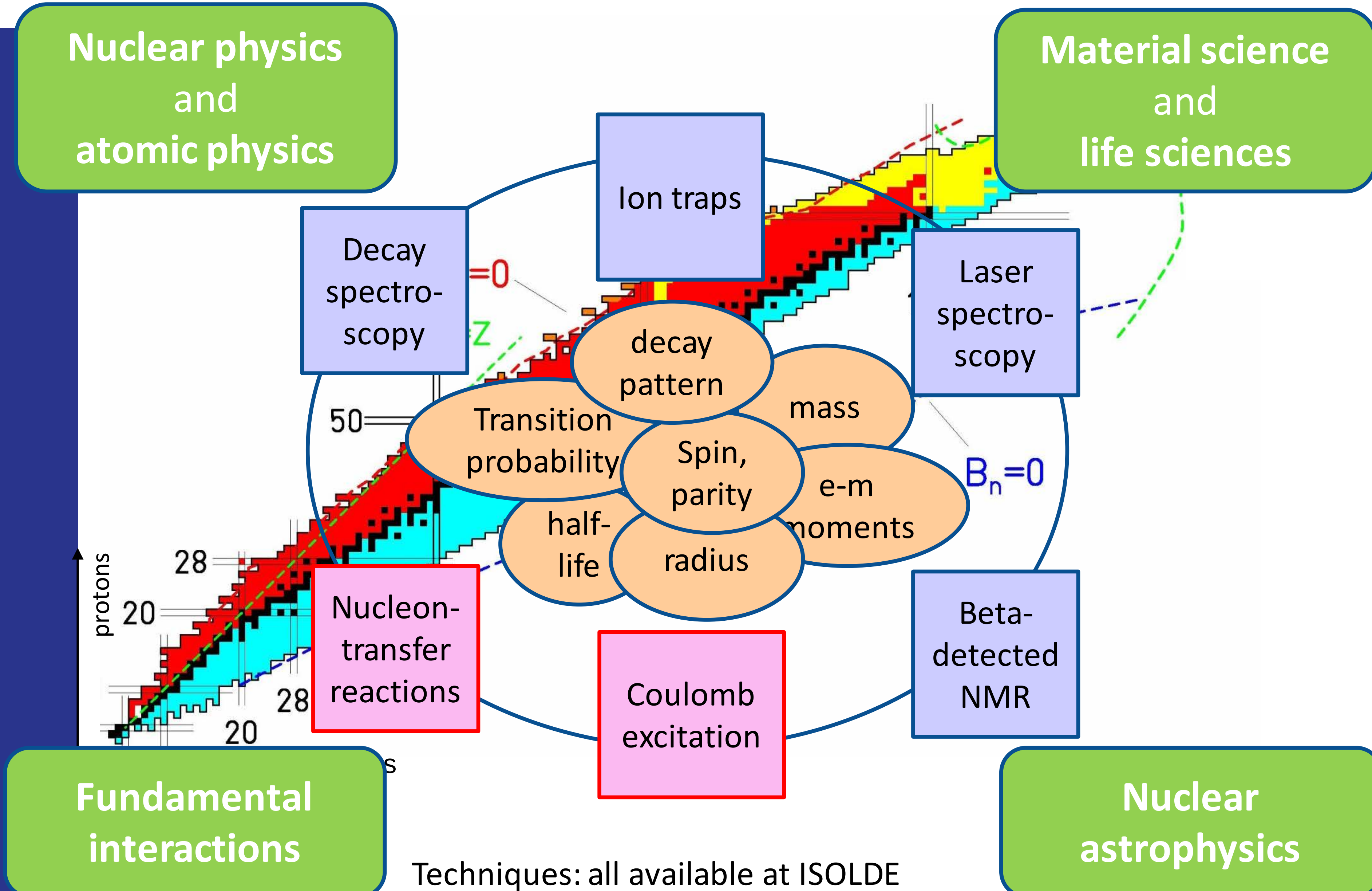
ISOLDE physics in the HIE-ISOLDE era

Miguel Madurga
EP-Dept, CERN

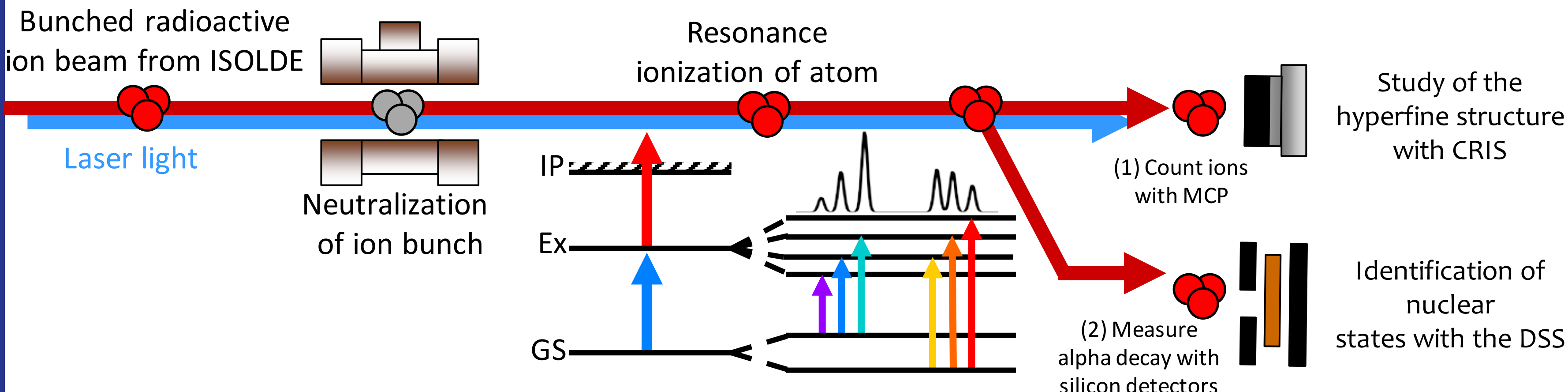
ISOLDE: Research with Radiactive Nuclei



Techniques: all available at ISOLDE

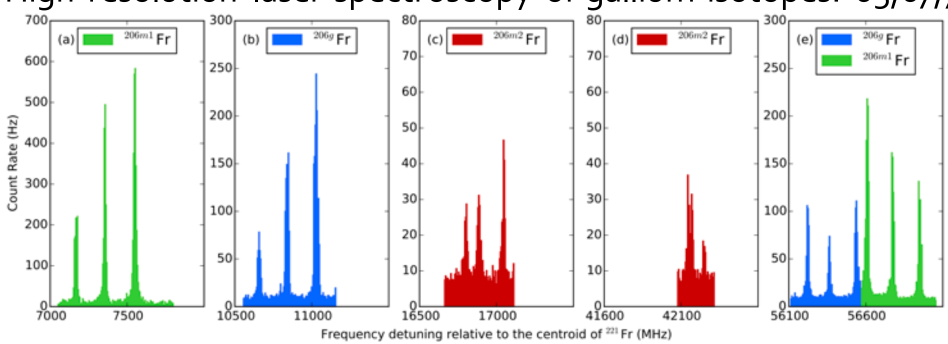
2015 – 2016 Low energy beam campaign

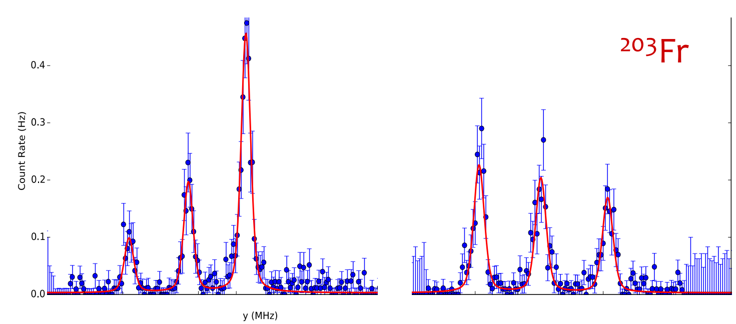
The CRIS experiment: Highlights from 2015



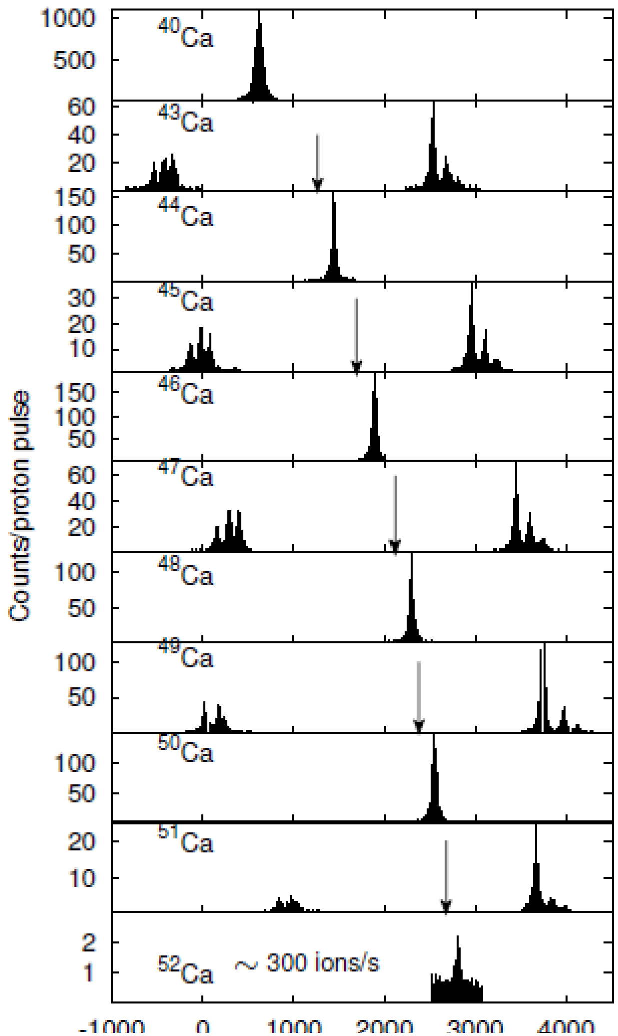
- Publication of first high-resolution laser spectroscopic studies for CRIS R.P. de Groote *et al.*, PRL **115** 132501 (2015)
- Laser-assisted decay spectroscopy performed on states of 206Fr K.M. Lynch et al., Phys. Rev. C, **93** 014319 (2016)
- Hyperfine structure of short-lived 214Fr ($t_{1/2}$ = 5 ms) studied G.J. Farooq-Smith et al., In preparation (2016)

- High-resolution laser spectroscopy of francium isotopes: 203,207Fr
- High-resolution laser spectroscopy of gallium isotopes: 65,67,75,79-82Ga





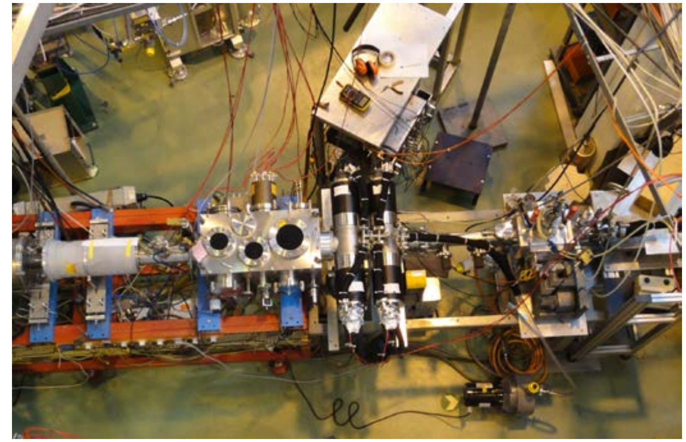
COLLAPS



PHYSICAL REVIEW C 91, 041304(R) (2015)

Ground-state electromagnetic moments of calcium isotopes

R. F. Garcia Ruiz,[1,*] M. L. Bissell,[1] K. Blaum,[2] N. Frömmgen,[3] M. Hammen,[3] J. D. Holt,[4,5,6] M. Kowalska,[7] K. Kreim,[2] J. Menéndez,[4,5,8] R. Neugart,[2,3] G. Neyens,[1] W. Nörtershäuser,[4] F. Nowacki,[9] J. Papuga,[1] A. Poves,[10] A. Schwenk,[4,5] J. Simonis,[4,5] and D. T. Yordanov[2]



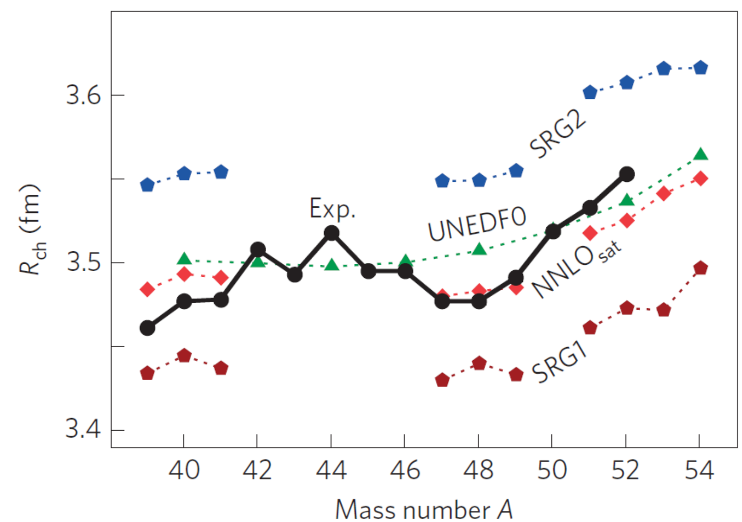
nature physics

ARTICLES

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3645

Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]

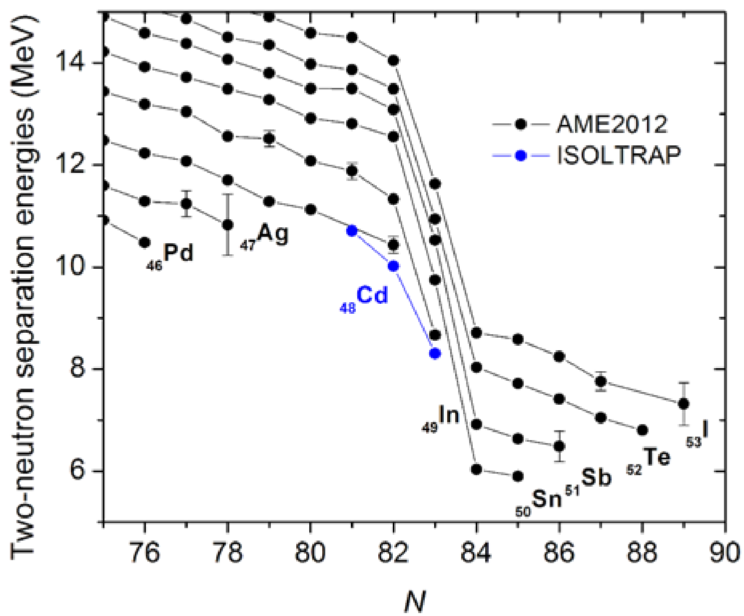


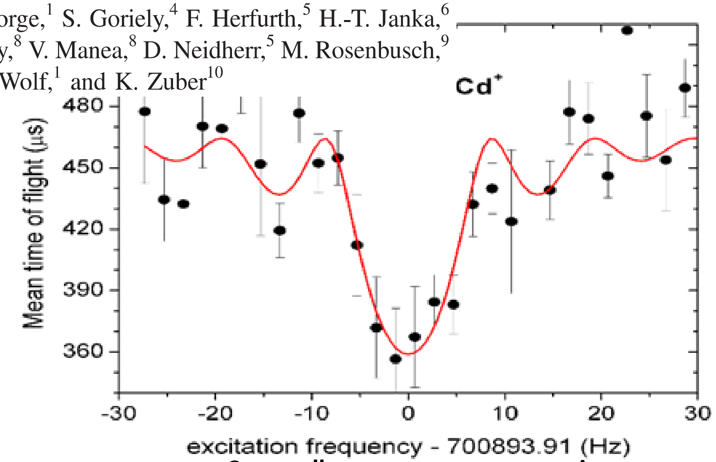
ISOLTRAP mass measurements of $^{129-131}$Cd

PRL **115,** 232501 (2015) PHYSICAL REVIEW LETTERS week ending 4 DECEMBER 2015

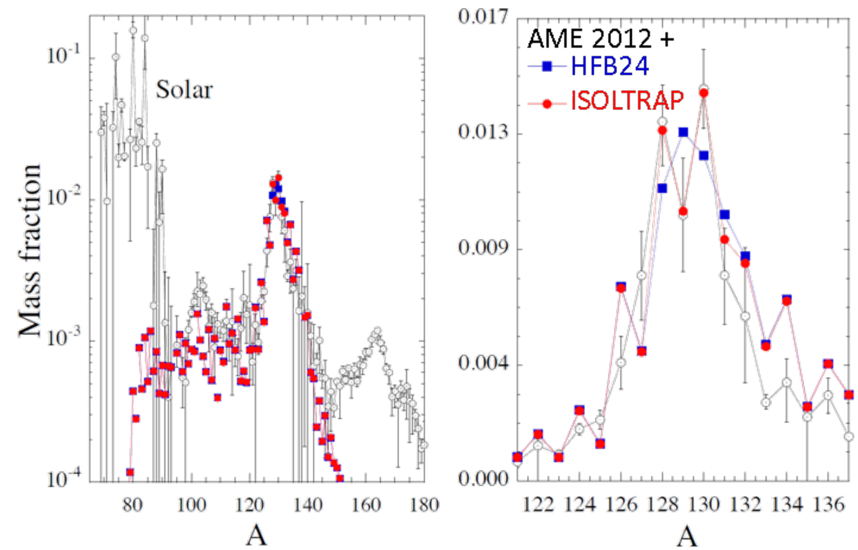
Precision Mass Measurements of $^{129-131}$Cd and Their Impact on Stellar Nucleosynthesis via the Rapid Neutron Capture Process

D. Atanasov,[1] P. Ascher,[1] K. Blaum,[1] R. B. Cakirli,[2] T. E. Cocolios,[3] S. George,[1] S. Goriely,[4] F. Herfurth,[5] H.-T. Janka,[6] O. Just,[6] M. Kowalska,[7] S. Kreim,[1,7] D. Kisler,[1] Yu. A. Litvinov,[1,5] D. Lunney,[8] V. Manea,[8] D. Neidherr,[5] M. Rosenbusch,[9] L. Schweikhard,[9] A. Welker,[10] F. Wienholtz,[9] R. N. Wolf,[1] and K. Zuber[10]





Core-collapse supernova scenario



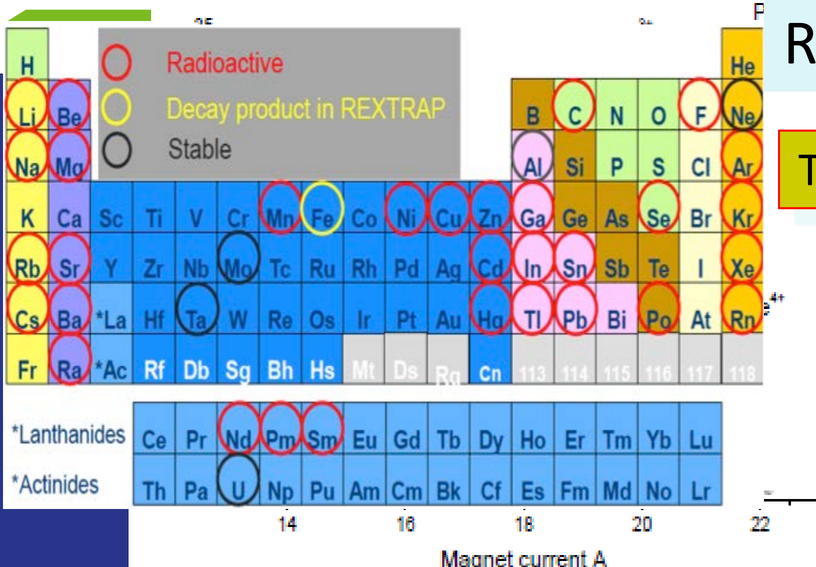
- Masses of ^{129,130}Cd determined with the Penning trap, ^{131}Cd with the MR-TO MS.
- New values are an important input to r-process simulations around the *A* = 130 abundance peak.

M. Wang *et al.*, Chinese Physics C **36**, 1603 (2012).

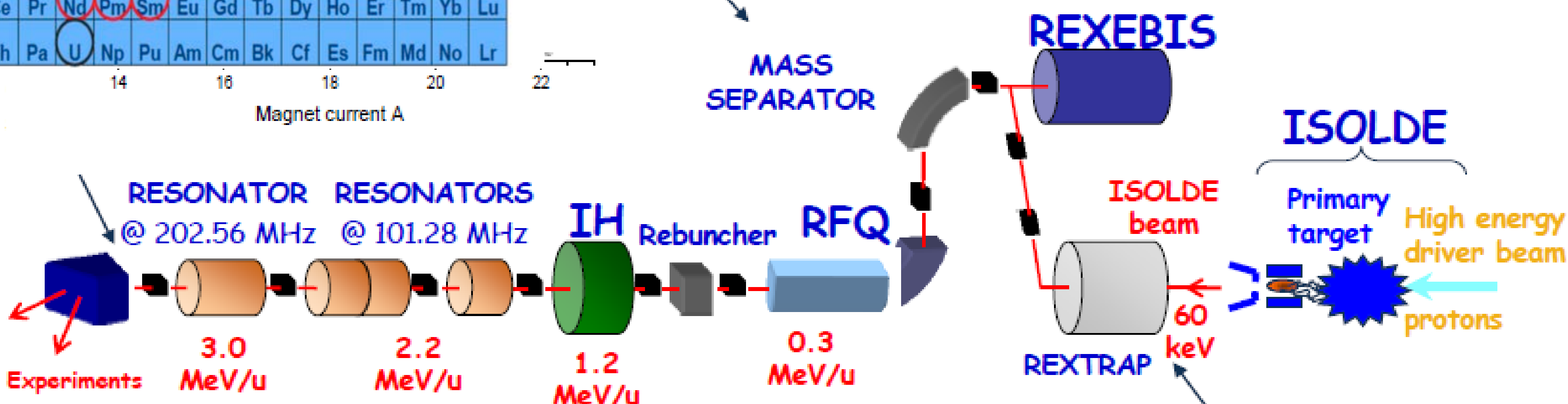
Post-accelerator: REX-ISOLDE

REX-ISOLDE started in 2001

Total efficiency : 1 -10 %

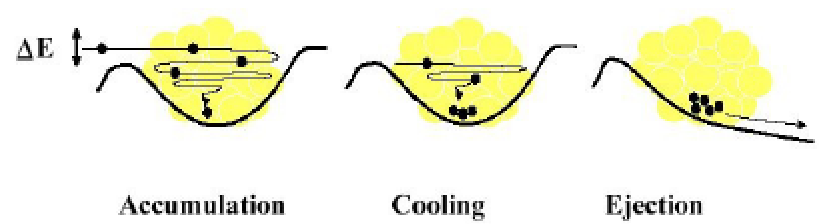


* charge breeding
* 1^{+} to $A/Q = 2 - 4.5$



* longitudinal accumulation and bunching
* transverse phase space cooling

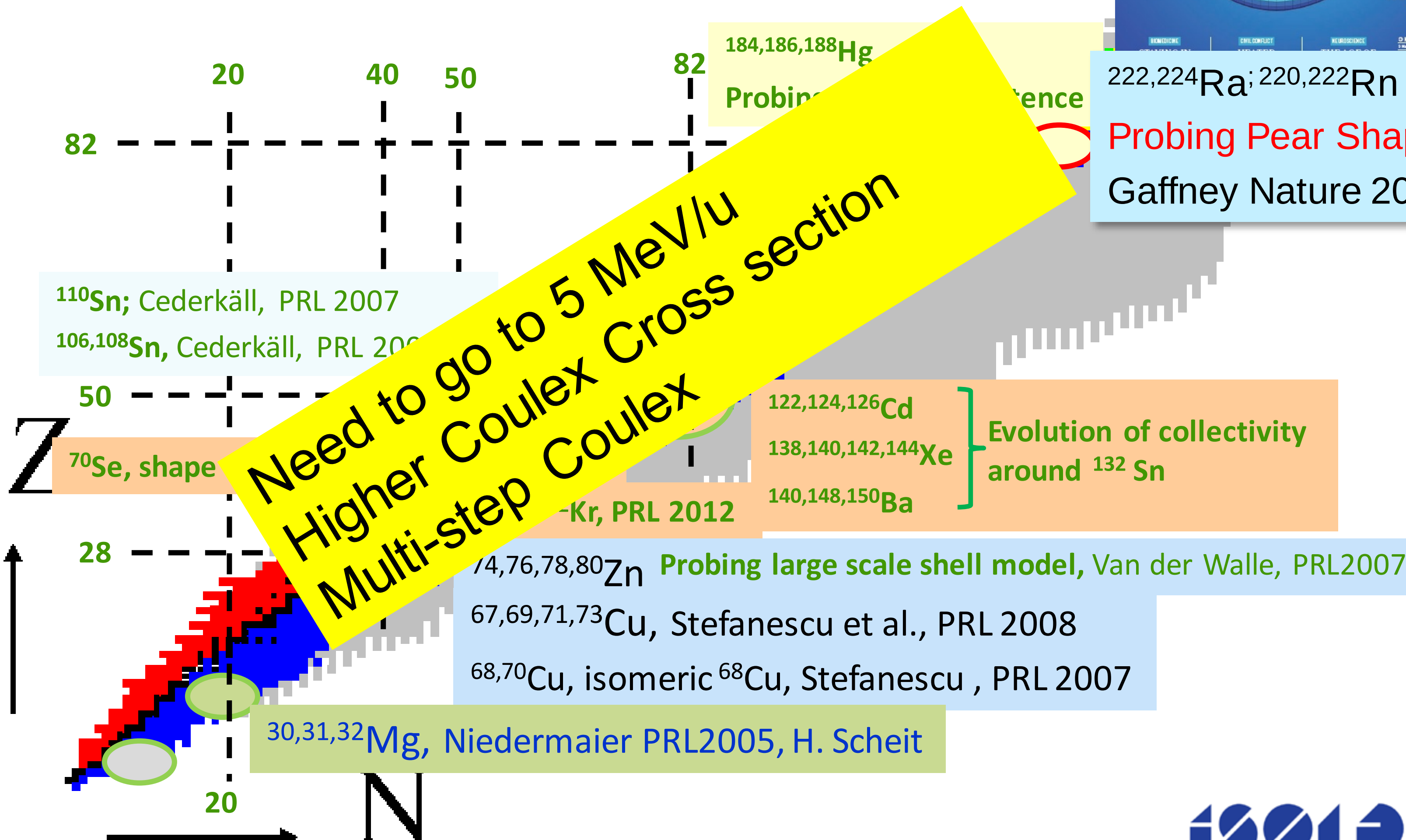
* 6 cavities
* 100 and 200 MHz, ~100 kW
* 300 keV/u to 3 MeV/u



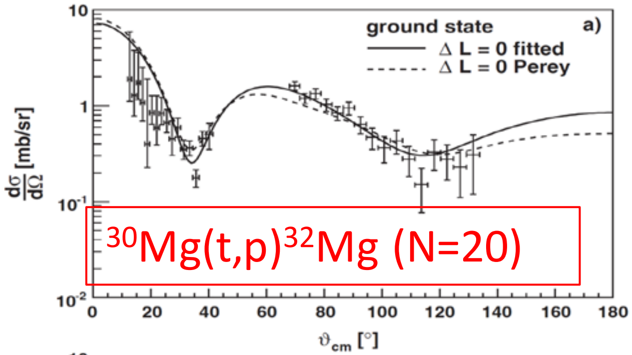
Physics program @ REX

Coulomb excitation with Miniball:

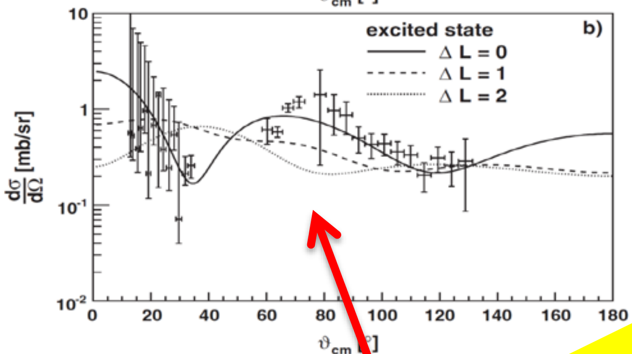
- collectivity versus individual nucleon behaviour



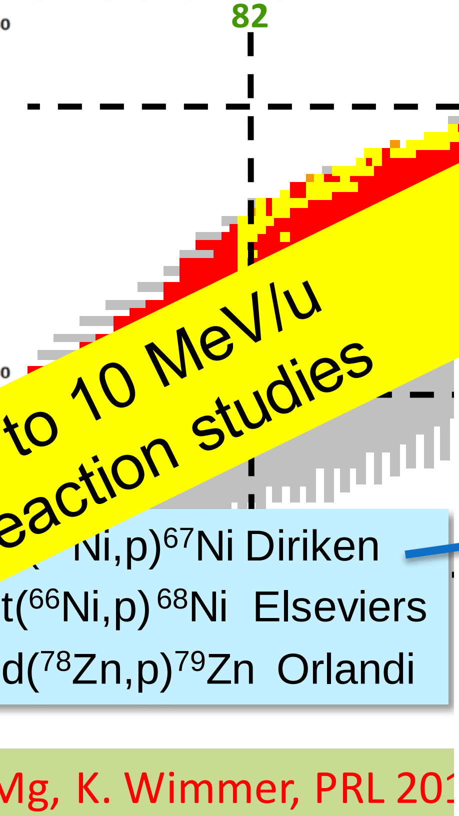
Transfer Reactions @ REX

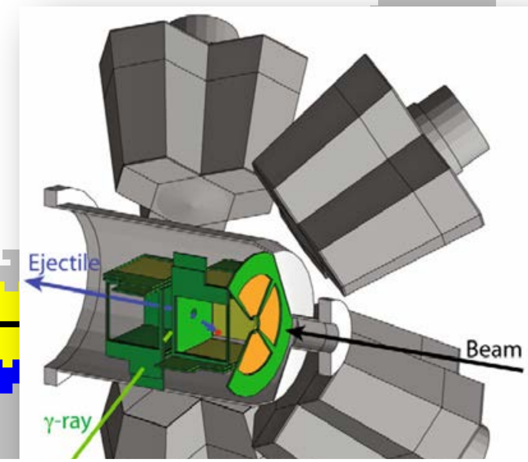


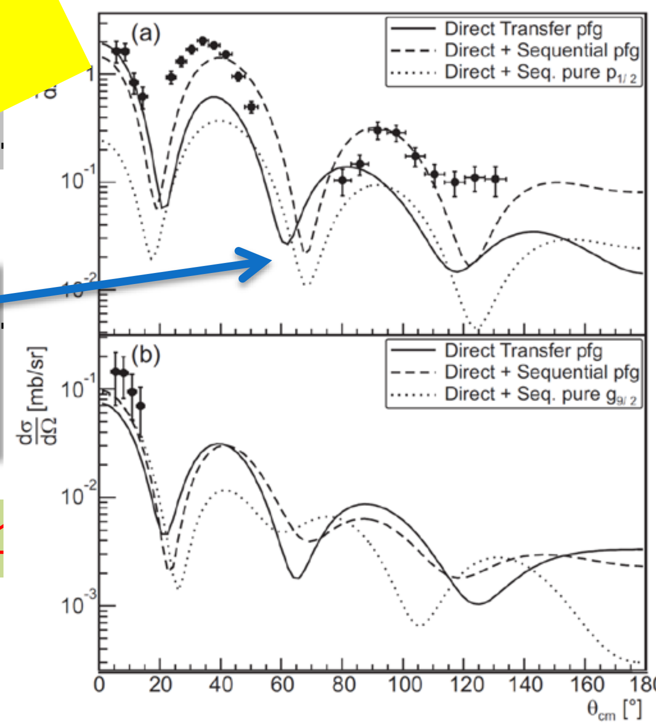
^{30}Mg(t,p)^{32}Mg (N=20)



- ...eaction studies:
- ...operties
- ...structures







t(^{72}Zn,p)^{73}Zn Hellgartner...
t(^{44}Ar,p)^{46}Ar Now...

Need to go to 10 MeV/u
Transfer reaction studies

...Ni,p)^{67}Ni Diriken
t(^{66}Ni,p)^{68}Ni Elseviers
d(^{78}Zn,p)^{79}Zn Orlandi

d(^{30}Mg,p)^{31}Mg, K. Wimmer, PRL 201...

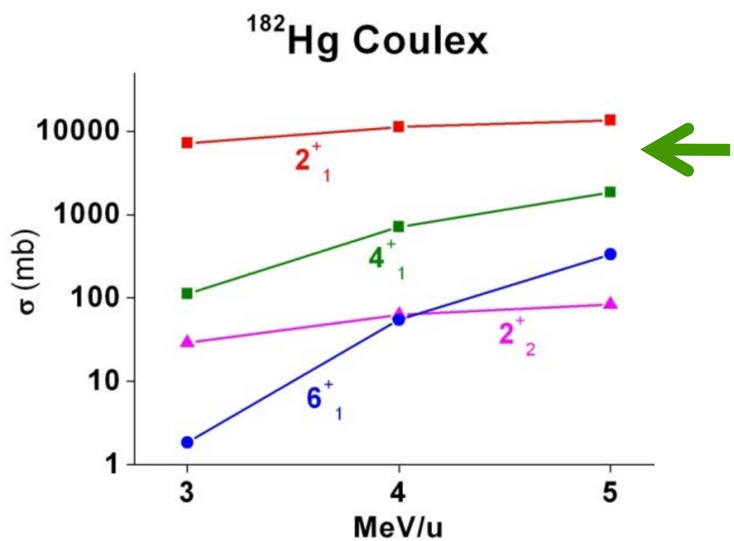
Light nuclei, halos & clusters
d(^{8}Li,p)^{9}Li*; Tengborn PRC (2011) d(^{9}Li,p)^{10}Li
d(^{11}Be,p)^{12}Be Johansen PRC (2013)

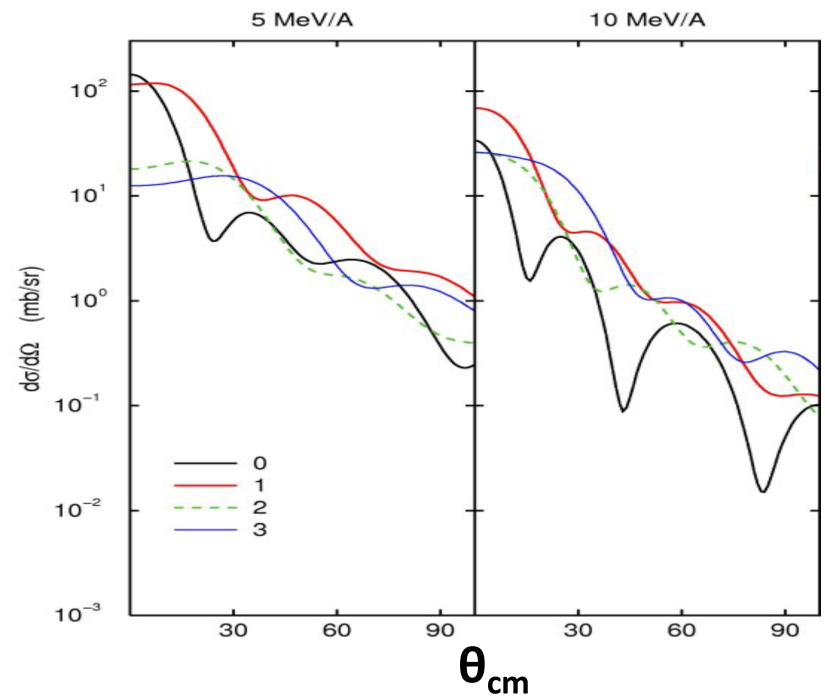
Advantages of HIE-ISOLDE

Design study: Intensity & Beam quality & Efficiency

Phase 1&2: Energy upgrade to 5.5 MeV /A → 10 MeV /A

$^{32}Mg(d,p)^{33}Mg$





- ❑ Access to a wealth of spectroscopic information
- ❑ From the absolutes intensities of $4^+/2^+$ (multistep coulex)

⇒Access to the sign of deformation

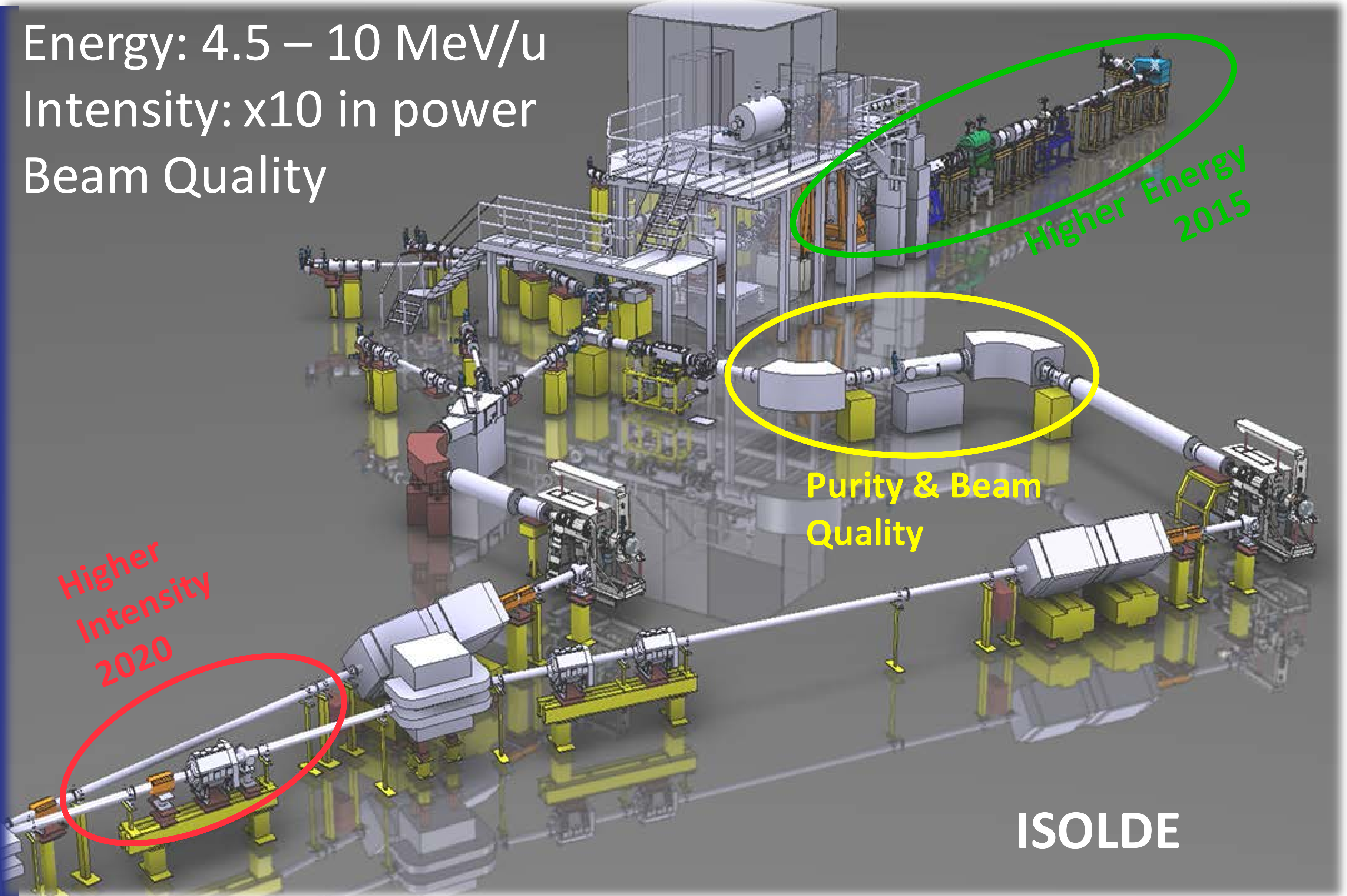
- ❑ Single particle information through the spectroscopic factors
- ❑ High energy needed to learn about the "l" transfer

HIE-ISOLDE Opportunities:

Reaction	Physics	Optimum energy
(d,p), (^{3}He,α), (^{3}He,d), (d,n),… transfer	Single-particle configurations, r- and rp-process for nucleosynthesis	10 MeV/u
(^{3}He,p), (d,α), (p,t), (t,p)	pairing	5-10 MeV/u
Few-nucleon transfer	Structure of neutron-rich and proton-rich nuclei	8 MeV/u
Unsafe Coulomb excitation	High-lying collective states	6-8 MeV/u
Compound nucleus reactions	Exotic structure at drip line	5 MeV/u
Coulomb excitation, g-factor measurements	Nuclear collectivity and single-particle aspects	3-5 MeV/u
(p,p'γ), (p,α), …	nucleosynthesis	2-5 MeV/u

The HIE-ISOLDE project

Energy: 4.5 – 10 MeV/u
Intensity: x10 in power
Beam Quality



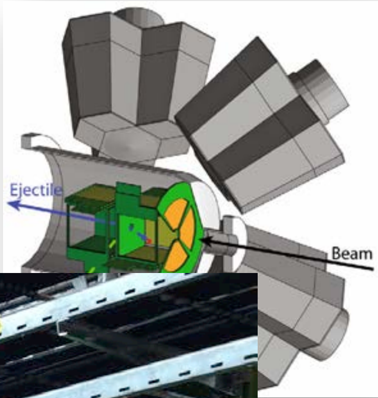
First Cryomodule 2015 for 4.3 MeV/u

2016: Installation of Cryomodules 1 & 2

HEBT installation

XT01 HW done. Alignment done. Hall probes & field regulation racks to be installed .
XT00/02: Finish installation End of June 2015.
XT03 will be kept with complete infrastructure but without elements.

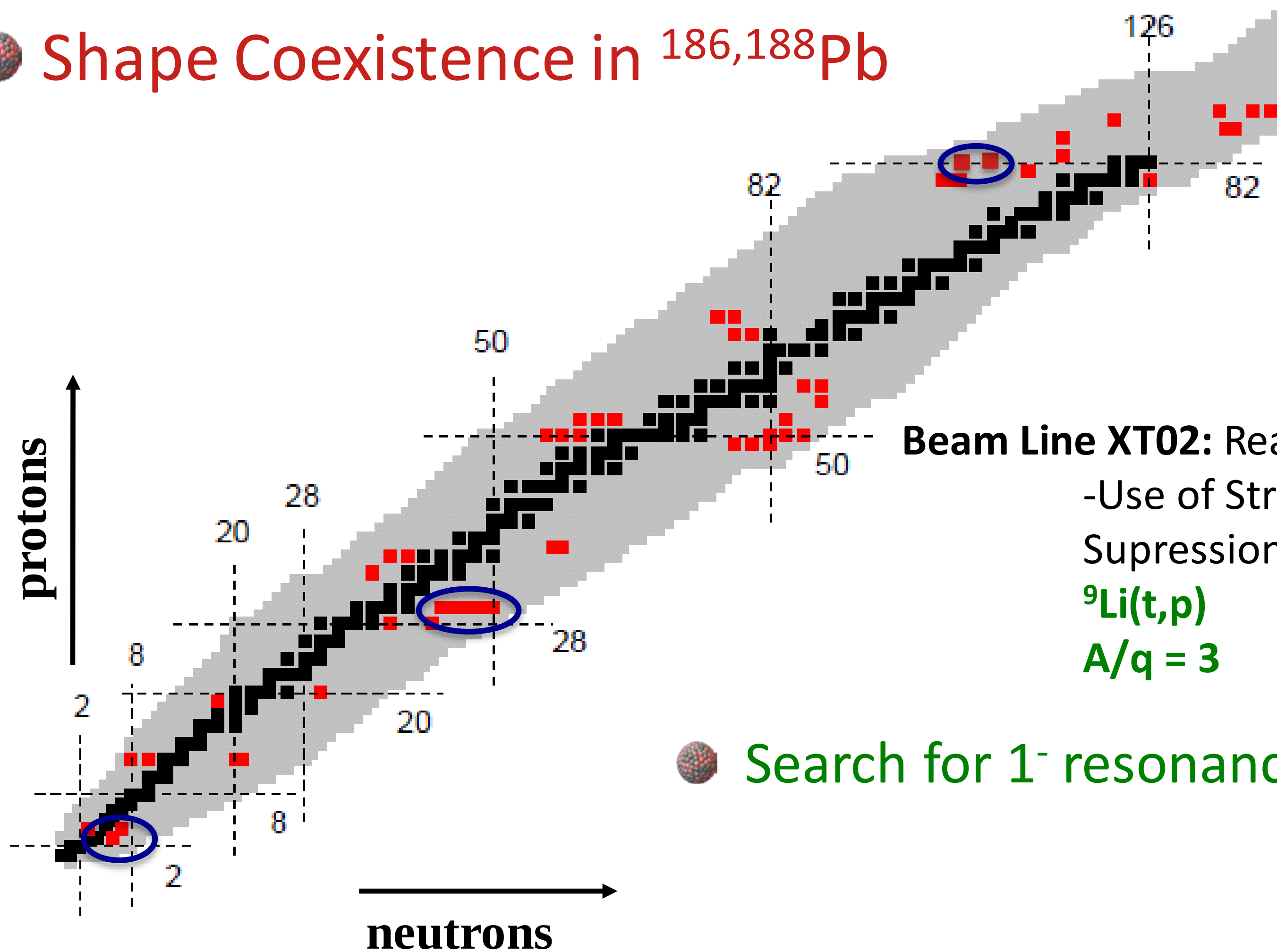
Installation of experiments



First 2015 experiments @ HIE-ISOLDE

Beam line XT01

- Collectivity versus Single Particle in Zn region
- Shape Coexistence in $^{186,188}Pb$



Beam Line XT02: Reaction experiment

-Use of Stripper foils (^{12}C,^{18}O)

Supression $10^{-5} – 10^{-6}$

$^{9}Li(t,p)$

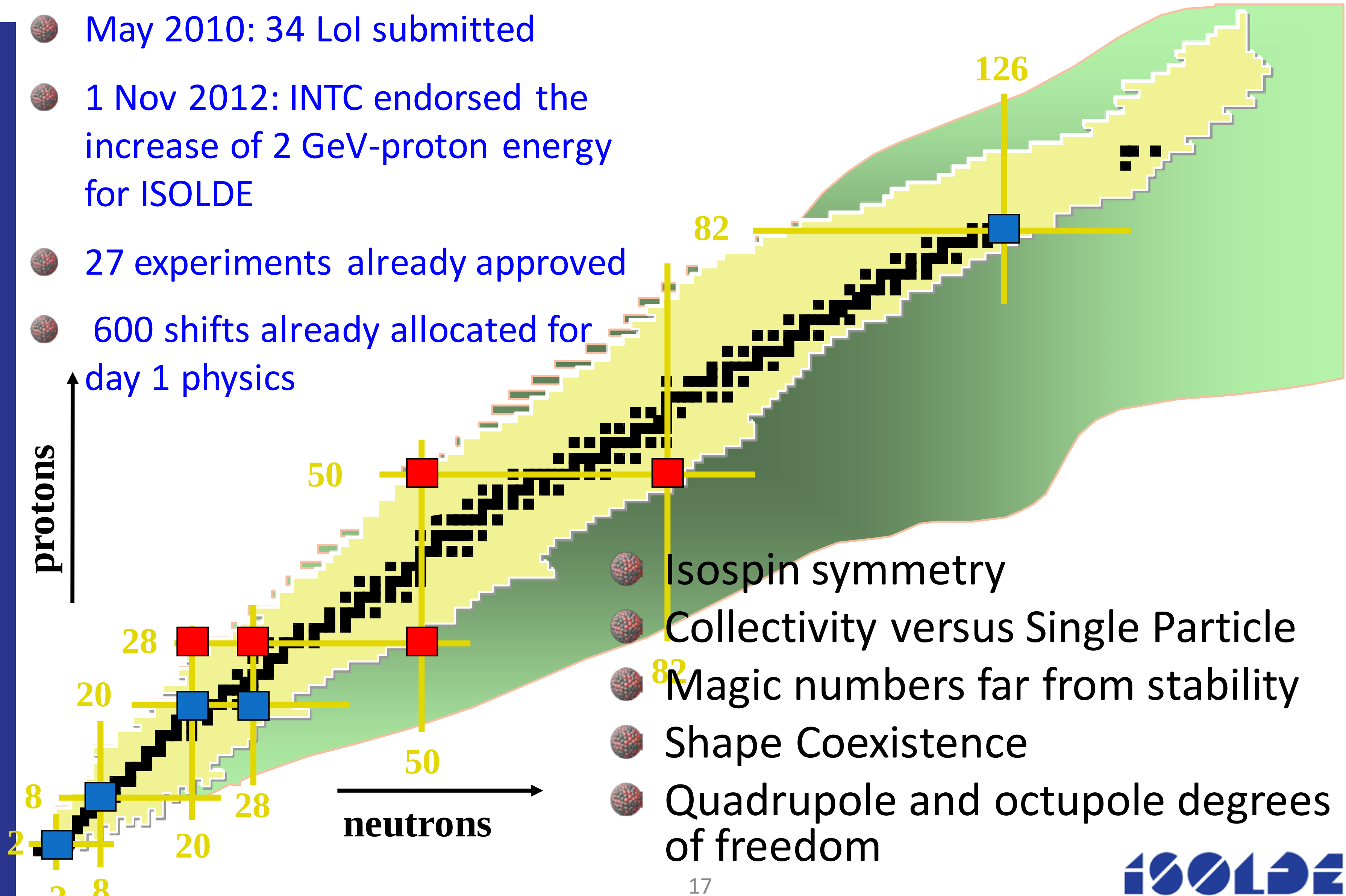
A/q = 3

- Search for 1^{-} resonances in ^{11}Li

ISOLDE

Physics @ HIE-ISOLDE

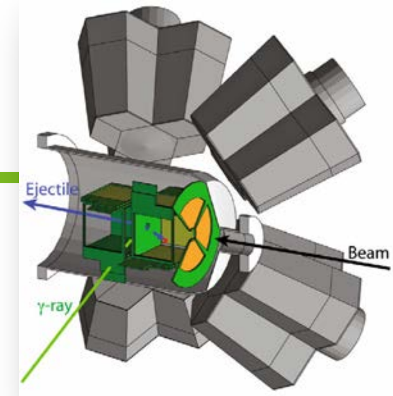
- May 2010: 34 LoI submitted
- 1 Nov 2012: INTC endorsed the increase of 2 GeV-proton energy for ISOLDE
- 27 experiments already approved
- 600 shifts already allocated for day 1 physics



- Isospin symmetry
- Collectivity versus Single Particle
- Magic numbers far from stability
- Shape Coexistence
- Quadrupole and octupole degrees of freedom

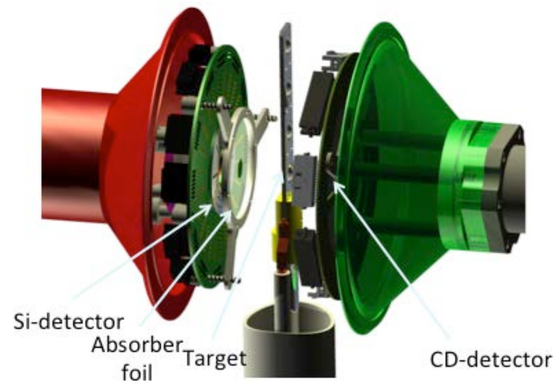
ISOLDE

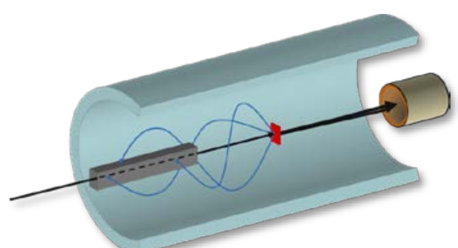
Instrumentation

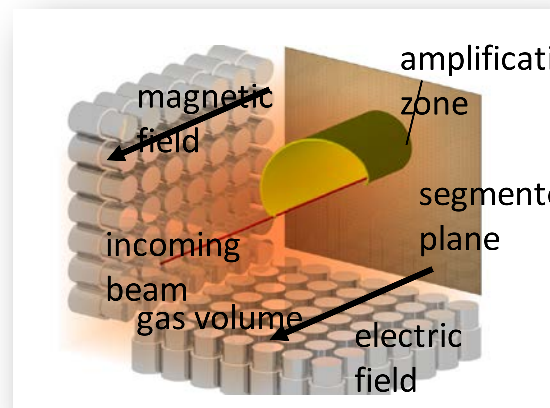


Approved

- Miniball + T-REX (upgrade planned) : COULEX + Transfer — 22
- Multipurpose reaction chamber — 2
- CORSET chamber for fusion-fission reactions — 1
- SPEDE: added to Miniball+T-REX — 1
- ISOL Solenoidal Spectrometer: ISS (Hall →@ TSR)
- MAYA/ACTAR: resonant scattering + transfer — 1
- Zero type spectrometer
- TSR storage ring



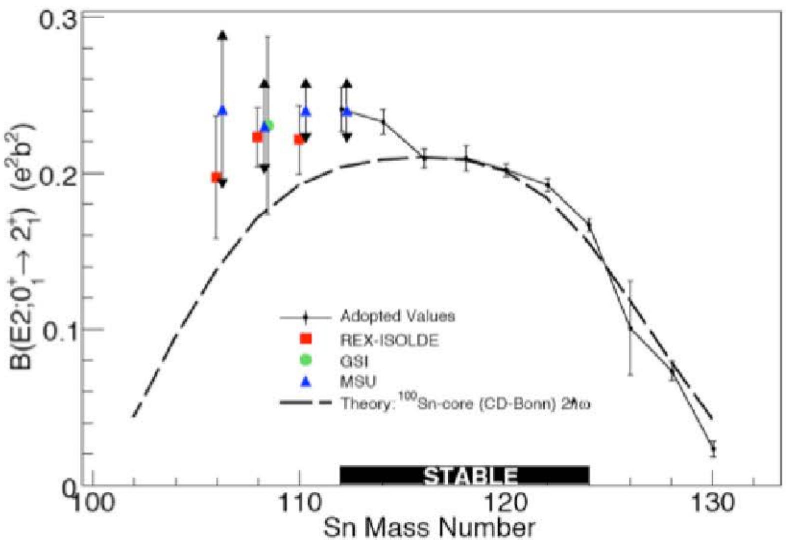




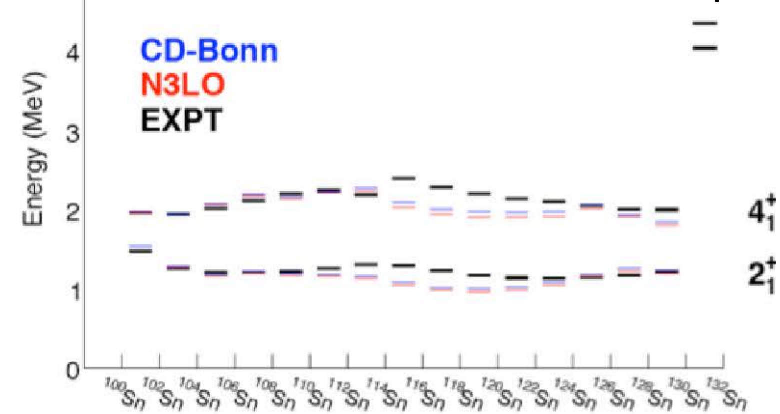
2016 Day 1 experiments

IS561

Transfer Reactions and Multiple Coulomb Excitation in the ^{100}Sn Region



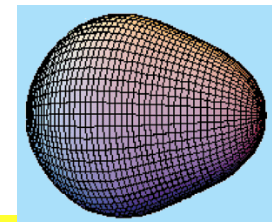
Large deviations of B(E2) from theory observed in neutron deficient Sn isotopes



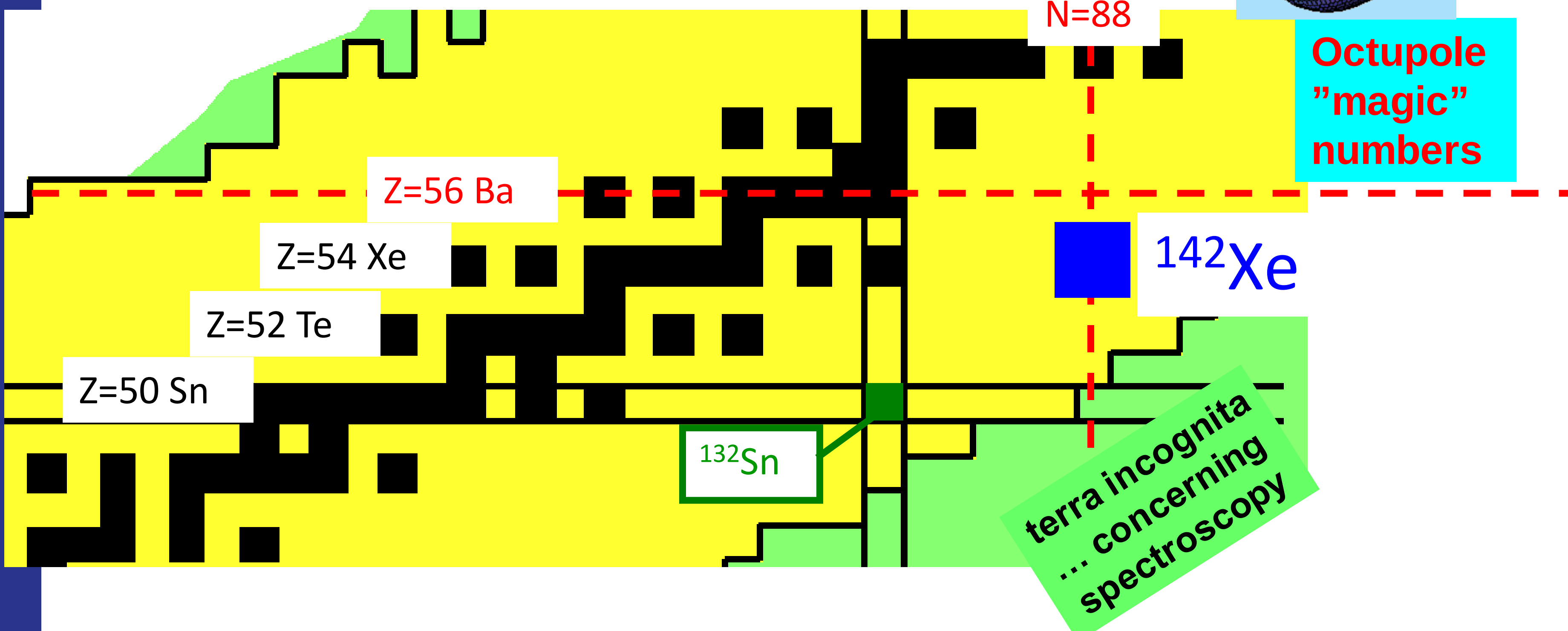
- Coulomb excitation at 4.5 MeV/u for population of the 2^+ and 4^+ states in ^{110,108,106}Sn and when feasible in the lighter even-mass isotopes.
- Coulomb excitation at 4.5 MeV/u of the even-mass Cd istopes with focus on expanding measurements to ^{100}Cd.
- Transfer reactions to one-quasi particle dominated states.

IS548: Evolution of quadrupole and octupole collectivity north-east of ^{132}Sn: the even Xe

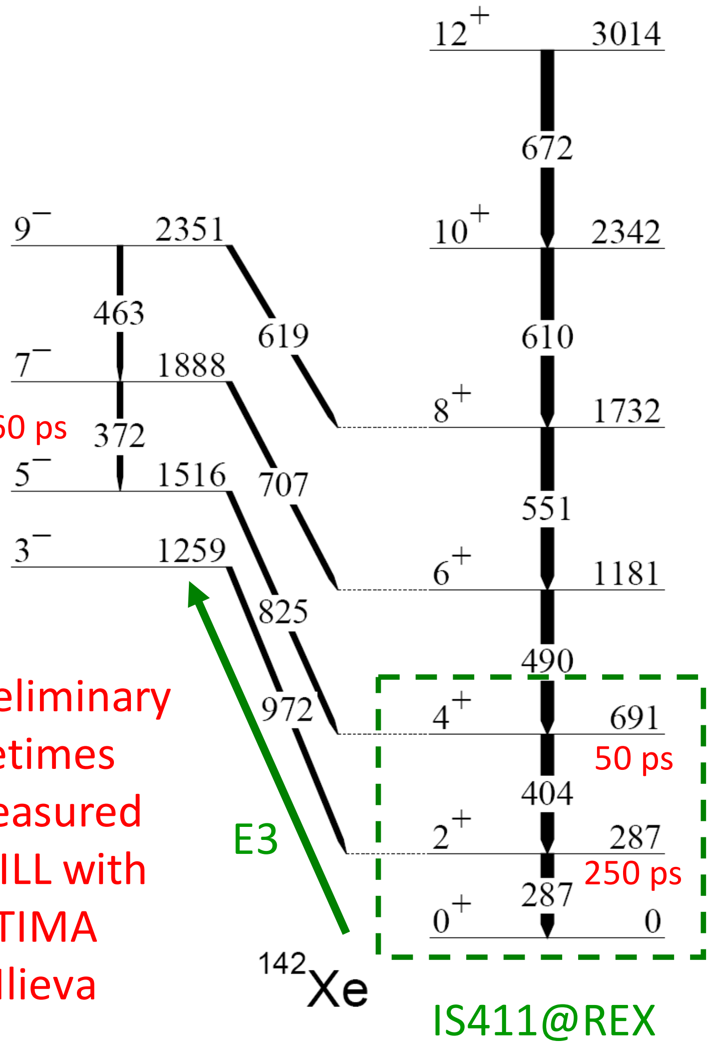
- **Neutron-rich Xe isotopes:**
  - **regular behaviour at low spin/excitation energy (IS411)**
  - **onset of octupole collectivity ($\nu f_{7/2} \leftrightarrow \nu i_{13/2}$)**



Octupole "magic" numbers



IS548: Evolution of quadrupole and octupole collectivity north-east of ^{132}Sn: the even Xe



Preliminary lifetimes measured at ILL with FATIMA
S. Ilieva

- ... we will have the D_0 value soon for ^{142}Xe from a fast timing experiment at ILL
  The long lifetime points towards a decreasing D_0 from ^{140}Xe to ^{142}Xe !?!
- new (or better) lifetimes may come from a recent fast timing experiment at ANL

HOWEVER

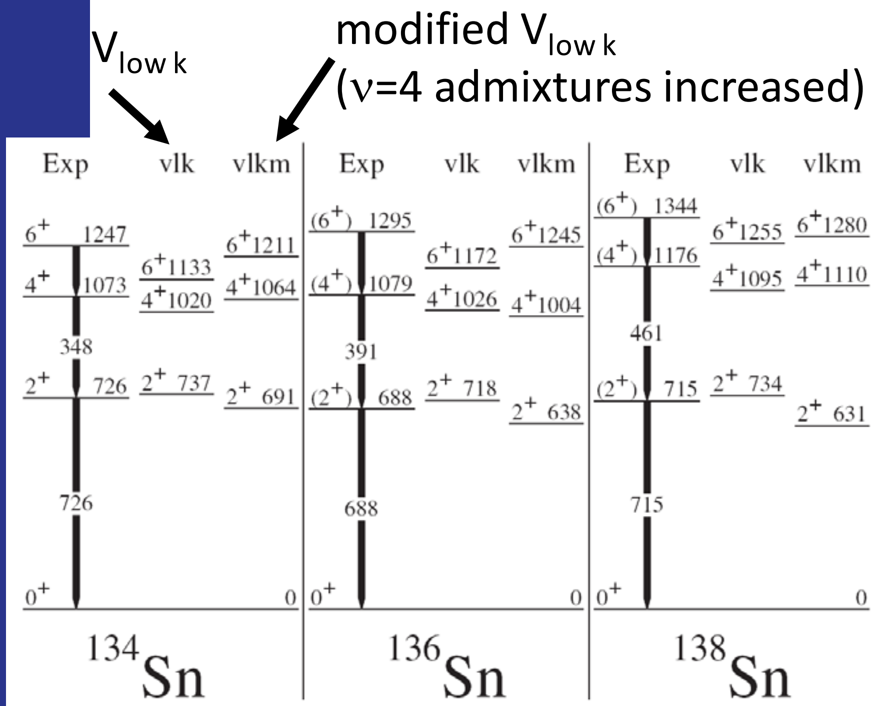
- No B(E3) values known in Xe above N=82!

... can be determined by Coulomb excitation only

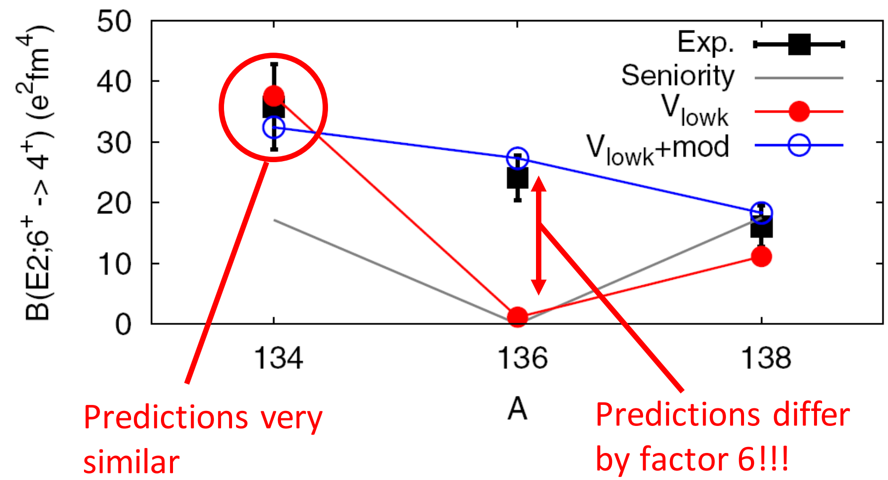
<u>Physics aims</u>

- transition and diagonal quadrupole MEs for higher spin states ($I^\pi > 4^+$)
- B(E3) values

IS549: Coulomb excitation of neutron-rich ^{134,136}Sn isotopes



G.S. Simpson et al., PRL 113, 132502 (2014)



Physics aims

- **transitional quadrupole MEs**
  - ➔ **B(E2) values**
- **diagonal E2 MEs**
  - ➔ **quadrupole moments Q_2**

... for 2^+ and 4^+ states in ^{134,136}Sn

Only known B(E2, 0 ➔ 2) value
... but large error:
^{134}Sn: 0.029(5) e^2b^2
R. L. Varner et al., EPJ A 25, s01, 391 (2005)

6^+ is isomeric!!
➔ Coulomb excitation will end at 4^+ state!

IS607

Origin of heavy proton-rich nuclei

- Beam energies from 3.6 - 5 MeV/u to cover stellar temperatures for $^{59}Cu(p,\alpha)$ reaction from 2.5 - 4 GK
- 2.1E5 ^{59}Cu ions per second on CH_2 target

Competition between (p,α) and (p,γ)

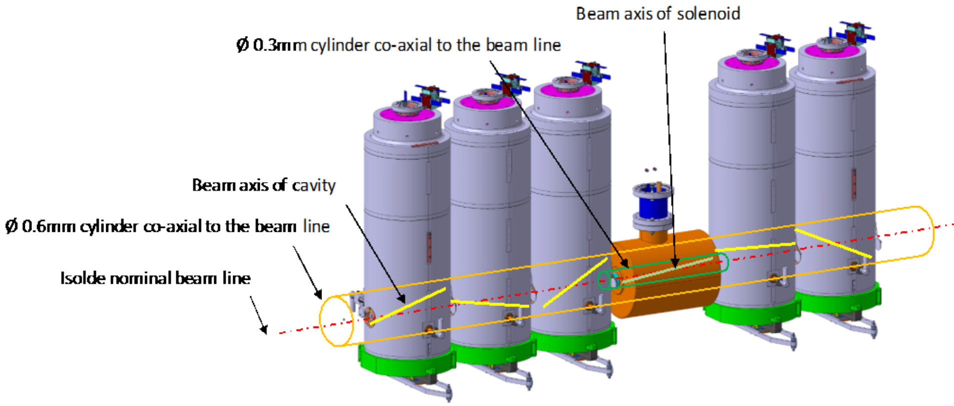
HIE ISOLDE allows **first** measurement of key reaction $^{59}Cu(p,\alpha)$, and with **highest** beam intensity available world-wide

C. Fröhlich (p-process workshop, Cyprus, 2015)

high temperature (above ~3 GK)
low temperature

Status as of June 2016

- Rex-ISOLDE fully operational
- HIE-ISOLDE cryo modules 1 & 2 installed and fully aligned
  - LN2 temperature achieved early June
  - 4K nominal temperature to be achieved today
- Machine commissioning to begin mid-August
- Ready for Physics campaign @ 5.5 MeV/u in September



Conclusions

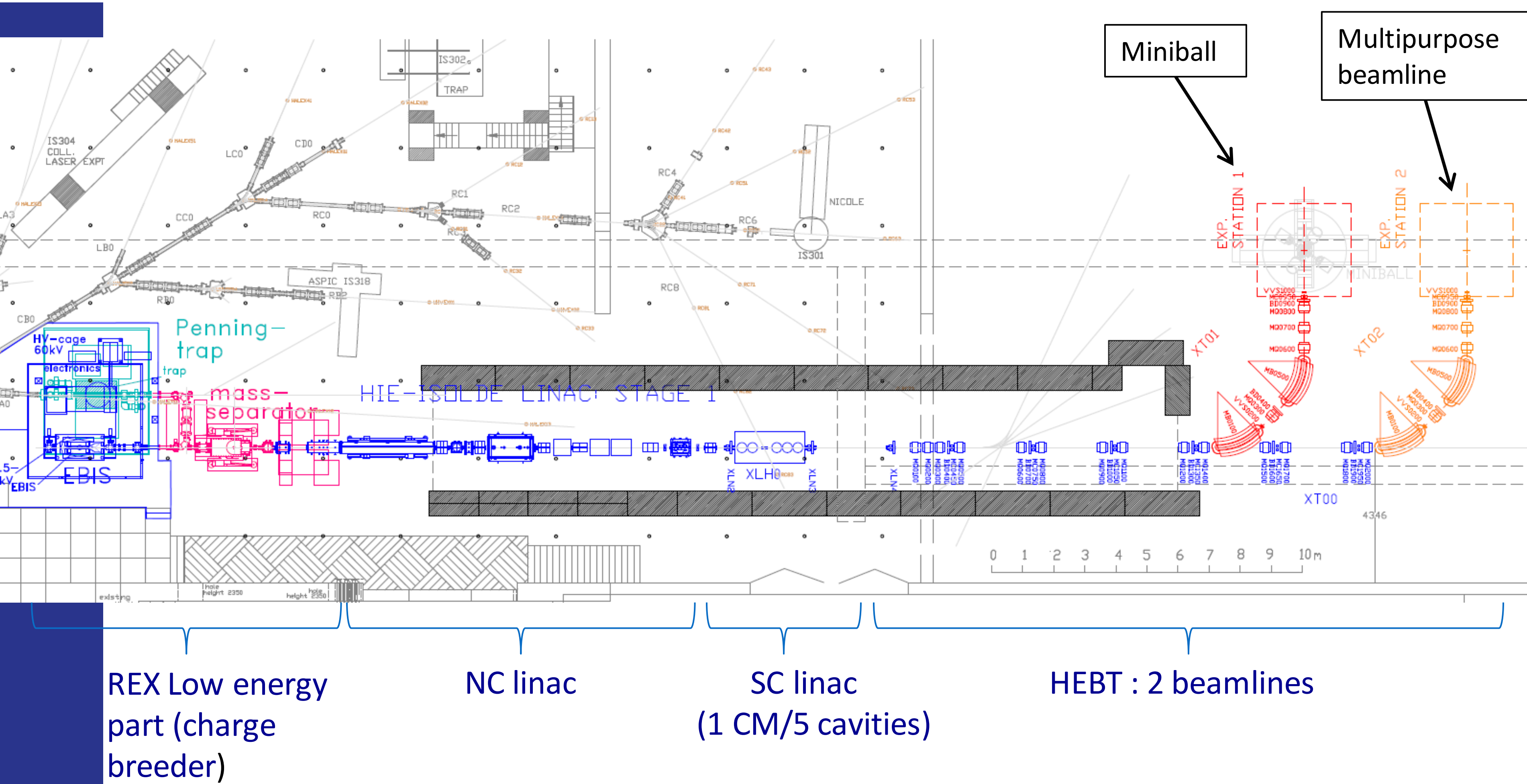
- Plenty of challenging physics at ISOLDE and waiting for the starting of HIE-ISOLDE!
- Many new groups and devices have been attracted by the increase of energy of the post-accelerated beams.
- **HIE-ISOLDE Phase 1: Start of the 4.3 MeV/u, physics program achieved in autumn 2015. Reaching 5.5 MeV/u in summer 2016.**
- **Vibrant Day 1 nuclear physics program in 2016**

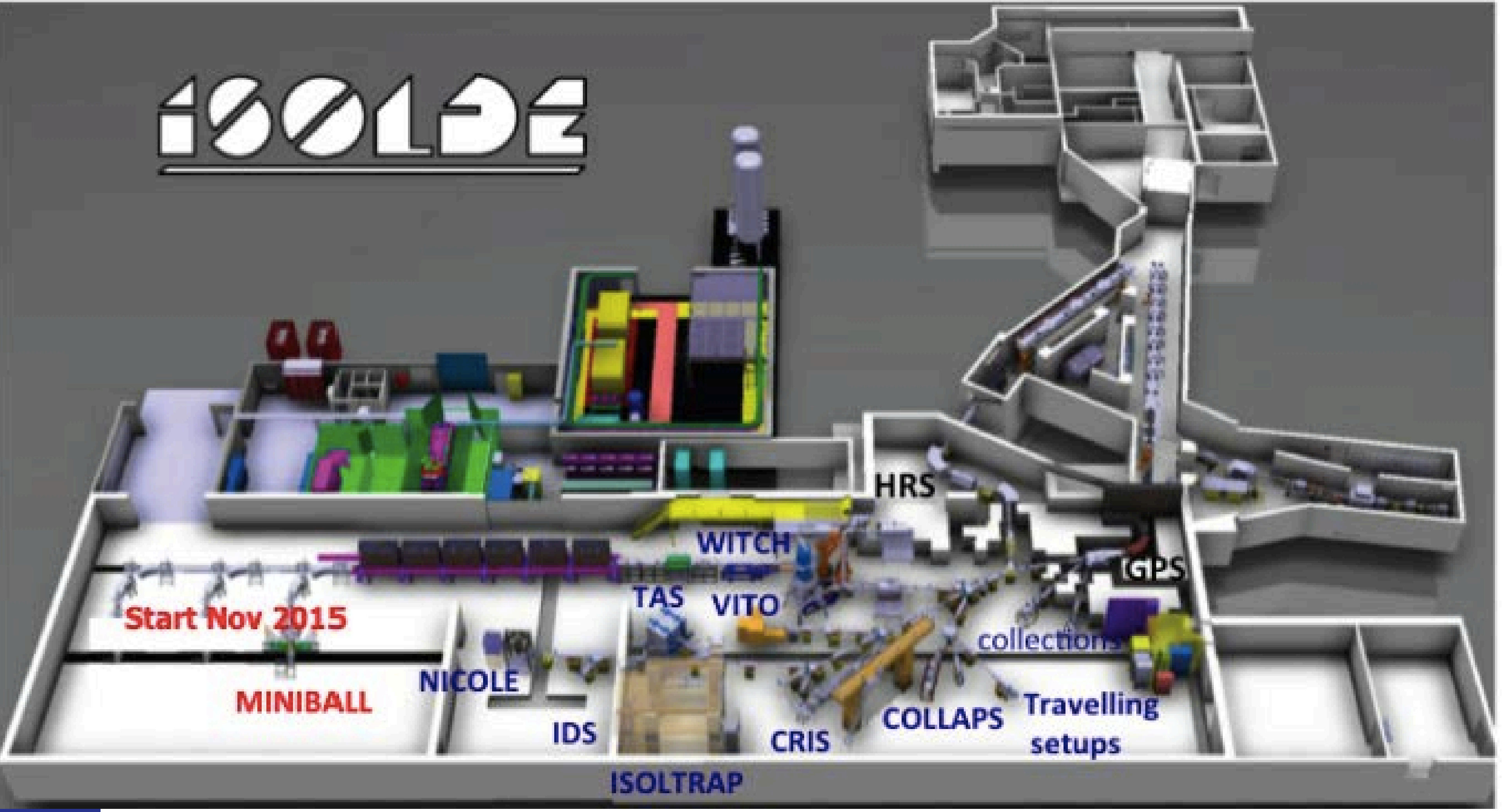
Thanks for your attention !

HIE-ISOLDE Beam parameters

Parameters HIE-ISOLDE Stage1	Value	Units
Mass to charge ratio A/q	2.5 to 4.5	
Output kinetic energy for A/q 4.5	1.2 – 5.5	MeV/u
Output kinetic energy for A/q 2.5	1.2 – 8.6	MeV/u
RF base frequency	101.28	MHz
RF period	9.87	ns
Max. rep. rate (NC linac)	50	Hz
Max RF pulse length (NC linac)	2	ms
EBIS pulse length	50 – 500	us
Transverse normalised emittance (90%)	0.07 (rms), 0.3 (90%)	mm.mrad
Longitudinal emittance (86%)	0.35 (rms), 1.5 (86%)	ns.keV/u
Energy spread	< 0.6 % (FWHM)	

HIE-ISOLDE 2015

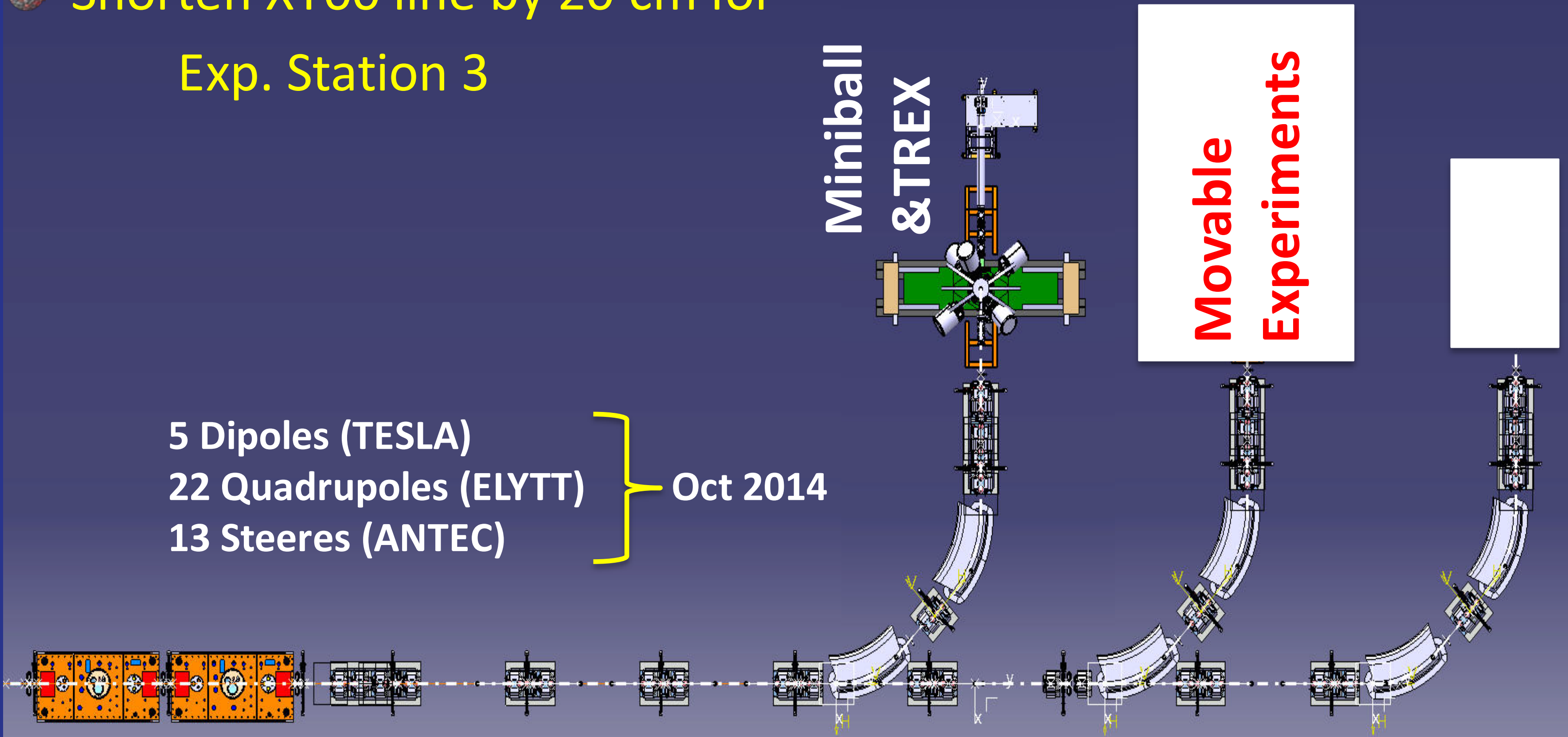



HRS
WITCH
GPS
TAS
VITO
Start Nov 2015
collections
NICOLE
MINIBALL
Travelling
setups
IDS
COLLAPS
CRIS
ISOLTRAP

Proposed Three beamlines

- Layout can accommodate 3rd experimental station
- Fully modular (3x repeat of same solution)
- Shorten XT00 line by 20 cm for

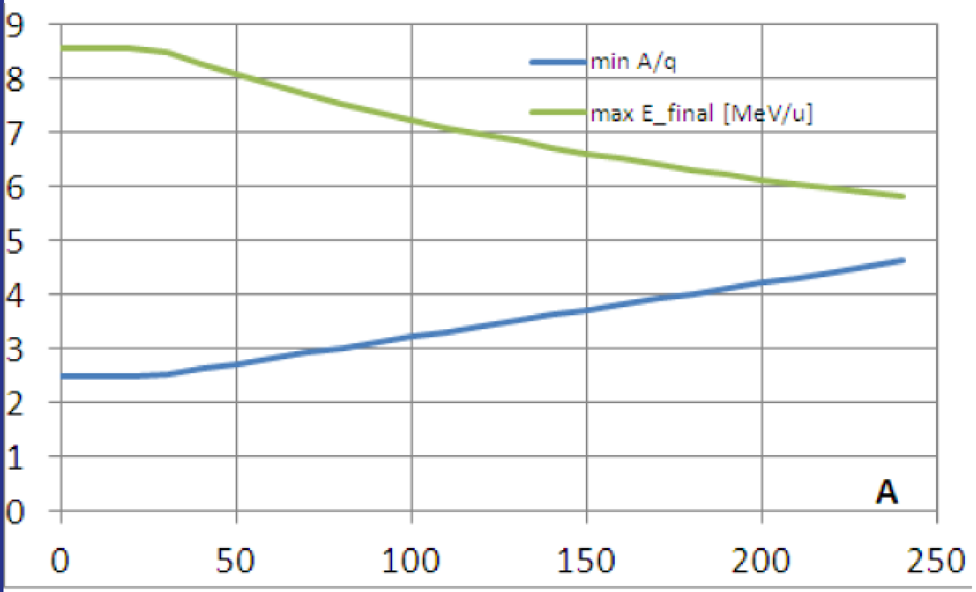
  Exp. Station 3

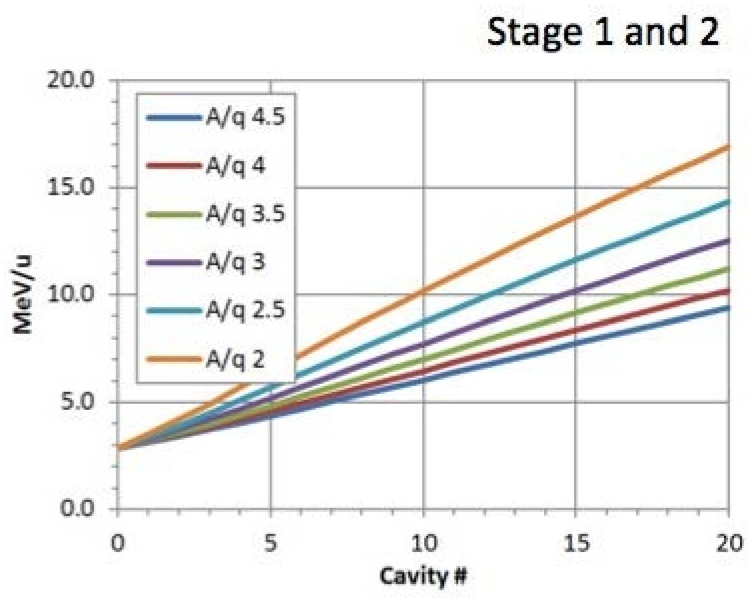


Beam Parameters

- A/q = 4.5 and energy 5.5 MeV/u are the nominal parameters of the facility.
- Higher energy and lower A/q ➔ Decrease in efficiency

  Increase in breeding time





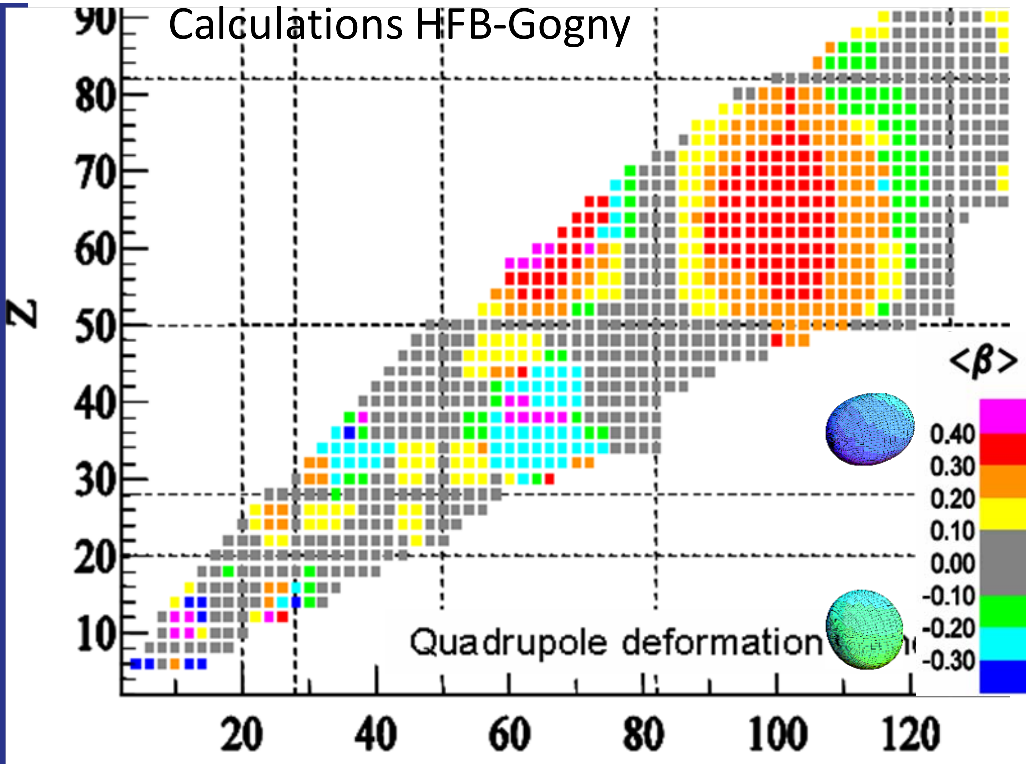
E_final = 2.9 + 14/(A/q) [MeV/u]

Assuming 6 MV/m

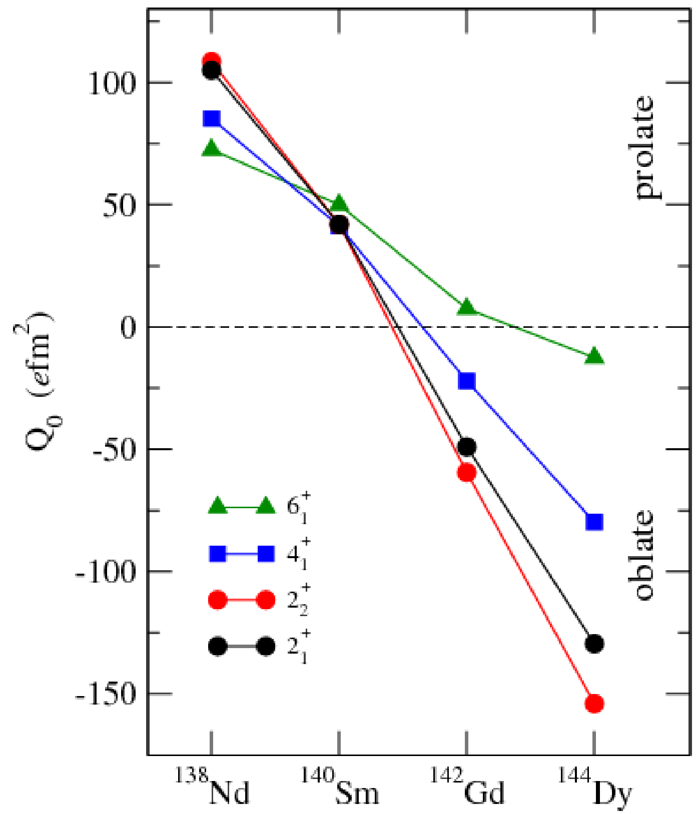
A/q = 4.5 E =1. 2 – 5.5 MeV/u

A/q = 2.4 E= 1.2 - 8.6 MeV/u

Shape Coexistence



Calculations predict transition from prolate to oblate shape with increasing proton number along N=78

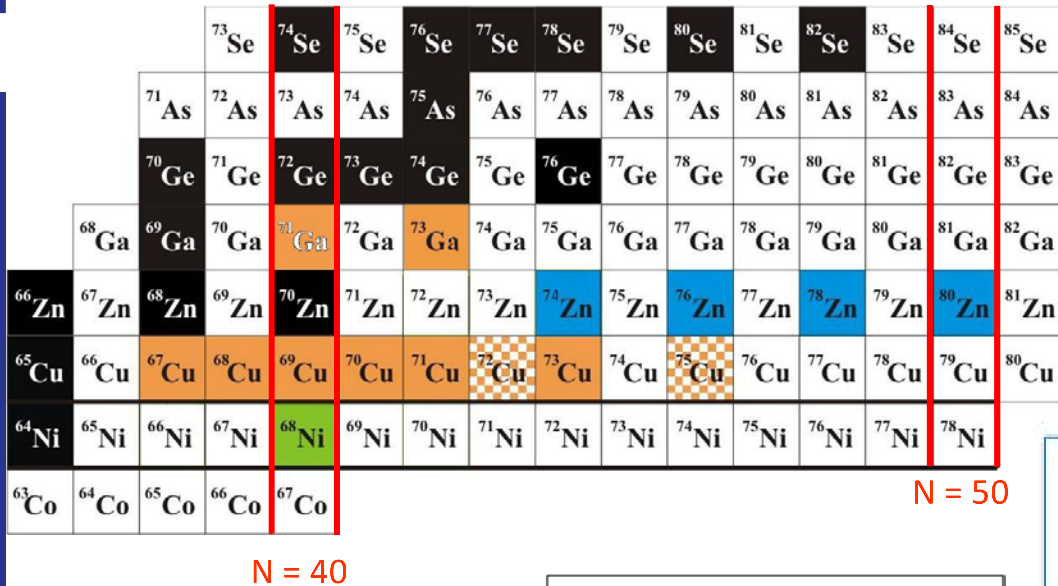


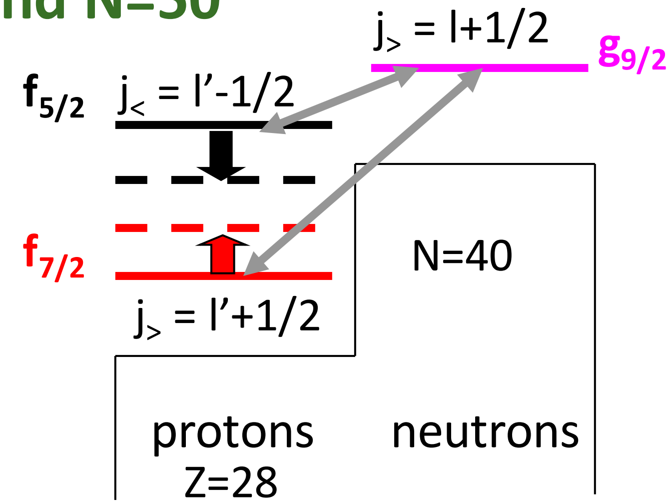
Regions of shape transitions and coexistence
- ➢ measurement of collective properties
- ➢ stringent test of nuclear structure theory

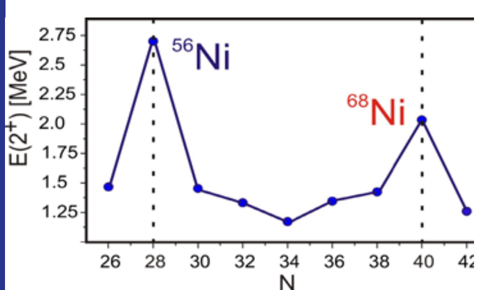
Experimental:
- ➢ Lifetime measurements ⇒ B(E2)
- ➢ Coulomb excitation ⇒ B(E2), Q_s

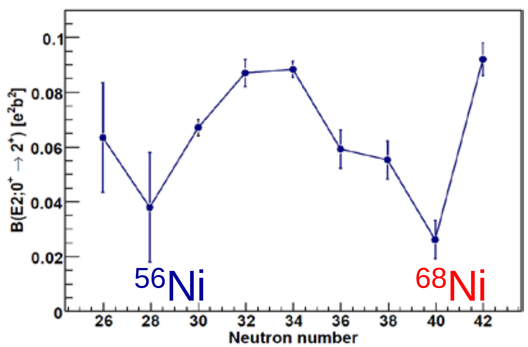
ISOLDE

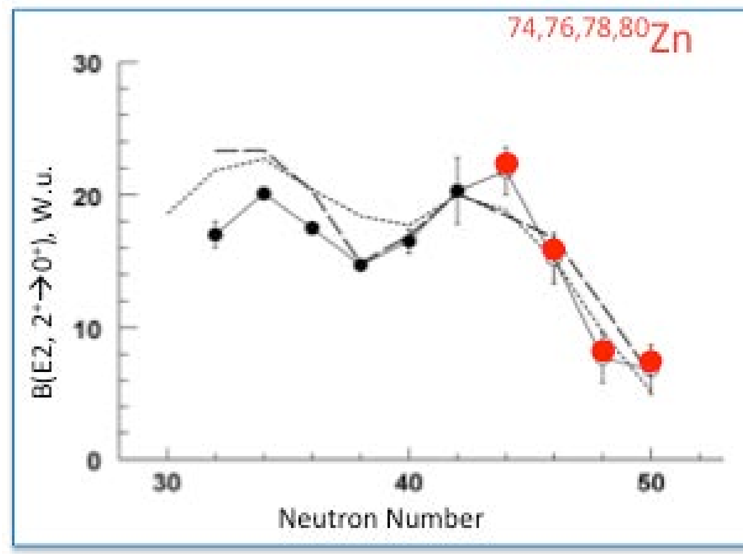
Evolution of collectivity around N=40 and N=50





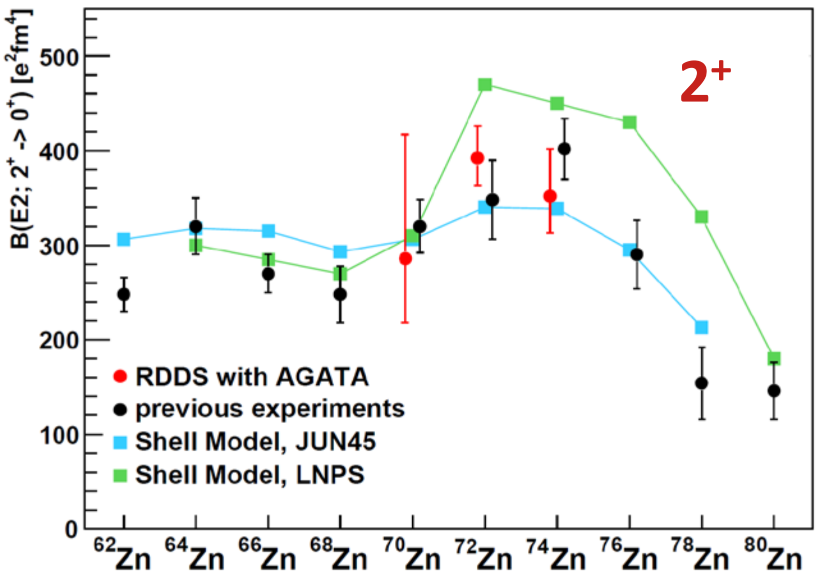




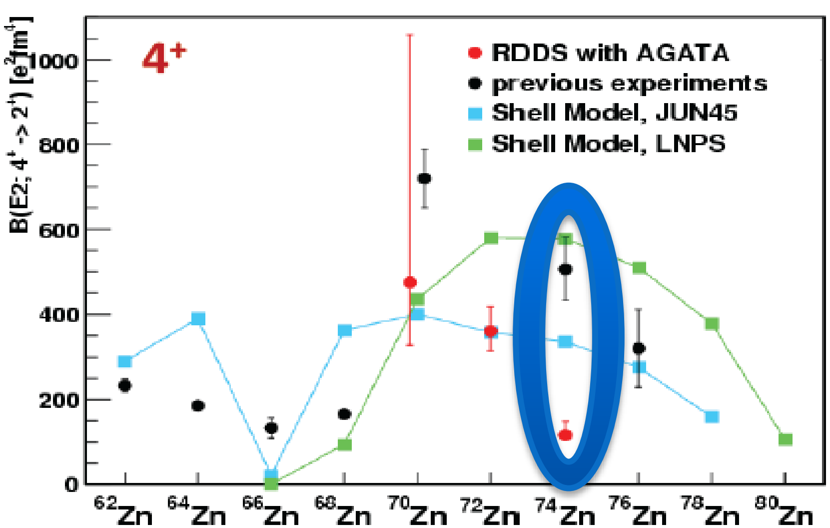


- ❑ What is the nature of the N=40 shell closure?
- ❑ How large is the N=50 shell gap at ^{78}Ni?
- ❑ What does the effective proton-neutron interaction look like ?

Previous Measurements of Zn Isotopes

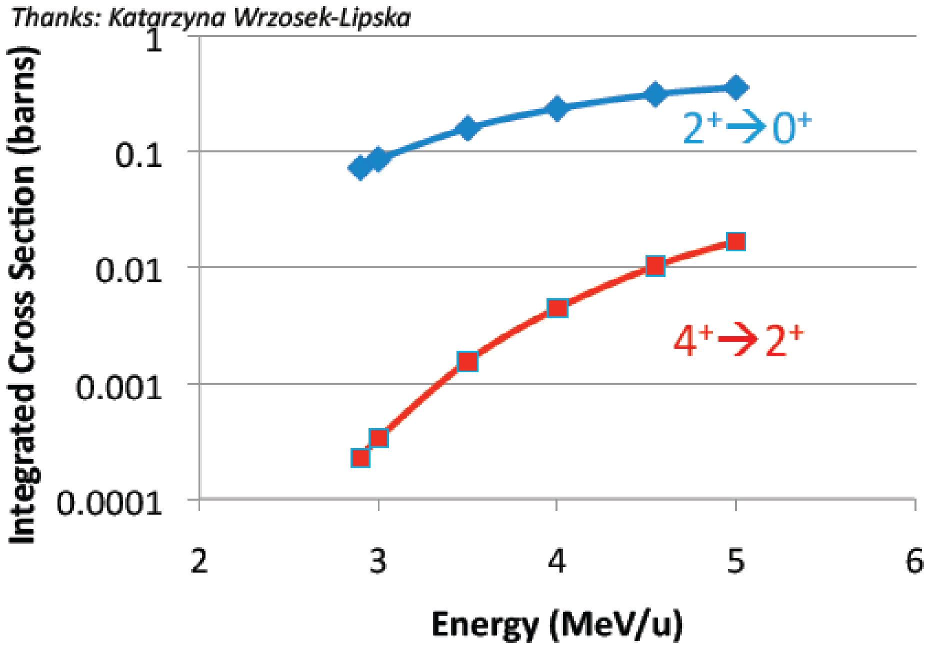


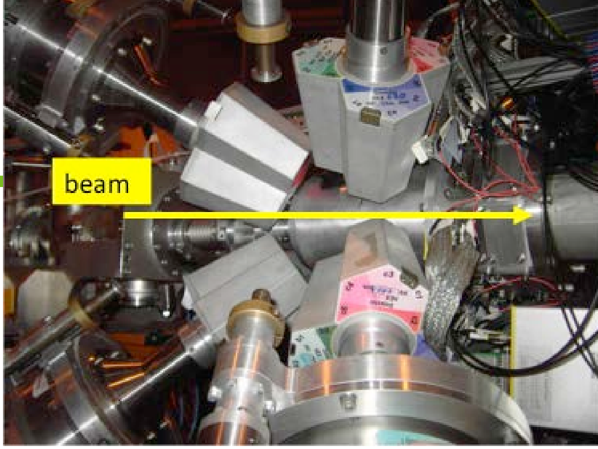
- ✓ Maximum collectivity at ^{74}Kr
- ✓ Agreement between previous results from Miniball and AGATA [PRC87 (2013) 054302]



- ✓ Large disagreement for ^{74}Zn B(E2)
- ✓ The reduced value for ^{74}Zn is not predicted by any model.
- ✓ Remeasure the half-life of 4^+ state is needed.

Coulomb Excitation $^{74\text{-}80}Zn$ @ 4.5 MeV/u





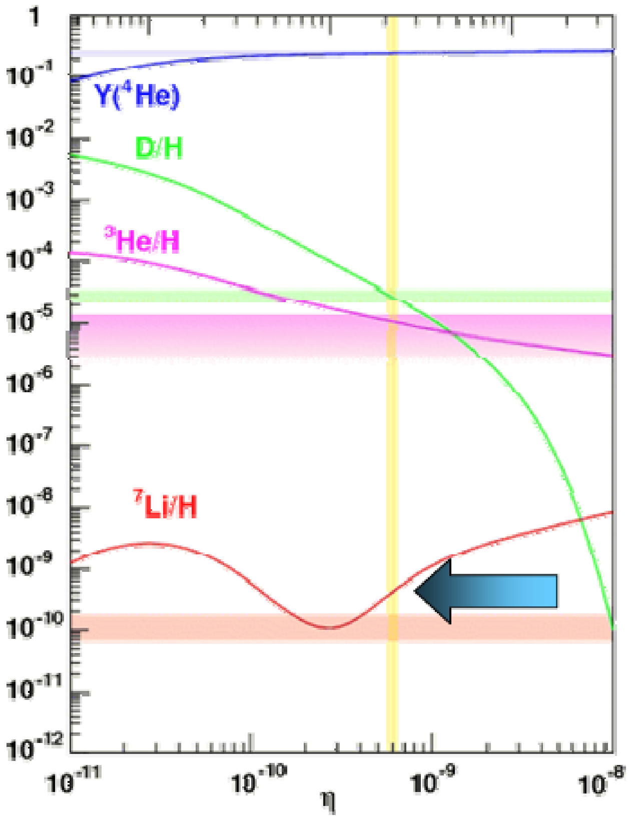
- Measure B(E2: $4^+\rightarrow2^+$) and B(E2: $6^+\rightarrow4^+$)
- Clarify discrepancies with half-lifes measurements
- Observation of 4^+ in ^{80}Zn
- Identification of non Yrast states

UC Target + quartz trasfer line

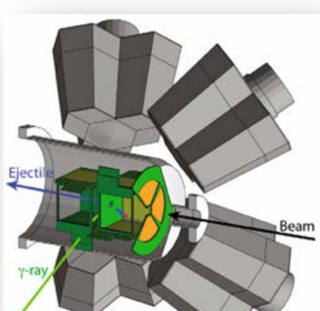
- Expected Zn intensity: $10^6 – 10^4$ pps
- Laser Ionization: RILIS
- Expected Ga and Rb contamination
- Beam energy 4.55 MeV/u

Energy (MeV/u)	Intensity (pps)	$2^+\rightarrow0^+$	$4^+\rightarrow2^+$	$6^+\rightarrow4^+$	Total shifts
4.55	$5\cdot10^5$	$6.9\cdot10^4$	2235	n.n.	3
4.55	$5\cdot10^5$	$5.4\cdot10^4$	1470	n.n.	3
4.55	10^5	5100	37(**)	0.15 (**)	12
4.55	10^4	130	20 (*)	0.00012 (*)	12

Adressing the ^{7}Li cosmological Problem (IS554)



Observed values represented by bands, predicted values represented by lines.



A factor of 4 in abundance of primordial ^{7}Li abundance while good agreement of ^{2}H, ^{3,4}He.

Theory $$^{7}\mathrm{Li/H} = 5.12\,^{+0.71}_{-0.62} \times 10^{-10}$$

Observation $$^{7}\mathrm{Li/H} = 1.23\,^{+0.34}_{-0.16} \times 10^{-10}$$

Explore the alternative of resonance enhancement of nuclear reactions

➔Via ^{7}Be(d,p)2α

The destruction of ^{7}Be can be high due to the narrow resonance in ^{9}B at 16.7MeV ($5/2^{+}$)

- This resonance can be very strong
- At the limit of quantum mechanically allowed value for the deuteron separation width
- Er = 170 -220 keV ;
- Deuteron Separation width Γ_d = 20 – 40 keV
- Achieved if the interaction radius for deuterium > 9 fm

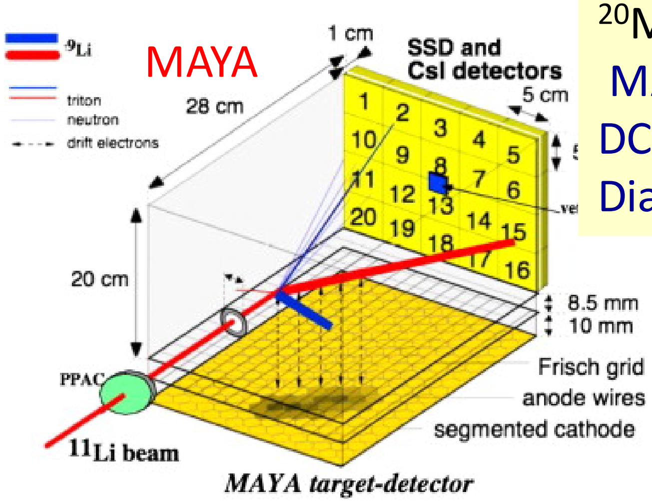
- Experiment ^{7}Be(d,p) and (d,d) at 35 MeV at T-REX

Study of n=8 gap beyond stability (IS564)

- **Study of the unbound proton-rich nucleus ^{21}Al with resonance elastic and inelastic scattering using an active target**
- The N=8 shell gap at the proton-drip line known up to ^{20}Mg
- The next isotope in the chain is ^{21}Al -> no experimental data

  - -Upper limit of $T_{1/2}$<35 ns

    M. G. Saint-Laurent, et al., PRL 59, 33 (1987).
  - Unknown Spin and Parity -> ^{21}O (5/2+)

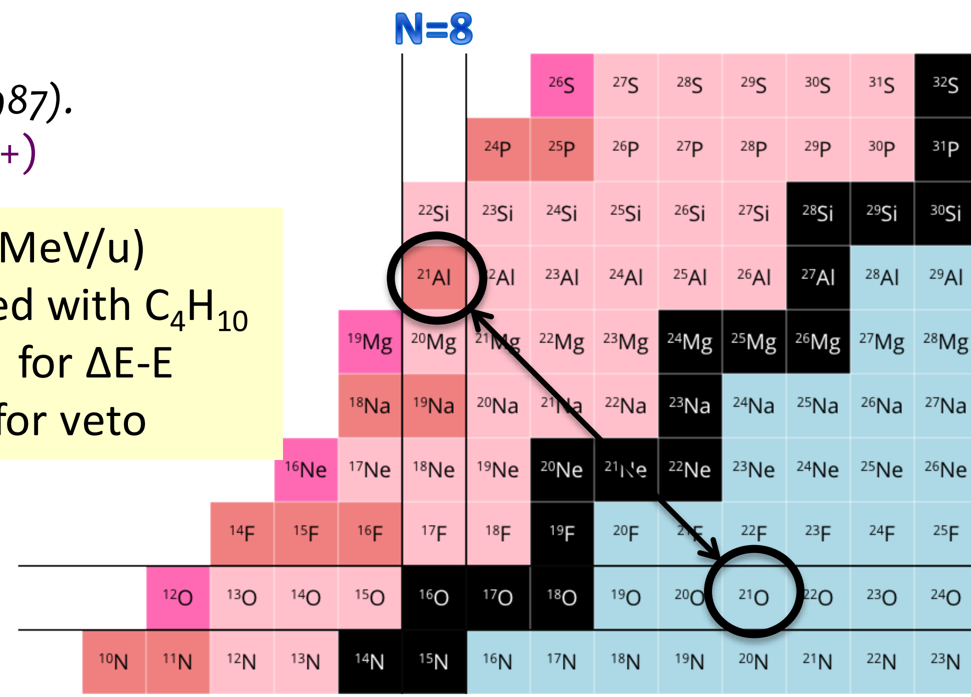


^{20}Mg (5.5 MeV/u)

MAYA filled with C_4H_{10}

DC+Si+CsI for ΔE-E

Diamond for veto

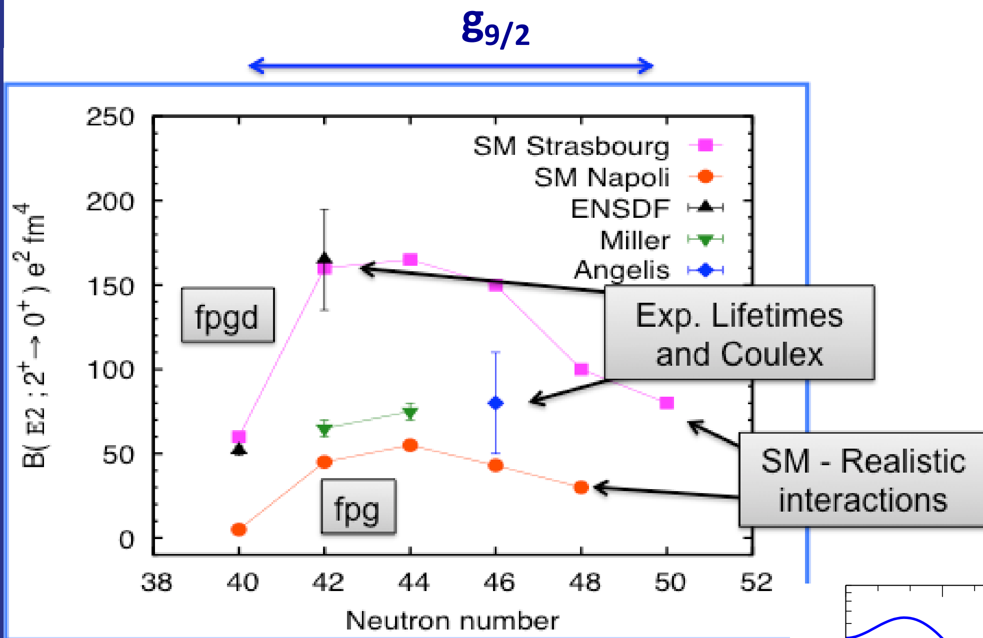


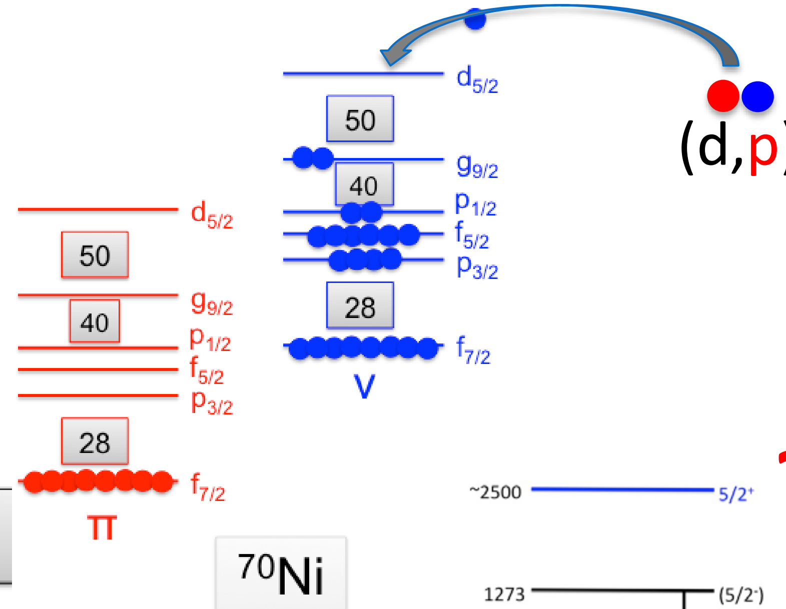
<u>ADVANTAGES</u> compared to conventional thick target method:

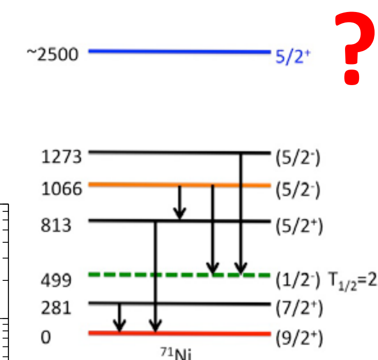
1) Background from C can be discriminated.
2) Inelastic and elastic can be separated.

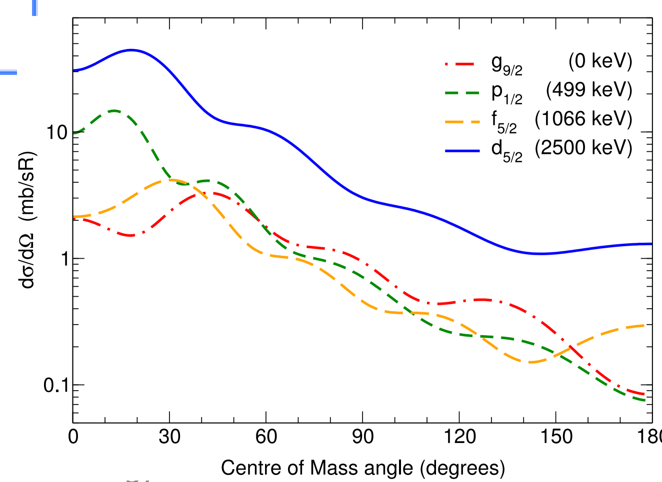
Shell Evolution in Ni-isotopes (IS555)

- Large theoretical and experimental discrepancies. For Ni –isotopes beyond N= 40.



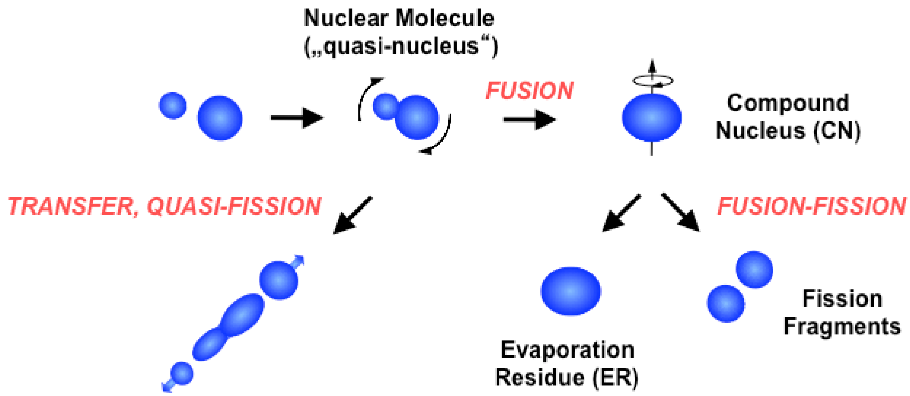






- Transfer reaction to characterize the 5/2$^+$ state in ^{71}Ni by looking to proton angular distribution with T-REX

Search for the new magic numbers above ^{208}Pb?(IS550)



- **Nuclei with N ≈ 184 are still far**
- **Nuclei with Z > 118 are still unknown**

- Study of quasi-fission and fusion-fission with ^{94,95}Rb projectiles with Corset
- $^{95}Rb + {}^{209}Bi \rightarrow Z_1 + Z_2 = \mathbf{120}$, $N_1 + N_2 = \mathbf{184}$

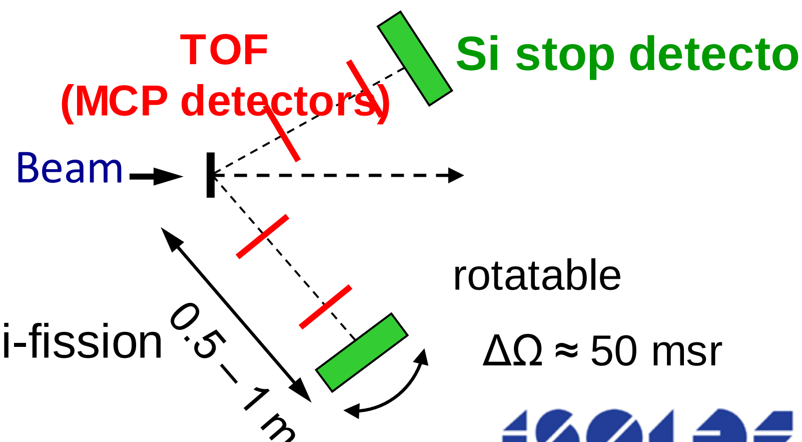
Z = 114, 120 or 126

N = 184

?

- Shell closures indicated by an increase of fission barriers and half-lives
- **Influence expected in *quasi-nuclei***

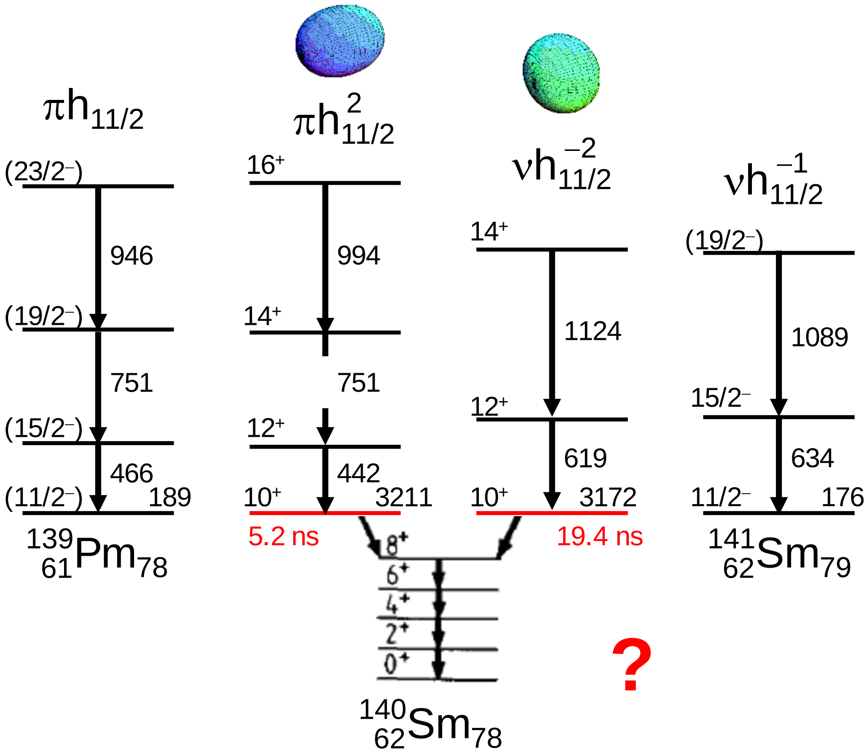
$$\sigma_{ER} = \sigma_{capture} \times P_{CN} \times P_{survival}$$



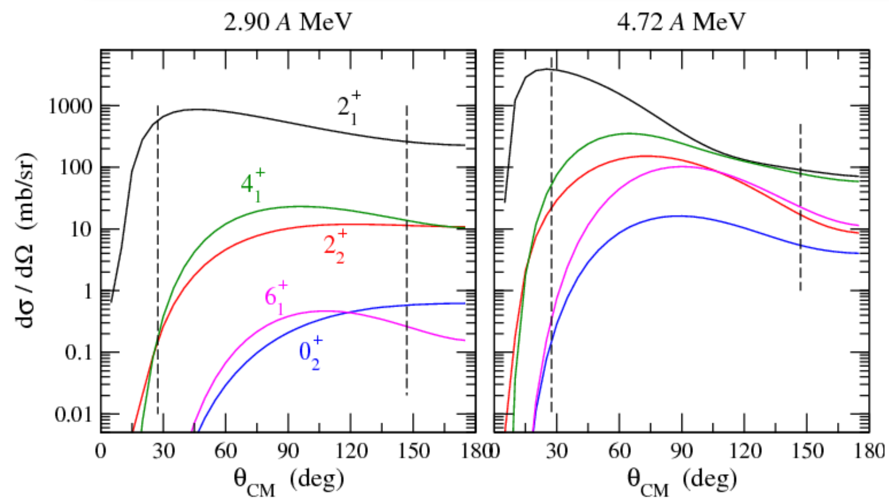
Asymmetric component → transfer, quasi-fission

Symmetric component → fusion-fission

Shape transition & shape Coexistence in ^{140}Sm (IS558)

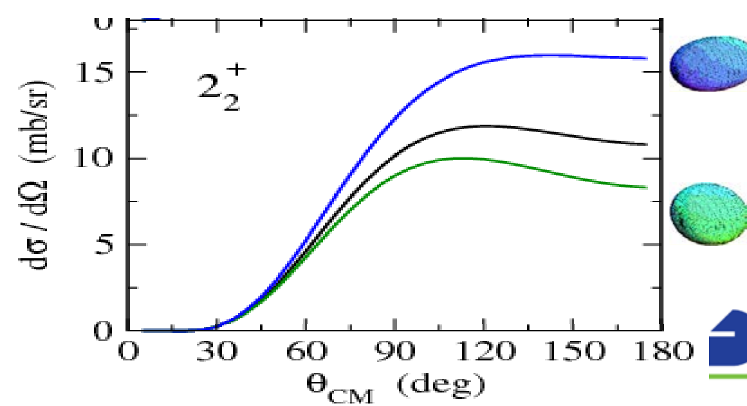


large gain for multi-step excitation for higher beam energies from HIE-ISOLDE



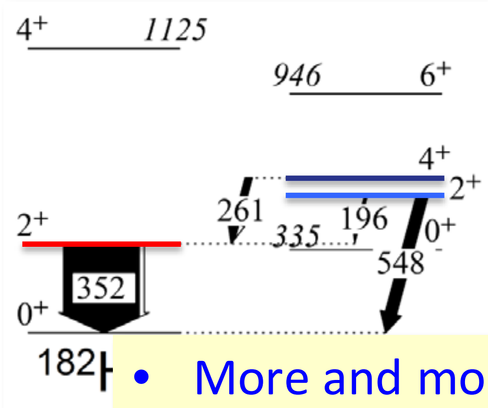
excitation cross sections for ^{140}Sm + ^{208}Pb
- experimental excitation energies
- matrix elements from theory

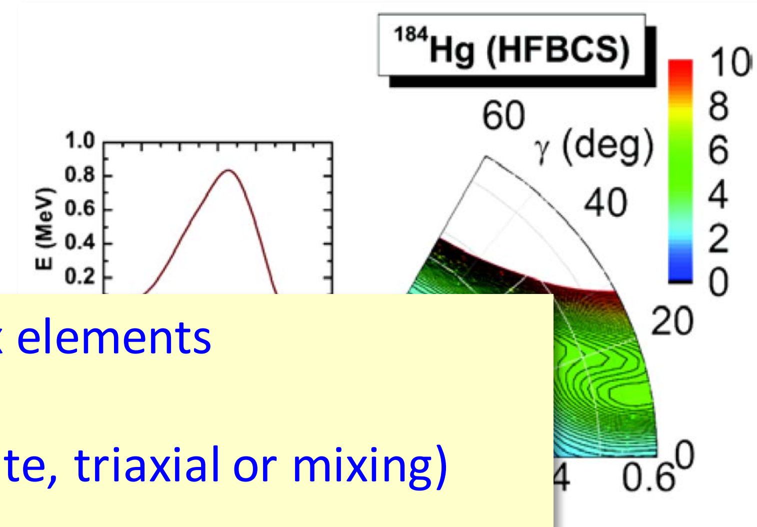
Regions of shape transitions and coexistence
- measurement of collective properties
- stringent test of nuclear structure theory



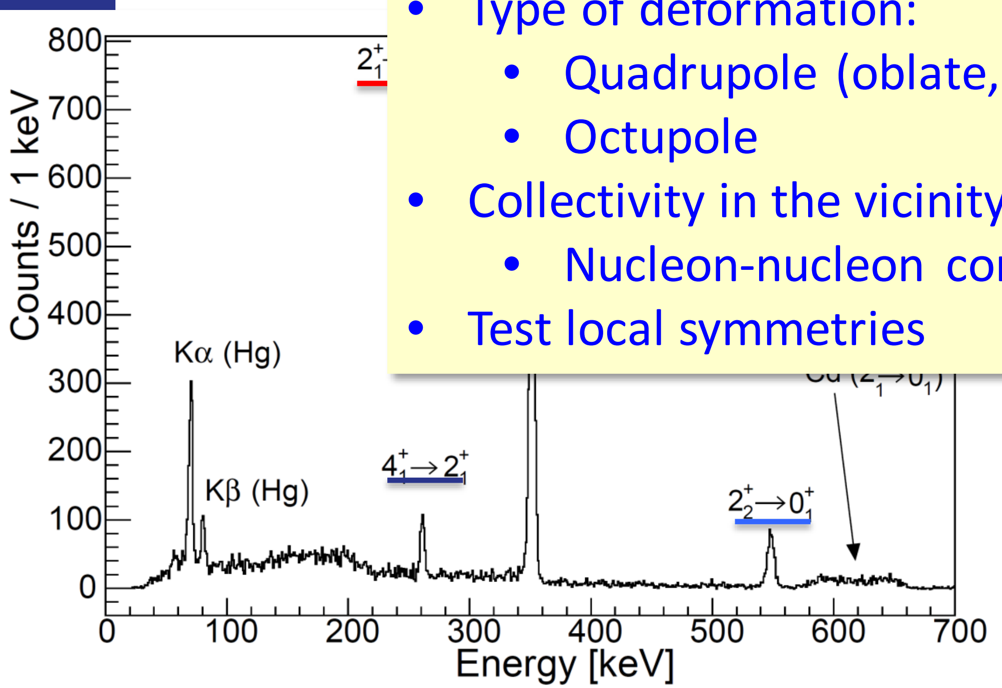
Experimental:
- Lifetime measurements ⇒ B(E2)
- Coulomb excitation ⇒ B(E2), Q_s

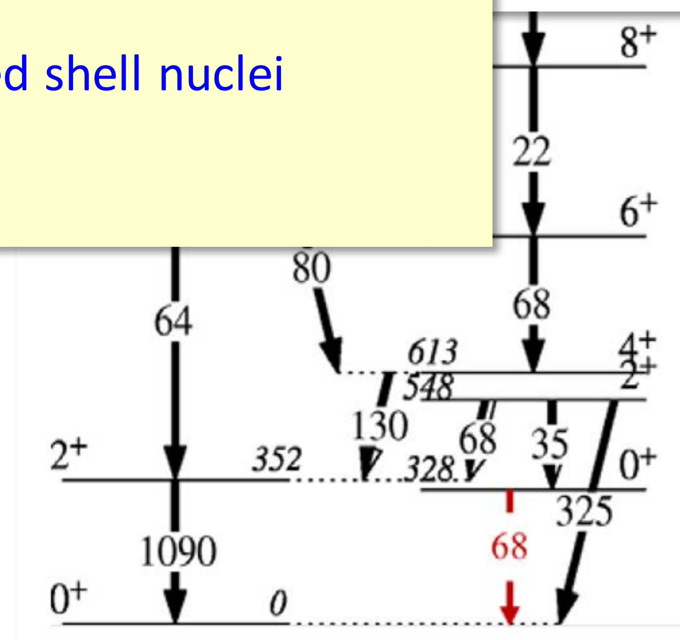
Coulomb excitation of ^{182}Hg





- More and more precise matrix elements
- Type of deformation:
  - Quadrupole (oblate, prolate, triaxial or mixing)
  - Octupole
- Collectivity in the vicinity of closed shell nuclei
  - Nucleon-nucleon correlation
- Test local symmetries

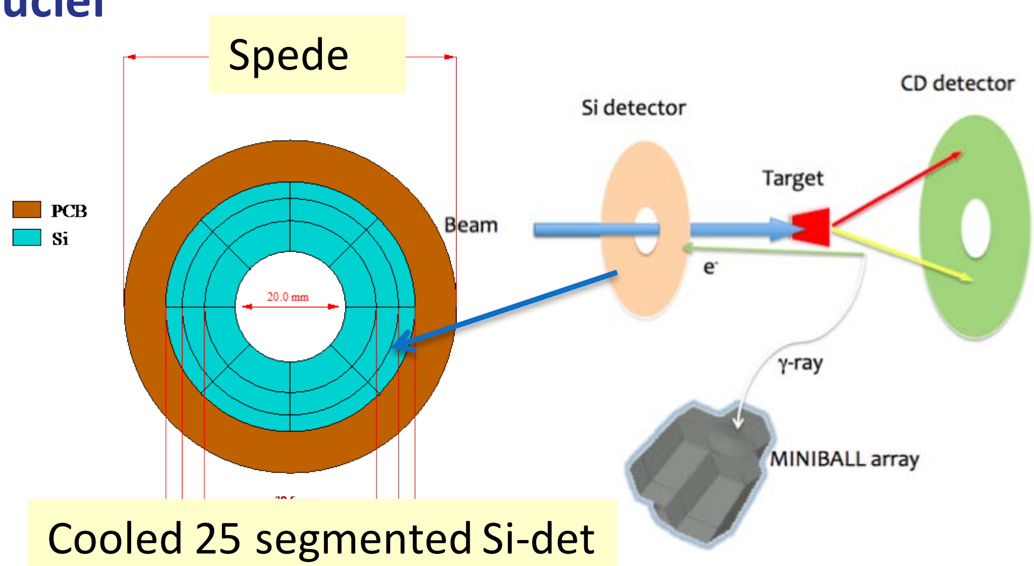




New candidates for EDM Measurements (IS552)

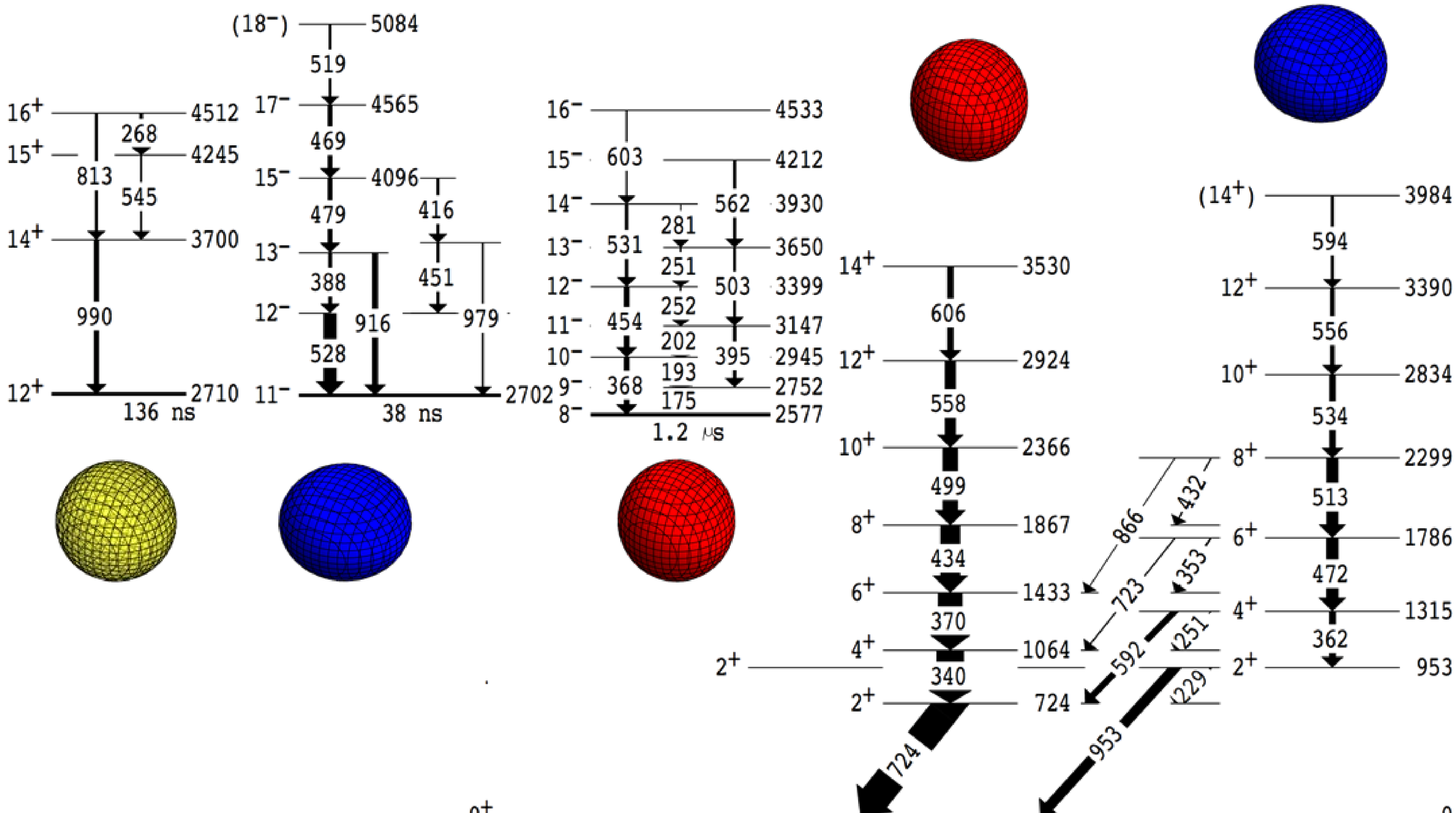
- The observation of a non-zero EDM indicates T-violation beyond the Standard Model.
- Octupole-deformed nuclei will have enhanced nuclear “Schiff” moments due to the presence of nearly degenerate parity doublets (seen in odd mass nuclei) and large collective octupole deformation.
- Presently **$|d(^{199}Hg)| < 3.1\times10^{-29}$ e.cm,** ***PRL 102 (2009) 101601***
- ***Octupole deformed nuclei will have 100-1000 higher* sensitivity compared with stable nuclei**

- Characterization of ^{221}Ra
- increased of a factor of 5 from 3 to 5,5 MeV/u
- Measurements of γ and e- conversion to determine the ΔE of parity doublet.



IS561: Coulomb excitation of $^{(186),188}$Pb

- Region of shape coexistence
- Deduce level scheme of 188Pb @ Argonne (Dracoulis Phys. Rev C **67**, 051301(R) 2003)



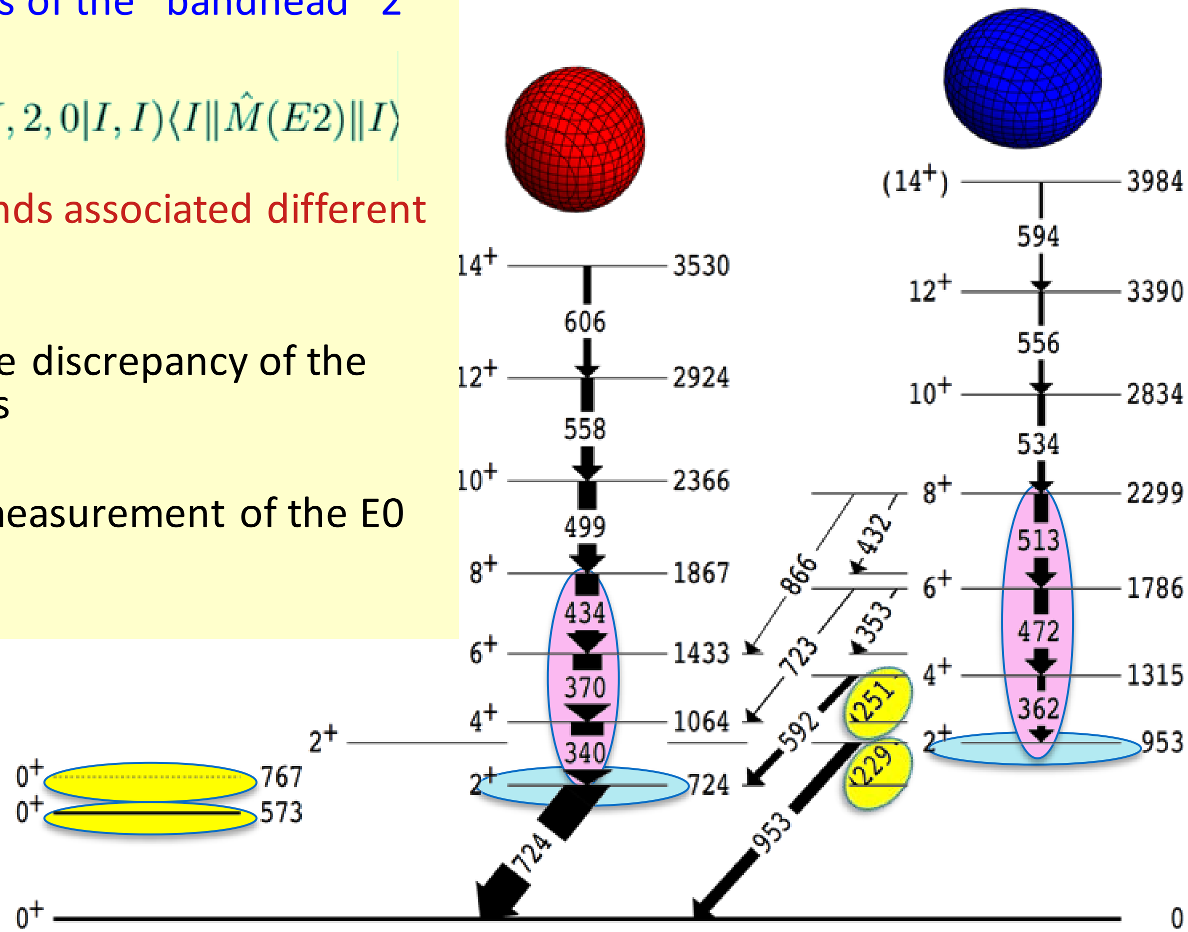
From Janne Pakarinen

Aim of the IS561 Experiment: ^{188}Pb

- Directly measure shapes of the "bandhead" 2^+ states

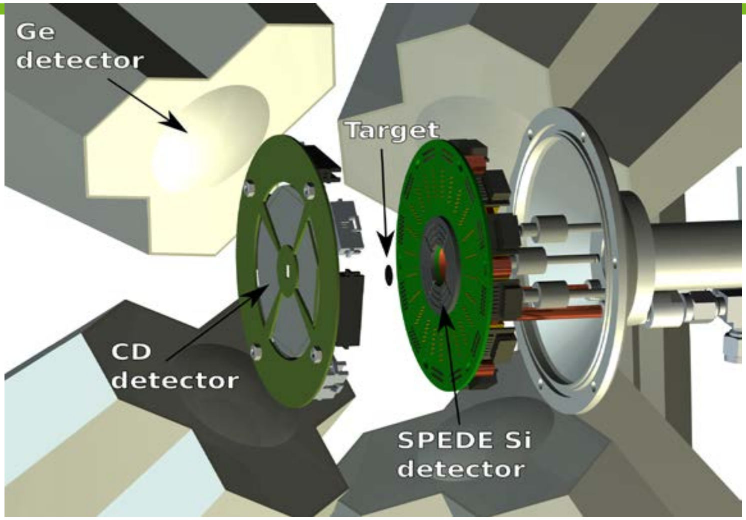
$$eQ_{sp} = \sqrt{\frac{16\pi}{5}}\frac{1}{\sqrt{2I+1}}(I,I,2,0|I,I)\langle I\|\hat{M}(E2)\|I\rangle$$

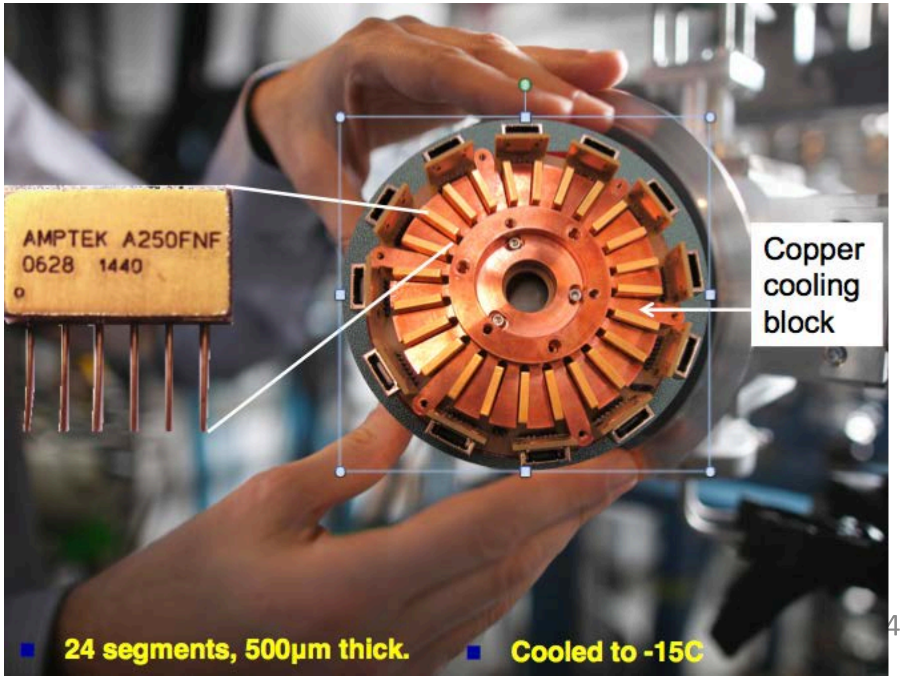
- Probe collectivity of bands associated different shapes
- Determine the long time discrepancy of the position of the 0+ states
- Investigate mixing via measurement of the E0 transitions



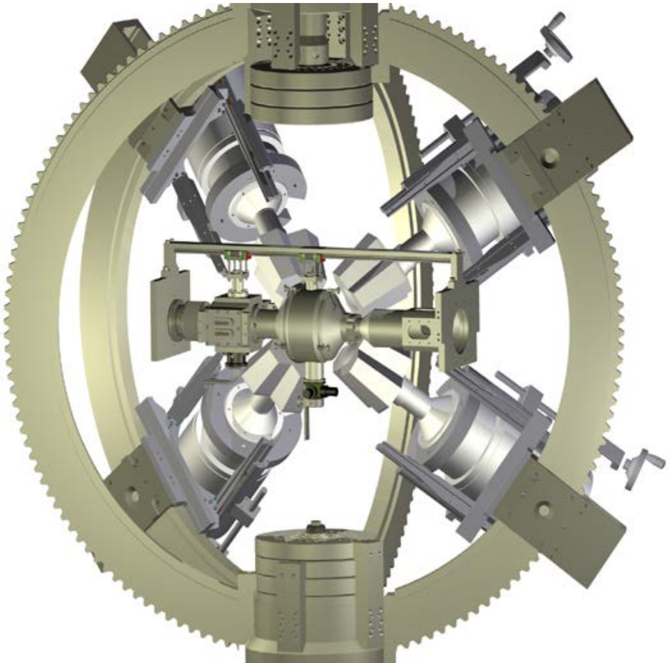
IS561

- UCx target + RILIS
- HIE-ISOLDE beam ~10^6pps @ MINIBALL
- Energies: 3.5 and 4.1MeV/u
- Two targets: ^{112}Cd and ^{48}Ti
- Typical MINIBALL set-up + SPEDE
- Measure: e^-, γ, ejectiles

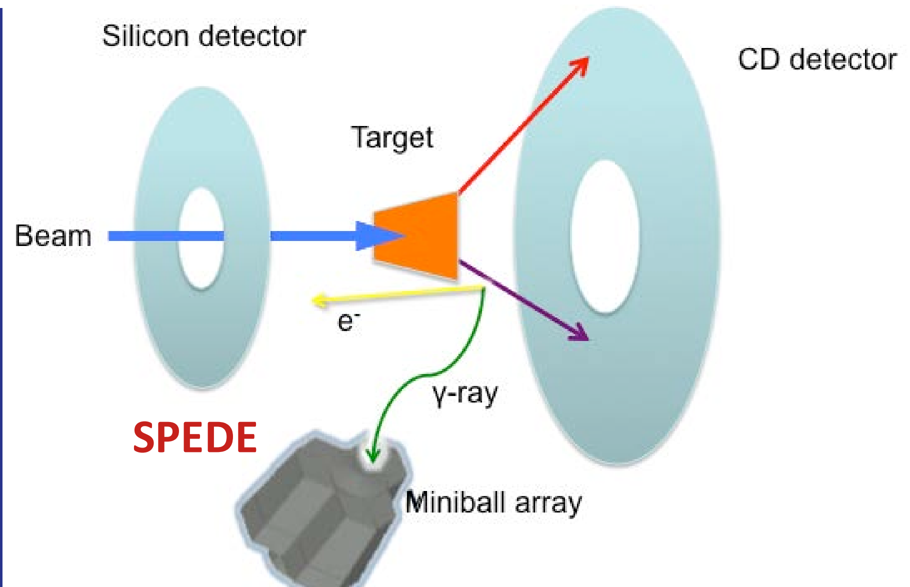


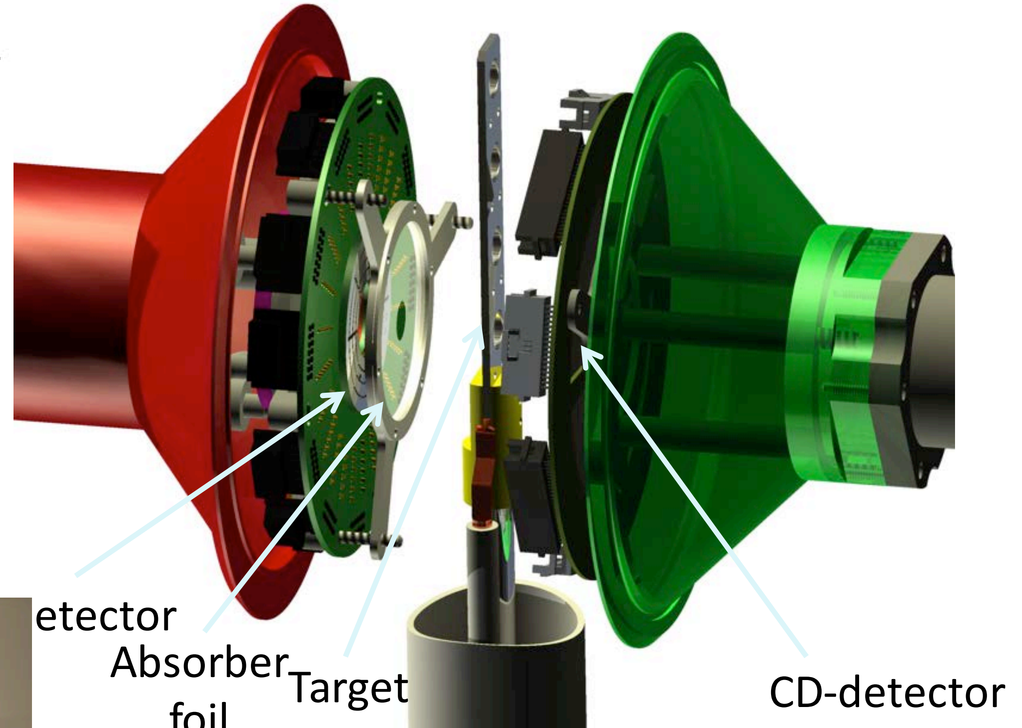


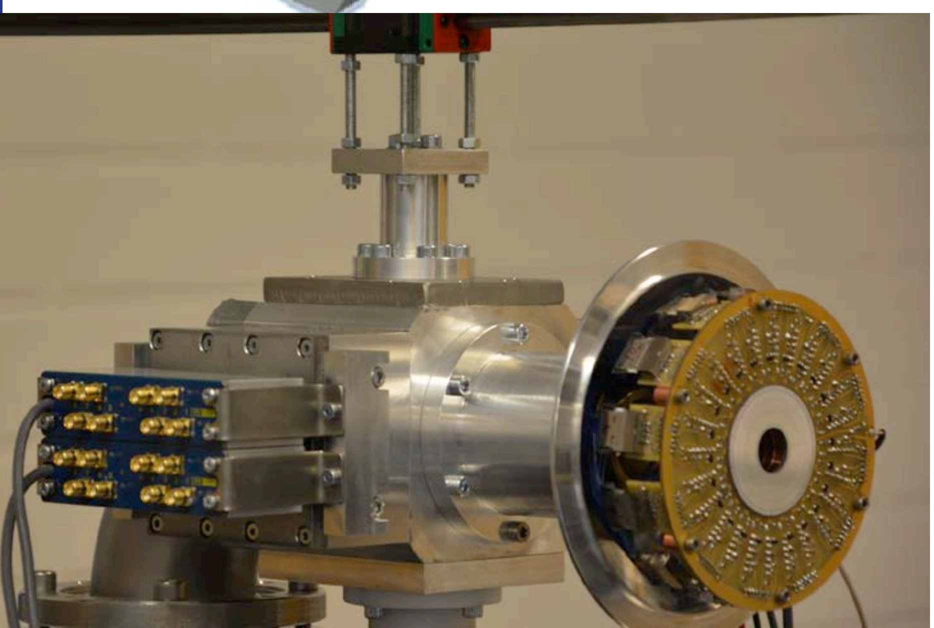
SPEDE in Miniball



Electron Spectrometer: SPEDE







Designed and built in Jyväskylä (Finland)
To be installed in July 2015