Nuclear physics: the ISOLDE facility

Lecture 3: Physics of ISOLDE

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on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Outline

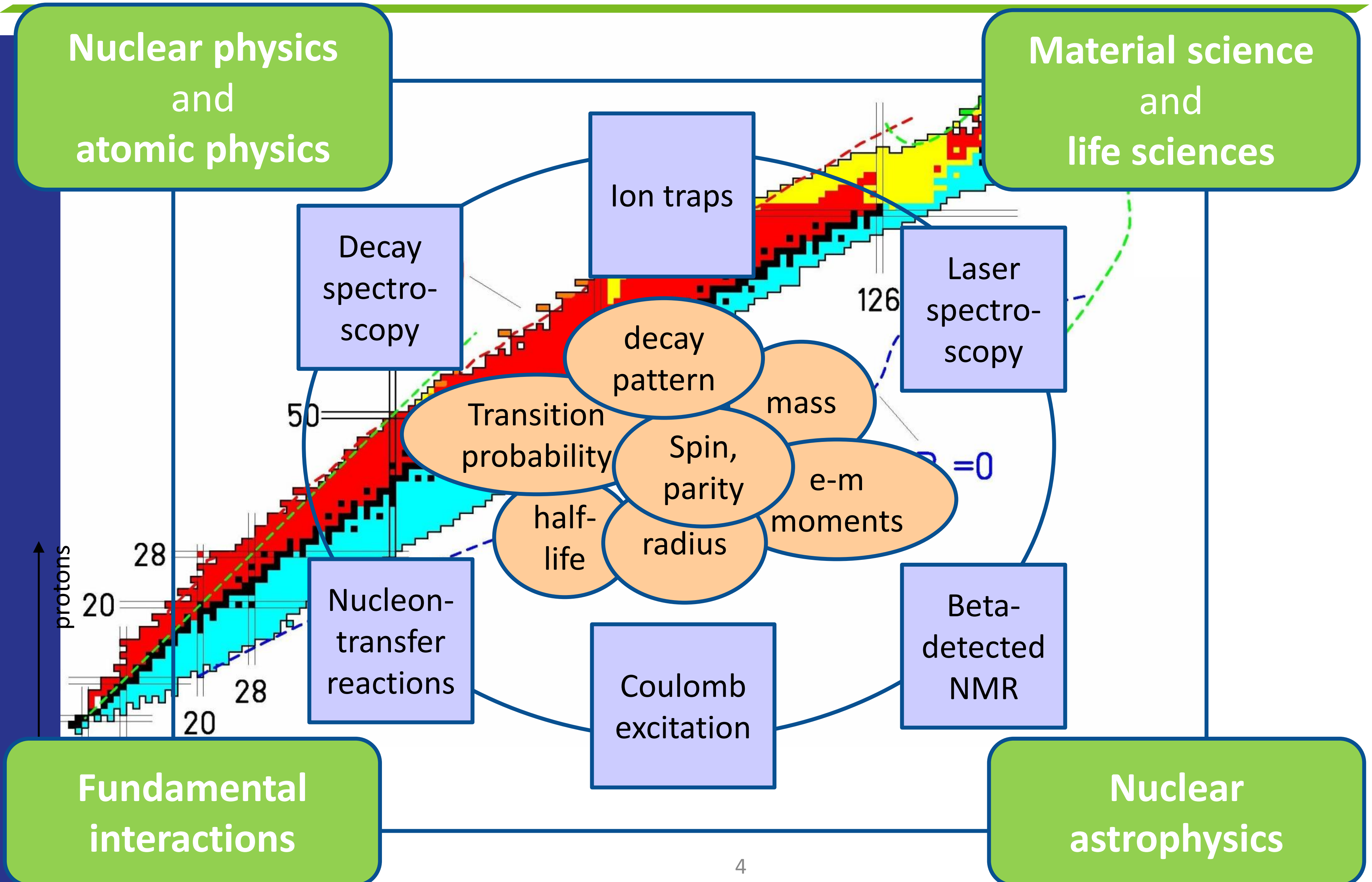
Aimed at both physics and non-physics students

- Lecture 1: Introduction to nuclear physics
- Lecture2: CERN-ISOLDE facility
- **This lecture**: Physics of ISOLDE
  - Measured properties
  - Used techniques
  - Recent results

Small quiz 3

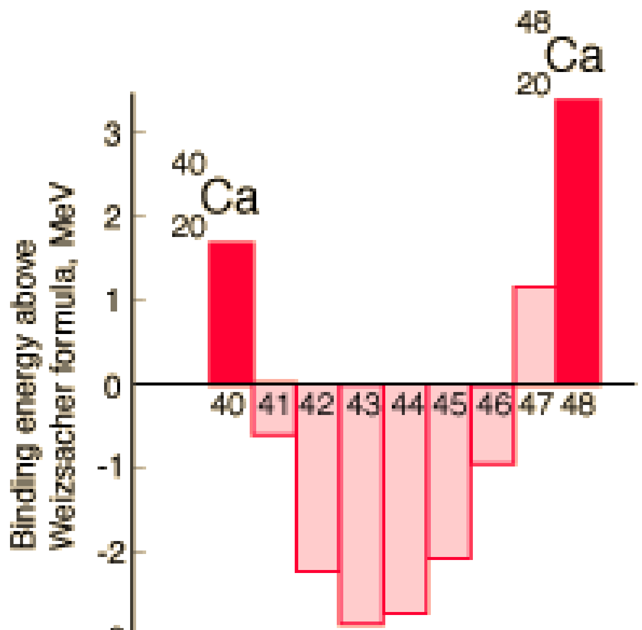
- Which isotopes were studied in the last 4 *Nature* journals (since 2012)?

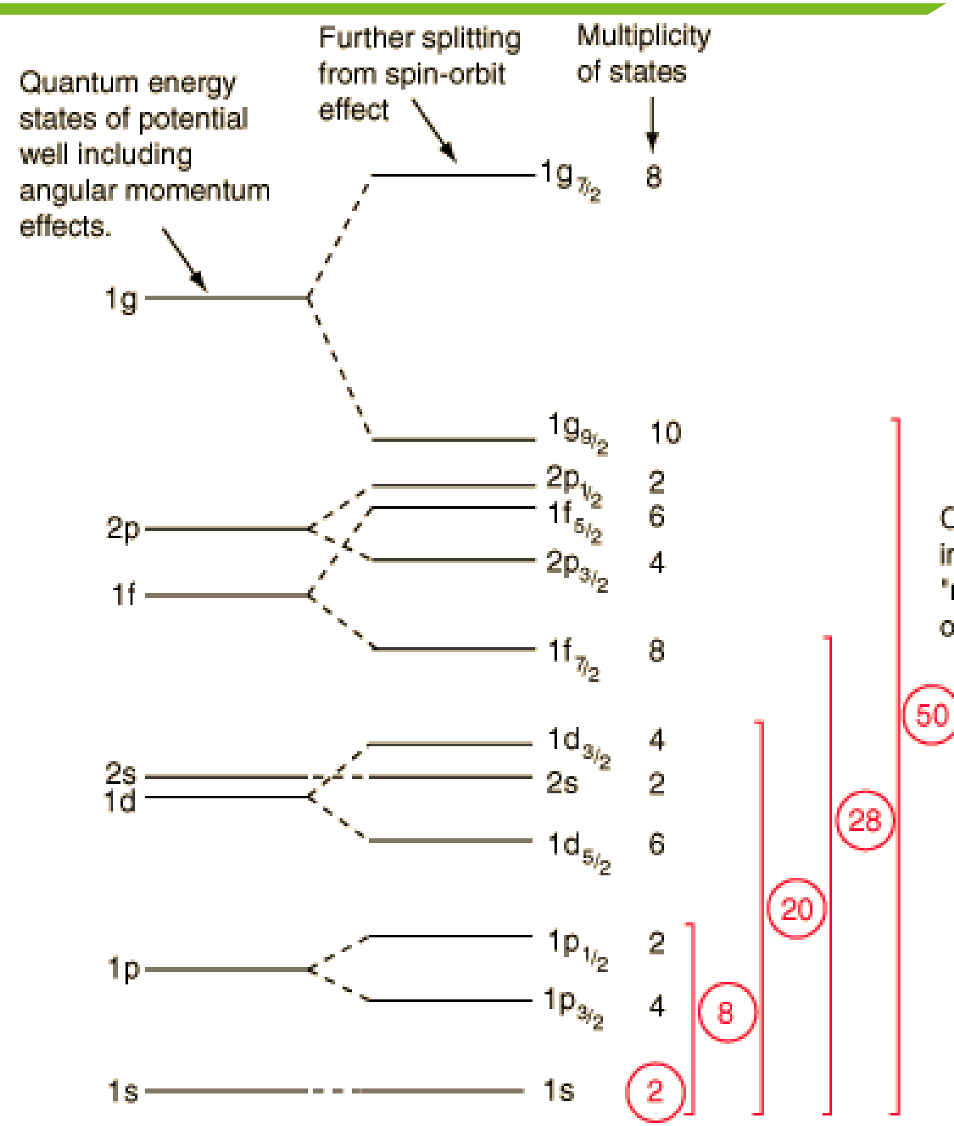
ISOLDE physics topics



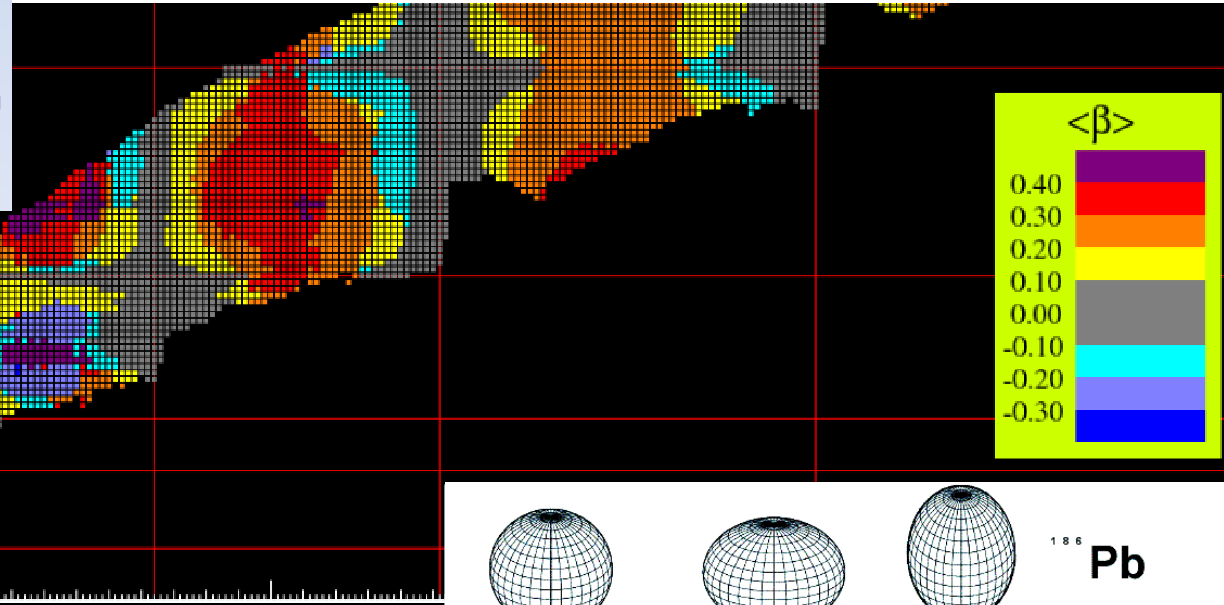
Nuclear shell model

- Created in analogy to the atomic shell model (electrons orbiting a nucleus)
- Based on the observation of higher stability of certain nuclei
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called 'magic'
- Nuclei move in a self-created potential

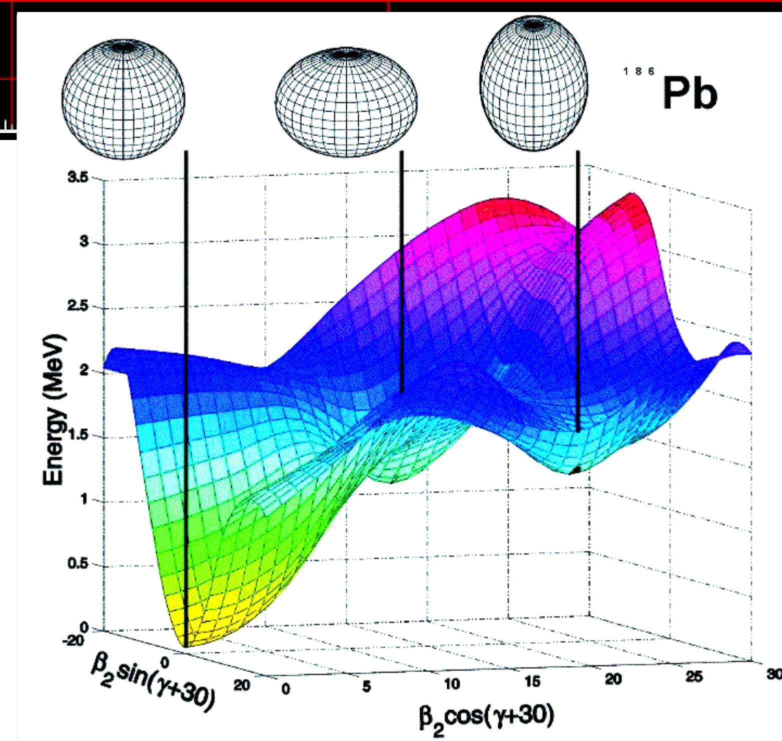




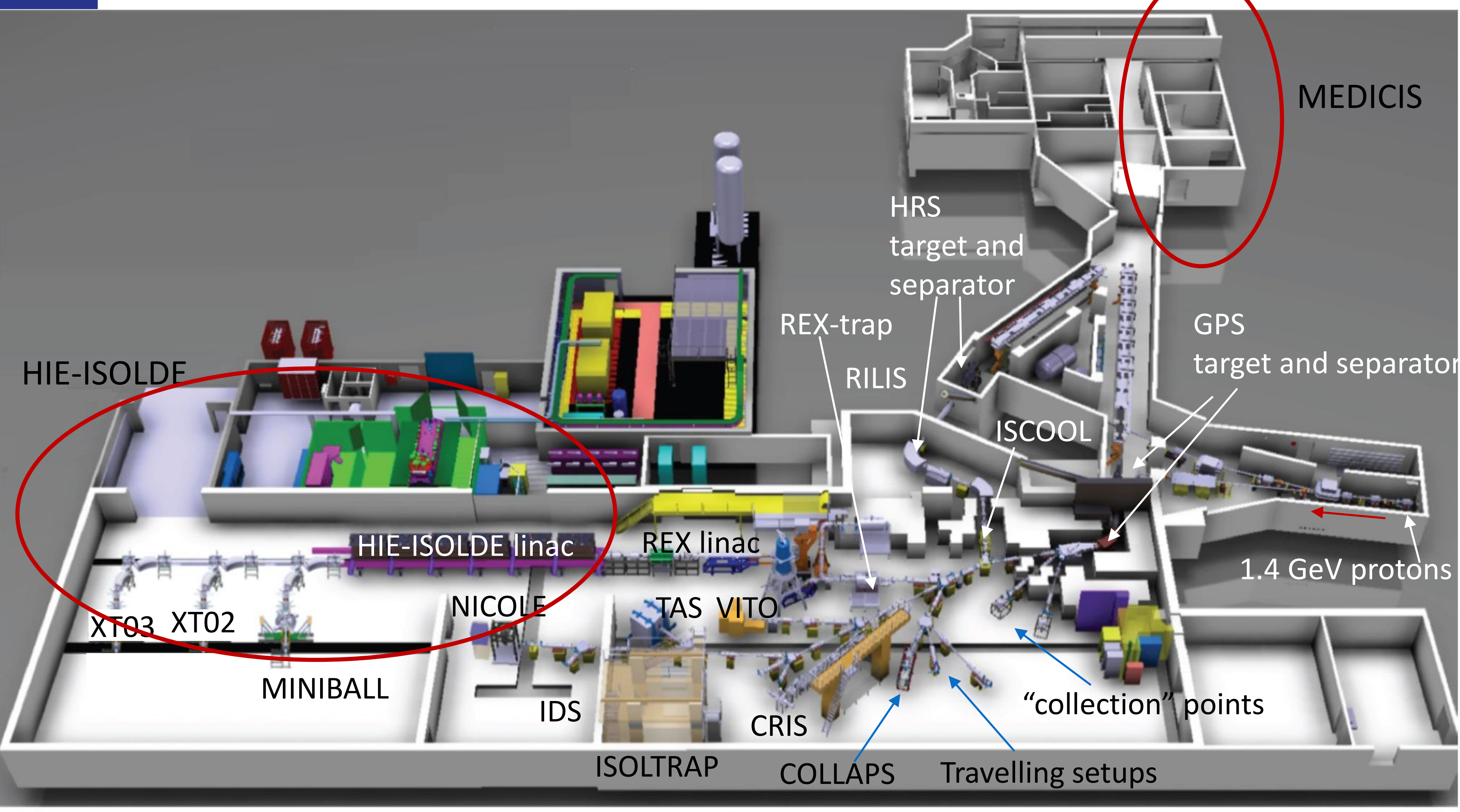
Mean-field models



- Each particle interacts with an average field generated by all other particles: mean field
- Mean field is built from individual excitations between nucleons
- No inert core
- Very good at describing deformations
- Can predict properties of very exotic nuclei
- Not so good at closed shells



ISOLDE experimental setups

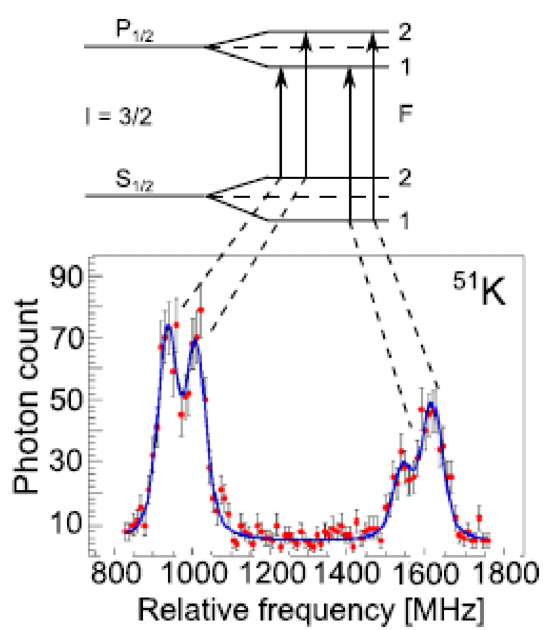


Laser spectroscopy and nuclear properties

Lasers allow studying **ground-state (and isomeric) properties of nuclei,** based on:

Atomic **hyperfine structure (HFS)**
(interaction of nuclear and atomic spins)

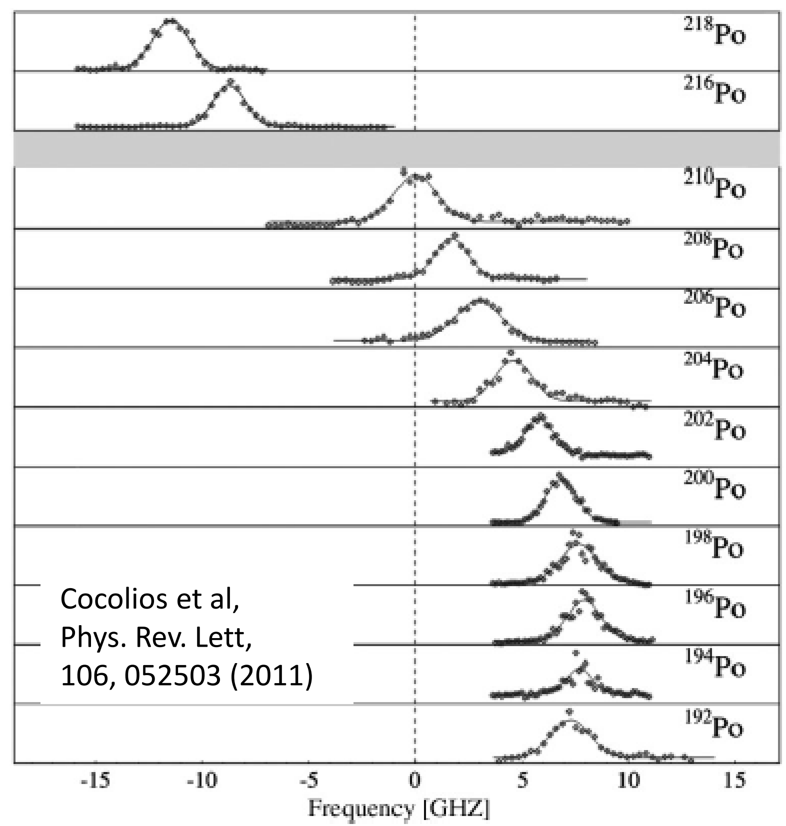
- HFS details depend on:
  - Spin -> orbit of last proton&neutron
  - Magnetic dipole moment -> orbits occupied by p&n
  - Electric quadrupole moment -> deformations



Yordanov et al, Phys. Rev. Lett., 110, 172503 (2013)

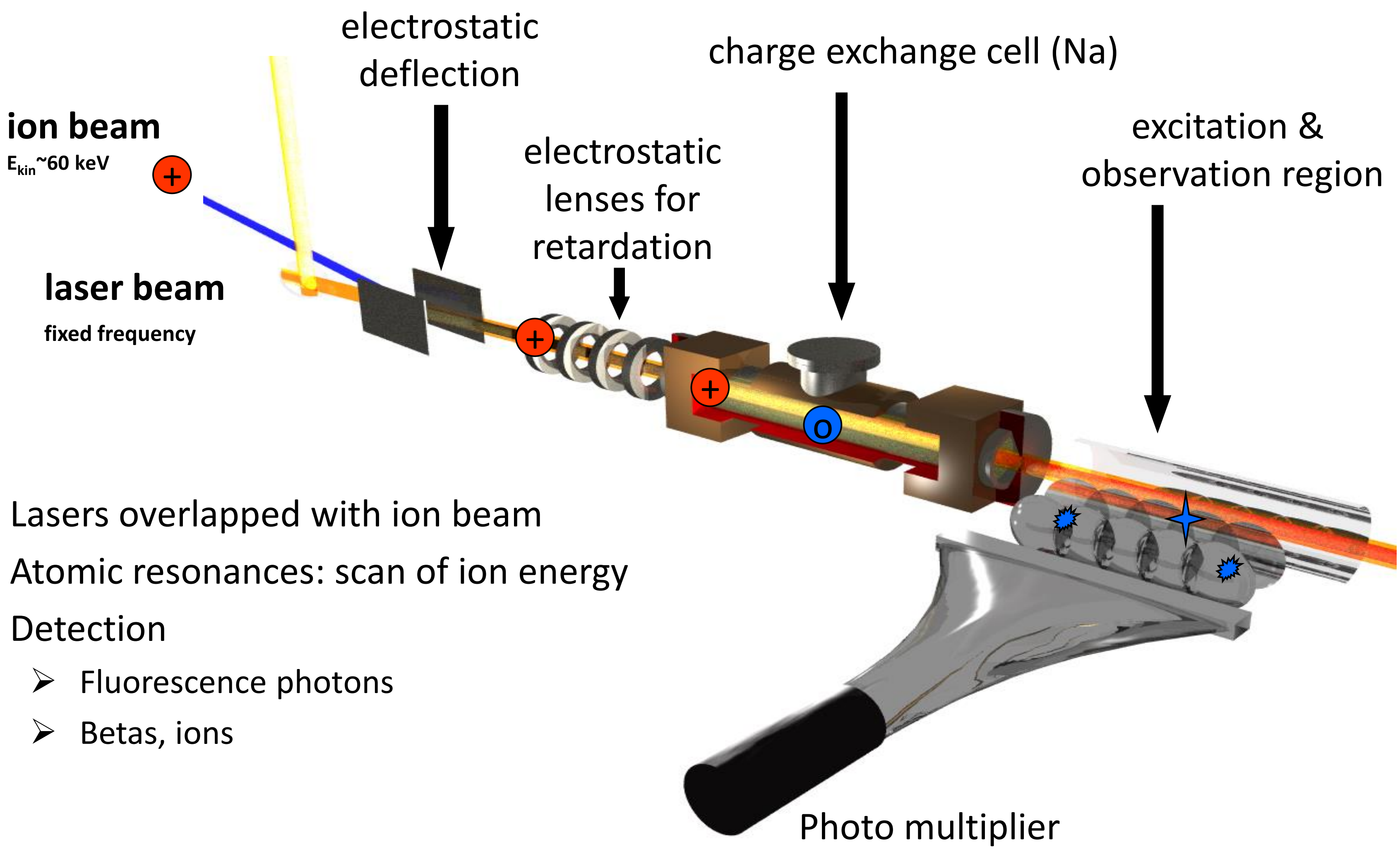
Isotope shifts (IS) in atomic transitions
(change in mass and size of different isotopes of the same chemical element)

- IS between 2 isotopes depends on:
  - difference in their masses & charge radii



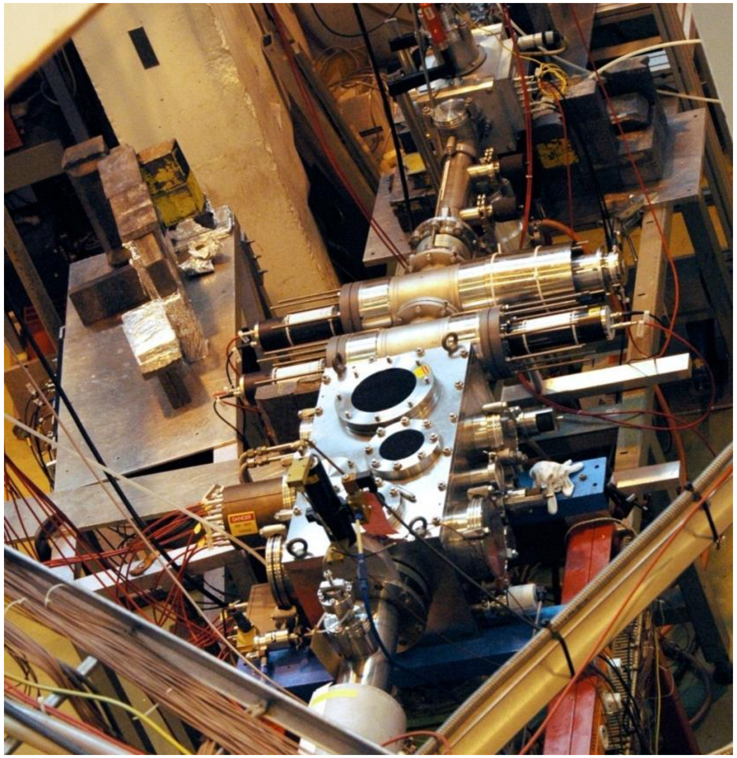
Cocolios et al, Phys. Rev. Lett, 106, 052503 (2011)

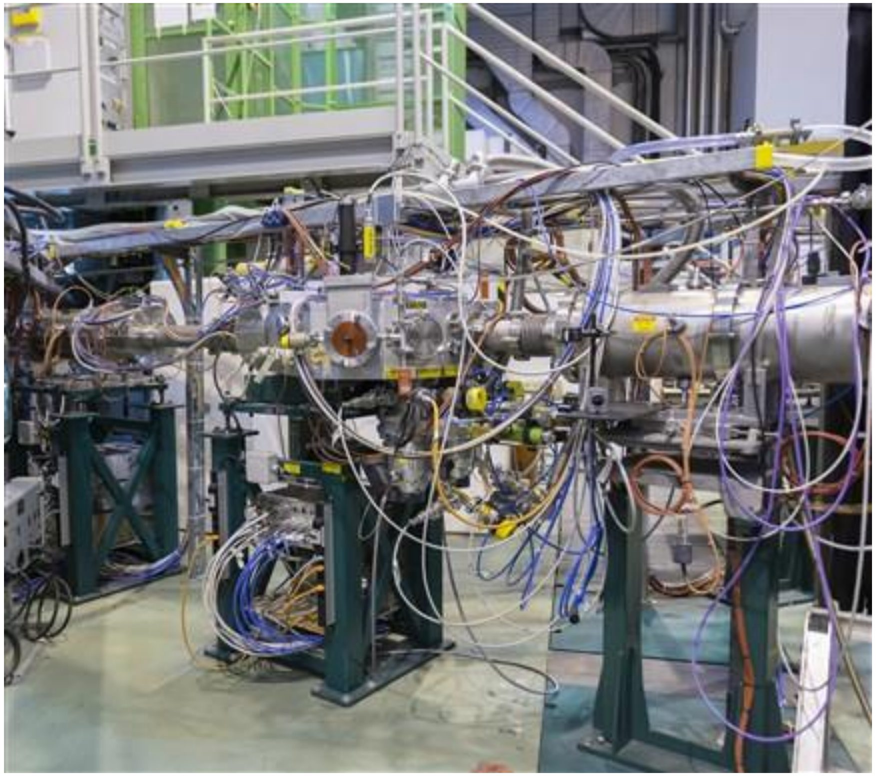
Collinear laser spectroscopy

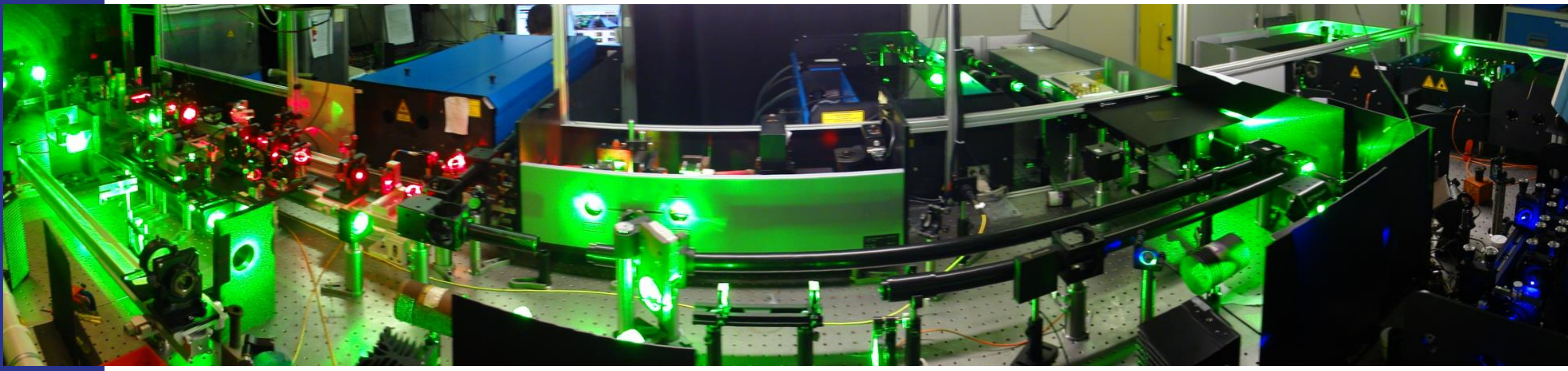


- Lasers overlapped with ion beam
- Atomic resonances: scan of ion energy
- Detection
  - Fluorescence photons
  - Betas, ions

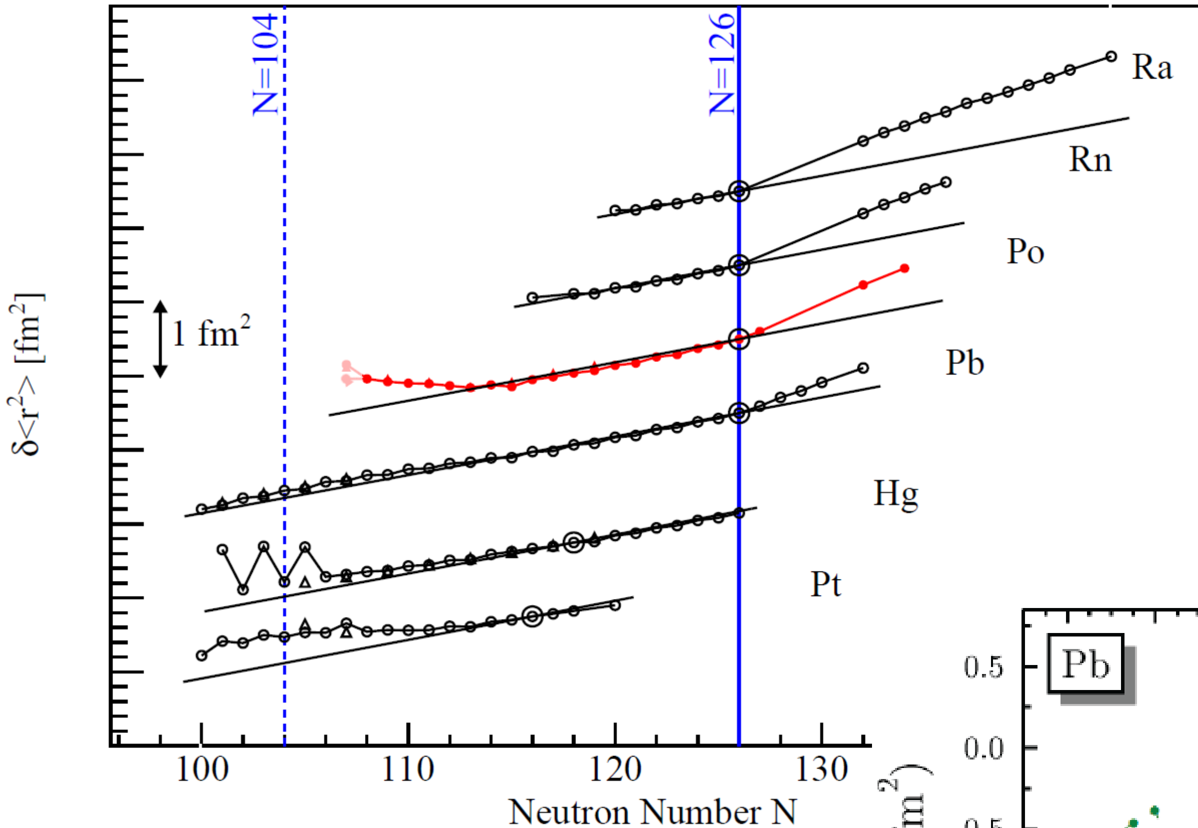
COLLAPS, CRIS, RILIS







Charge radii around lead

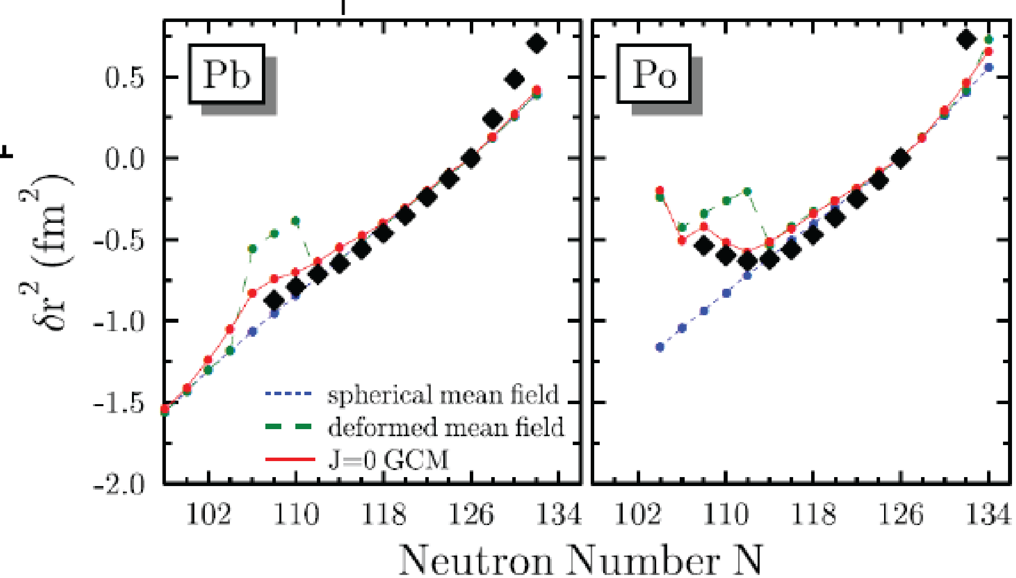


Isotope shifts measured with RILIS setup (part of data shown):

Regions of deformation visible

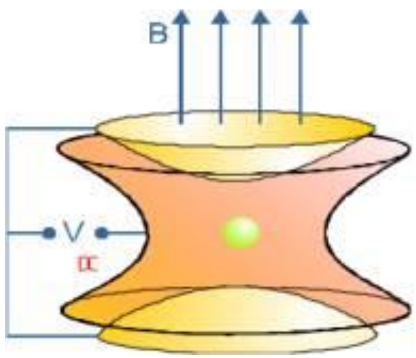
T.E. Cocolios et al., PRL 106 (2011) 052503
M. Seliverstov et al., EPJ A41(2009) 315
H. De Witte et al., PRL 98 (2007) 112502

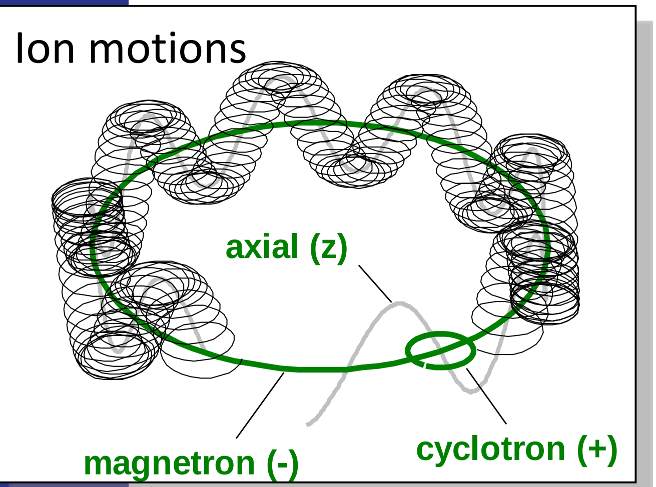
Radii described well with mean field models

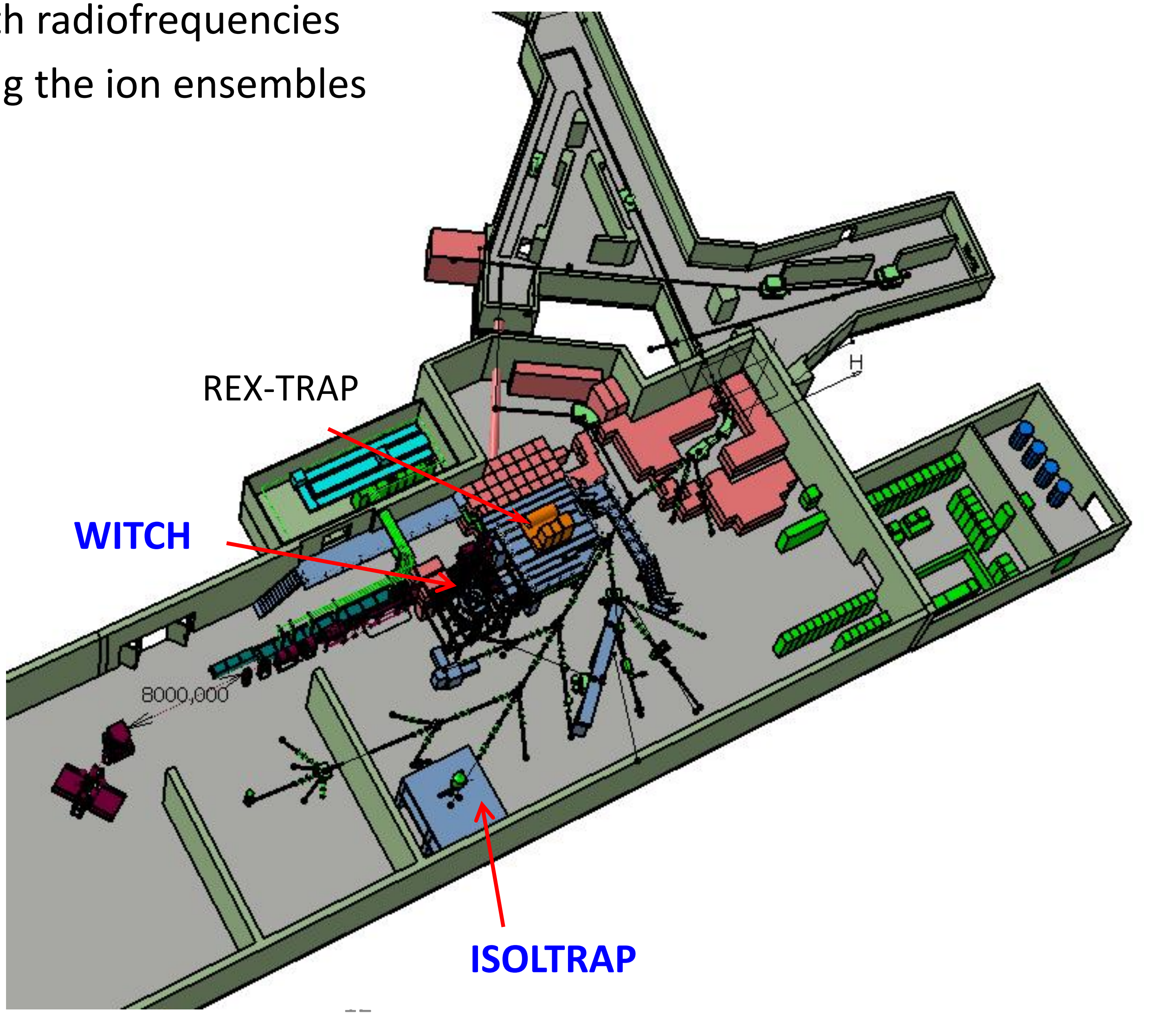


Studies with ion traps

- Penning trap = cross of magnetic and electric field
- Ion manipulation with radiofrequencies
- Possibility of purifying the ion ensembles

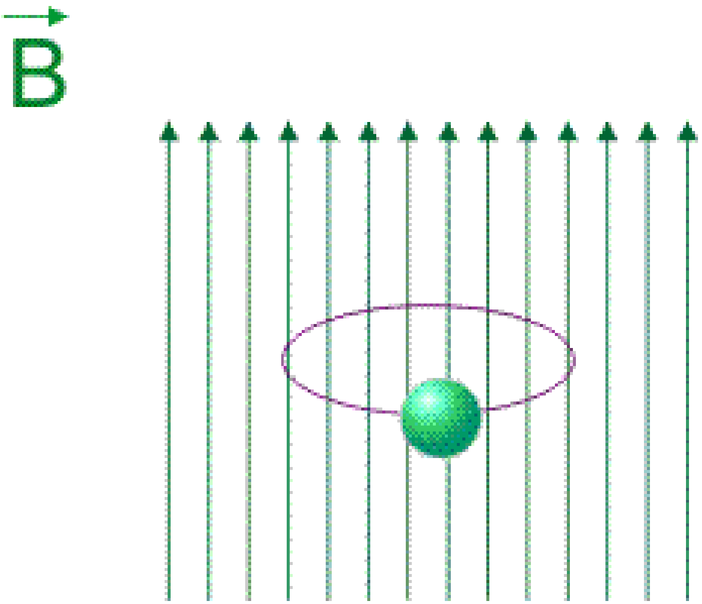






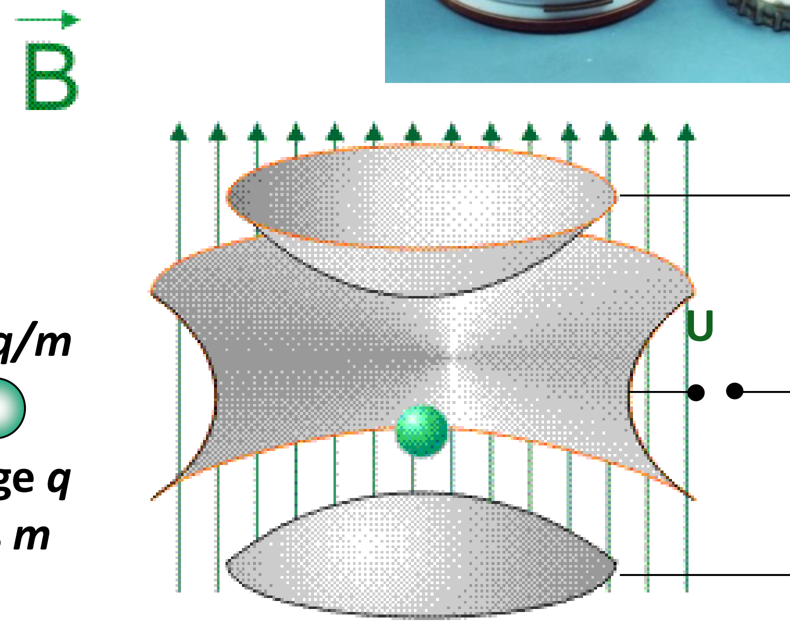
Penning-trap mass spectrometry

- Penning trap
  - superposition of static magnetic and electric field
  - Ion manipulation with radiofrequencies



Ion *q/m*

Charge *q*
Mass *m*



Free cyclotron frequency is inversely proportional to the mass of the ions!

$$\omega_c = qB/m$$

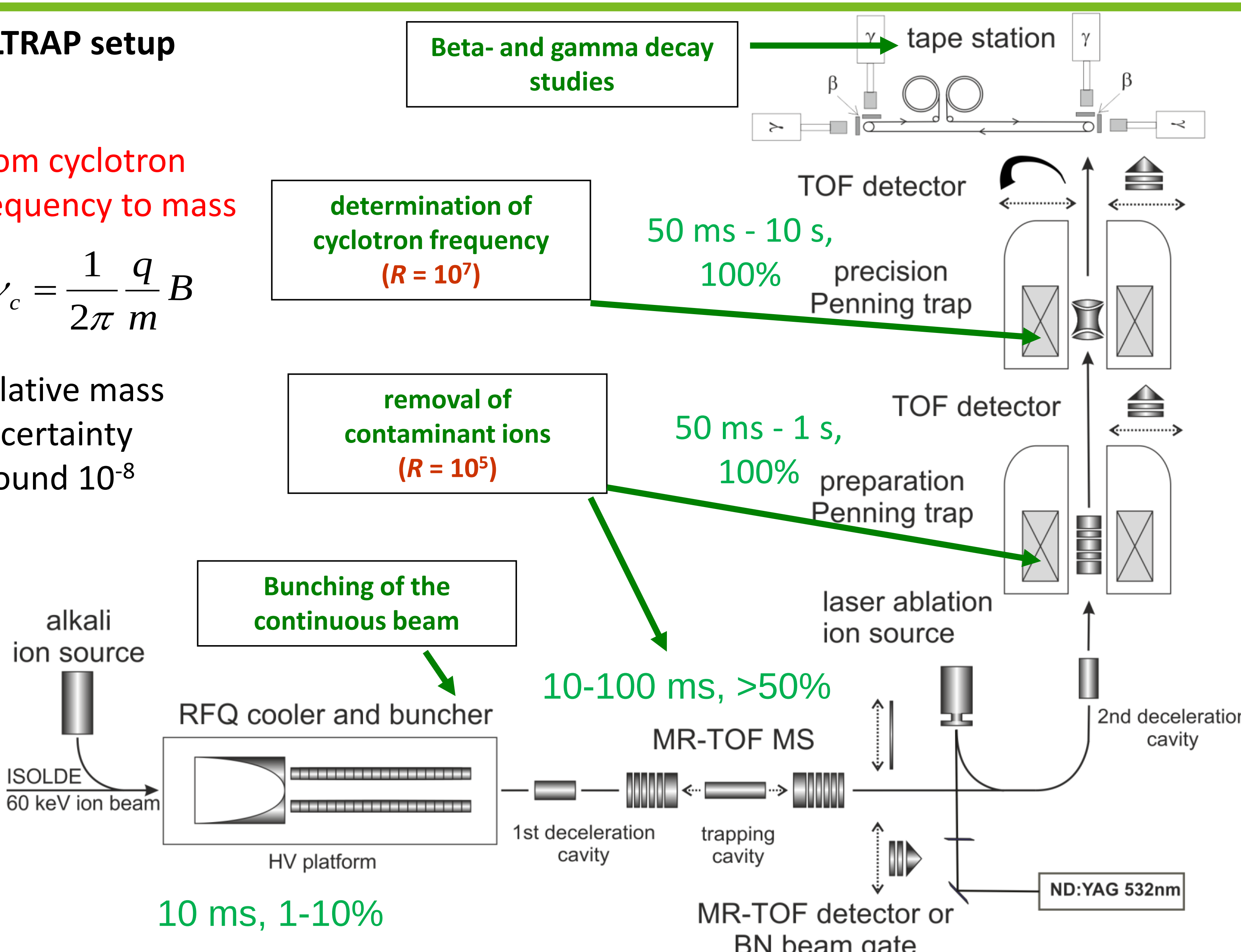
Penning-trap mass spectrometry

ISOLTRAP setup

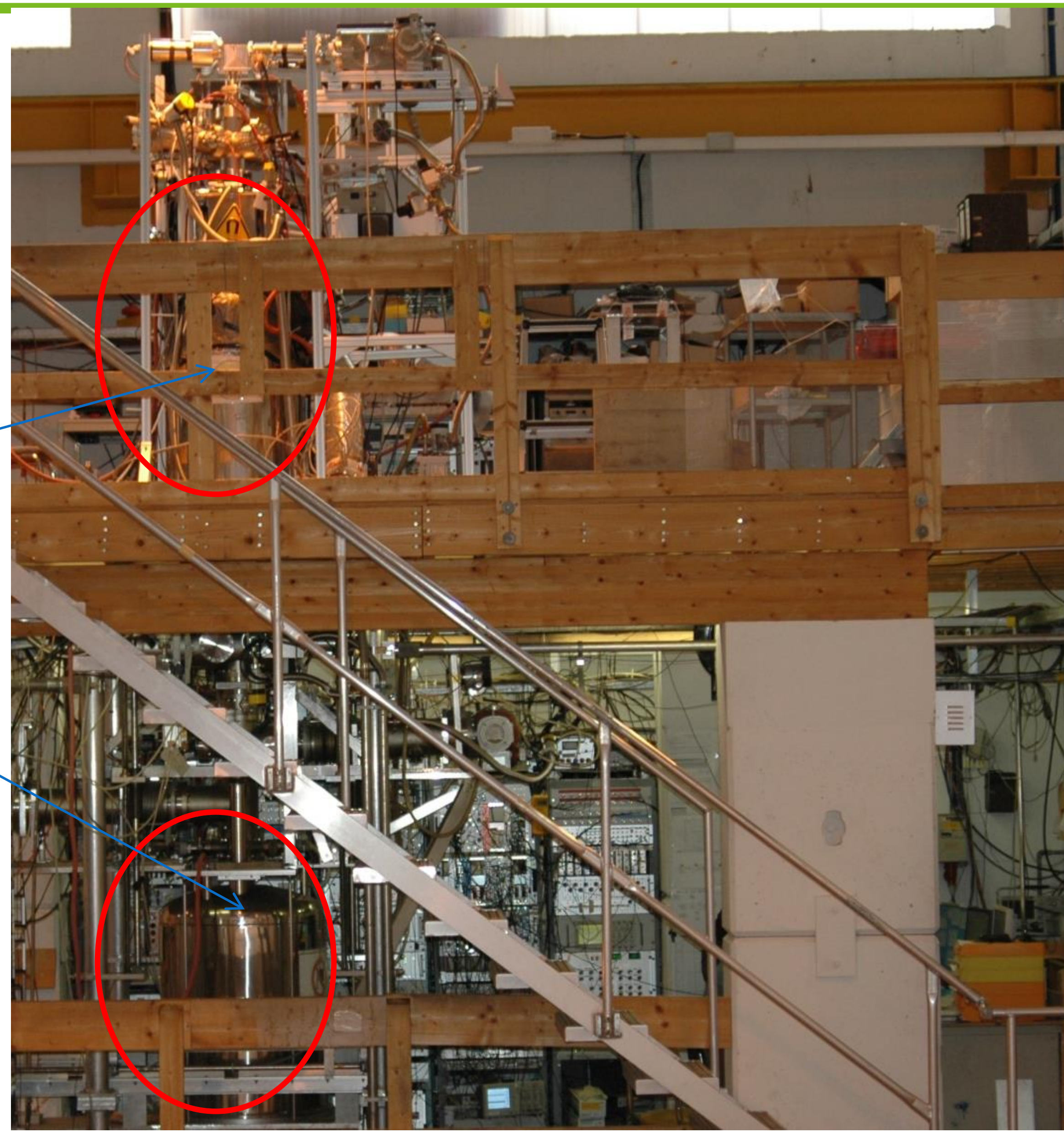
From cyclotron frequency to mass

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Relative mass uncertainty around 10^{-8}



ISOLTRAP

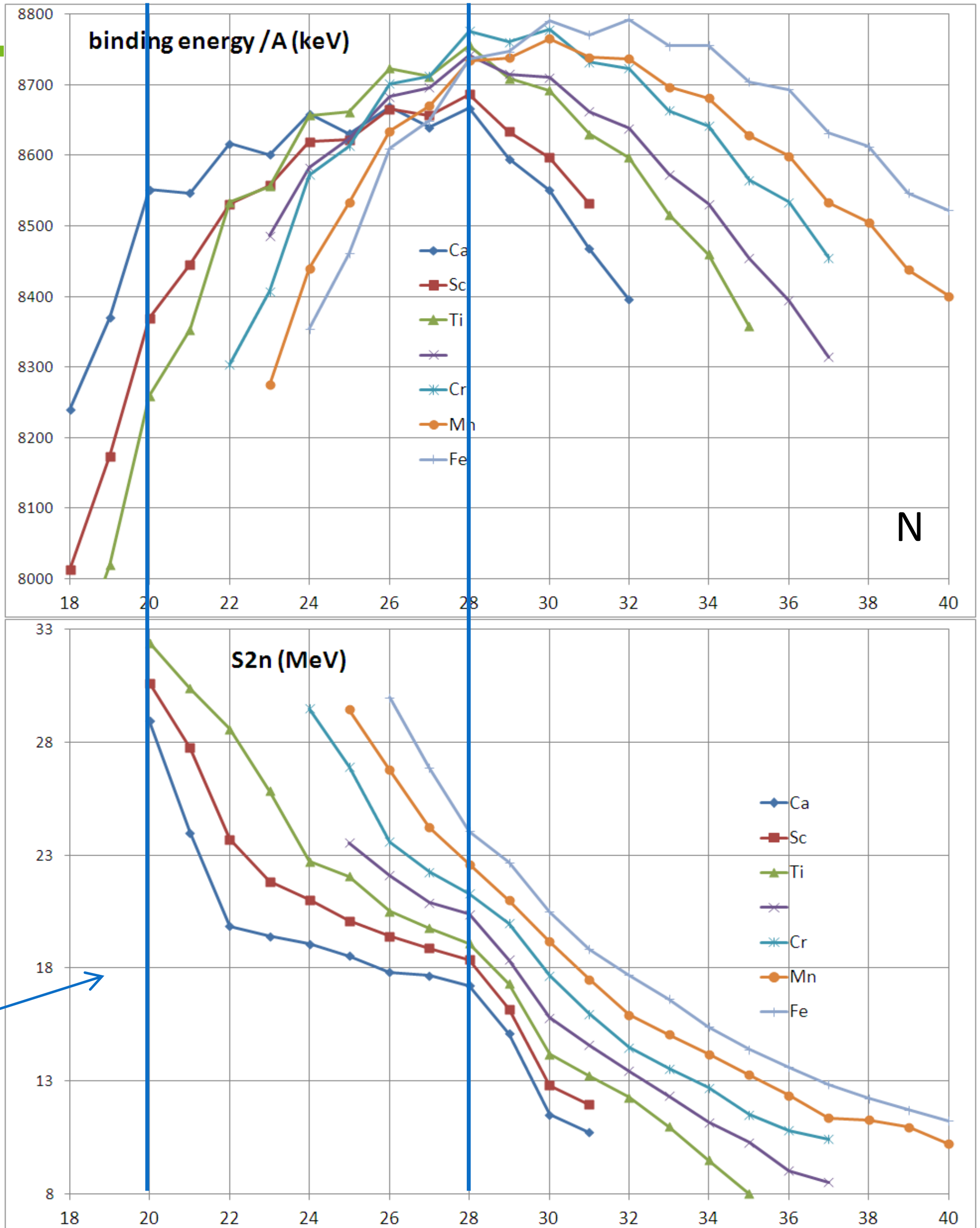


Masses and nuclear structure

- Mass filters (mass differences) to "filter out" specific effects, e.g.
  - Differences in binding energies (one- or two-neutron/proton separation energies)

Two-neutron separation energy

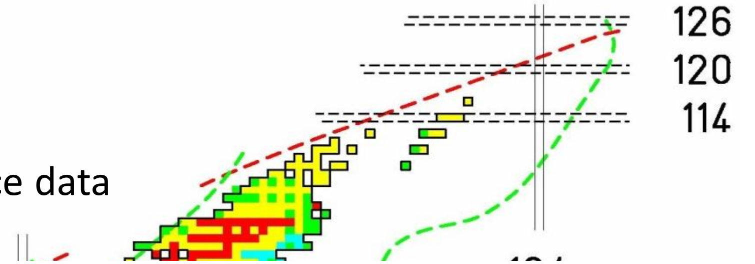
$$S_{2n} = B(N-2, Z) - B(N, Z),$$



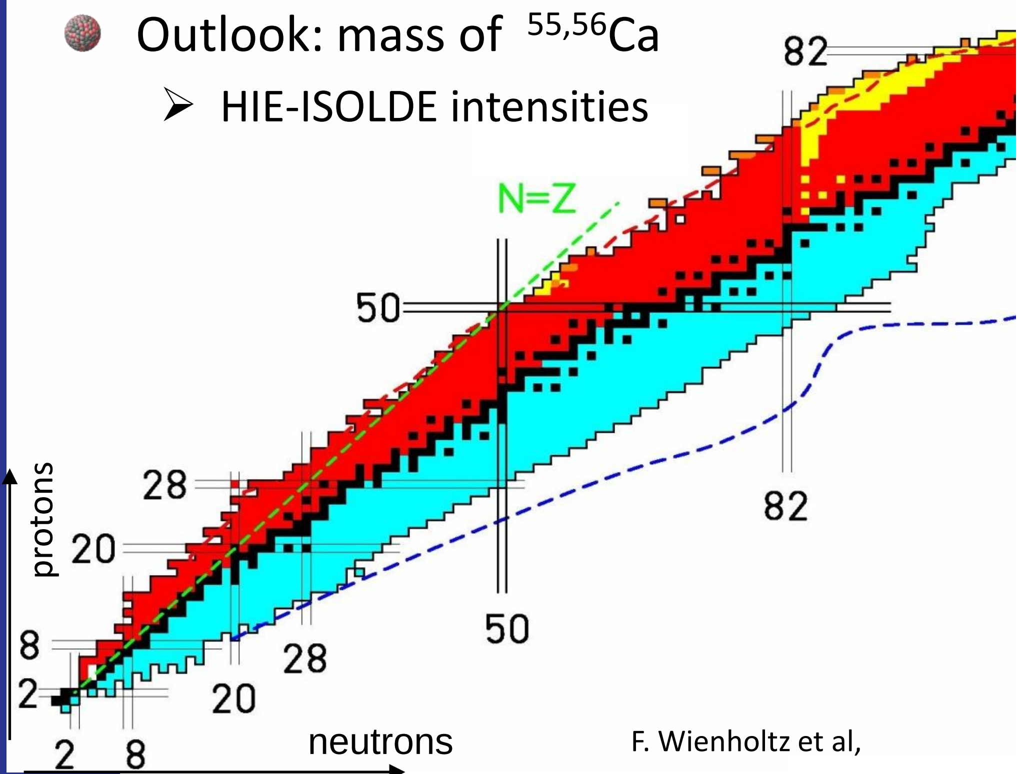
Closed shells visible as a sudden drop after the magic number (N=20 and 28)

Calcium-54 and nuclear forces

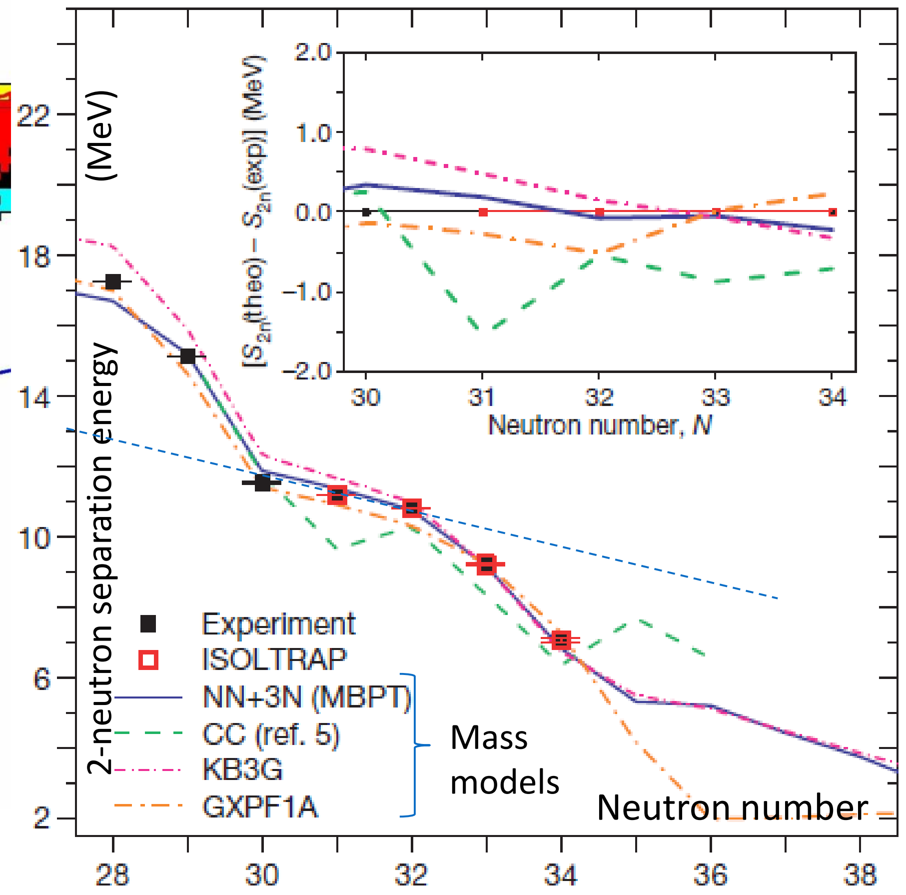
- Shell closures: backbone of nuclear structure
  - They change far from stability – how and why?
- Masses of neutron-rich calcium isotopes
  - Three-body nucleon forces required to reproduce data
  - New neutron shell closure at N=32



- Outlook: mass of ^{55,56}Ca
  - HIE-ISOLDE intensities



F. Wienholtz et al,
Nature 498 (2013), 346

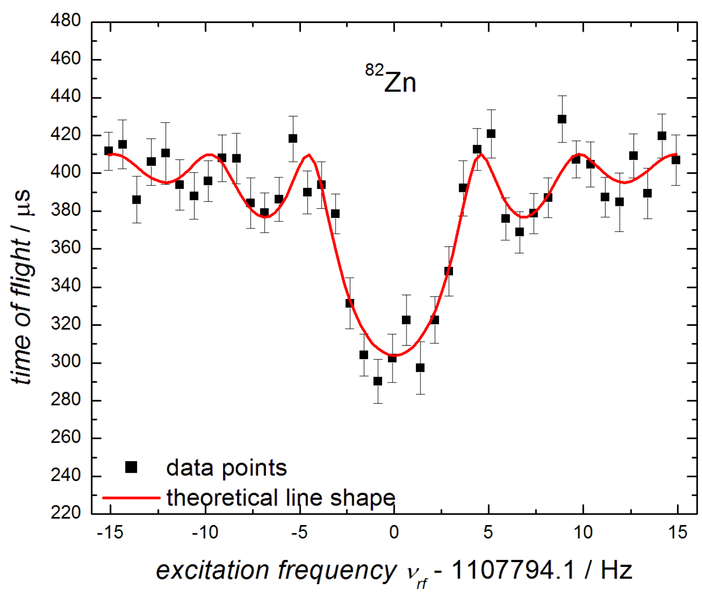


Mass of zinc-82

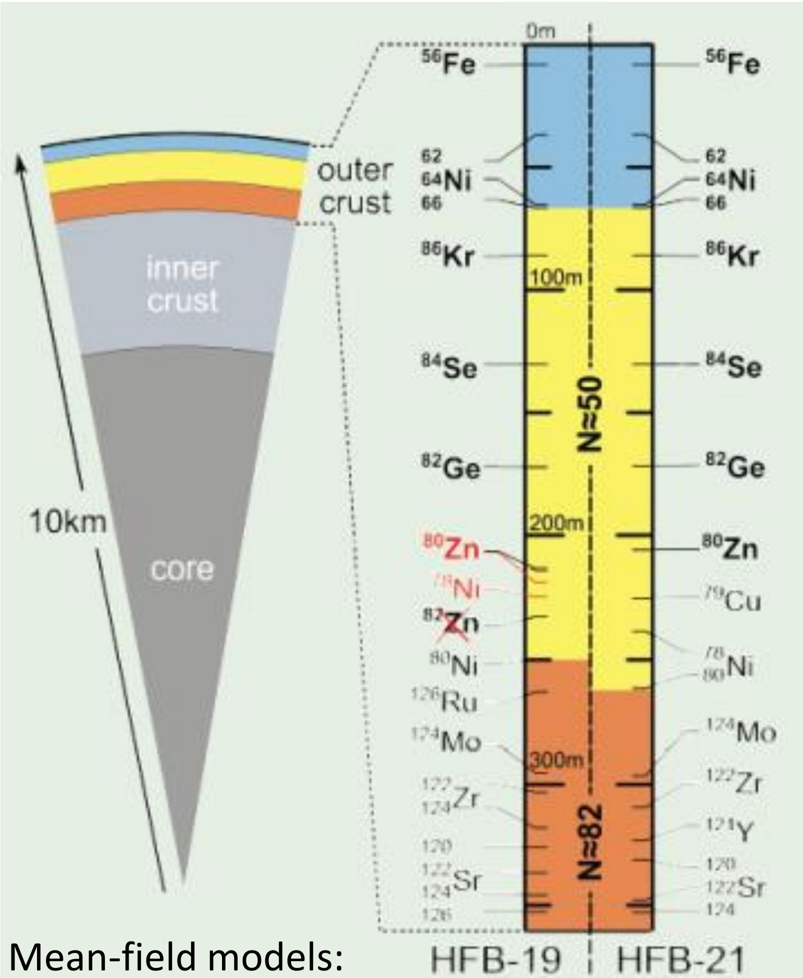
After several attempts at ISOLTRAP and elsewhere

Neutron-star composition:
- Test of models
- 82Zn is not in the crust

- Combined ISOLDE technical know-how:
  - neutron-converter and quartz transfer line (contaminant suppression)
  - laser ionisation (beam enhancement)

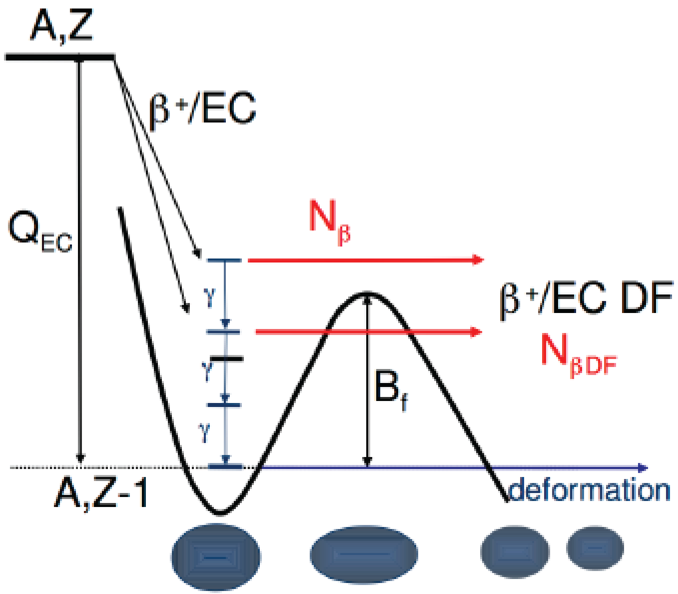


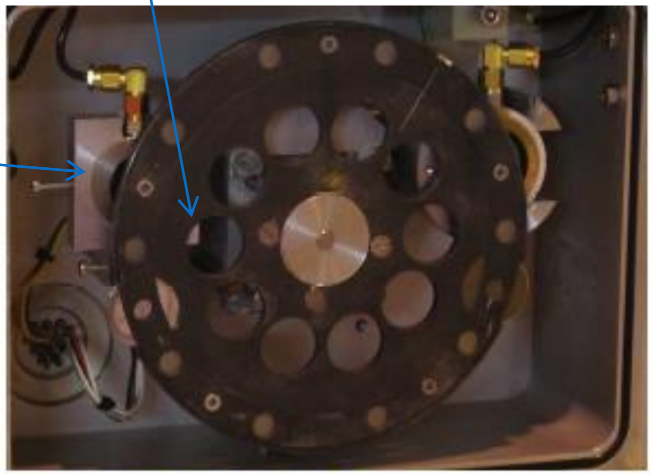
R.N. Wolf et al, Phys. Rev. Lett. 110, 041101 (2013)



Decay spectroscopy

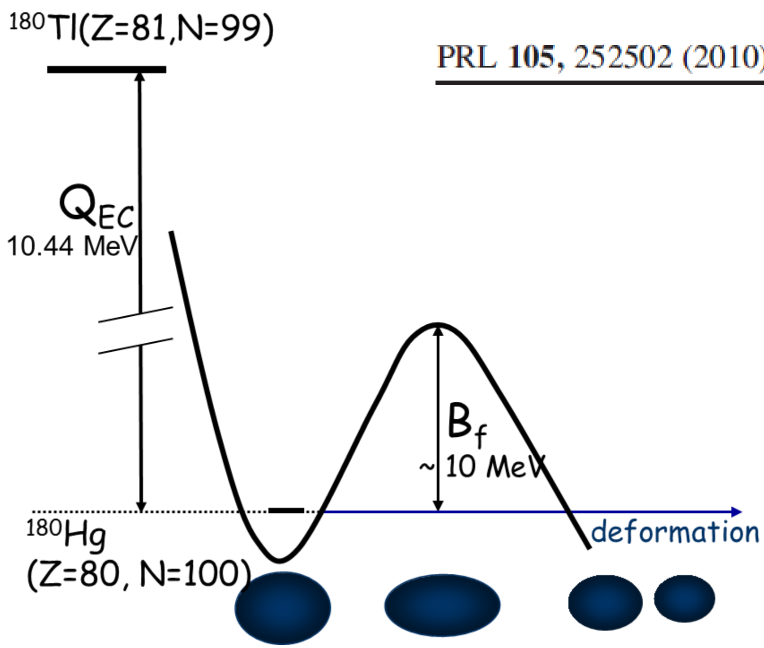
- Different detectors to sensitive to emitted:
  - Alpha particles
  - Beta particles
  - Gamma rays
  - Protons or neutrons
- For example WINDMILL setup:
  - Alpha and gamma detectors
  - Used for studies of beta-delayed fission (i.e. fission following a beta decay)

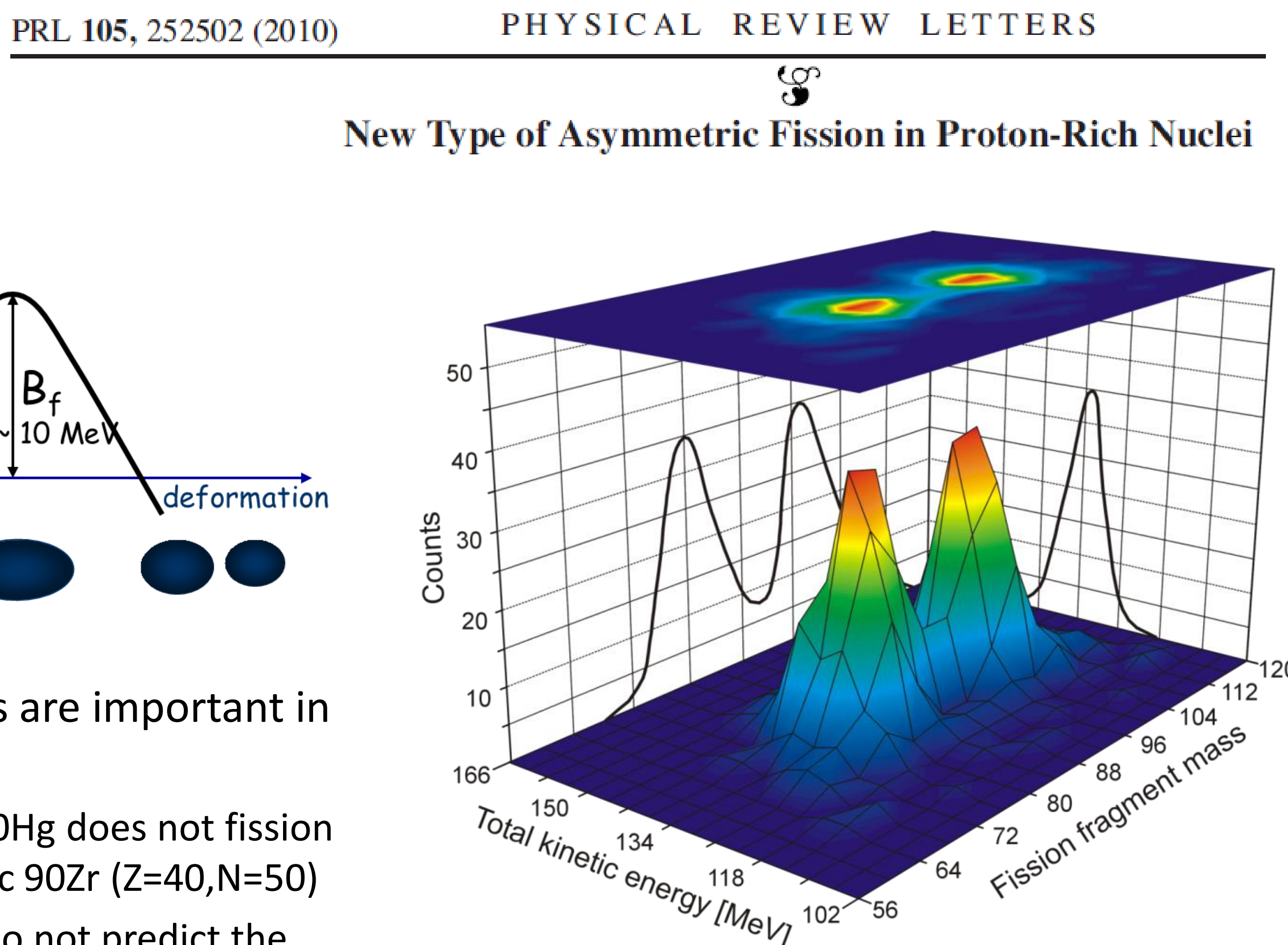




Beta-delayed fission of mercury-180

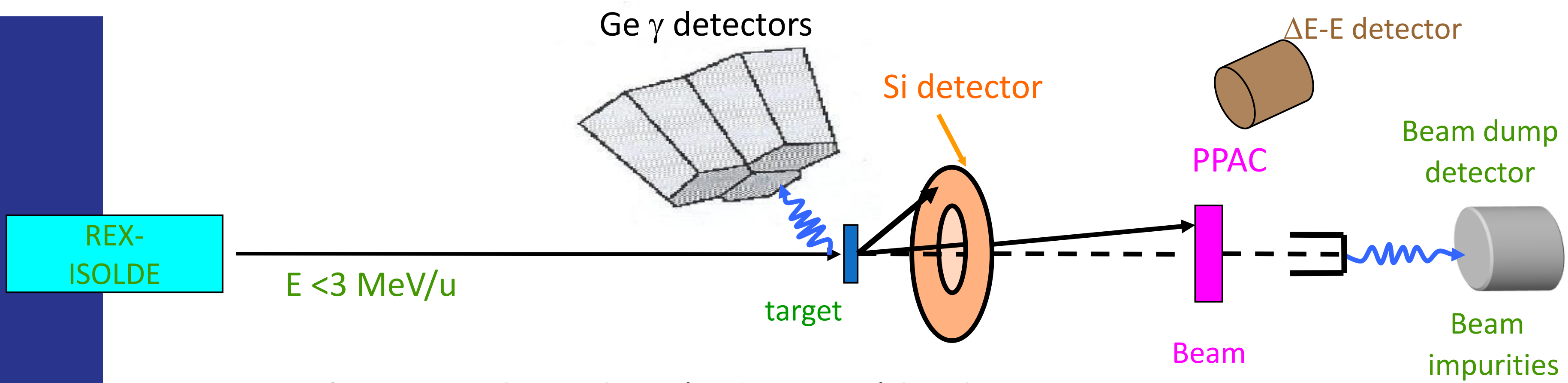
WINDMILL setup



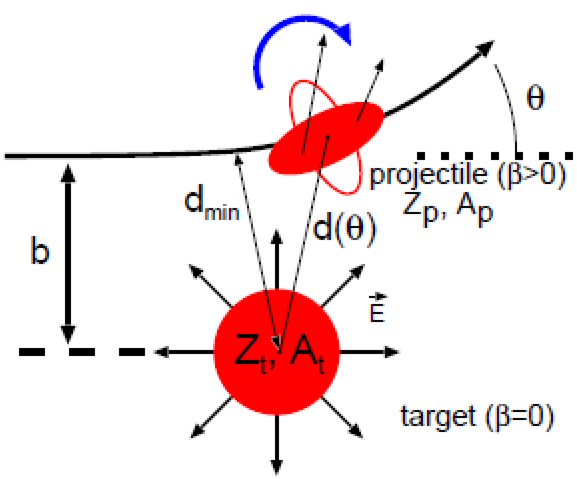


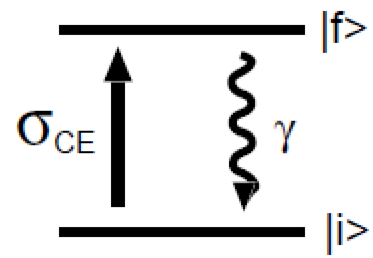
- Nuclear shell effects are important in fission, but:
  - Unexpectedly 180Hg does not fission in two semi-magic 90Zr (Z=40,N=50)
  - Fission theories do not predict the results correctly

Coulomb excitation



Excitation of a projectile nucleus (radioactive) by the electromagnetic field of the target (made of stable nuclei)

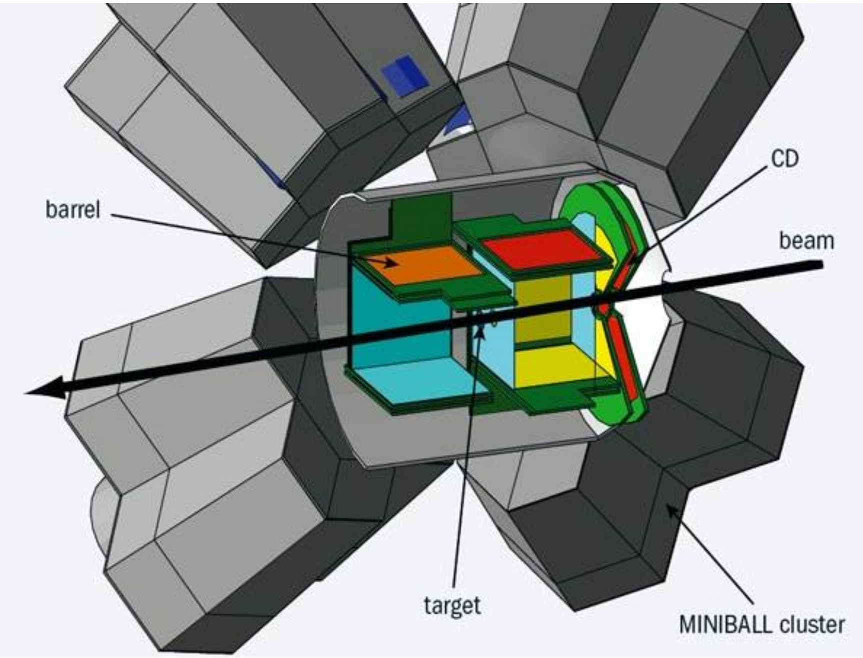




Observables: Transition energies and intensities

=> Determine new excited levels and study deformations

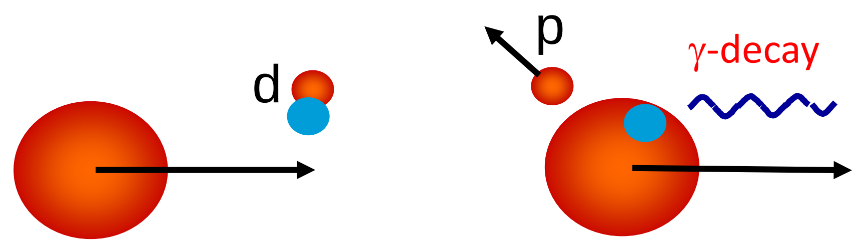
Nucleon-transfer reactions



Miniball + T-REX setup (Si detector barrel)

And/or SPEDE (conversion electrons):

gamma detectors and particle identification



Typical reactions: one or two-nucleon transfer (d,p), (t,p)

Observables
- energies of protons (+ E_g)
- angular distributions of protons (+ γ-rays)
- (relative) spectroscopic factors

Information:
- (single-particle) level energies
- spin/parity assignments
- particle configurations

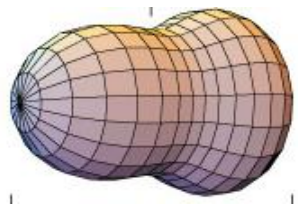
study single-particle properties of nuclei

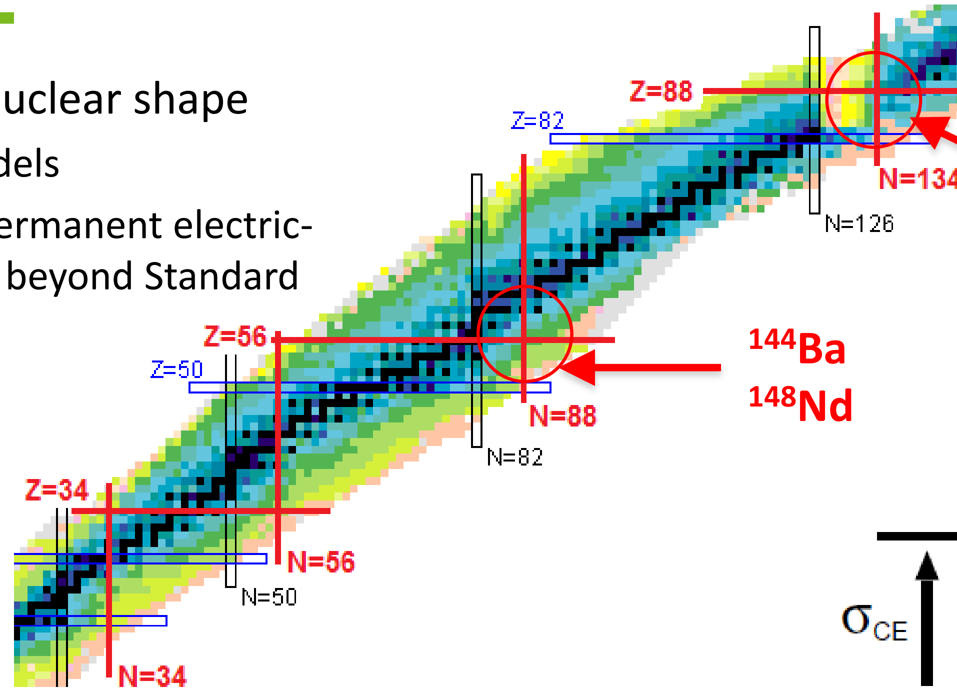
= > Similar configurations = large overlap of wave functions =

Large probability of transfer reaction

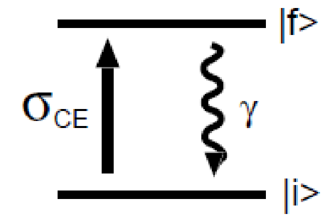
Octupole deformation and MINIBALL

- Octupole shape – very rare nuclear shape
  - Test ground for nuclear models
  - Important in searches for permanent electric-dipole moments (EDM) – beyond Standard Model

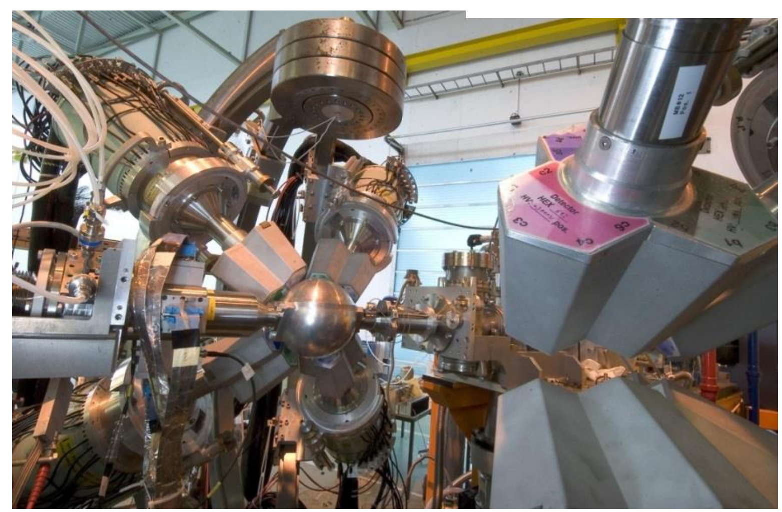




- Method: Coulomb excitation
  - Beam accelerated to 2.8 MeV/u
  - Excitation of a projectile nucleus by e-m field of the target nuclei



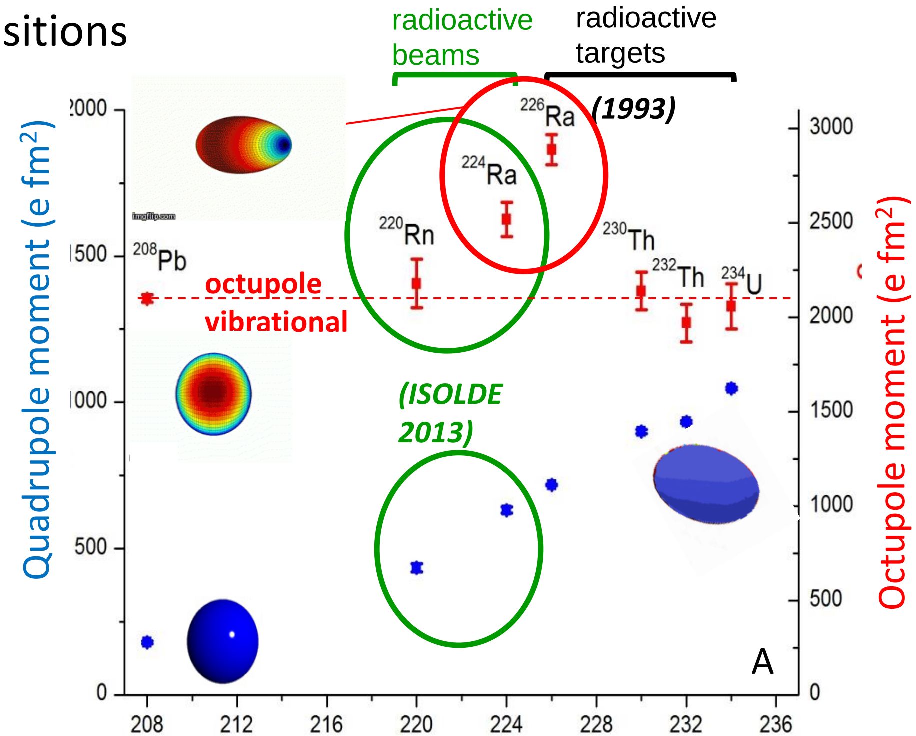
- Detection with MINIBALL gamma-array
  - Germanium detectors - high efficiency gamma detection
  - Silicon detectors for particle identification



L.P. Gaffney et al, Nature 497 (2013) 199

Pear-shape: beyond Standard Model

- Results: Enhanced electric-octupole transitions
  - ➢ direct measure of octupole correlations
- Pear shape shown experimentally in radium-224
- Best candidates for EDM searches identified: radium-223, 225
- Enhanced atomic EDM moment
  - ➢ Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei
  - ➢ In radium atoms, additional enhancement due to near-degeneracy of atomic states



- Outlook - HIE-ISOLDE:
  - ➢ Coulomb excitation on odd-mass radium and radon isotopes
  - ➢ Searches for permanent EDM in trapped radium isotopes
  - **=> Looking for physics beyond the Standard Model**

L.P. Gaffney et al, Nature 497 (2013) 199

Applications

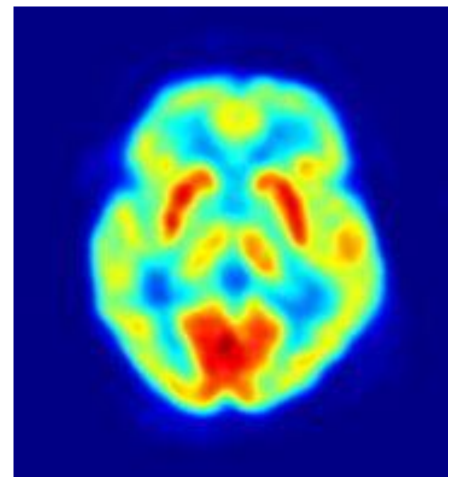
- Use known radiation from not totally exotic radioisotopes

- Profit from radionuclides:
  - Pure samples of radioisotopes (offline studies)
  - High detection efficiency for radiation (online studies)

- Techniques:
  - Emission Channeling
  - PAC (Perturbed Angular Correlations)
  - Diffusion
  - Photoluminescence

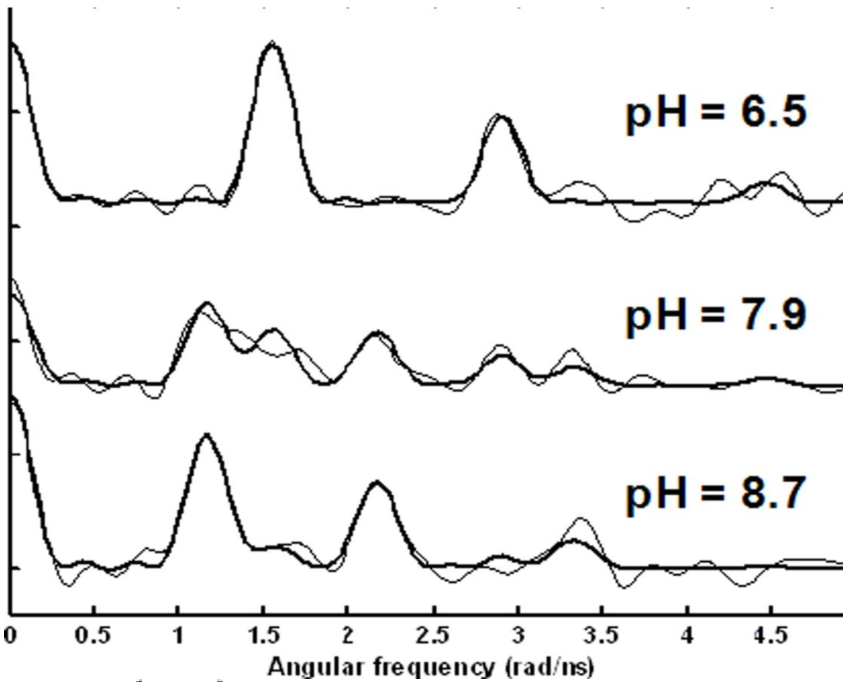
PET isotopes

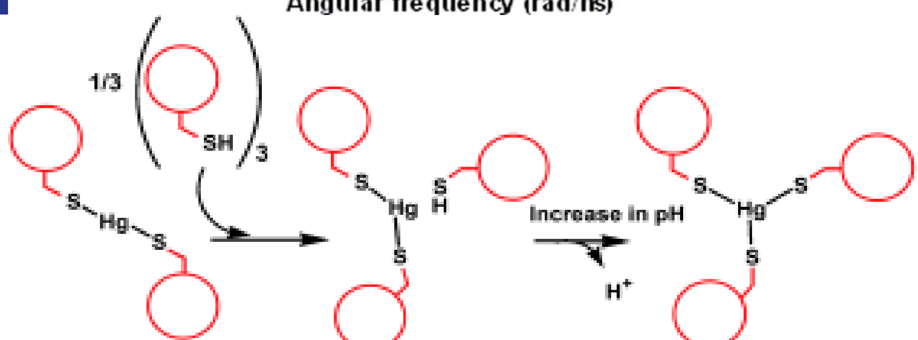
- PET (positron emission tomography) – uses β+ emitting nuclei and their annihilation inside the body in diagnosis and therapy
- Produced at ISOLDE and later investigated together with the creators of the PET technique at the Geneva Hospital

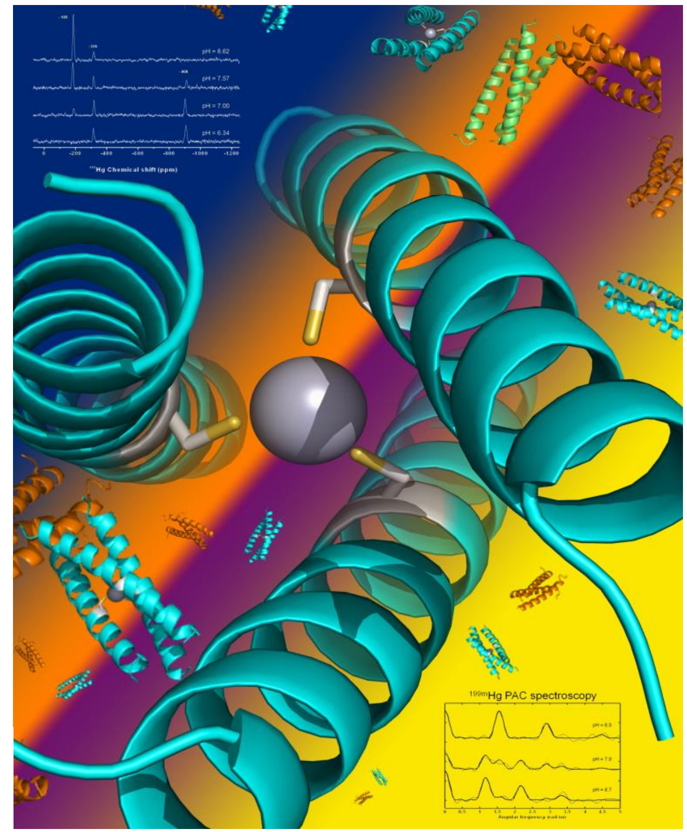


Heavy-ion toxicity

- Studied with Perturbed Angular Correlation method







Vibenholt J et al, Inorg. Chem (2012)

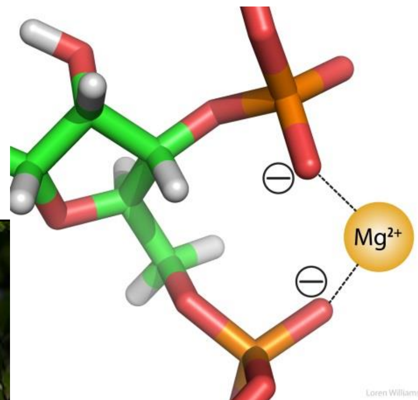
Biophysics and Parkinson disease

- Over 1/3 of all proteins require metal ions to function:

➢ Magnesium

Catalysis in cellular energy transformations

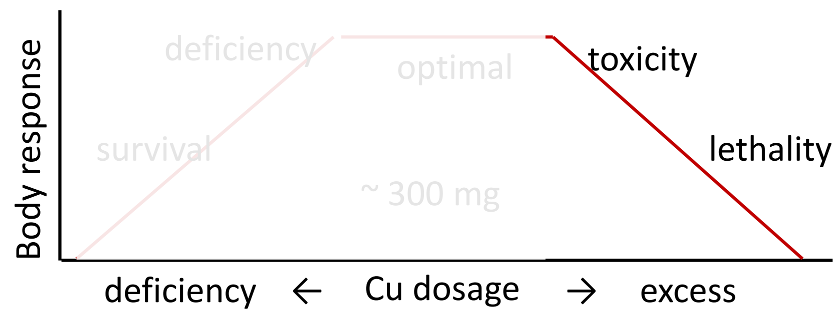
Photosynthesis - component of chlorophyll

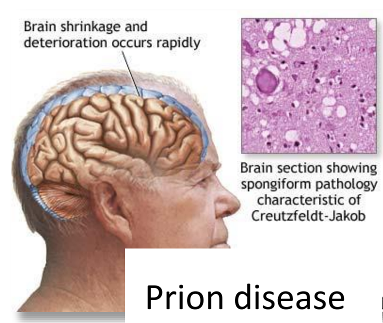


➢ Copper


Alzheimer’s disease


Wilson’s disease





Prion disease


Parkinson’s disease

- But they are difficult to study:

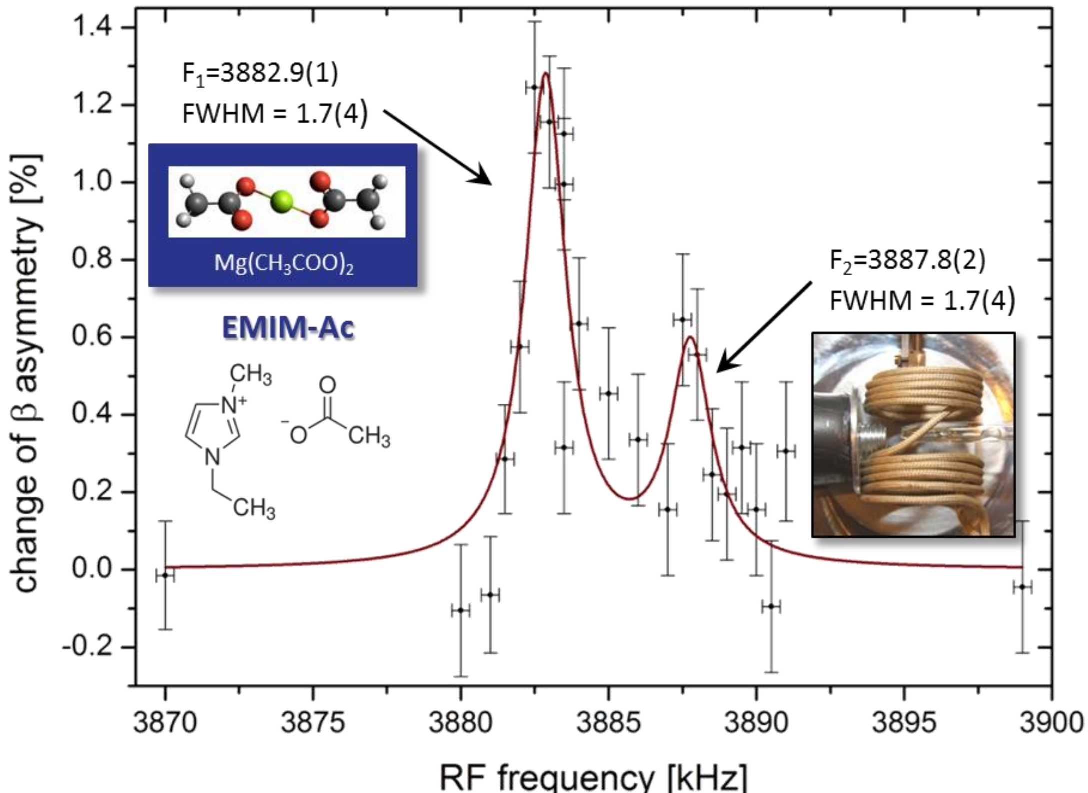
“Magnesium in biological chemistry is a Cinderella element: We know its hidden power and personality only indirectly since we are unable to label and follow it in a sensitive manner.”

Metals in biology and beta-NMR

- New approach – beta-Nuclear Magnetic Resonance
  - Beta-decay of polarized nuclei is anisotropic
  - Resonances observed as change in decay asymmetry
  - ⇒ **Up to 10^{10} more sensitive than conventional NMR**

COLLAPS setup

- Proof-of-principle experiment
  - Magnesium-31 beam
  - Polarization with lasers
  - 1st beta-NMR in a liquid
- Outlook:
  - Funding from CERN Knowledge Transfer Fund
  - First biological studies on Mg and Cu

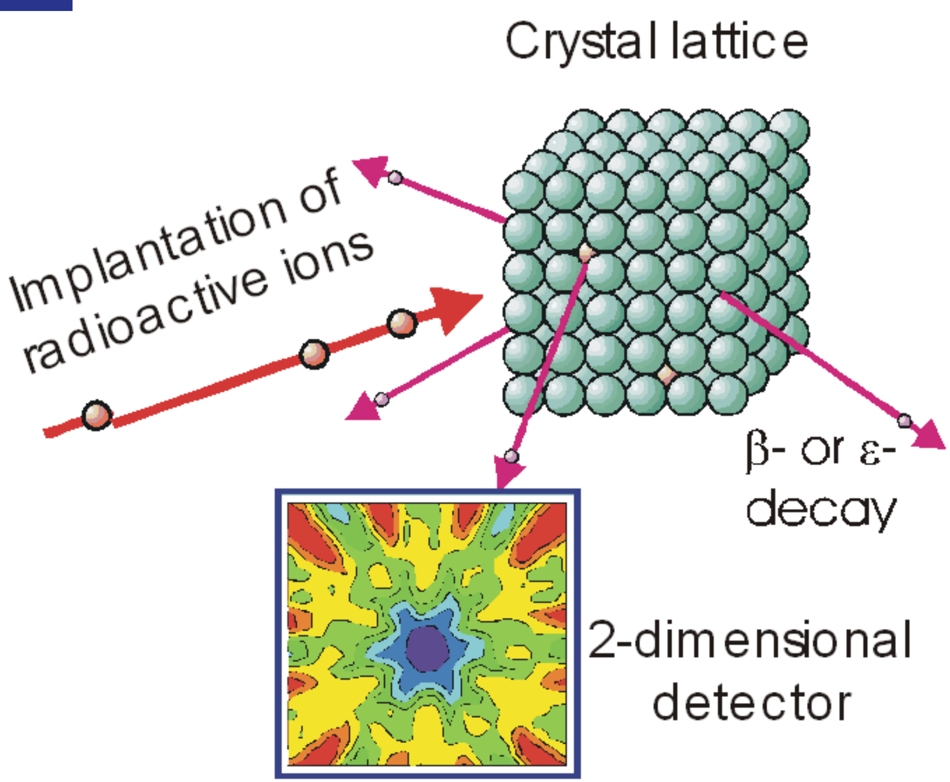


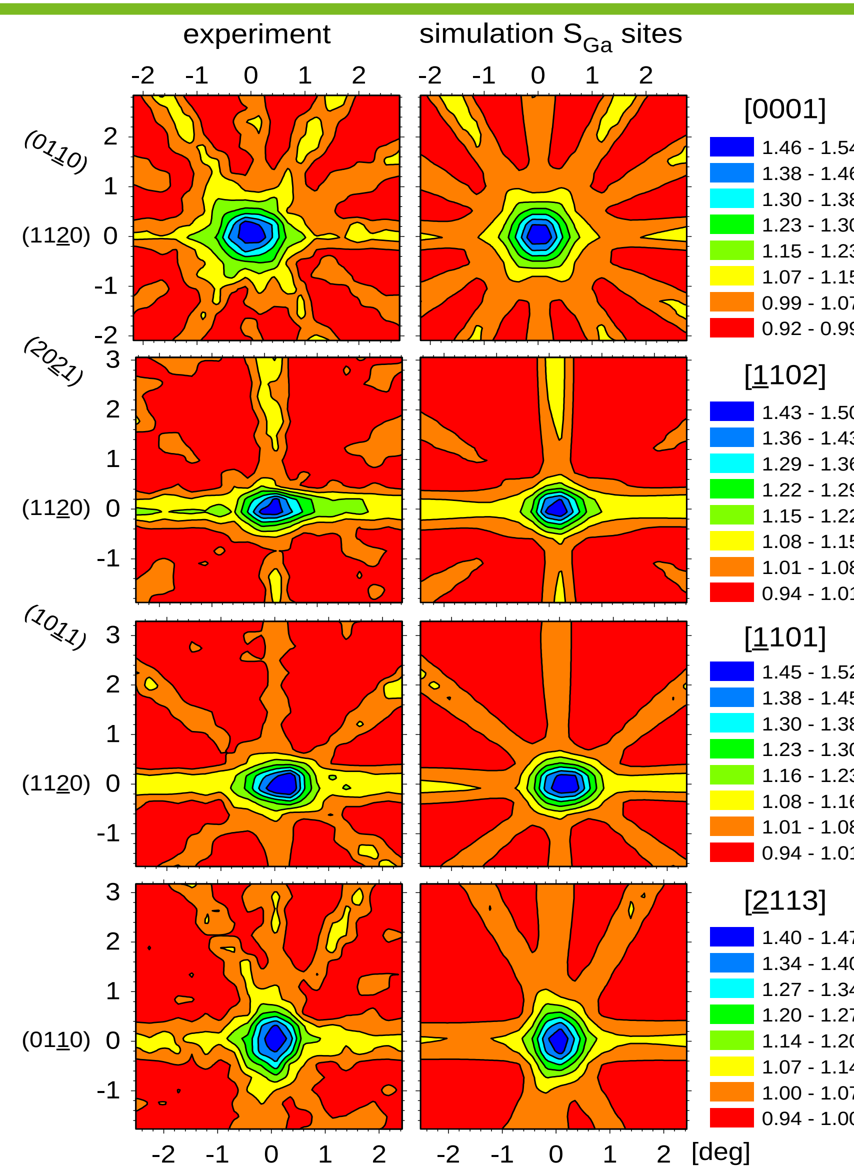
A. Gottberg, M. Stachura, M. Kowalska, et al, ChemPhysChem 15, 3929 (2014)

Soon be continued within MK'EU ERC Starting Grant

Material science

- Emission channeling
  - ➢ Position of implanted ions





Emission channelling pattern

New medical isotopes

Collection at ISOLDE

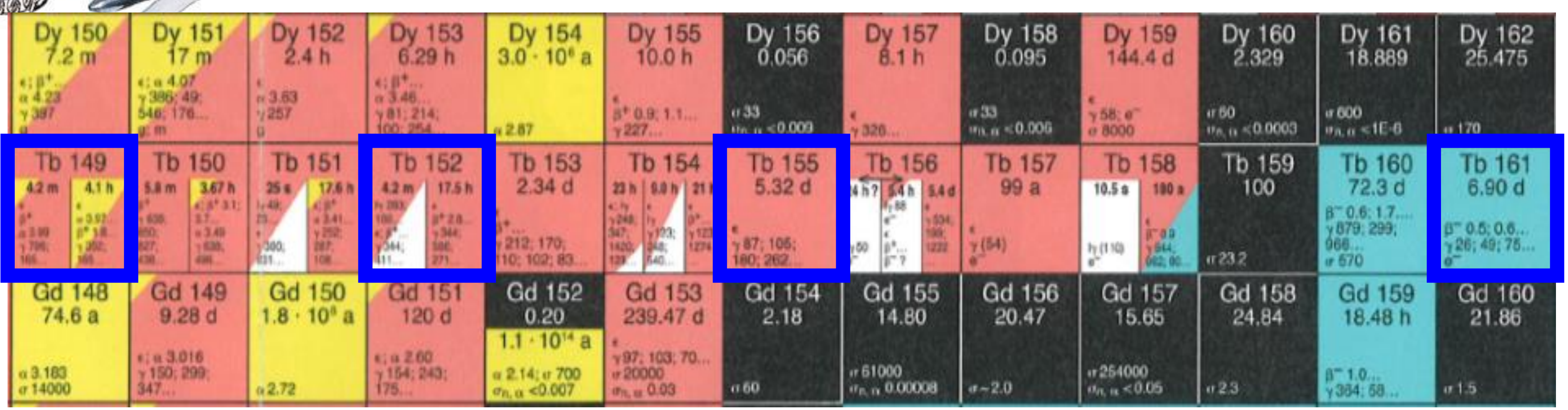
Radiochemical purification and labeling

Injection into mouse

PET/SPECT imaging and tumor treatment

- Theranostics = therapy and diagnostics together
  - Production of isotopes at ISOLDE
  - Chemical selection and mice treatment in PSI

- Soon at ISOLDE-Medicis



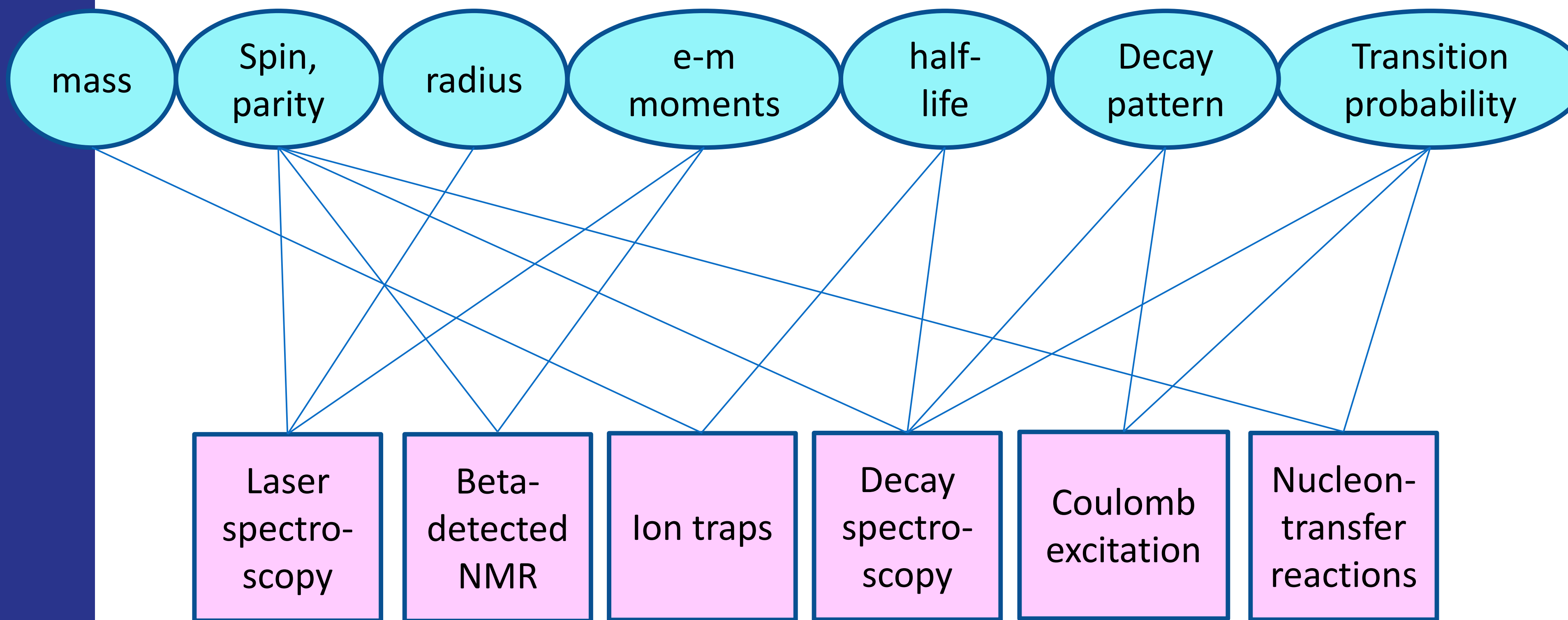
After U. Koster, C Müller et al. 2012 J. Nucl. Med. 53, 1951

Summary

- Research topics with radionuclides:
  - Nuclear and atomic physics
  - Astrophysics
  - Fundamental studies
  - Applications
- Studied properties:
  - mass, radius, spin, moments, half-life, decay pattern, transition probabilities
- Examples of ISOLDE experimental techniques
  - Laser spectroscopy
  - Ion traps
  - Decay spectroscopy
  - Coulomb excitation
  - Nucleon-transfer reactions
- Applications
  - Material science
  - Life sciences: bio- and medical

Studies of radioactive nuclides

Properties/observables (for ground states and isomers – long-lived excited states)

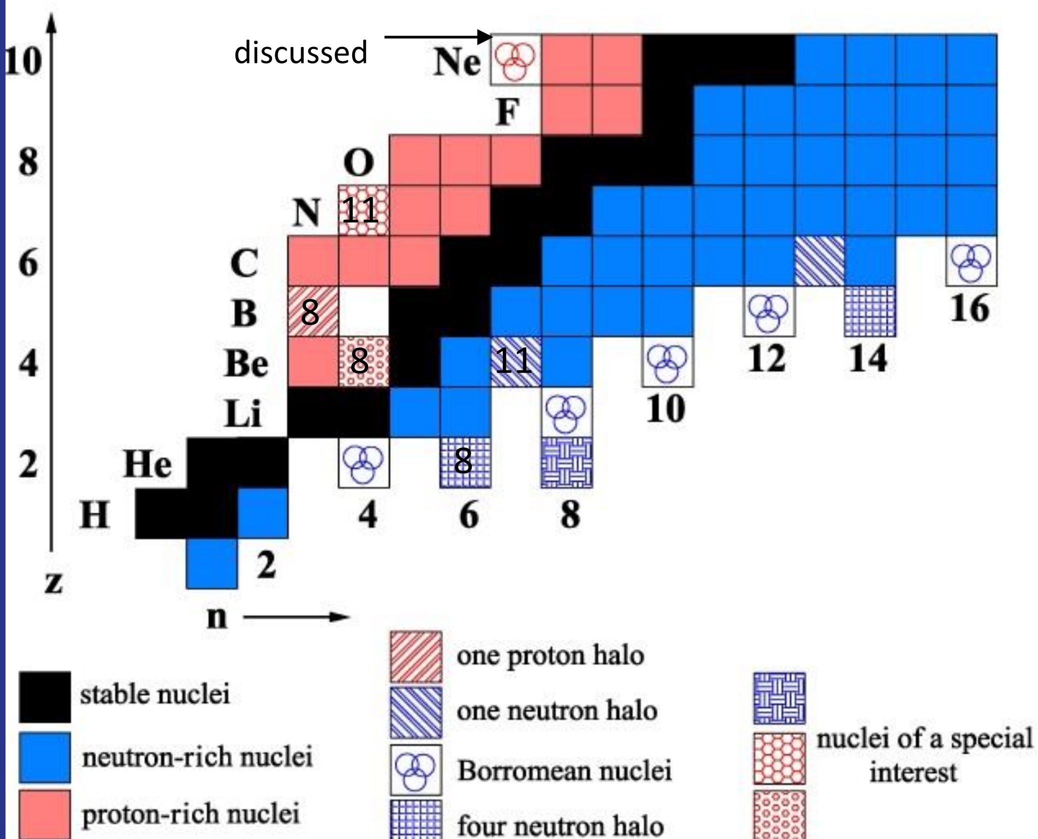


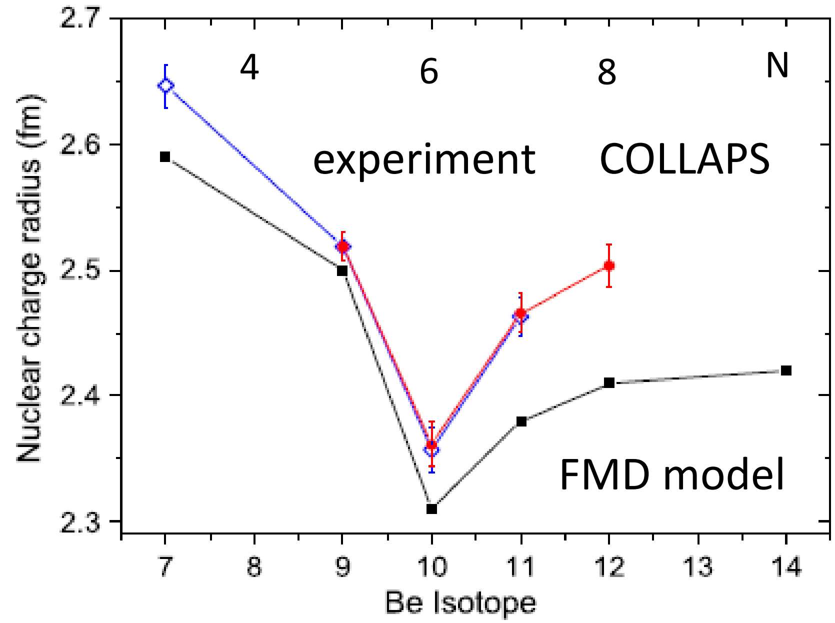
Techniques/ devices

To obtain the full picture: need to study several properties and use several techniques

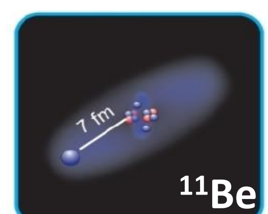
Charge radii of Be isotopes

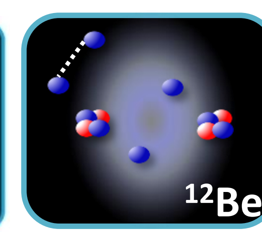
- **Halo:** nucleus built from a core and at least one neutron/proton with spatial distribution much larger than that of the core
  - ➢ Interaction of the core and halo nucleons not well understood





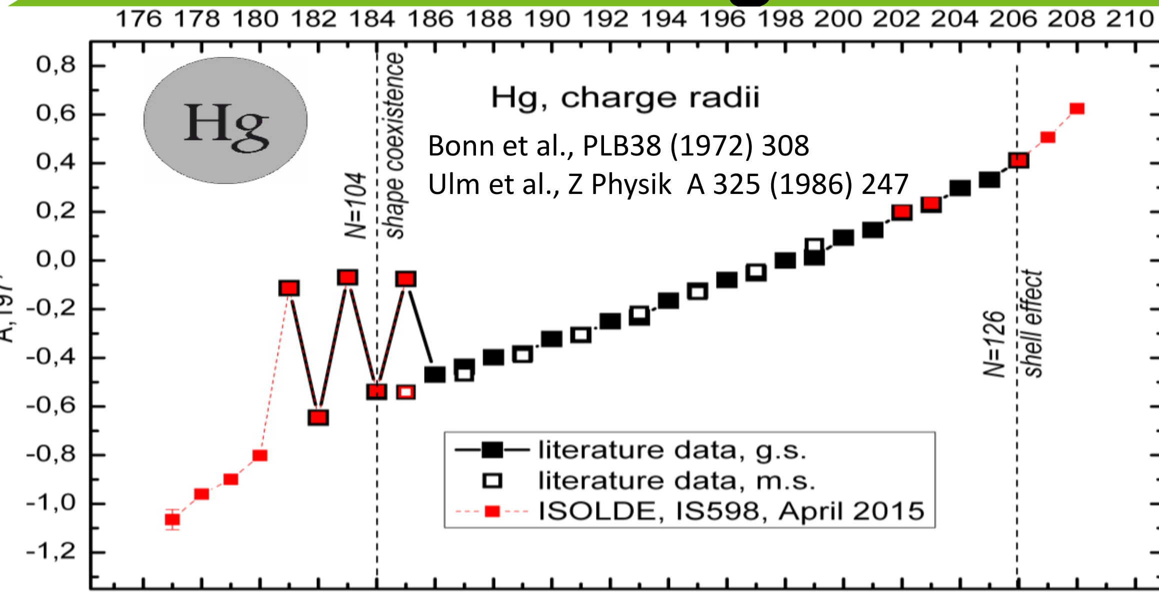
A. Krieger et al,
Phys. Ref. Lett. 108 (2012) 142501



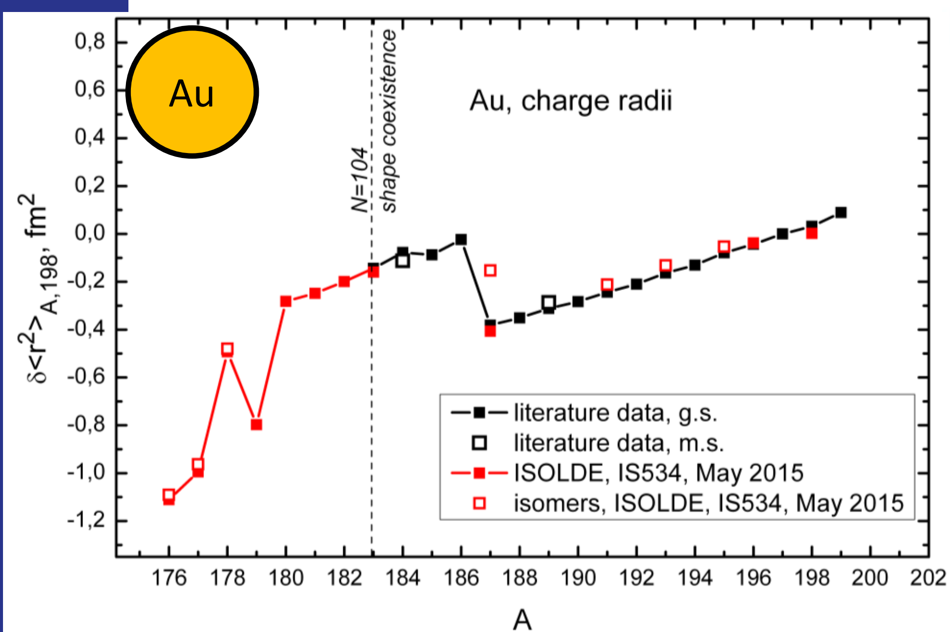


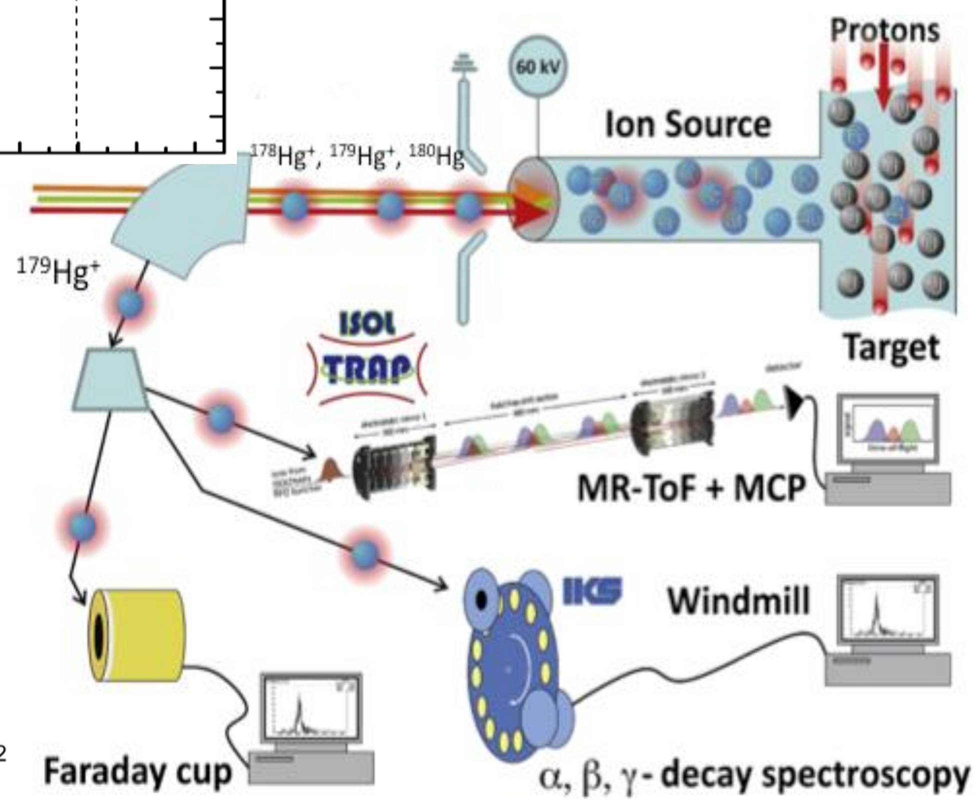
Combination of techniques: Charge radii of Hg & Au

RILIS, Windmill, ISOLTRAP teams



- Several techniques combined
- RILIS lasers to probe the hyperfine structure of Hg & Au isotopes
- Detection:
  - Alpha spectroscopy with Windmill
  - Selective ion counting in MR-ToF





EDM searches in radionuclides

odd-*A* Rn [TRIUMF]

odd-*A* Ra [Argonne]

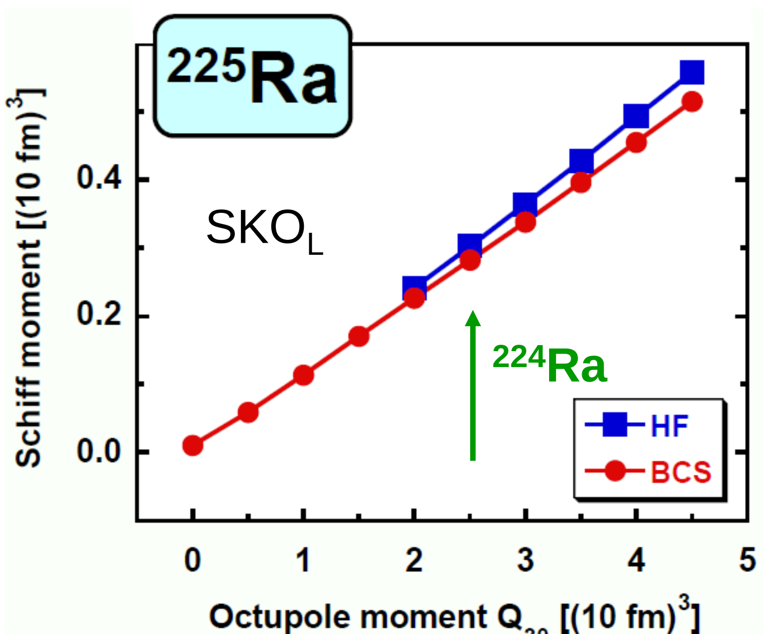
odd-*A* Ra [Groningen]

odd-*A* Rn:

^{219,221}Rn inferior to ^{223,225}Ra

Next step: ^{223,225}Rn
HIE-ISOLDE (CERN)

odd-*A* Ra:



Next step: ^{225}Ra directly
TSR@HIE-ISOLDE

Fundamental studies with traps

determine beta-neutrino ($\beta\nu$) correlation in β decay of ^{35}Ar with $(\Delta a/a)_{stat} \leq 0.5$ %
=>test the Standard Model

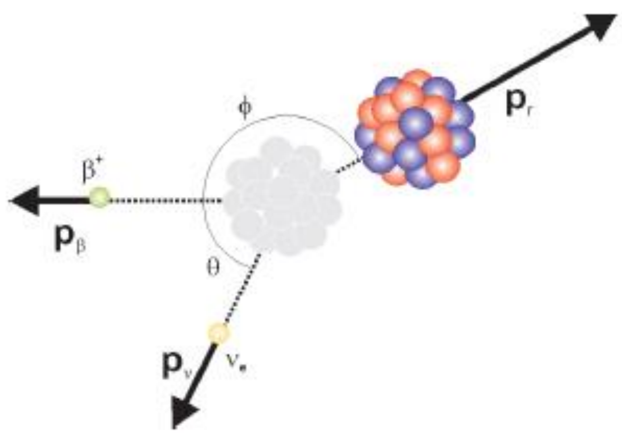
$$H_\beta = H_S + H_V + H_T + H_A + H_P$$

e.g: Fermi β decay $(0^+ \rightarrow 0^+)$

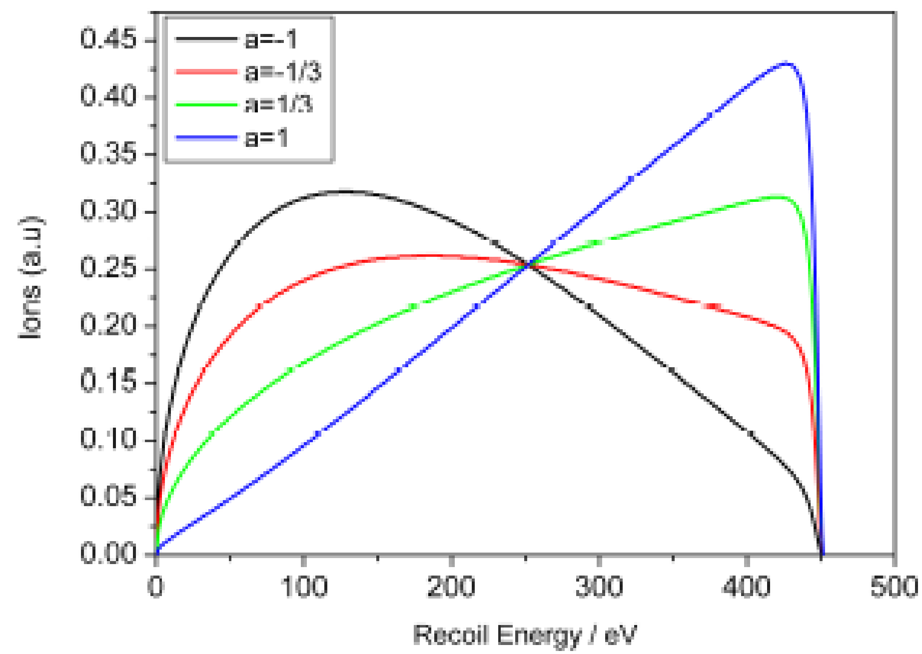
$$a \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

Angular distribution of β radiation

$$W(\theta) \approx 1 + a\frac{v}{c}cos\theta$$



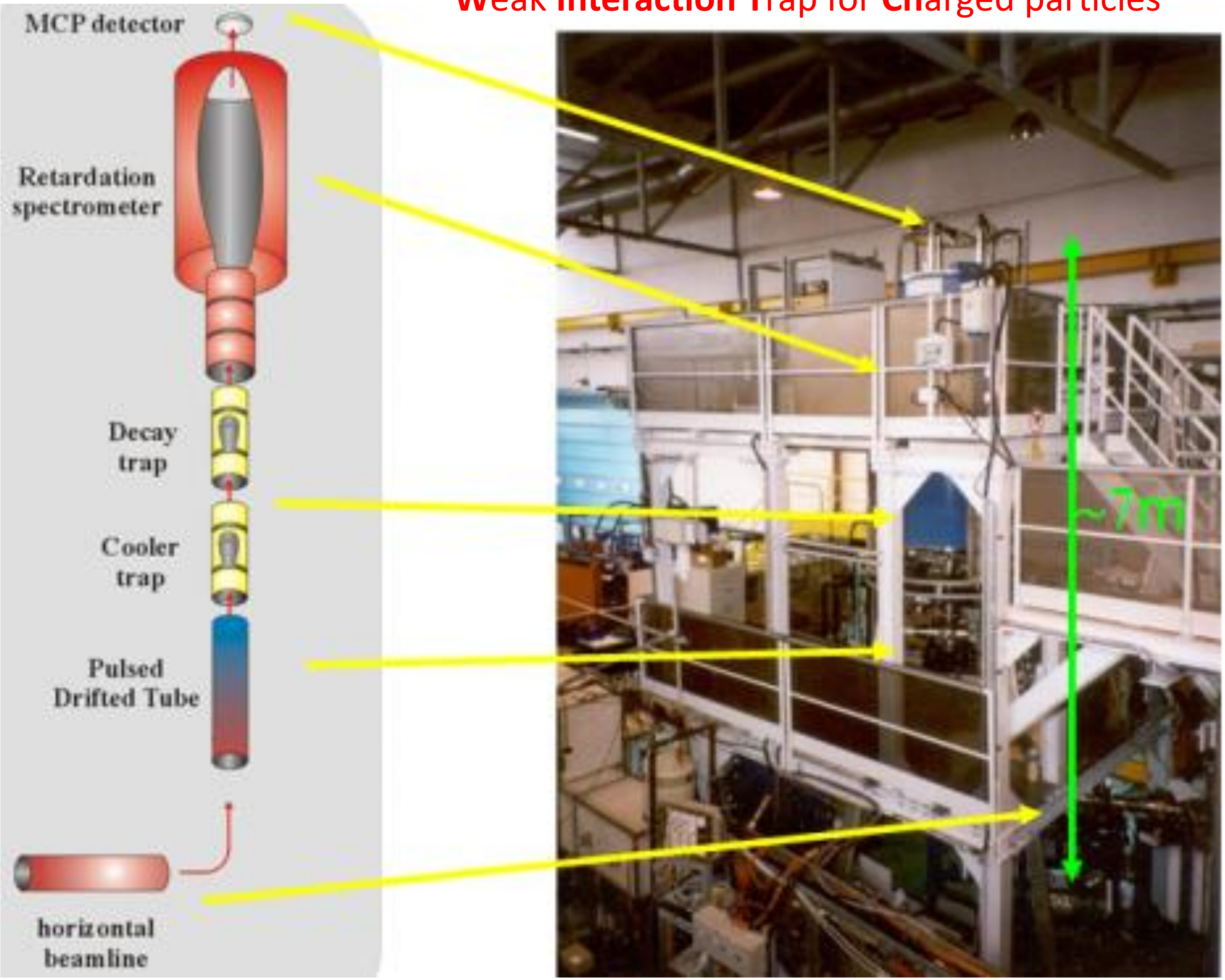
Simulated ion recoil for different *a*



Current experimental limits:
(from nuclear & neutron β decay)
$\frac{C_S}{C_V} < 7\%$, $\frac{C_T}{C_A} < 9\%$[1]

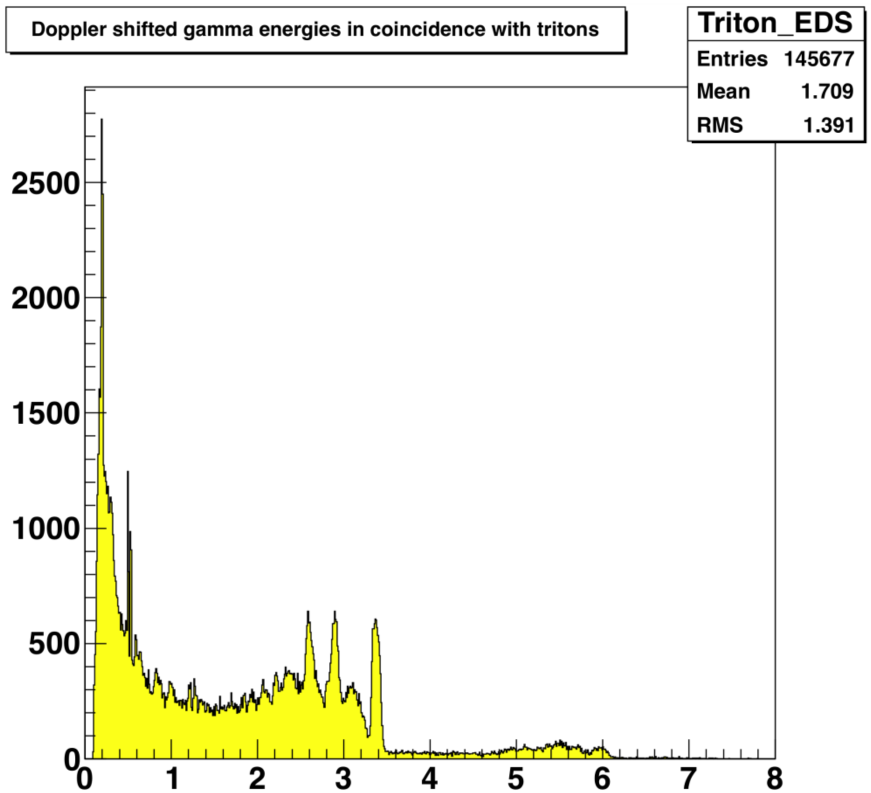
WITCH

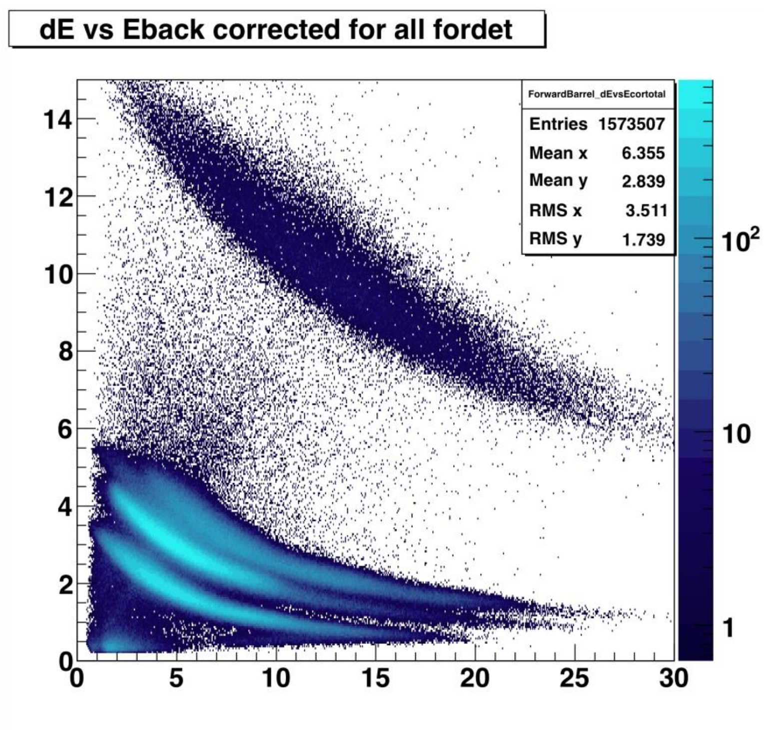
Weak **Interaction T**rap for **Ch**arged particles



Transfer reactions on beryllium-11

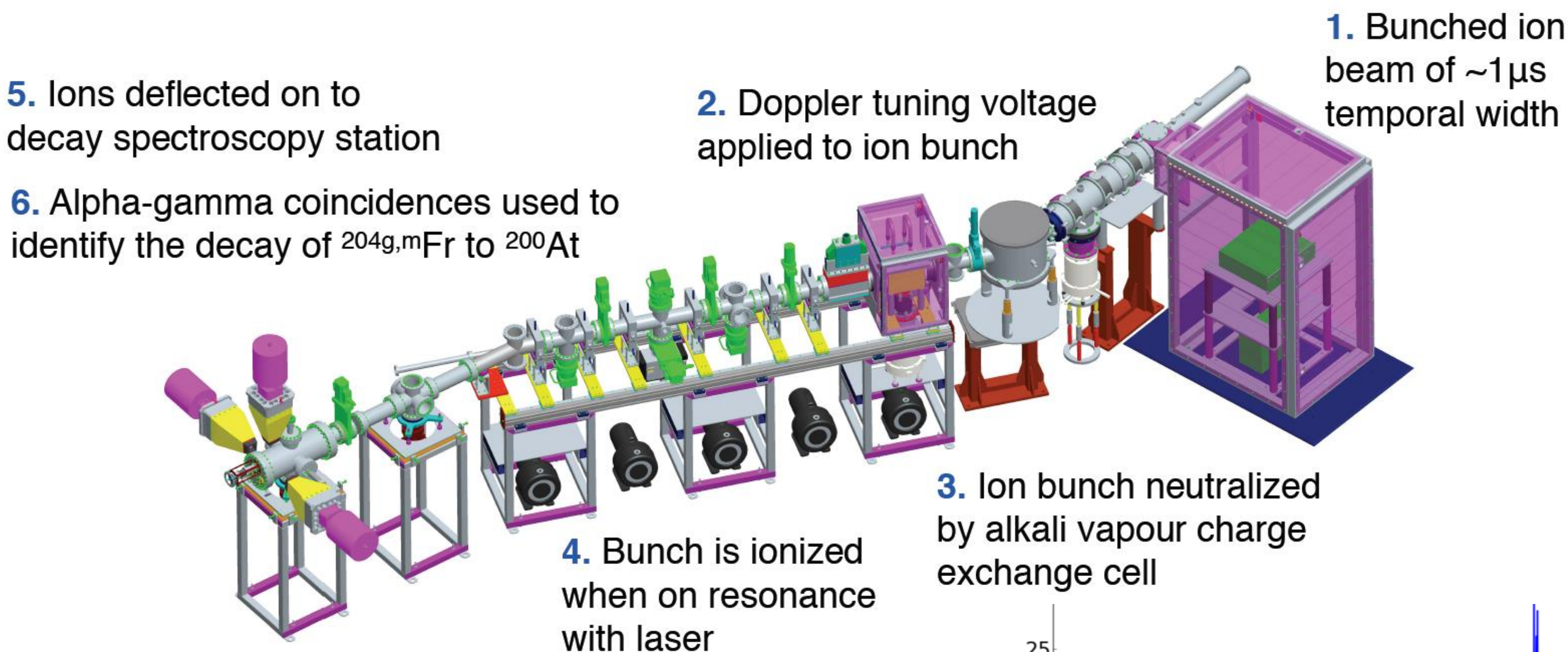
- 11Be:
  - Halo nucleus
  - Cluster structures in neighbours
  - N=8 broken in 12Be

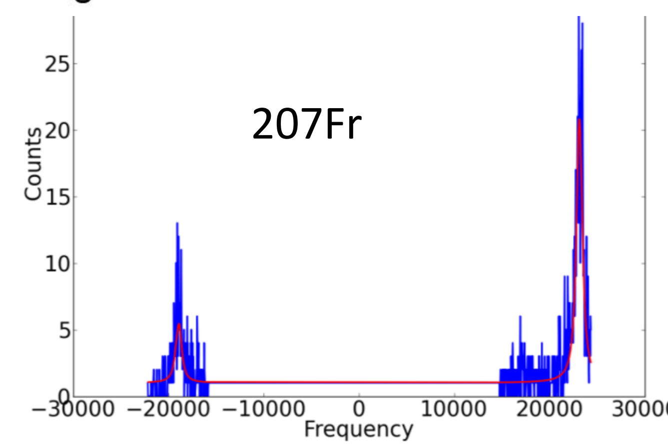




CRIS

- Collinear Resonant Ionisation Spectroscopy
- High sensitivity, lower resolution -> perfect for heavy ions

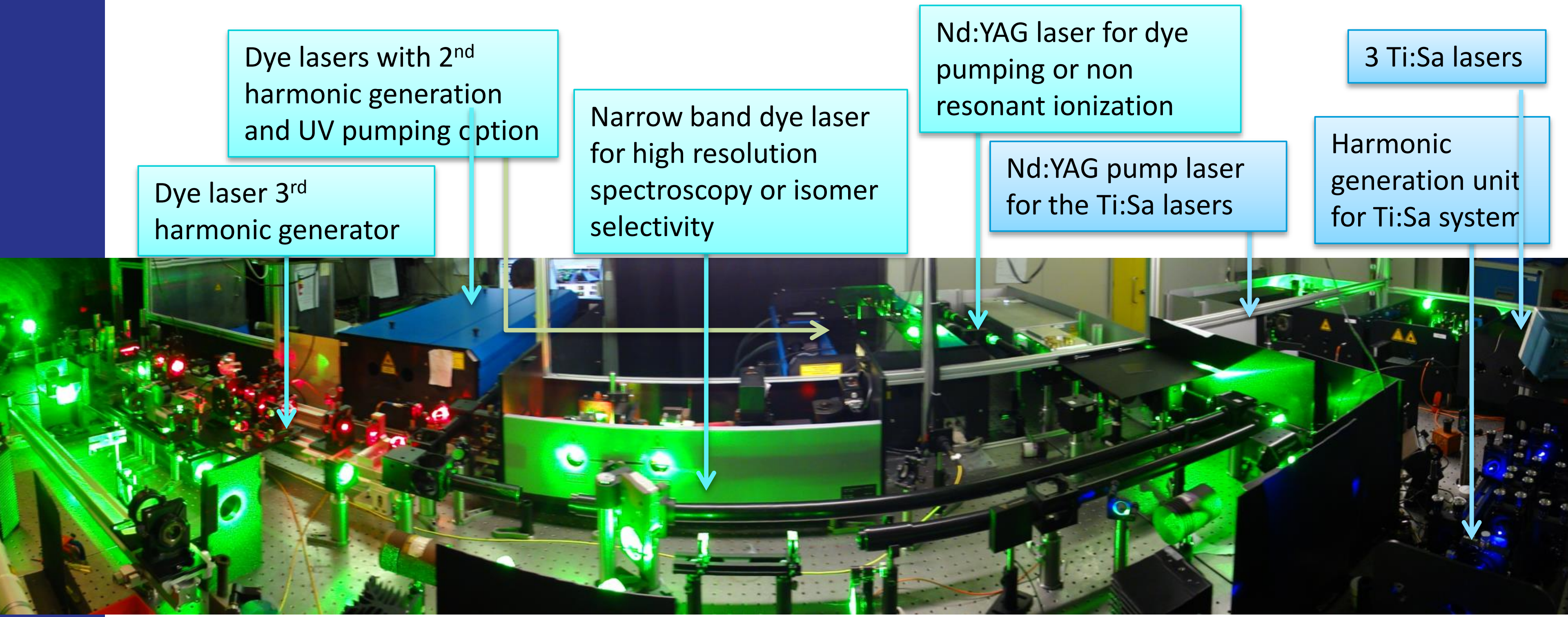




Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes

RILIS

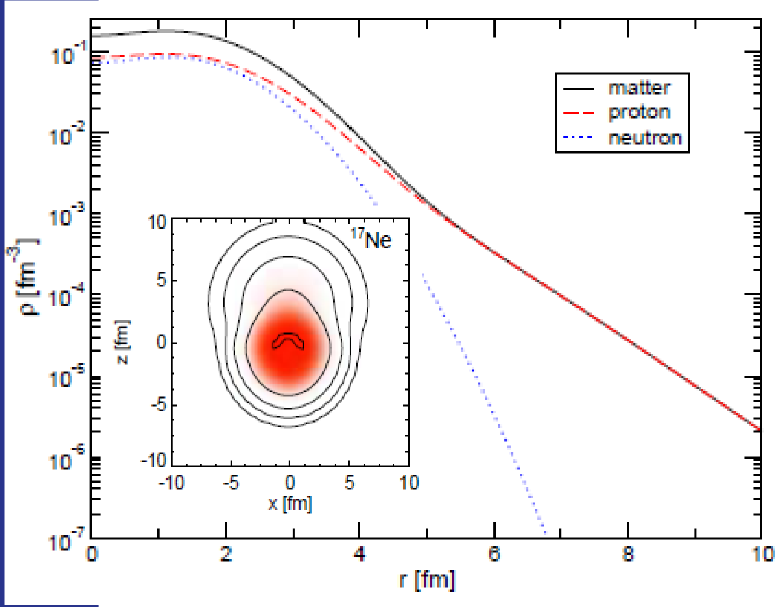
- Resonant Ionization Laser Ion Source

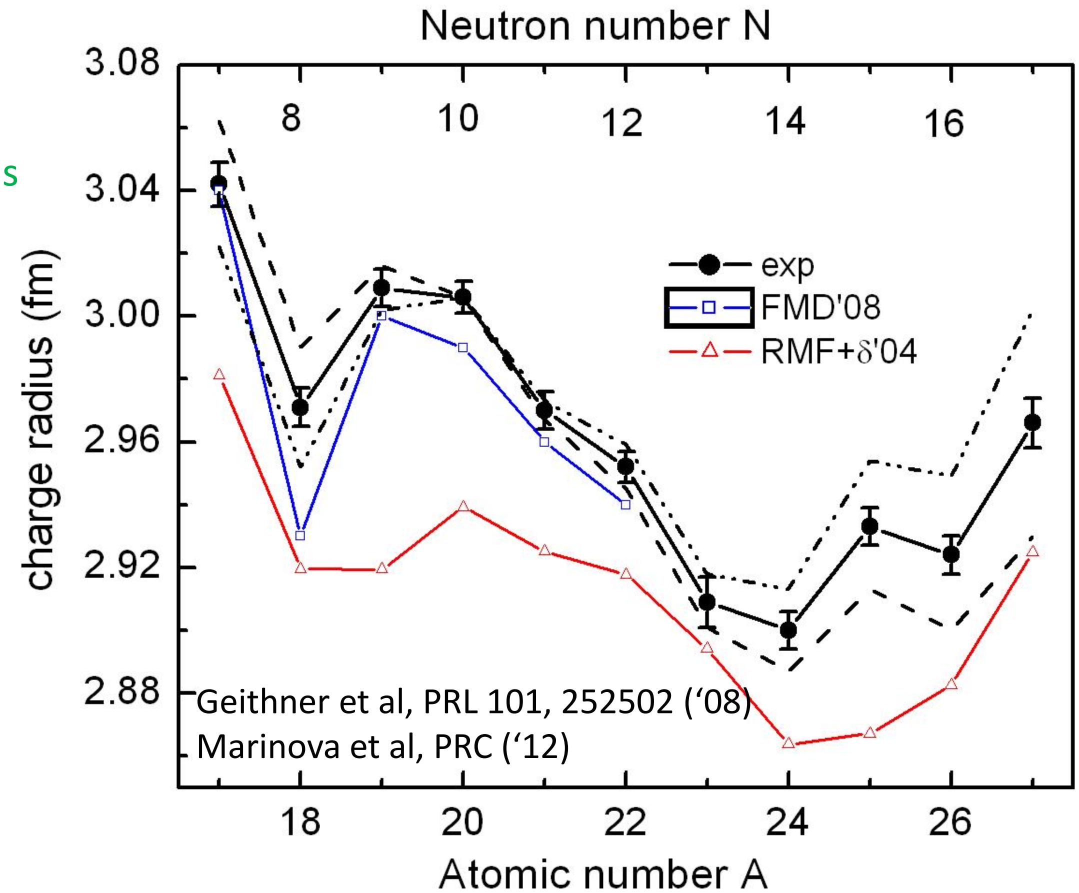


COLLAPS – Ne charge radii

Laser spectroscopy

Intrinsic density distributions of dominant proton FMD configurations





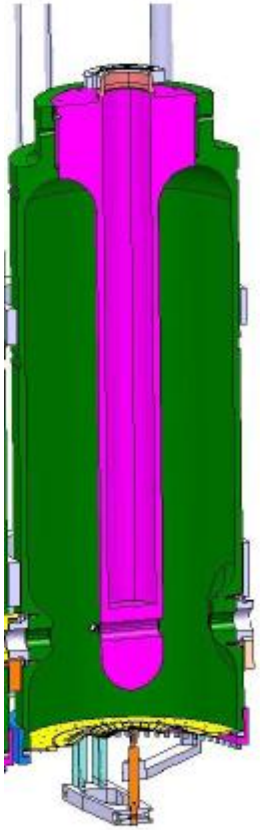
Geithner et al, PRL 101, 252502 ('08)

Marinova et al, PRC ('12)

HIE-ISOLDE

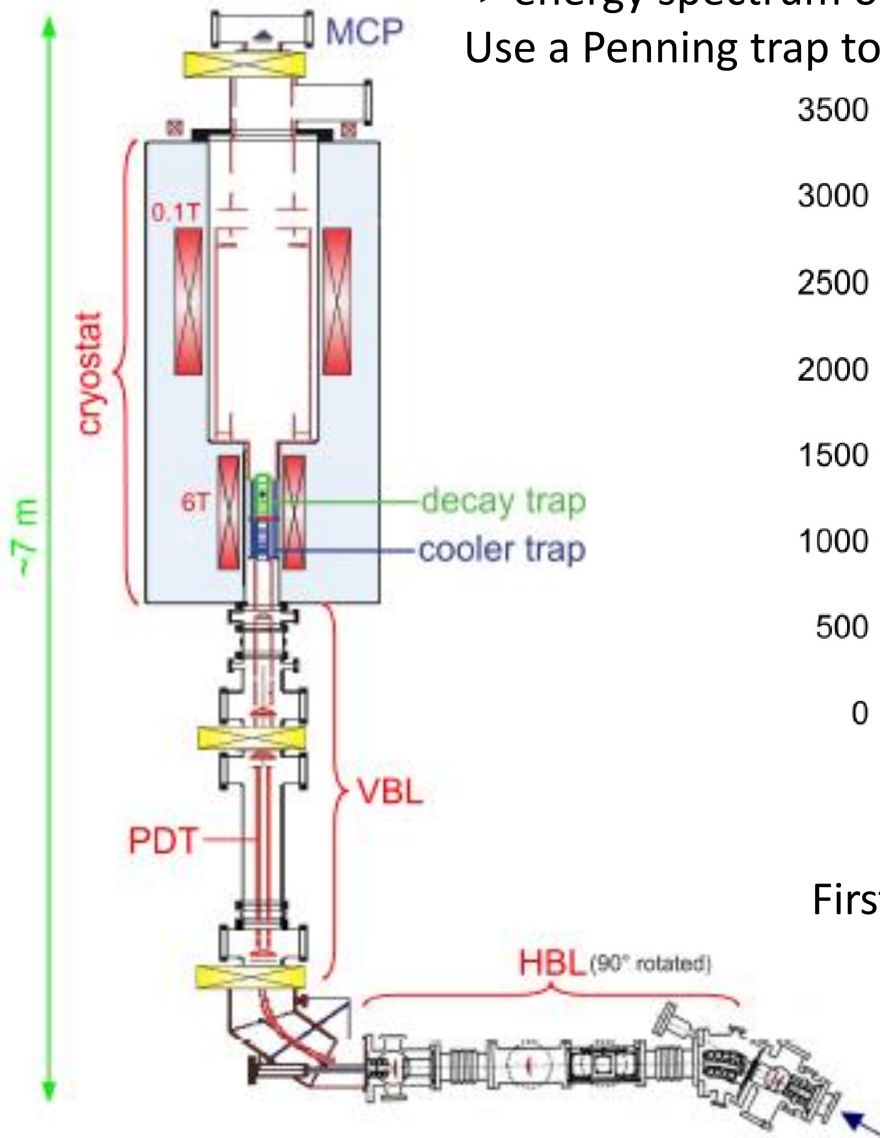
Quarter-wave resonators
(Nb sputtered)

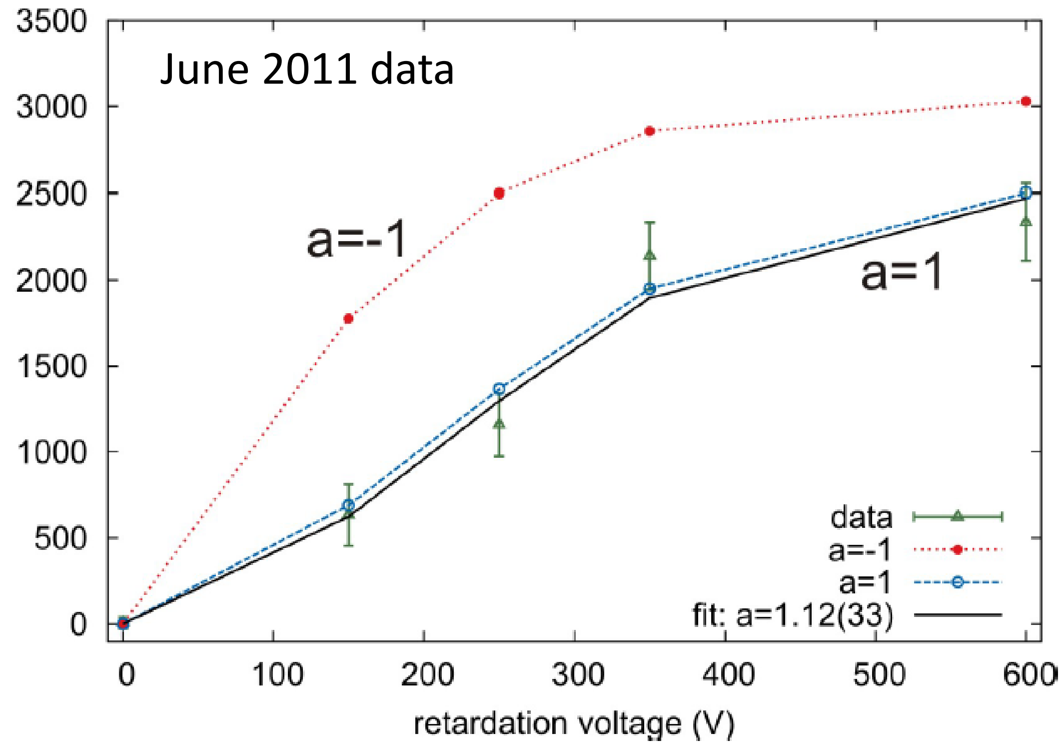
- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ β_0=10.3% and 12@ β_0=6.3%)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase fs= -20 deg
- 2.5<A/q<4.5 limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal matching section (incorporated in the lattice)
- New beam transfer line to the experimental stations



WITCH

-> energy spectrum of recoiling ions with a retardation spectrometer
Use a Penning trap to create a small, cold ion bunch



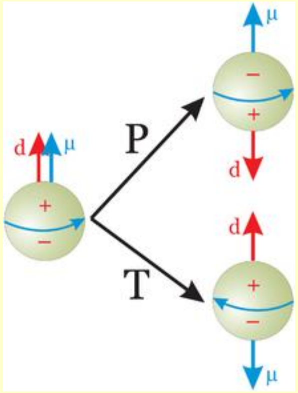


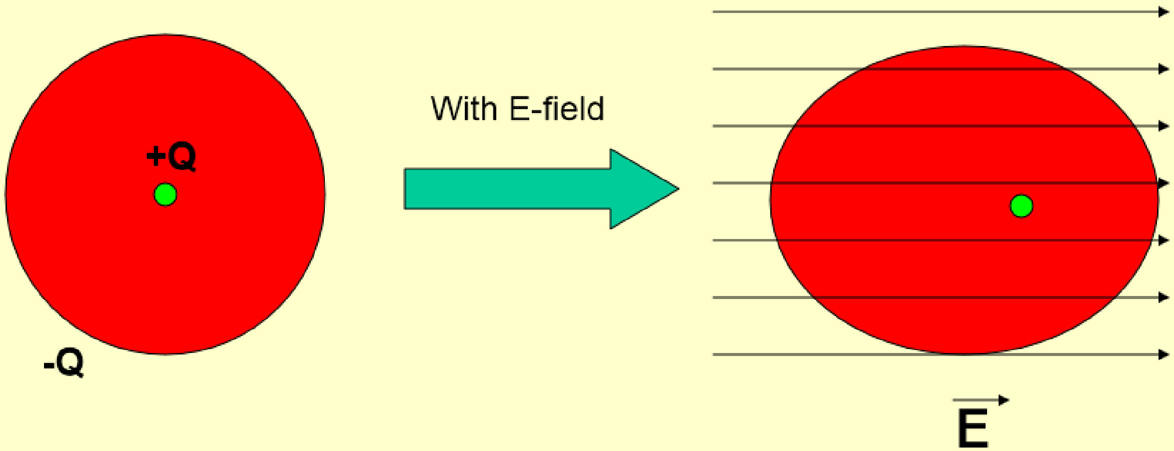
First high-statistics run in Nov 2011: under analysis

M. Beck et al., Eur. Phys. J. A47 (2011) 45
M. Tandecki et al., NIM A629 (2011) 396
S. Van Gorp et al., NIM A638 (2011) 192

EDM

Static Electric Dipole Moment implies CP-violation





Schiff Theorem: neutral atomic system of point particles in electric field readjusts itself to give zero E field at all charges.

BUT: finite size and shape of nucleus breaks the symmetry

EDM

V Spevak, N Auerbach, and VV Flambaum
PR C **56** (1997) 1357

related to Q_3

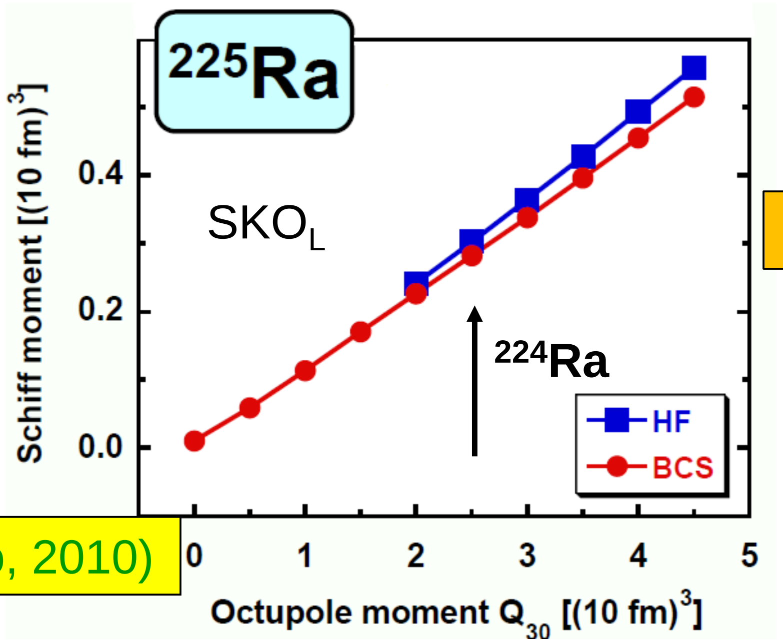
P,T-violating n-n interaction

Schiff moment:

$$S = -2\frac{J}{J+1}\frac{<\hat{S}_z><\hat{V}_{PT}>}{\Delta E}$$

energy splitting of parity doublet

Schiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nuclei



^{219,221}Rn inferior to ^{223,225}Ra

J Dobaczewski (Trento, 2010)

EDM searches

odd-*A* Rn [TRIUMF]

odd-*A* Ra [Argonne]

odd-*A* Ra [Groningen]

odd-*A* Rn:

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Next step: ^{223,225}Rn
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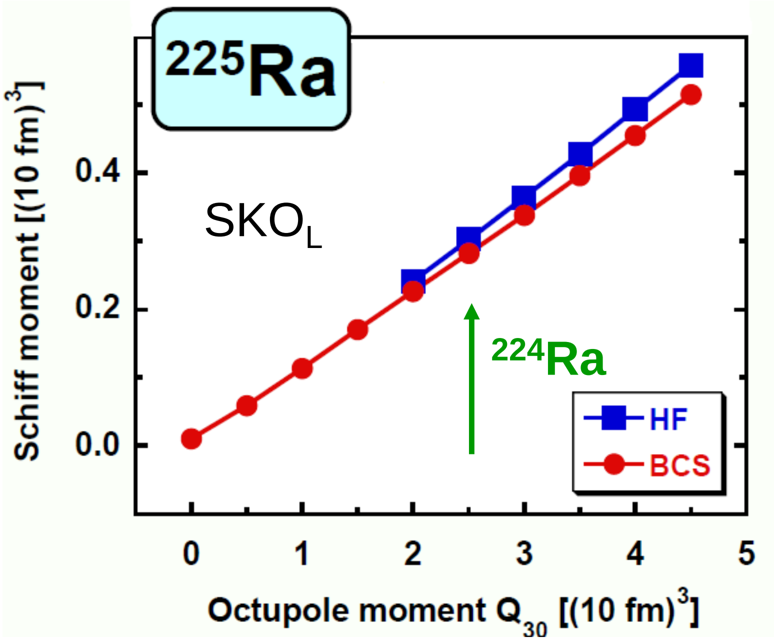


Next step: ^{225}Ra directly
TSR@HIE-ISOLDE

EDM

In units of $e\text{–}cm$, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	1.9×10^{-27}	^{205}Tl atom	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	2.1×10^{-28}	atom cell	10^{-33}	10^{-28}

A non-exhaustive list:

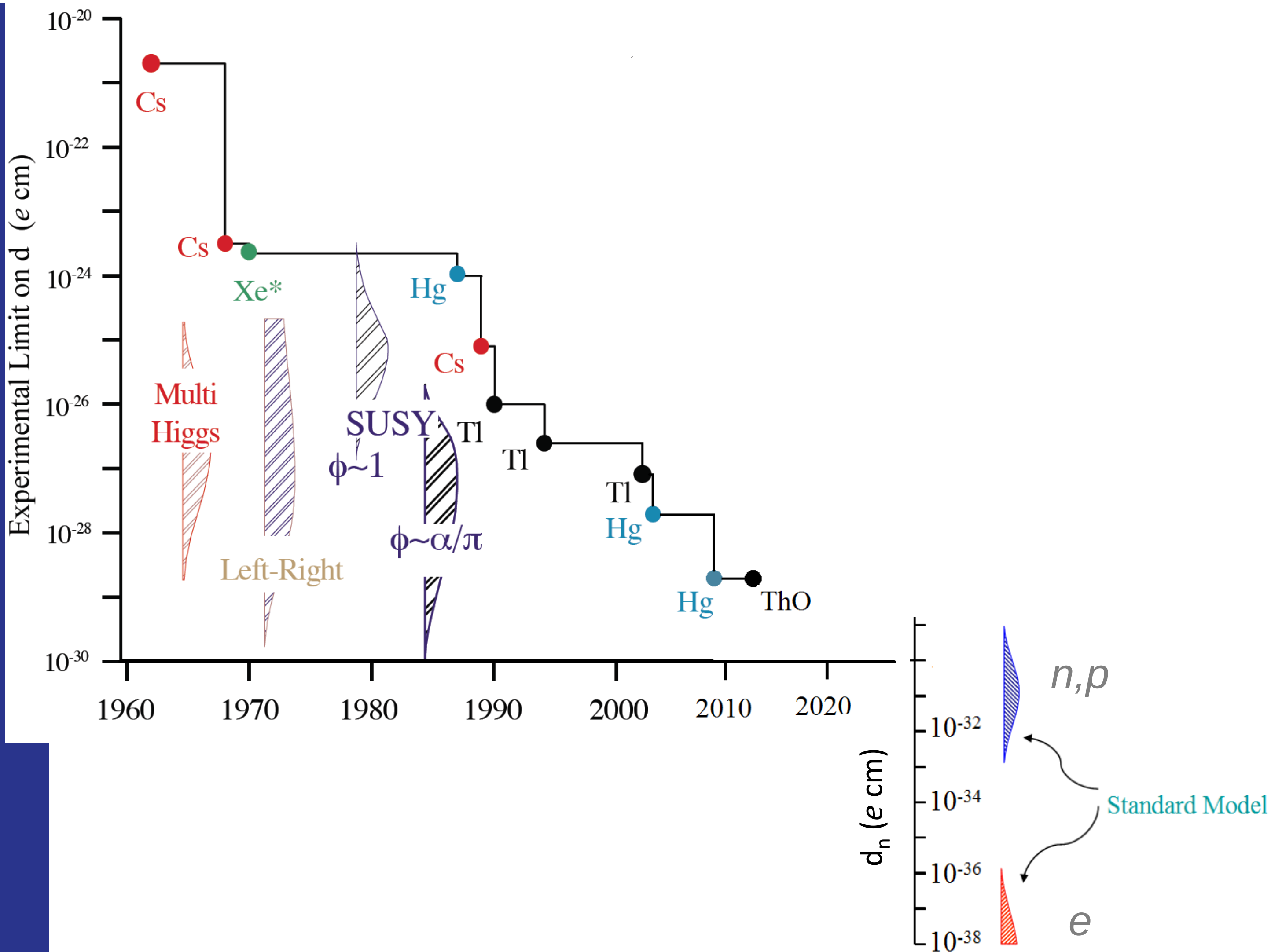
Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

Matter-antimatter

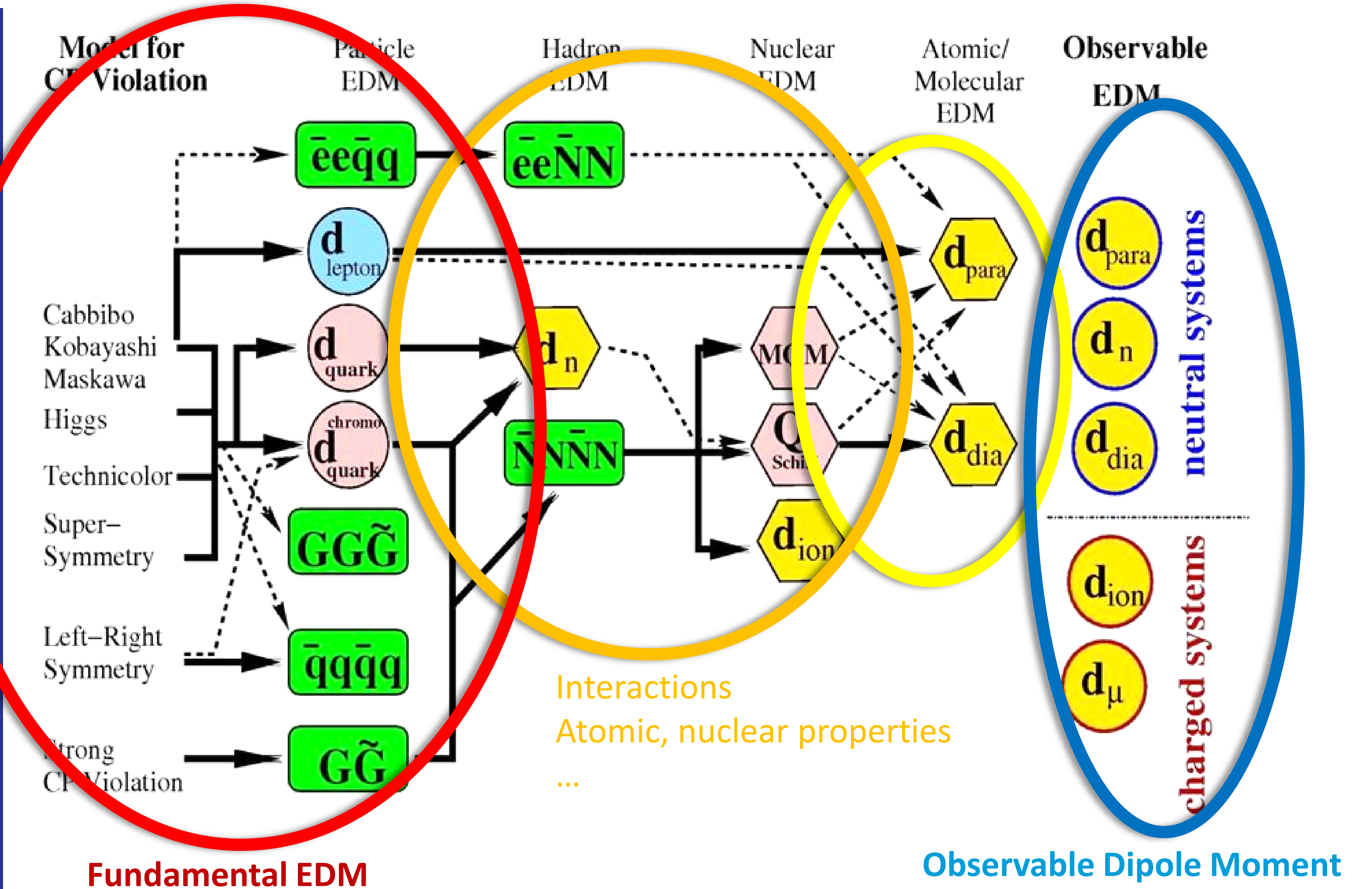
- Sakharov conditions require CP symmetry violation
- This violation is observed in electro-weak interaction, but probably cannot account for matter-antimatter imbalance
- No evidence for CP violation in strong interaction
- **$|d(n)| < 3.1\times10^{-26}$ e cm** ***(Baker et al PRL 97 (2006) 131801)***
- **$|d(^{199}Hg)| < 3.1\times10^{-29}$ e cm** ***(Griffith et al PRL 102 (2009) 101601)***
- **$|d(ThO)| < 8.7\times10^{-29}$ e cm** ***(Baron et al arXiv:1310.7534v2 (2013))***

- **In many cases provides best test of extensions of the Standard Model**
- **that violate CP symmetry.**
- *Accounted for by cancellations?*
- *– study of minimal supersymmetric SM (J Ellis)*

- *CP violation in the lepton sector is not known, could also account for matter-antimatter difference*

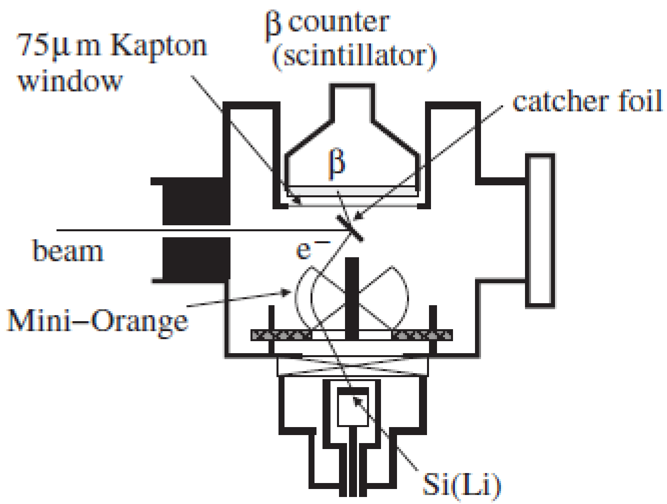


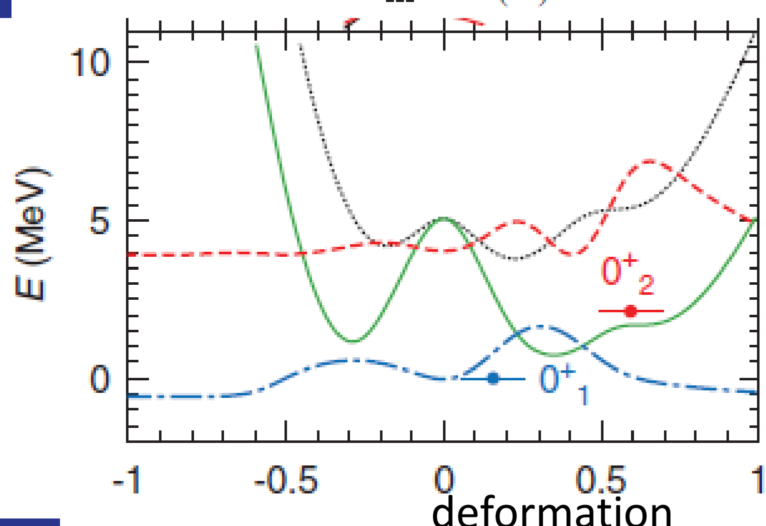
Experimental Limit on d (e cm)
10-20
10-22
10-24
10-26
10-28
10-30
Cs
Cs
Xe*
Hg
Cs
Tl
Tl
Tl
Hg
Hg
ThO
Multi
Higgs
Left-Right
SUSY
φ~1
φ~α/π
1960
1970
1980
1990
2000
2010
2020
d_n (e cm)
10-32
10-34
10-36
10-38
n,p
e
Standard Model


Model for CP Violation
Particle EDM
Hadron EDM
Nuclear EDM
Atomic/ Molecular EDM
Observable EDM
Cabbibo Kobayashi Maskawa
Higgs
Technicolor
Super–Symmetry
Left–Right Symmetry
Strong CP Violation
ēeq̄q
d lepton
d quark
chromo d quark
GGG̃
q̄qq̄q
GG̃
ēeN̄N
d n
N̄NN̄N
MQM
Q Schiff
d ion
d para
d dia
d para
d n
d dia
neutral systems
d ion
d μ
charged systems
Interactions
Atomic, nuclear properties
…
Fundamental EDM
Observable Dipole Moment

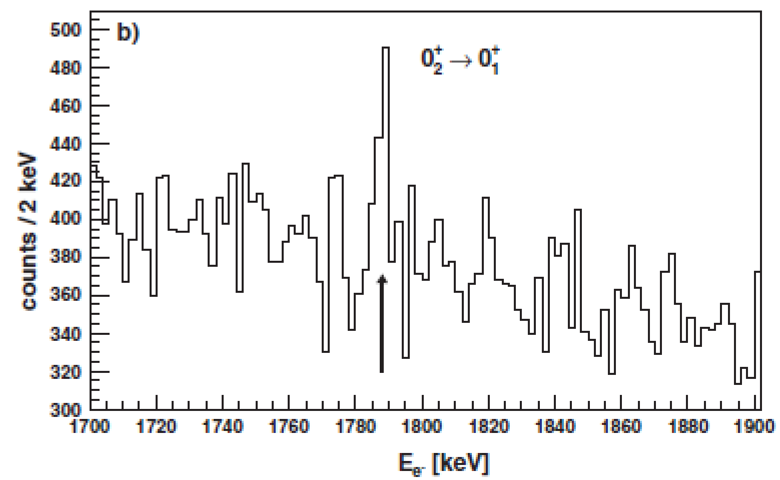
30Mg: E0 transition

E0 decay of 30Mg
electron spectrometer





Identification of 0+ state at 1789 keV ; small mixing amplitude with spherical ground state => deformed state



30Mg: spherical 0+ground-state, deformed 1st 0+ state (2 neutrons across N=20) => **shape coexistence**

W. Schwerdtfeger et al., Phys. Rev. Lett. 103, 012501 (2009)

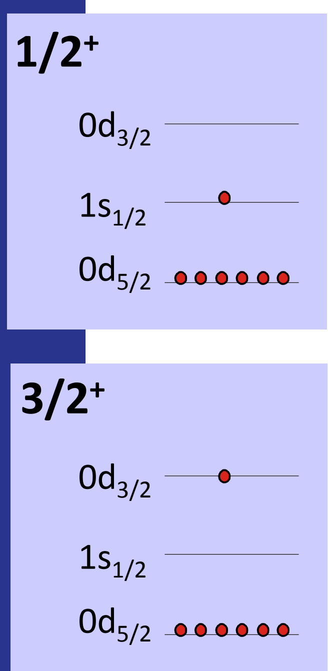
Laser spectroscopy and nuclear physics

- **Spin** (orbital+intrinsic angular momentum), **parity** (I^{π})
- Nuclear ***g*-factor** and **magnetic** dipole **moment** (g_I and μ_I)
- Electric quadrupole moment (Q)
- **Charge radius** ($\langle r^2 \rangle$)

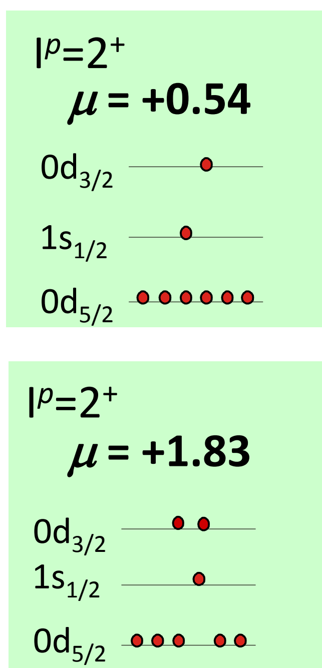
Give information on:

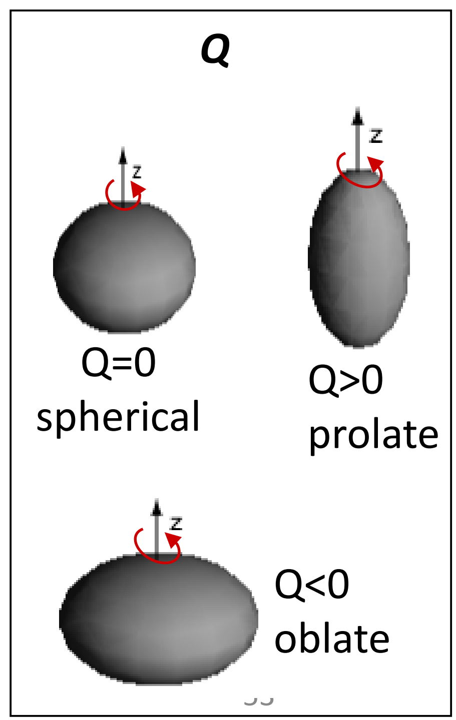
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

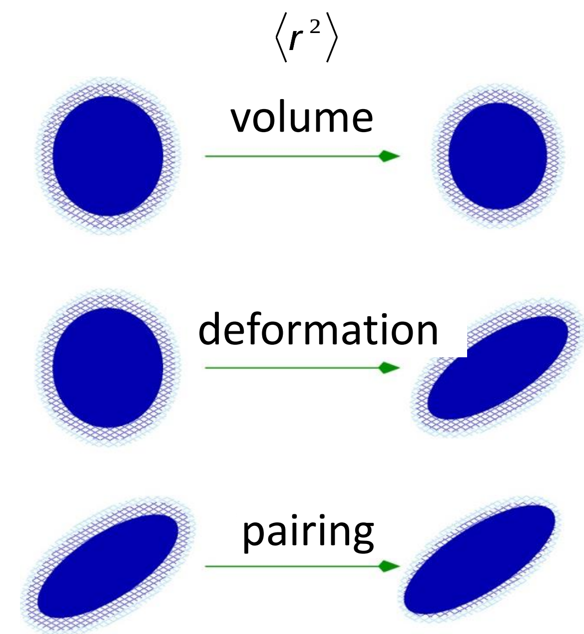
***I*$^{\pi}$**



***g**$_I$* and μ_I







Laser spectroscopy

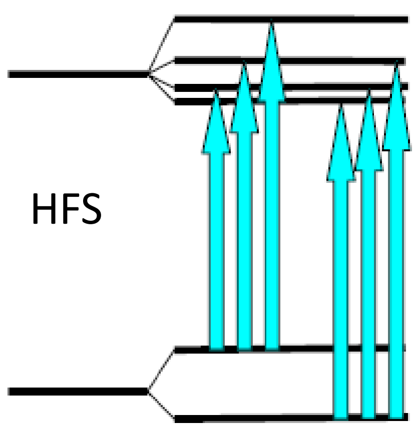
Atomic **hyperfine structure**

(interaction of nuclear and atomic spins)

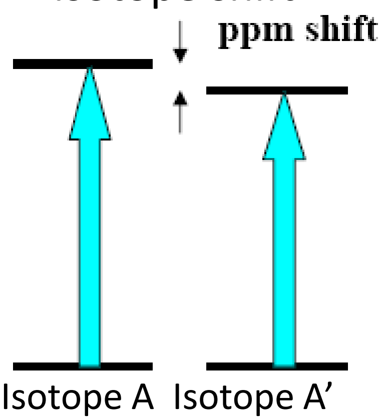
$$\Delta E_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I \cdot J}$$

where $K = F(F+1) - I(I+1) - J(J+1)$

$$A = \frac{\mu_I H_e(0)}{I \cdot J} \qquad B = eQV_{zz}(0)$$



Isotope shift



Isotope shifts in atomic transitions

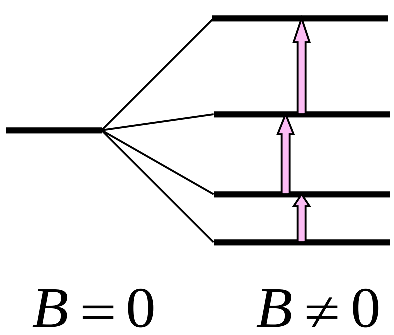
(change in mass and size of different isotopes of the same chemical element)

$$\delta\nu^{A,A'} = (K_{NMS} + K_{SMS}) \times \frac{A' - A}{A'A} + F \times \delta\langle r^2 \rangle^{A,A'}$$

Nuclear Magnetic Resonance – NMR

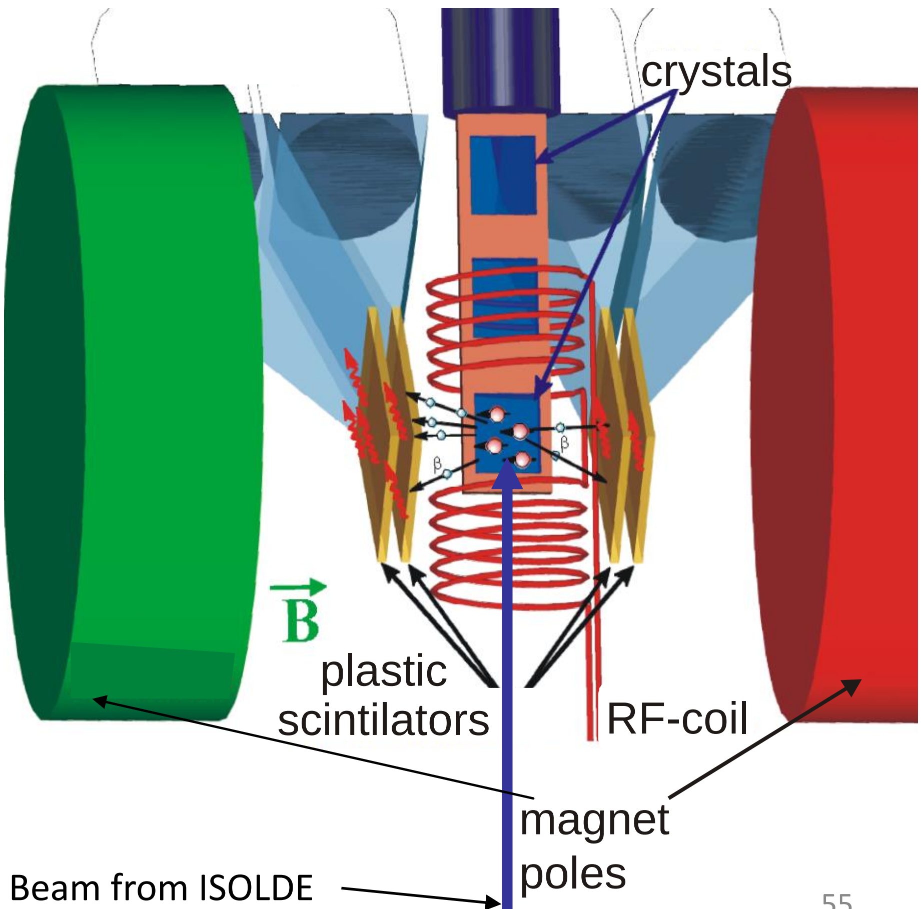
(Zeeman splitting of nuclear levels)

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$



Beta-detected NMR

Beta particles (e-,e+) can be used as a detection tool, instead of rf absorption
(beams down to 1000 ions/s can be studied)

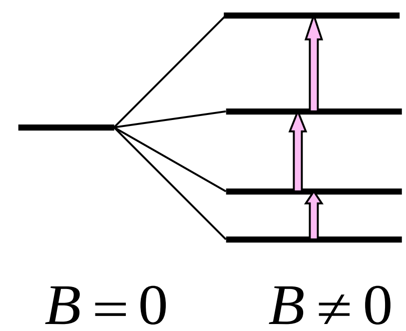


Measured asymmetry:

$$A = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}$$

Nuclear Magnetic Resonance – NMR
(Zeeman splitting of nuclear levels)

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$



Results:
Magnetic and electric moments of nuclei
(position of last nucleons, shapes)