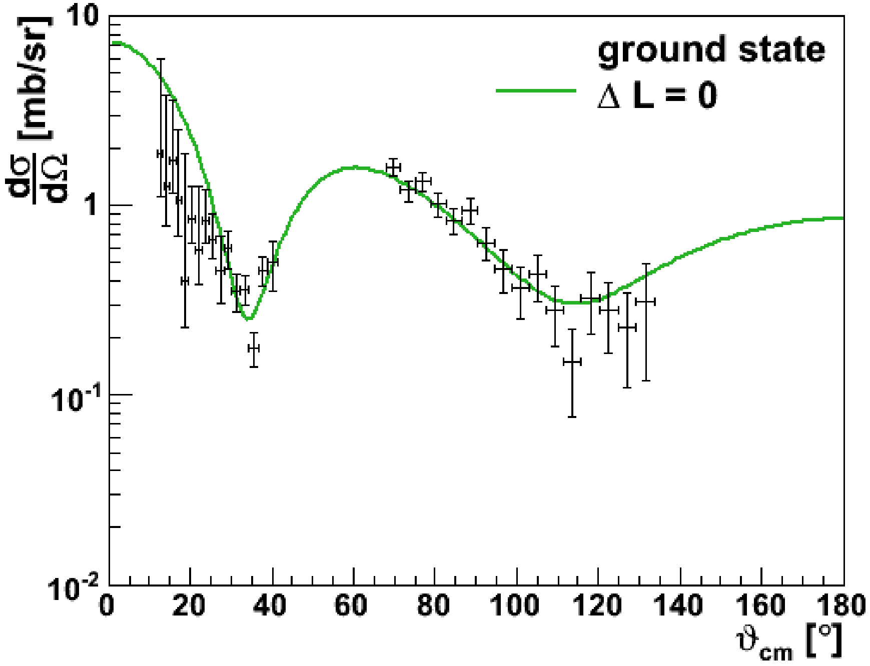
		$E_x(2_1^+)$ (MeV)	$E_x(0_2^+)$ (MeV)	$B(E2, 0_1^+ \to 2_1^+)$ (e^2 fm^4)	$\rho^2(E0) \times 10^{-3}$	$B(E2, 0_2^+ \to 2_1^+)$ (e^2 fm^4)
^{30}Mg	(T)	2.03	2.11	334.6	46	181.5
	(E)	1.482	1.789	241(31) [9]	26.2 ± 7.5	53(6)
^{32}Mg	(T)	1.35	2.60	455.7	41	56.48
	(E)	0.885	...	454(78) [5]	...	...

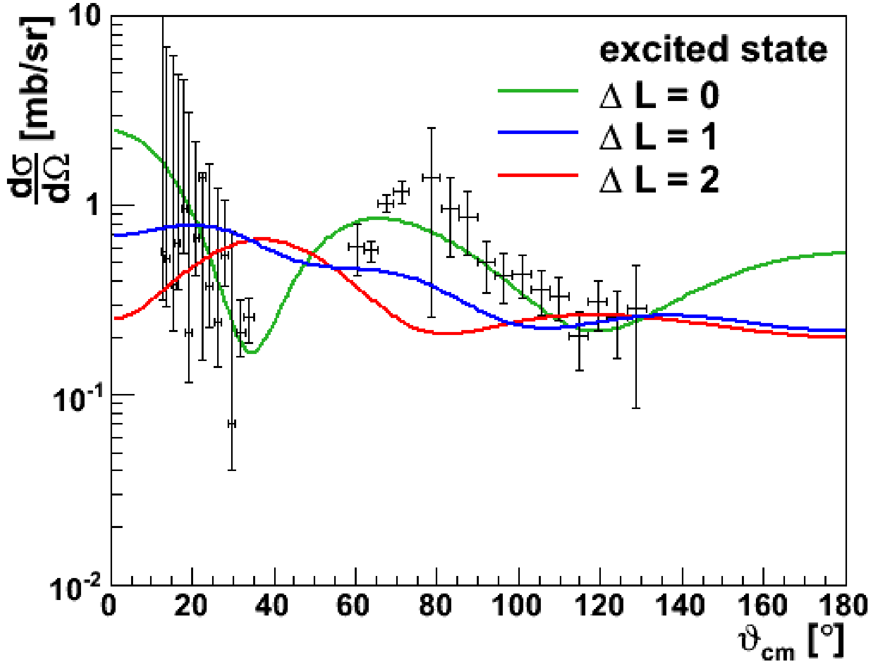
W. Schwerdtfeger, et al; PRL 103, 012501 (2009)

t(^{30}Mg, ^{32}Mg)p – two-neutron transfer

- ^{3}H loaded Ti foil (40 μg/cm^2 ^{3}H, 10 GBq)
- ^{30}Mg @ 2 MeV/u
- $4 \cdot 10^4$ part/s / 150 h beam on target
- Q_{00} = -295(20) keV
- Two states populated: ground state and new state at 1083(33) keV

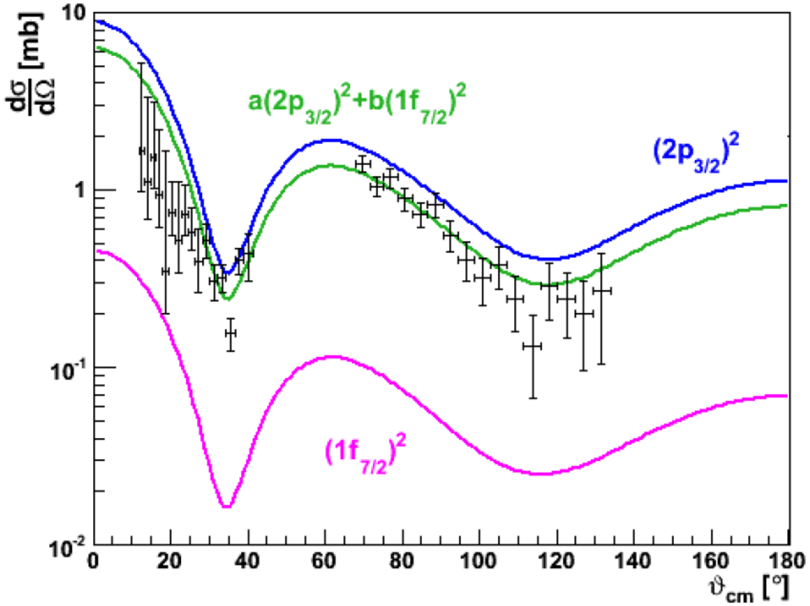






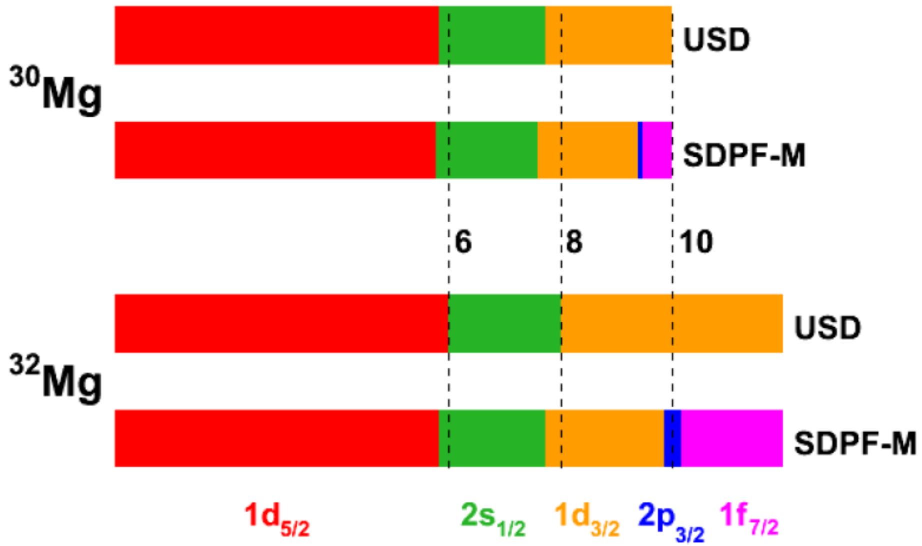
K. Wimmer et al; PRL 105, 252501 (2010)

Transfer to ground state in ^{32}Mg

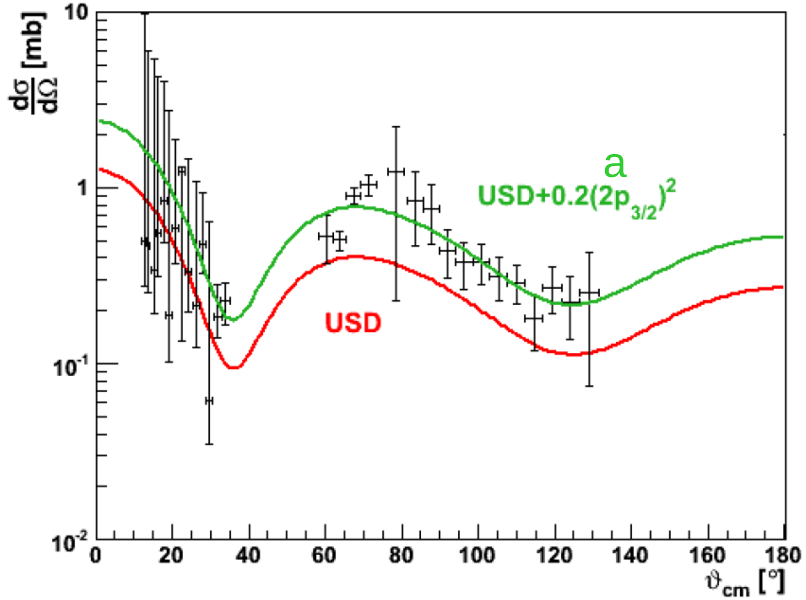


g.s. occupation numbers using effective USD / SDPF-M interactions:

B. H. Wildenthal, Prog. Part. Nucl. Phys. 1, 5 (1984) T. Otsuka et al., Prog. Part. Nucl. Phys. 47, 319 (2001)



Transfer to excited 0^+ state in ^{32}Mg



Transfer to ground state in ^{32}Mg

- pure transfer to $(f_{7/2})^2$ to small
- large contribution from $(p_{3/2})^2$ needed (a > 0.7)

… SDPF-M underestimates the $\nu p_{3/2}$ content in the wave functions

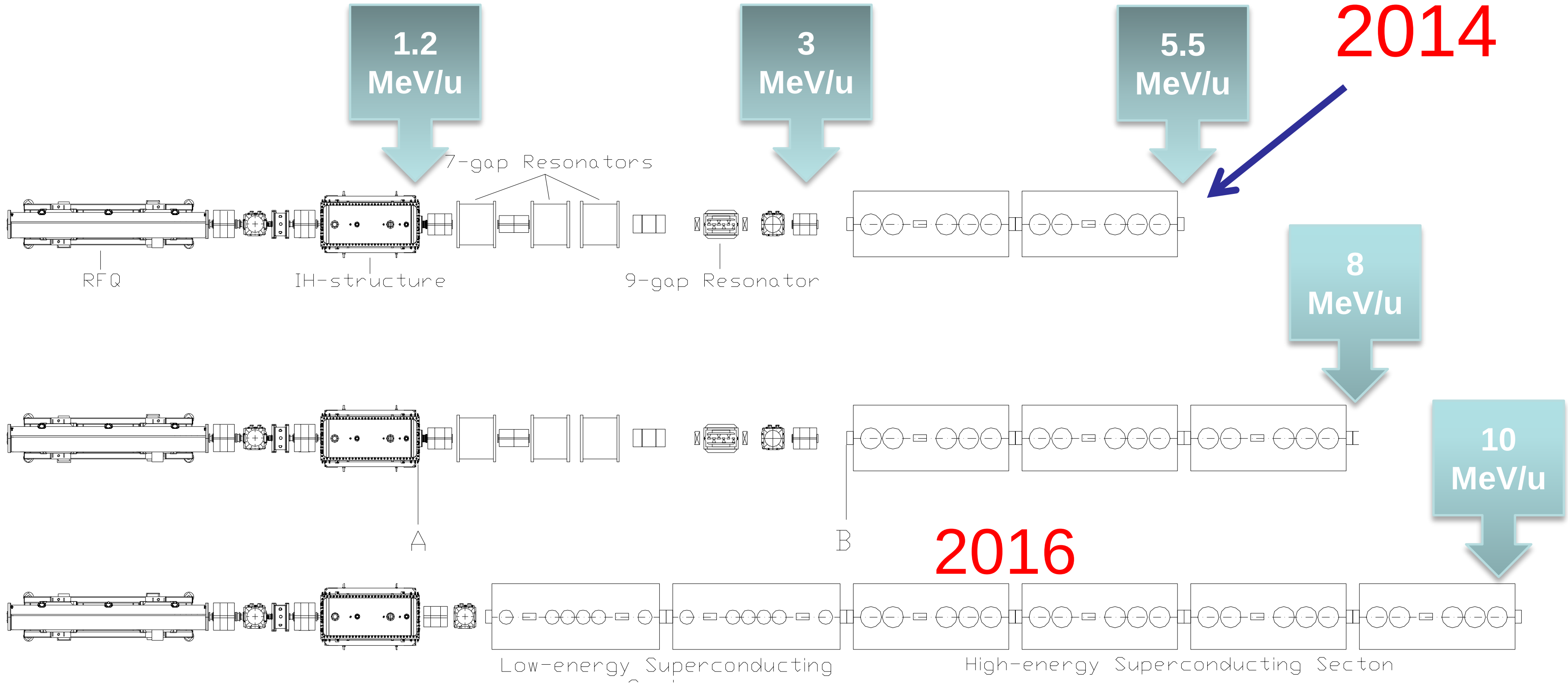
Transfer to excited 0^+ state in ^{32}Mg

- wave function similar to g.s. in ^{30}Mg
- two-neutron spectroscopic amplitudes for pure sd → sd transitions
- cross section underestimated, small $(p_{3/2})^2$ amplitude (a ≈ 0.3)

K. Wimmer et al; PRL 105, 252501 (2010)

HIE-ISOLDE

- intensity upgrade
- energy upgrade



HIE-ISOLDE

instrumentation for energetic beams

- Main workhorse : MINIBALL + TREX
- New detectors :
  - MAYA/ACTAR active target
  - SPEDE - SPectrometer for Electron DEtection in radioactive beam
  - HELIOS superconducting magnet for charged particle detection
  - PARIS (**P**hoton **A**rray for studies with **R**adioactive **I**on and **S**table beams)
  - GASPARD (**GA**mma **S**pectroscopy and **PA**rticle **D**etection)
  - Neutron detectors
- Magnetic spectrometer or separator for channel selection
- Storage Ring
- Special requirements
  - Time of Flight detection => buncher + chopper
  - Slow EBIS extraction
  - Beam spot

Short term perspectives

• 2011 campaign

- Coulex experiments:

  $^{188;..,198}Pb$, ^{140}Nd, ^{96}Kr, ^{220}Rn, ^{208}Rn, ^{128}Cd, ^{72}Kr, ^{30}Na, ^{98}Sr

- transfer experiments

- g-factor measurements

Discussion of physics campaign during CERN shut down period
MINIBALL workshop
University of Cologne
27.-28. February or March 5.-6. March 2012.

• 2012 campaign

• 2013 CERN shut down

Summary

- MINIBALL spectrometer perfectly suited for REX-ISOLDE
- Physics case covers nuclei in the range from ^{17}F to ^{224}Ra
- First years: Shell model physics and Coulomb excitation
- Recent developments:
  - heavy beams
  - T-REX transfer reactions & γ-ray spectroscopy
- Major perspective: HIE-ISOLDE