ISOLDE Highlights and the HIE- ISOLDE Project

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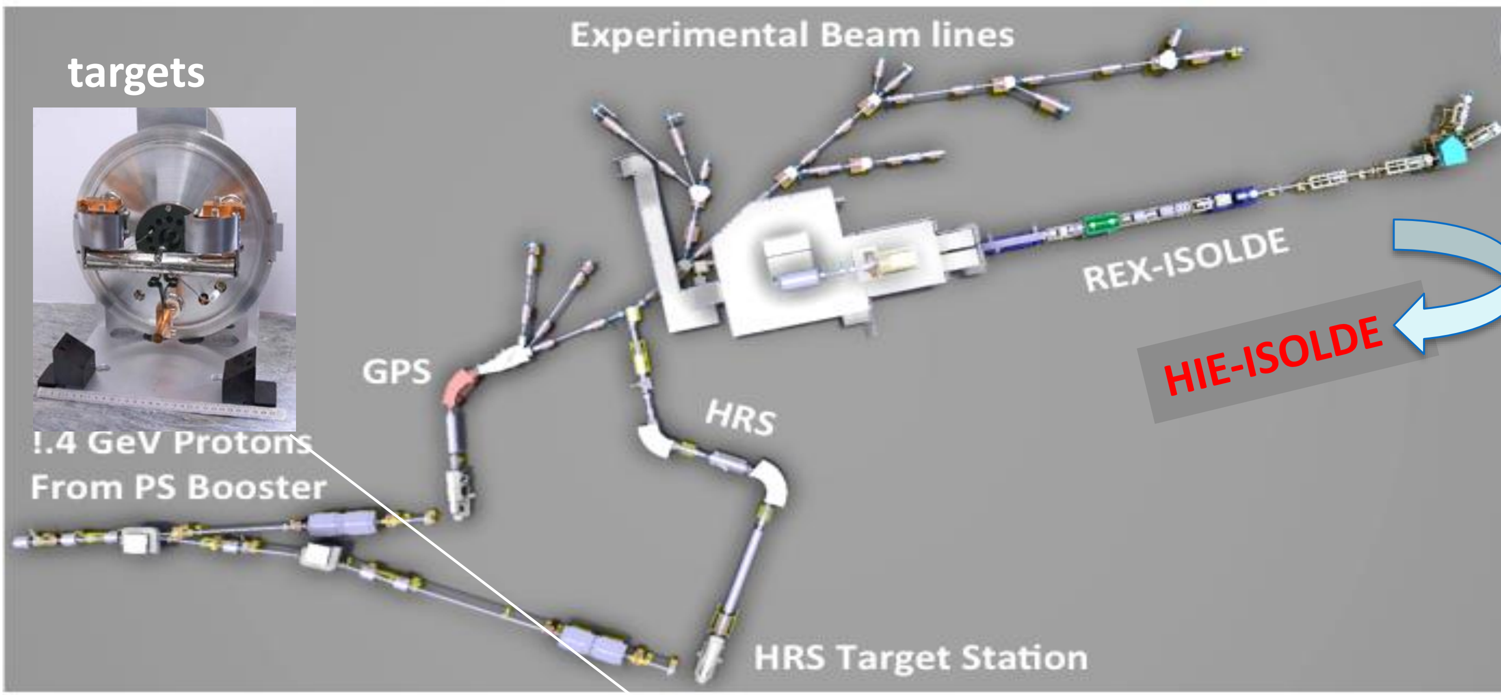
ISOLDE Facility

- ISOLDE is the CERN radioactive beam facility.
- “Oldest running experiment” at CERN
- Provides low energy or post-accelerated beams
- **> 800 Users from > 200 Institutions, 50 experiments / year**



Linac4
PSB upgrade

(2020)

intensity (2uA -> 6uA)
energy (1.4 -> 2GeV)

Prehistory + today

- First ISOL beam: Copenhagen 1951
- ISOLDE approved 1964
- First radioactive beam 1967, positioned at SC (worth a visit !)
- Several upgrades until SC was closed 1990
- Restart at PS-Booster in 1992
- Two hall enlargements, REX in 2001, HIE in 2015….

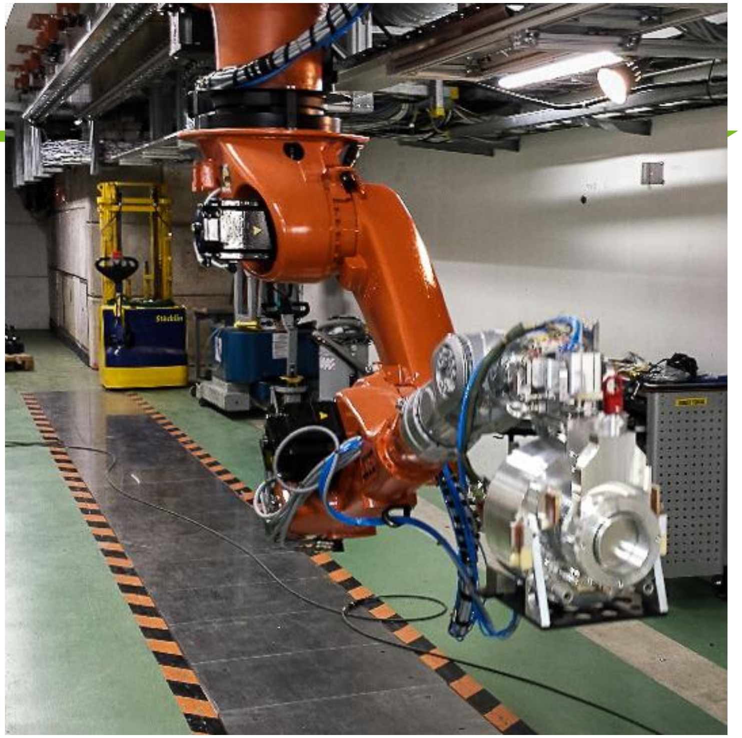
- ISOLDE Collaboration (16 members) have MoU with CERN

- Proposals through INTC to Research Board

- Fruitful collaboration with many other radioactive beam facilities

- 132 active experiments, 117 theses 2012-2016

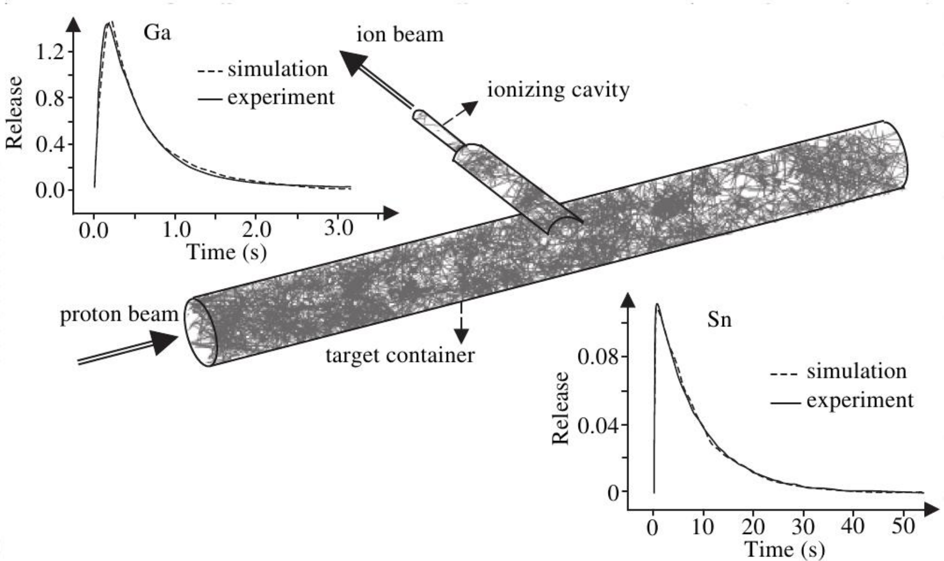
ISOLDE Targets

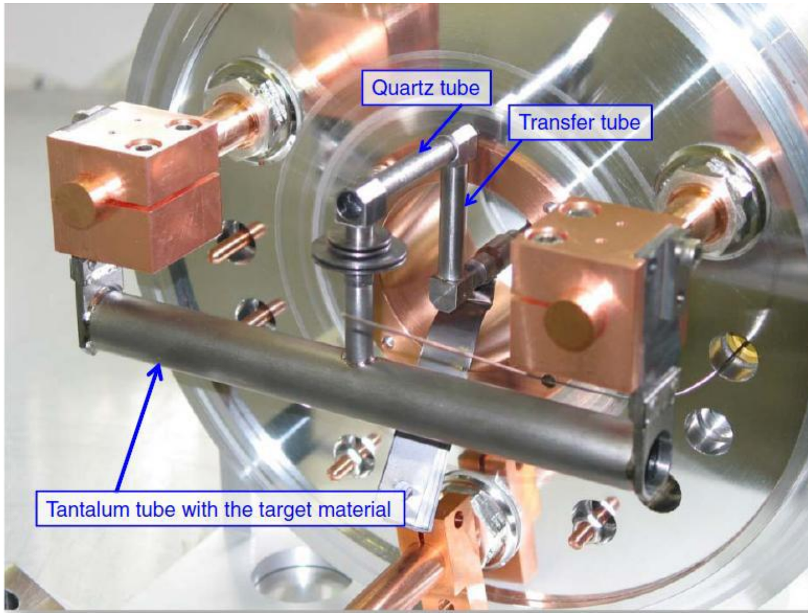


- Main challenge: extracting the $10^{-1} – 10^{12}$ nuclei (one isotope) produced in the reaction from the 10^{23} nuclei in the target

- Targets:
  UCx, SiC, Ta, LaCx, CaO, ZrO….

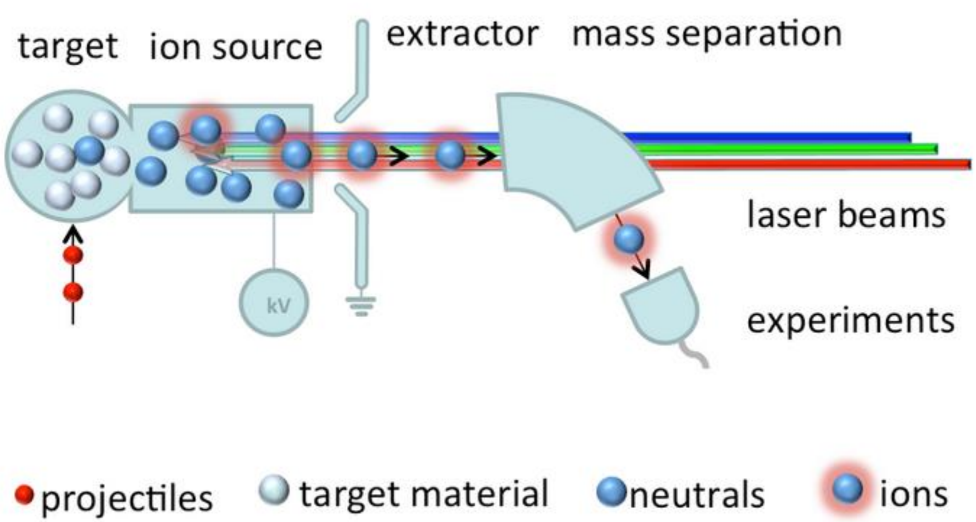
- The diffusion into the ion source is controlled by the target and transfer line temperature

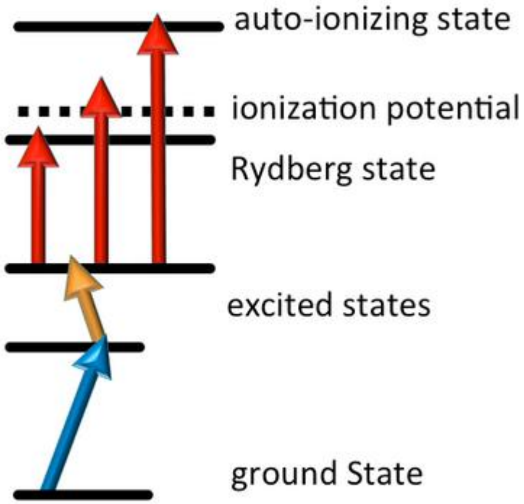




Ion Sources

- **Hot-cavity**
  - W heated at > 2000 C
  - High ionization efficiencies for some nuclei
- **Plasma**
  - Electrons are extracted from a hot cathode and accelerated into a low pressure plasma
  - When passing through the plasma, the atoms get ionized with very high efficiency (up to 50%)
- **LASER – RILIS** (Resonance Ionization Laser Ion Source)
  - Used at ISOLDE since 1994
  - Based on the selective ionization of a single atomic species





Gain in yield due to p energy increase

- Yield: $Y = I \, X \, \sigma \, \varepsilon_{rel} \, \varepsilon_{ion} \, \varepsilon_{sep} \, \varepsilon_{transp}$

Proton beam intensity (I)

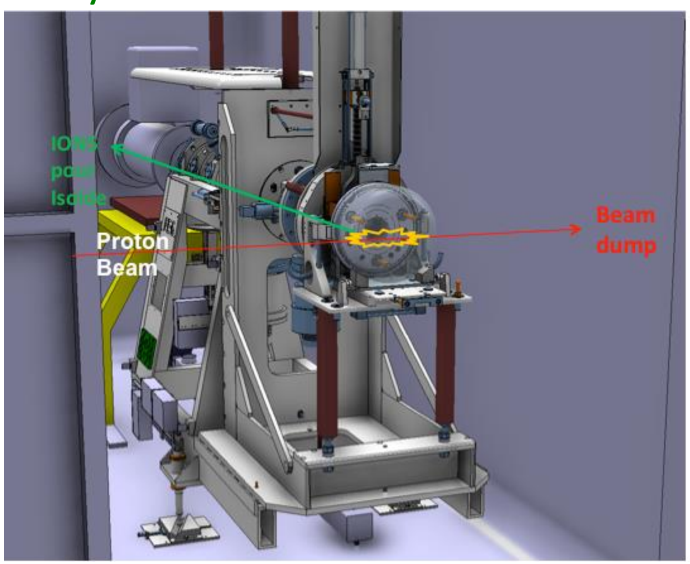
Target thickness (X)

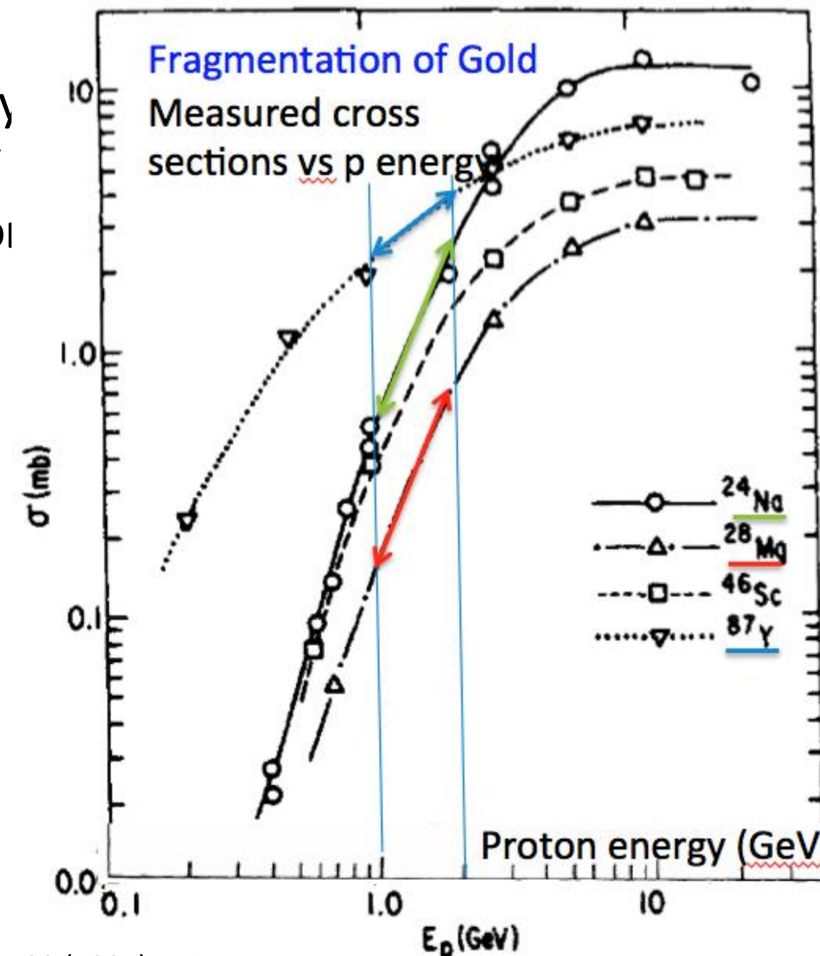
Production cross section (σ)

Efficiencies (release, ionization, mass-separation, transport)

Yield scales linearly with Proton beam intensity

- Increase in proton energy from 1/1.4 GeV to 2 GeV **increase the cross section** and thus **the yield.**

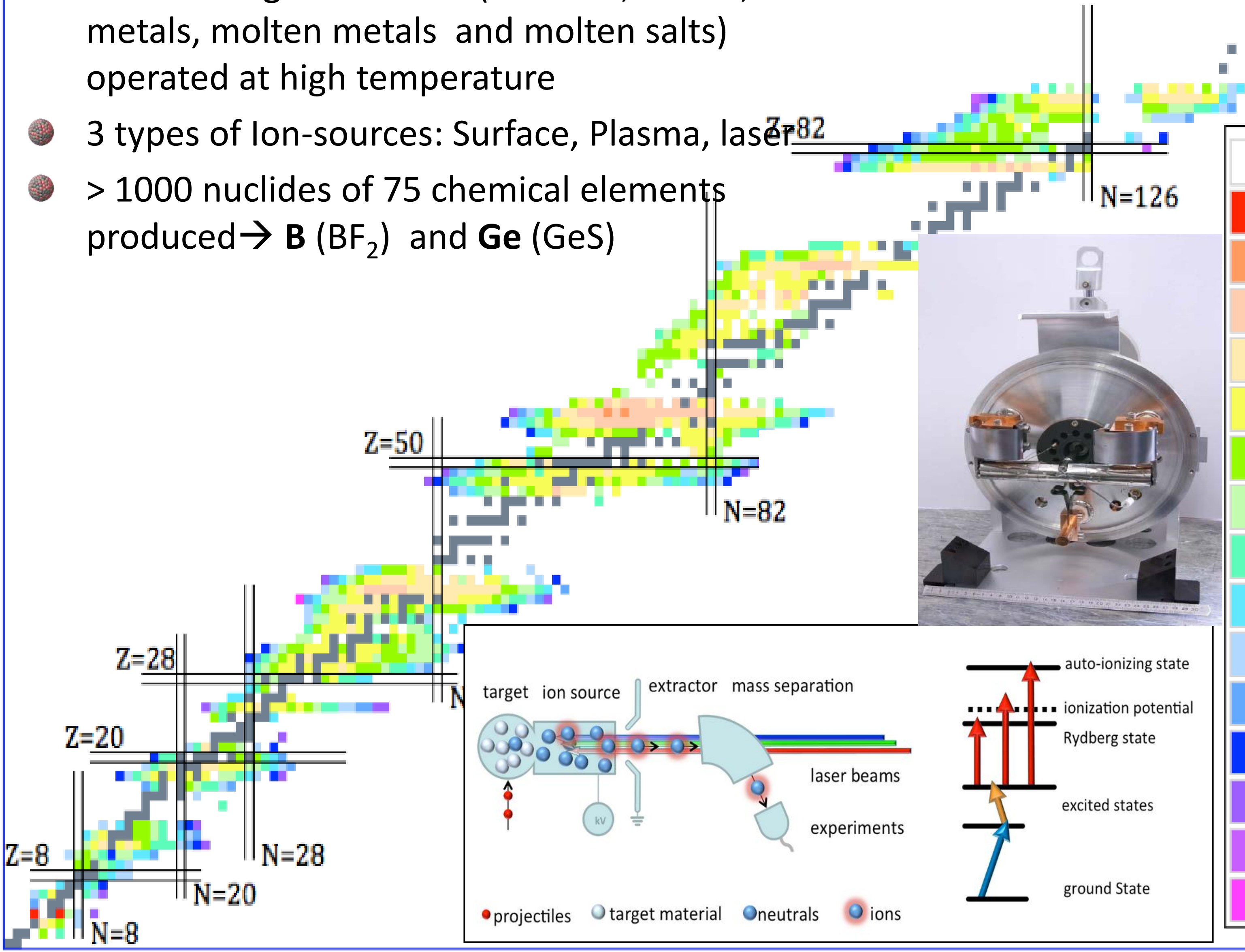




H. L. Ravn et al., NIM B 88 (1994) 441

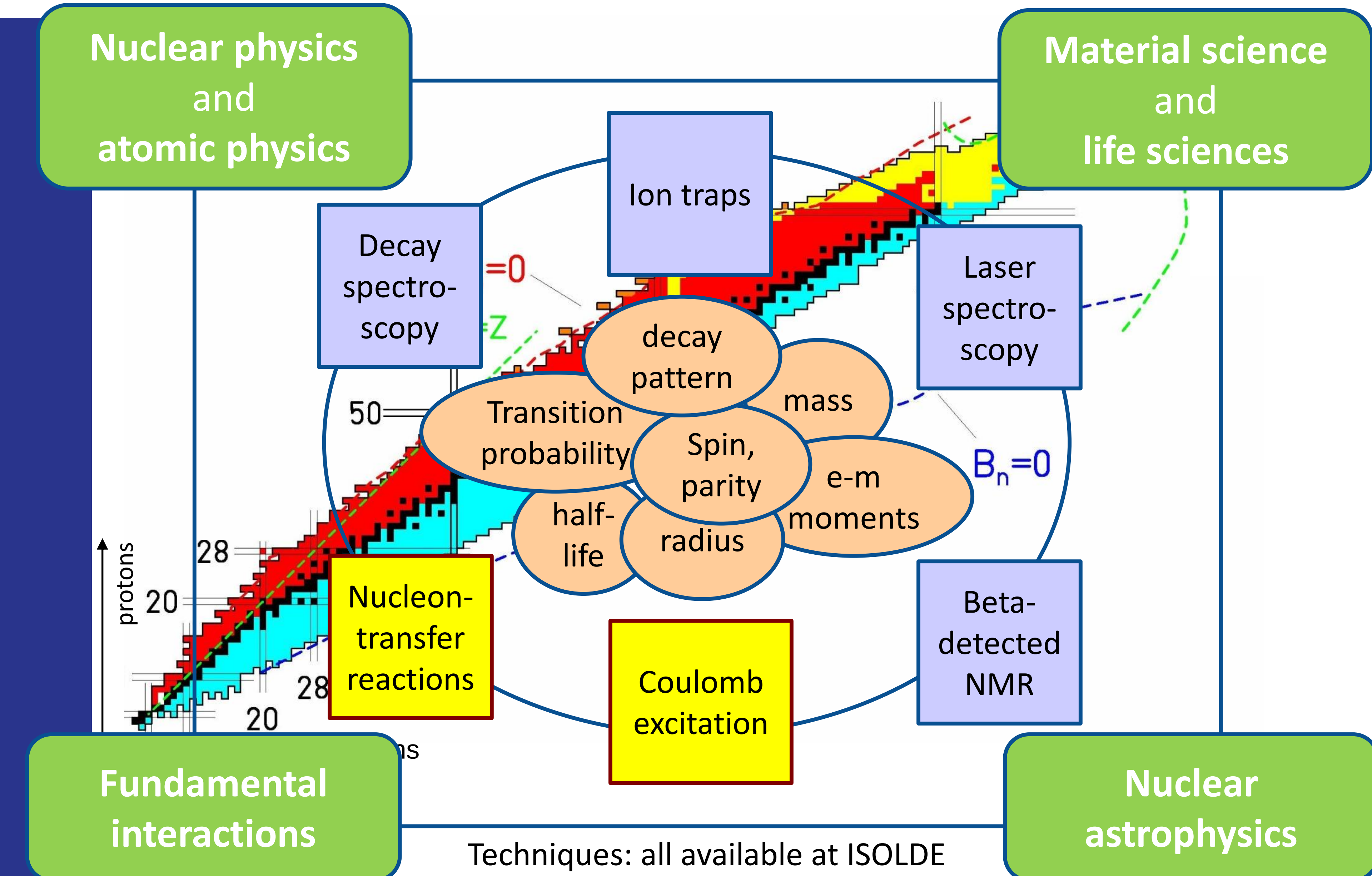
Produced Nuclei: 50 y Experience

- Over 20 target materials (carbides, oxides, solid metals, molten metals and molten salts) operated at high temperature
- 3 types of Ion-sources: Surface, Plasma, laser
- > 1000 nuclides of 75 chemical elements produced→ **B** (BF_2) and **Ge** (GeS)

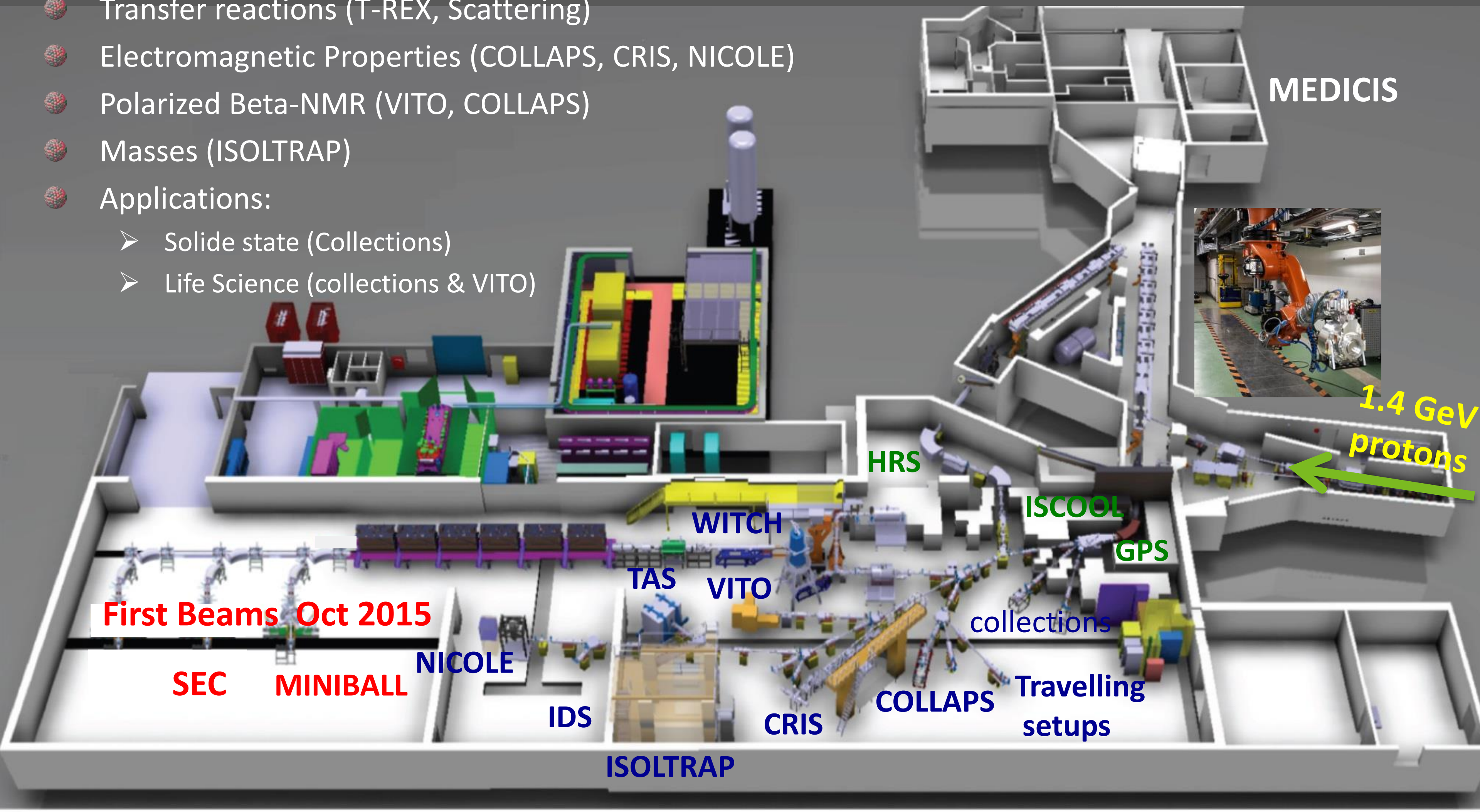


Yield (ions/µC)		
10^{13}	-	10^{12}
10^{12}	-	10^{11}
10^{11}	-	10^{10}
10^{10}	-	10^{9}
10^{9}	-	10^{8}
10^{8}	-	10^{7}
10^{7}	-	10^{6}
10^{6}	-	10^{5}
10^{5}	-	10^{4}
10^{4}	-	10^{3}
10^{3}	-	10^{2}
10^{2}	-	10^{1}
10^{1}	-	10^{0}
10^{0}	-	10^{-1}
10^{-1}	-	10^{-2}

Research with radioactive nuclides



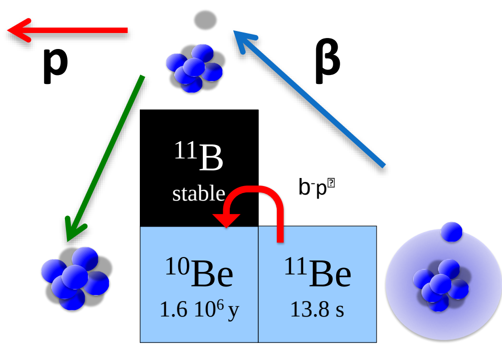
- Decay spectroscopy (IDS, TAS,..)
- Coulomb excitation (MINIBALL)
- Transfer reactions (T-REX, Scattering)
- Electromagnetic Properties (COLLAPS, CRIS, NICOLE)
- Polarized Beta-NMR (VITO, COLLAPS)
- Masses (ISOLTRAP)
- Applications:
  - Solide state (Collections)
  - Life Science (collections & VITO)



— Post-accelerated Exps (5.5 MeV/u); — Low Energy (30-60kV) Exps, — Machine elements

Recent Highlights and types of experiments

βp in halo ^{11}Be nuclei: Quasi-free n → p decay

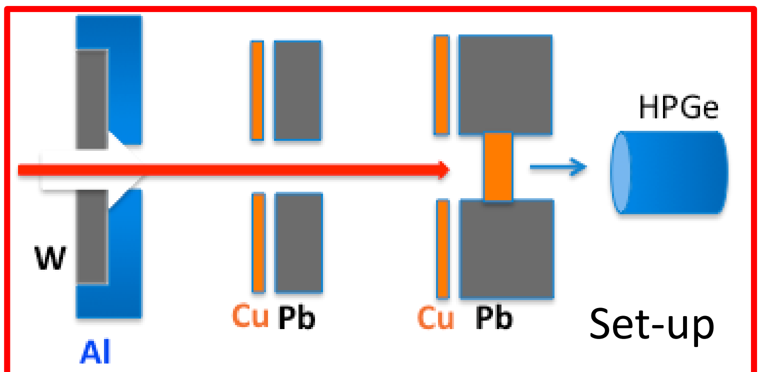


- ✓ **βd** observed in ^{6}He & ^{11}Li halo nuclei decay directly to the continuum → simpler mode in 1n-halo nuclei → βp
- ✓ ^{11}Be best case to search for βp, $Q_{\beta p}$ = 280.7 keV
- ✓ Expected B.R. 3×10^{-8} assuming direct decay

  D. Baye & Tursonov, Phys. Lett. 696 (2011) 464
- ✓ Previous attempt gave unconclusive result with

BR = $2.5(25) \times 10^{-6}$; Borge et al., J. Phys G 40 (2013) 035109

A 200 keV 10^{-8} proton branch is challenging to detect → Detect ^{10}Be daughter by AMS



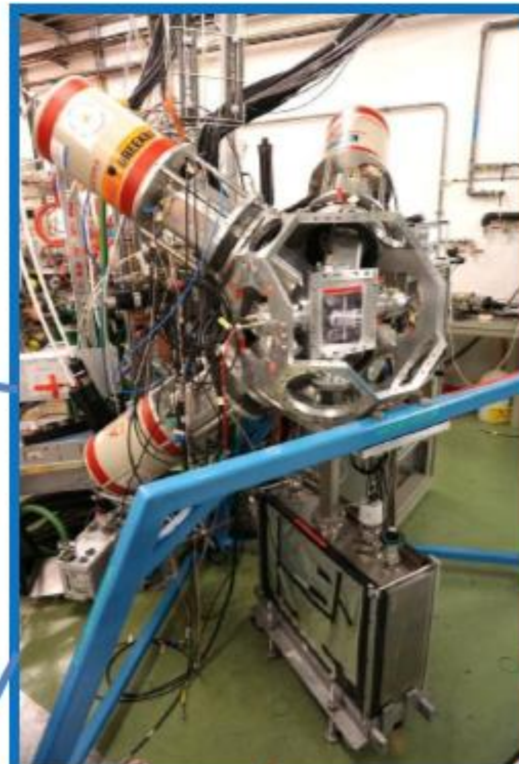
- Contaminations measured to be negligible.
- B.R. = $8.4(6) \times 10^{-6}$ Consistent with previous results
- New resonance in ^{11}B ? → OTPC

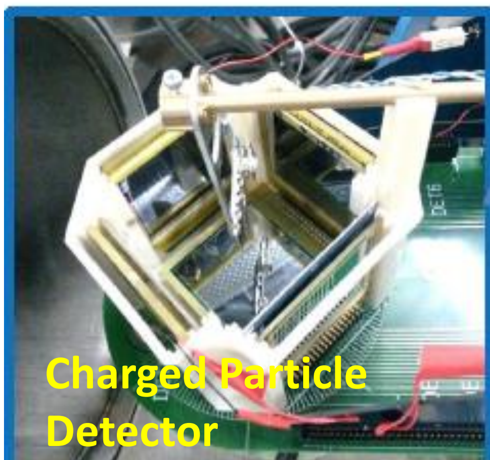
❖ The new decay mode is a consequence of halo structure, peripheral decay of the neutron halo + intense super allowed transition near Q-value observed in other neutron rich drip line nuclei. Riisager et al, Phys Lett. B732 (2014) 305

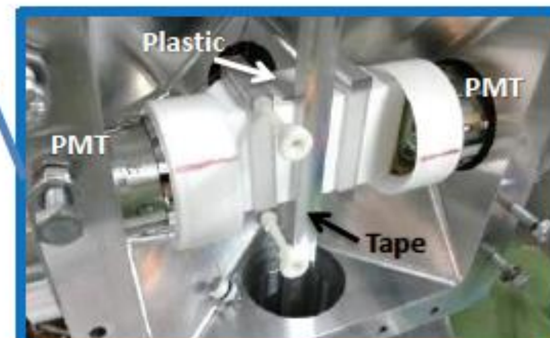
New Permanent setup: IDS

Very versatile Setup

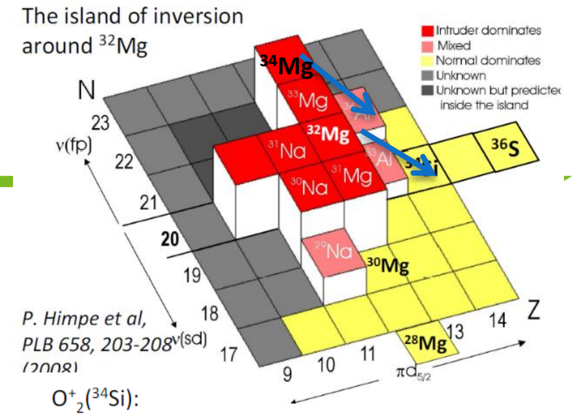
From proton rich ^{20}Mg to very neutron rich ^{132}Cd



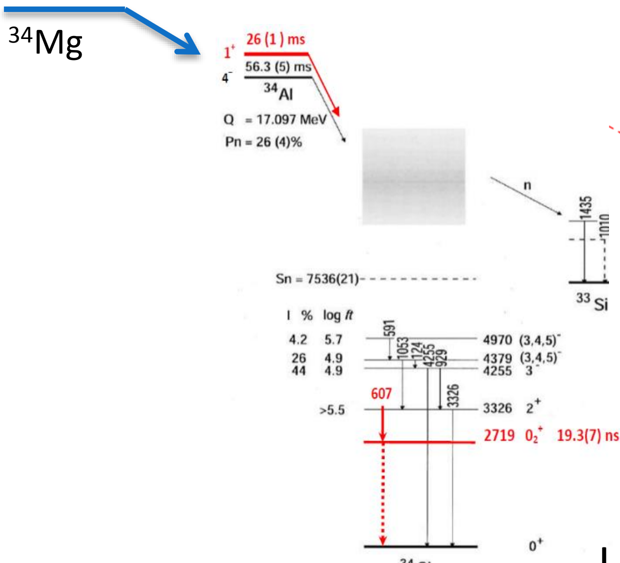


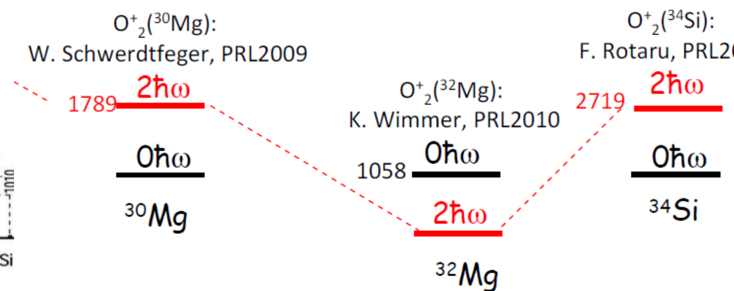


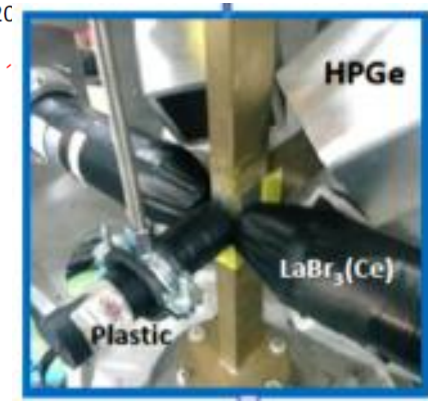
Extent of the Island of Inversion: β-decay of ^{34}Mg



- Results GANIL-LISE: Rotaru, Grevy PRL 2012





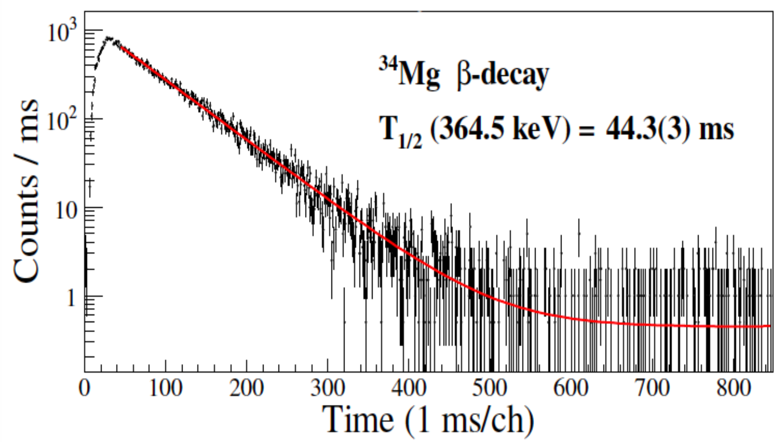


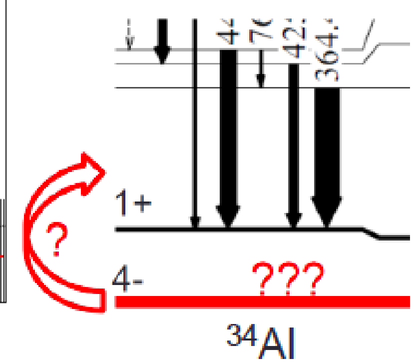
- Long lived isomer in ^{34}Al of $J^\pi = 1^+$ (T = 26(1) ms)
- 0^+ at 2719 keV in ^{34}Si

Langevin NPA 1984 / $T_{1/2}$ = 20(10) ms

Results 2015

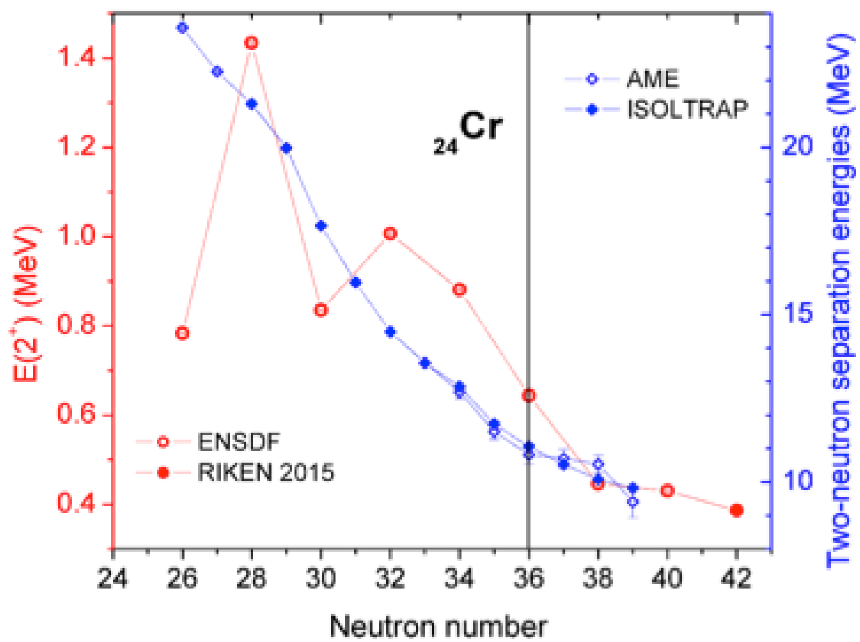
- 2 times > yield
- Improved setup
- $T_{1/2}$ of ^{34}Mg
- B(E2; $2^+ \rightarrow 0^+$) in ^{34}Si
- Identification of isomeric state and gs, Lica et al., PRC 95 (2017) 021301

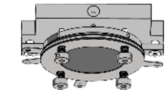




ISOLTRAP mass spectrometer

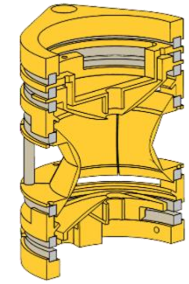
- Study of the onset of collectivity at N=40 deformation in n-rich chromium beams $^{50-63}Cr$



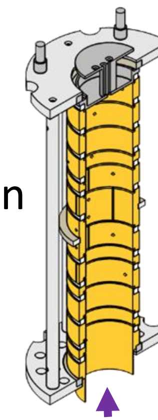


MCP

M. König *et al.*, **142**, 95 (1995).

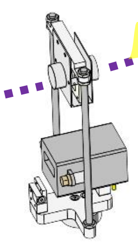


Precision trap

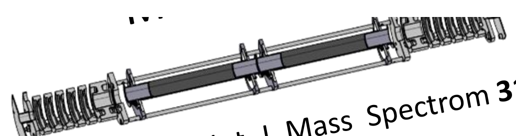


Preparation trap

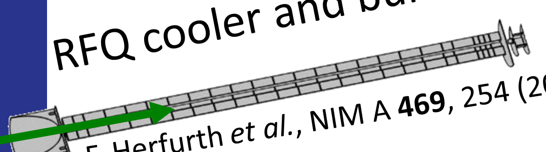
G. Savard *et al.*, Phys. Lett. A **158**, 247 (1991).



Bradbury-Nielsen beam gate



R. N. Wolf *et al.*, Int. J. Mass Spectrom **313**, 8 (2012)

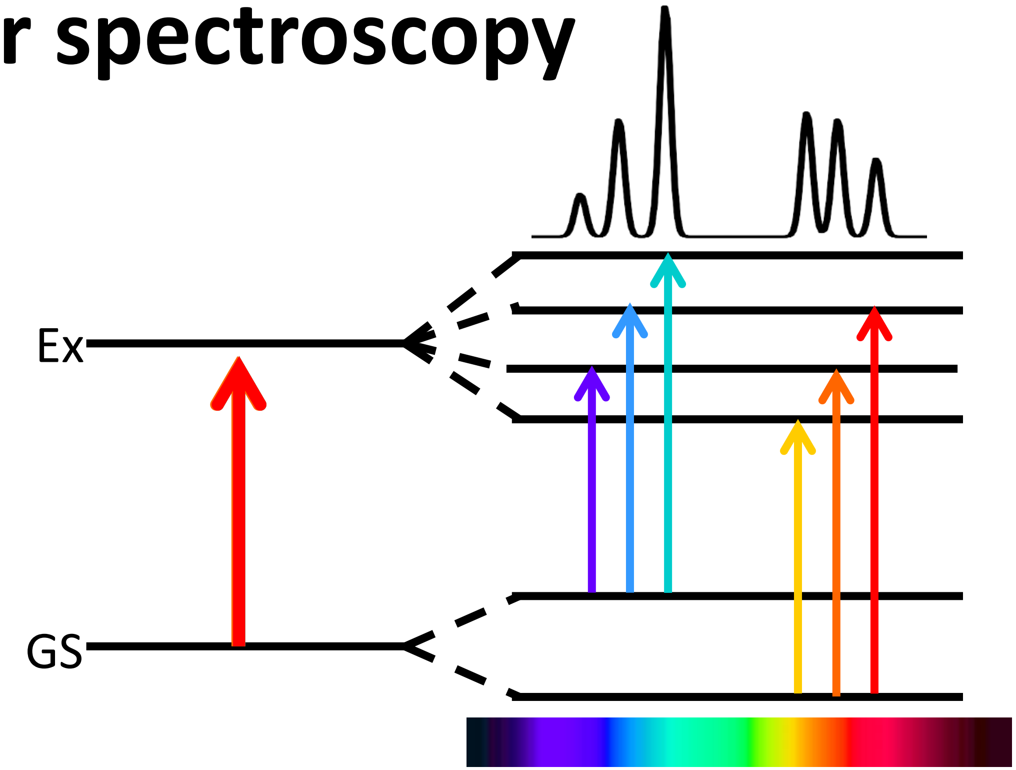


RFQ cooler and buncher

F. Herfurth *et al.*, NIM A **469**, 254 (2001).

Courtesy of V. Manea

Laser spectroscopy



- Probe the hyperfine structure of the energy levels of the electron
  - Scan the laser frequency of the resonant transition
- Nuclear observables extracted with model-independence:

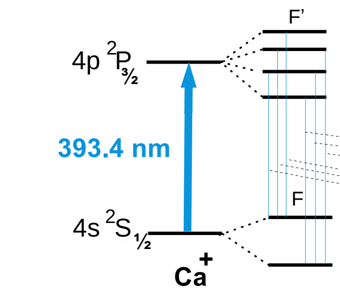
$\delta\langle r^2 \rangle^{A,A'}$ — Change in mean square charge radii

μ_I — Magnetic dipole moment

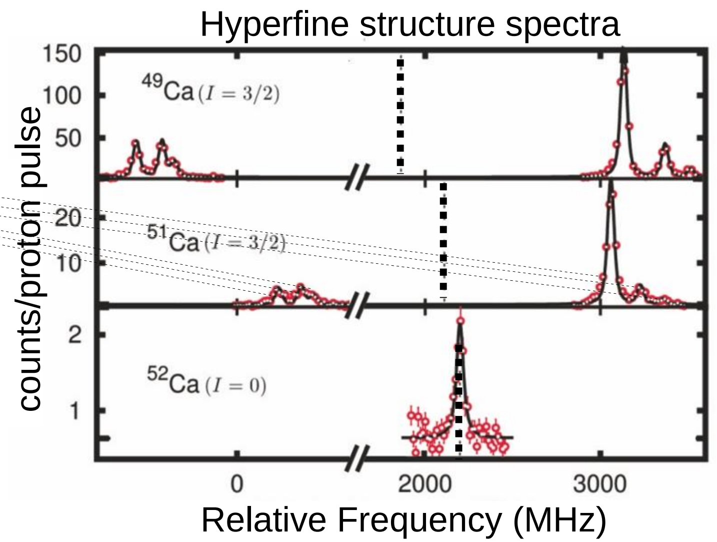
Q_S — Electric quadrupole moment

I — Nuclear spin

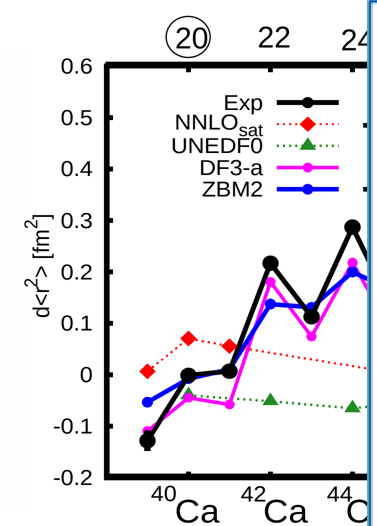
Exploring the nature of N=32

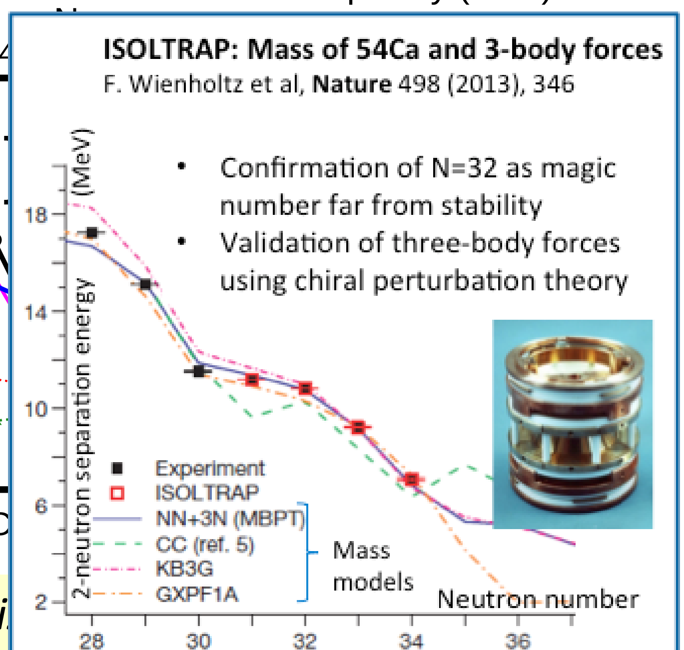


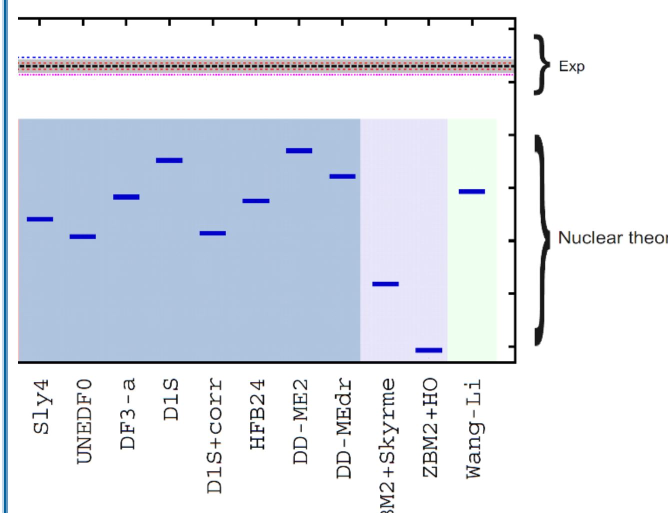
Level scheme for resonance excitation



- Collinear laser Spectroscopy study of Ca-isotopes: $^{40-52}$Ca
- Change in nuclear size produces a shift in the hfs.

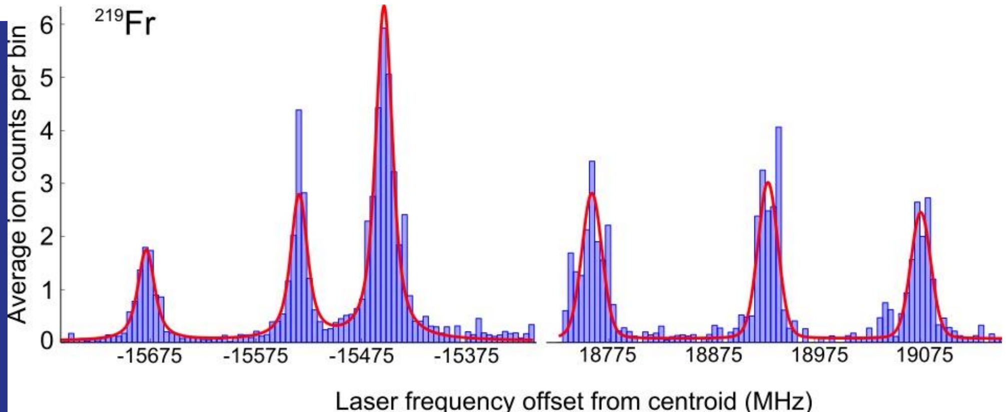


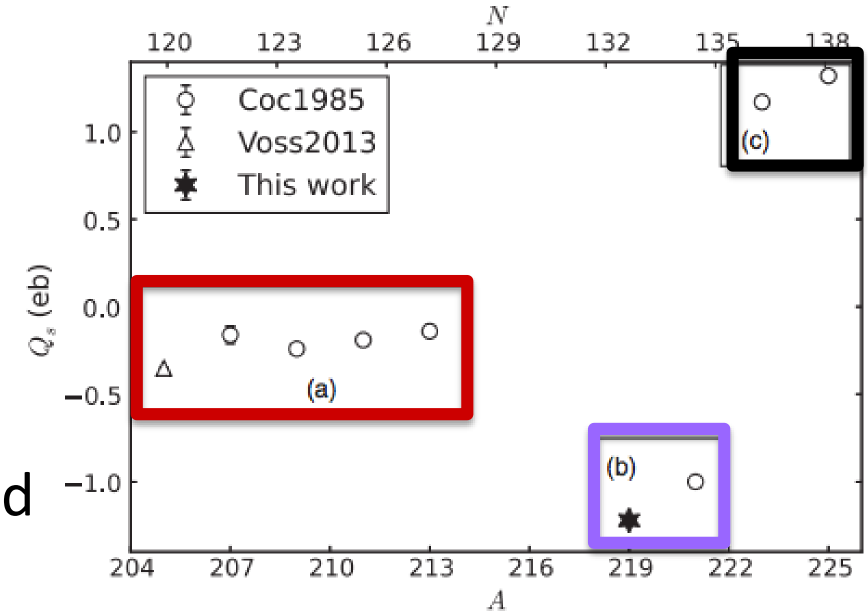




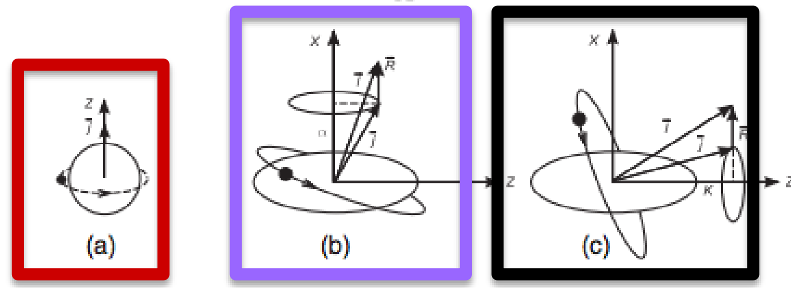
NuP *R. F Garcia Rui* ... **12 (2016) 594**

Quadrupole moment of ^{219}Fr





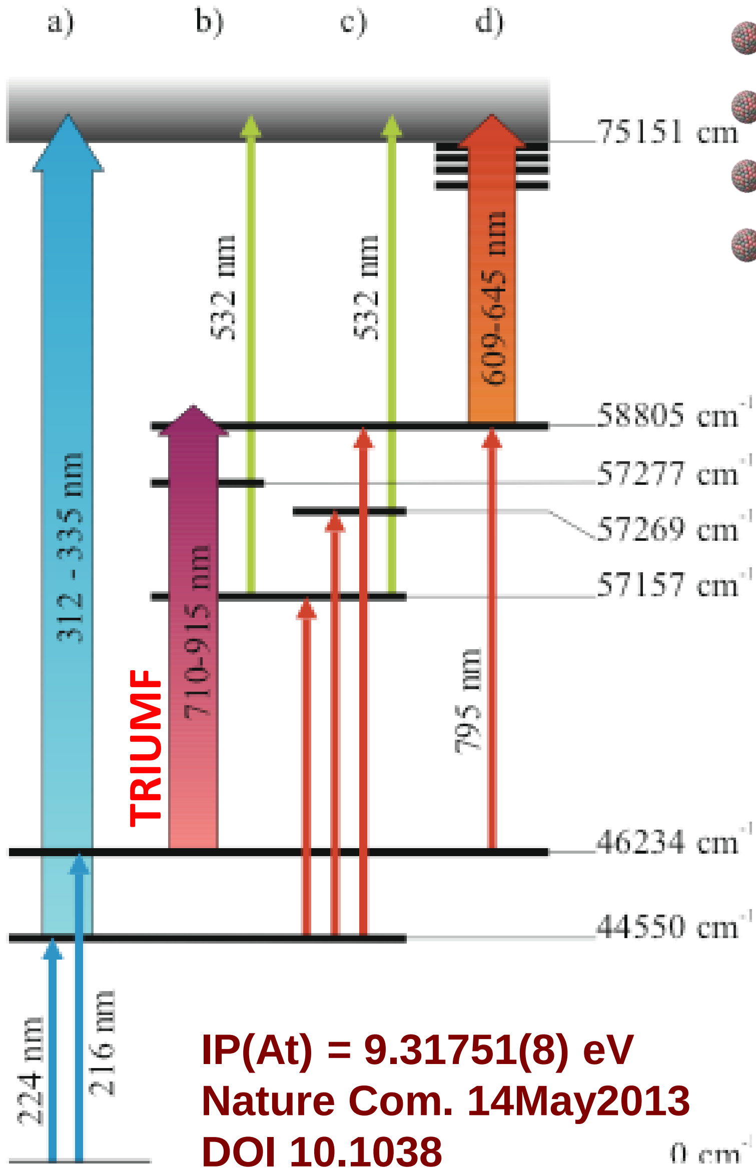
- HFS of short-lived ^{219}Fr measured
  - $t_{1/2}$ = 22 ms
  - Linewidth of 20(1) MHz
- Q_s = -1.21(2) eb
- β_2 = 0.094



- Spherical up to N=126 → Sudden deformation in gs for $^{219\text{-}225}$Fr
  - Strongly negative to strongly positive Q_s
  - Changing influence of Coriolis mixing on prolate-deformed structures

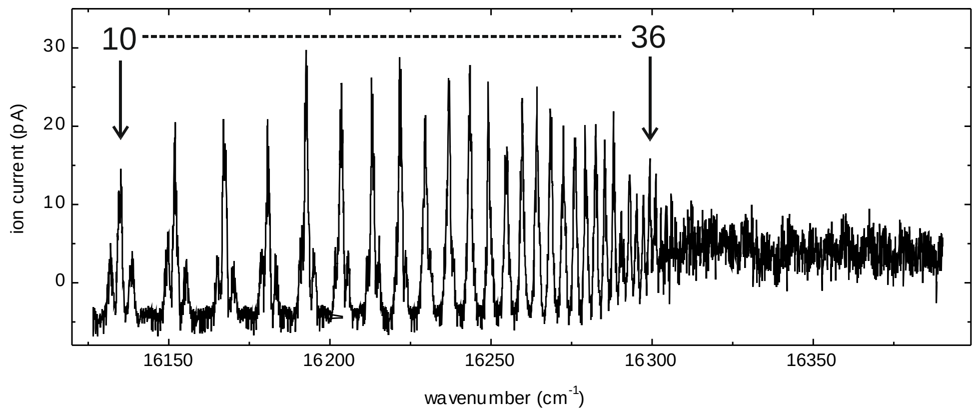
R.P. de Groote et al., Phys. Rev. Lett. **115** 132501 (2015)

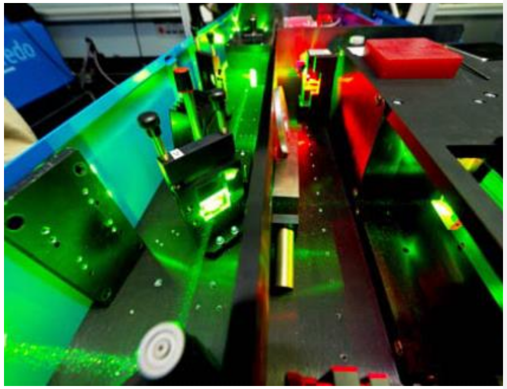
Atomic properties of Astatine

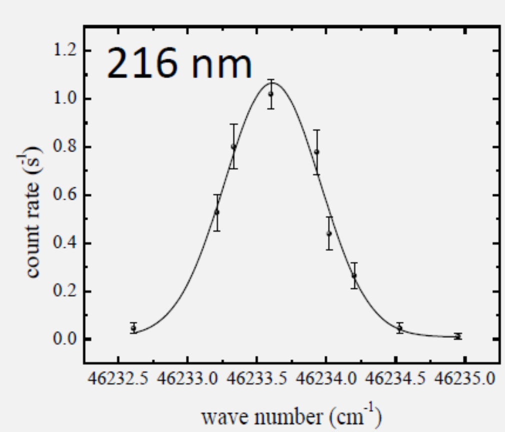


IP(At) = 9.31751(8) eV
Nature Com. 14May2013
DOI 10.1038

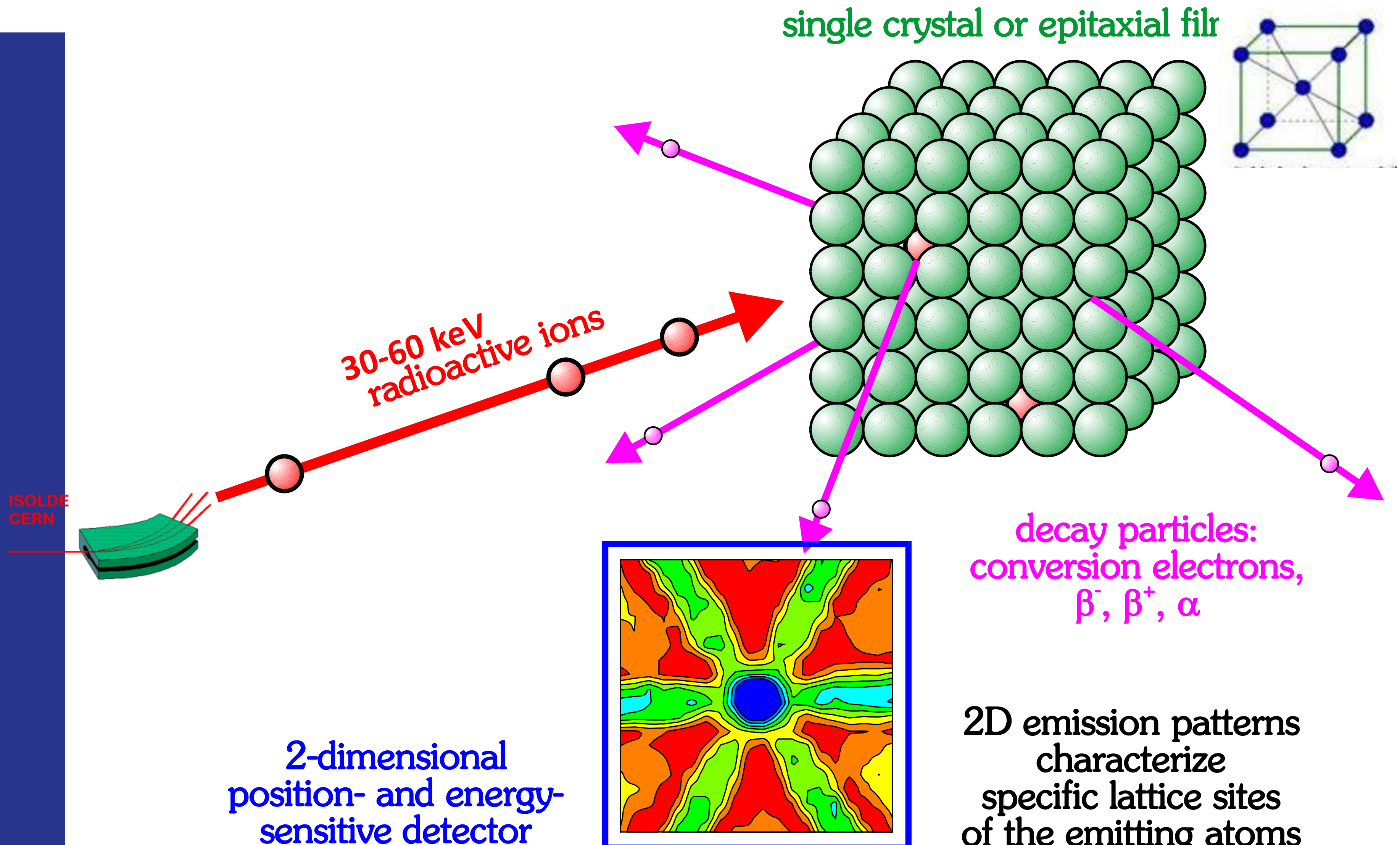
- Determination of ionising potential
- Identification of new atomic transitions
- Comparison with atomic theory
- Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP







Emission channeling at ISOLDE

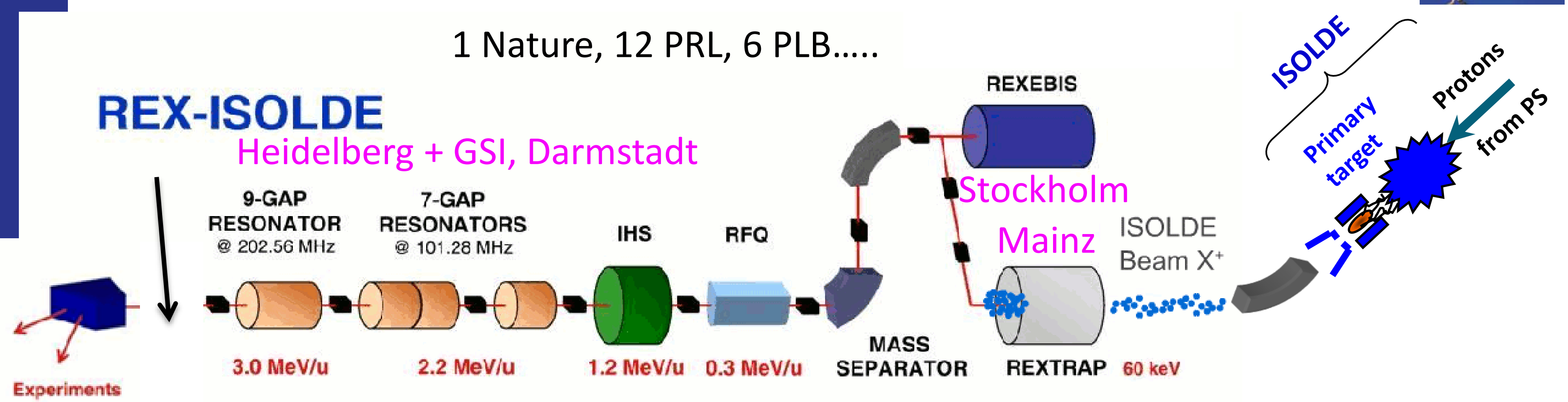


ESS W-target – release test

Post-accelerator: REX-ISOLDE

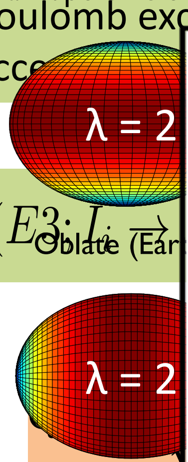
- **Built @ different Universities**
- Approved in 1994 as an experiment: "Radioactive EXperiment.."
- First beams @ 2.2 MeV/u in Oct 2001
- Upgrade to 3.1 MeV/u completed in 2004
- REX Universal post-accelerator from He to Ra (A=224) > **100 different beams**
- In 2006 a new hall extension in preparation for HIE-ISOLDE

1 Nature, 12 PRL, 6 PLB.....



Searching for pear-shaped nuclei at ISOLDE

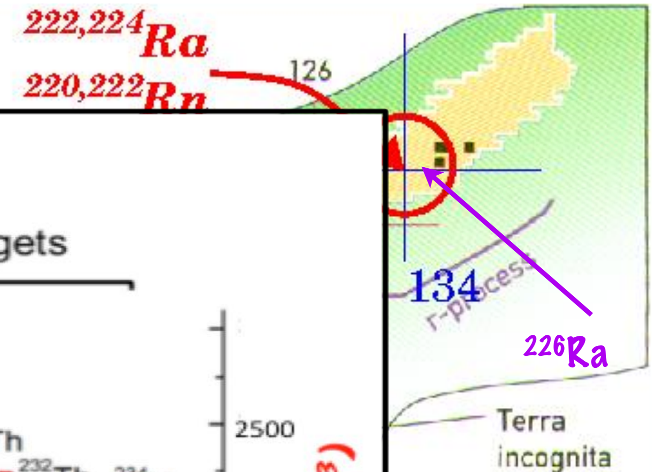
Quadrupole deformation
Coulomb excitation to directly
acce



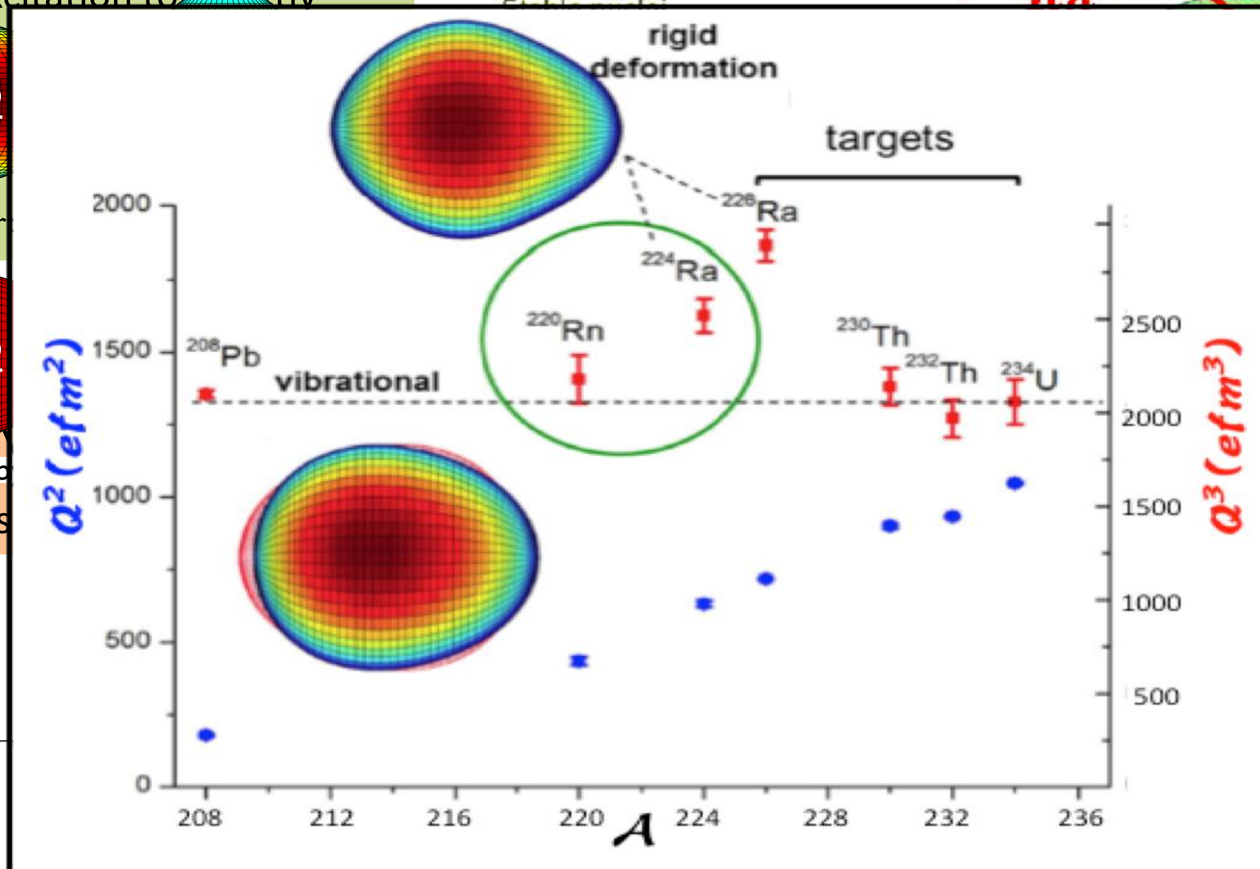
$B(E3; I_i \rightarrow$

B(E3) ≳ 30 s

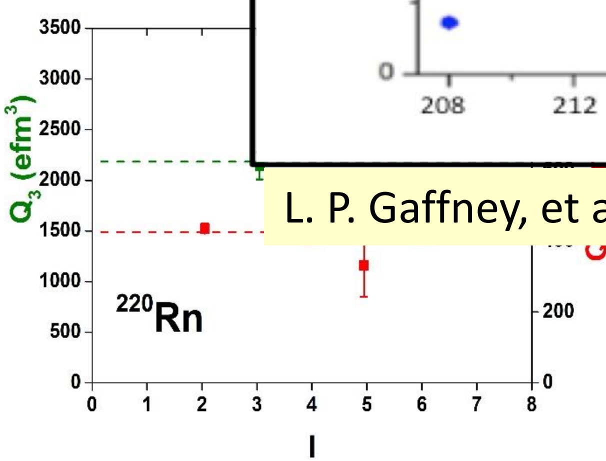
β_3

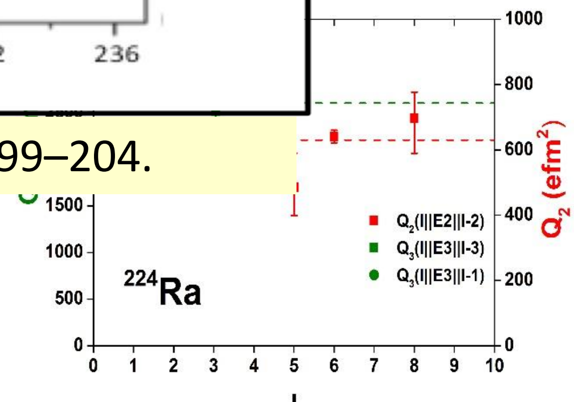


enhancement



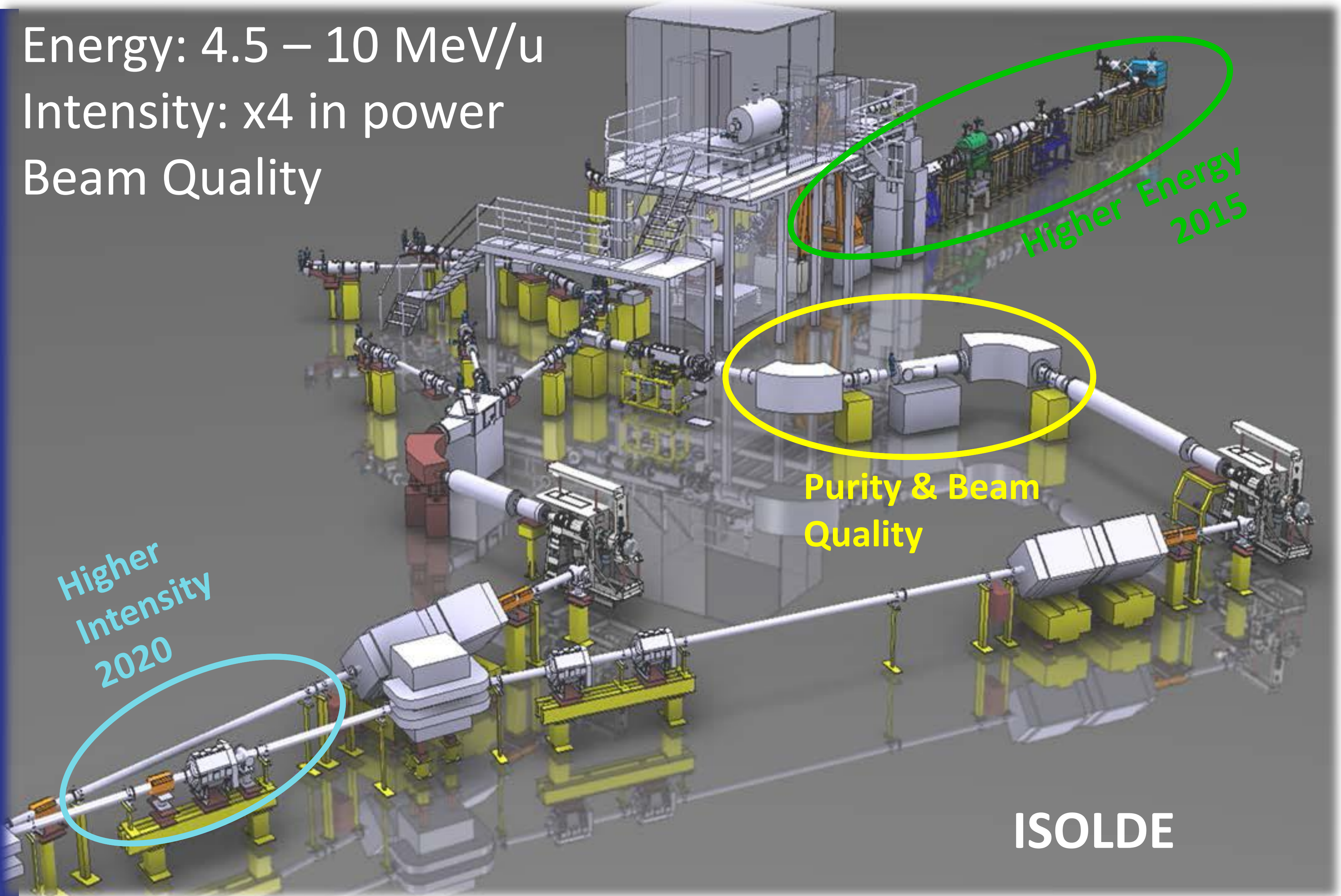
L. P. Gaffney, et al. (2013). Nature, **497**(7448), 199–204.





The HIE-ISOLDE project (2010 -)

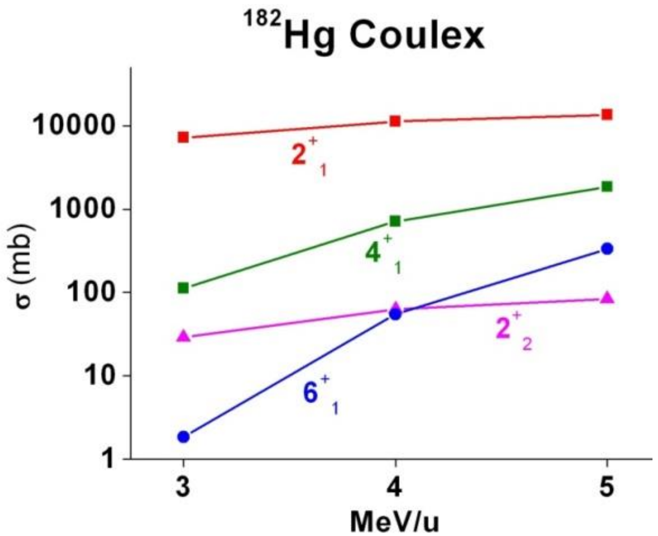
Energy: 4.5 – 10 MeV/u
Intensity: x4 in power
Beam Quality



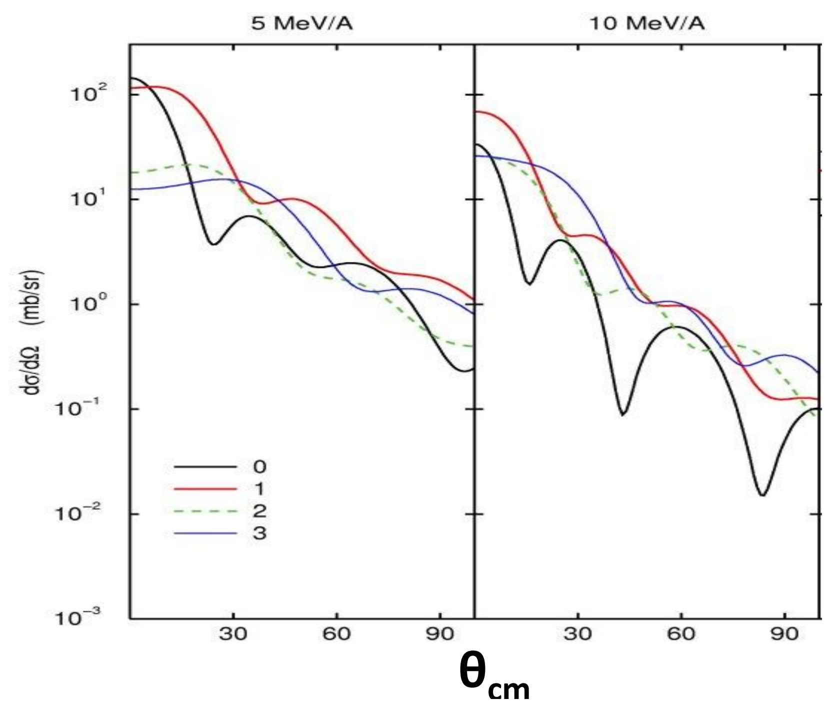
Advantages of HIE-ISOLDE

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

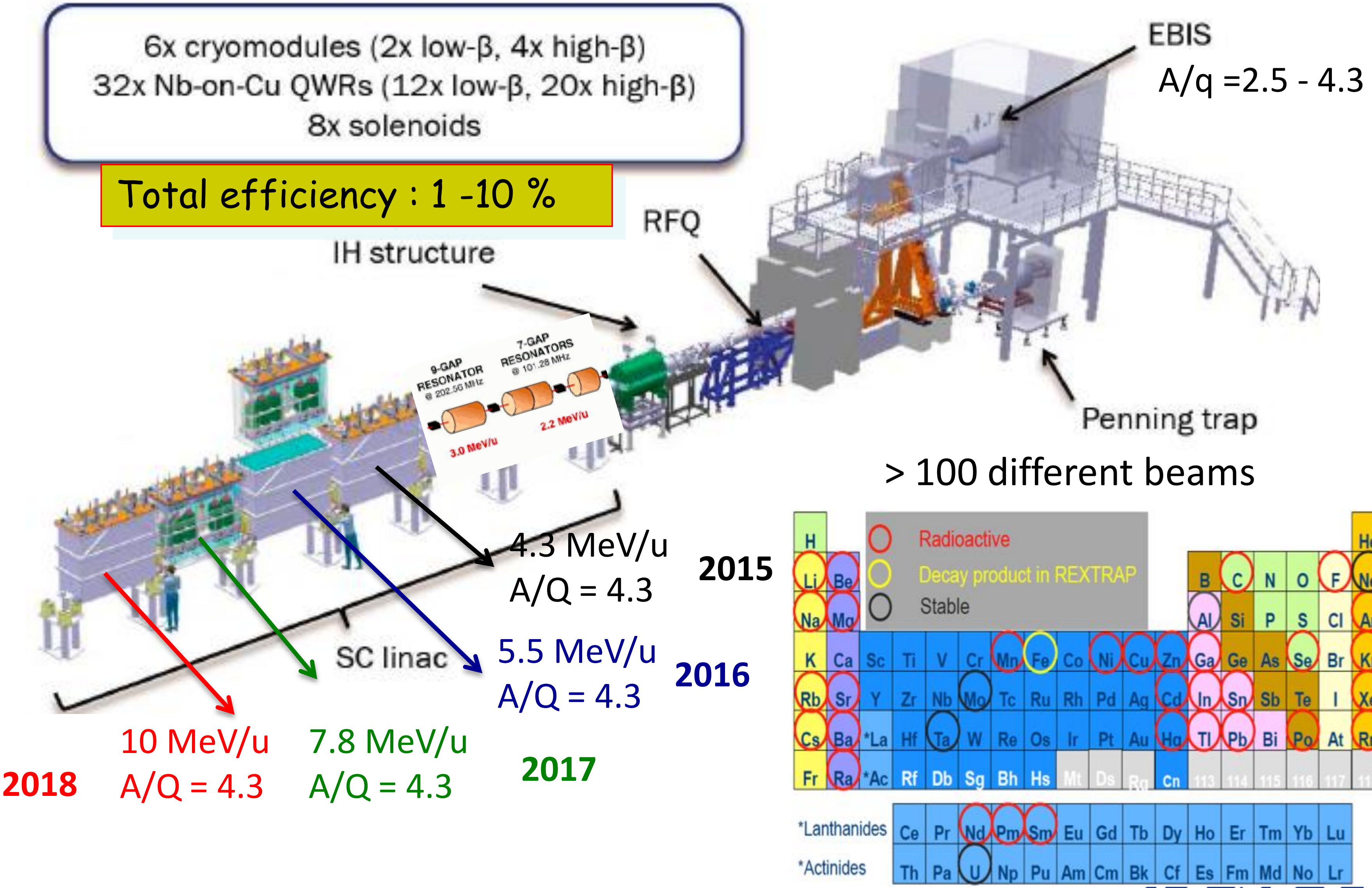


- ❑ Access to a wealth of spectroscopic information
- ❑ From the absolutes intensities of $4^+/2^+$ (multistep coulex)

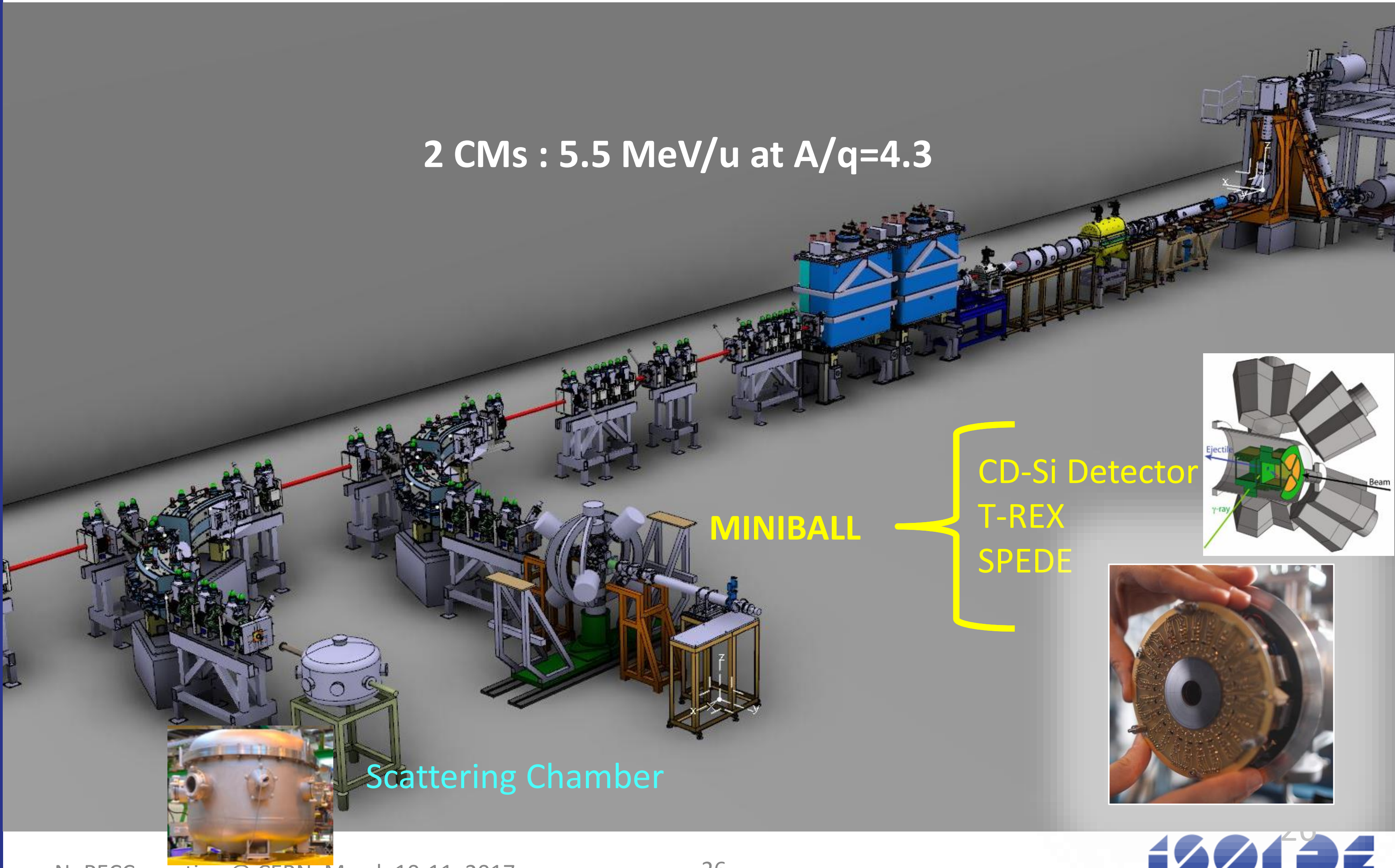
⇒Access to the sign of deformation

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

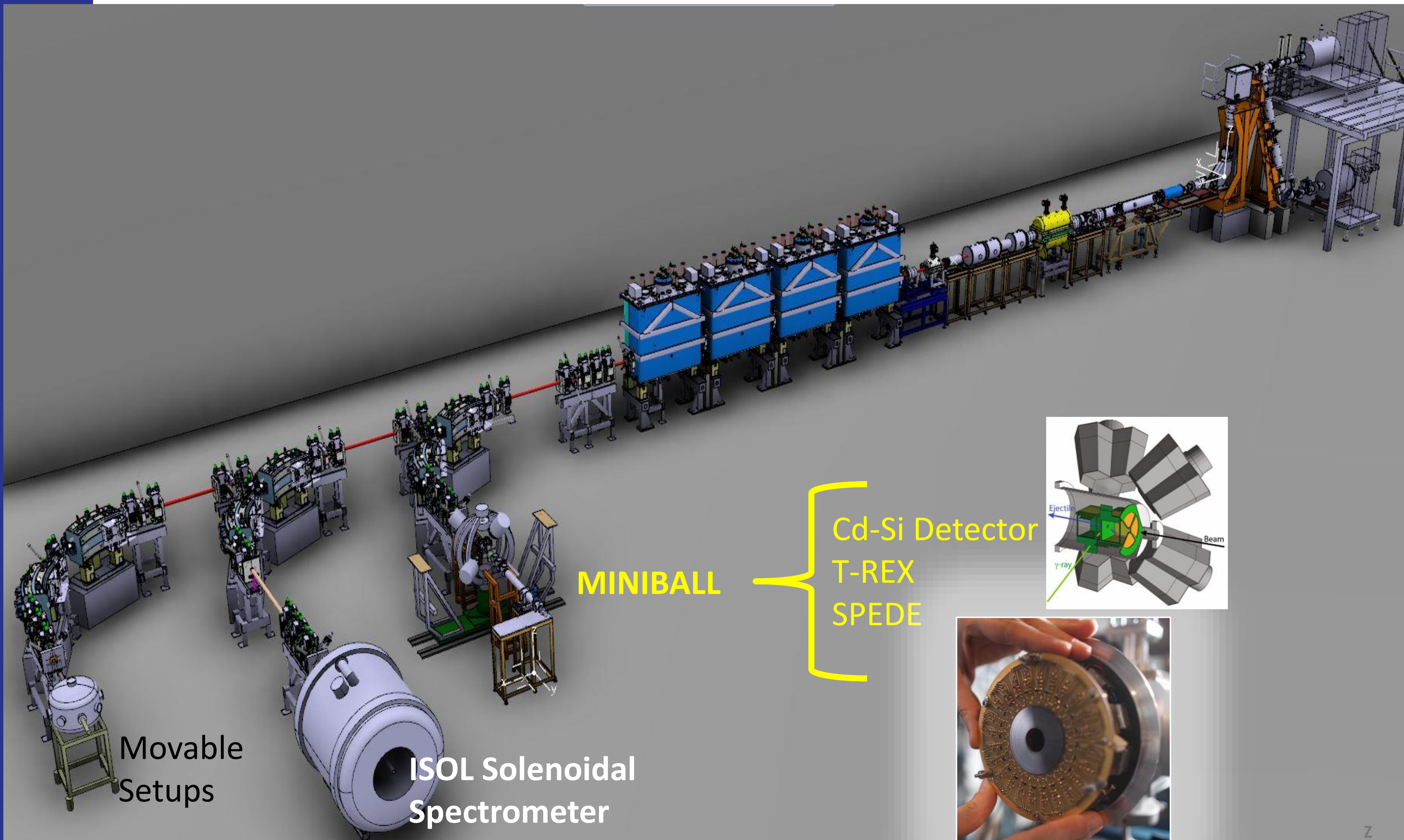
High Energy Increase HIE-ISOLDE



HIE-ISOLDE Phase 1 (2010-2016)



HIE-ISOLDE Phase 2 (2017-2018)

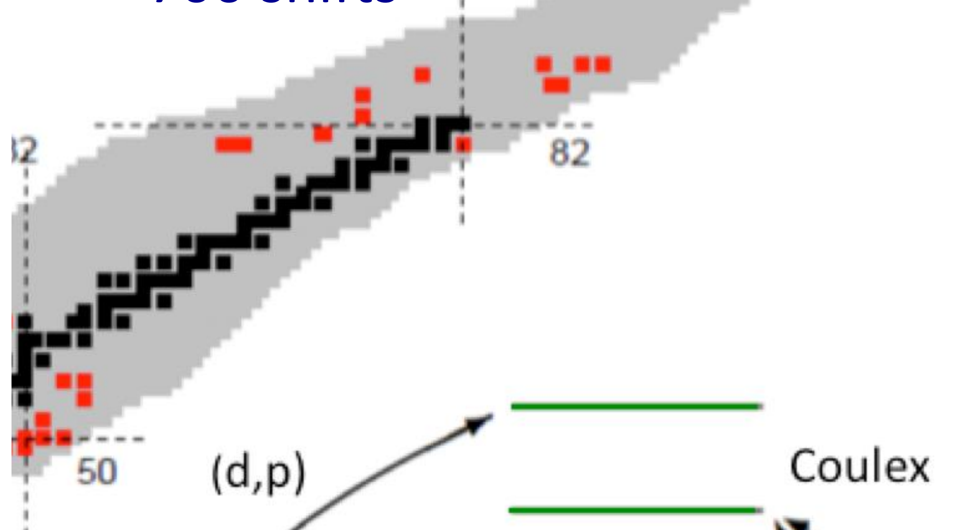


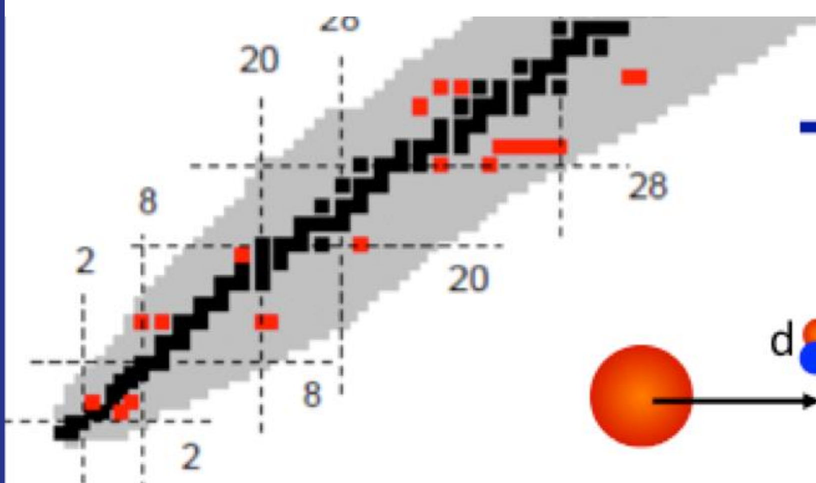
Physics at HIE-ISOLDE

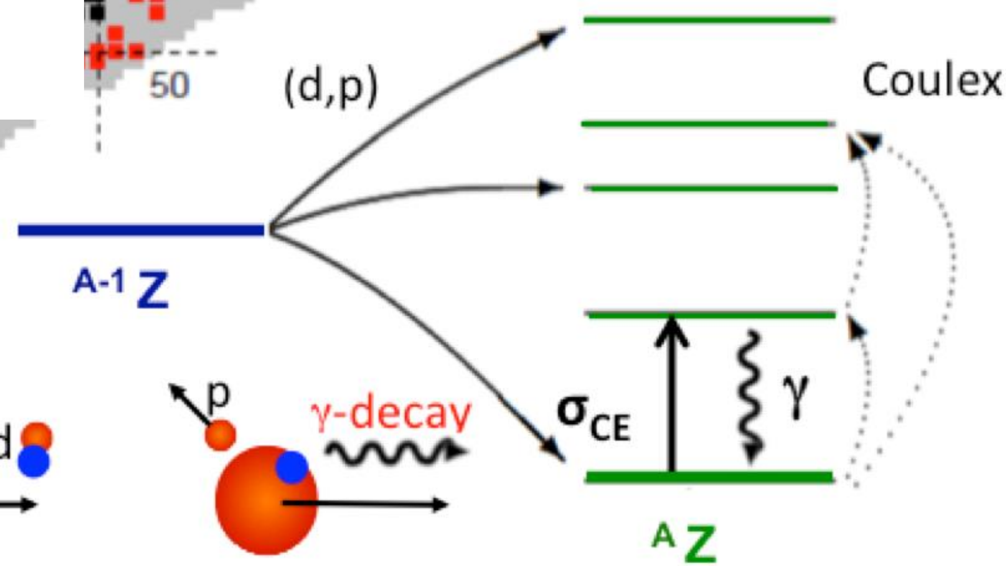
The new energy window gives the opportunity to address new physics questions

- 35 Experiments approved
  > 700 shifts

- Isospin symmetry
- Magic numbers far from stability
- Collectivity versus Single Particle
- Shape Coexistence
- Quadrupole and Octupole degrees of freedom
- Reaction for nucleo-synthesis studies





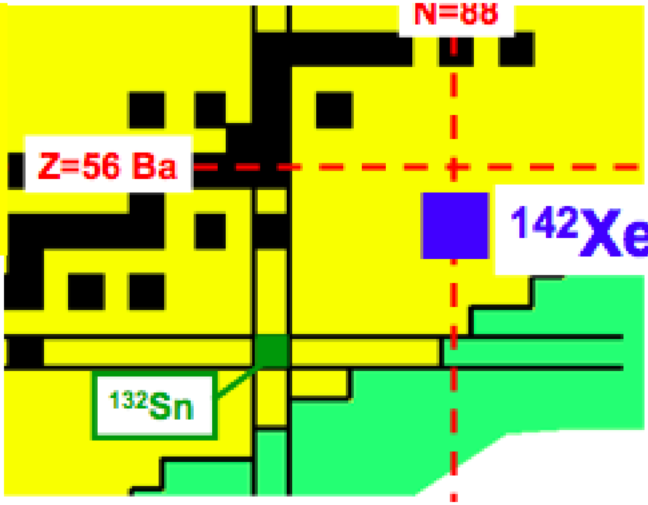


Radioactive beams @ 5.5 MeV/u

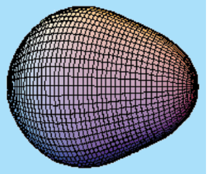
- HIE-ISOLDE stage 1 with 2 cryomodules producing physics
- First radioactive beams on 9 September 2016 ^{110}Sn
- Coulomb excitation of ^{78}Zn, ^{110}Sn, ^{132}Sn, ^{142}Xe

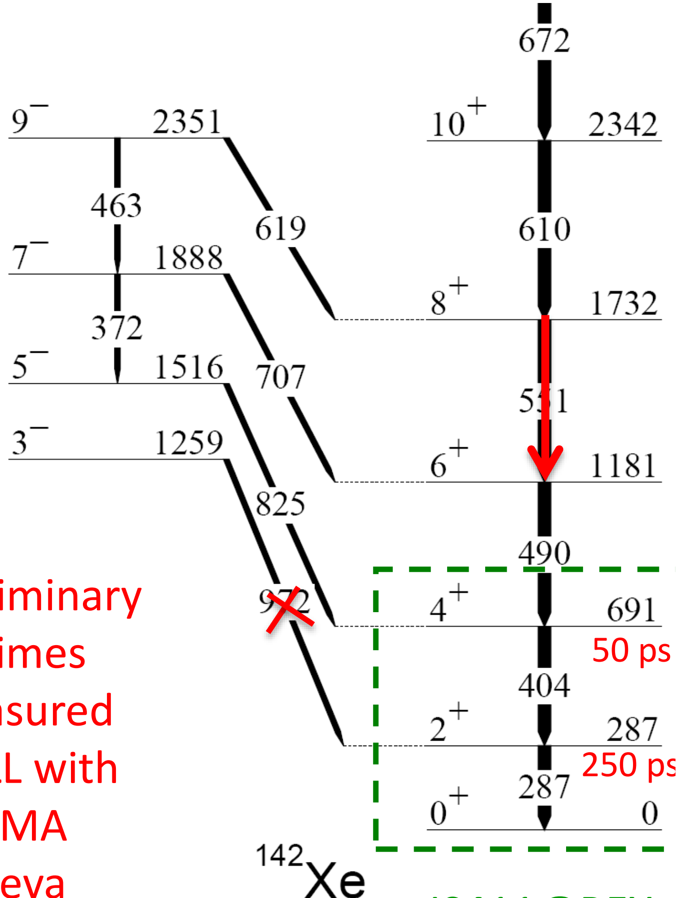
Evolution of Quadrupole and Octupole collectivity in n-rich Xe

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



Octupole "magic" numbers

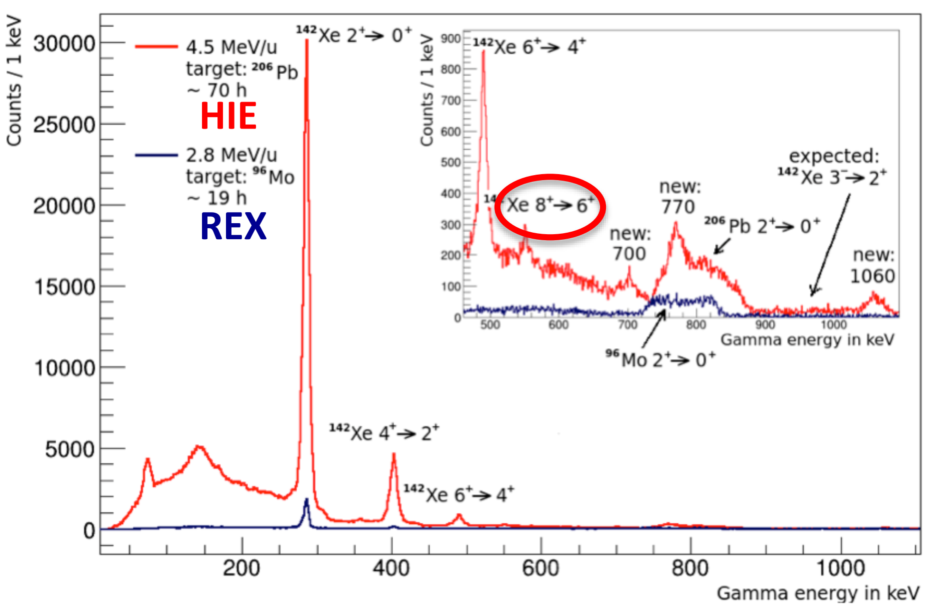




Preliminary lifetimes measured at ILL with FATIMA S. Ilieva

IS411@REX

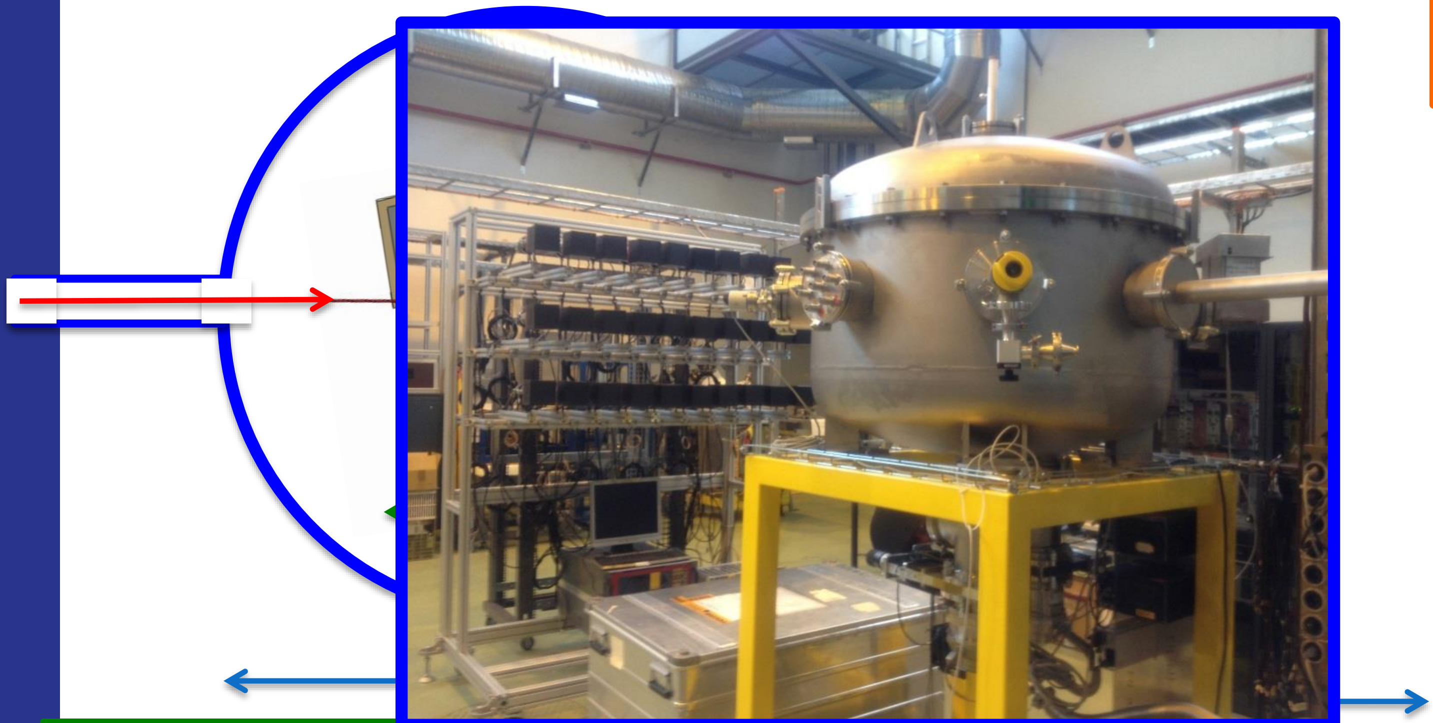
Doppler corrected with respect to Xe

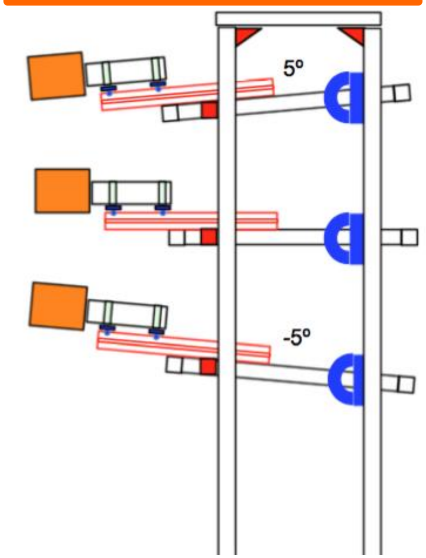


Transfer reactions at the neutron Dripline

- **Study of ^{9}Li (d,p) to study ^{10}Li resonances @ 6.8 MeV/u (2016)**
- Study of ^{9}Li (t,p) to study @ 8.7 MeV/u:
  - ^{11}Li halo composition / 2n spectroscopic factor
  - Search for resonances just above the threshold on ^{11}Li predicted by 3-body models
  - Isotropic Neutron emission?

SAND:
30 (2x12+6) **n-detectors**
2º angular resolution,





Charge particle set-up: **angular resolution 1-3º**
1x S3 DSSD in forward direction covering angles **6 – 32º**
5x DSSD telescopes surrounding target en forma pentagon **44 – 104º**
1x DSSD telescope en backward direction **94 – 134º**

Summary & Outlook

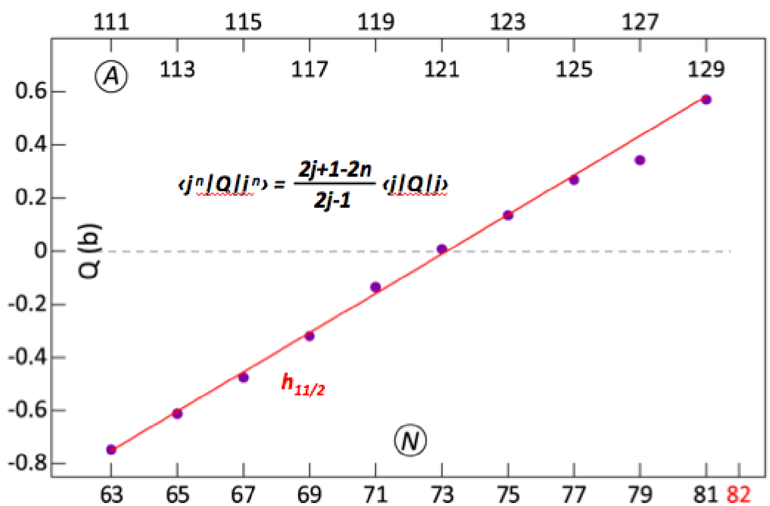
- ISOLDE operative since almost 50 years is in continuous transformation to stay at the forefront of nuclear physics research.
- Plenty of challenging physics at ISOLDE and HIE-ISOLDE!
- Many new devices and groups have been attracted by the increase of energy of the post-accelerated beams.
- **HIE-ISOLDE stage 1 in operation with energies of 5.5 MeV/u for A/Q =4. & 6.8 MeV/u for A/Q = 3.**
- In 2017: third cryomodule connected reaching energies of 7.5MeV/u for A/q = 4 and 3rd beamline.
- **In 2018: energies up 10 MeV/u for A/q = 4.**

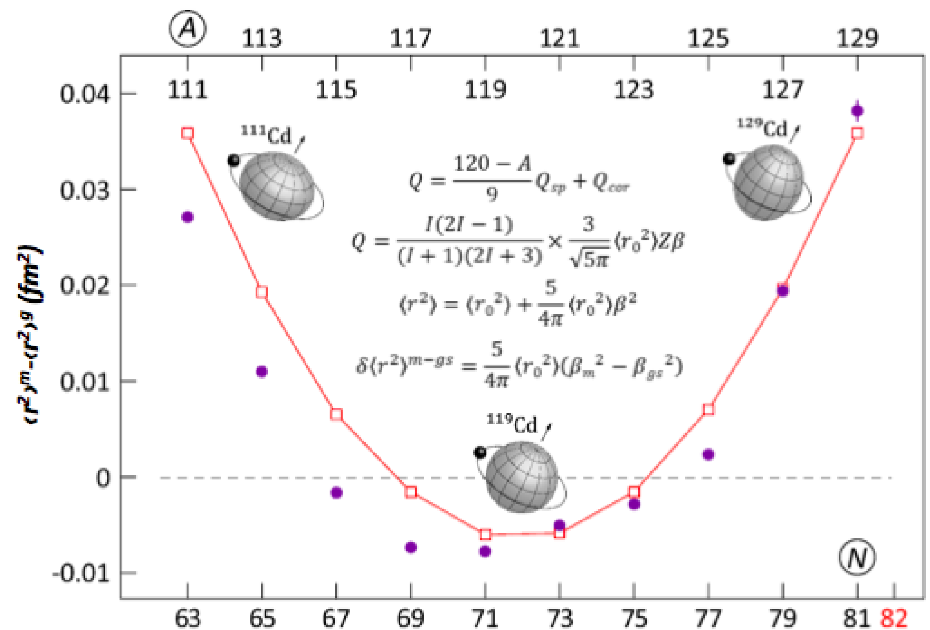
Thanks for your attention !

Cd-nuclei: too simple or too complex?

- N-Rich Cd isotopes of importance for the r-process:
  - $^{129-131}$Cd masses determined @ISOLTRAP   Atanasov, PRL115 (2015) 232501
  - βn with VANDLE @ IDS
  - Radii and Q-moments @ COLLAPS

Simple Structure in Complex Cd isotopes: Q of 11/2$^-$ States



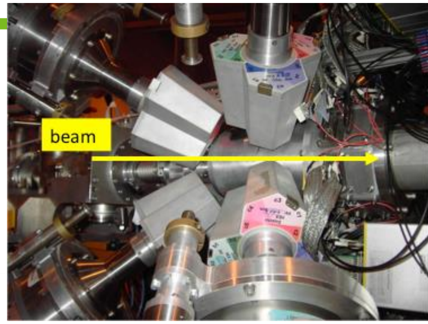


Simplicity due to filling of the $h_{11/2}$.
Expected for extreme shell model (6-odd)
Contribution from degenerated orbitals
Proton-core polarization

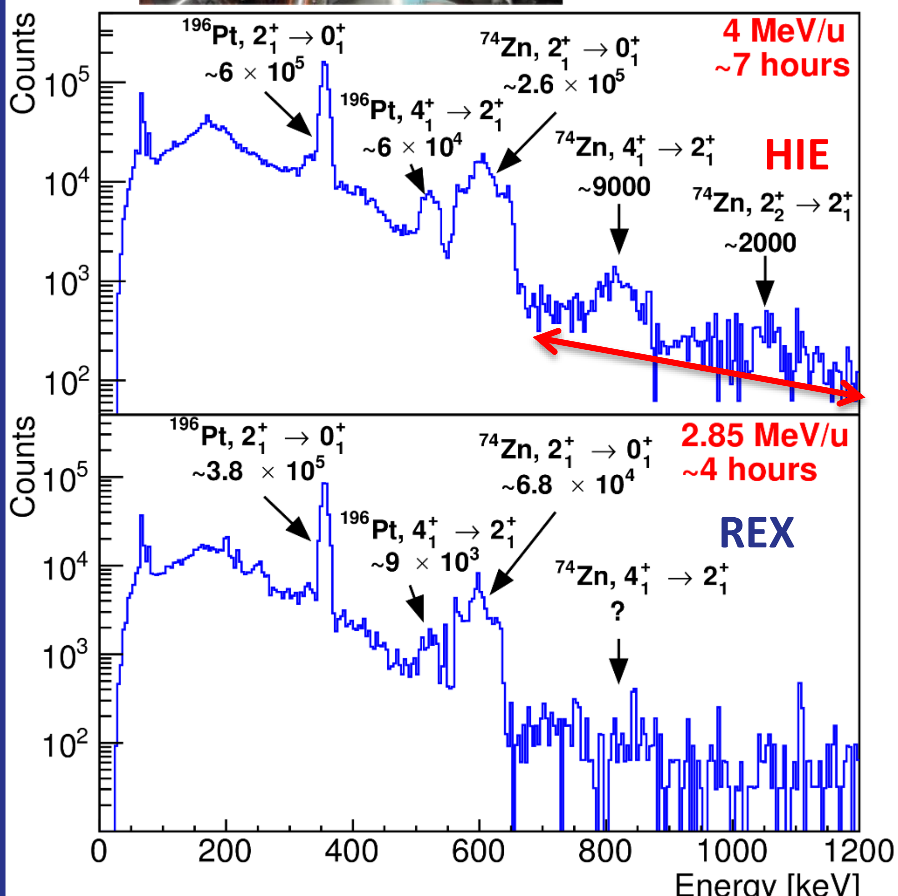
Parabolic behaviour!!!
filling of the $h_{11/2}$ starting oblate and then prolate.

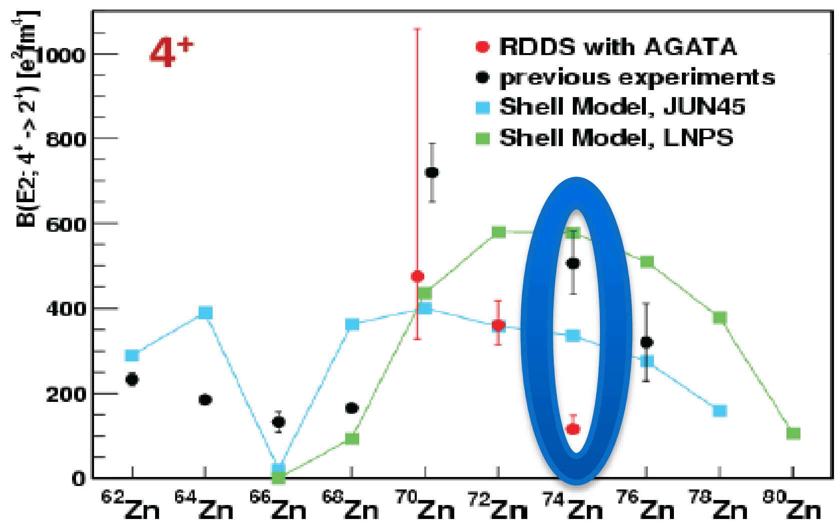
Yordanov, PRL 110 (2013) 192501   PRL 116 (2016) 032501

First Radioactive beams in 2015 @ 4 MeV/u



- Coulomb excitation of ^{74}Zn and ^{76}Zn studied at higher energy.
- Excitation energy domain enlarged!



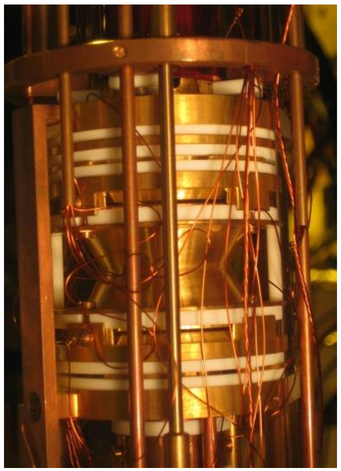


- ✓ Large disagreement for ^{74}Zn B(E2)
- ✓ Louchart PRC87 (2013) 054302 (AGATA) and Van der Valle PRC79 (2009) 014309

ISOLDE

Experimental Techniques

Traps for masses



$\omega_c = qB / m$

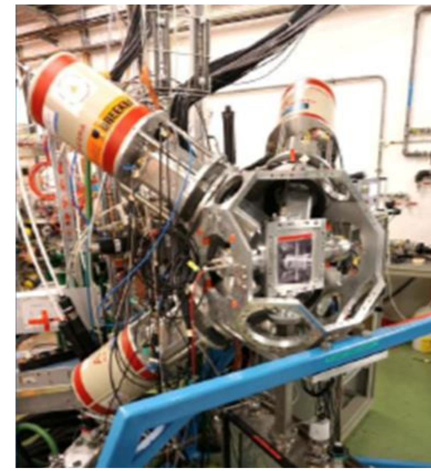
Talk by K. Blaum!

Lasers for radii & e-m moments

$$\delta\nu_{\mathrm{IS}}^{AA'} \propto \Delta\left|\Psi(0)\right|^2 \delta\left\langle r^2\right\rangle^{AA'}$$

Talk by B. Cheal!

Versatile Decay Station: IDS



$N(t) = N_0\, e^{-t/\tau}$

Talk by S. Paulauskas, A. Andreyev!

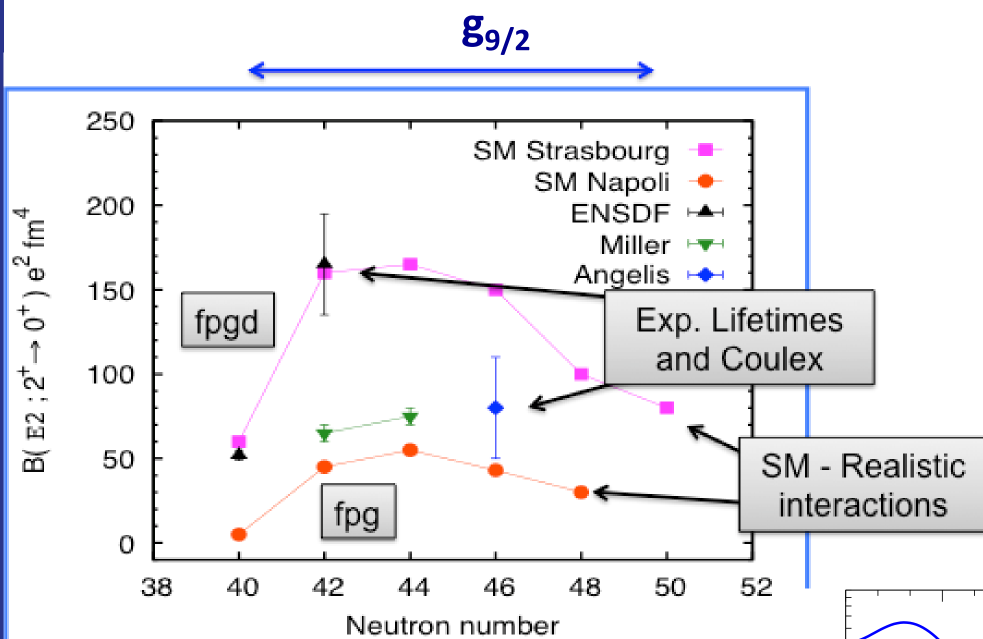
Post-acceleration For Reaccions studies

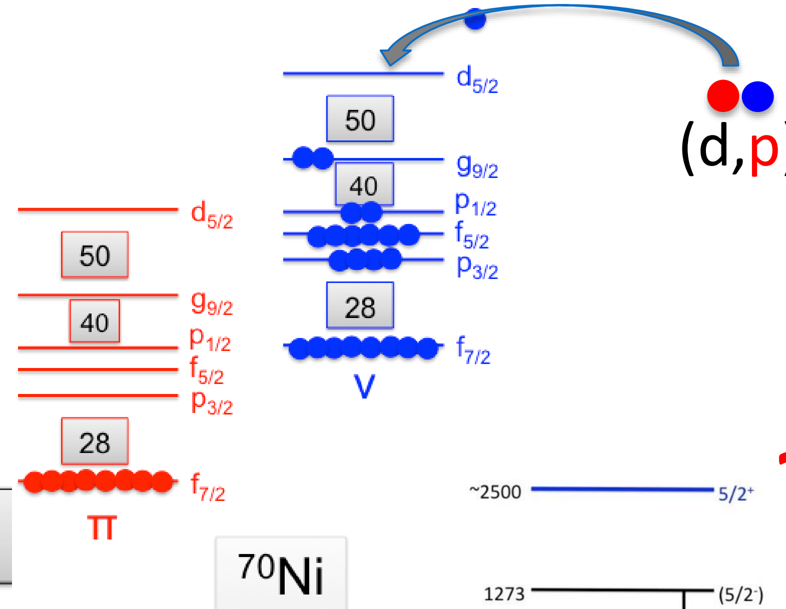
Shapes

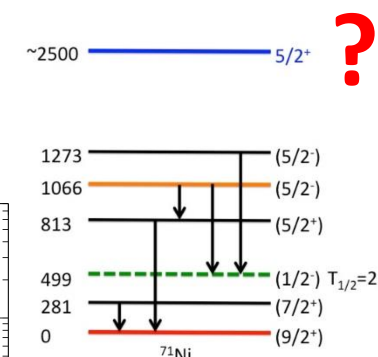
$$R = \frac{B(E2, 4^+ \rightarrow 2^+)}{B(E2, 2^+ \rightarrow 0^+)}$$

Shell Evolution in Ni-isotopes (IS555)

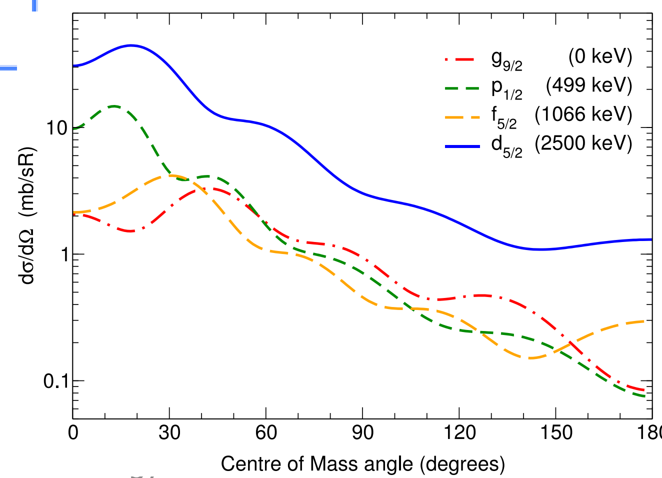
- Large theoretical and experimental discrepancies. For Ni –isotopes beyond N= 40.



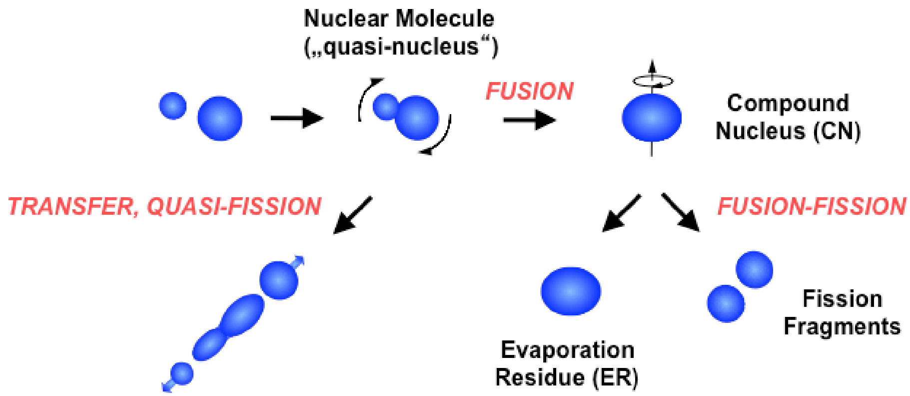




- Transfer reaction to characterize the 5/2$^+$ state in ^{71}Ni by looking to proton angular distribution with T-REX



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
- $^{95}\text{Rb} + {}^{209}\text{Bi} \rightarrow Z_1 + Z_2 = \mathbf{120}$, $N_1 + N_2 = \mathbf{184}$

Asymmetric component → transfer, quasi-fission

Symmetric component → fusion-fission

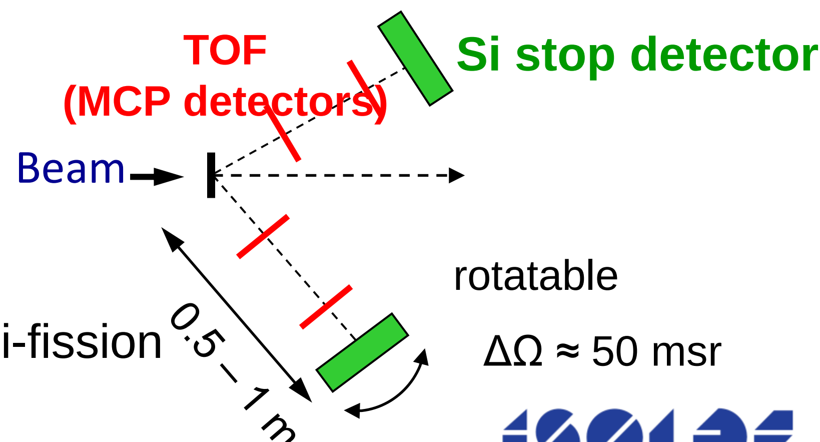
Z = 114, 120 or 126

N = 184

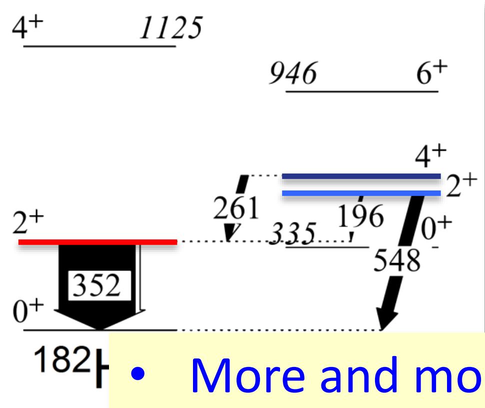
?

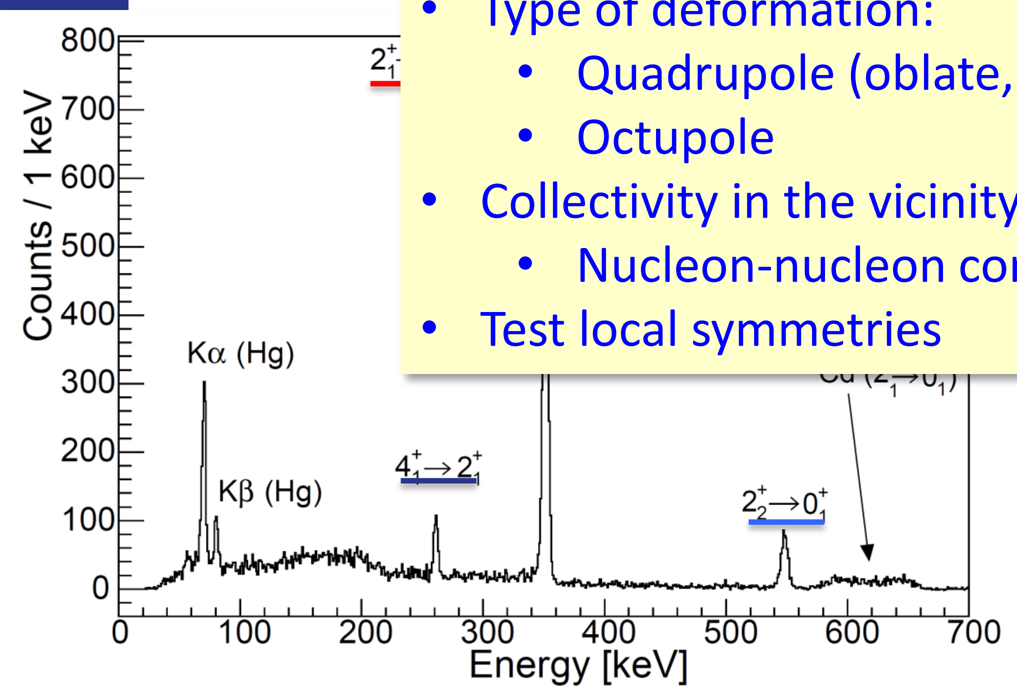
- Shell closures indicated by an increase of fission barriers and half-lives
- **Influence expected in *quasi-nuclei***

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

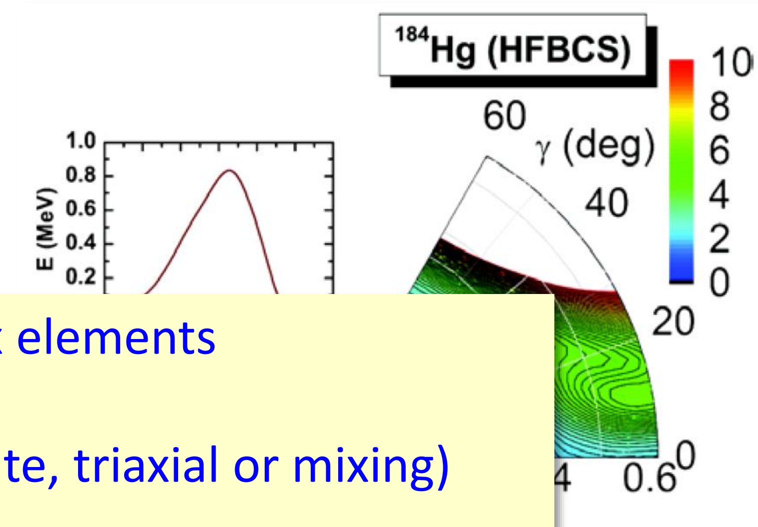


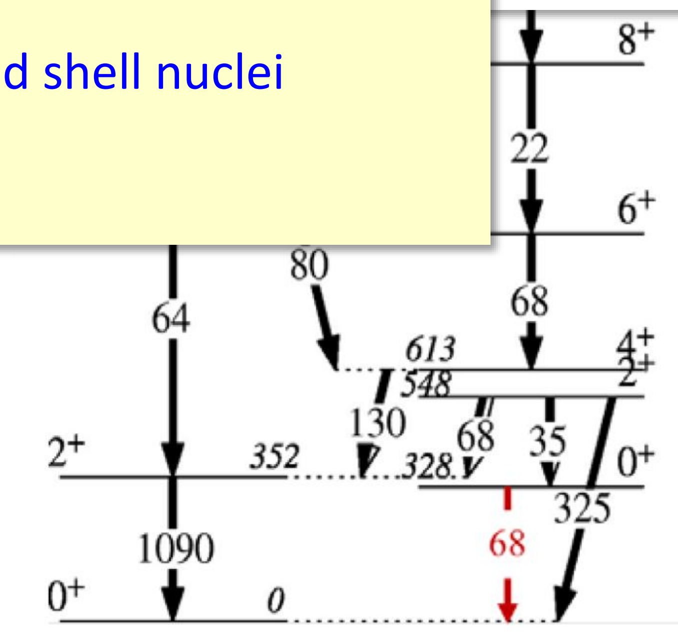
Coulomb excitation of ^{182}Hg





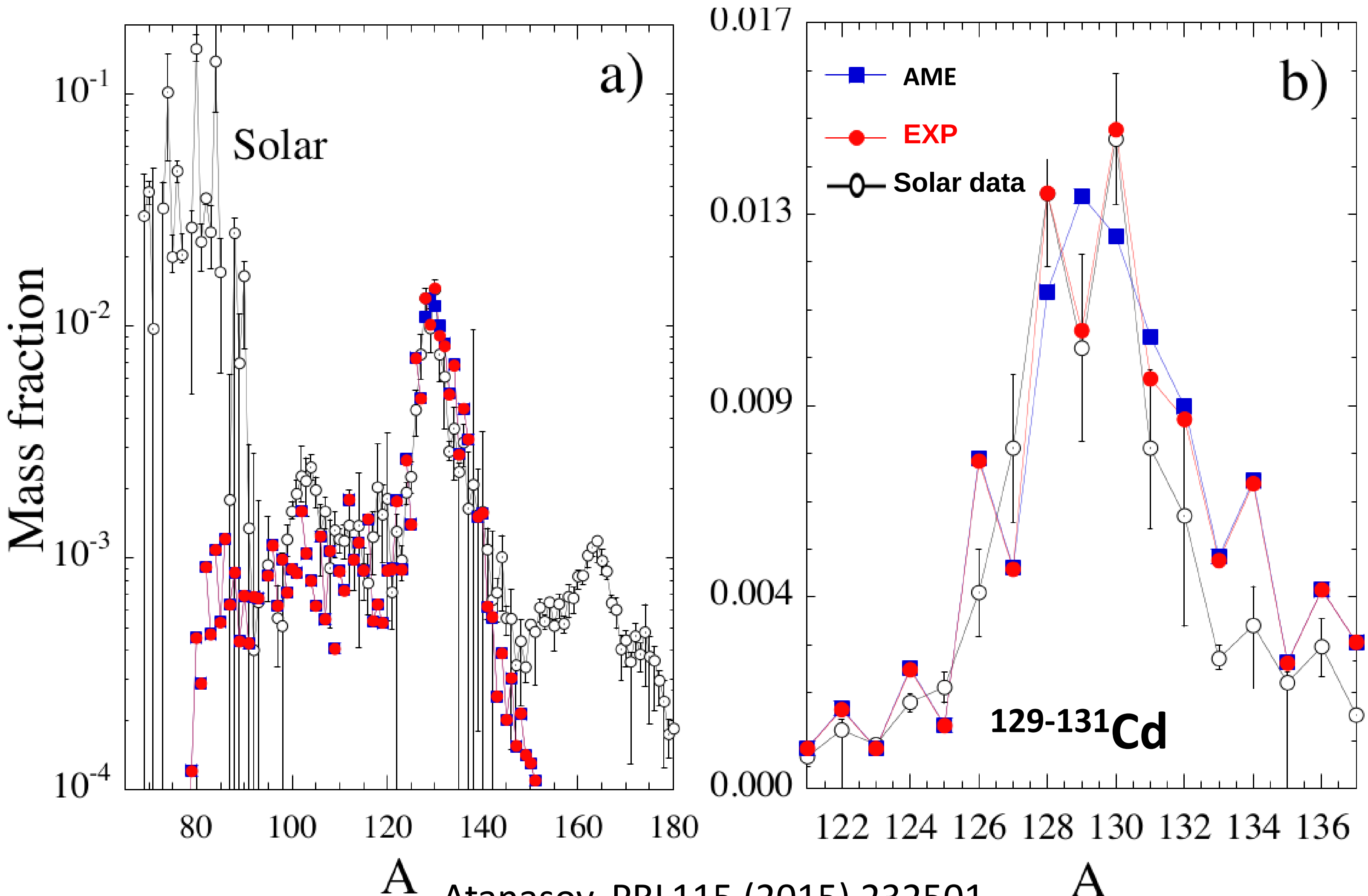
- More and more precise matrix elements
- Type of deformation:
  - Quadrupole (oblate, prolate, triaxial or mixing)
  - Octupole
- Collectivity in the vicinity of closed shell nuclei
  - Nucleon-nucleon correlation
- Test local symmetries





ISOLTRAP masses of n-rich cadmium isotopes

Data favour Core Colapse Supernova in this region



Atanasov, PRL115 (2015) 232501