Nuclear Physics at the ISOLDE-facility at CERN

Lecture 3: Nuclear Physics research and Applied research at ISOLDE

Gerda Neyens
CERN, EP-SME-IS and KU Leuven University, Belgium

gerda.neyens@cern.ch

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**: **Nuclear Physics and Applications at ISOLDE**
  - What observables do we measure for nuclear structure research at ISOLDE ?
  - Which experimental techniques are used ?
  - Recent results with each method
  - A few selected applied research topics

Literature: Focus on Exotic Beams at ISOLDE: A Laboratory Portrait
Journal of Physics G44 (June 2017)
> 23 papers on the ISOLDE facilities and physics at ISOLDE

Small quiz

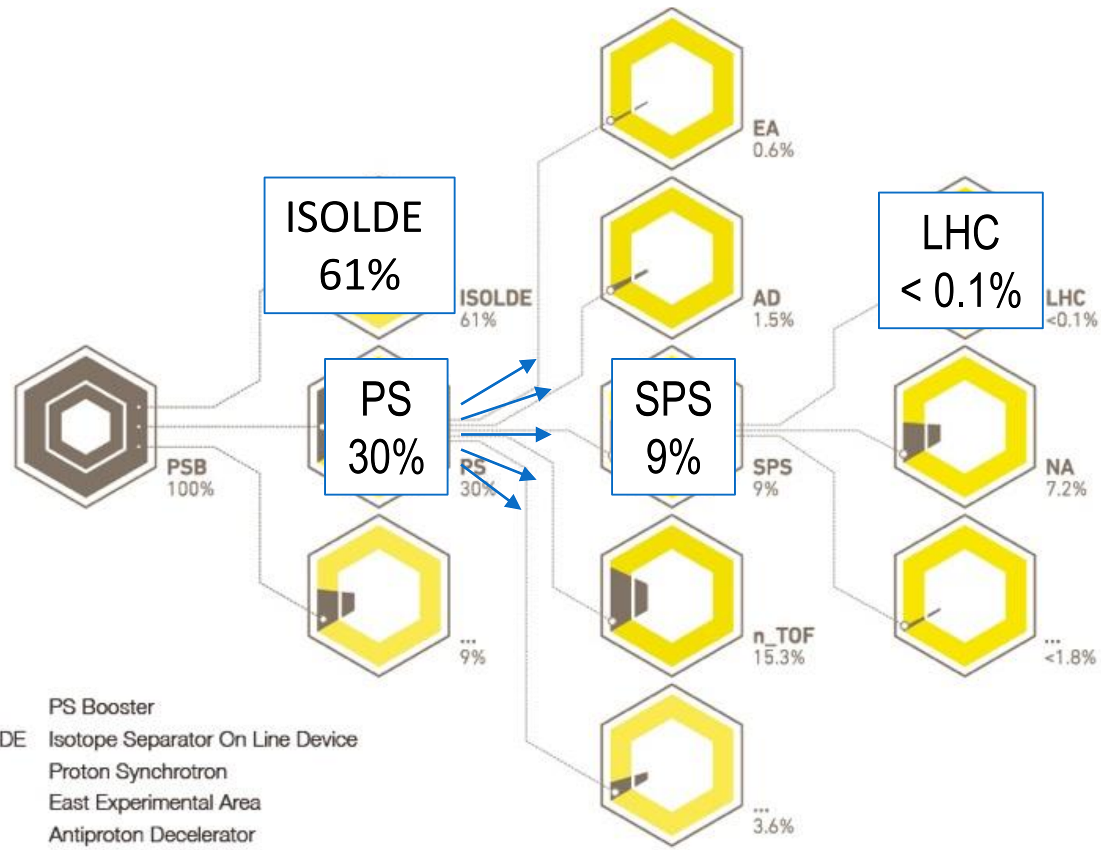
- Who are the two most important VIP's in this photo ?

King Philip of Belgium
Prof. Francois Englert (noble price winner 2013 – Higgs-boson)

Where protons are used at CERN

In 2016

$1.3\ 10^{20}$ protons in total in PSB

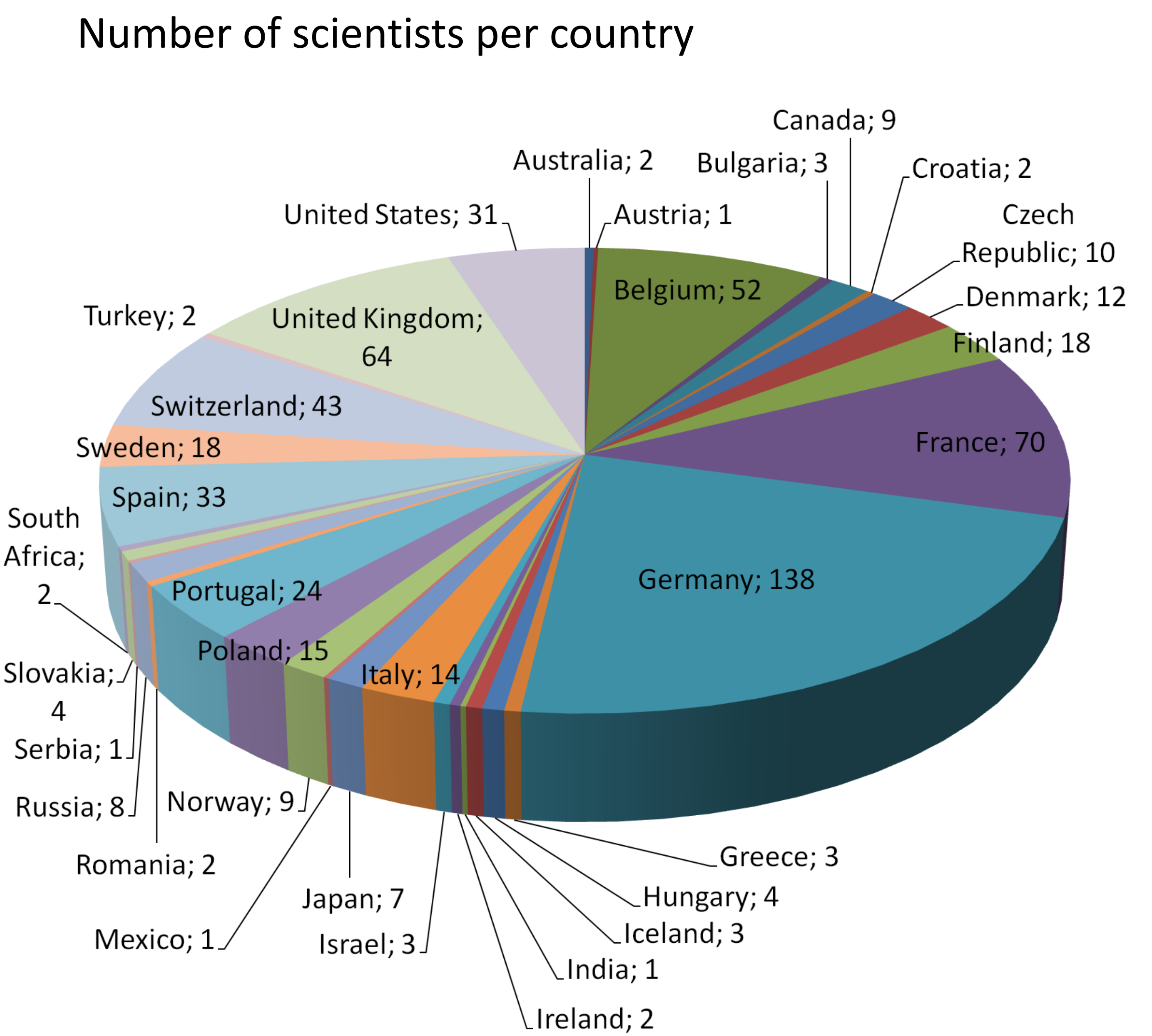


PSB	PS Booster
ISOLDE	Isotope Separator On Line Device
PS	Proton Synchrotron
EA	East Experimental Area
AD	Antiproton Decelerator
SPS	Super Proton Synchrotron
n_TOF	Neutron Time-of-Flight facility
LHC	Large Hadron Collider
NA	North Experimental Area
...	Other uses, including accelerator studies (machine development)

Quantity of protons used in 2016 by each accelerator and experimental facility, shown as a percentage of the number of protons sent by the PS Booster

***1.34×10^{20} protons** were accelerated in the accelerator complex in 2016. This might sound like a huge number, but in reality it corresponds to a minuscule quantity of matter, roughly equivalent to the number of protons in a grain of sand. In fact, protons are so small that this amount is enough to supply all the experiments. The LHC uses only a tiny portion of these protons, less than 0.1%, as shown in the diagram.*

The ISOLDE users community

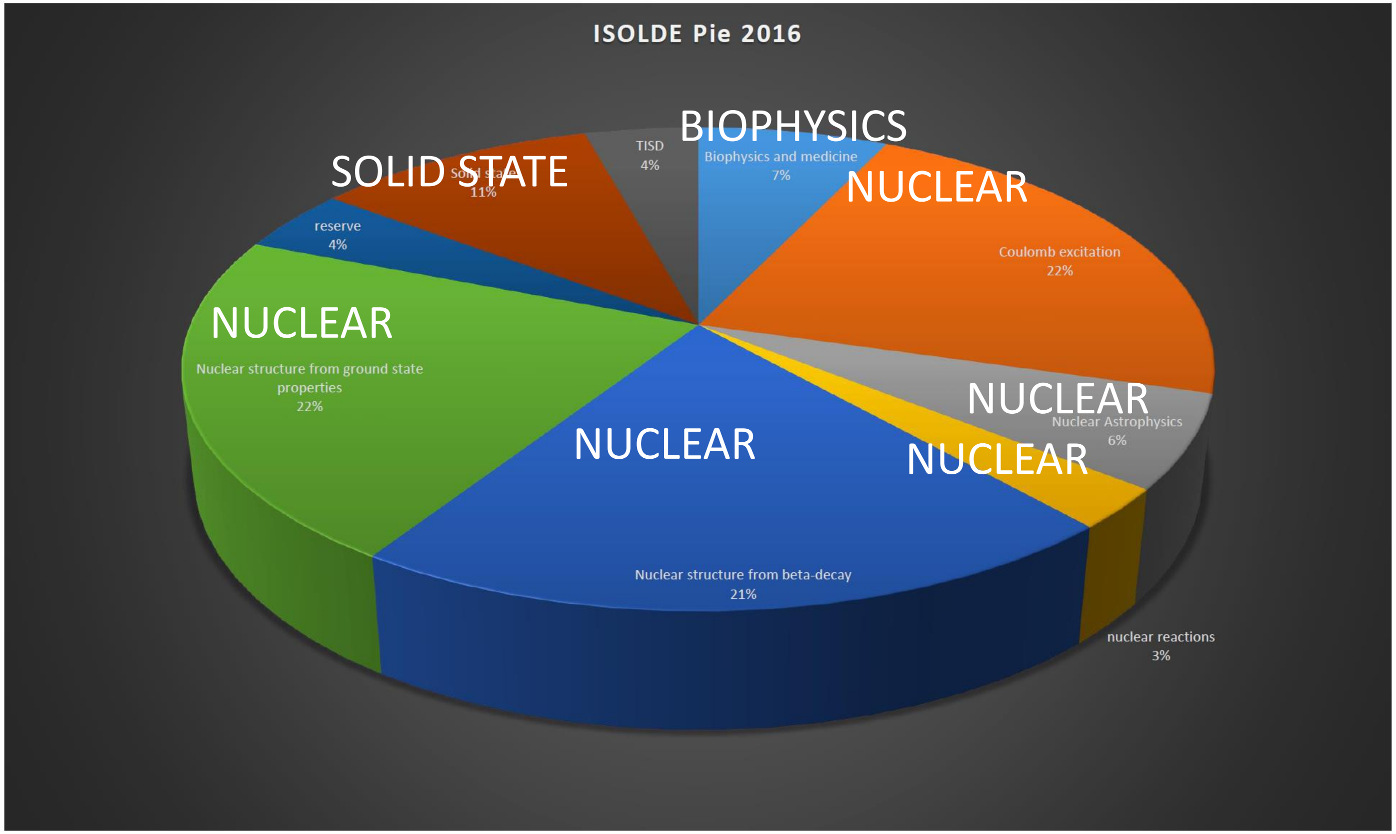


- > 800 scientists from 209 institutes from 41 countries
- ~ 50 experiments/year
- > 20 PhD's per year
- > 80 publications/year of which many high-impact (PRL, PLB, Nature, …)

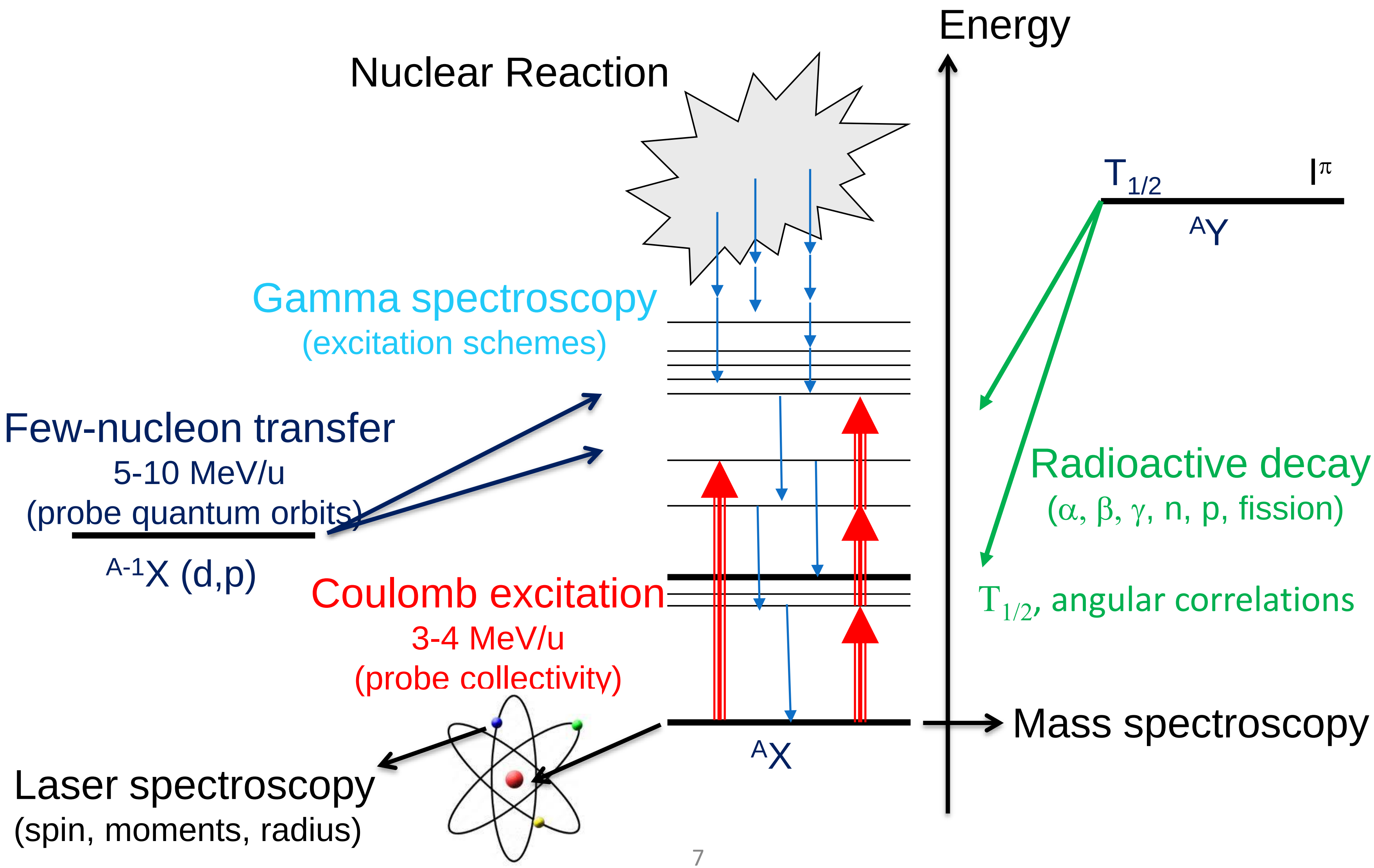
5 main users countries: Germany, France, UK, Belgium, Switzerland

Nuclear Physics experiments

- About 75% of all beam time !
  - 40% for low-energy experiments
  - 35% for experiments with post-accelerated RIB (still in upgrade phase)
- About 15% is for Bio and medical physics related research
- About 20% is for Solid State Physics research



Experiments to probe nuclear structure



LOW ENERGY NUCLEAR PHYSICS EXPERIMENTS

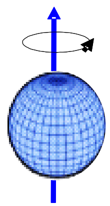
Laser Spectroscopy (Collinear and in the RILIS ion source)

Mass Measurements (Penning Trap)

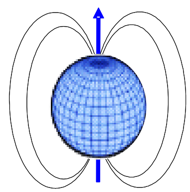
Decay Spectroscopy (ISOLDE Decay Station)

Laser spectroscopy

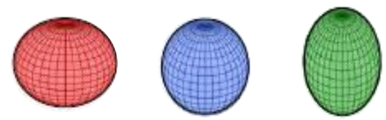
Determine nuclear ground state properties (and long-lived isomers)



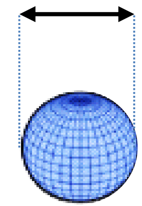
Spin I



Magnetic dipole moment μ (probe wave function)

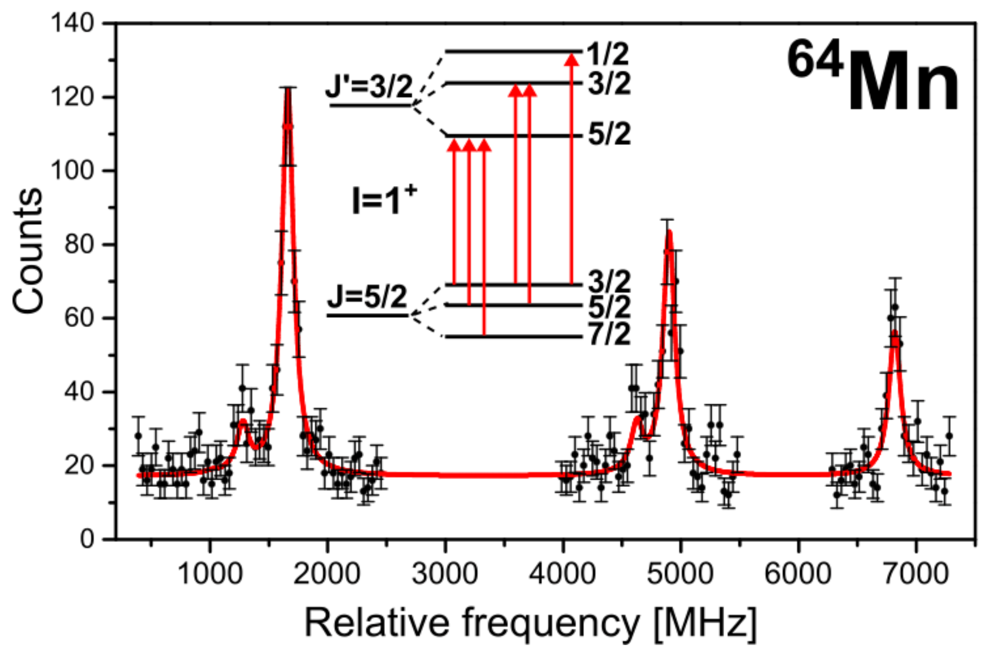


Electric Quadrupole moment Q_s (shape)

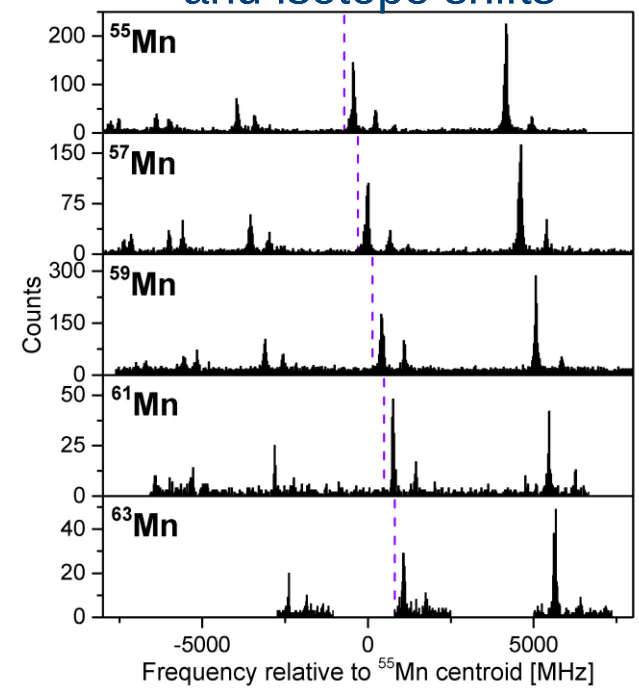


Charge radius $\delta\langle r^2\rangle$ (size)

Measure the **atomic** hyperfine splitting

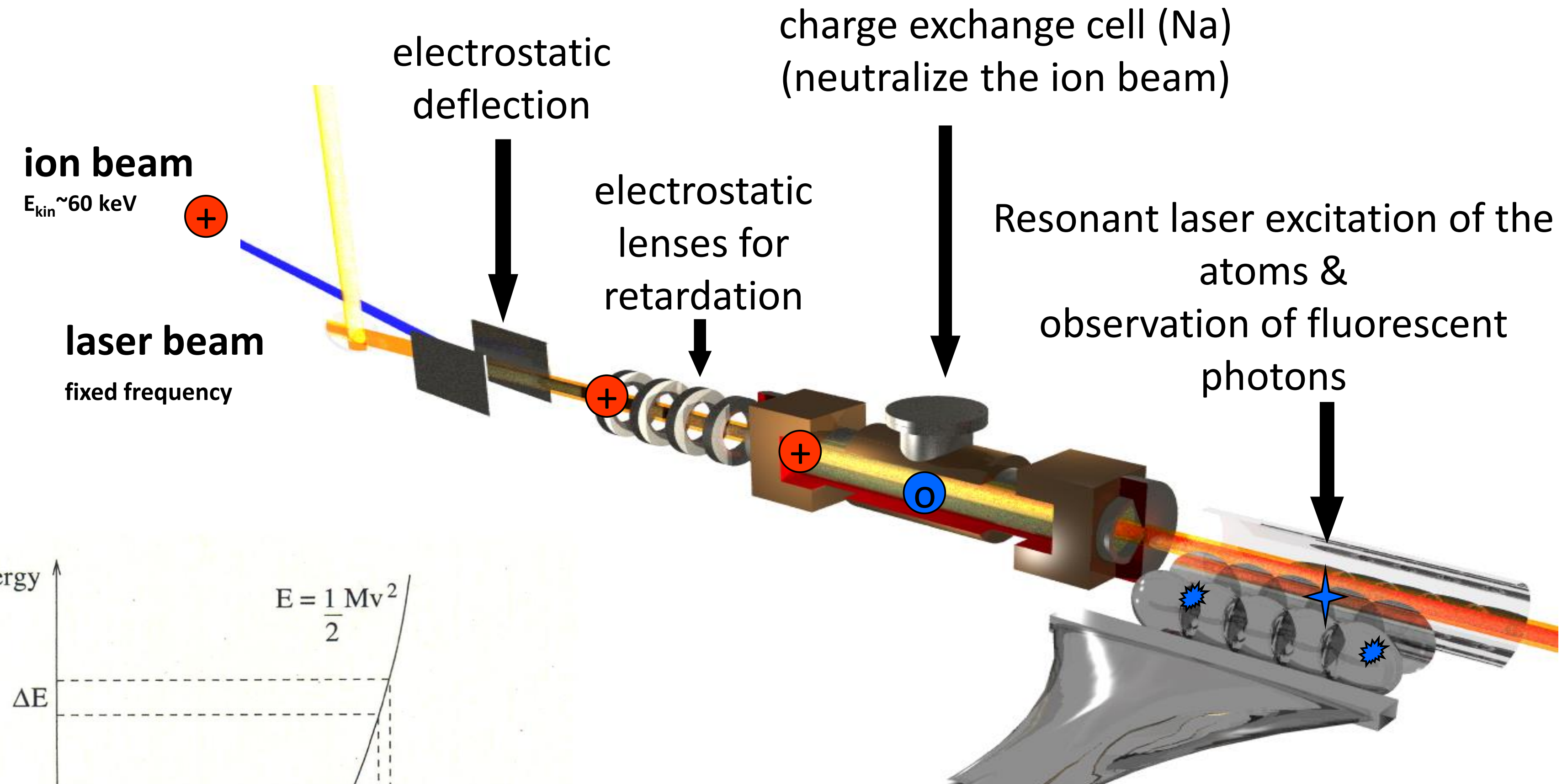


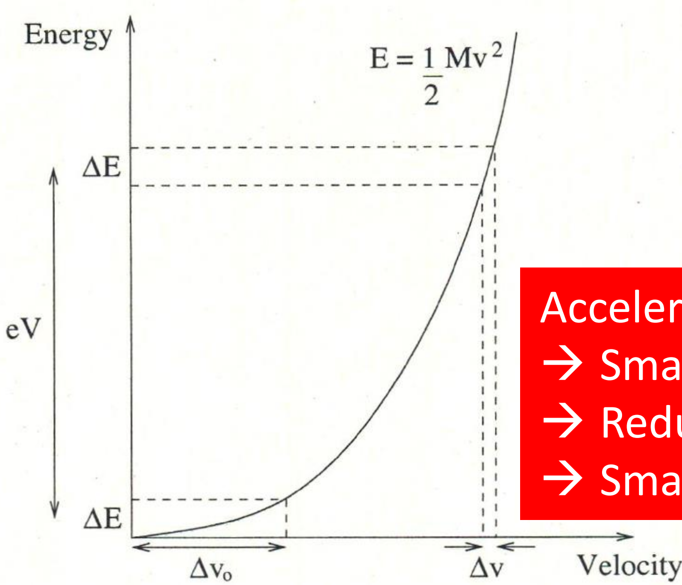
and isotope shifts



Collinear laser spectroscopy

Since late 70'ies

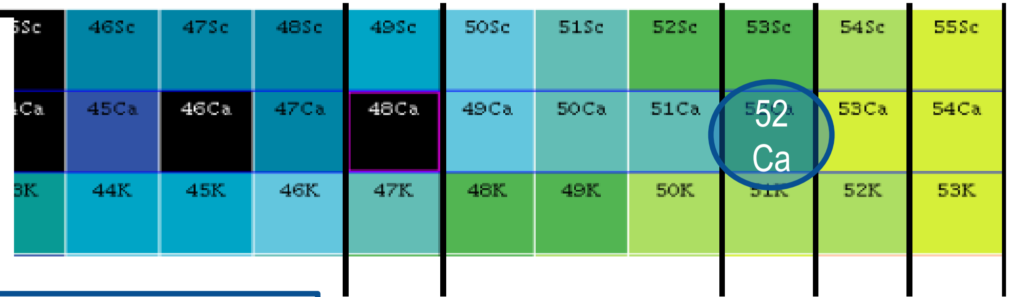




Accelerated beam
→ Small relative velocity spread
→ Reduction of Doppler Broadening
→ Small line widths – resolve all hyperfine peaks

Collinear laser spectroscopy on Ca isotopes

10^7 ions/s



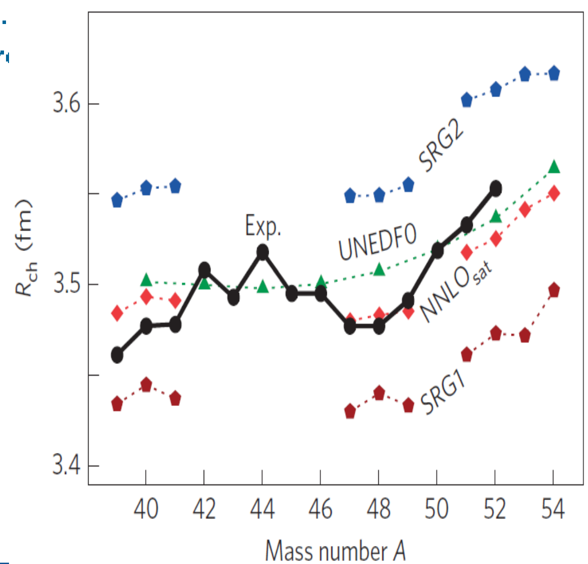
1992

2013: New magic numbers suggested from masses and energies

nature physics 2016

Unexpectedly large charge radii of neutron-rich calcium isotopes

R. F. Garcia Ruiz, M. L. Bissell, K. Blaum, A. Ekström, N. Frömmgen, G. Hagen, M. Han
K. Hebeler, J. D. Holt, G. R. Jansen, M.
Neyens, W. Nörtershäuser, T. Papenbr
& D. T. Yordanov



nature

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz, D. Beck, K. Blaum, Ch. Borgmann, M. Breitenfeldt, R. B. Cakirli, S. George, F. Herfurth, J. D. Holt, M. Kowalska, S. Kreim, D. Lunney, V. Manea, J. Menéndez, D. Neidherr, M. Rosenbusch, L. Schweikhard, A. Schwenk, J. Simonis, J. Stanja, R. N. Wolf & K. Zuber

Affiliations | Contributions | Corresponding author

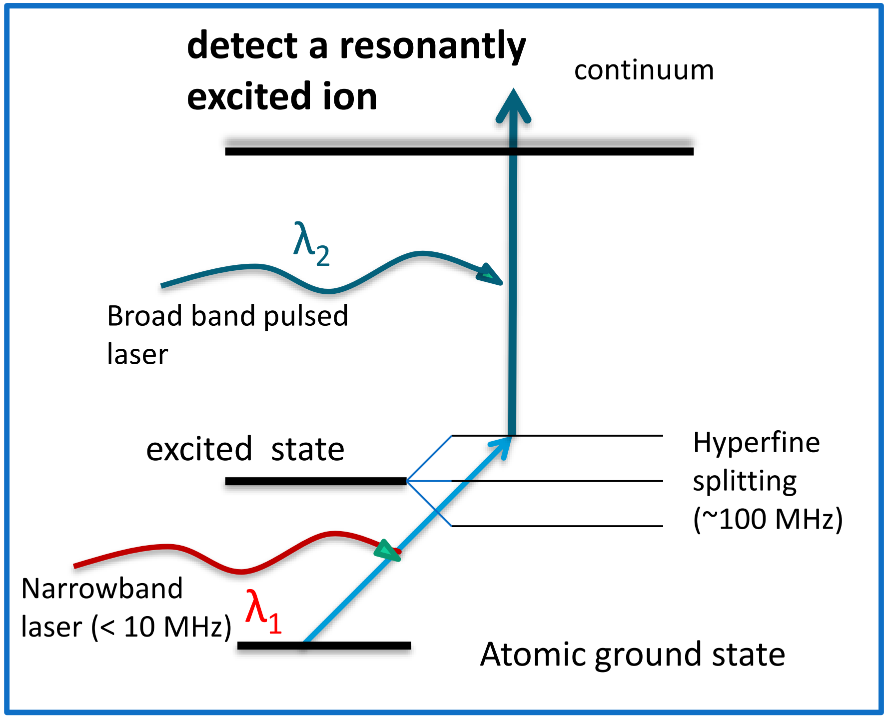
nature

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck, S. Takeuchi, N. Aoi, P. Doornenbal, M. Matsushita, H. Wang, H. Baba, N. Fukuda, S. Go, M. Honma, J. Lee, K. Matsui, S. Michimasa, T. Motobayashi, D. Nishimura, T. Otsuka, H. Sakurai, Y. Shiga, P.-A. Söderström, T. Sumikama, H. Suzuki, R. Taniuchi, Y. Utsuno, J. J. Valiente-Dobón & K. Yoneda

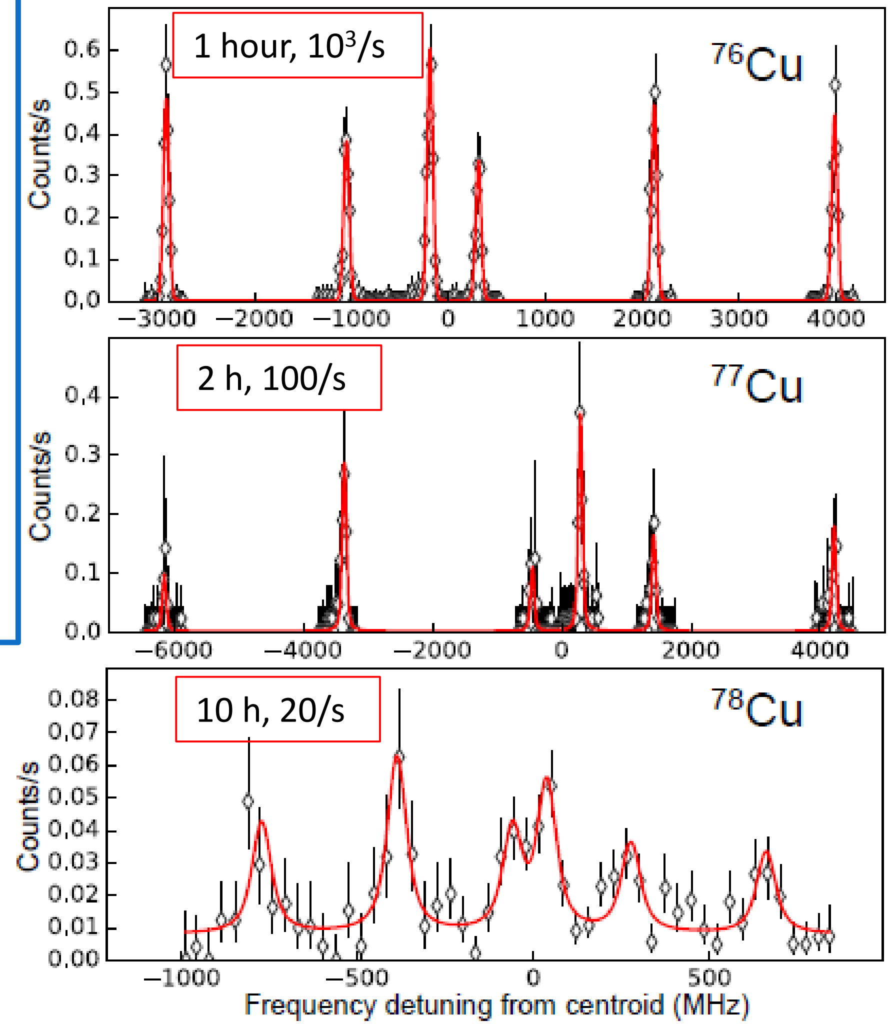
Collinear Resonance Ionization Spectroscopy (CRIS)

sensitivity improved by another factor 10 - 100 !



- ultra-low background (1 event /10 min)
- high efficiency (~1-5 %)
- high resolution (~ 20-60 MHz)
- current sensitivity 10-20 ions/s

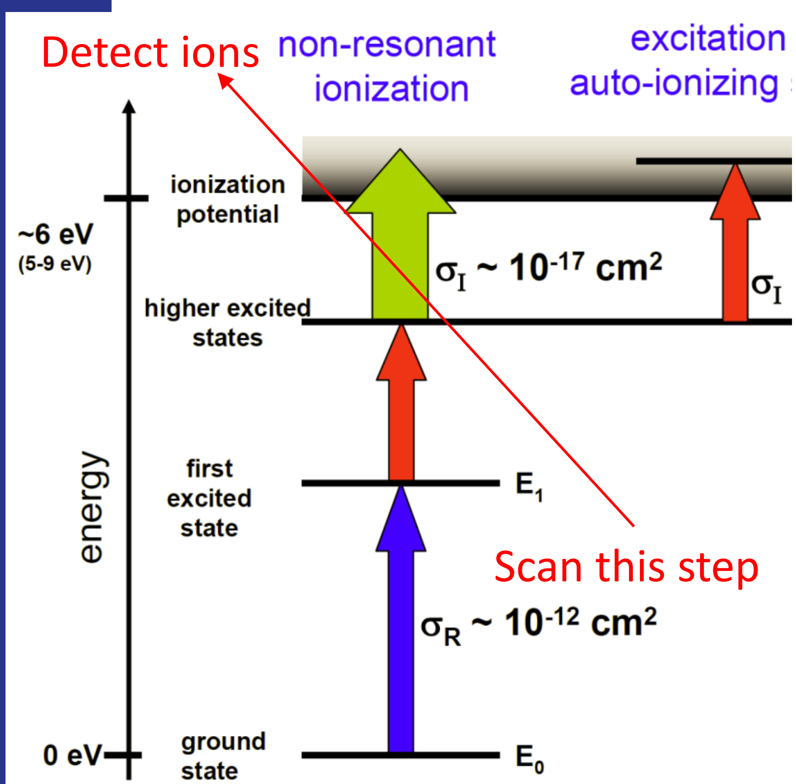
Most recent result @ ISOLDE
HFS of 63-78Cu
(R.P. de Groote et al., submitted to PRL)

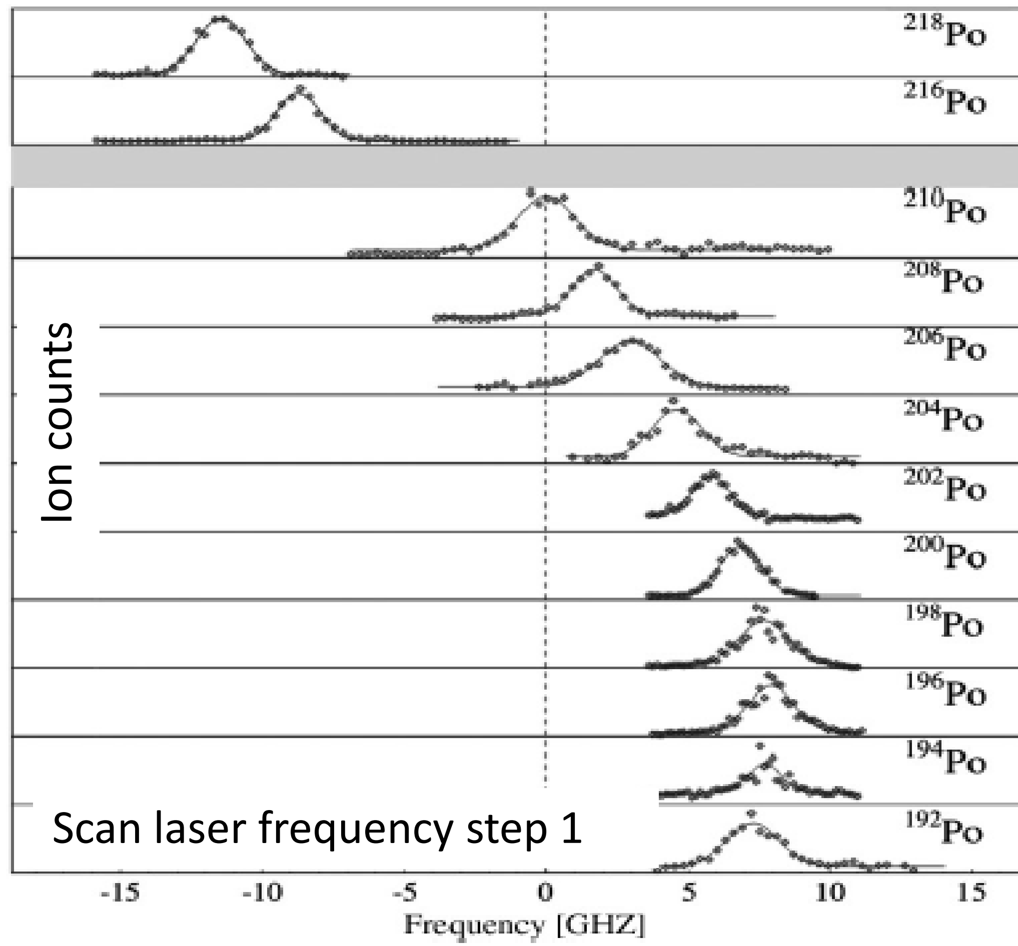


In-source laser spectroscopy

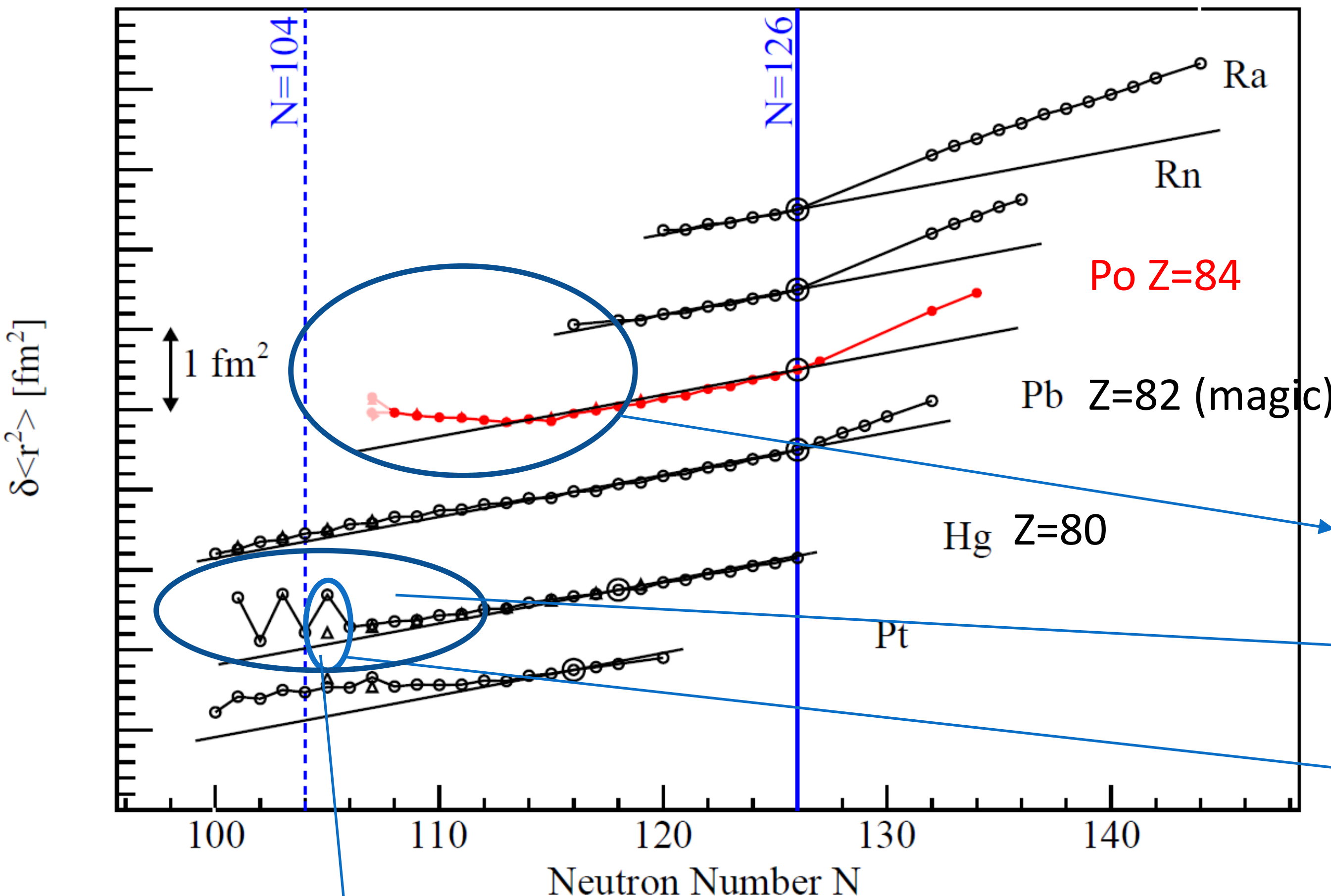
Use selective **Resonance Ionization Laser Ion Source (RILIS)** to do spectroscopy

- More sensitive (< 1 ions/s needed)
- Less resolution (few GHz !)
- Isotope shifts (no qua





Charge radii around lead



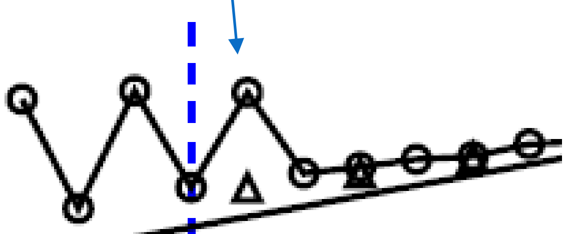
Isotope shifts measured with **RILIS** setup

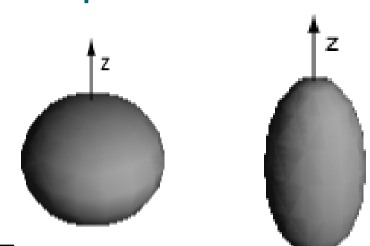
Most exotic Po: < 1/s

➔ Onset of deformation

➔ Shape staggering

➔ Shape coexistence

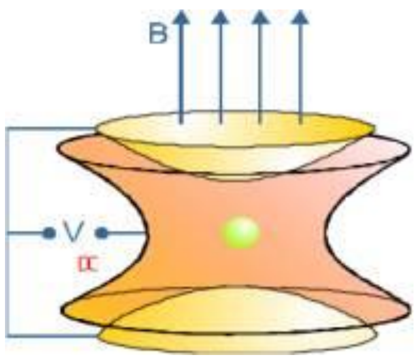


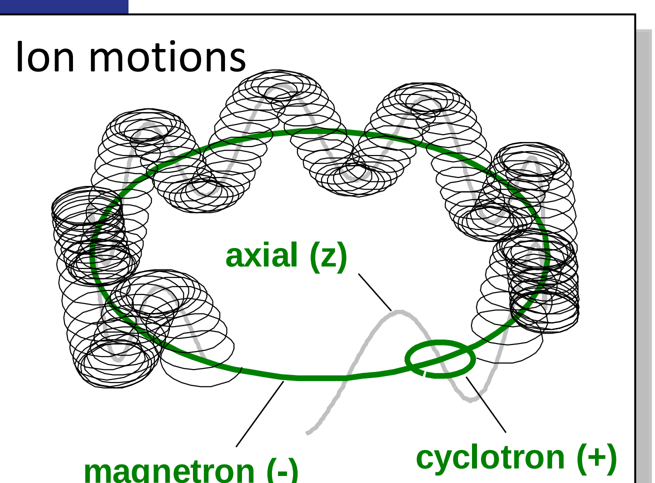


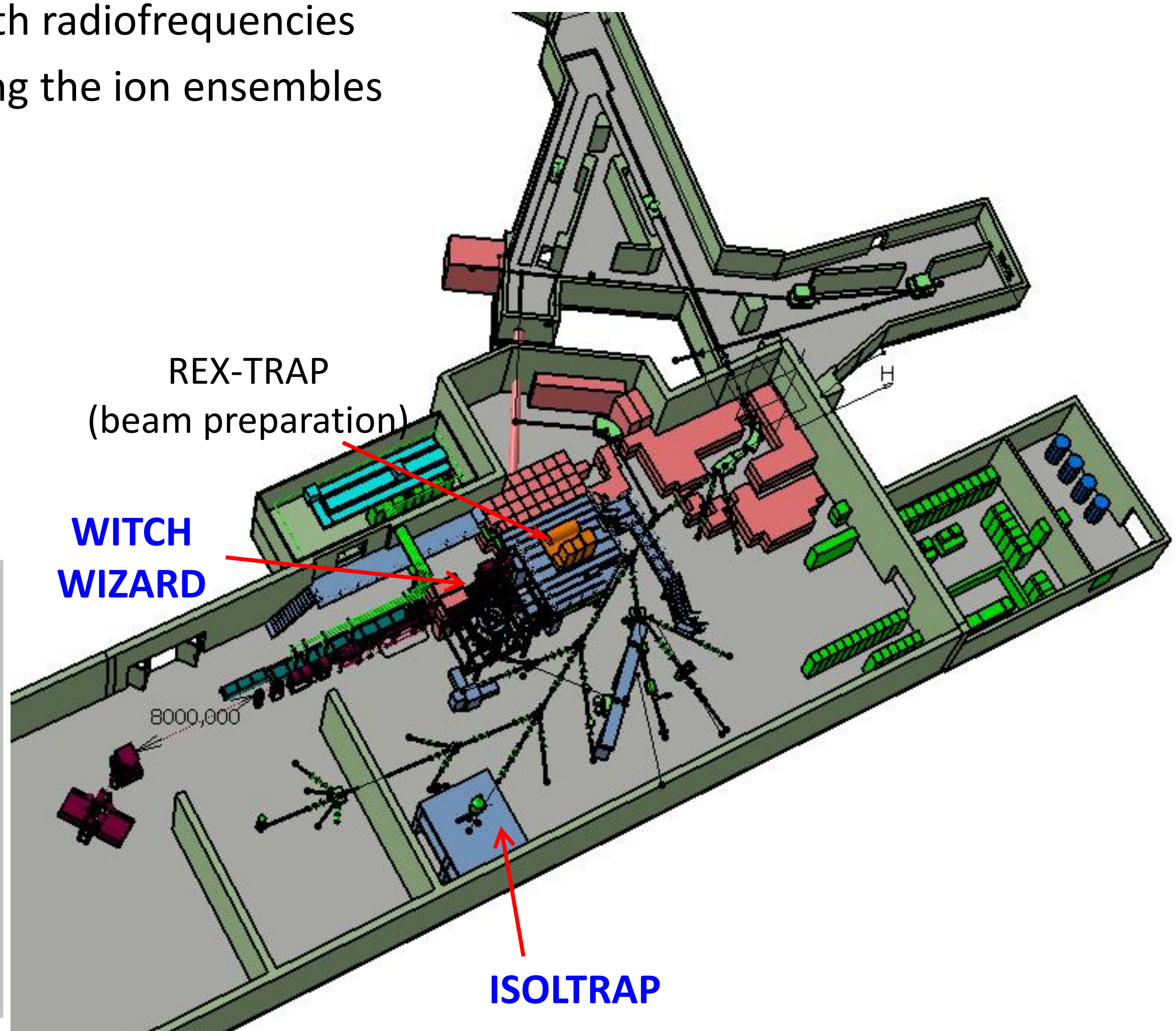
STUDY INTERPLAY BETWEEN COLLECTIVE AND SINGLE PARTICLE BEHAVIOR

Studies with ion traps

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

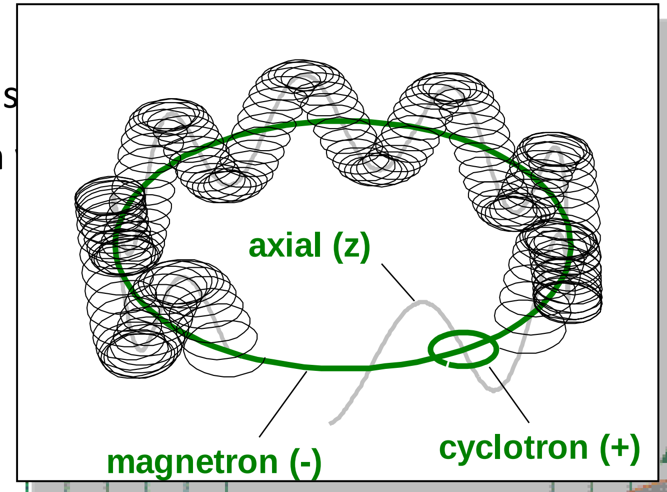


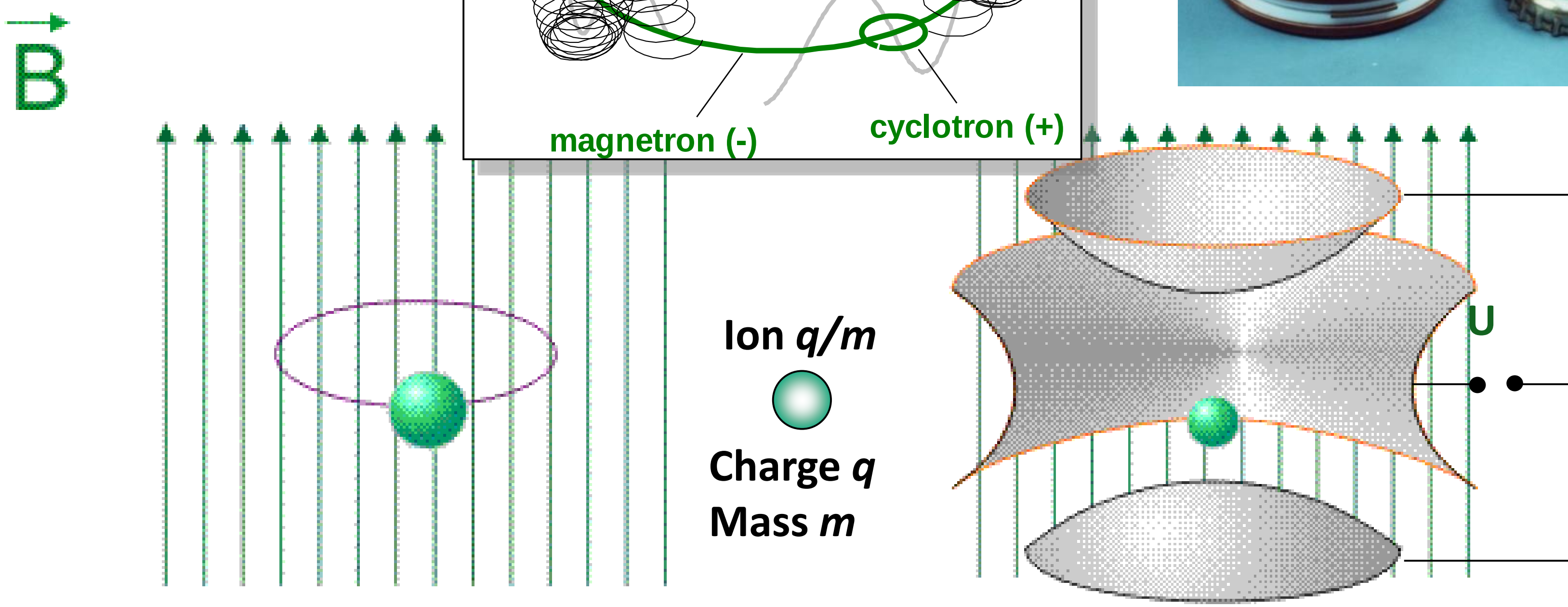




Penning-trap mass spectrometry

- Penning trap
  - superposition of s
  - Ion manipulation





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

$$\omega_c = qB/m$$

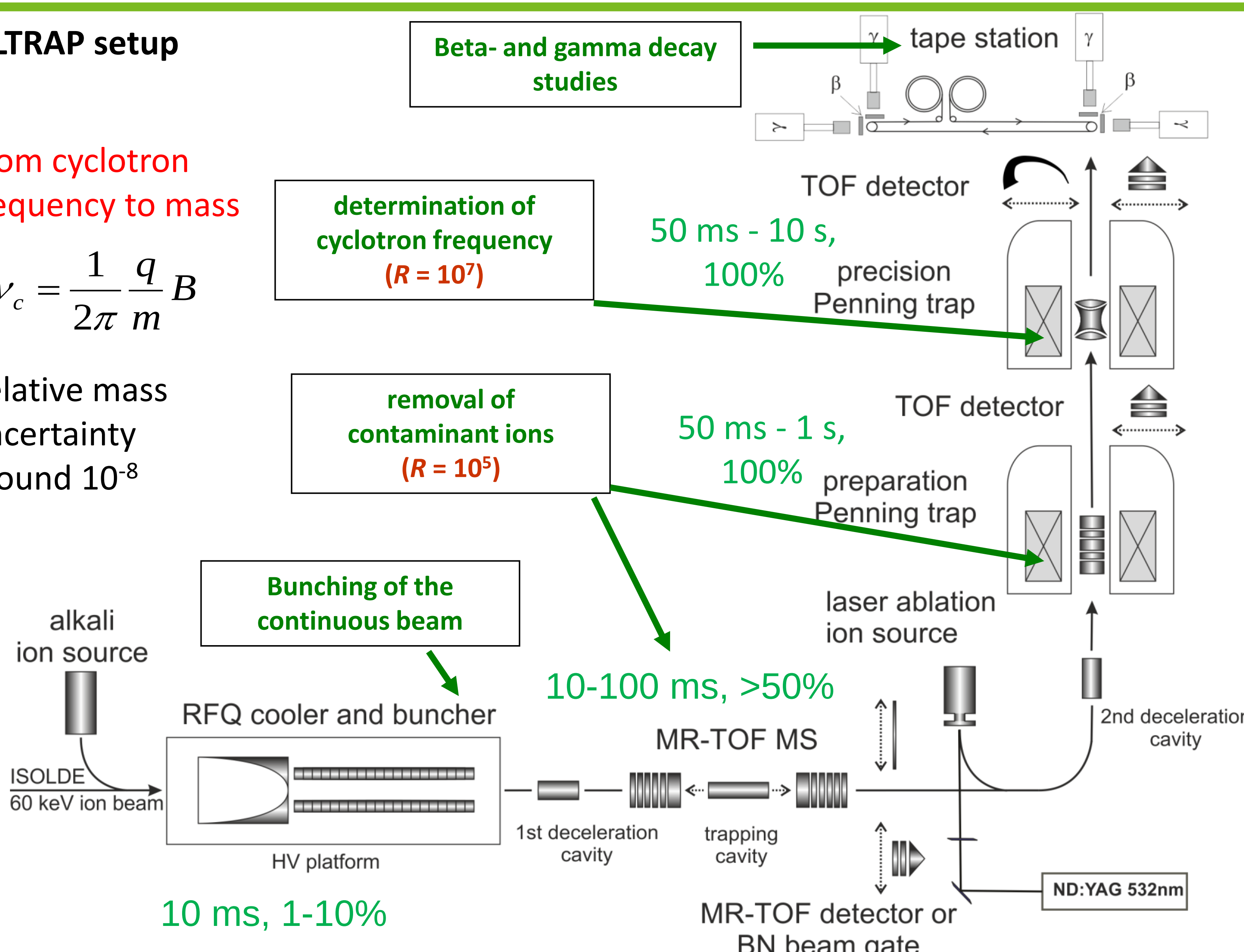
Penning-trap mass spectrometry

ISOLTRAP setup

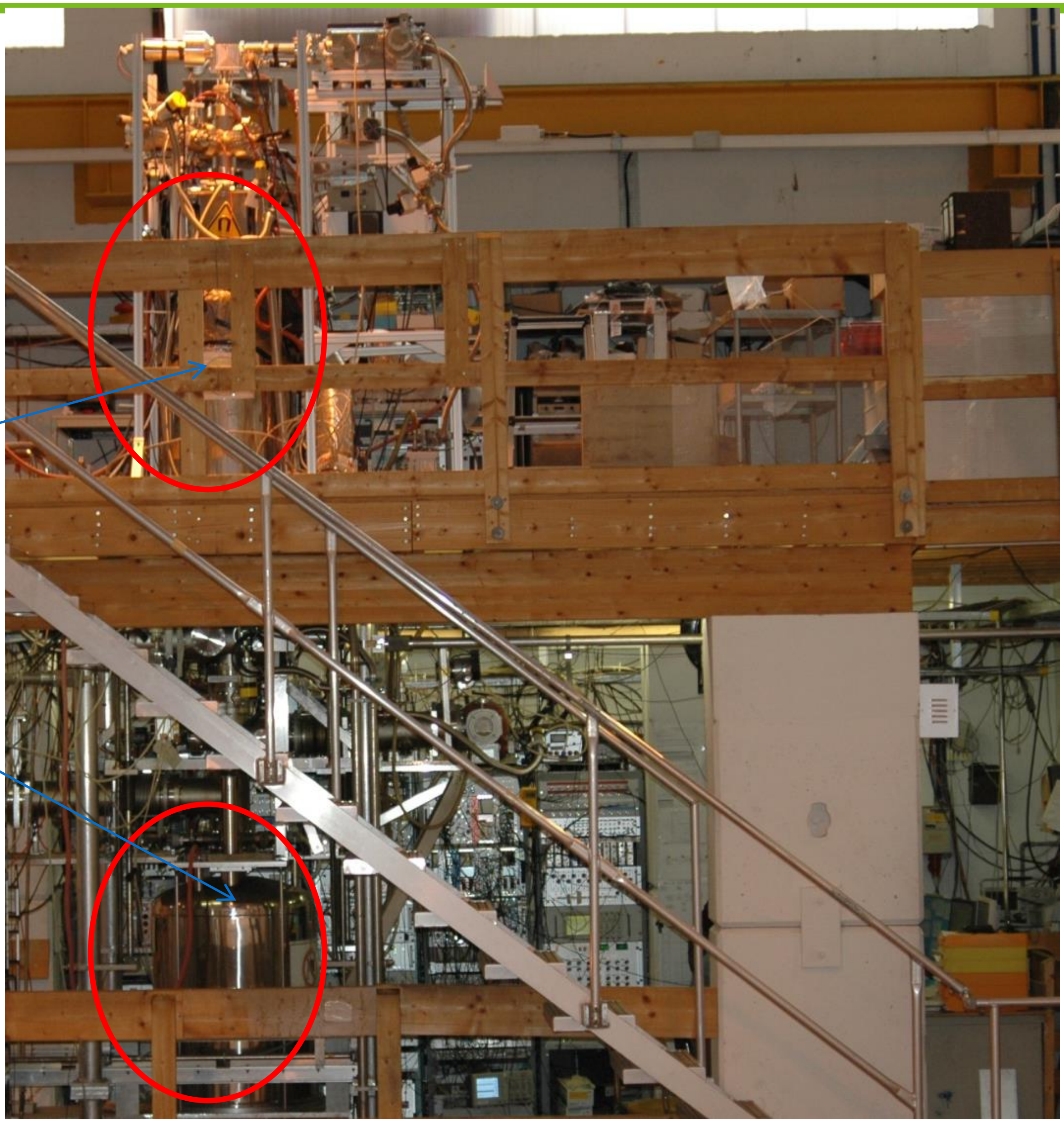
From cyclotron frequency to mass

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

Relative mass uncertainty around 10^{-8}



ISOLTRAP

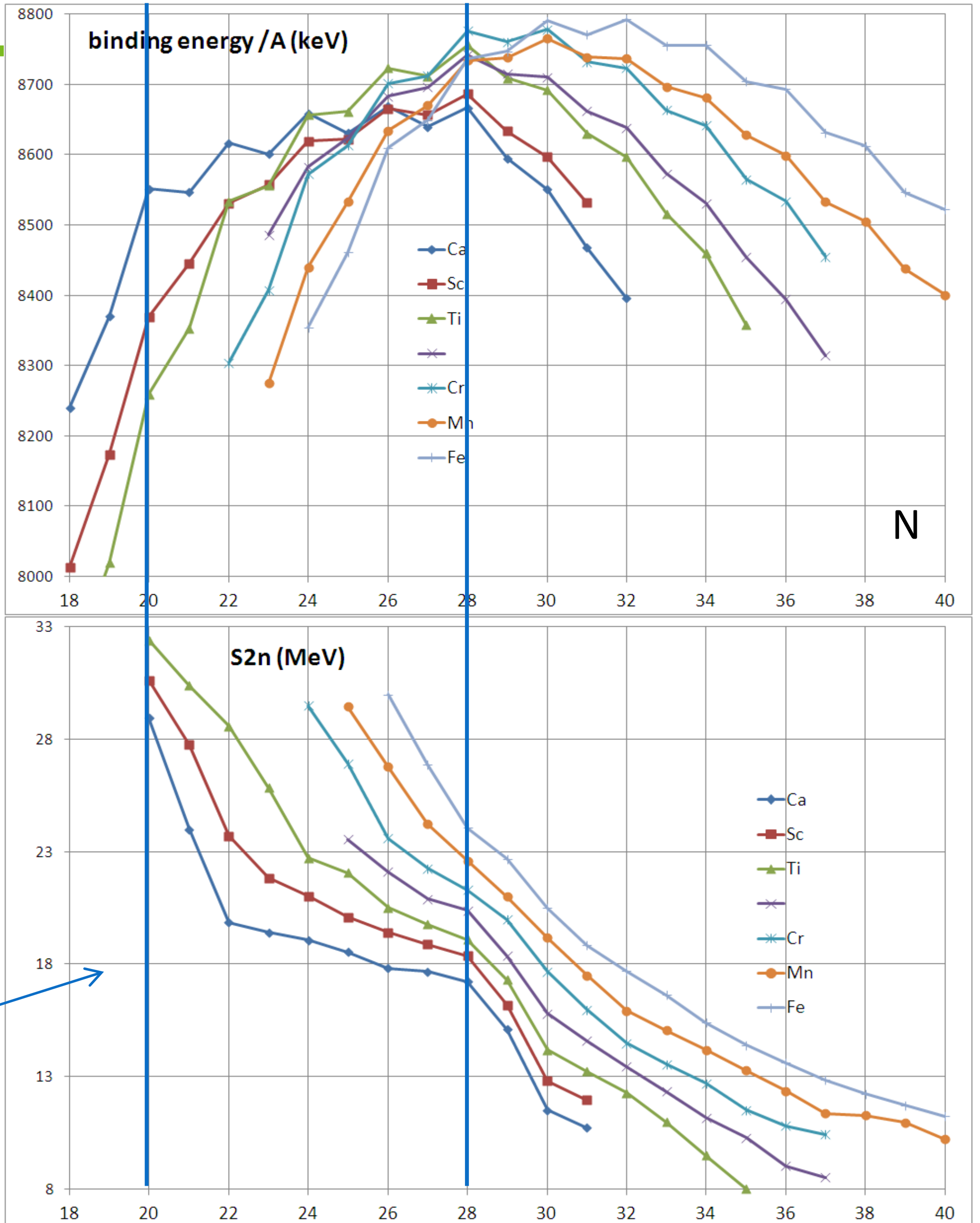


Masses and nuclear structure

- 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

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

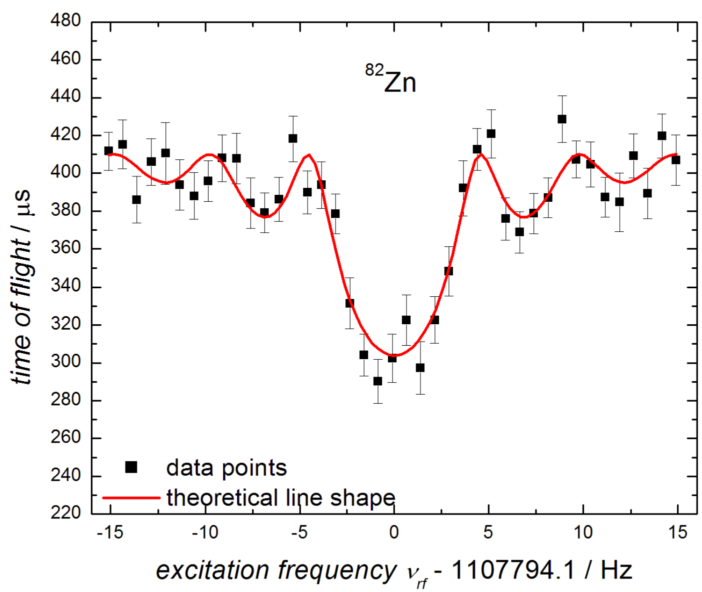


Closed shells visible as a sudden drop after the magic number (N=20 and 28)

Mass of zinc-82

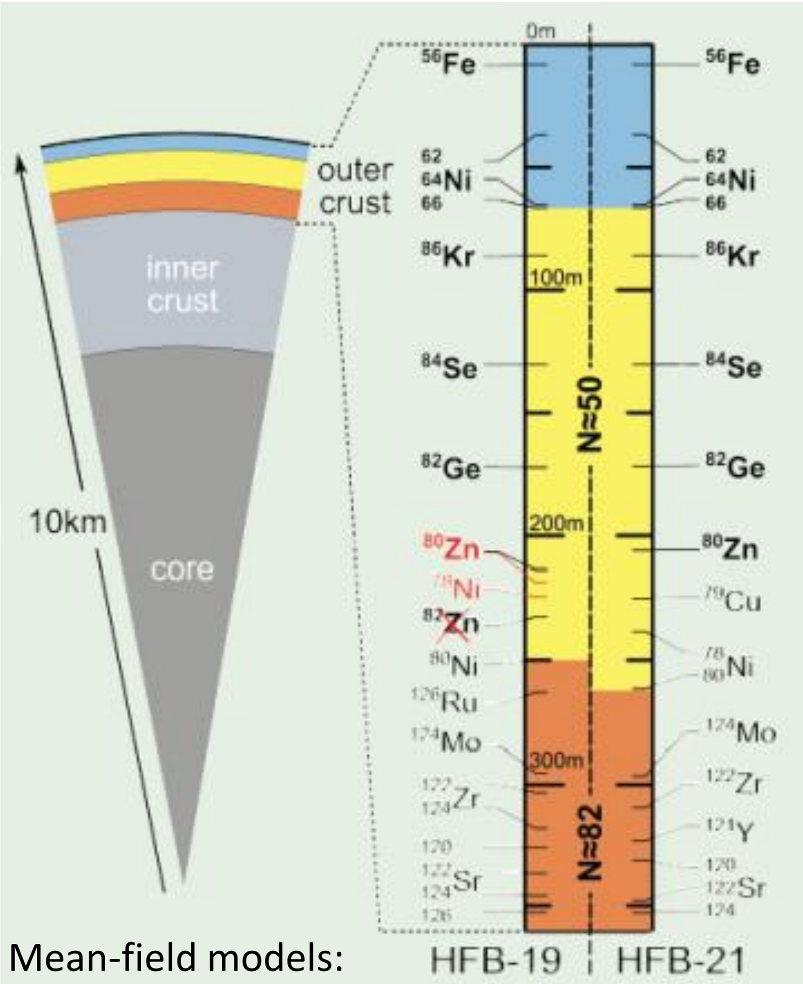
After several attempts at ISOLTRAP and elsewhere

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



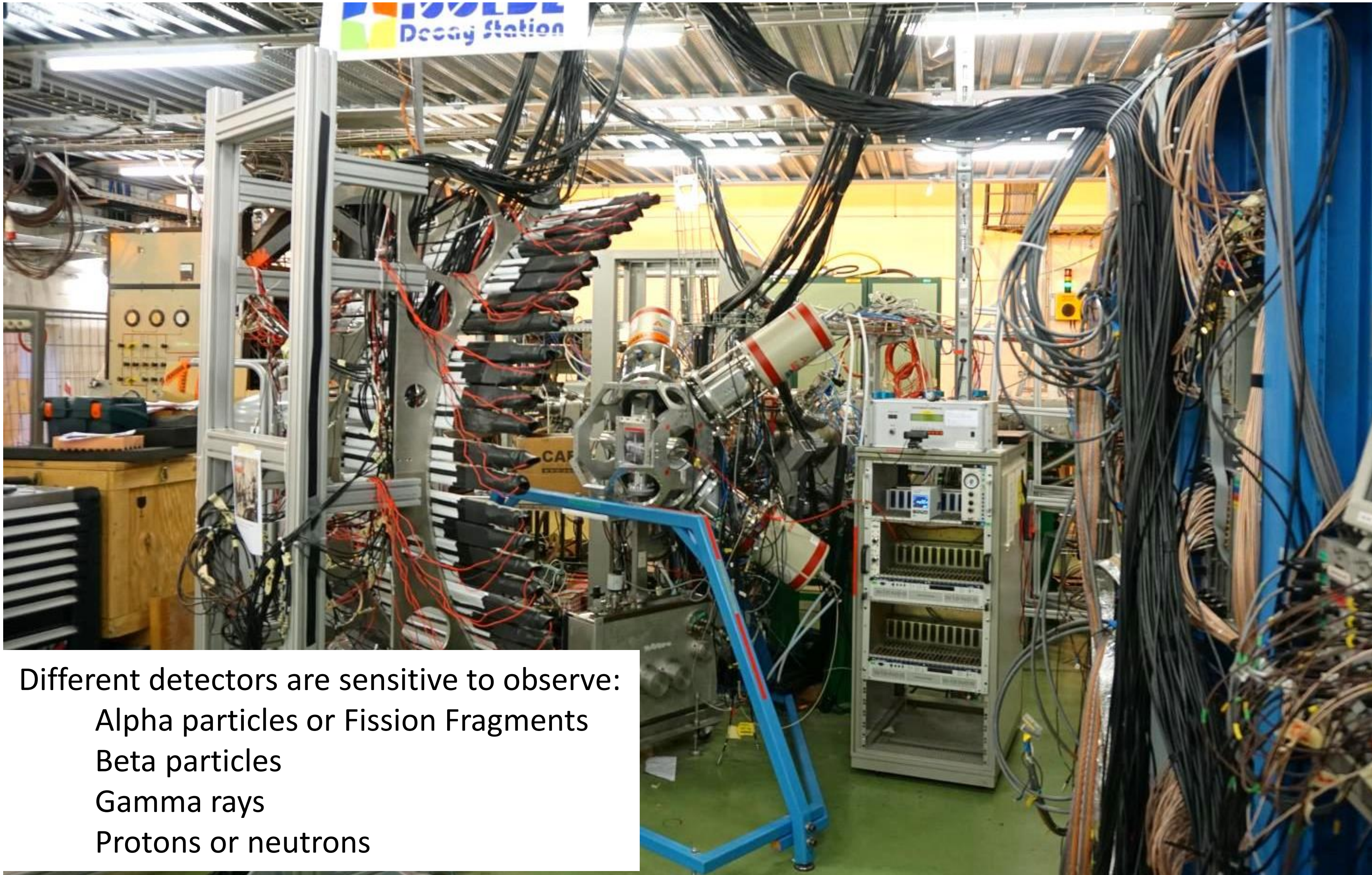
R.N. Wolf et al, Phys. Rev. Lett. 110, 041101 (2013)

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



Decay spectroscopy:
the ISOLDE Decay Station (IDS)

Dedicated (but flexible) set-up since 2014

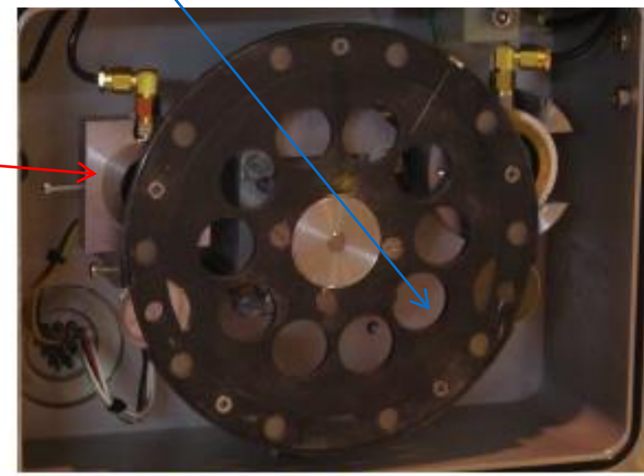


Different detectors are sensitive to observe:
- Alpha particles or Fission Fragments
- Beta particles
- Gamma rays
- Protons or neutrons

Decay spectroscopy:
the Windmill (KU Leuven design)

C foil for implantation (90 nm thick)

Si detector for FF



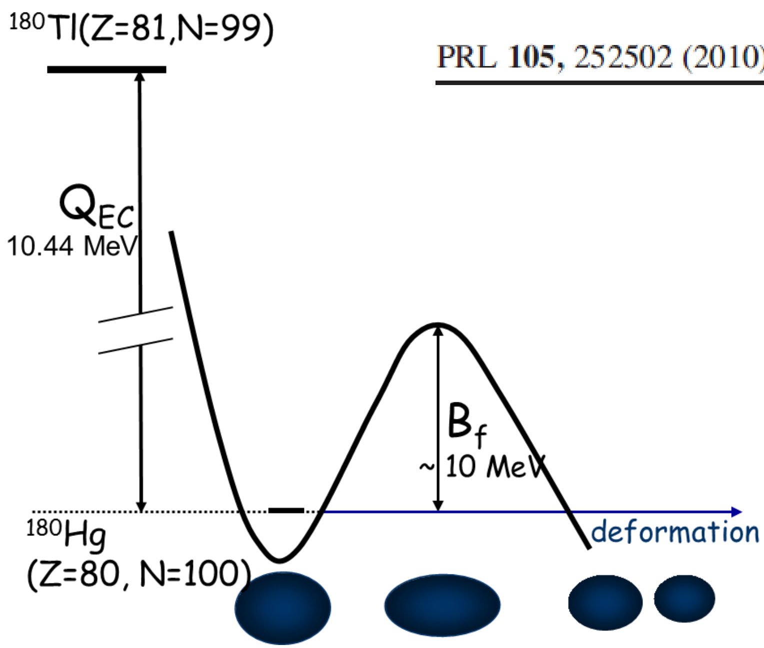
- Very thin C foils to **implant a heavy radioisotope**
  - ✓ 40 keV ^{180}Tl stops in a few nm of C

- **Ligther Fission Fragments** (FF) or **alpha particles** are emitted from the isotope, and can leave the very thin C foil
  - ✓ Detection using Si-detectors

- **Gamma rays** detected with HPGe detectors

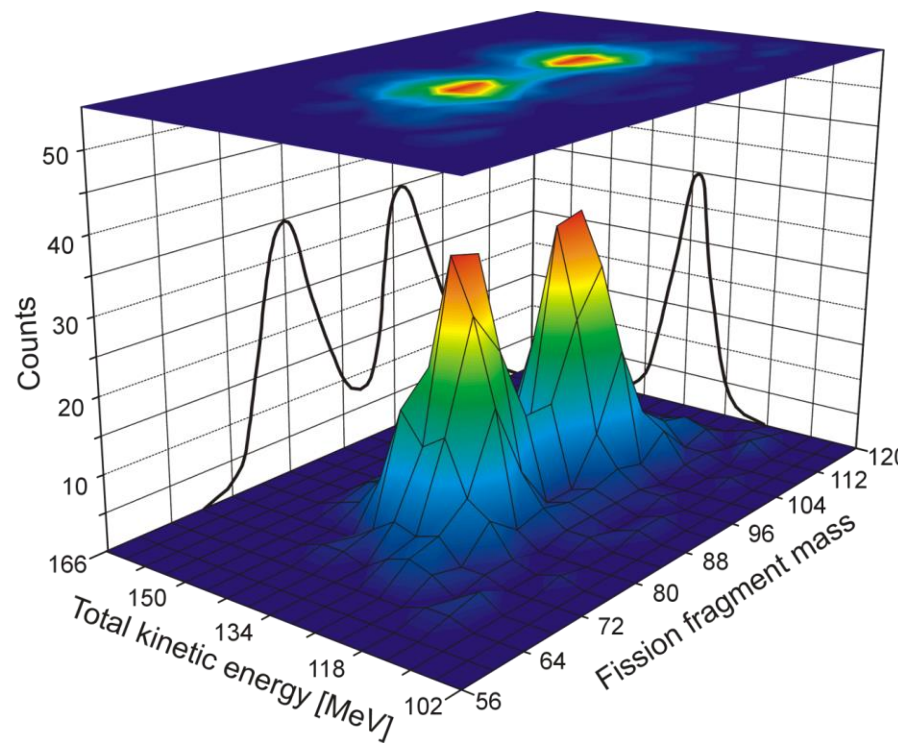
Beta-delayed fission of mercury-180

WINDMILL setup



PRL **105**, 252502 (2010) PHYSICAL REVIEW LETTERS

New Type of Asymmetric Fission in Proton-Rich Nuclei



- 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

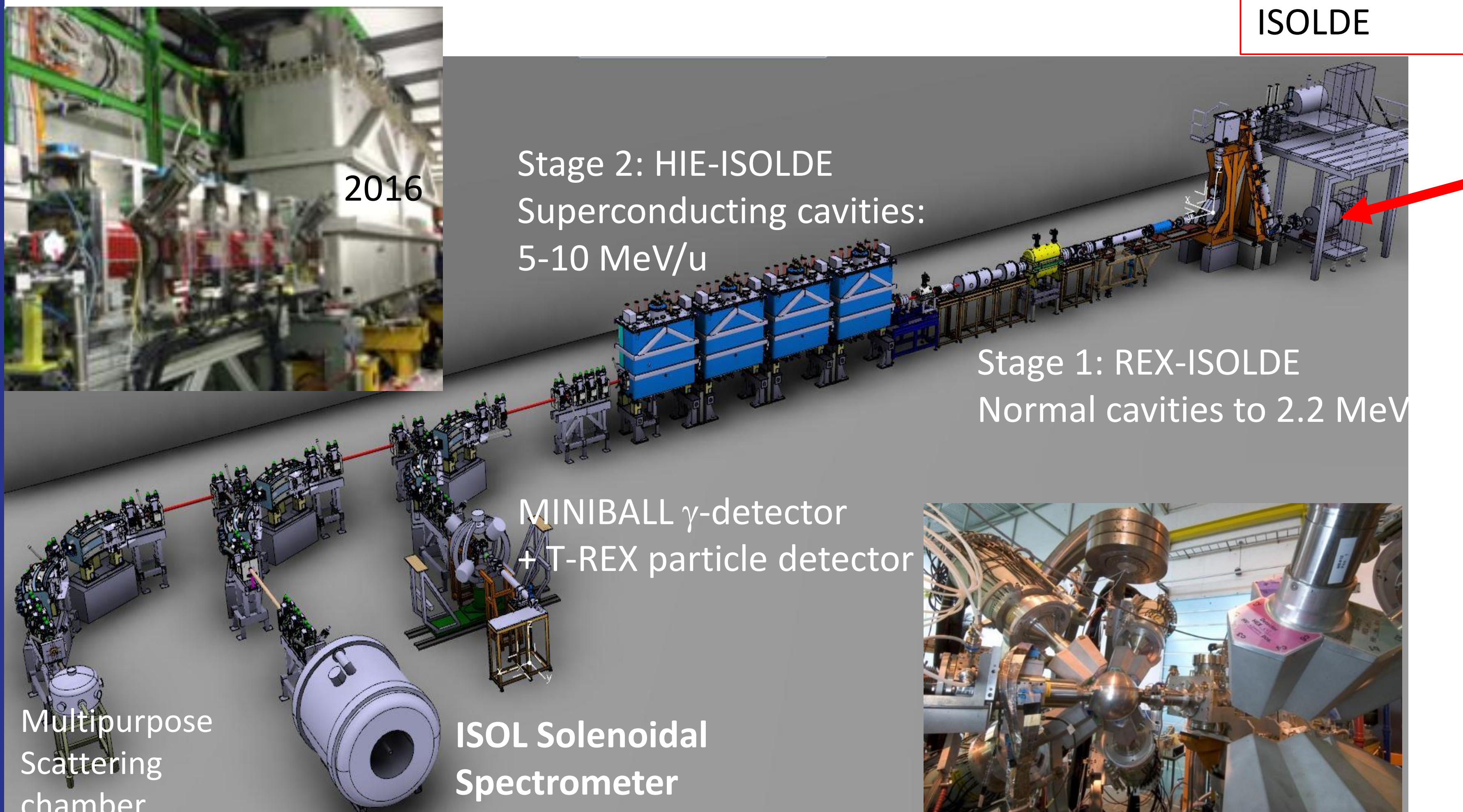
HIGH ENERGY NUCLEAR PHYSICS EXPERIMENTS with accelerated RIB's

Coulomb excitation (3-4 MeV/u max)

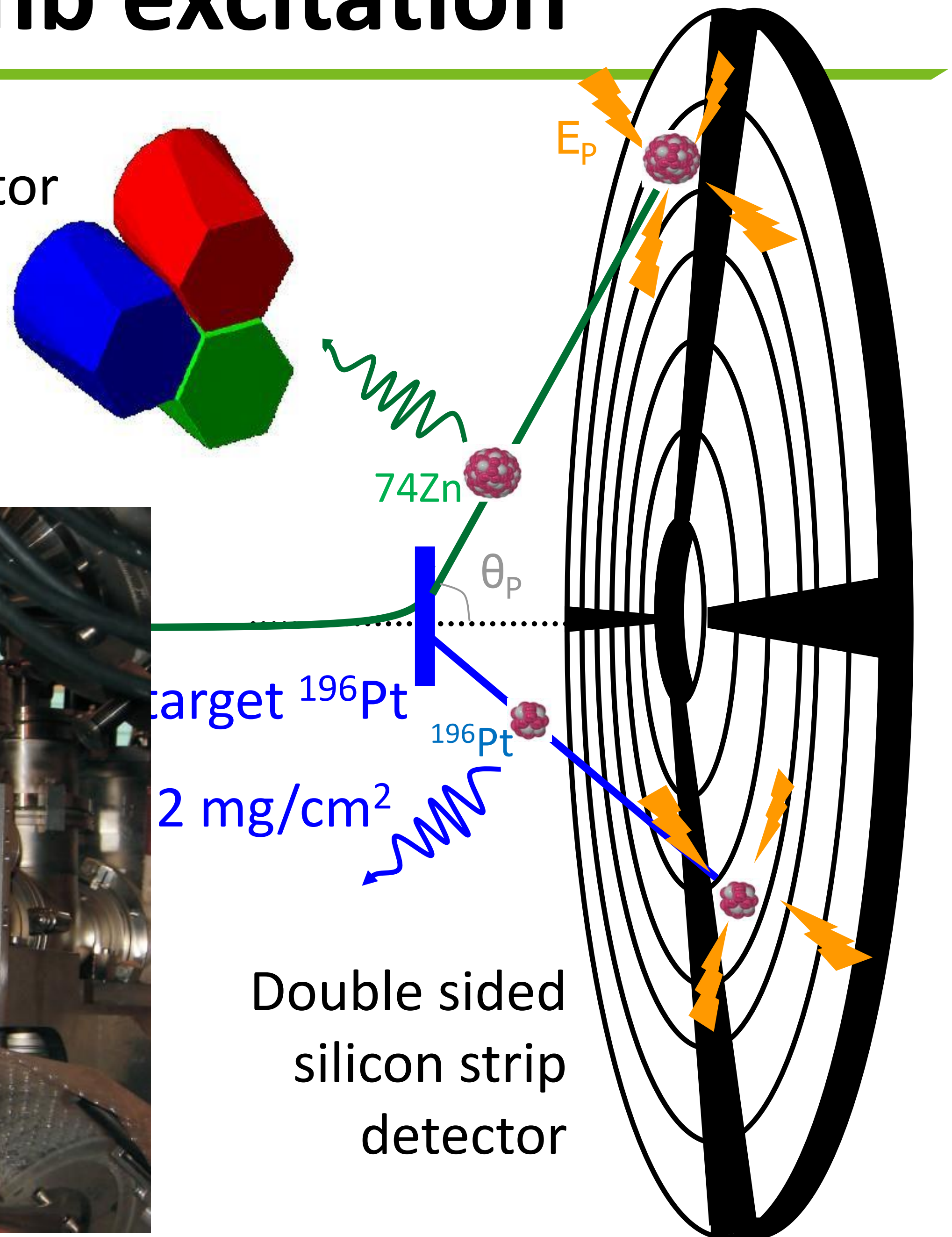
Transfer reaction (5-10 MeV/u)

RIB from ISOLDE-CERN: the HIE-ISOLDE post-accelerator

2016: max 5 MeV/u (2 superconducting cavities)
2017 (this week): first beams at 7 MeV/u (3 cavities)
2018: max energy reached (10 MeV/u) (4 cavities)

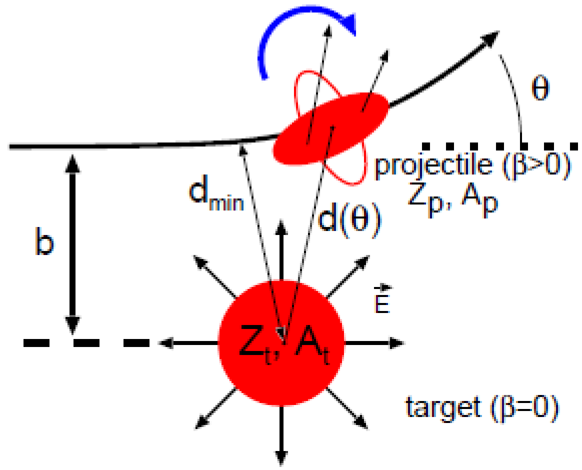


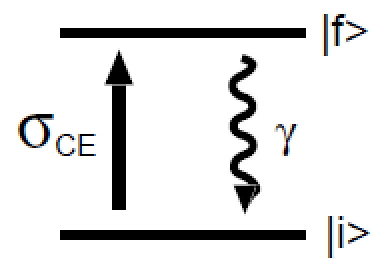
Coulomb excitation



Coulomb excitation

Excitation of an accelerated (radioactive) nucleus by the electromagnetic field of the target (made of stable nuclei)

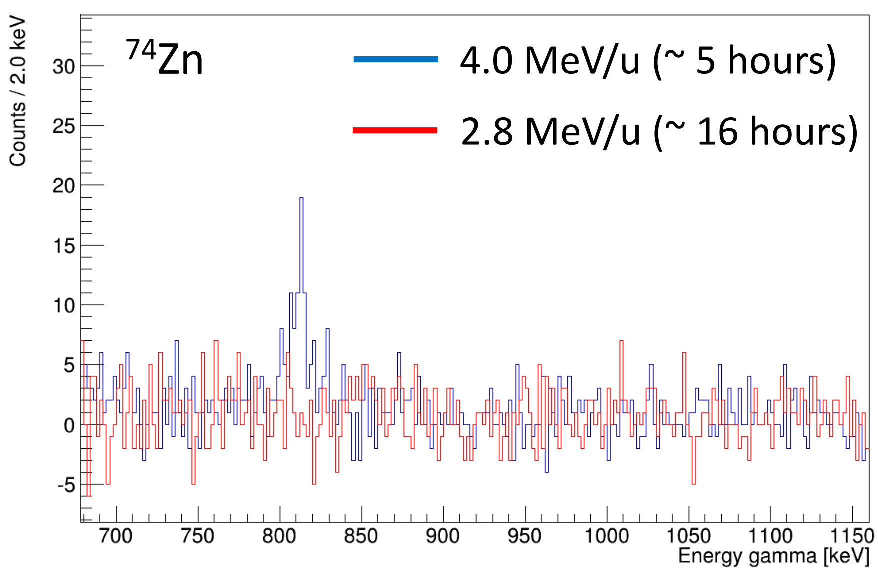


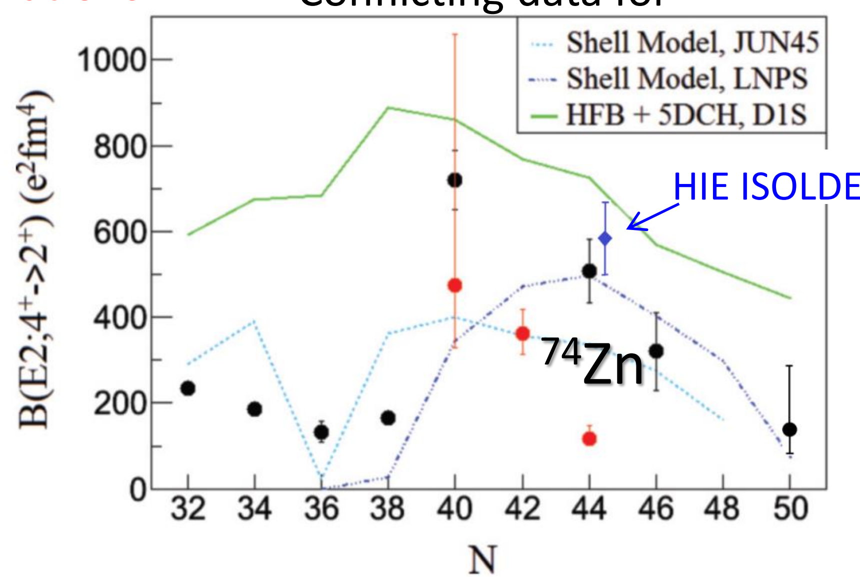


Observables: Transition energies and intensities

=> Determine new excited levels and study deformations

Conflicting data for

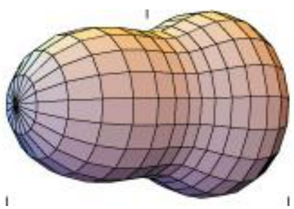


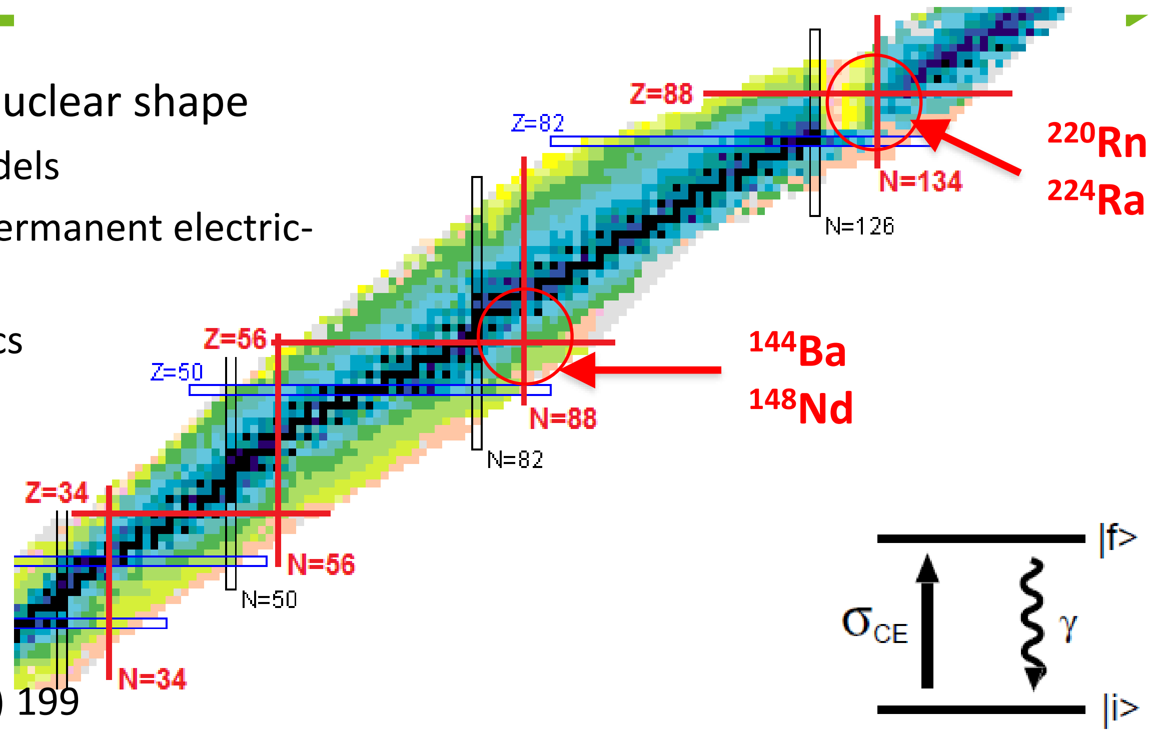


Octupole deformation from Coulex

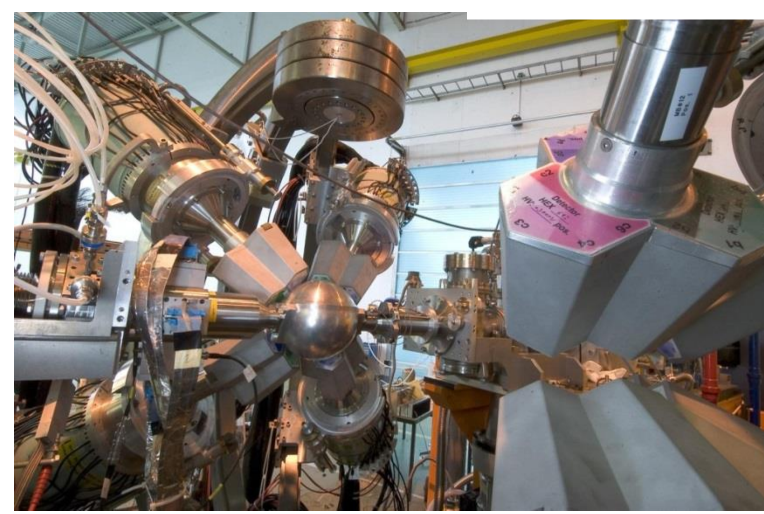
- Octupole shape – very rare nuclear shape
  - Test ground for nuclear models
  - Important in searches for permanent electric-dipole moments (EDM) –

  beyond Standard Model Physics





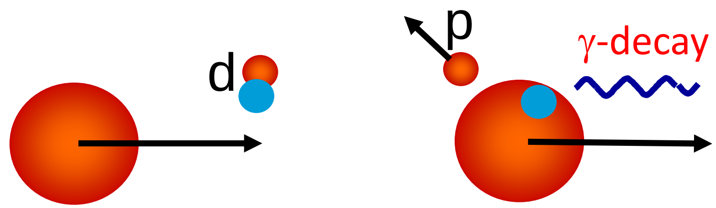
L.P. Gaffney et al, Nature 497 (2013) 199



Nucleon-transfer reactions

Typical reaction: transfer of a neutron

Accelerated RIB
(5-10 MeV/u)



Observables
- energy of protons and emitted RIB
- γ-rays
- angular distributions of protons (+ γ-rays)

Information:

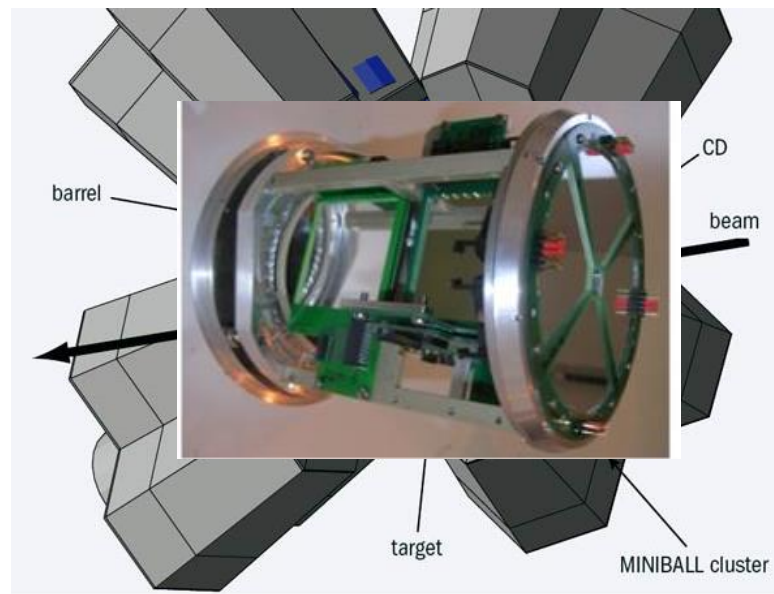
(single-particle) level energies

spin/parity of levels

Miniball + T-REX setup (Si detector barrel)

gamma detectors and particle identification

study single-particle properties of nuclei
= > Similar configurations = large overlap of wave functions = Large probability of transfer reaction



Applications

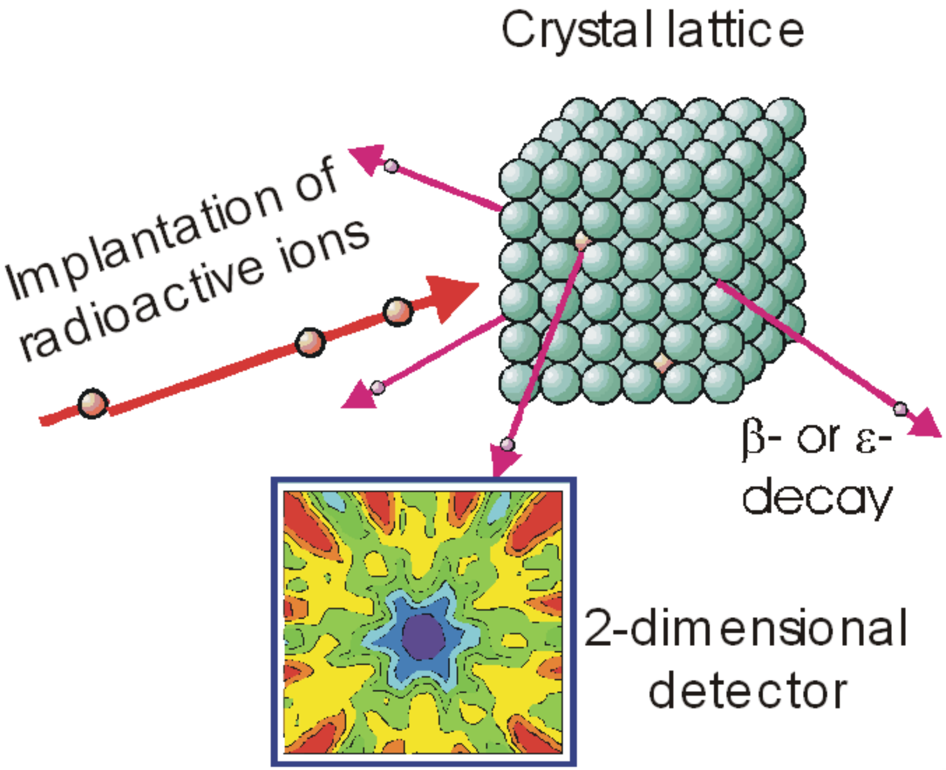
- Use known radiation from not totally exotic radioisotopes

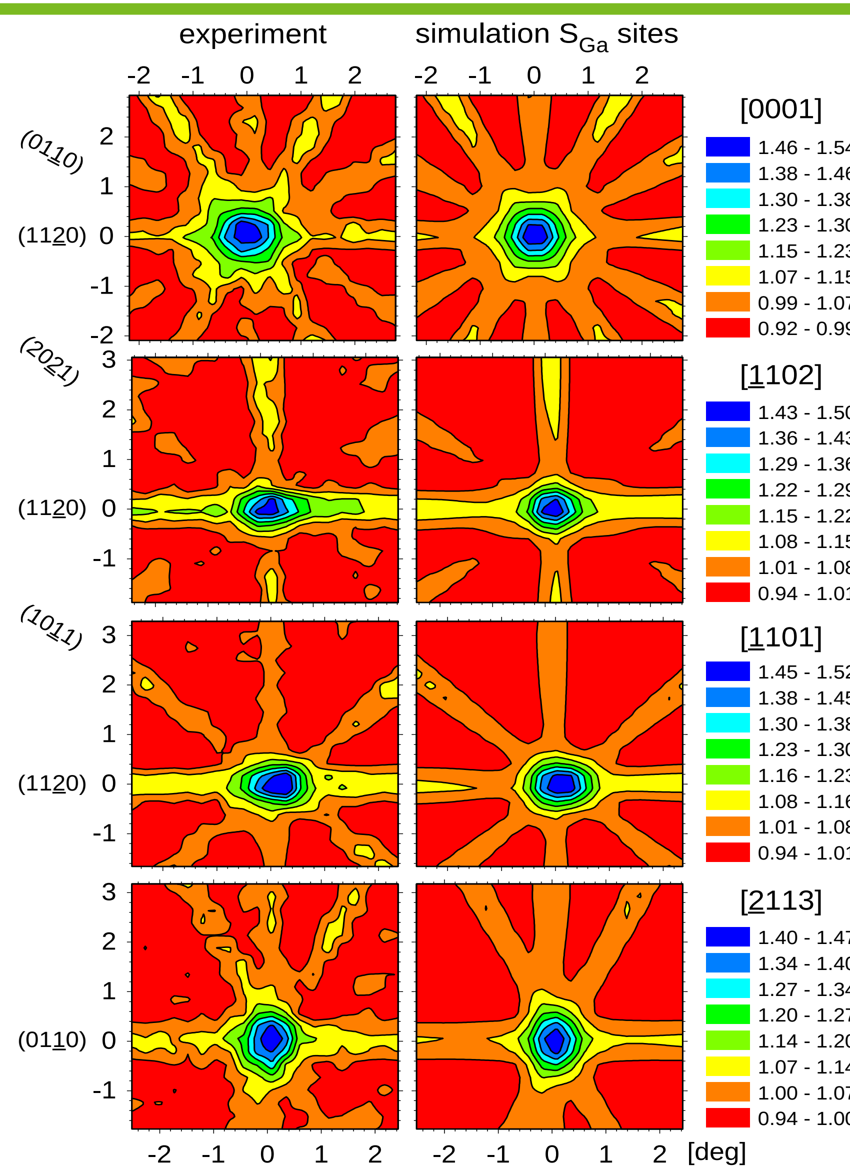
- Profit from radionuclides:
  - Pure samples of radioisotopes (offline studies)
  - High detection efficiency for radiation (online studies)

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

Material science

- Emission channeling
  - ➢ Position of implanted ions

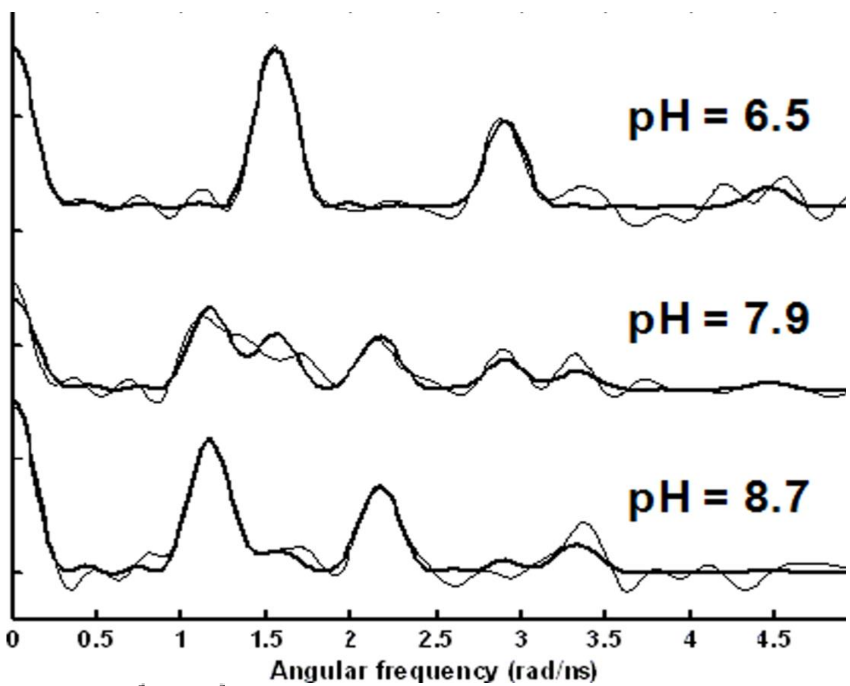


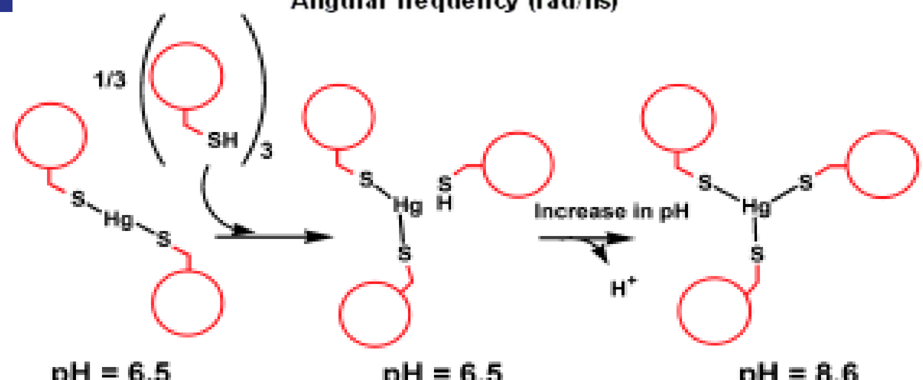


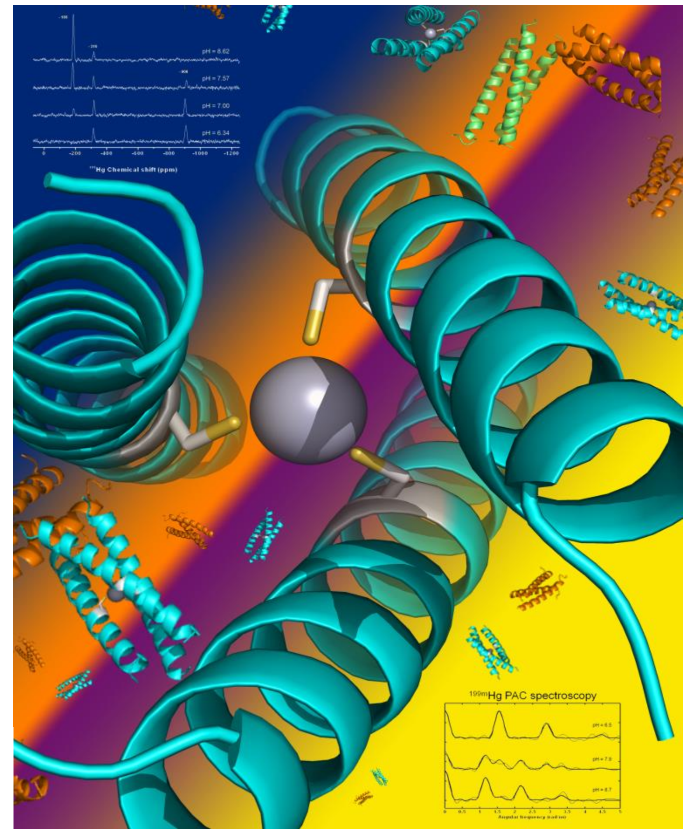
Emission channelling pattern

Heavy-ion toxicity

- Studied with Perturbed Angular Correlation method







Vibenholt J et al, Inorg. Chem (2012)

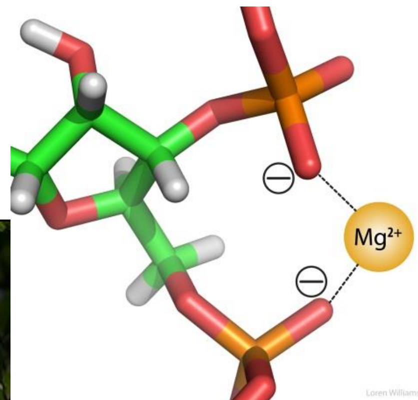
Biophysics and Parkinson disease

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

➢ Magnesium

Catalysis in cellular energy transformations

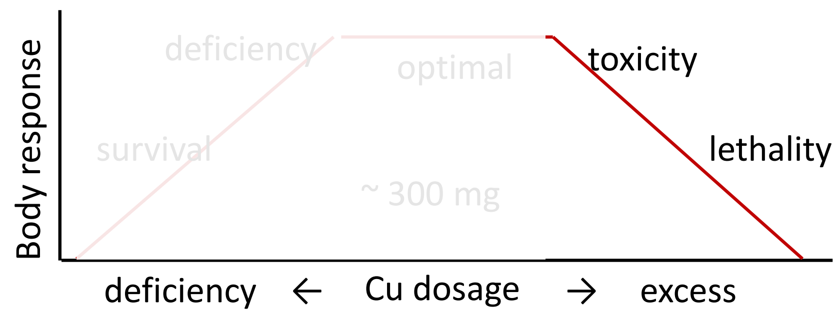
Photosynthesis - component of chlorophyll

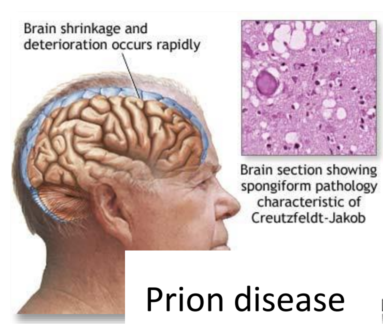


➢ Copper


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

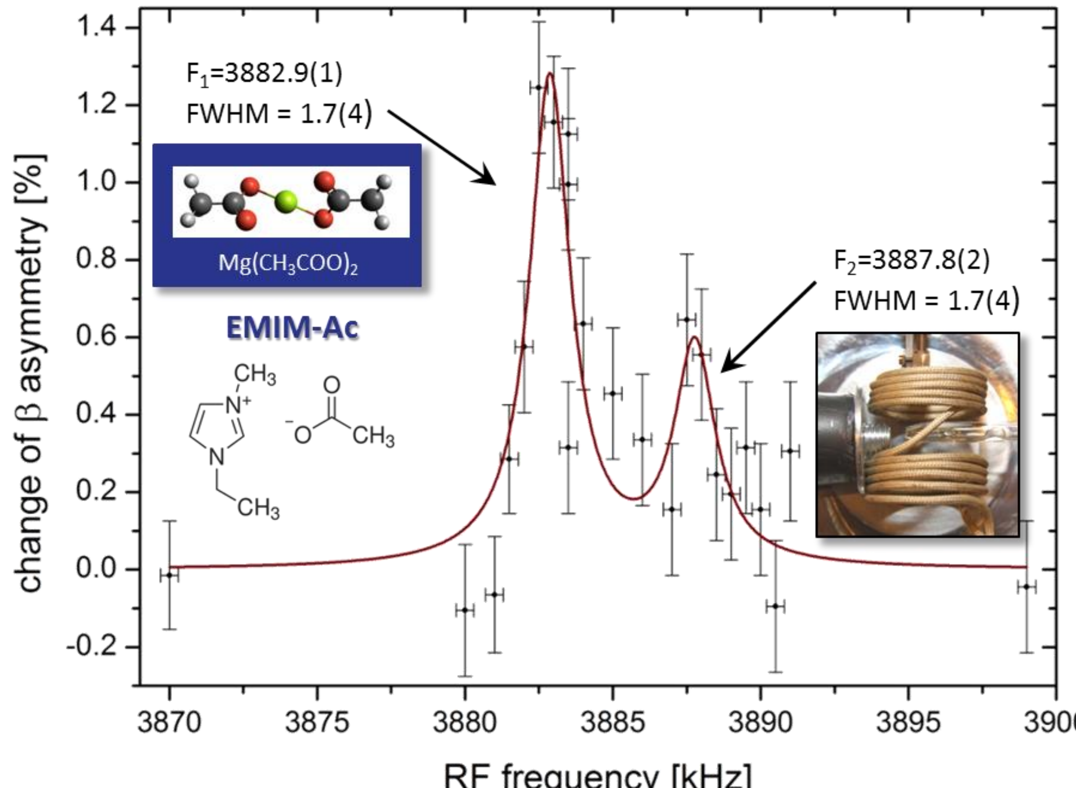
- New approach – **beta-Nuclear Magnetic Resonance**
  - Beta-decay of polarized nuclei is anisotropic
  - Resonances observed as change in decay asymmetry

  ⇒ **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:
  - First biological studies on Mg and Cu

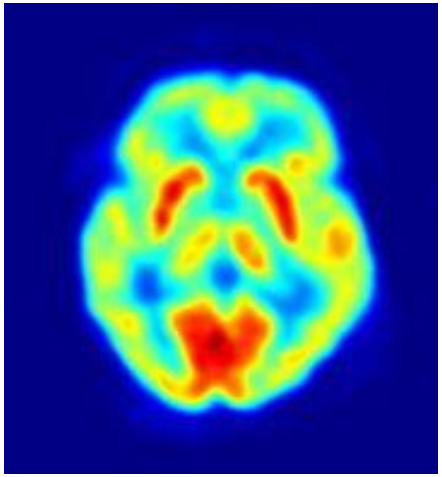


A. Gottberg, M. Stachura, M. Kowalska, et al, ChemPhysChem 15, 3929 (2014)

Soon be continued within MK'EU ERC Starting Grant

new PET isotopes

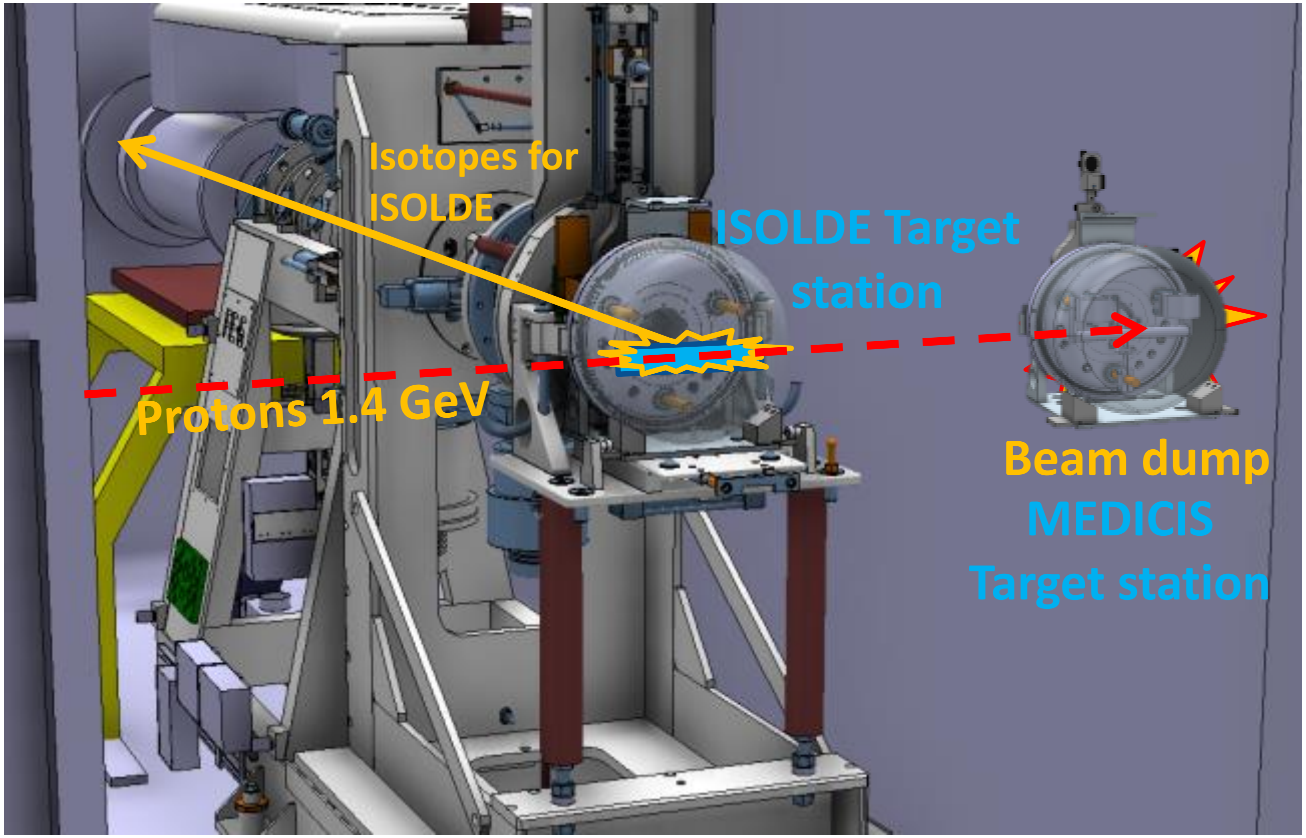
- PET (positron emission tomography) – uses β+ emitting nuclei and their annihilation inside the body in diagnosis and therapy
- Produced at ISOLDE and later investigated together with the creators of the PET technique at the Geneva Hospital



Applications: MEDICIS at ISOLDE

Production of medical isotopes for trials (not commercial use) via ISOLDE “dump” protons

-> little ISOLDE + chemical preparation



Use protons (~90%) normally lost into the **Beam Dump**

New medical isotopes

Collection at ISOLDE

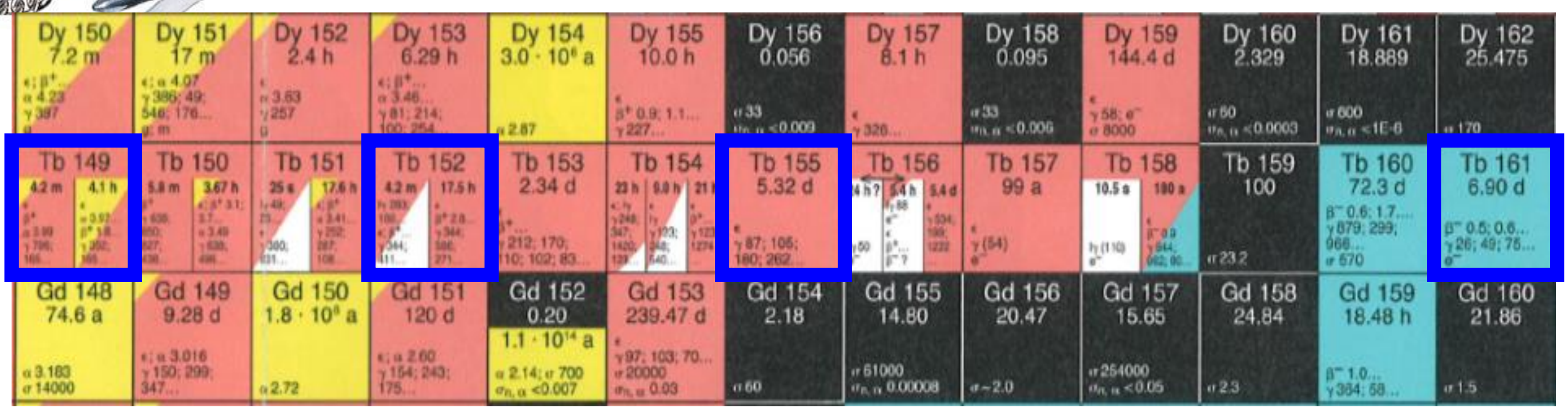
Radiochemical purification and labeling

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

A visit to ISOLDE ?

CONTACT Kara Lynch by end of this week latest

kara.marie.lynch@cern.ch

THE FIRST 24 PERSONS THAT SIGN UP
WILL GET A GUIDED TOUR

Already registered:

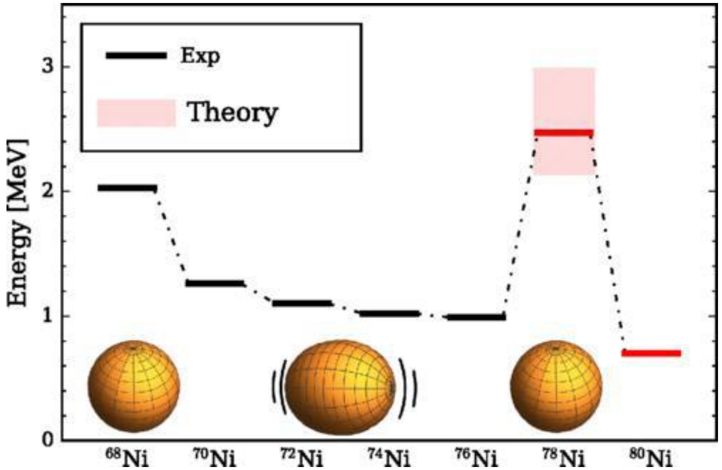
Maisam Pyarali
Etienne Fayen
Lauren Weiss

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

VISIT: Kara Lynch
kara.marie.lynch@cern.ch
Only first 24 applicants!

Nuclear moments and spins near exotic (doubly magic?) ^{78}Ni



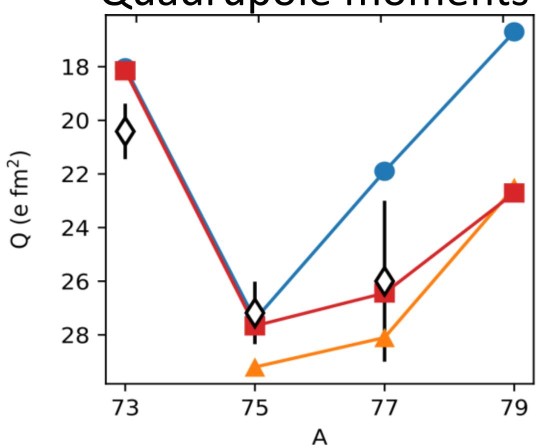
Theoretical models predict ^{78}Ni is doubly magic

Closest we can get: **^{78}Cu** = ^{78}Ni –p –n

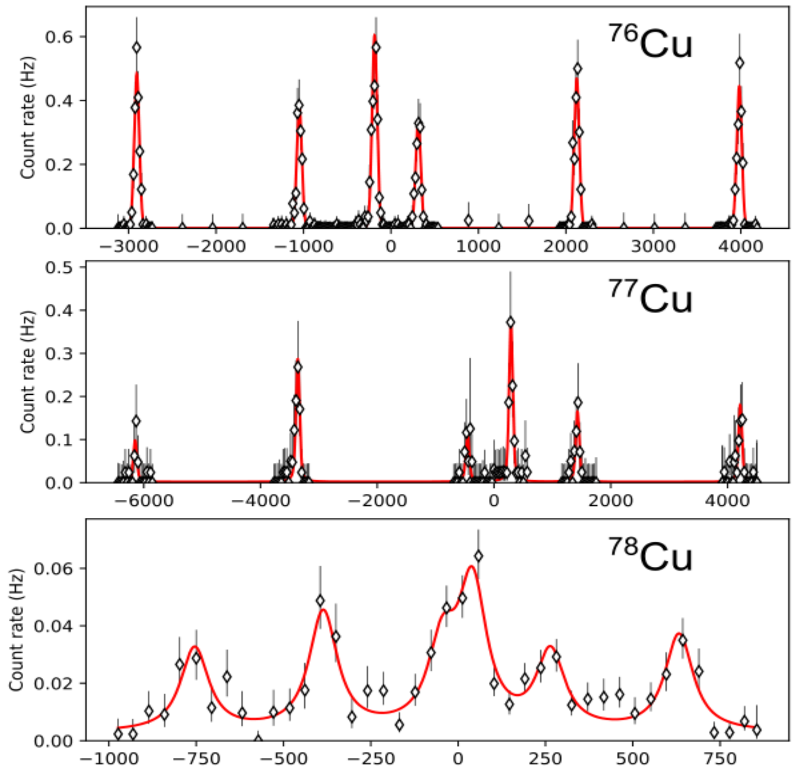
20 ions/s produced at ISOLDE

➔ To measure shape: need CRIS !

Quadrupole moments



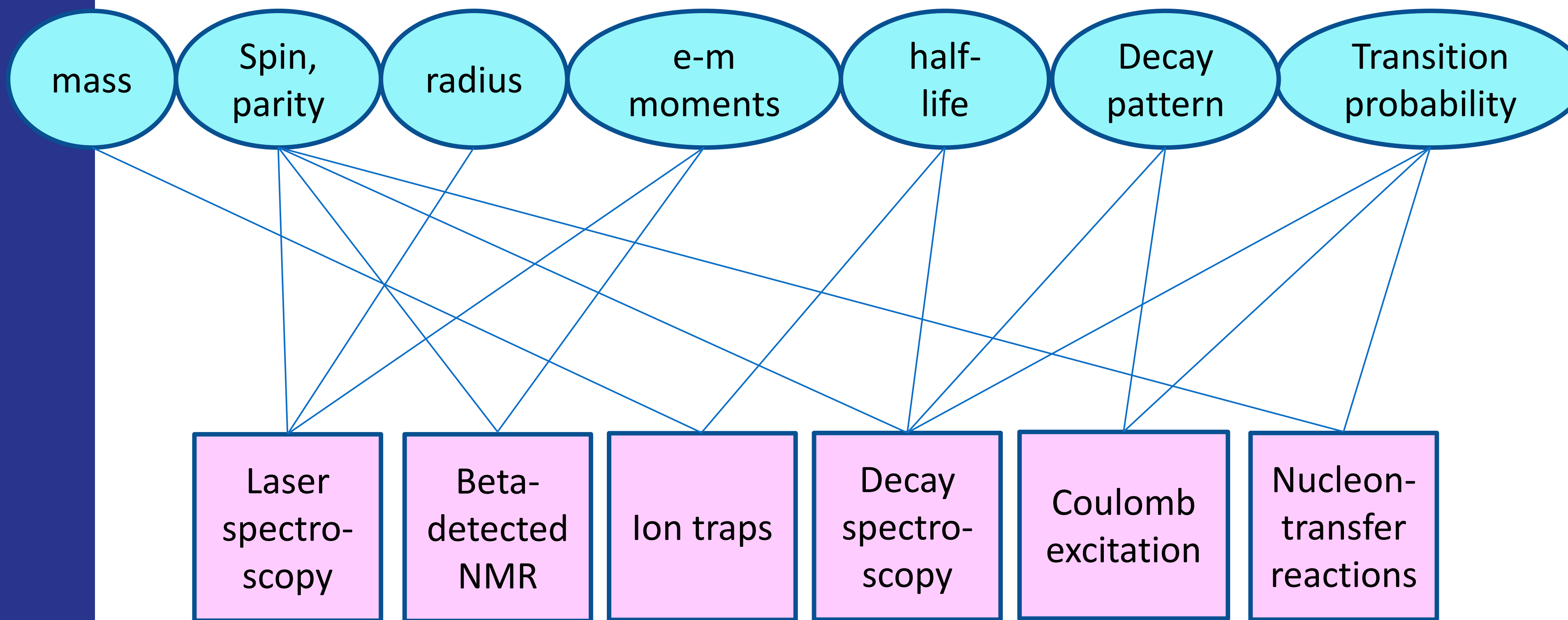
→ TEST MODERN THEORIES



R.P. de Groote et al., submitted to Phys Rev Lett.

Studies of radioactive nuclides

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

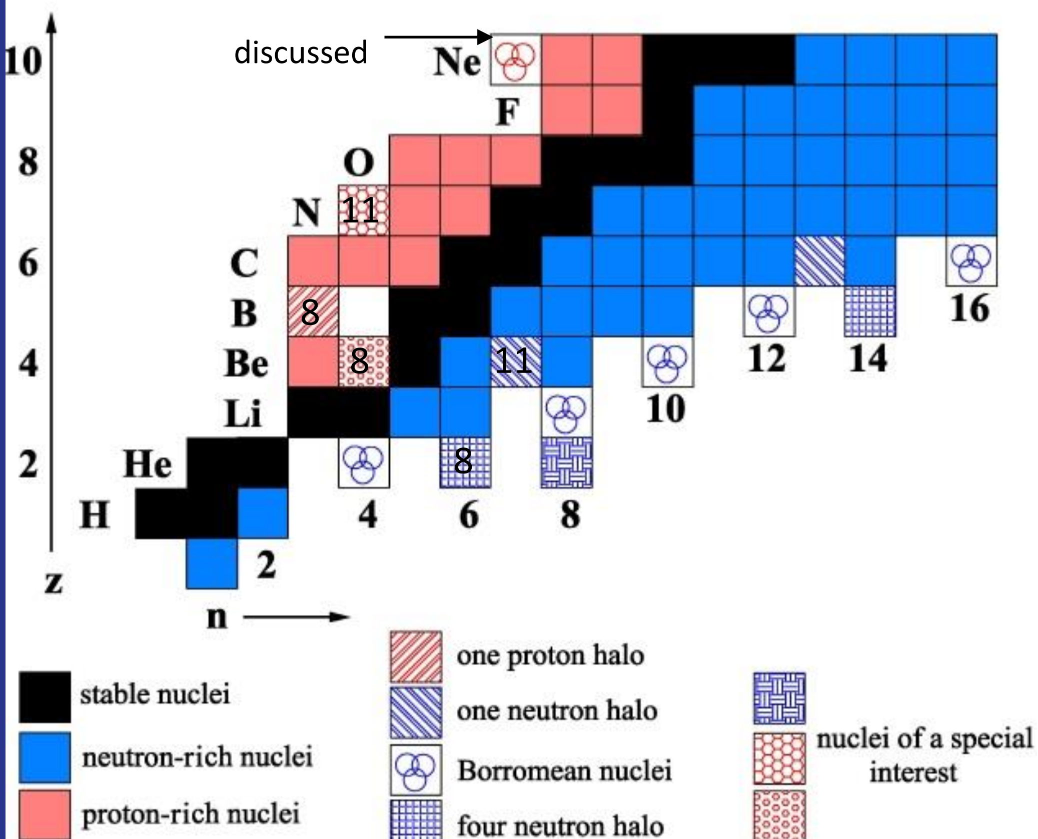


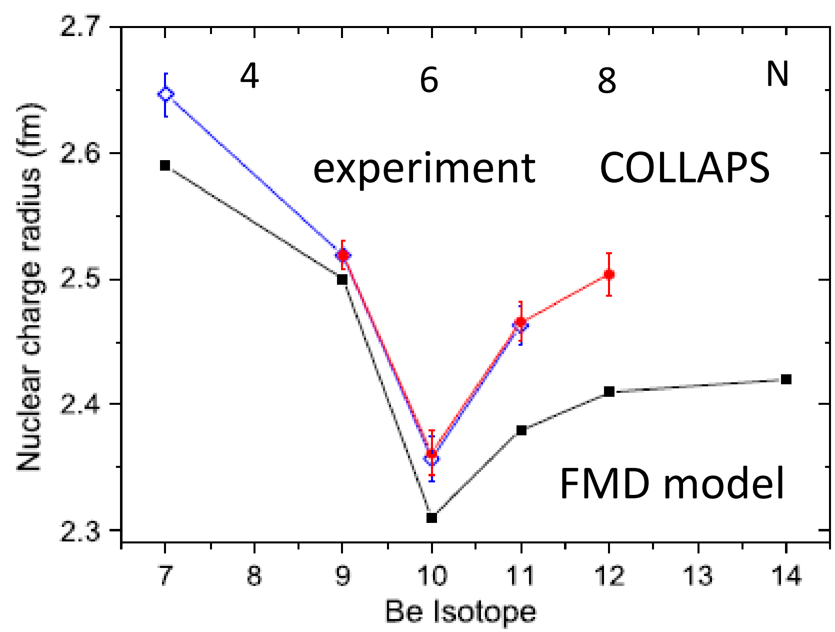
Techniques/ devices

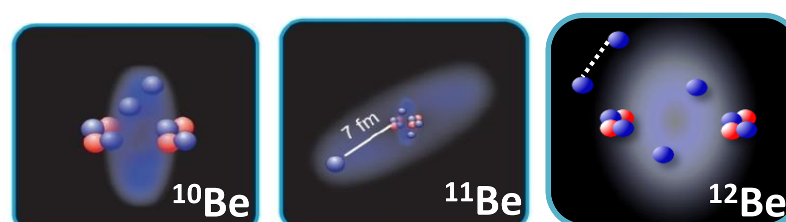
To obtain the full picture: need to study several properties and use several techniques

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

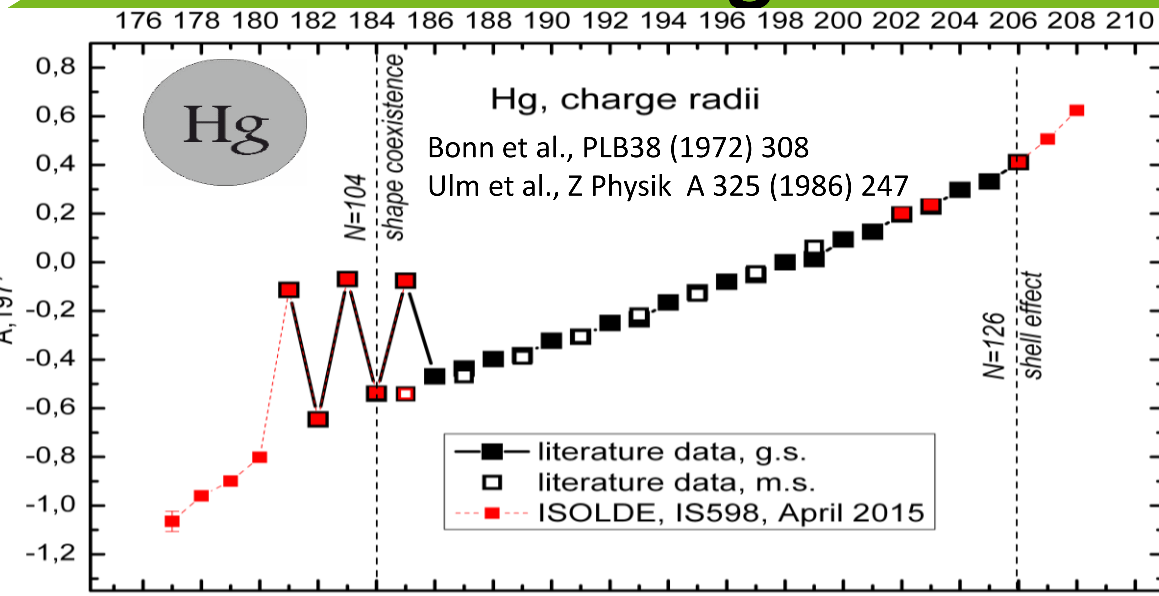






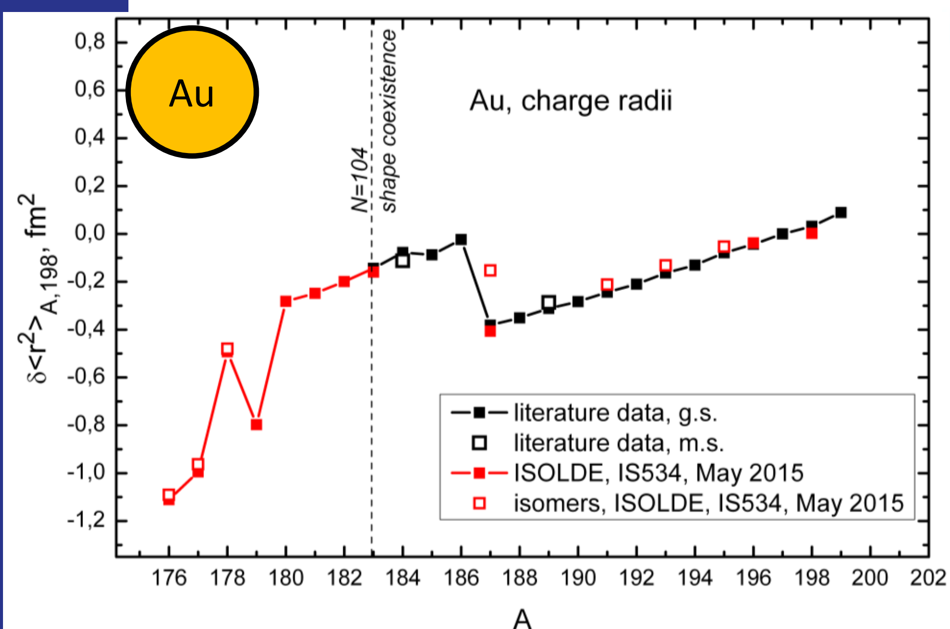
A. Krieger et al,
Phys. Ref. Lett. 108 (2012) 142501

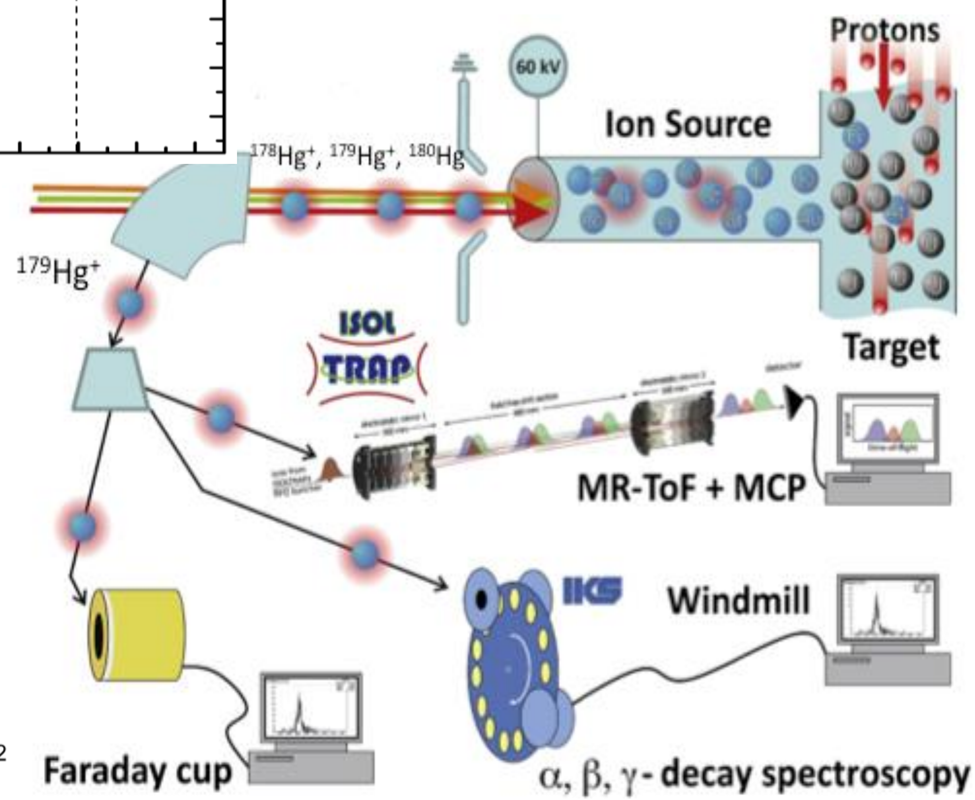
Combination of techniques: Charge radii of Hg & Au



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]

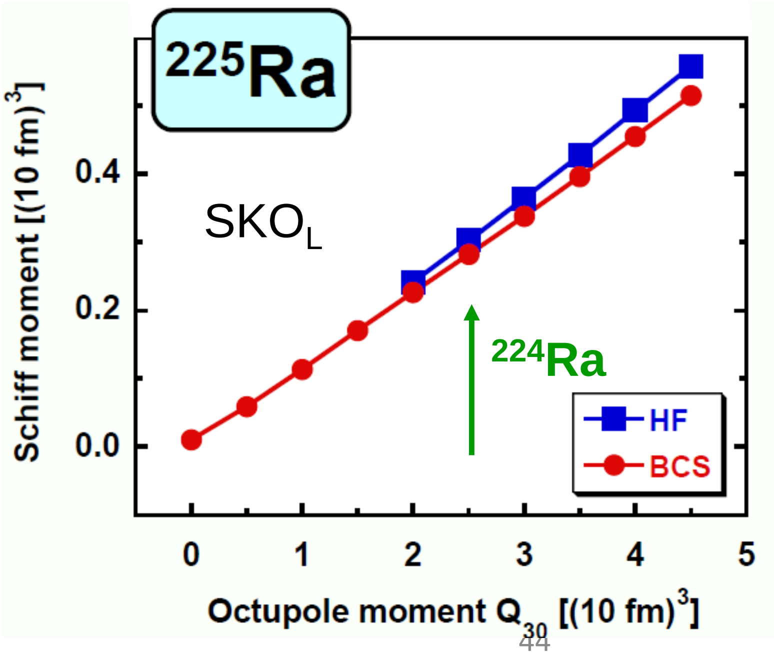
odd-*A* Ra [Groningen]

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

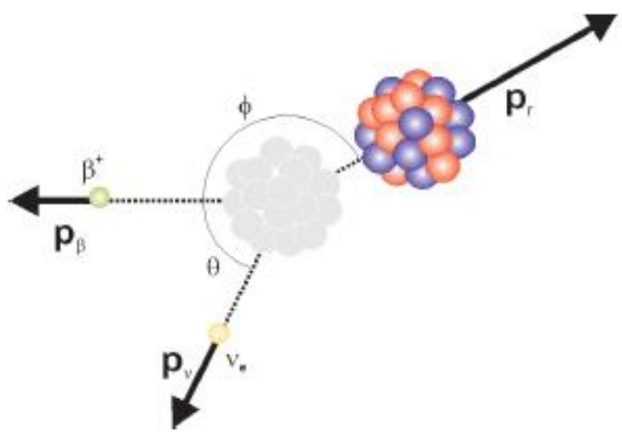
$$H_\beta = H_S + H_V + H_T + H_A + H_P$$

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

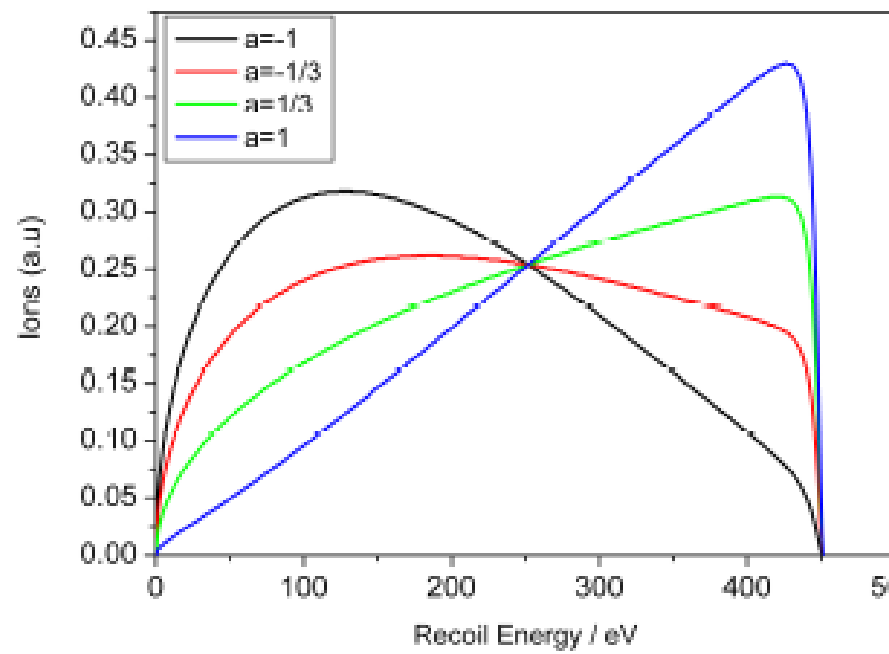
$$a \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

Angular distribution of β radiation

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



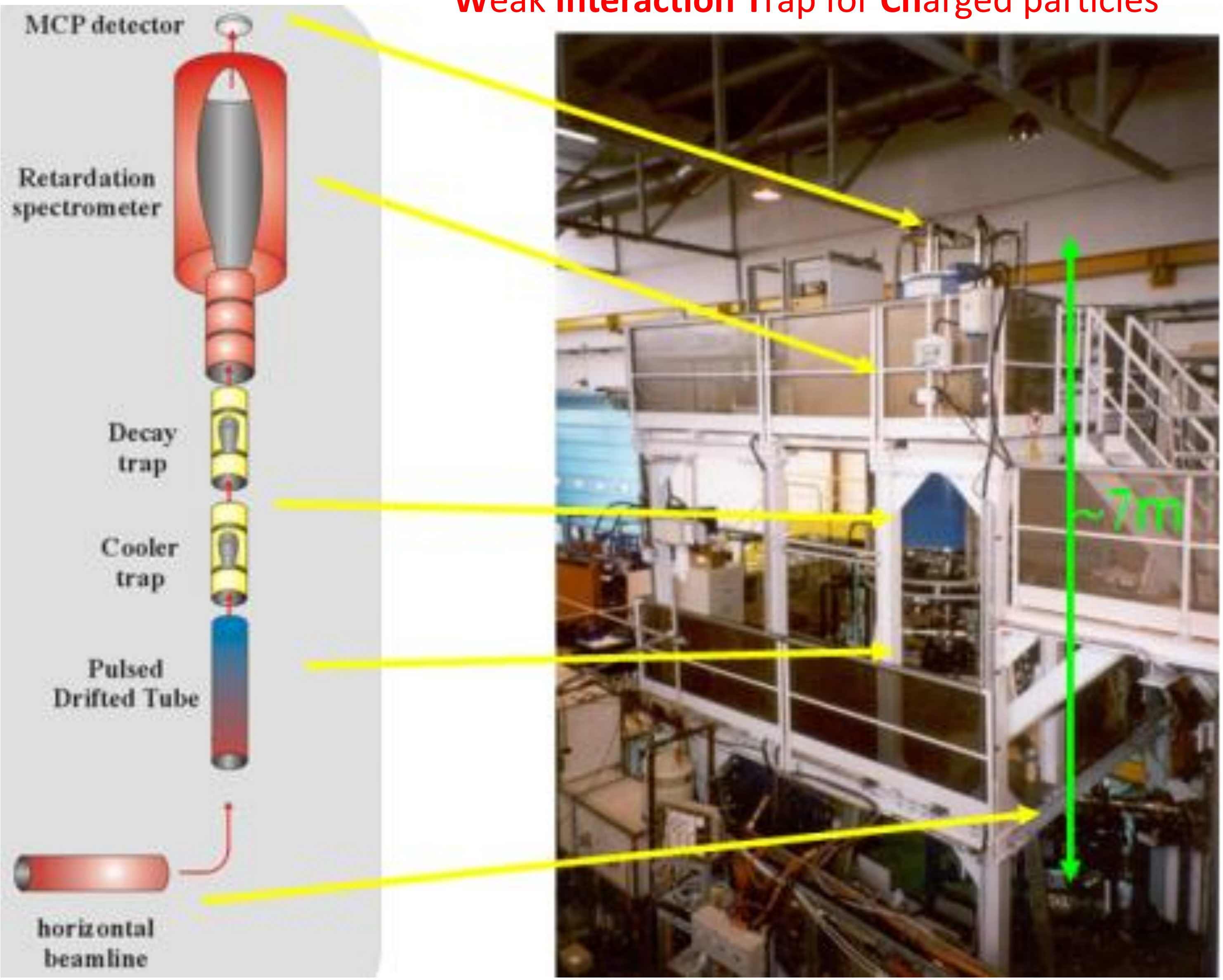
Simulated ion recoil for different *a*



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

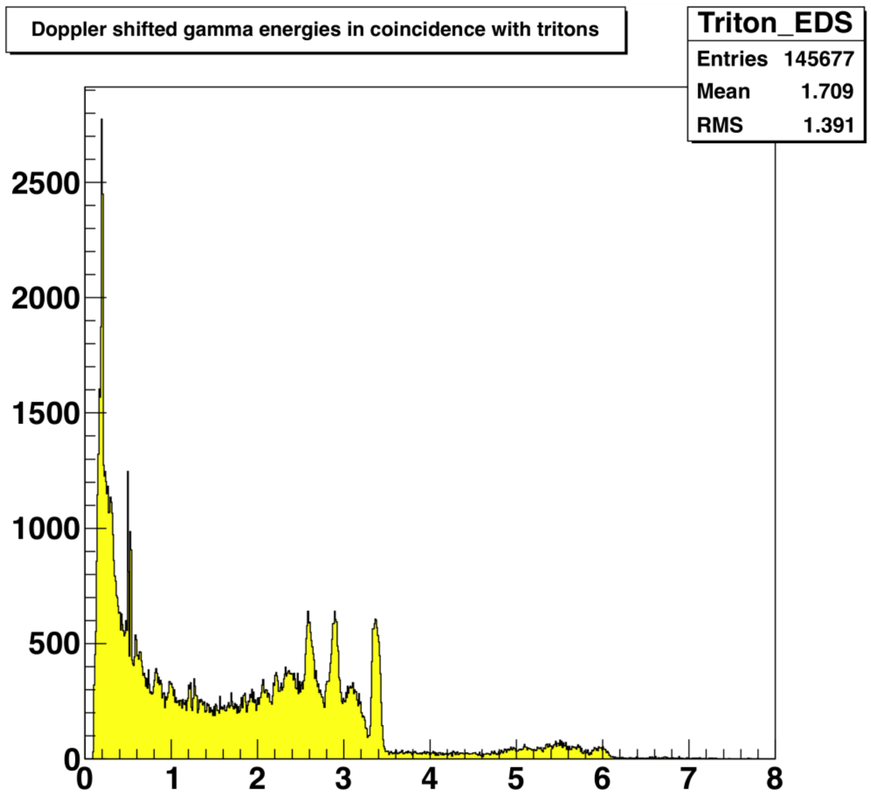
WITCH

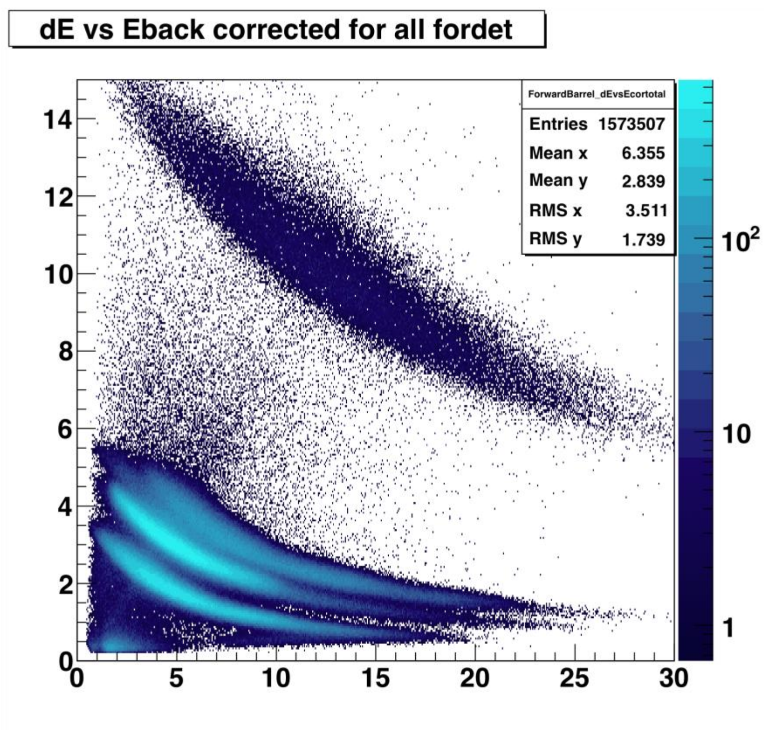
Weak **Interaction** **T**rap for **Ch**arged particles



Transfer reactions on beryllium-11

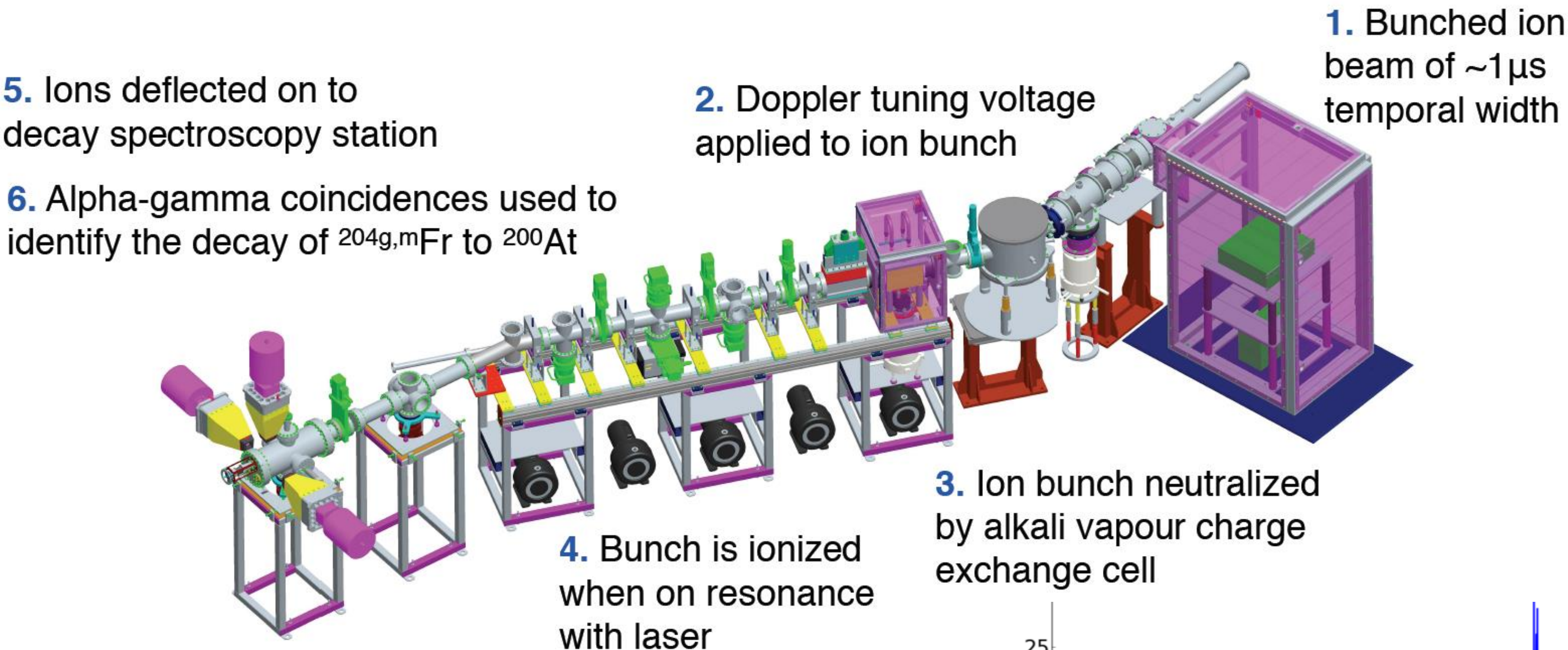
- 11Be:
  - Halo nucleus
  - Cluster structures in neighbours
  - N=8 broken in 12Be

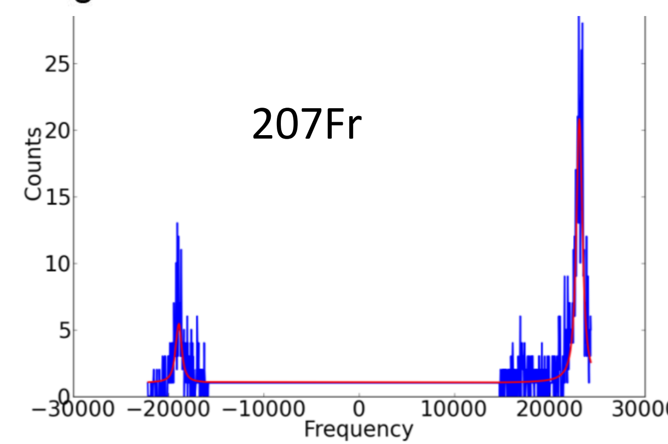




CRIS

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

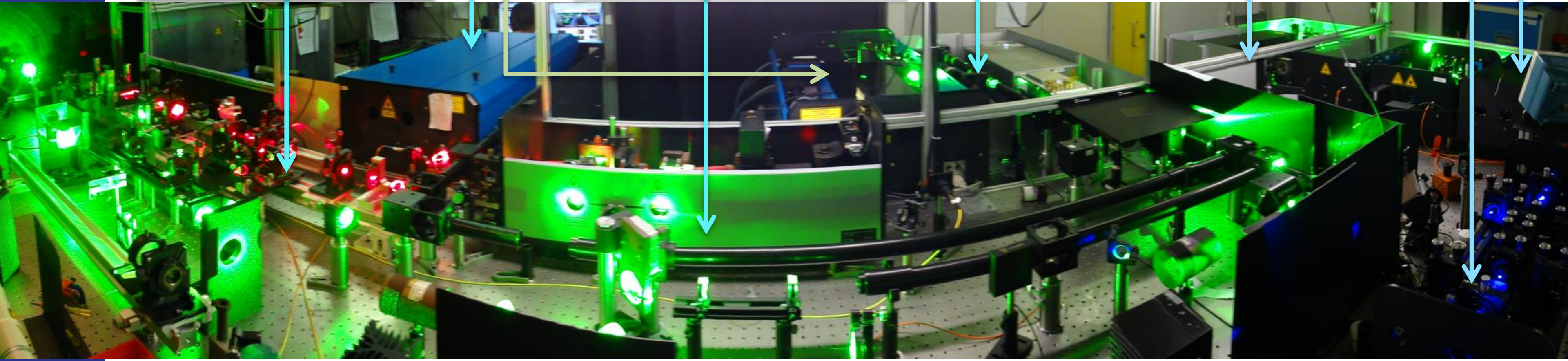




Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes

RILIS

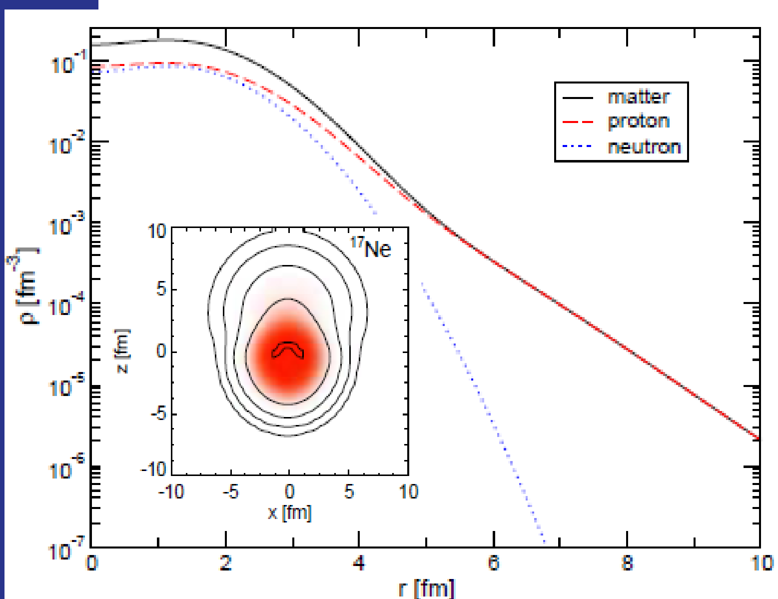
- Resonant Ionization Laser Ion Source

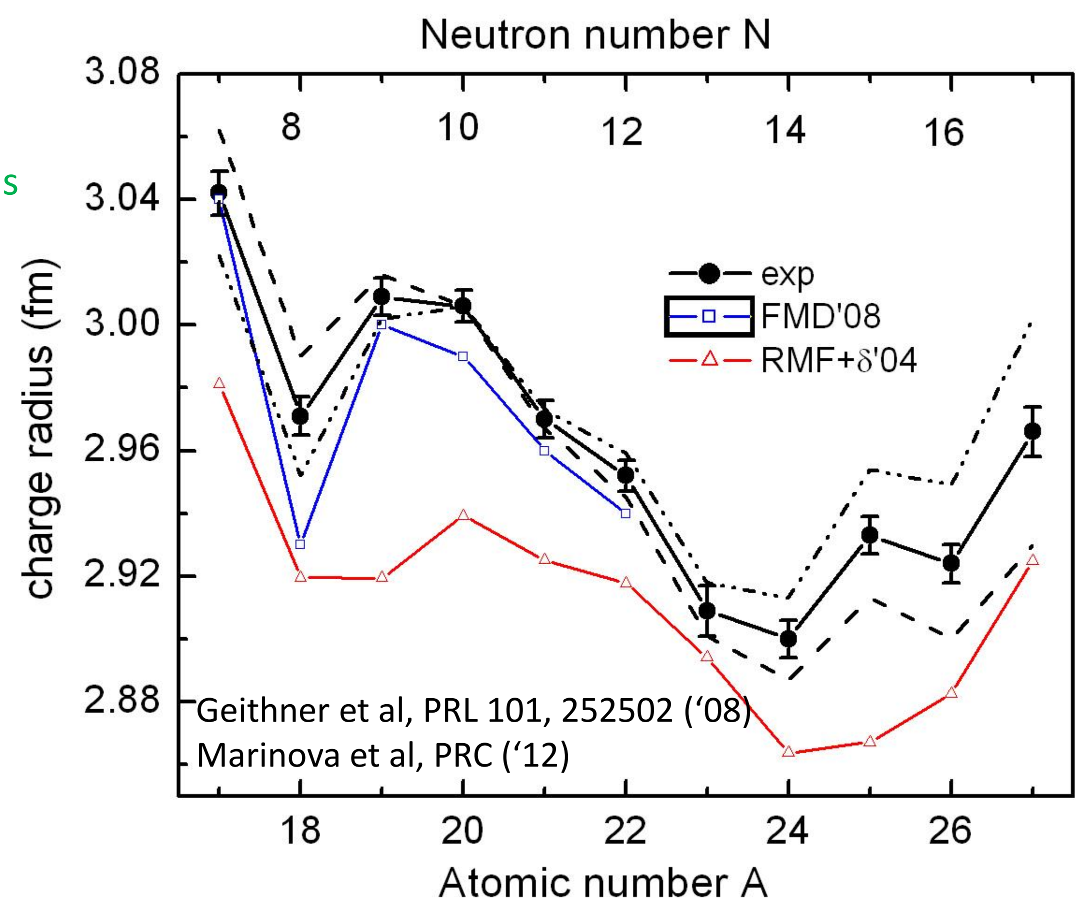


COLLAPS – Ne charge radii

Laser spectroscopy

Intrinsic density distributions of dominant proton FMD configurations

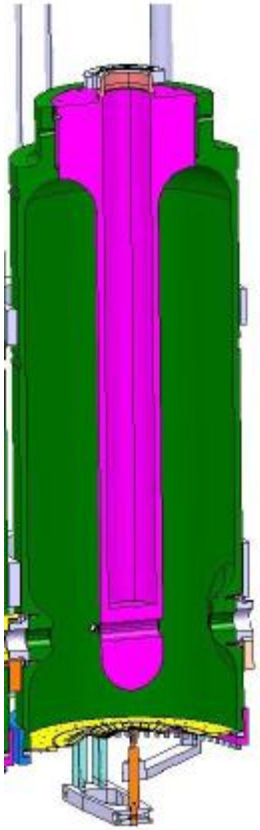




HIE-ISOLDE

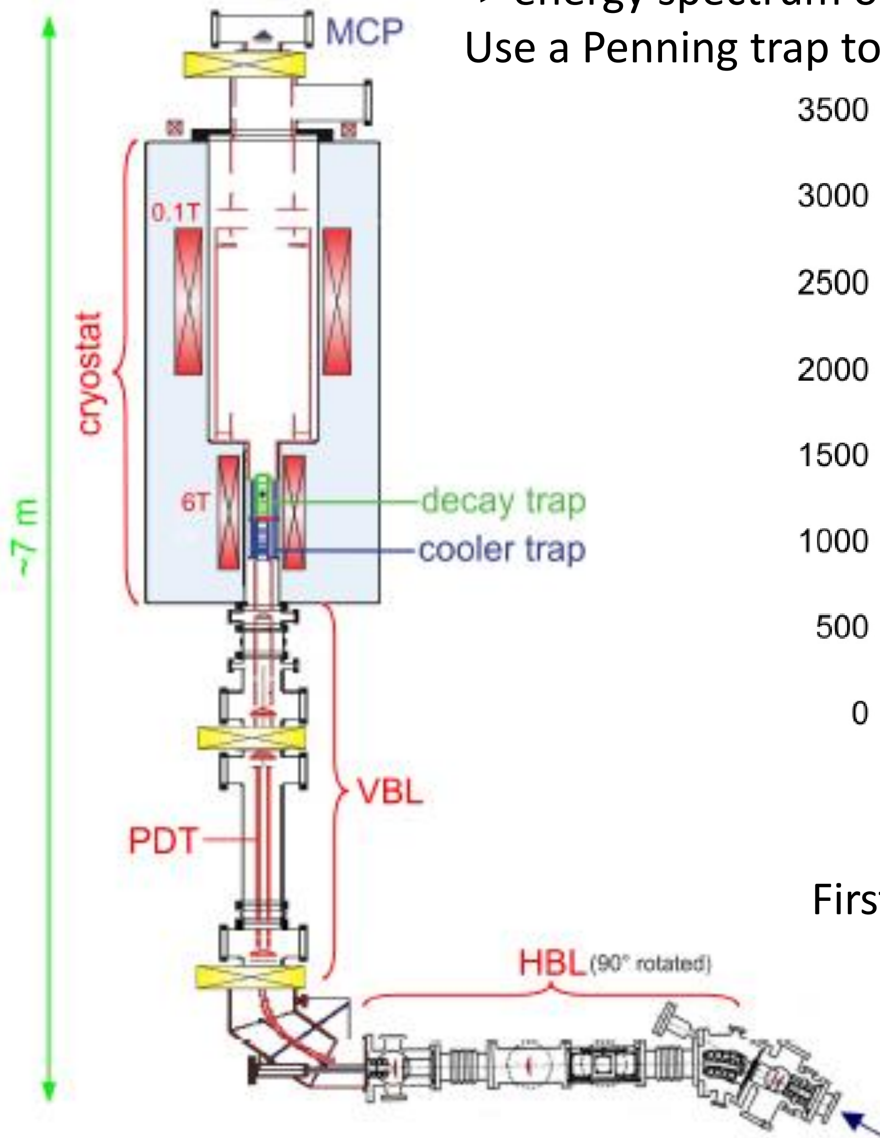
Quarter-wave resonators
(Nb sputtered)

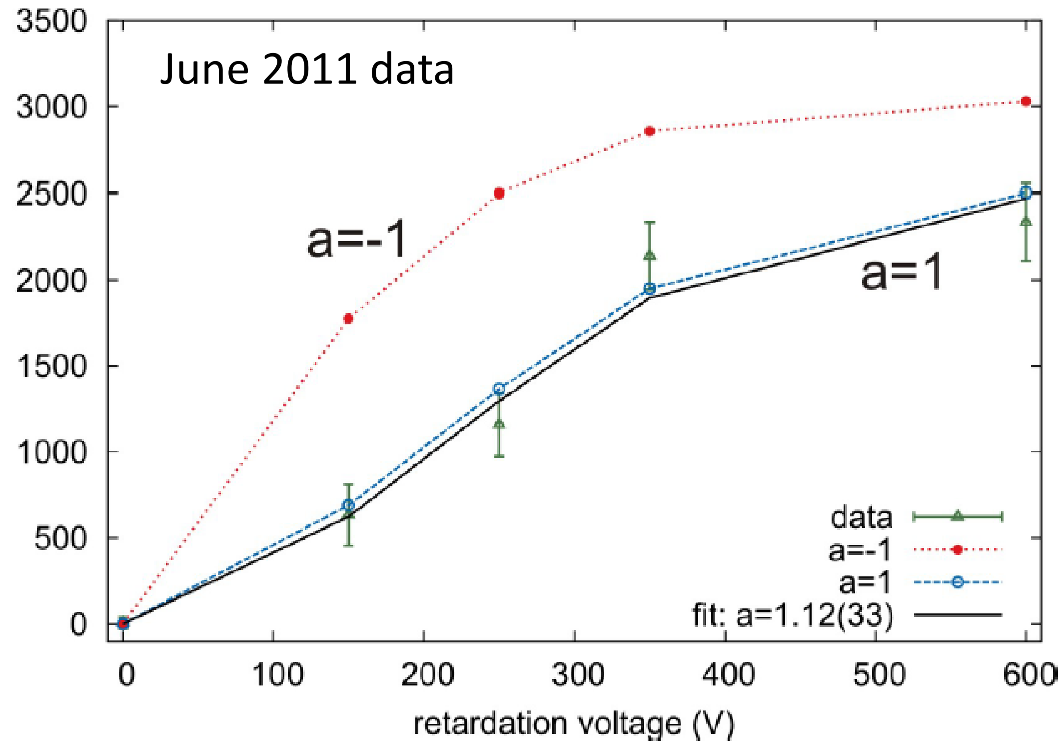
- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ β_0=10.3% and 12@ β_0=6.3%)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase fs= -20 deg
- 2.5<A/q<4.5 limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal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



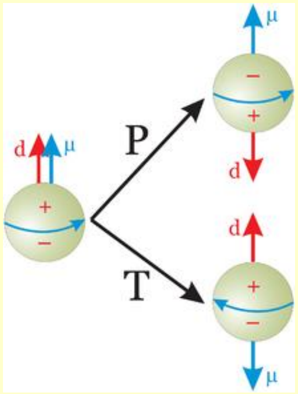


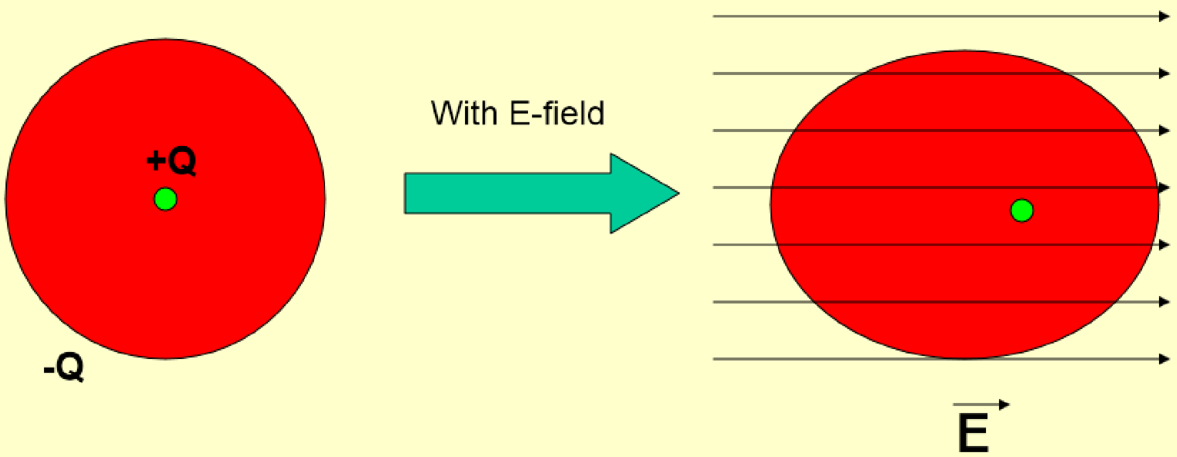
First high-statistics run in Nov 2011: under analysis

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

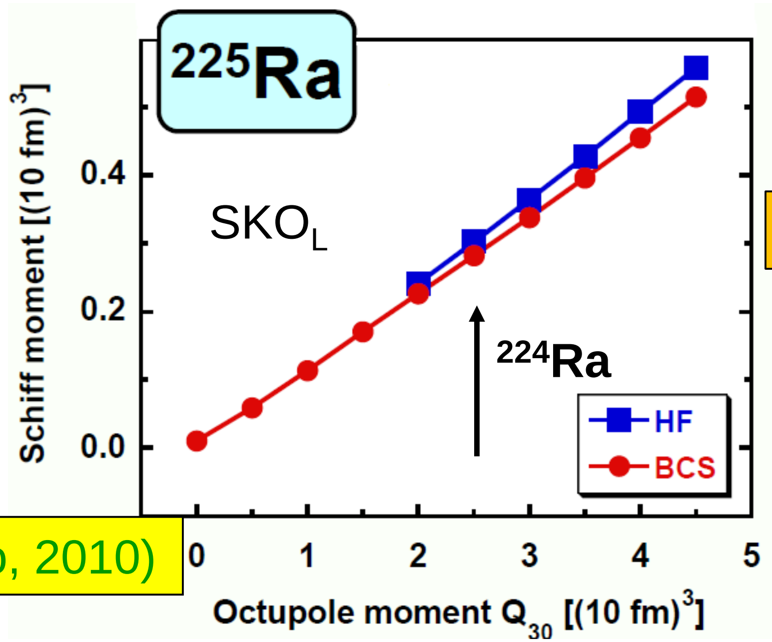
P,T-violating n-n interaction

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]

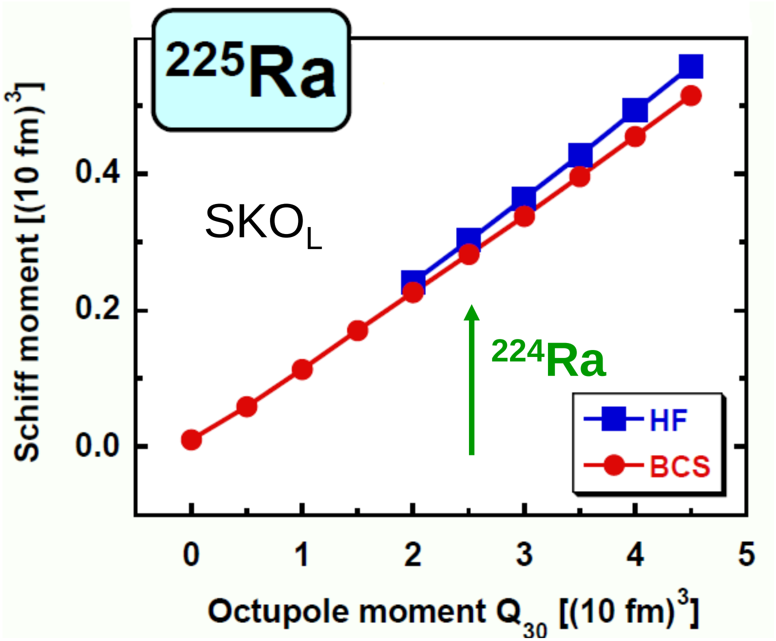
odd-*A* Ra [Groningen]

odd-*A* Rn:

^{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

EDM

In units of *e–cm*, selected EDM limits are:

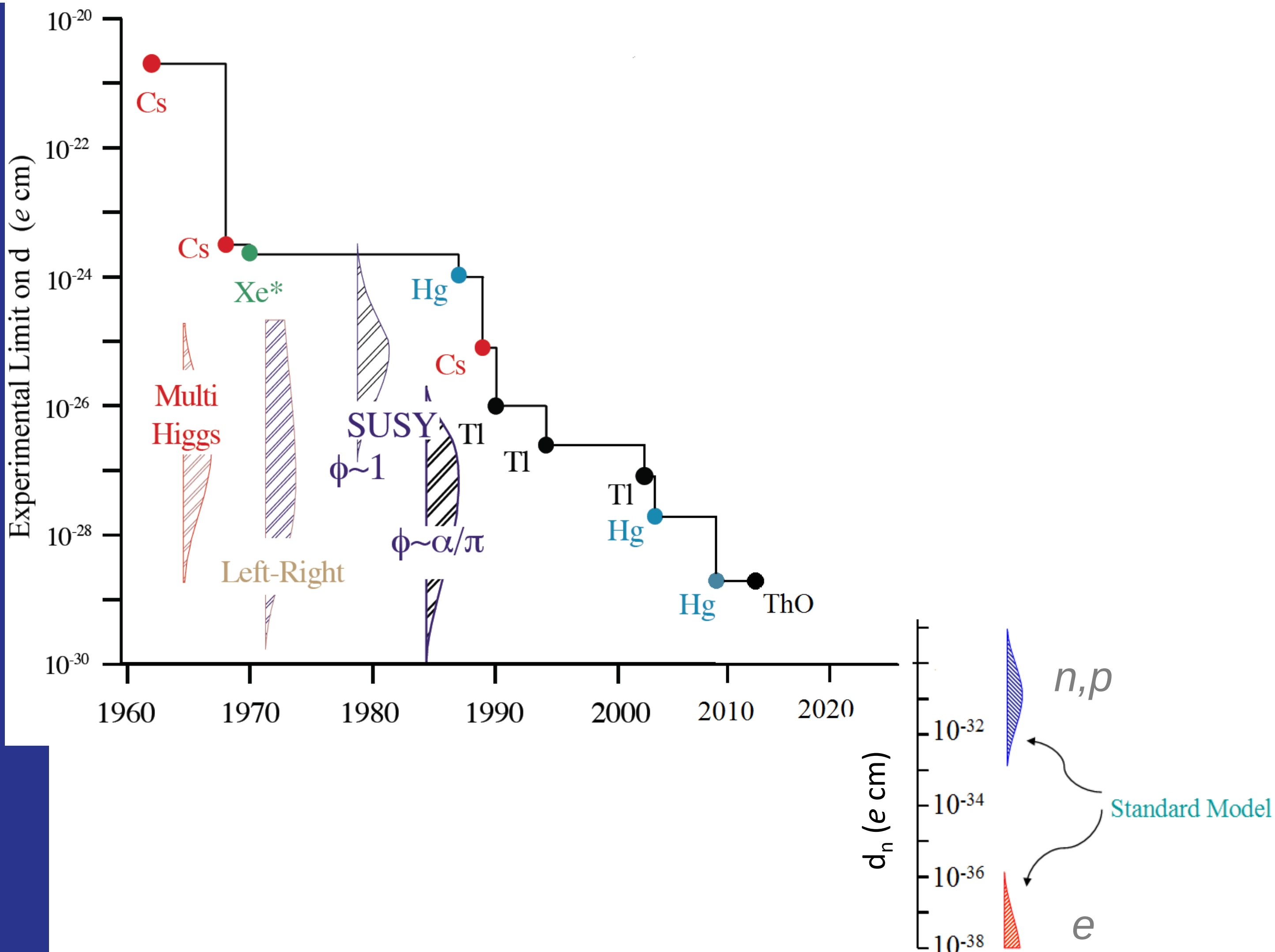
Particle	EDM limit	System	SM Prediction	New Physics
e	1.9×10^{-27}	^{205}Tl atom	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}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

A non-exhaustive list:

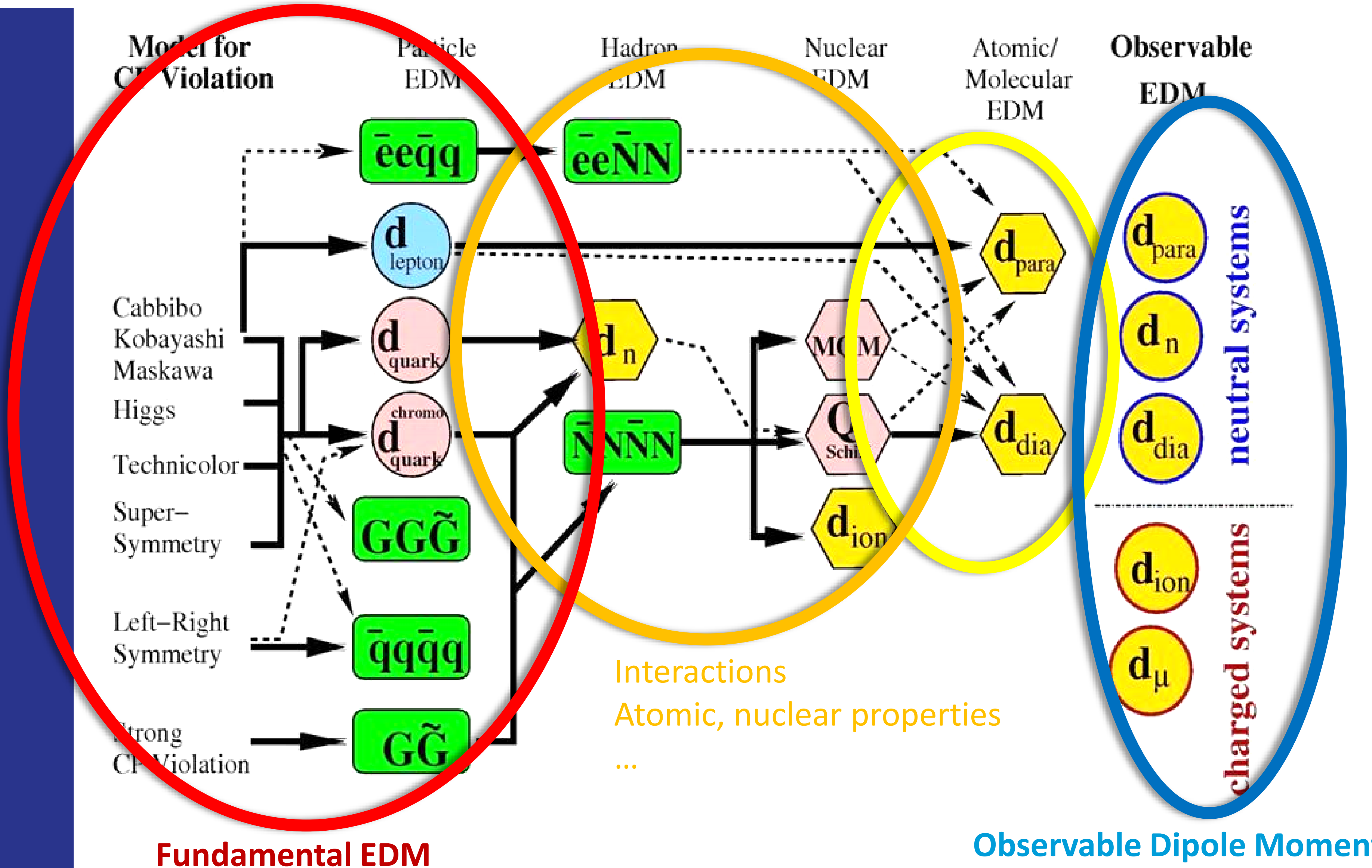
Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (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*



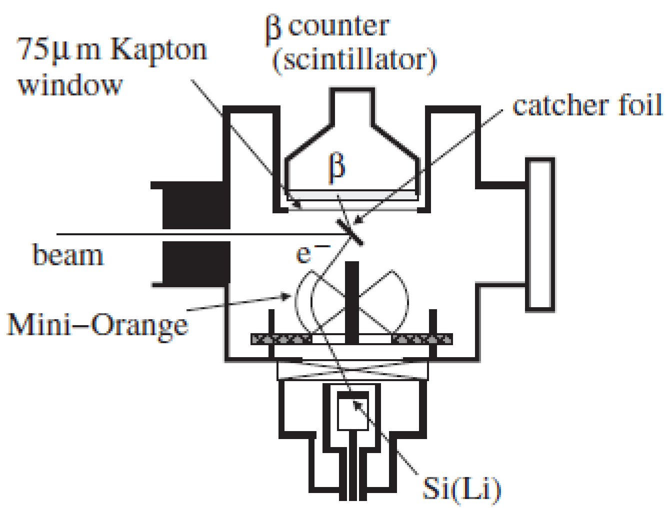
Experimental Limit on d (e cm)
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
1960
1970
1980
1990
2000
2010
2020
Cs
Cs
Xe*
Hg
Cs
Tl
Tl
Tl
Hg
Hg
ThO
Multi Higgs
Left-Right
SUSY
$\phi \sim 1$
$\phi \sim \alpha/\pi$
d_n (e cm)
10^{-32}
10^{-34}
10^{-36}
10^{-38}
n,p
e
Standard Model



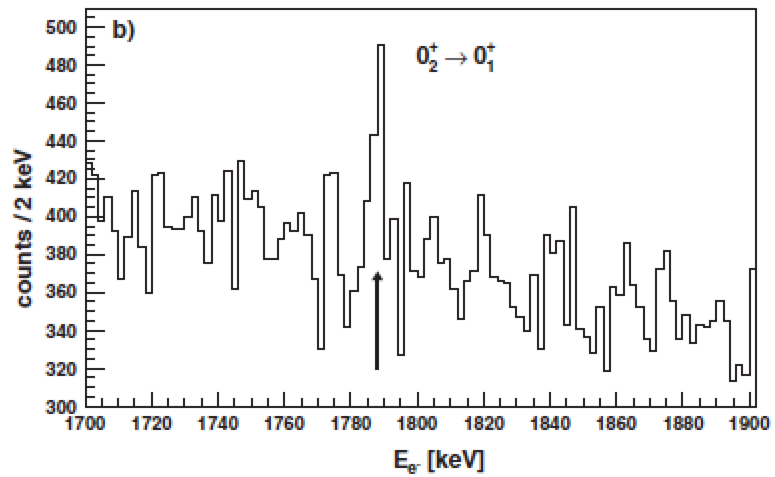
Model for CP Violation
Particle EDM
Hadron EDM
Nuclear EDM
Atomic/ Molecular EDM
Observable EDM
Cabbibo Kobayashi Maskawa
Higgs
Technicolor
Super–Symmetry
Left–Right Symmetry
Strong CP Violation
eeqq
eeNN
d lepton
d quark
chromo d quark
GGG
qqqq
GG
d n
NNNN
MQM
Q Schiff
d ion
d para
d dia
d para
d n
d dia
neutral systems
d ion
d μ
charged systems
Interactions
Atomic, nuclear properties
…
Fundamental EDM
Observable Dipole Moment

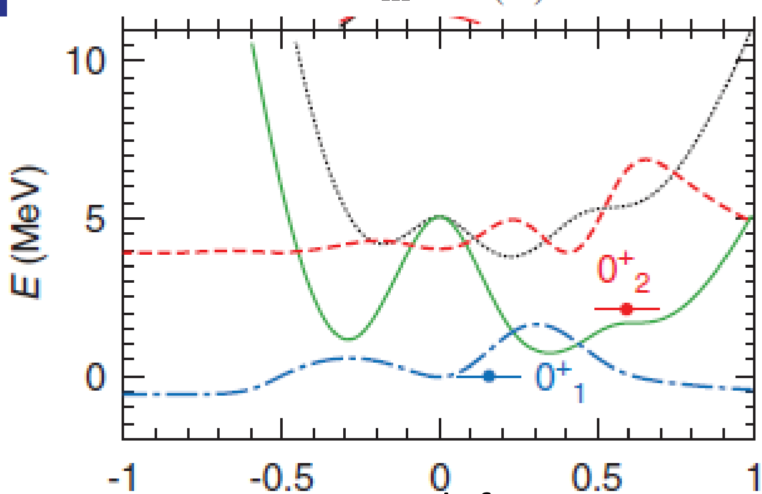
30Mg: E0 transition

E0 decay of 30Mg
electron spectrometer



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





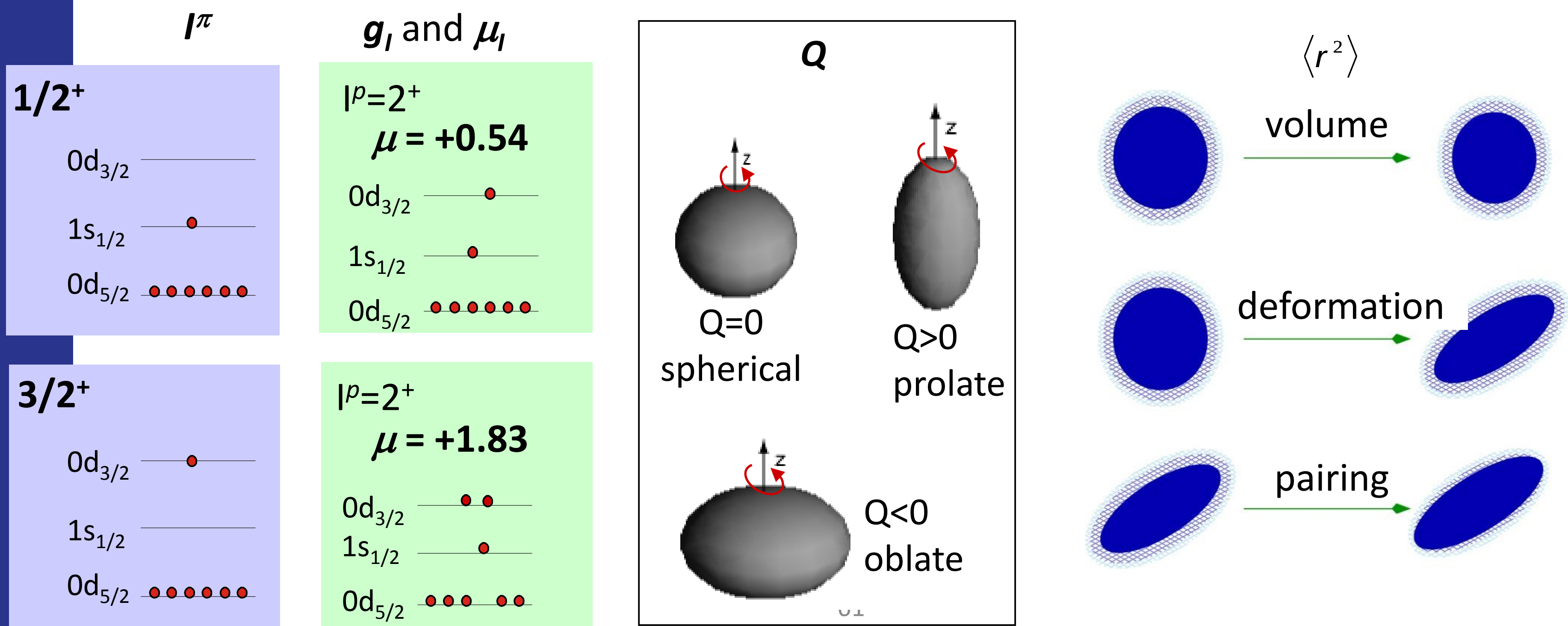
30Mg: spherical 0+ground-state, deformed 1st 0+ state (2 neutrons across N=20) => **shape coexistence**

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



Laser spectroscopy

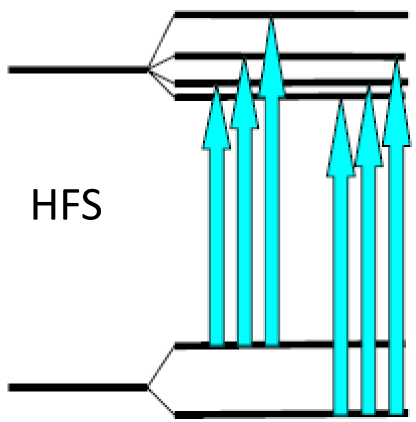
Atomic **hyperfine structure**

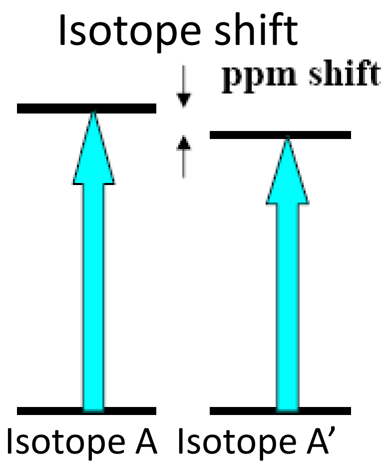
(interaction of nuclear and atomic spins)

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

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 shifts in atomic transitions

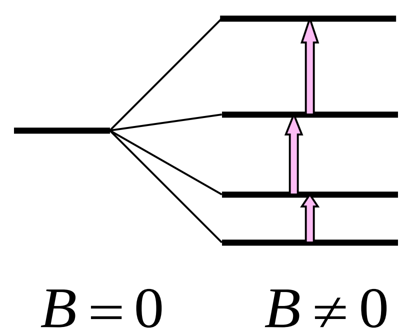
(change in mass and size of different isotopes of the same chemical element)

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

Nuclear Magnetic Resonance – NMR

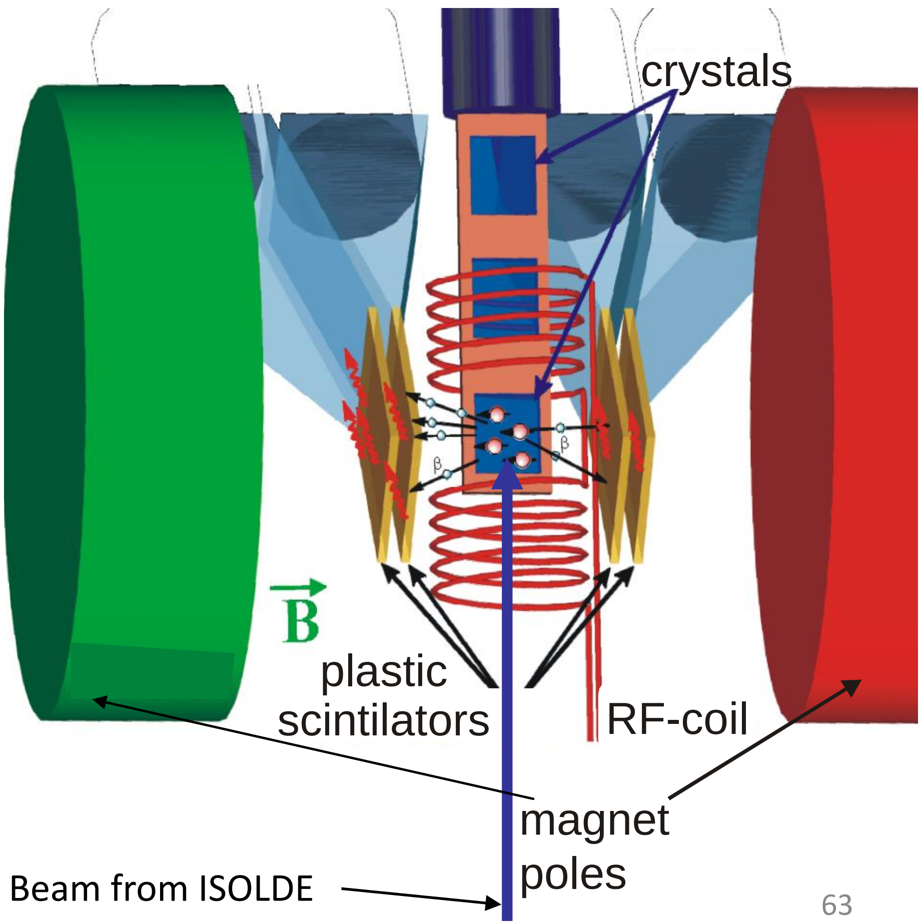
(Zeeman splitting of nuclear levels)

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



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)

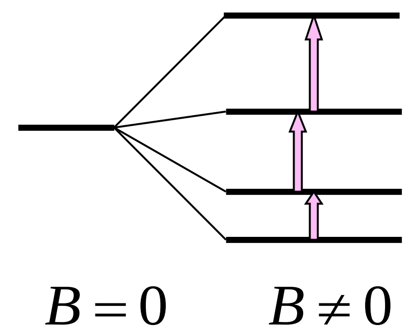


Measured asymmetry:

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

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

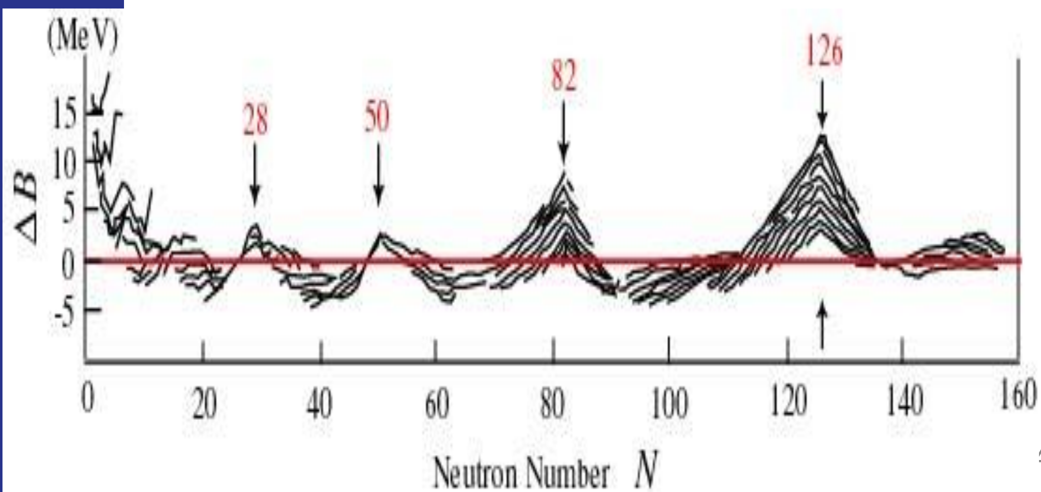
$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$

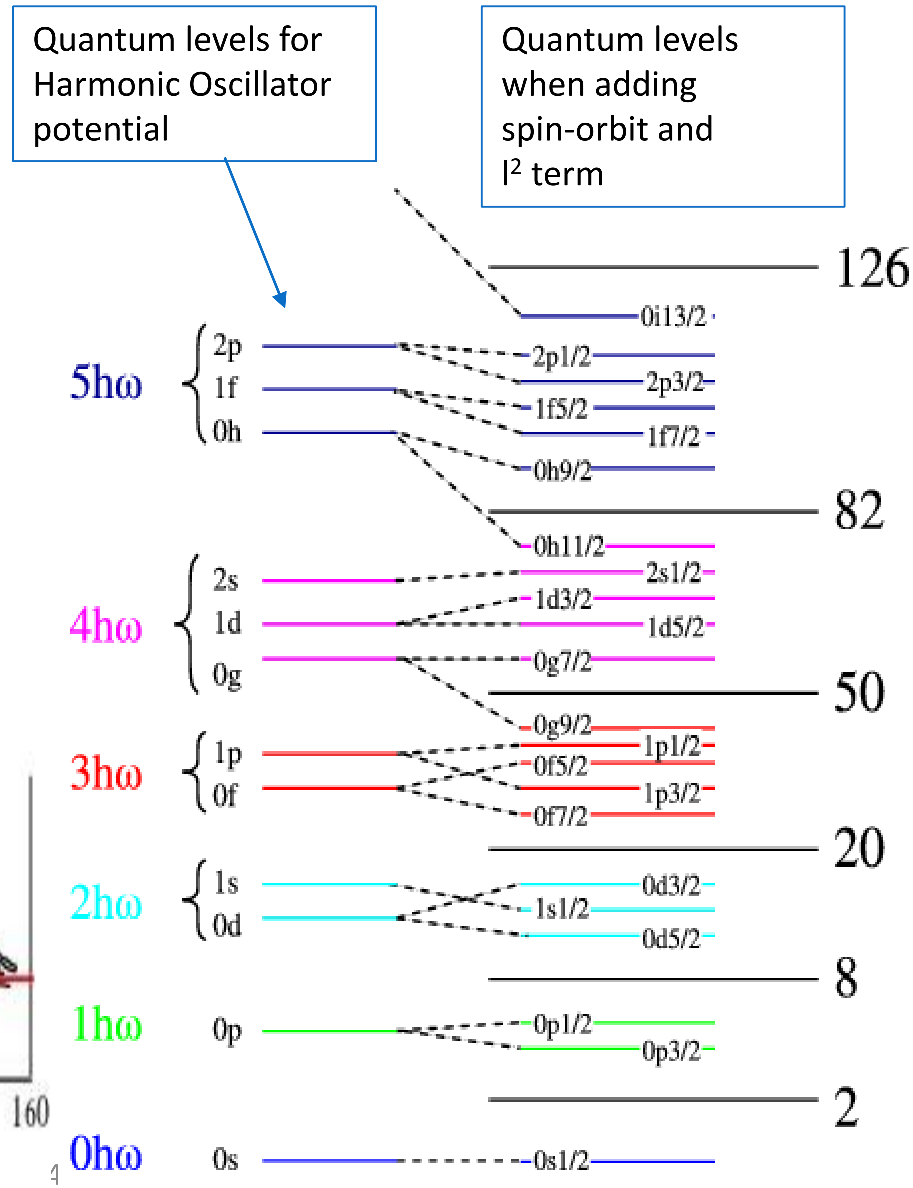


Results:
Magnetic and electric moments of nuclei
(position of last nucleons, shapes)

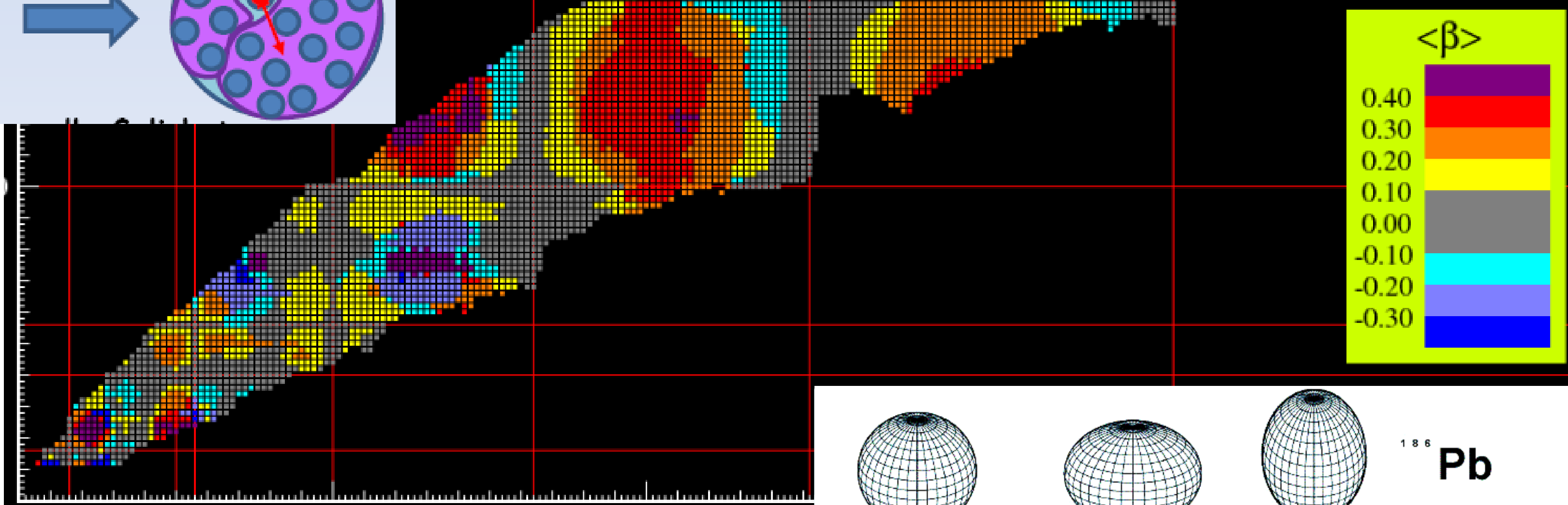
Nuclear shell model

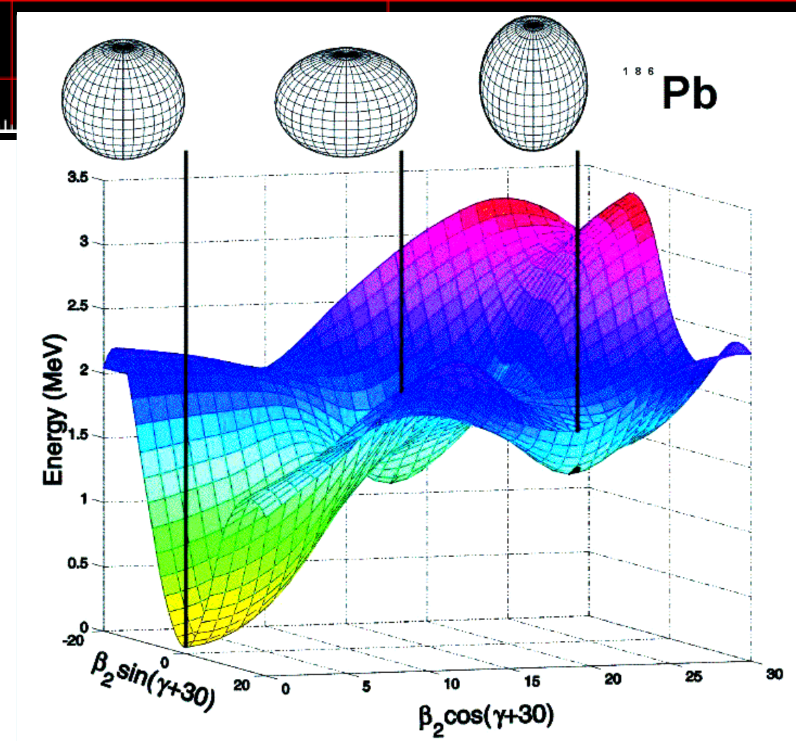
- Created in analogy to the atomic shell model (electrons orbiting a nucleus)
- Based on the observation of higher stability of certain nuclei
  - filled shell of neutrons or protons results in greater stability
  - neutron and proton numbers corresponding to a closed shell are called 'magic'
- Assumption: independent nuclei move in a self-created potential → solve Schrodinger Equation to derive quantum levels





Self-consistent Mean-field models

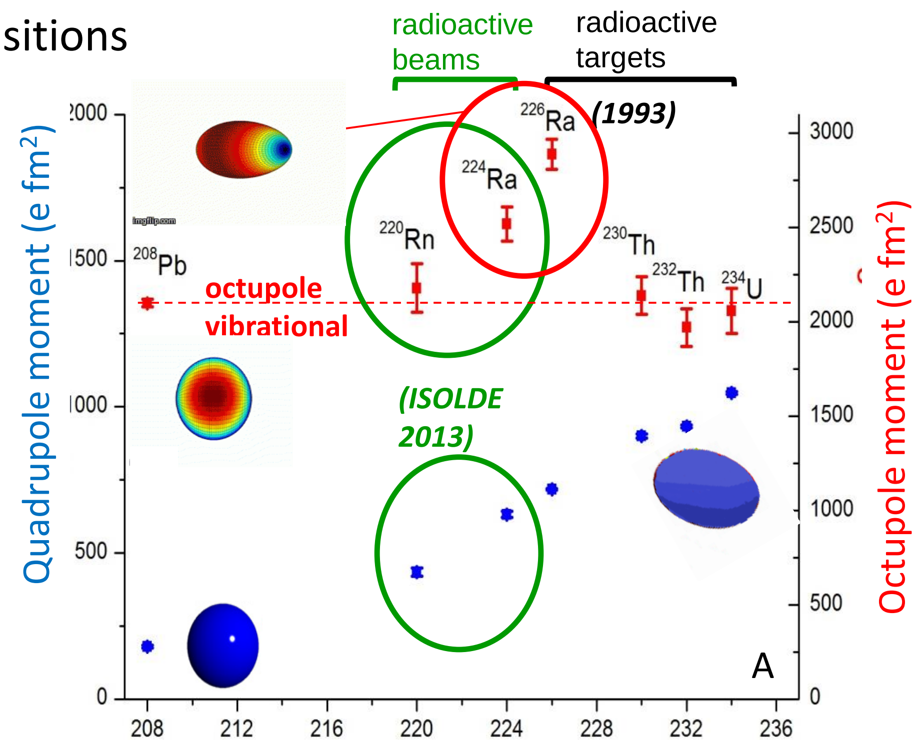




- Mean field is derived iteratively by solving the HF equations and by assuming a potential for the nucleon-nucleon interaction
- No inert core
- Very good at describing deformations
- Can predict properties of very exotic nuclei
- Not so good at closed shells

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