HIE ISOLDE: opportunities, challenges and importance

Piet Van Duppen
Instituut voor Kern- en Stralingsfysica
K.U.Leuven, Belgium

- Importance:
  key questions in nuclear physics, nuclear astrophysics, fundamental interactions and condensed matter

- Challenges:
  experiments with Radioactive Ion Beams to answer these questions

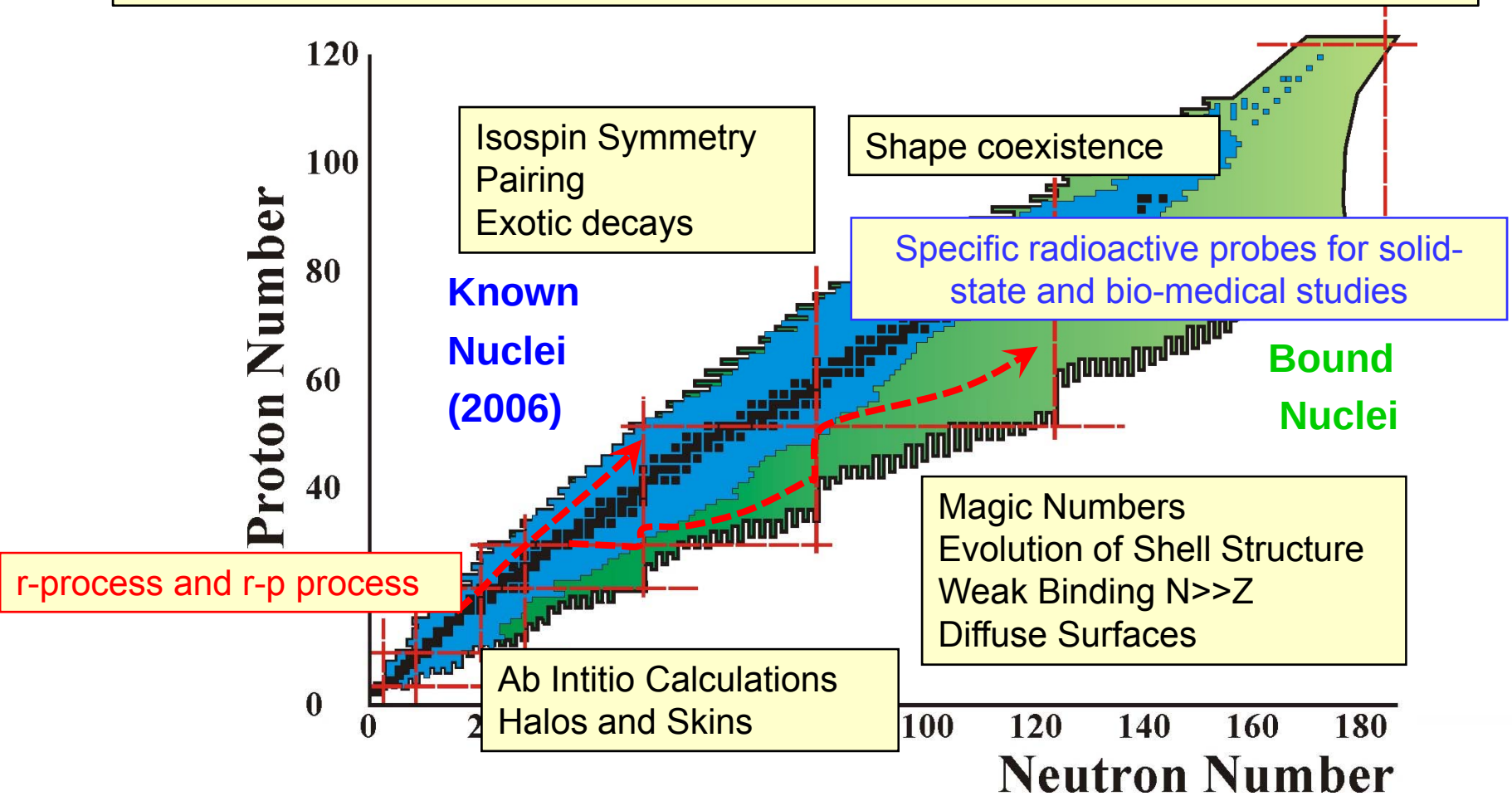
- Opportunities:
  HIE-ISOLDE - new and higher quality beams, higher energy

HIE – ISOLDE: challenges

Research with Radioactive Isotopes

- Decay and laser-spectroscopy
- Moments and mass measurements
- Solid-state physics experiments

- Coulomb excitation
- Transfer reactions
- Heavy-ion fusion reactions



HIE – ISOLDE: technical options (see talk M. Lindroos)

✓ENERGY:
Energy upgrade to 10 MeV/u and lower energy capacity

✓INTENSITY: ISOLDE proton driver beam intensity upgrade
strongly linked to PS Booster improvements including linac4

✓QUALITY: ISOLDE radioactive ion beam quality: broader spectrum and higher quality (purity, emittance, time structure)

HIE – ISOLDE: opportunities

✓Wide spectrum of radioactive ion beams

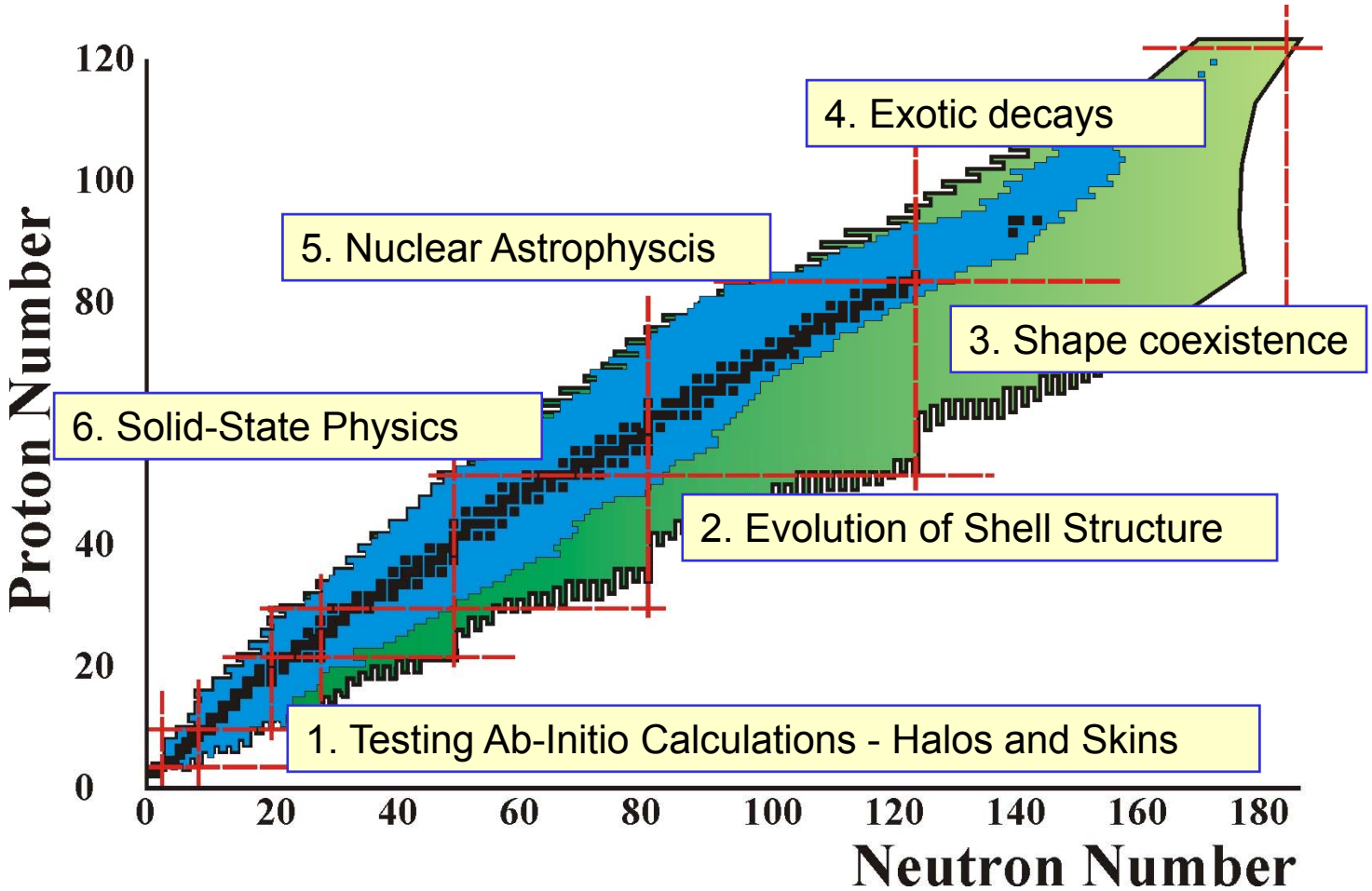
✓ Wide energy range: from rest to 10 MeV/u

✓ Pure beams occupying a small phase space: allows for low-intensity RIB experiments

✓ Isomeric beams: nuclear spin degree of freedom

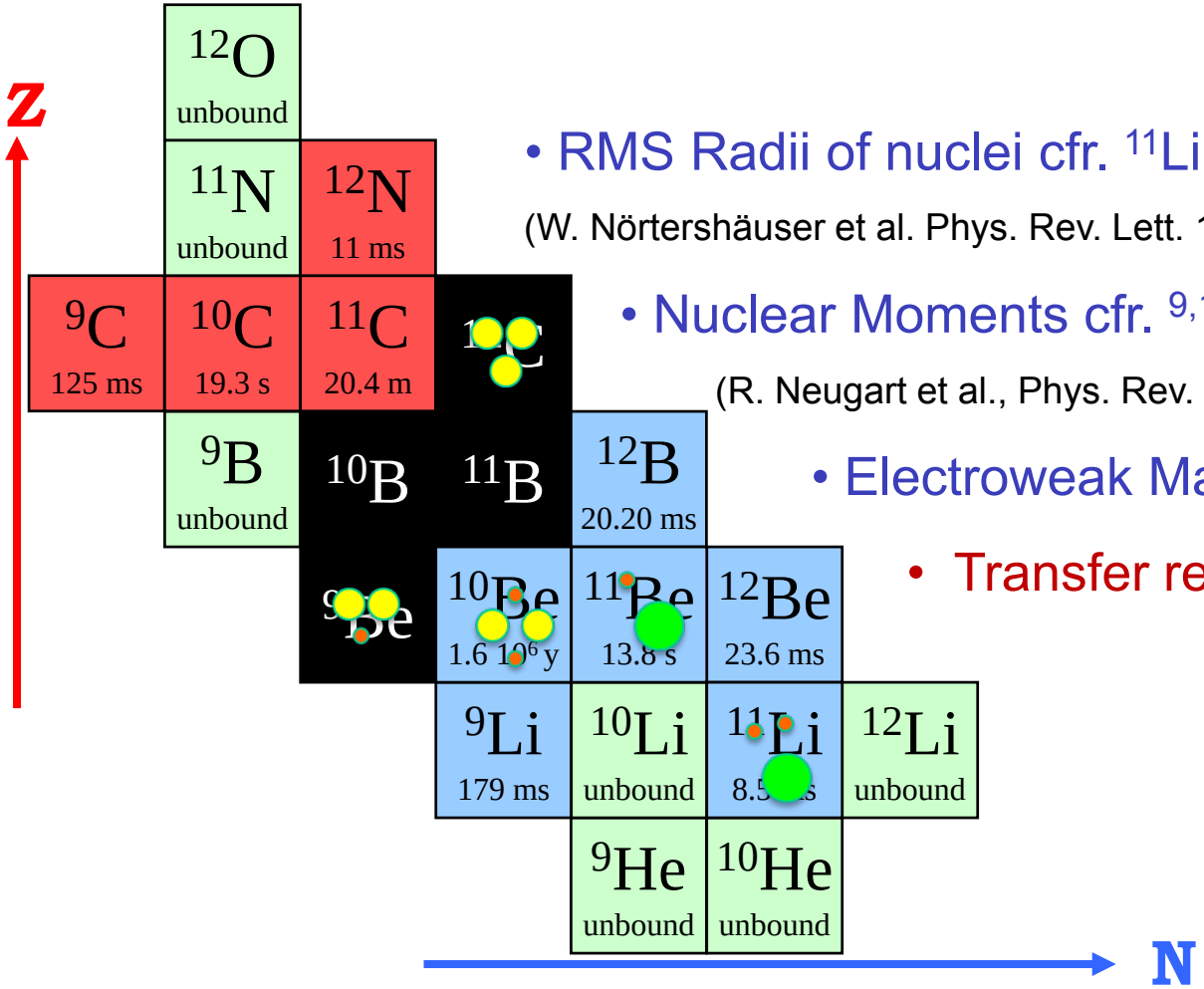
Intensity and quality upgrade and the extended variety of beams will create new opportunities to the current research programs (cfr. K. Riisager)
This presentation mainly focuses on the higher energy capabilities

HIE – ISOLDE: opportunities



- Fundamental Interactions: N. Severijns, M. Kowalska, M. Scheck ID 45, 52, 59, 66, 67, 69, 85
- Atomic physics: ID 93
- Bio-medical and medical applications: ID 44

1. Testing Ab-Initio Calculations



- RMS Radii of nuclei cfr. ^{11}Li, ^{9,10}Be (abstract ID 96)

(W. Nörtershäuser et al. Phys. Rev. Lett. 102 (2009) 062503)

- Nuclear Moments cfr. ^{9,11}Li (ID 20)

(R. Neugart et al., Phys. Rev. Lett. 101 (2008) 132502)

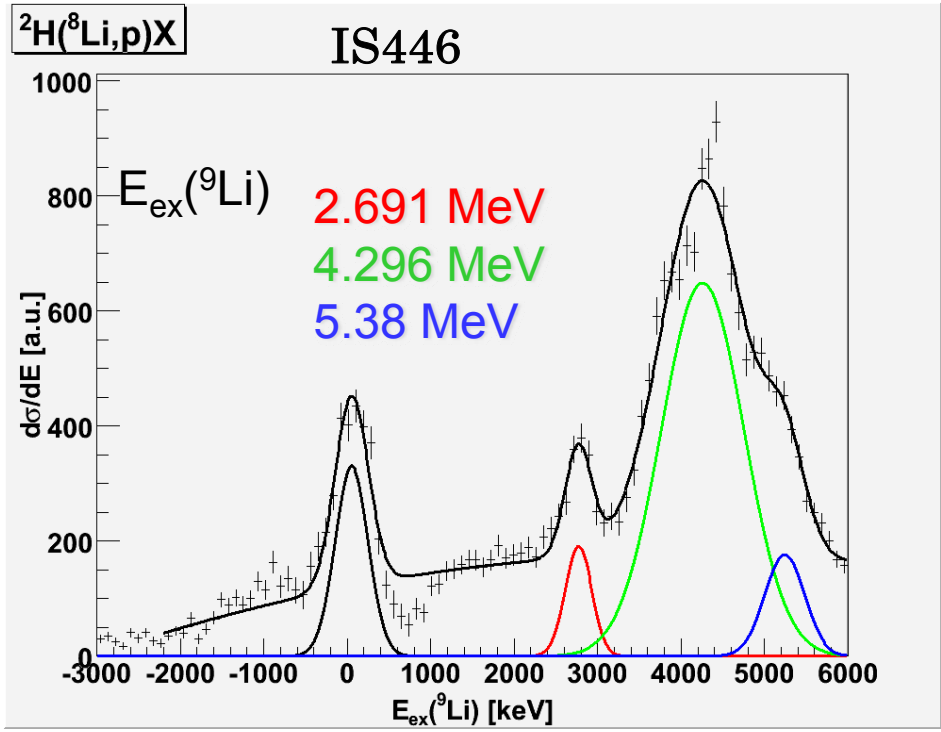
- Electroweak Matrix Elements
- Transfer reactions

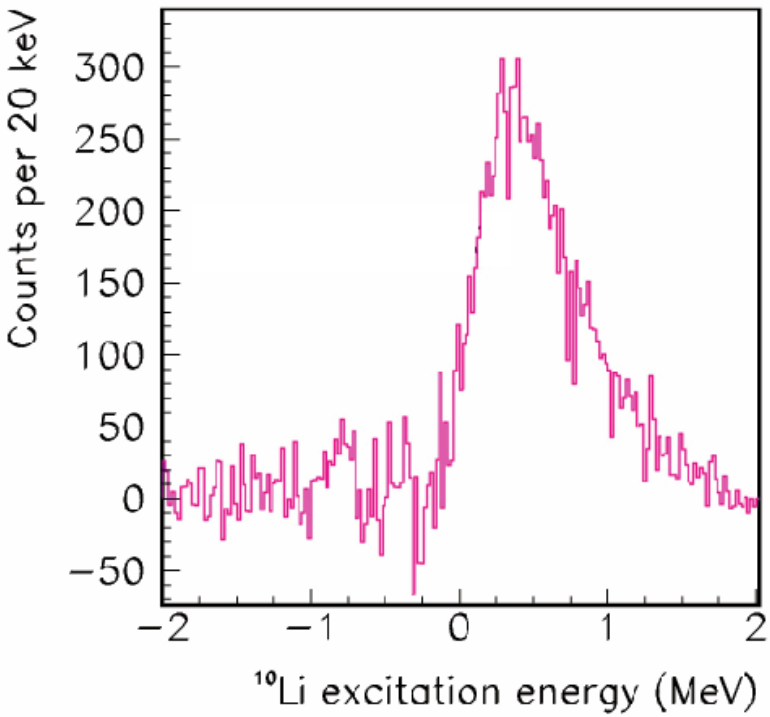
Transfer reactions

• REX-ISOLDE

d(^{8}Li,^{9}Li)p - 3.15 MeV/u, ~10^5/s
Tengborn et al.

d(^{9}Li,^{10}Li)p - 2.77 MeV/u, ~10^5/s
Kirsebom et al.





• Reaction studies with He beams:
  • ^{4}He(^{6}He,^{4}He)^{6}He @ LLN

R. Raabe et al.., Phys. Lett. B458, 1 (1999)

  • p(^{8}He,d)^{7}He @ SPIRAL-GANIL

F. Skaza et al., Phys. Rev. C 73, 044301 (2006)

  • ^{12}C(^{8}He,^{7}H->^{3}H+4n)^{13}N @ SPIRAL-GANIL

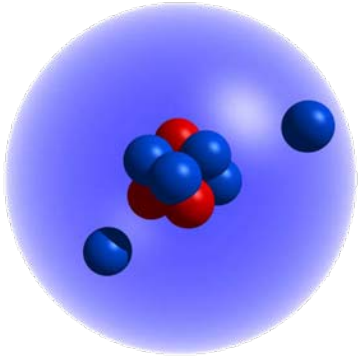
M. Caamaño *et al.*, Phys. Rev. Lett. 99, 062502 (2007)

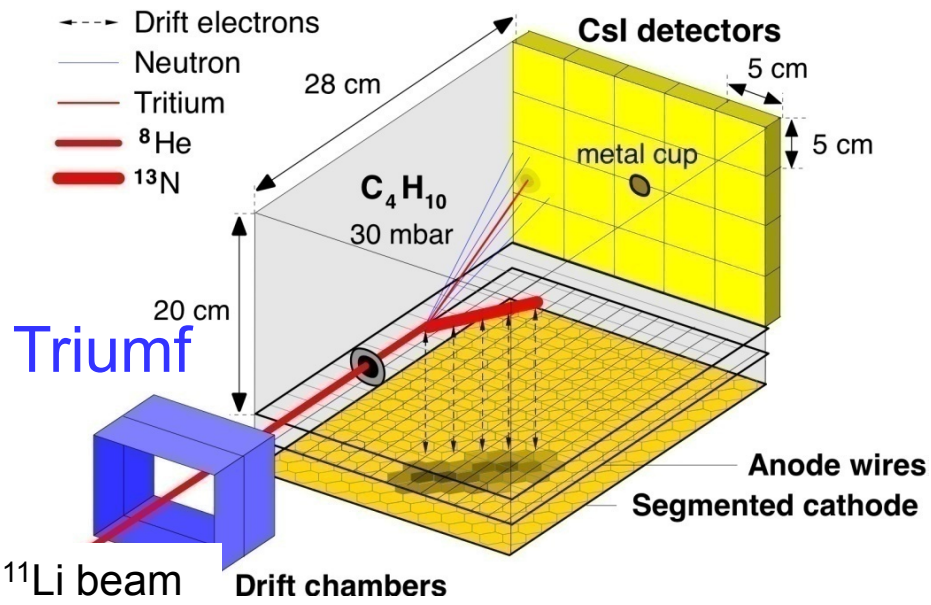
• Reaction studies with Li beams:
  • d(^{8}Li,^{9}Li)p @ ANL:

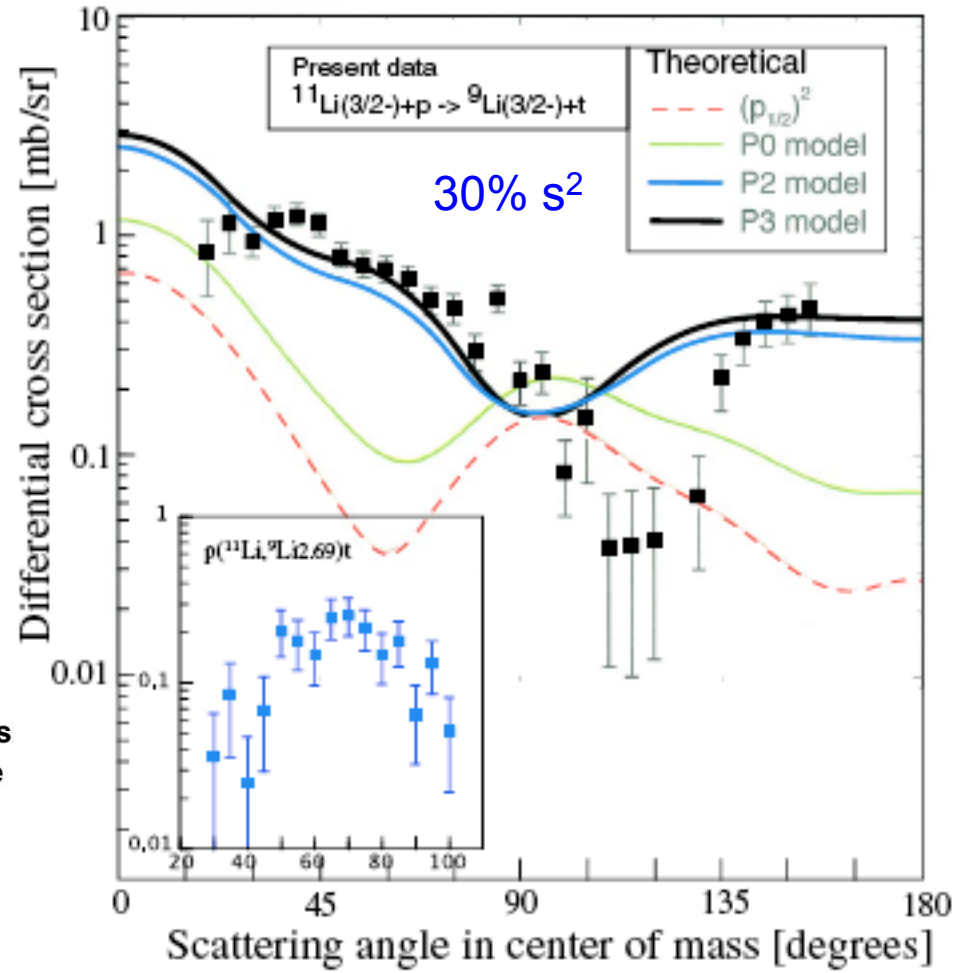
A. Wuosmaa *et al.* Phys. Rev. Lett. **94,** 082502 (2005)

Two neutron removal reaction: p(^{11}Li,^{9}Li)t

Active target - GANIL





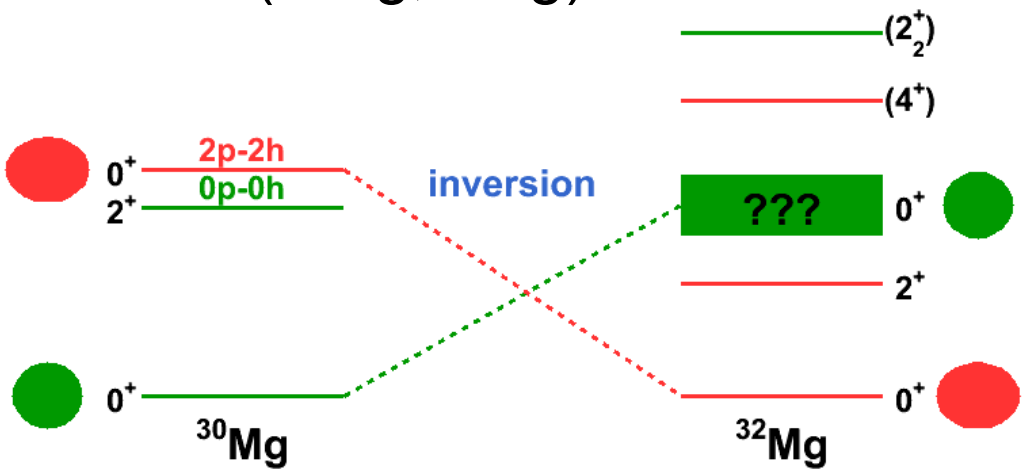


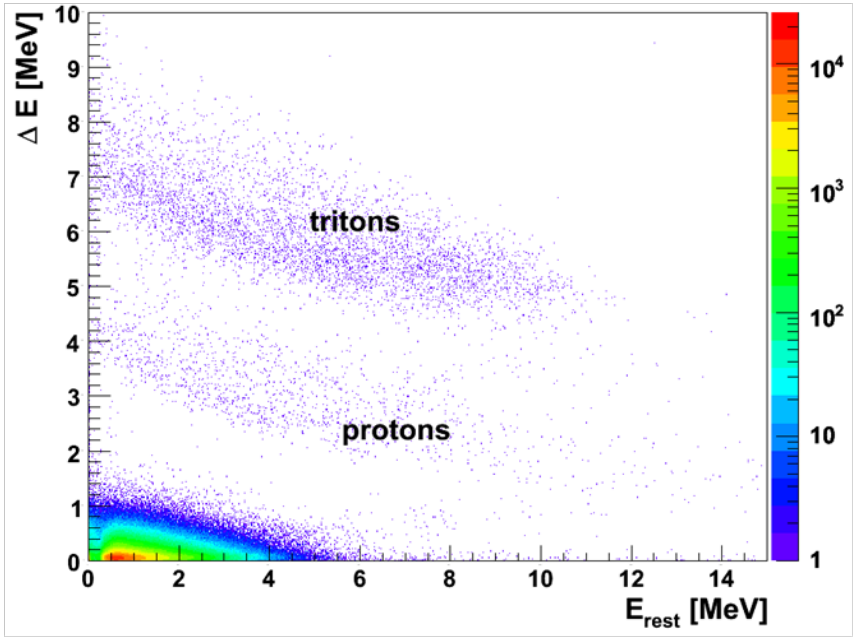
I. Tanihata *et al.* PRL **100**, 192502 (2008)

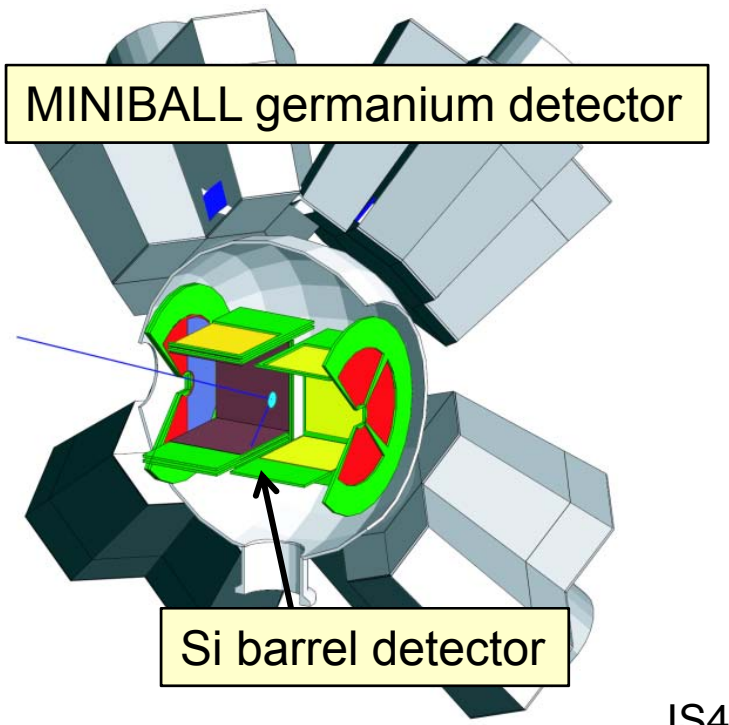
(see talk R. Raabe ID 75)

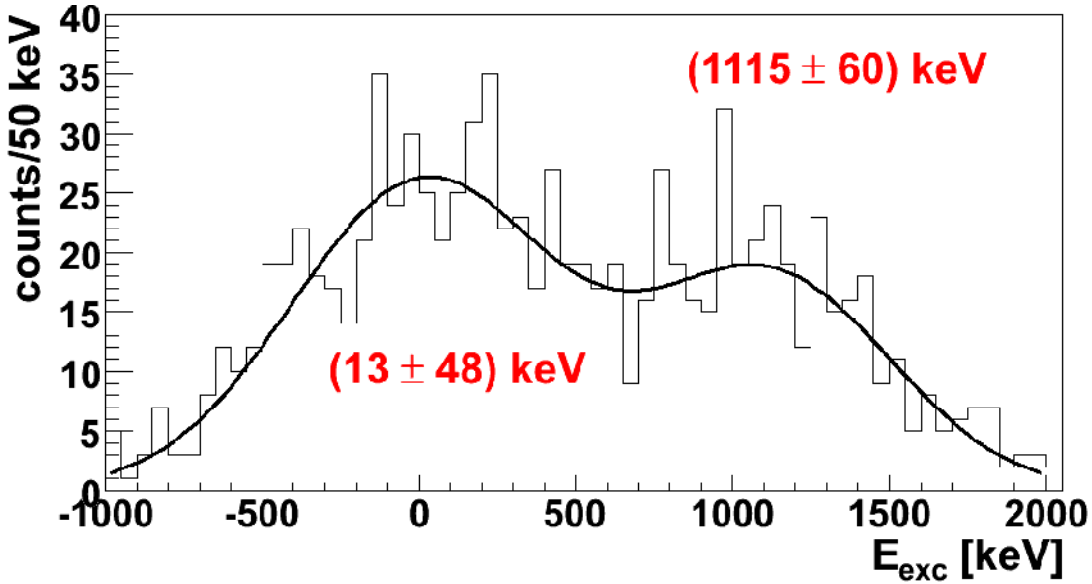
Two-neutron transfer reactions : radioactive beam onto a radioactive target

$^{3}H(^{30}Mg,^{32}Mg)^{1}H$









1. Test of Ab-Initio calculations – Halos and Skins

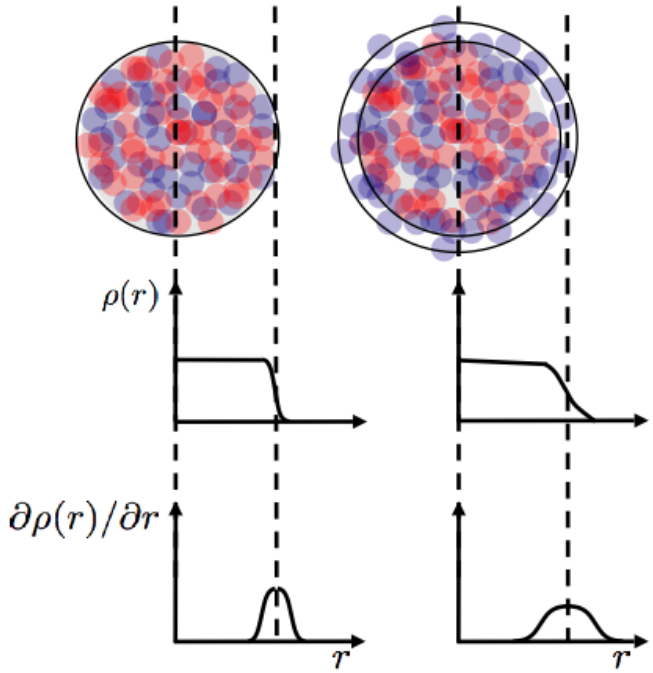
- Study properties of bound and un-bound states in light-mass(halo) nuclei – open quantum systems

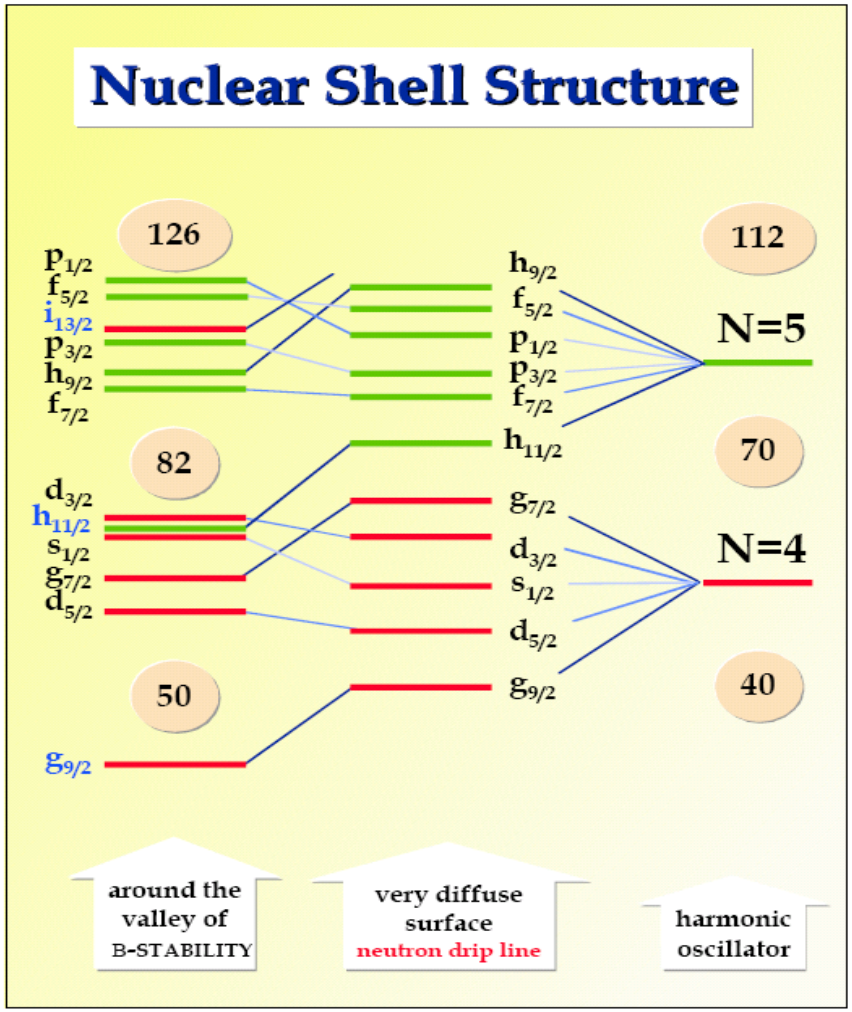
HIE-ISOLDE opportunities

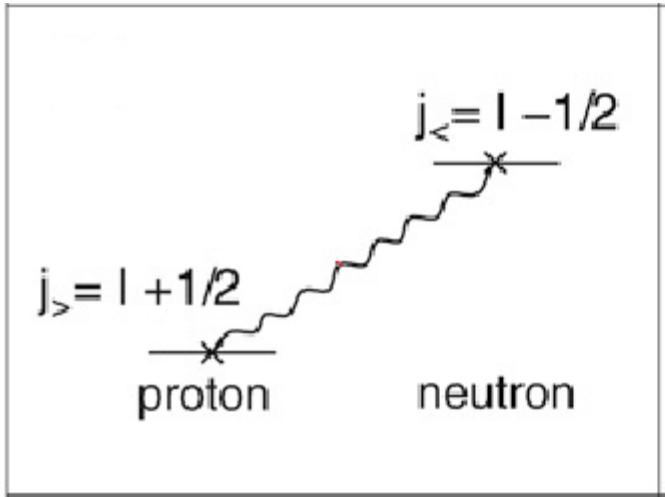
- Transfer reactions using heavier beams (A>8): $^{3}H(^{9}Li,p)^{11}Li$, $^{3}H(^{12}Be,p)^{14}Be$ and heavier masses (C, N and O)
- Higher energy (Q-value, higher cross sections, thicker targets, better angular momentum sensitivity, less model dependent analysis) and higher intensity
- Using active targets (also in the heavier mass region e.g. nickel and lead (see talk R. Raabe ID 75)
- Charge radii and moments (laser spectroscopy) (ID 22, 96)
- Decay studies using calorimetric detectors (ID89)

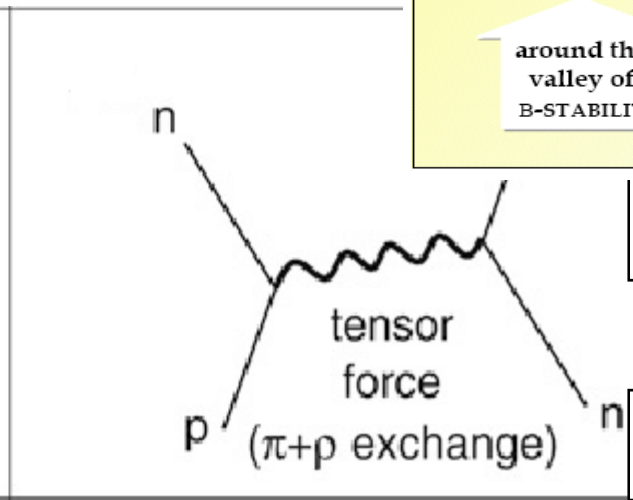
2. Evolution of Shell Structure

$$V_{so} = -V_0 \frac{1}{r} \frac{\partial U(r)}{\partial r} \ell.\mathbf{s}$$









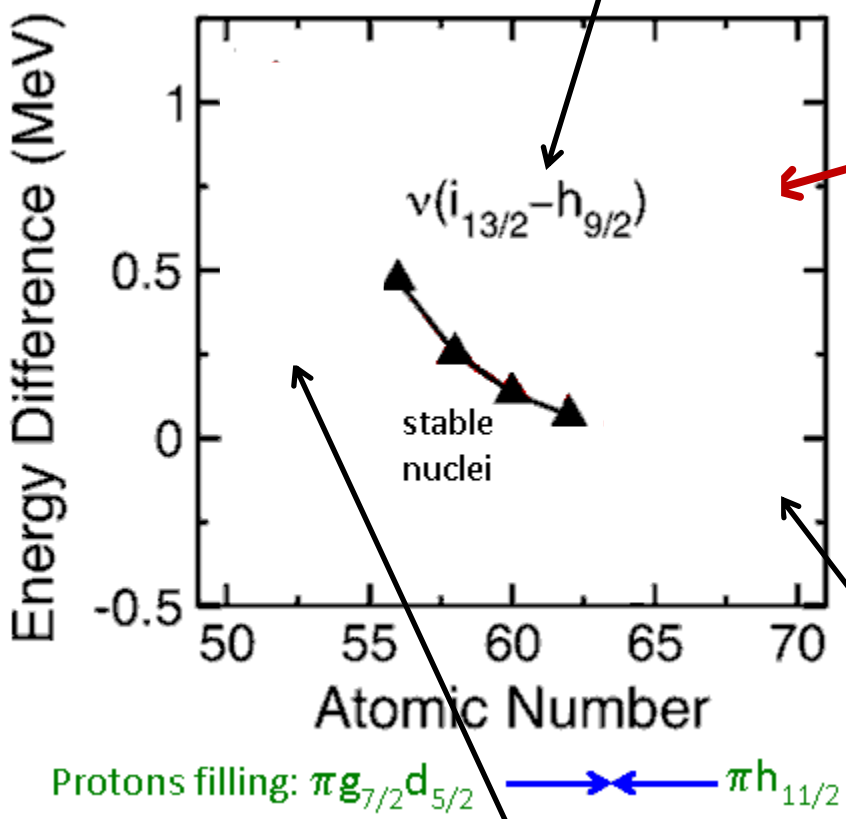
Dobaczewski et al.
Phys Rev Lett 72 (1994) 981

Otsuka et al.
Phys Rev Lett 95 (2005) 232502

Evolution of Shell Structure studied with transfer reactions

Measurements of one-neutron transfer on *stable* nuclei outside N=82

Kay et al.
Phys. Lett. B658 (2008) 216



Expect turnaround in trend, if tensor force drives changes, for higher Z.

Recent studies in the Sb region using Sn(α,t)
Schiffer et al. Phys Rev Lett 92 (2004) 162501

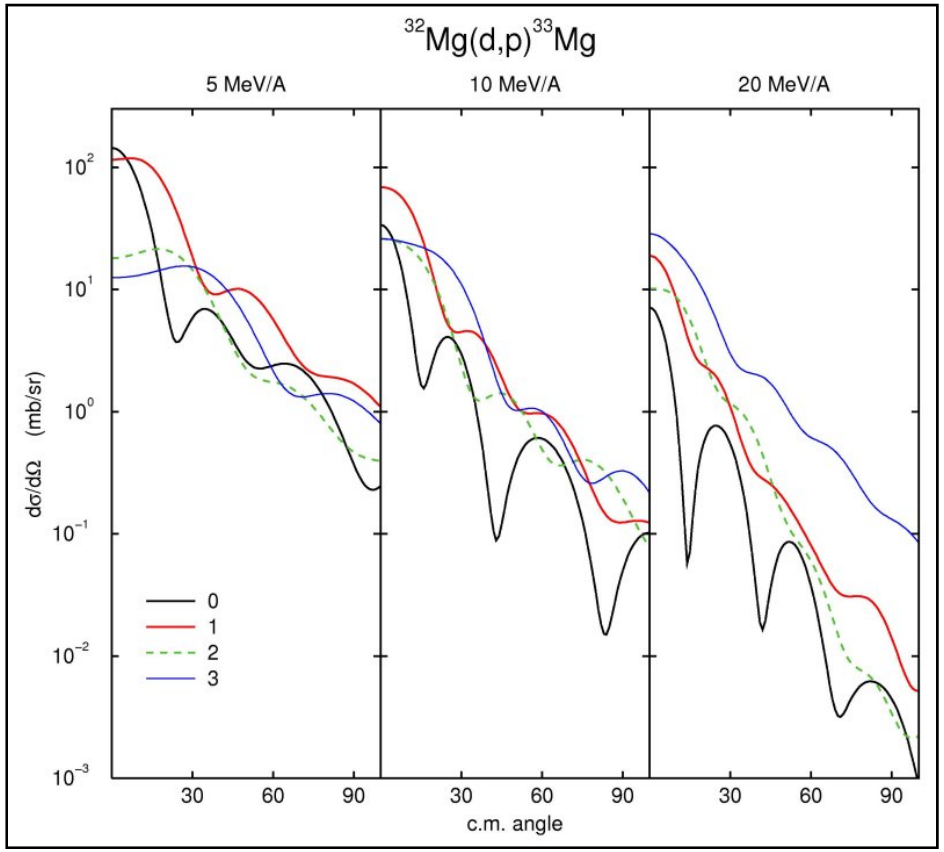
radioactive beams with high yields: ^{132}Sn, ^{134}Te

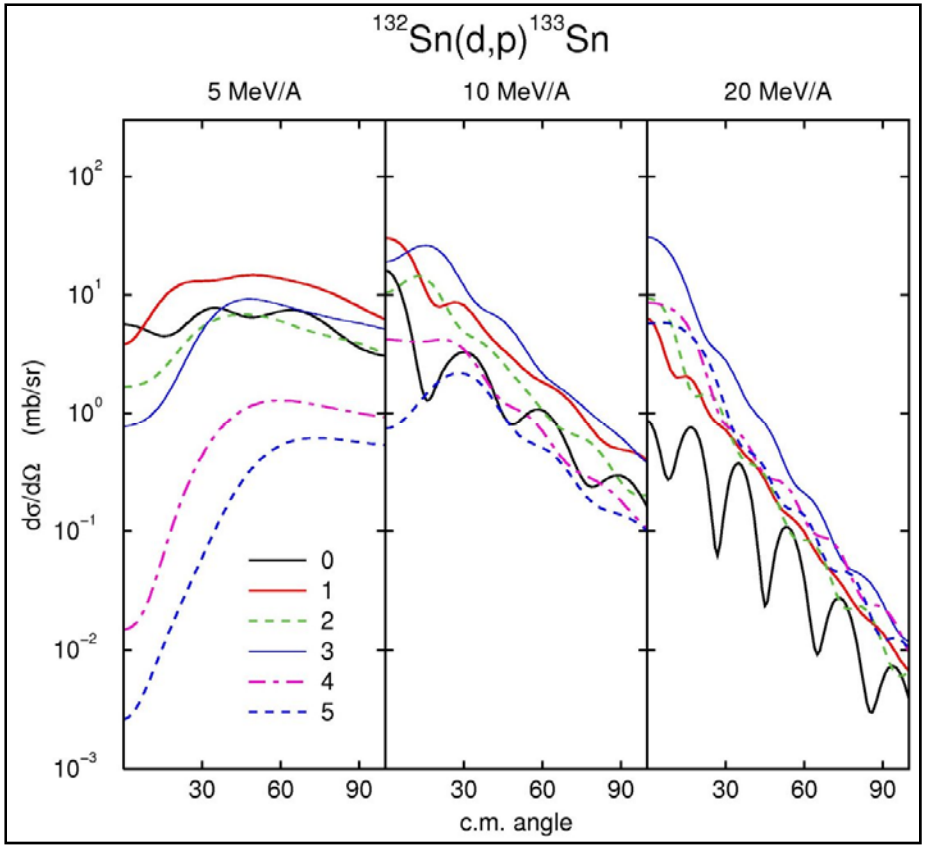
radioactive beams unique to ISOLDE with high yields: ^{146}Gd, ^{148}Dy, ^{150}Er

Testing outside Z=50 using beams of n-deficient Sn isotopes
Testing outside N=126 using beams like ^{206}Hg, ^{210}Po, ^{212}Rn and ^{214}Ra

Evolution of shell structure studied with transfer reactions

Transfer reactions need higher energy





2. Evolution of Shell Structure

• Identify energy gaps, spin, parity and the single-particle strength outside an inert core

HIE-ISOLDE opportunities

• Transfer reactions requires higher energy (5 - 10 MeV/u) for adequate cross sections, angular momentum-transfer assignments and minimise dependency on reaction models (ID 33)

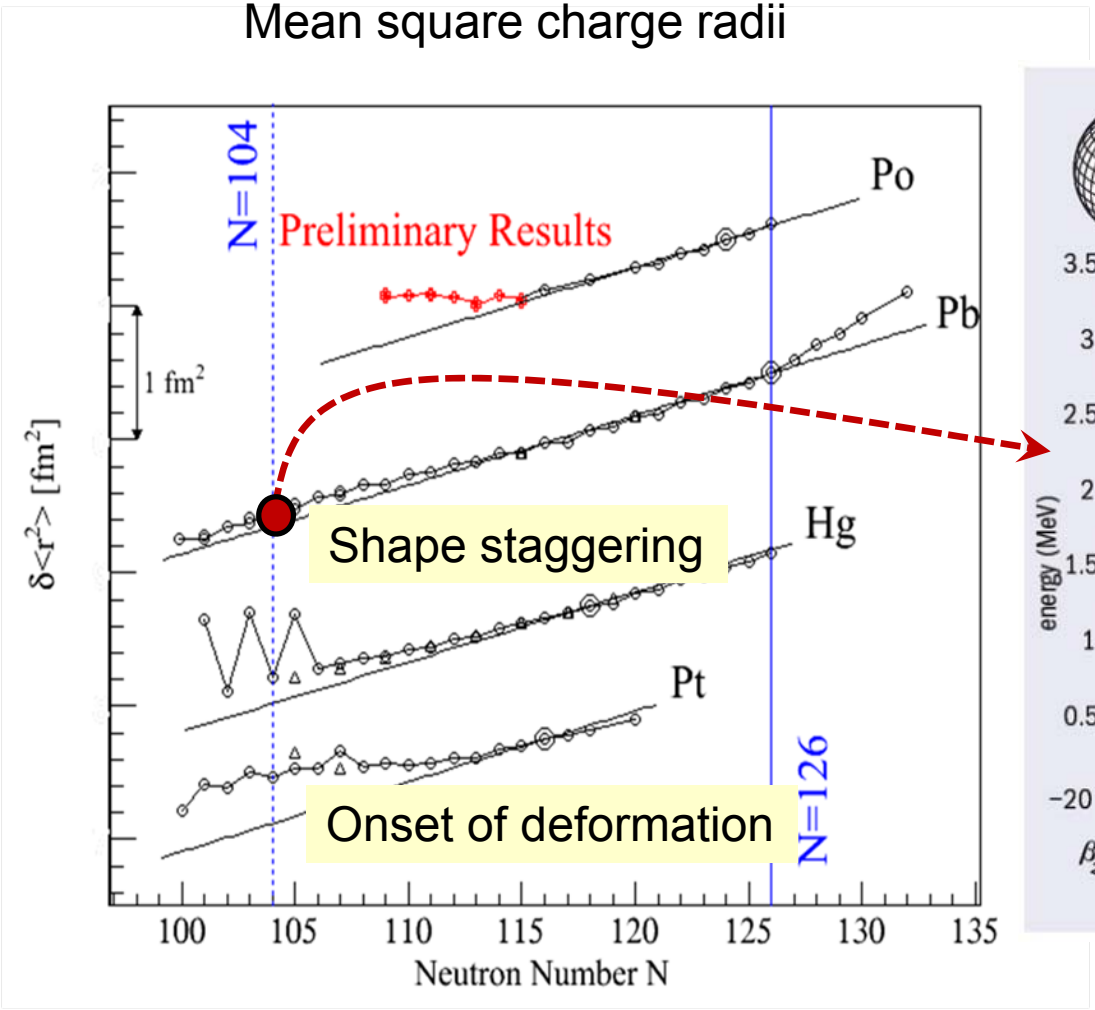
• Few-nucleon transfer reactions: production and study of medium spin states (ID 14)

• Wide spectrum of RIB available: study trend along closed proton/neutron shells

• Higher intensity allows decay, mass measurement and laser spectroscopy studies towards the neutron and proton drip lines (see talk K. Flanagan-ID 7, M. Kowalska-ID 85 and ID 20, 31, 53)

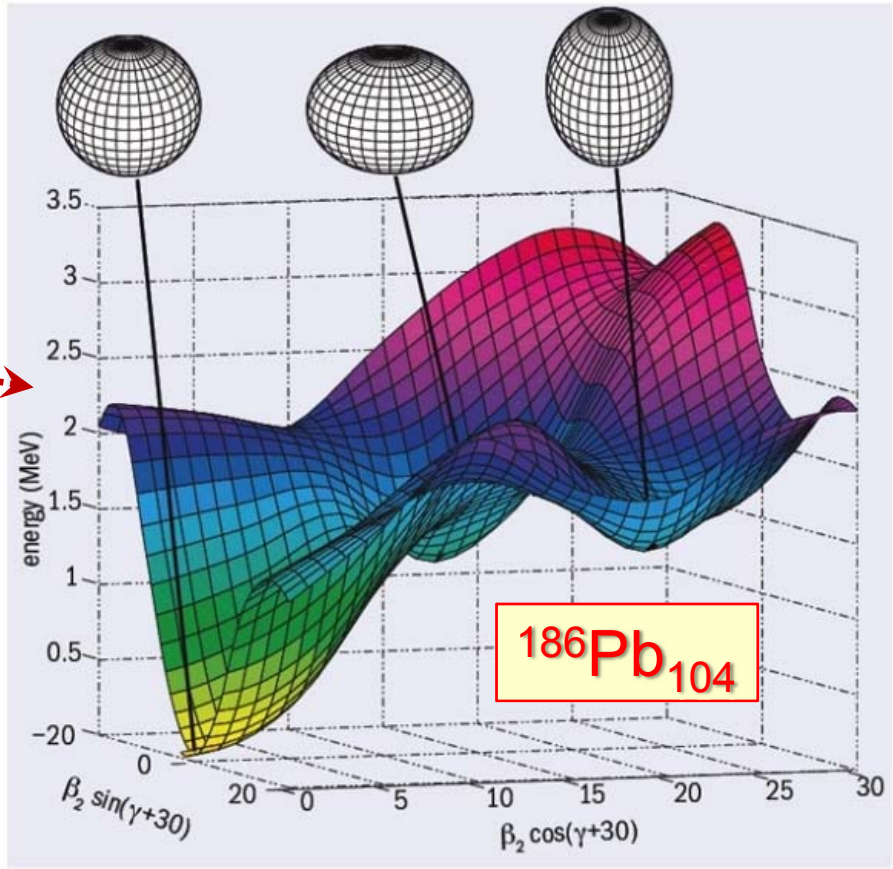
3. Shape co-existence in the lead region

Mean square charge radii



H. De Witte et al. PRL 98 (2007) 112501

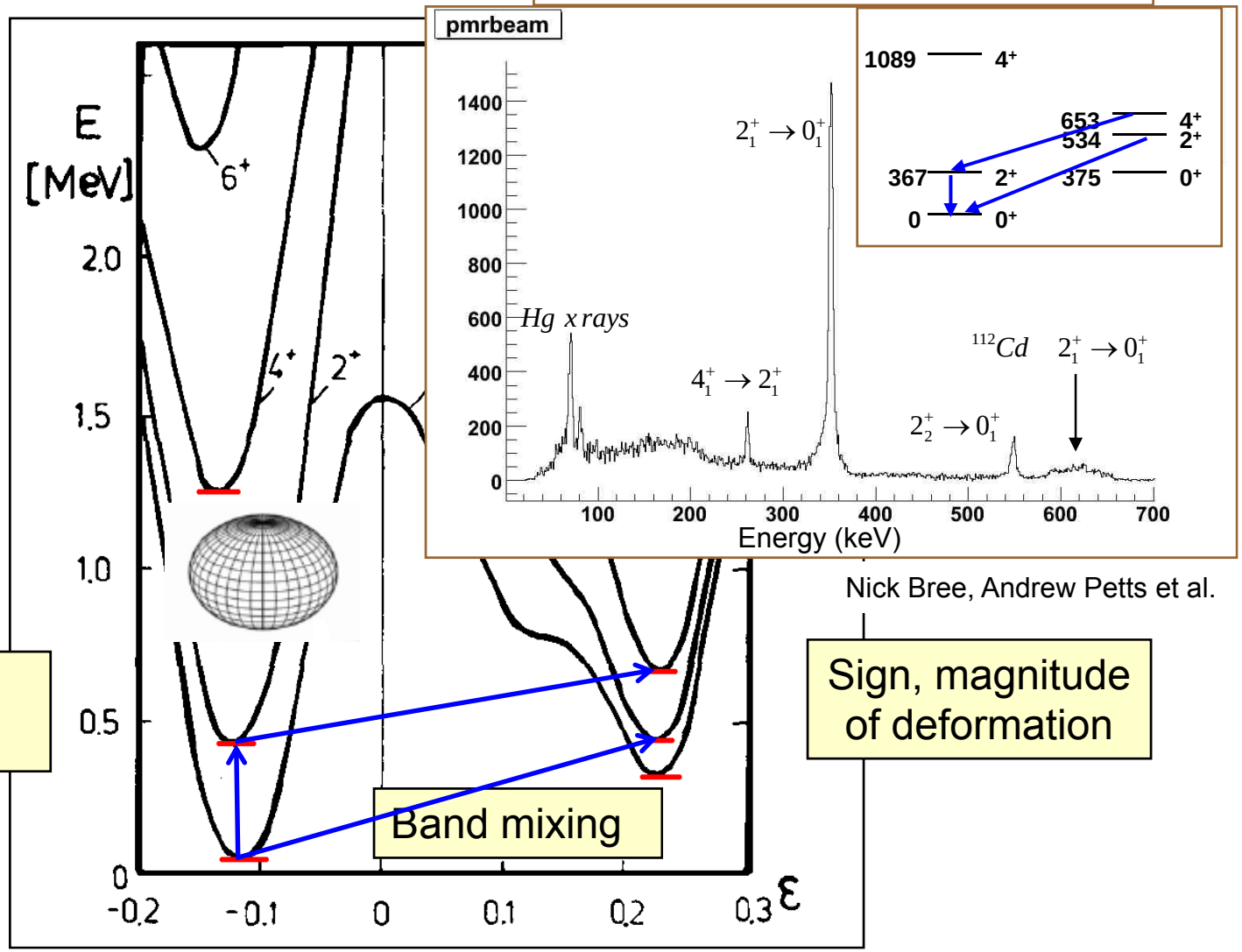
Potential energy surface



A.N. Andreyev et al., Nature 405, 430 (2000)

Shape co-existence in the lead region studied with Coulomb excitation

Coulomb excitation @ 3 MeV/u
^{184}Hg (3MeV/u) + ^{112}Cd



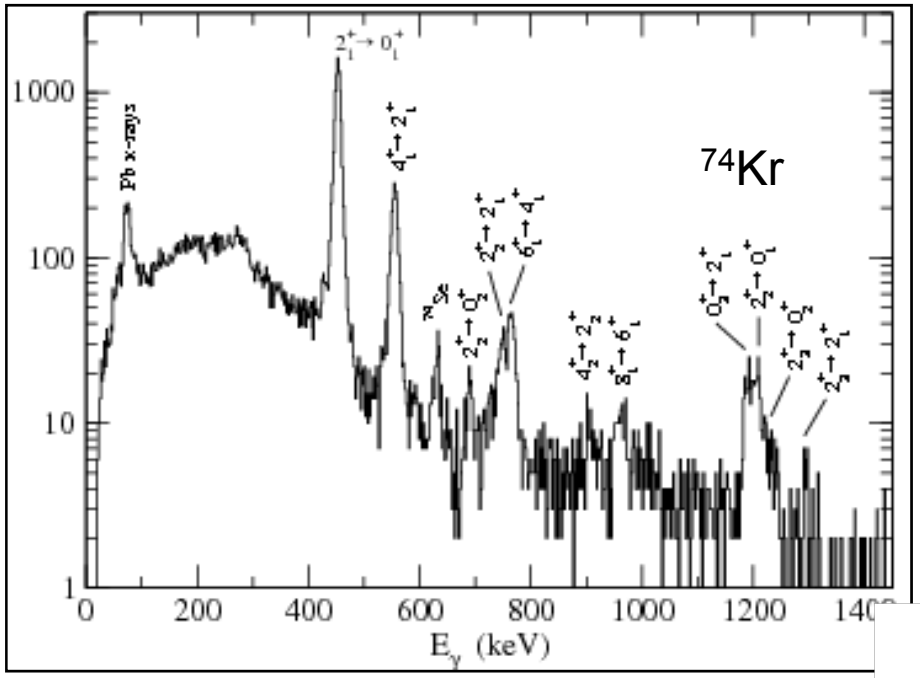
Nick Bree, Andrew Petts et al.

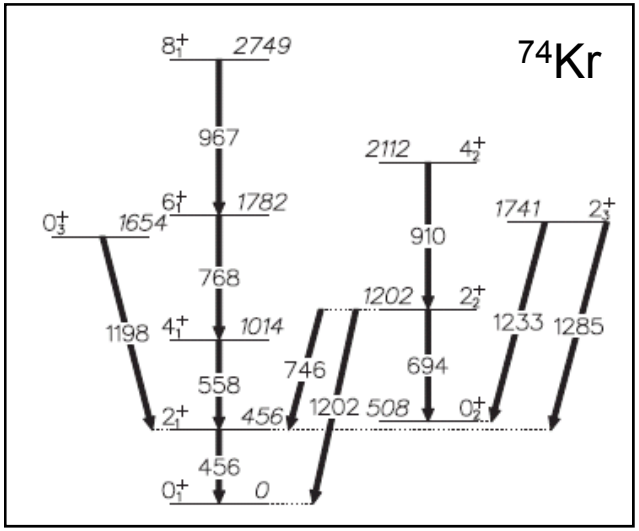
Strongly-coupled matrix elements

Sign, magnitude of deformation

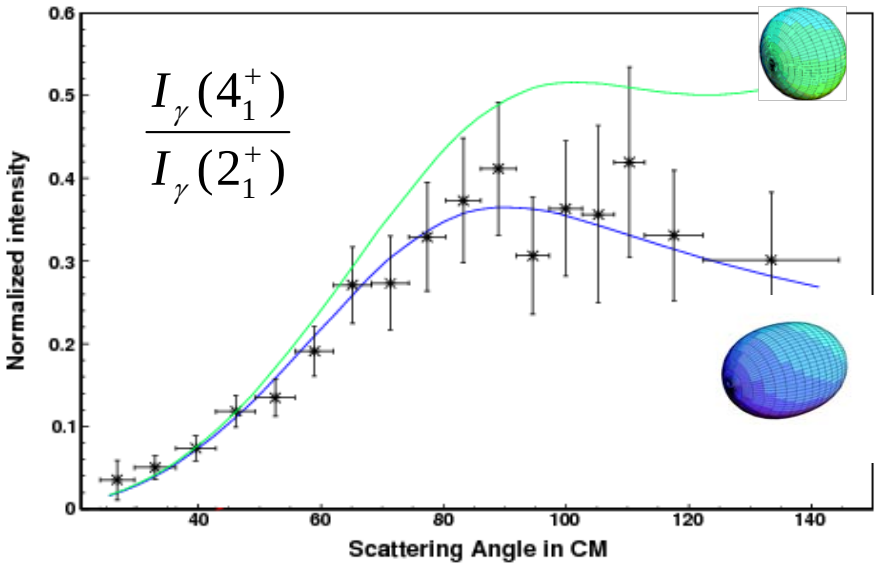
Band mixing

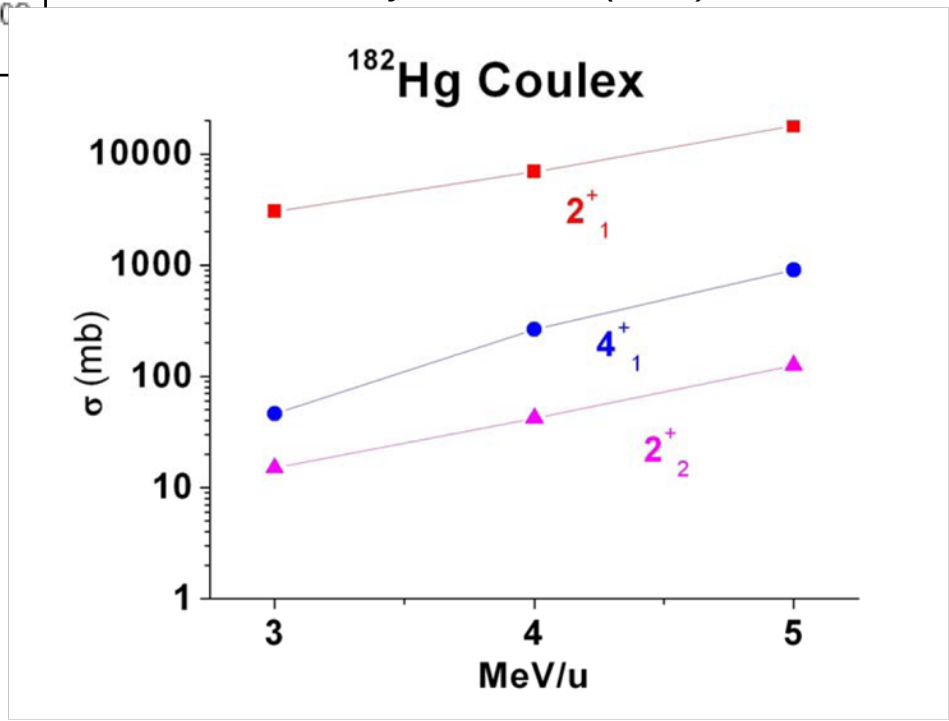
4.7 MeV/u ^{74}Kr radioactive beam - SPIRAL





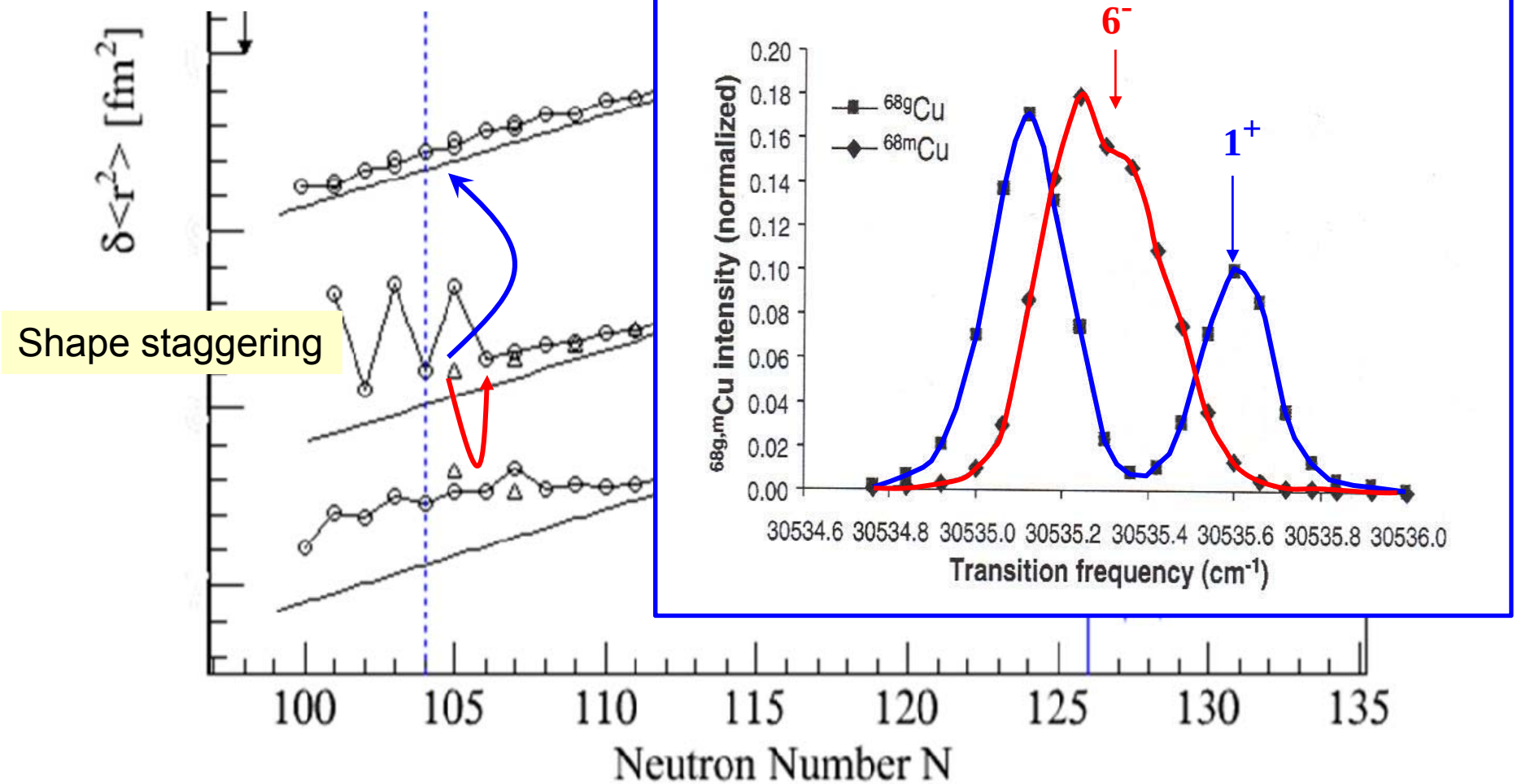
Clément et al. Phys. Rev C75 (2007) 054313





Shape co-existence studied with transfer reactions

- One-neutron transfer: $^{2}H(^{184}Hg,p)^{185}Hg$, $^{2}H(^{183m,g}Hg,p)^{184}Hg$ and other Pb, Po and Rn (isomeric) beams
- Two-proton transfer: $^{3}He(^{184}Hg,n)^{186}Pb$



3. Shape co-existence

- Coulex populates states strongly coupled to g.s. (e.g. non-yrast states)
- Distinction between prolate and oblate deformation
- Identify the microscopic (particle-hole) origin of shape-coexistence
- Determine the degree of collectivity and mixing
- Test of local symmetries

HIE-ISOLDE opportunities

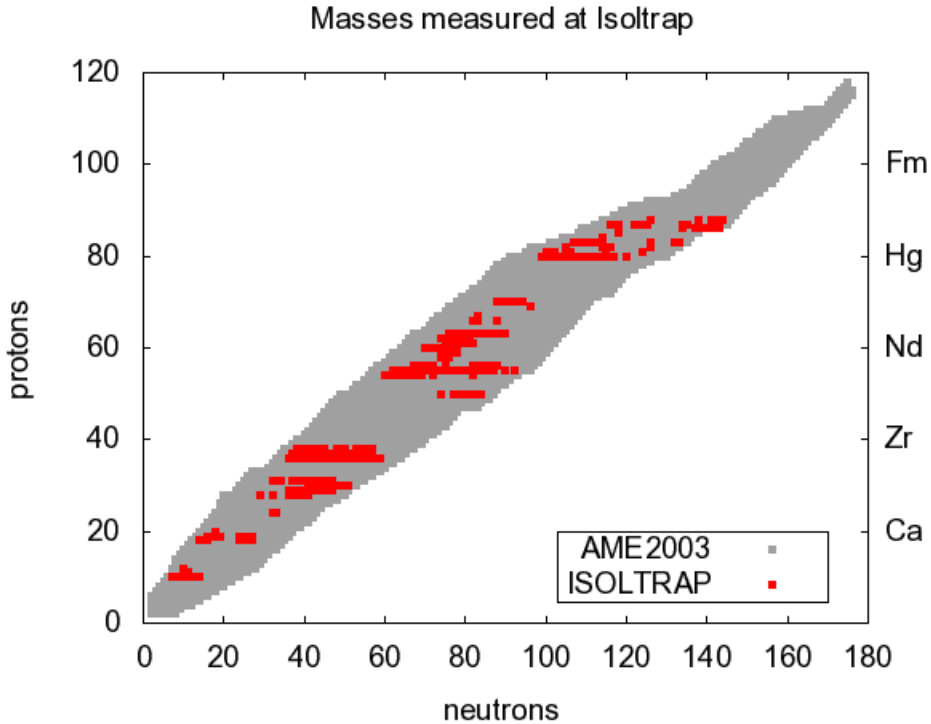
- Higher energy:

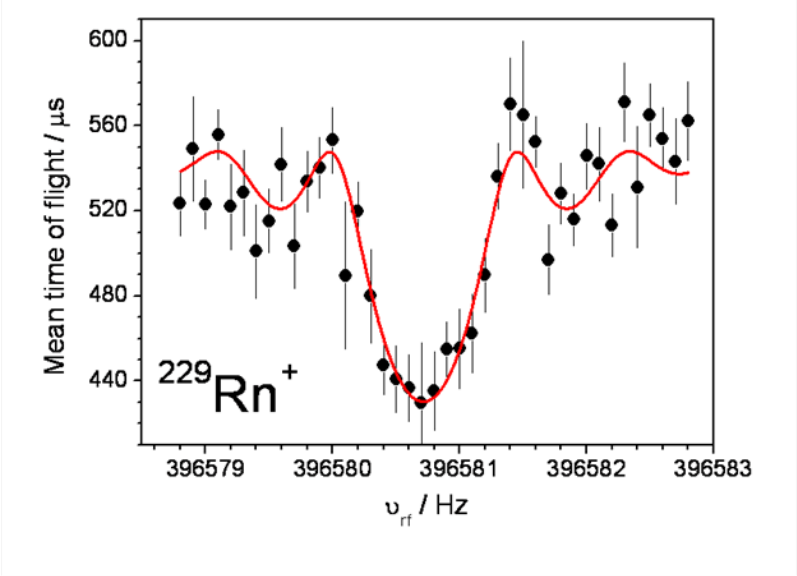
  Coulex: higher yields, multiple Coulex, higher sensitivity to the sign of Q

  Transfer: : higher sensitivity to angular momentum transfer, less model dependent spectroscopic factors (ANC's), better detection sensitivity
- Wide spectrum of RIB available: pin down N,Z specific aspects of shape co-existence (ID 6, 18, 62, 74, 83)
- Higher intensity: possibility to study weak reaction channels
- Isomeric beams: investigate underlying particle mechanism

Discovery of ^{229}Rn and the Structure of the Heaviest Rn and Ra Isotopes from Penning-Trap Mass Measurements

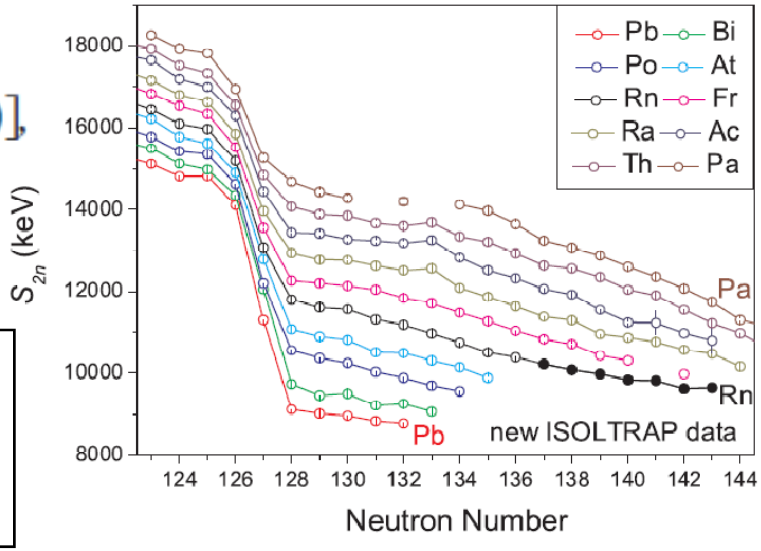
D. Neidherr et al. Phys. Rev. Lett. 102 (2009) 112501





$$\delta V_{pn}^{eo}(Z,N) = \tfrac{1}{2}[(B_{Z,N} - B_{Z,N-1}) - (B_{Z-2,N} - B_{Z-2,N-1})],$$

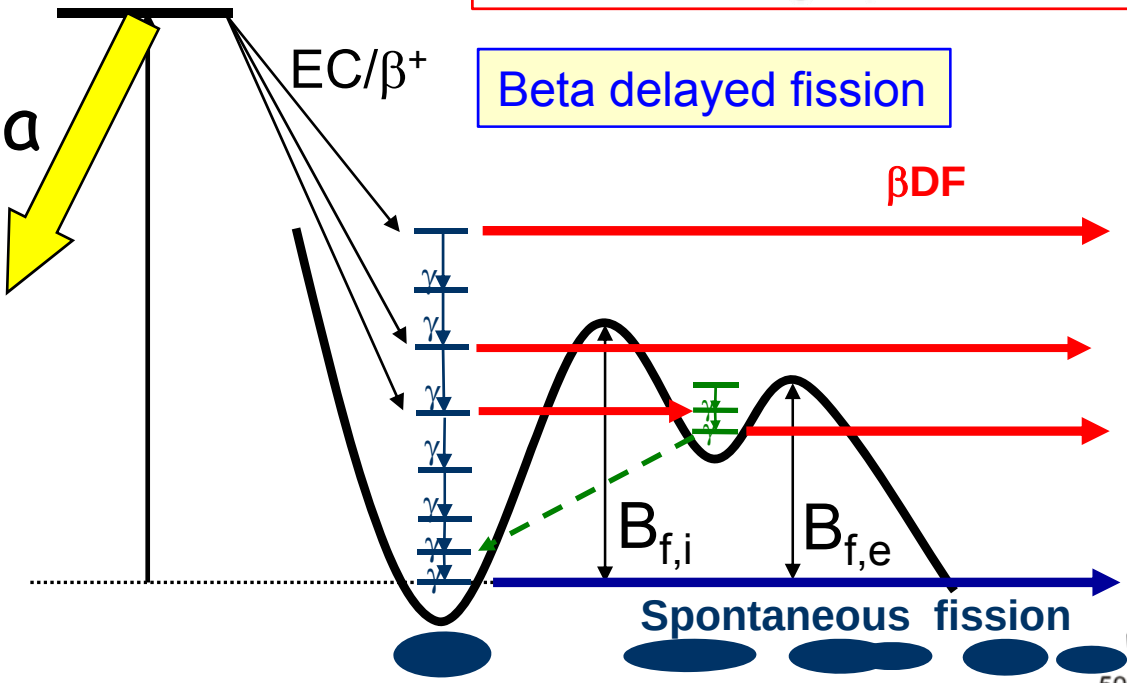
- systematic deviation from the general trend of δV_{pn} values, probably induced by the octupole deformation.



HIE-ISOLDE opportunities

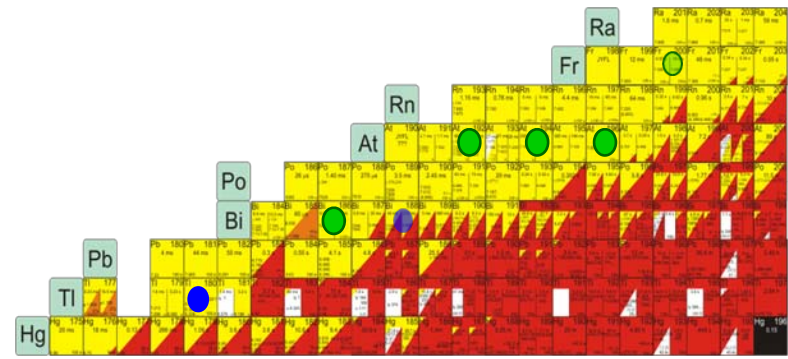
- Higher intensities: extended range of nuclei (cfr. talk M. Kowalska ID 85, M. Scheck ID52)

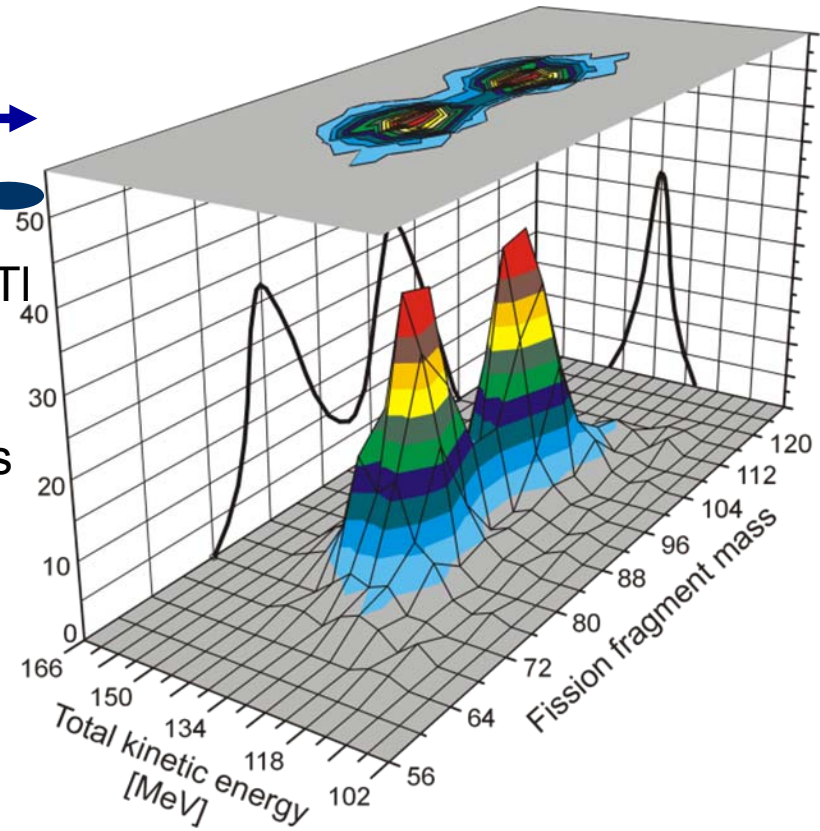
4. Rare charge-particle decay studies



Beta delayed fission

A.N. Andreyev et al.





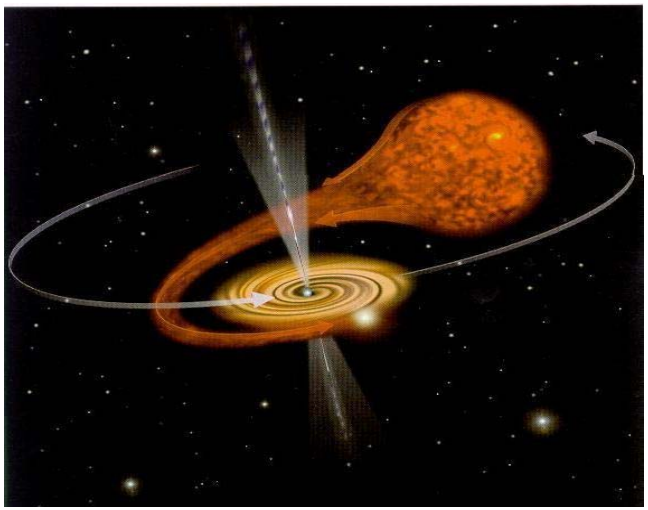
- Fission of ^{180}Hg observed in the beta decay of ^{180}Tl
- Unexpected asymmetric mass split
(^{180}Hg (Z=80, N=100) = 2 x ^{90}Zr (Z=40, N=50)
- Cold fission, important for the end of the r-process

HIE-ISOLDE opportunities

- Higher intensities, other nuclei
- Higher energy: implantation – decay
(absolute branching ratios) (ID 89)

5. Nuclear Astrophysics

X-ray bursts (rp-process)



- Dominated by (p,γ) and (α,p) reactions

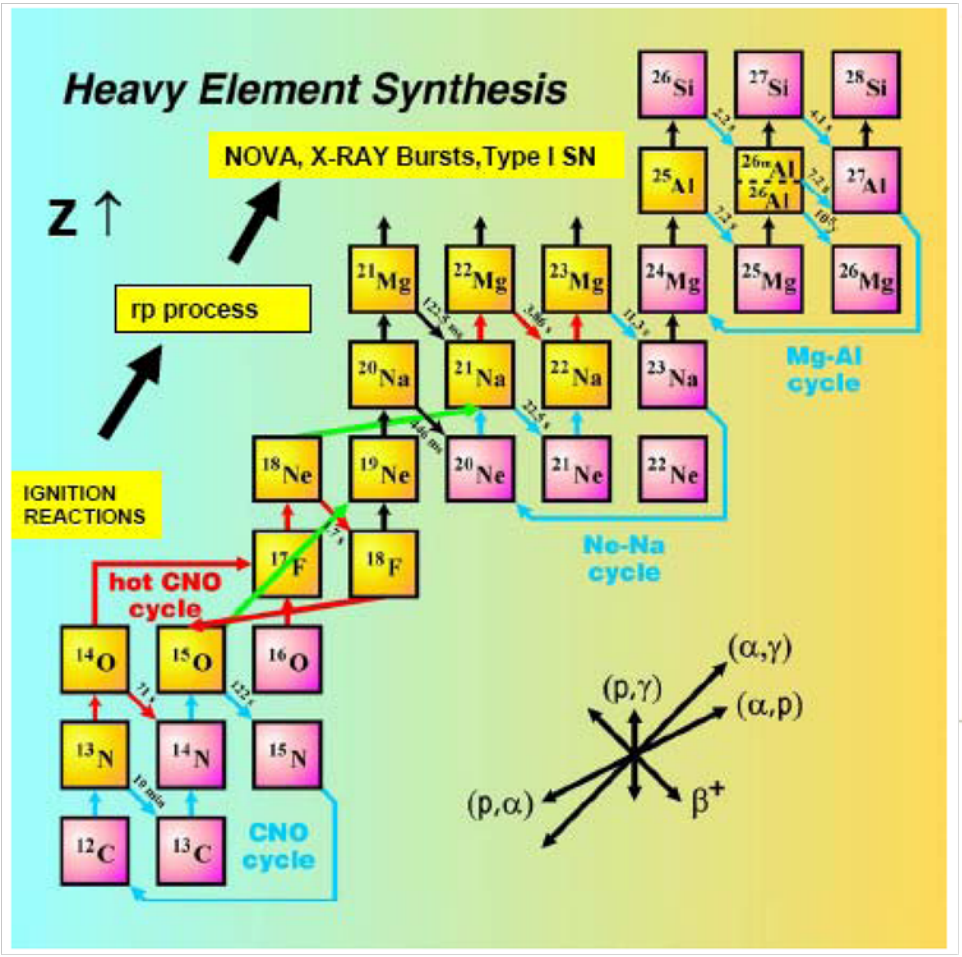
  - Direct (p,γ) or (^{3}He,d)/(d,n) as surrogate of (p,γ)
  - (p,α) as inverse of (α,p)

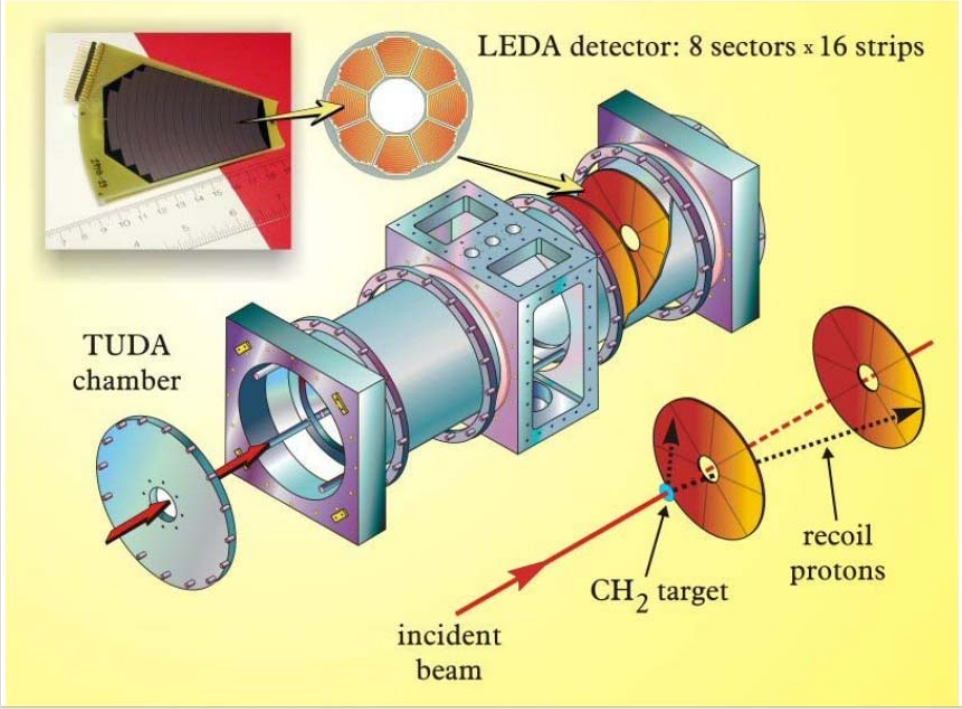
Supernovae (r-process)

- Dominated by (n,γ) reactions
  - r-process pathway largely unknown
  - understanding of shell evolution important

- (d,p) as surrogate of (n,γ)
(J. Cizewski et al. NIMB 261 (2007) 938)

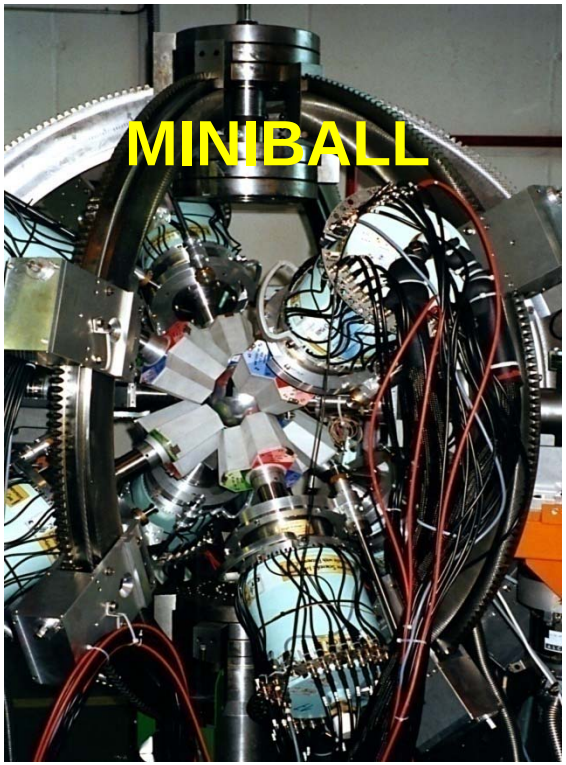
- measure global properties such as mass and lifetime very far from stability

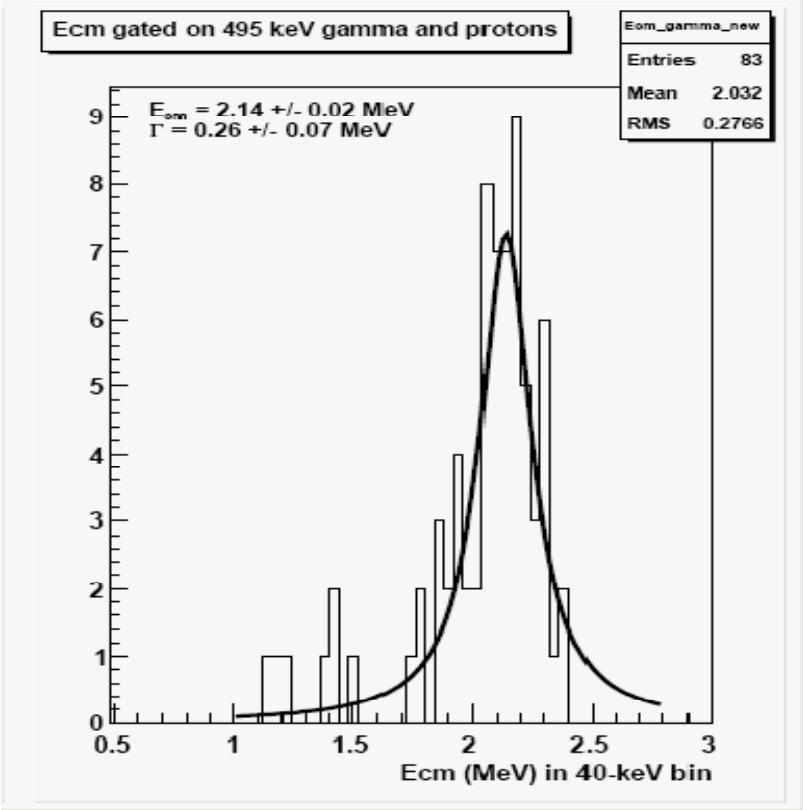




Louvain-la-Neuve, Triumf

Successful pioneering study of time reverse $^{17}F(p,\alpha)^{14}O$ reaction IS424





HIE-ISOLDE opportunities

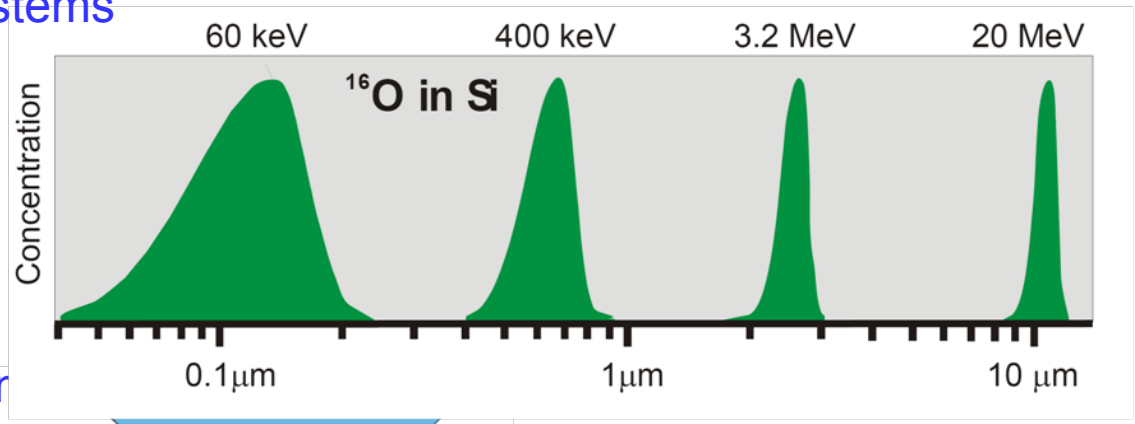
- Tunable energy to apply time reverse technique to other X-ray busters reactions
- Wide spectrum of RIB available
- Mass measurements, half life determinations: need for higher intensities

6. Solid-state physics

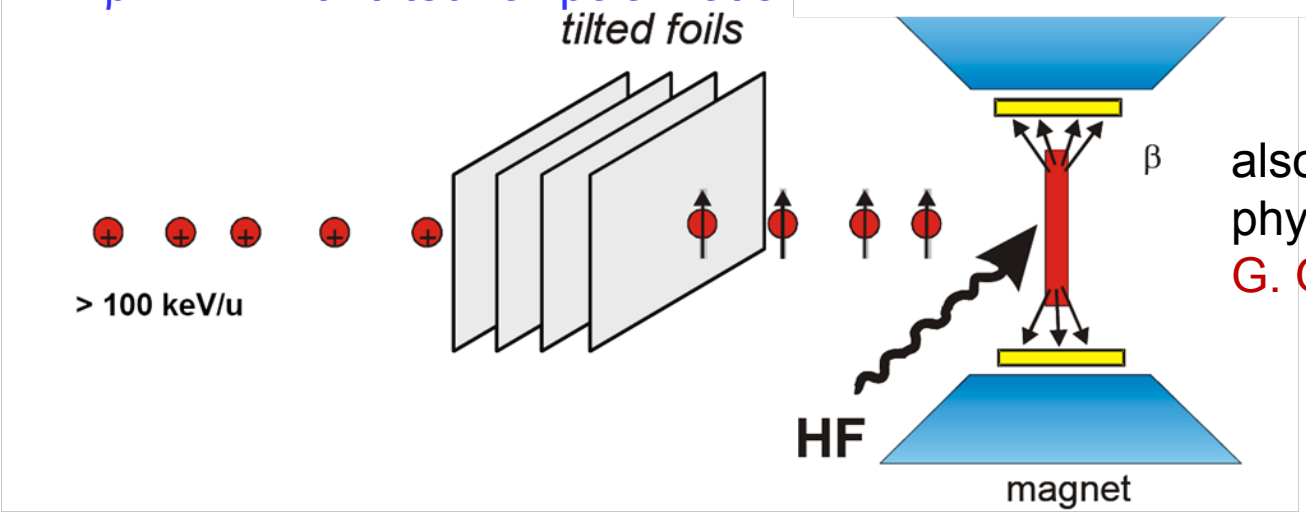
• How do minor impurities or defects influence the electrical and optical properties of different materials (e.g. in semiconductors, metals, oxides, high-Tc superconductors)? (the chemical nature and the structure of defects and the interaction between defects)

• Low energy beams (PAC, DLTS, Mossbauer, surface studies, emission channeling)
see talks U. Wahl ID 63, L. Hemmingsen ID 90, 64, 86, 88, 94, 96

• Diffusion in highly immiscible systems



• β-NMR with tilted-foil polarization



also applicable for nuclear physics experiments (see talk G. Georgiev ID 65)

HIE-ISOLDE: instrumentation for reactions

Existing equipement:

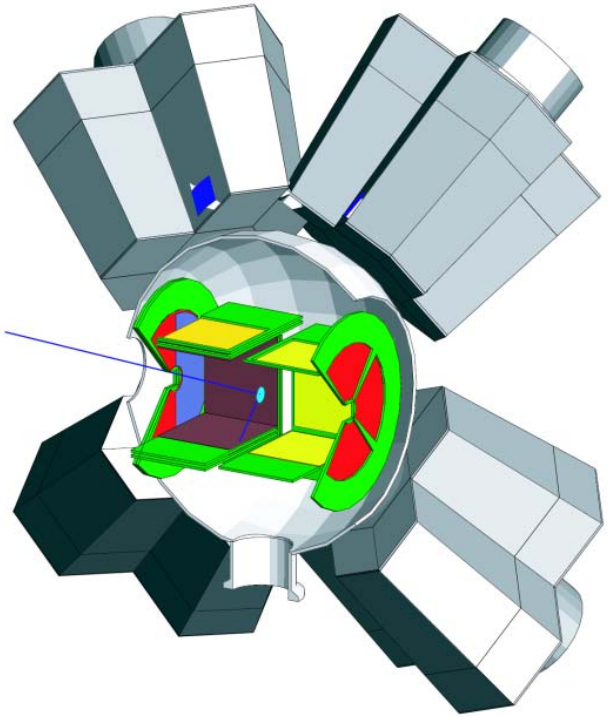
- MINIBALL segmented germanium detector array: Coulex, transfer, multi-nucleon transfer
- Silicon barrel detector and multi silicon detector system: transfer reactions

Prototype / design / preliminary study phase:

- Bragg detector: Coulex
- Separator: identification of the reaction products
- High resolution spectrometer: (p,d), (t,p), (α,p),…
- Active target: direct reactions

Under study:

- Neutron wall detector: (^{3}He,n),…

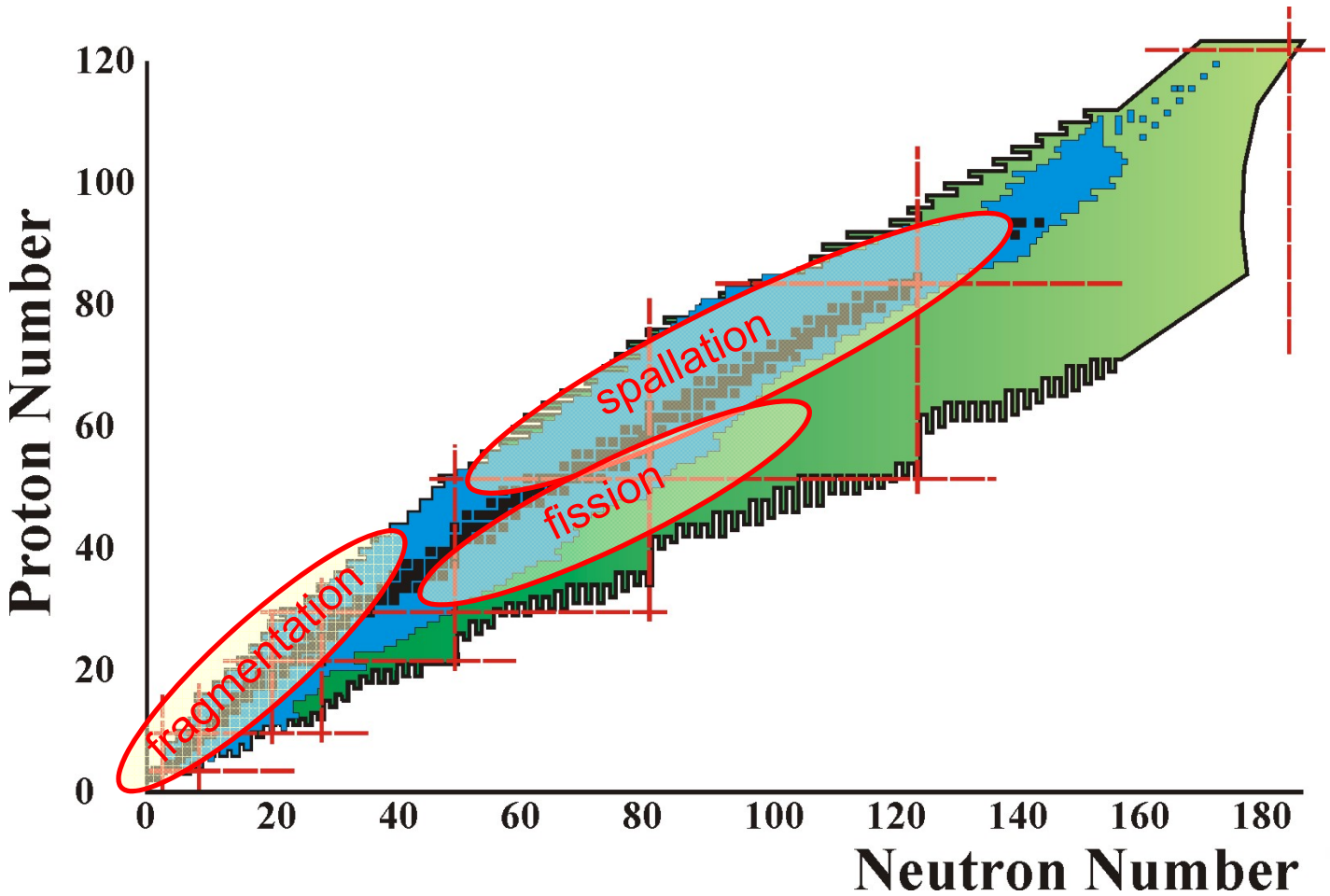


HIE-ISOLDE opportunities: higher energy

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 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

HIE-ISOLDE: uniqueness

- Large RIB beam variety: spallation, fission, fragmentation
- Universal acceleration scheme (REX-trap, EBIS)
- High quality beams: cooled and clean beams, isomeric beams
- Instrumentation: Penning traps, laser labs, silicon ball, MINIBALL detector, …



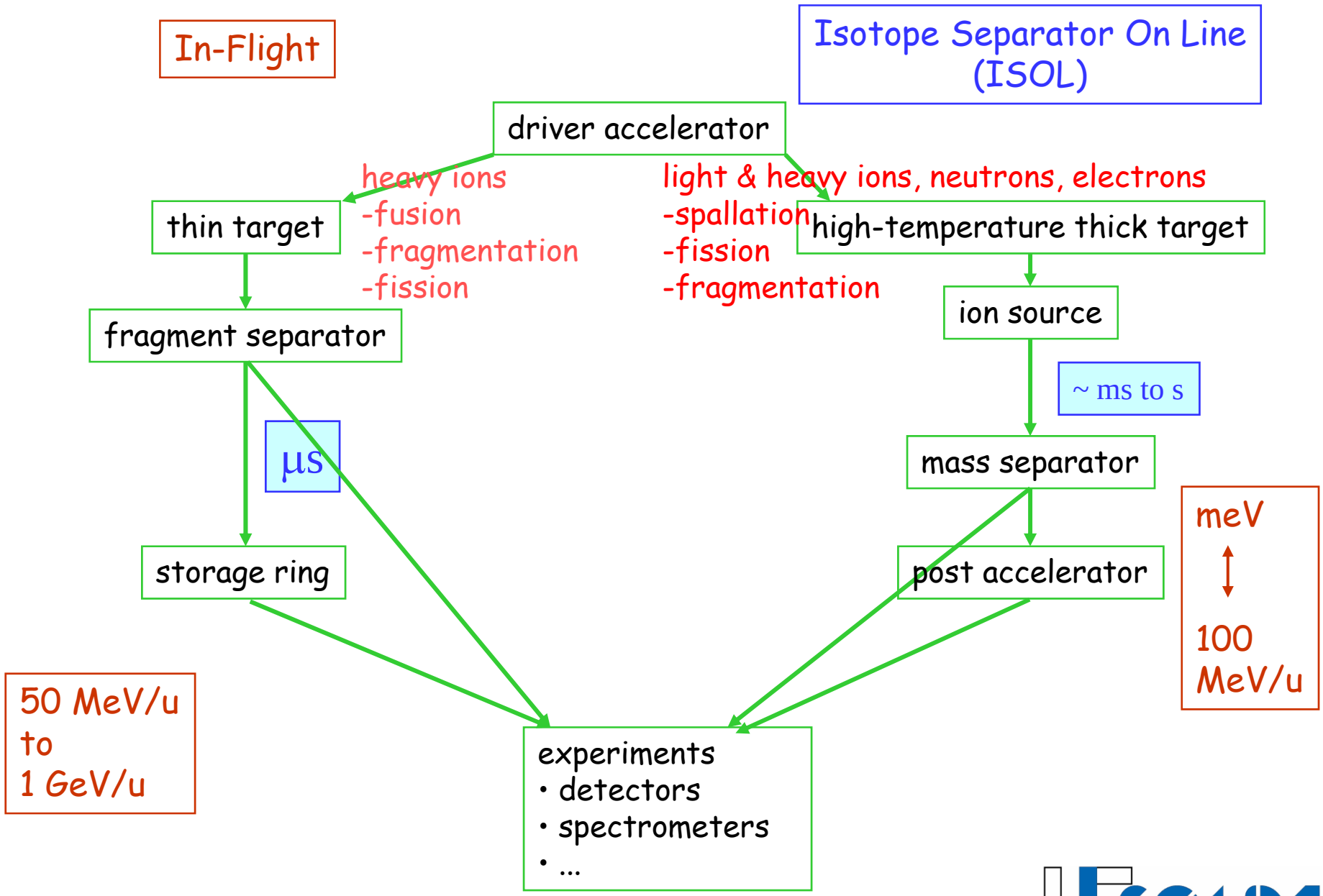
HIE-ISOLDE: importance, challenges and opportunities

- A unique facility for ISOL based radioactive ion beam research because of its large degrees of freedom in **N** and **Z**, in **energy** and in (to a certain extent) nuclear and atomic spin.
  - its wide spectrum of isotopes
  - broad energy range
  - high beam intensities and high beam quality

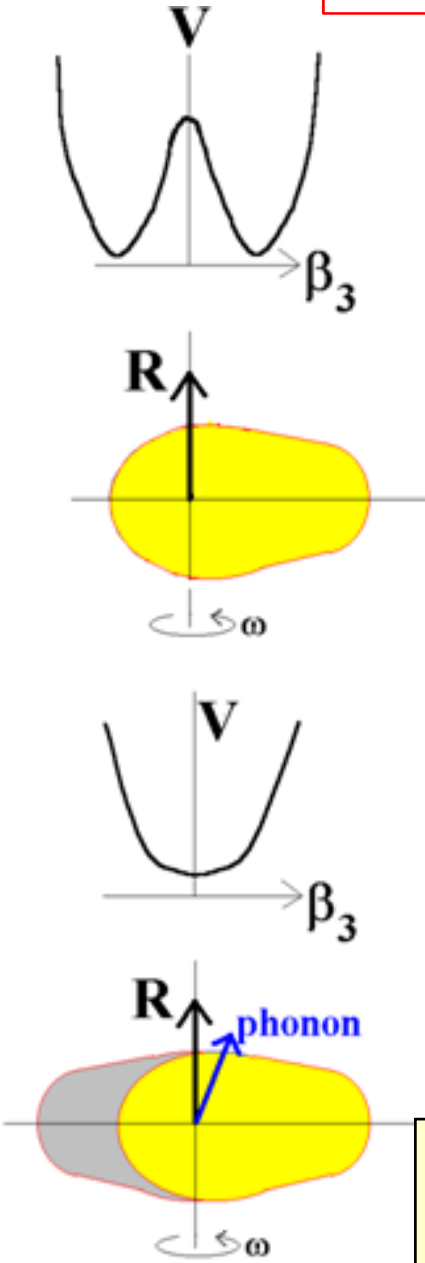
- Its aim is to answer important questions in
  - nuclear-structure physics
  - nuclear astrophysics
  - fundamental interaction studies
  - condensed matter research
  - atomic physics

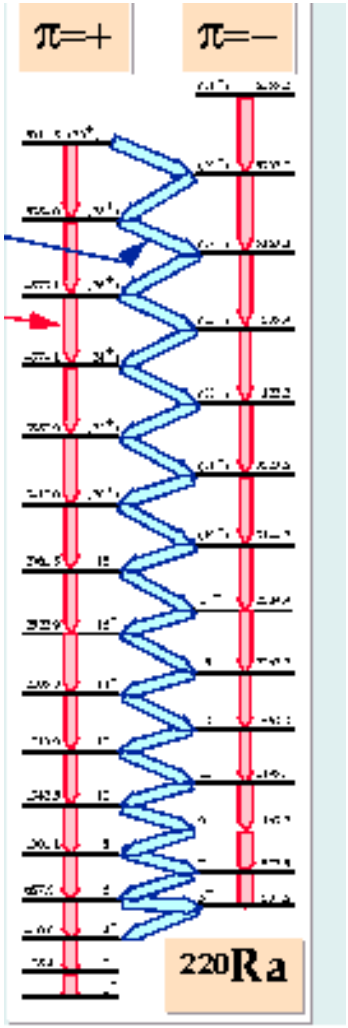
Many thanks to:
P. Butler, Y. Blumenfeld, H. Fynbo, A. Goergen, M. Huyse, K. Riisager,
N. Severijns, L. Hemmingsen, V. Amaral, U. Wahl,

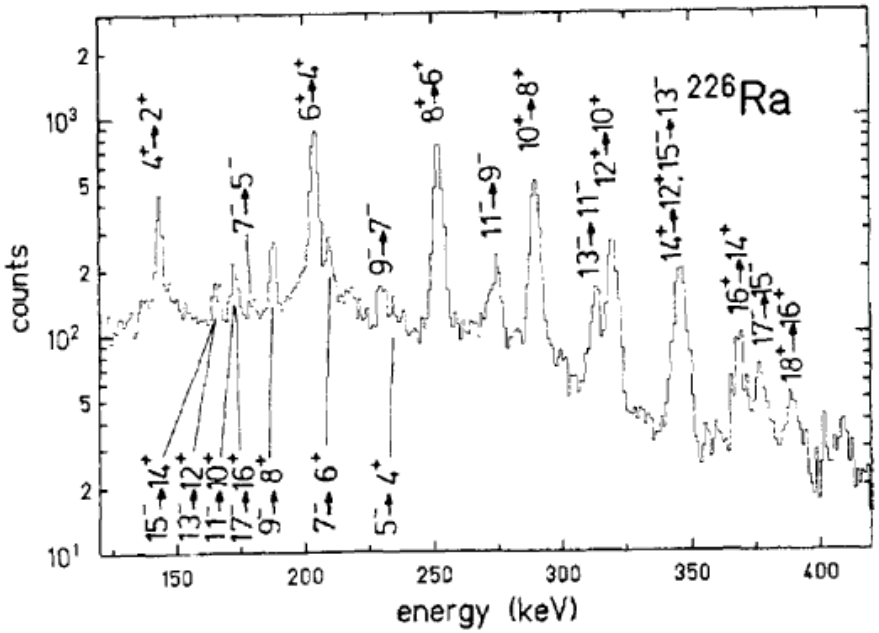
Radioactive Ion Beams: In-Flight versus ISOL

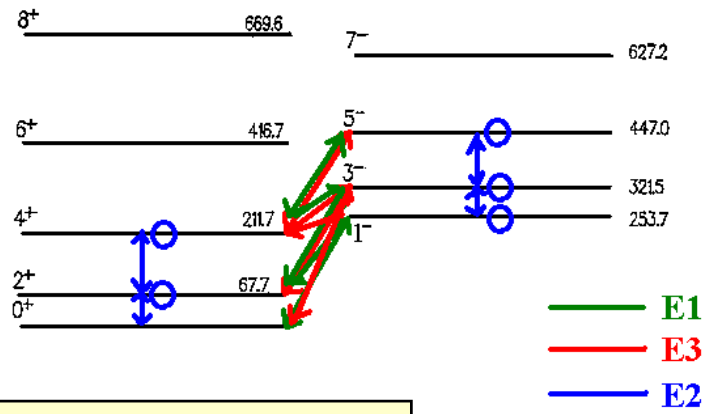


4. Octupole shapes and the Standard Model





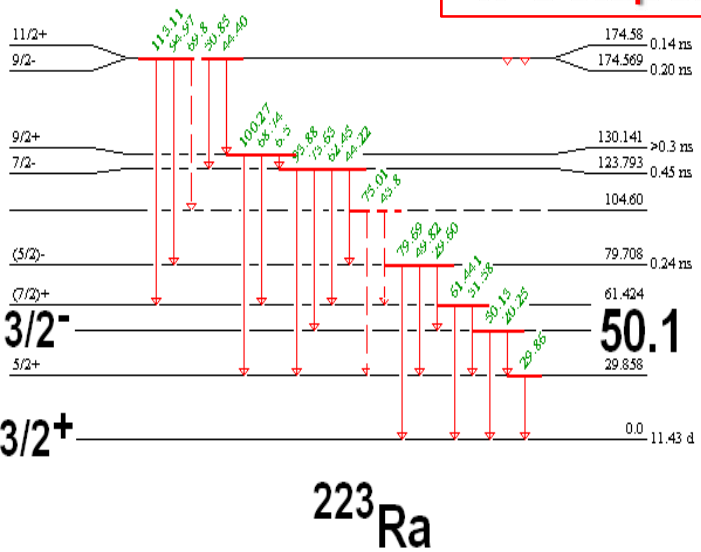




Coulomb excitation populates odd and even-even Radon and Radium with N~134

See talk M. Scheck ID 52

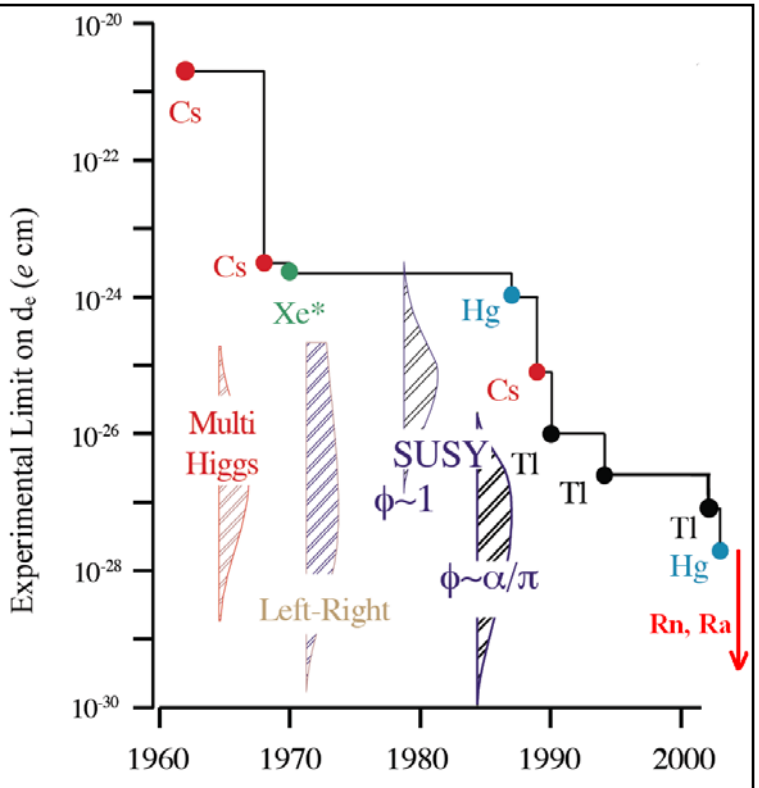
4. Octupole shapes and the Standard Model



Tests of *CP* invariance in hadronic sector from static Electric Dipole Moment (EDM) of atom (best limits so far from ^{199}Hg on $\theta_{QCD}, d_d, C_T, C_S, \varepsilon_q^{SUSY}, \varepsilon^{HIGGS}, \chi^{LR}$

M.V. Romalis et al., PRL 86 (2001) 2505

Expect enhancement (by 10^2) of EDM in *octupole* radioactive nuclei, e.g. ^{223}Rn ,^{225}Ra



Schiff moment is the quantity responsible for inducing an EDM in the electrons orbiting the nucleus:

Schiff moment

$$S \approx -\frac{2}{3}\langle \hat{S}_z \rangle \frac{\langle \hat{V}_{PT} \rangle}{E_0 - E_i}$$

parity doublet

$$\hat{S}_z = \frac{e}{10}\sum_p \left(r_p^2 - \frac{5}{3}\bar{r}_{ch}^2 \right) z_p$$

octupole deformation

Dobaczewski and Engel ,Phys. Rev. Lett. 94 (2005) 232502
L.I. Schiff, Phys. Rev. 132 (1963) 2194

HIE-ISOLDE opportunities

- High intensities, heavy isotopes
- Atomic parity violation studies (e.g. Ra): (ID 45)