Nuclear physics at CERN

Lecture 2: Science of ISOLDE

Meet ISOLDE trailer:
https://videos.cern.ch/record/2285037

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

Outline

Aimed at both physics and non-physics students

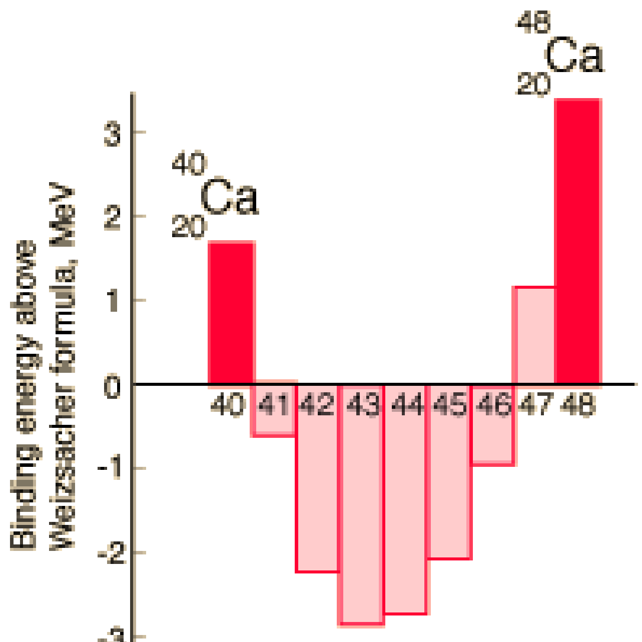
Lecture 1: Nuclear physics and ISOLDE facility

This lecture: Science of ISOLDE

- Measured properties and used techniques
- Recent studies in:
  - nuclear physics
  - nuclear astrophysics
  - fundamental studies
  - material science
  - biology
  - medicine

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



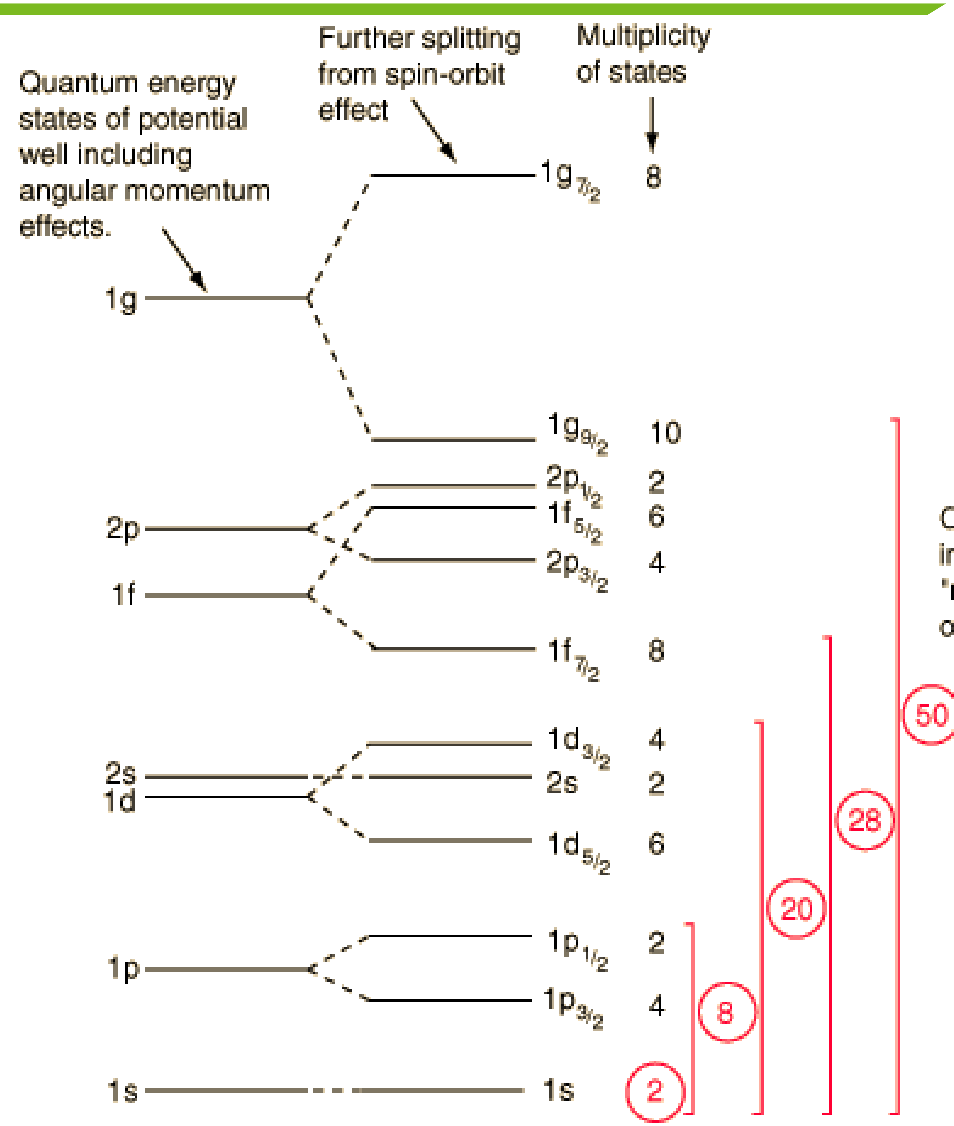
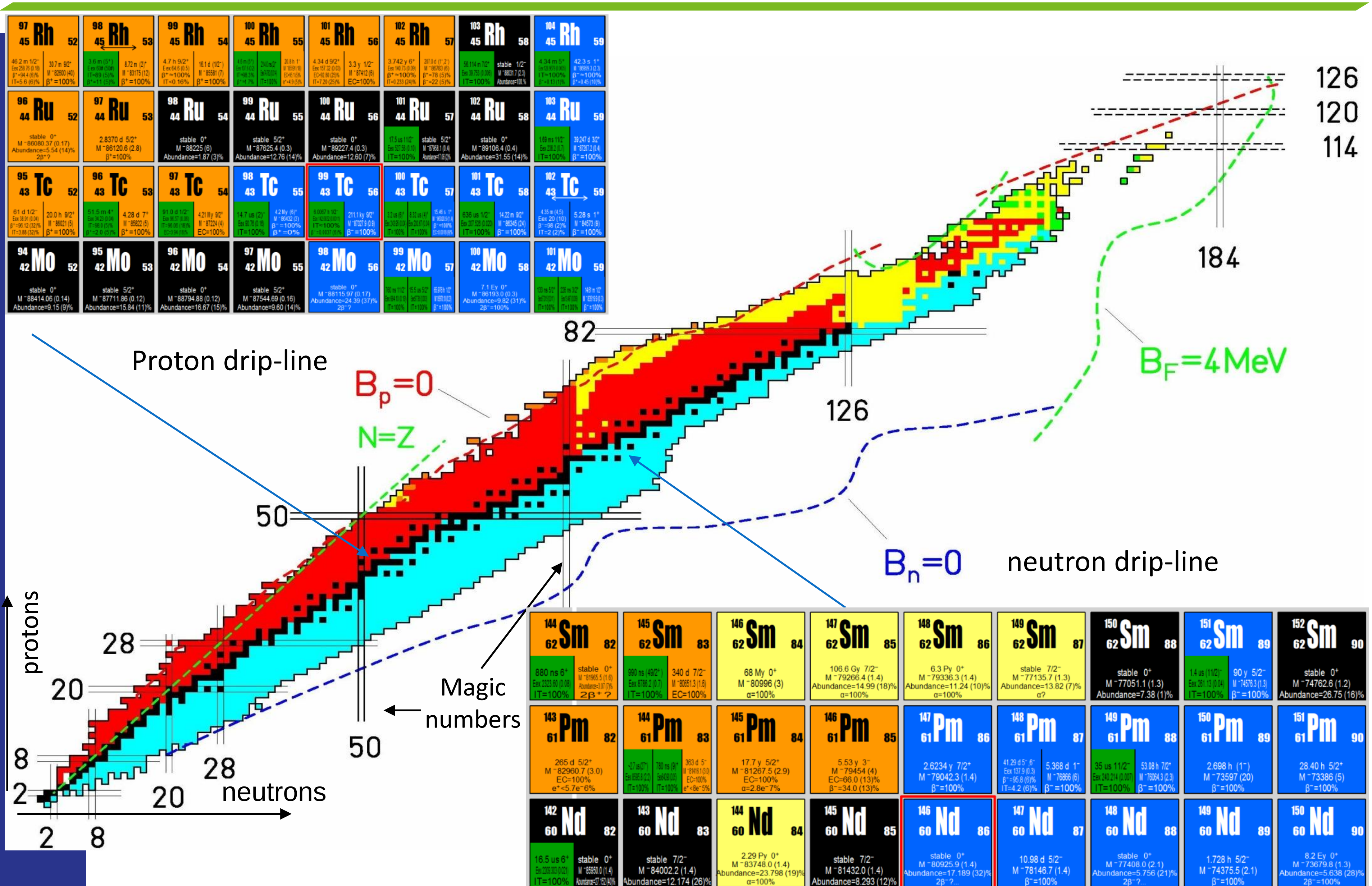
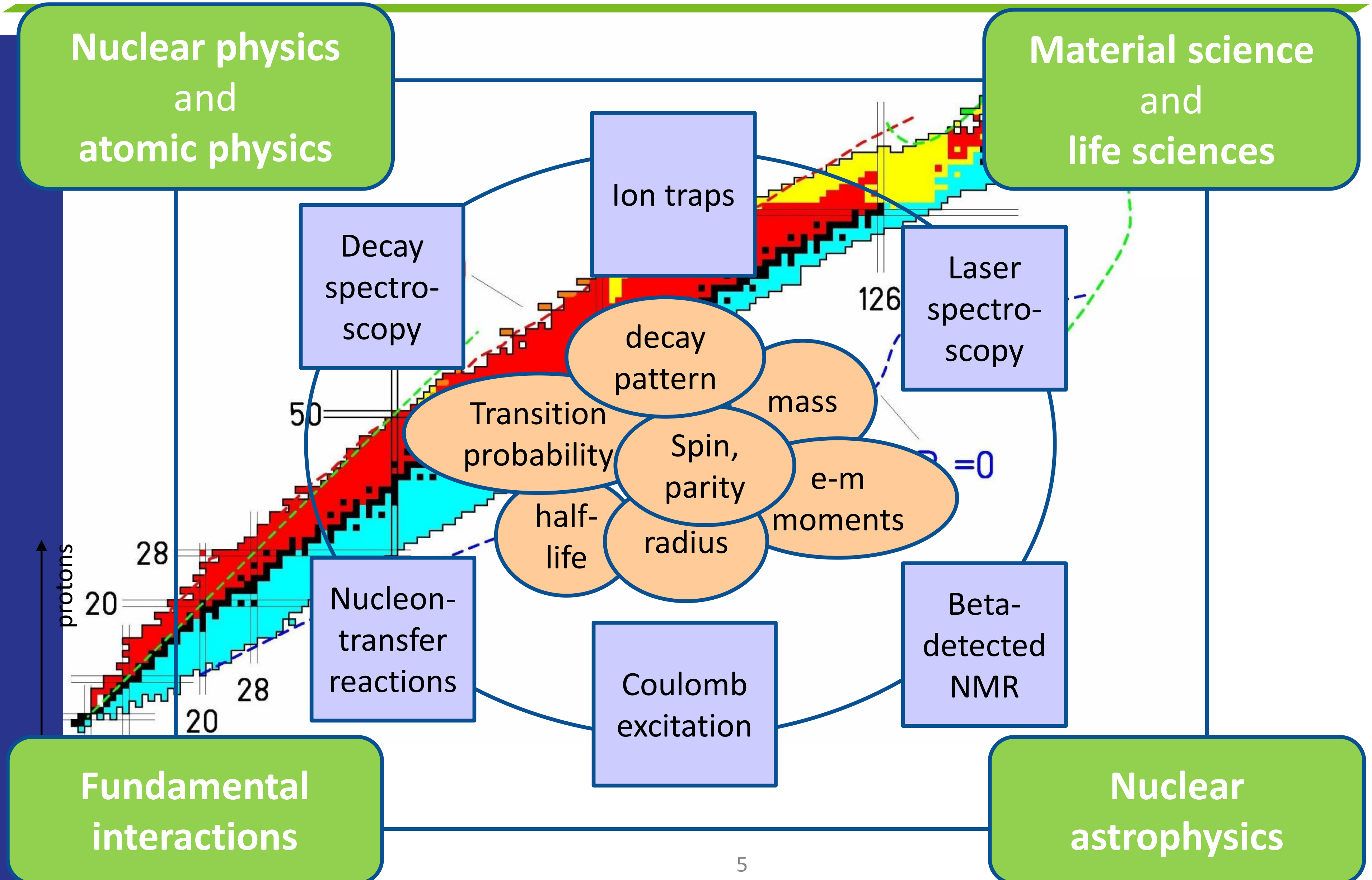


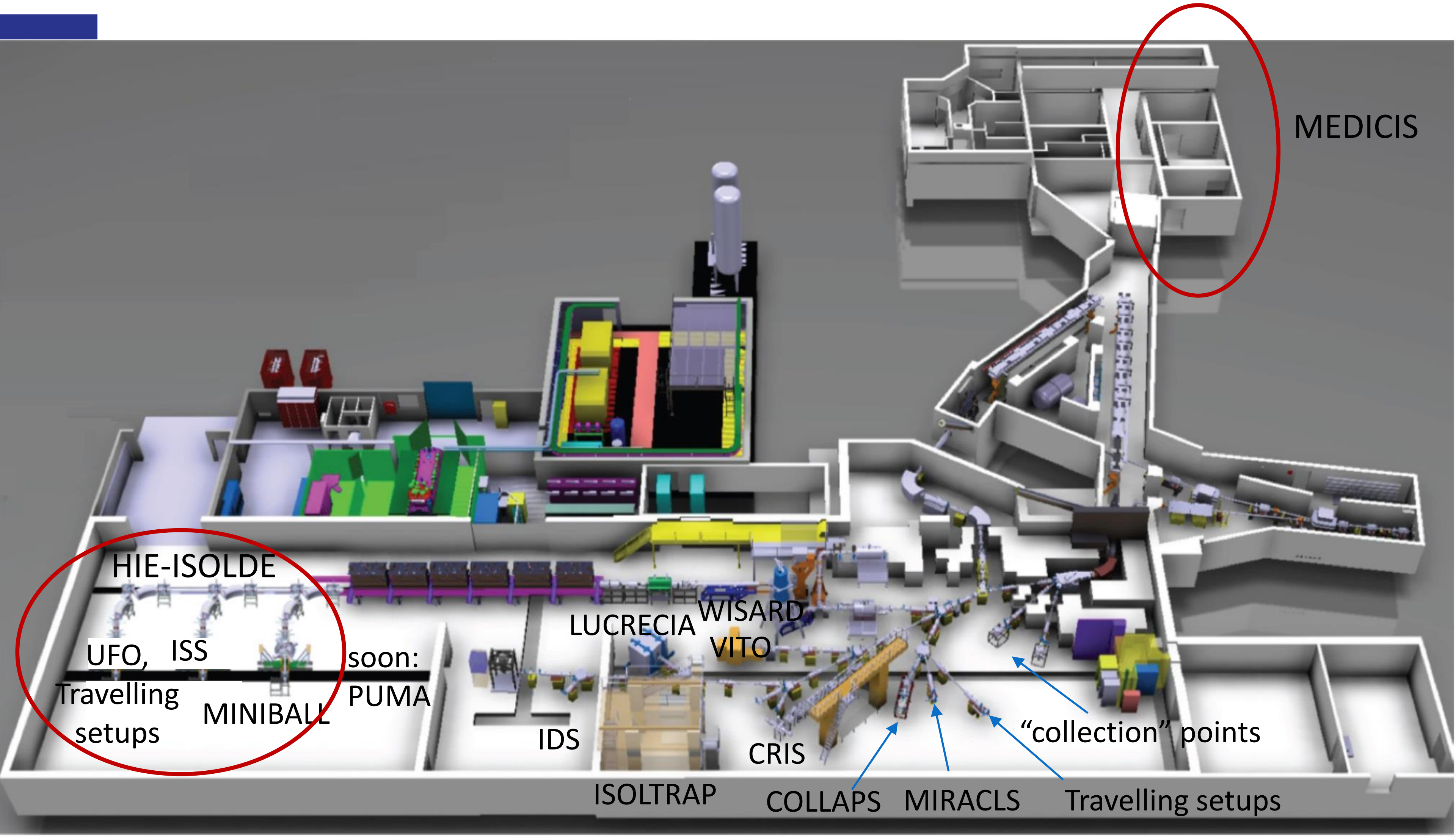
Chart of nuclei and shell model



ISOLDE techniques and physics topics



ISOLDE experimental setups



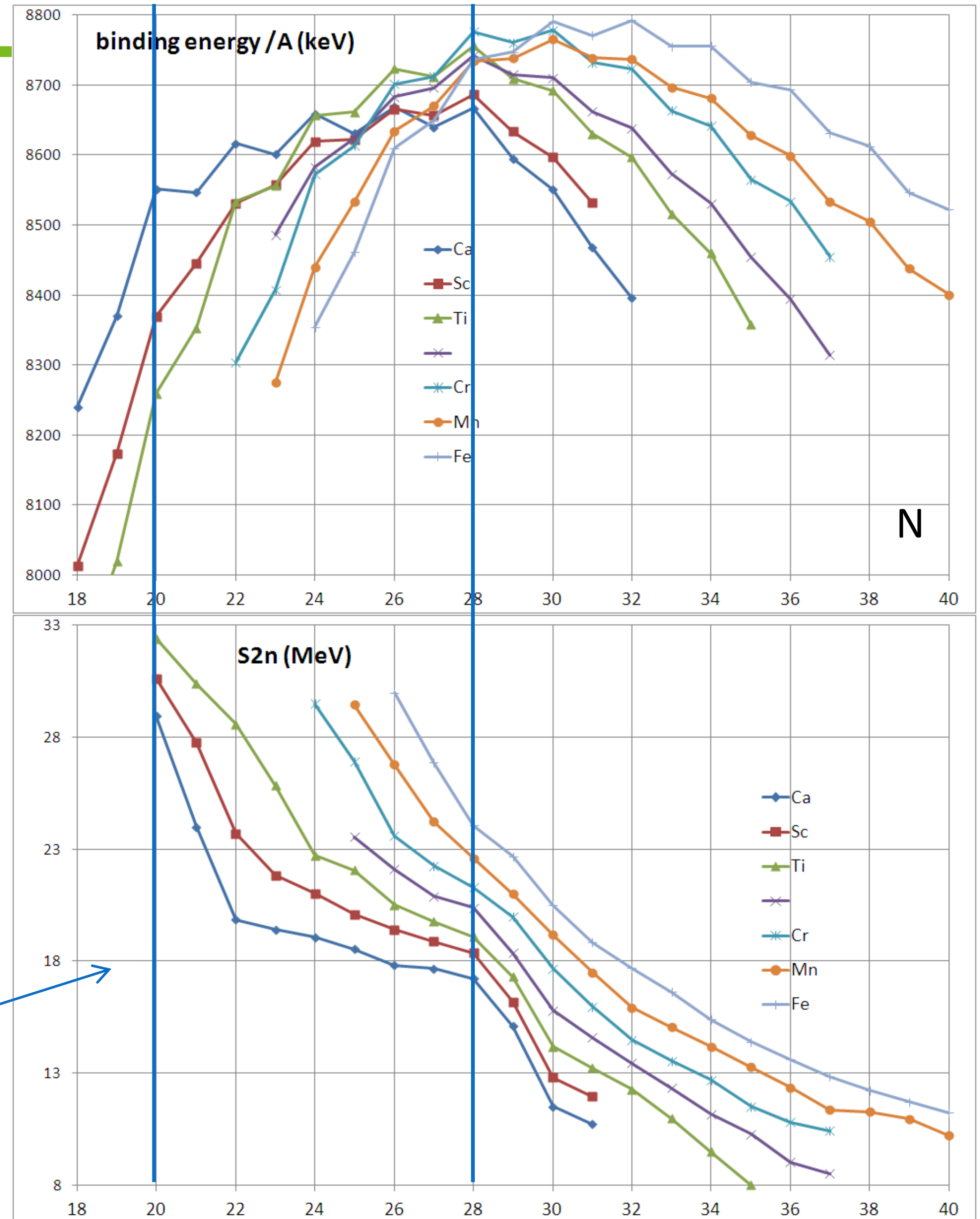
Examples of nuclear structure info from ISOLDE studies

Nuclear structure from atomic masses

- 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

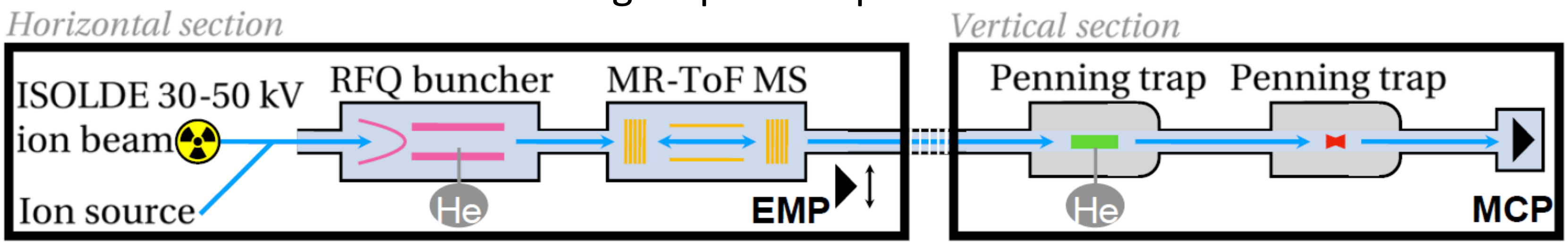
$$S_{2n} = B(N-2, Z) - B(N, Z),$$



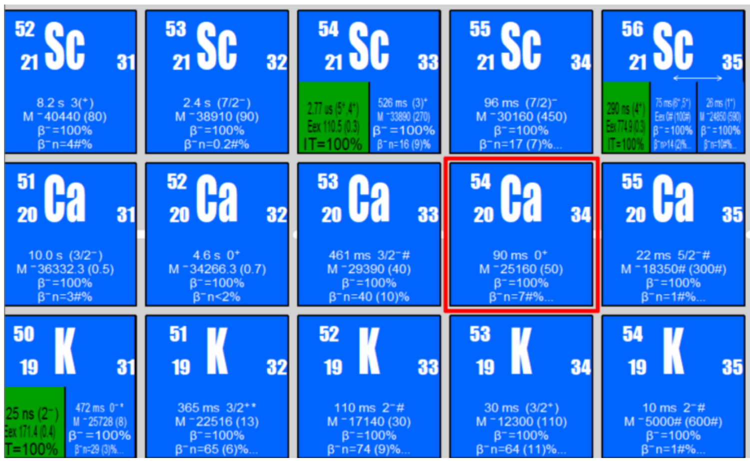
Closed shells visible as a sudden drop after the magic number (N=20 and 28)

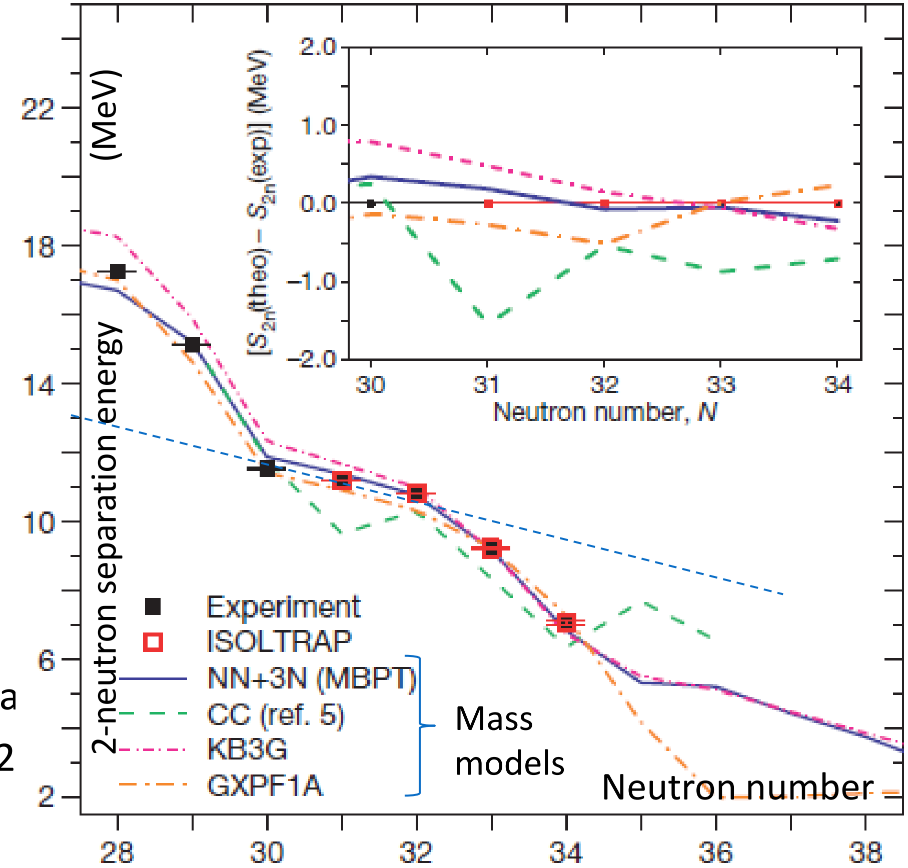
Mass of 54Ca and new closed shell

ISOLTRAP Penning-trap mass spectrometer



Z=20





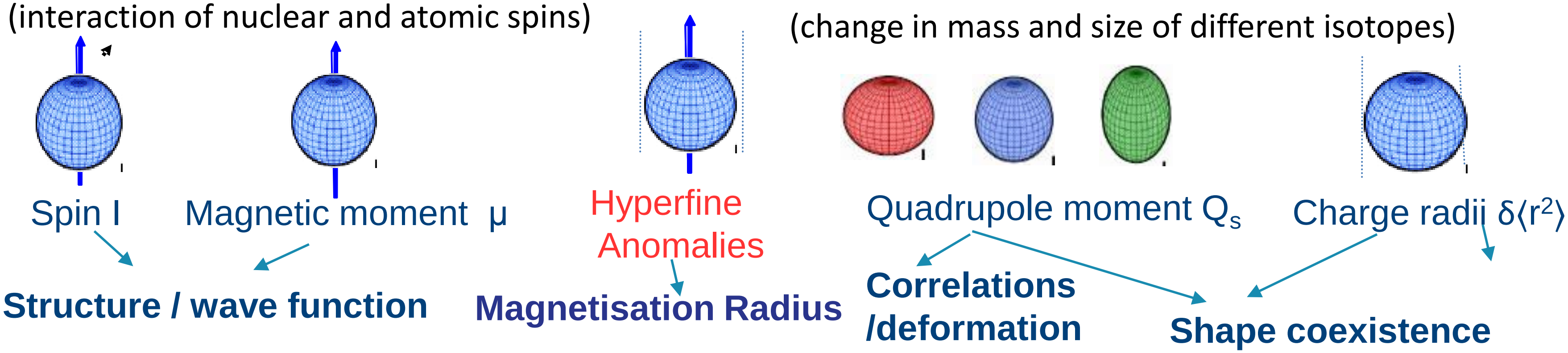
- Masses of neutron-rich calcium isotopes
  - ➢ 3-body nucleon forces required to explain data
  - ➢ Evidence of new neutron shell closure at N=32

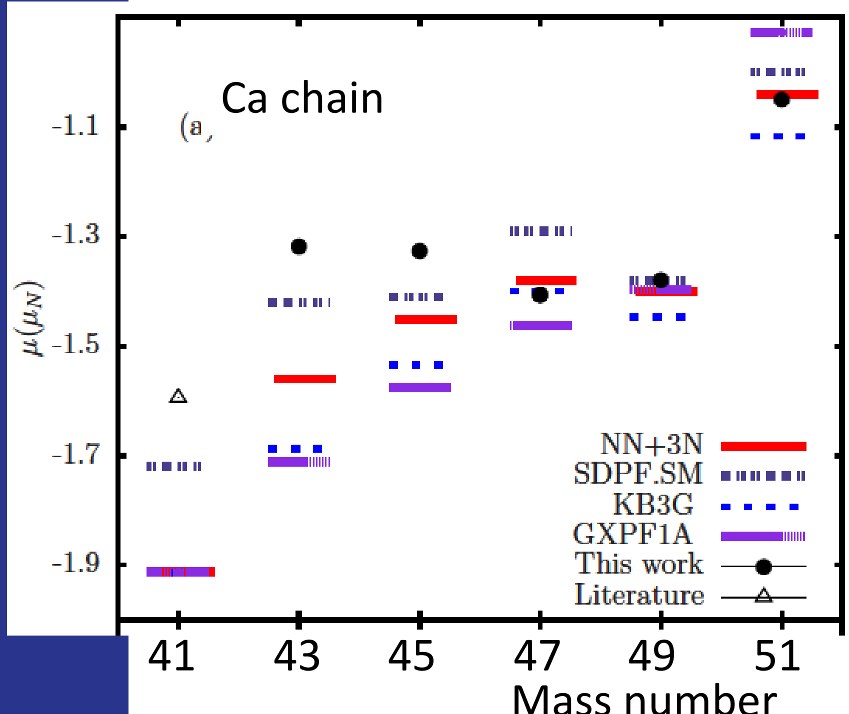
F. Wienholtz et al, Nature 498 (2013), 346

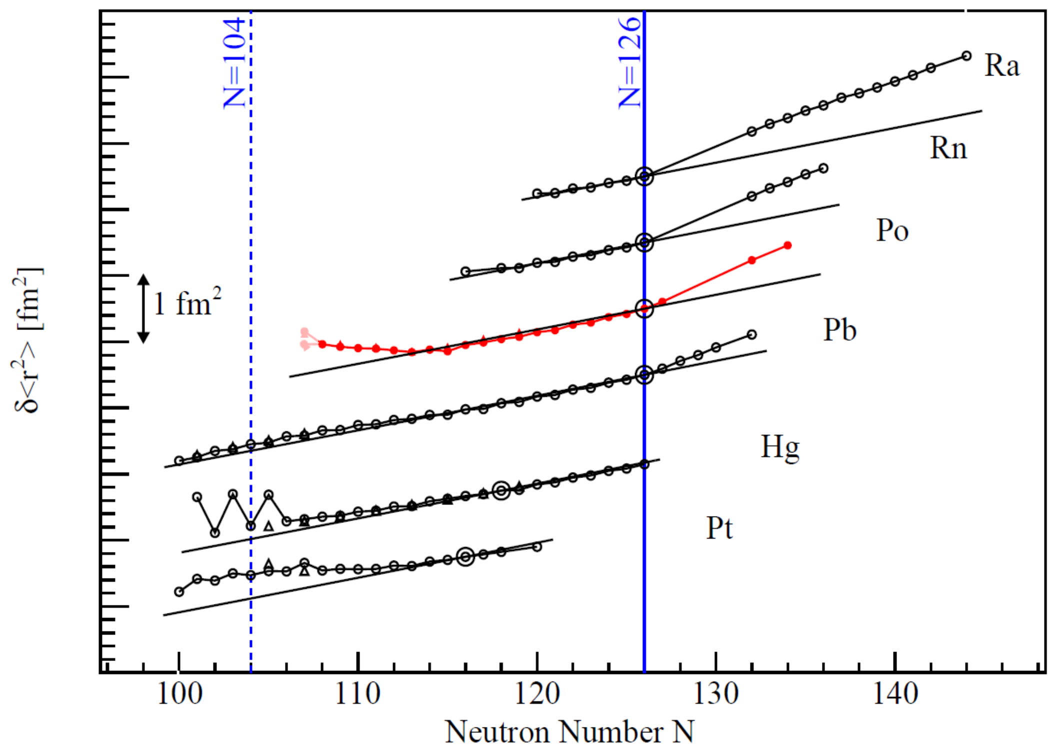
Nuclear structure from atomic transitions

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

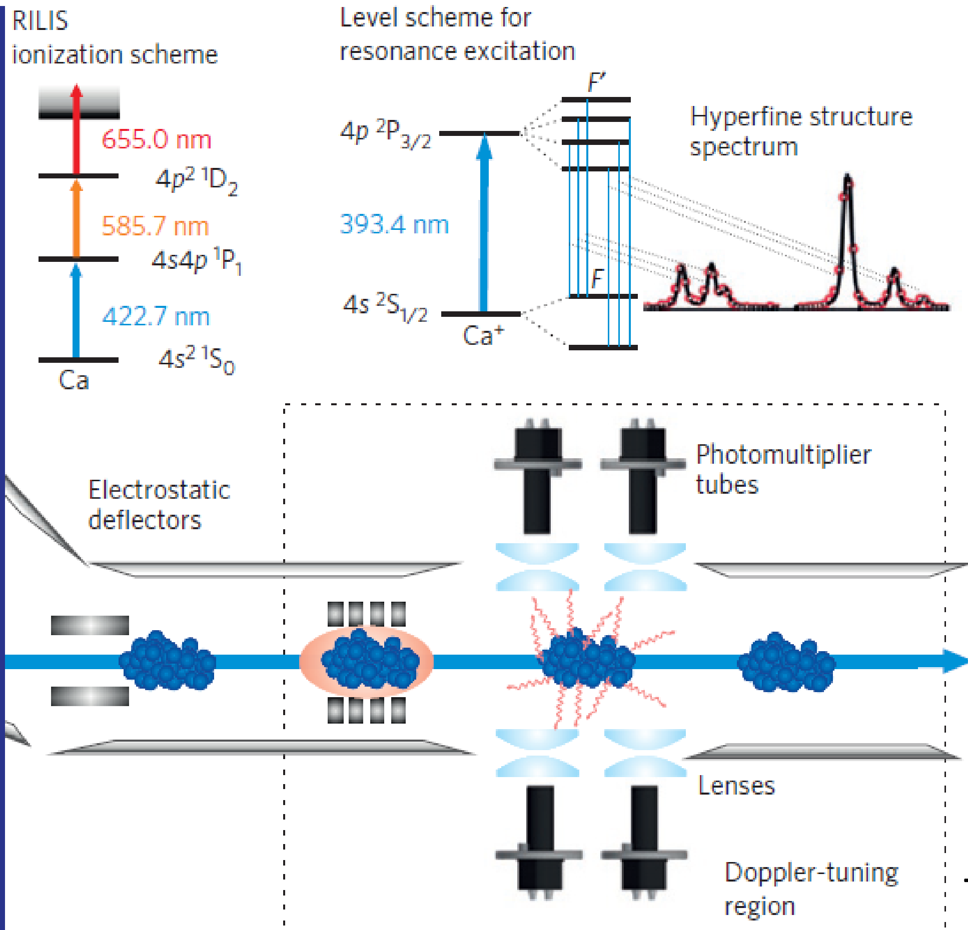
Isotope shifts (IS) in atomic transitions
(change in mass and size of different isotopes)

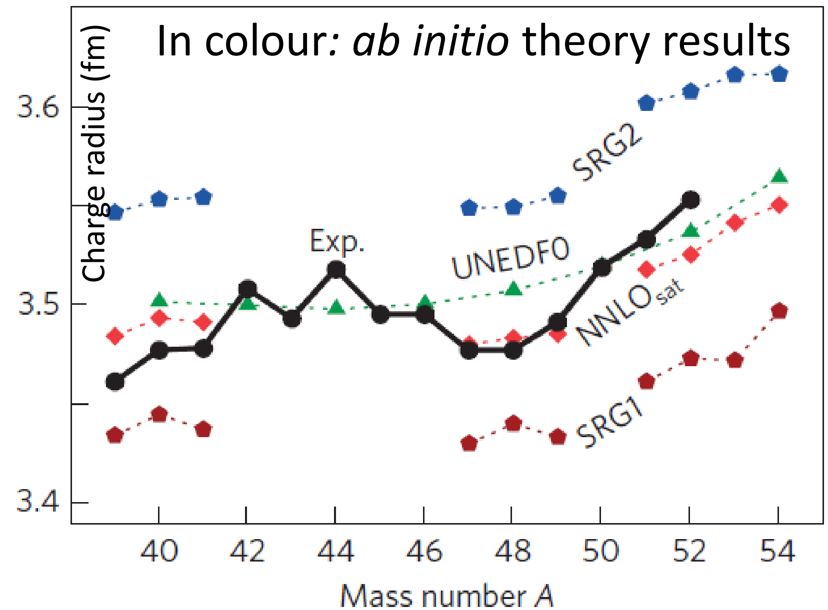






Charge radii towards ^{54}Ca & closed shells





Theory rather reproduces trend towards N=34

Charge radius of 54Ca crucial -> measured last week

COLLAPS setup
(others: CRIS, RILIS, VITO)

R. Garcia Ruiz et al, Nature Physics 12, 594-598 (2016)

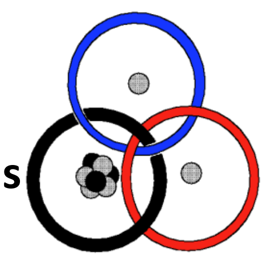
Halo nuclei & nuclear structure

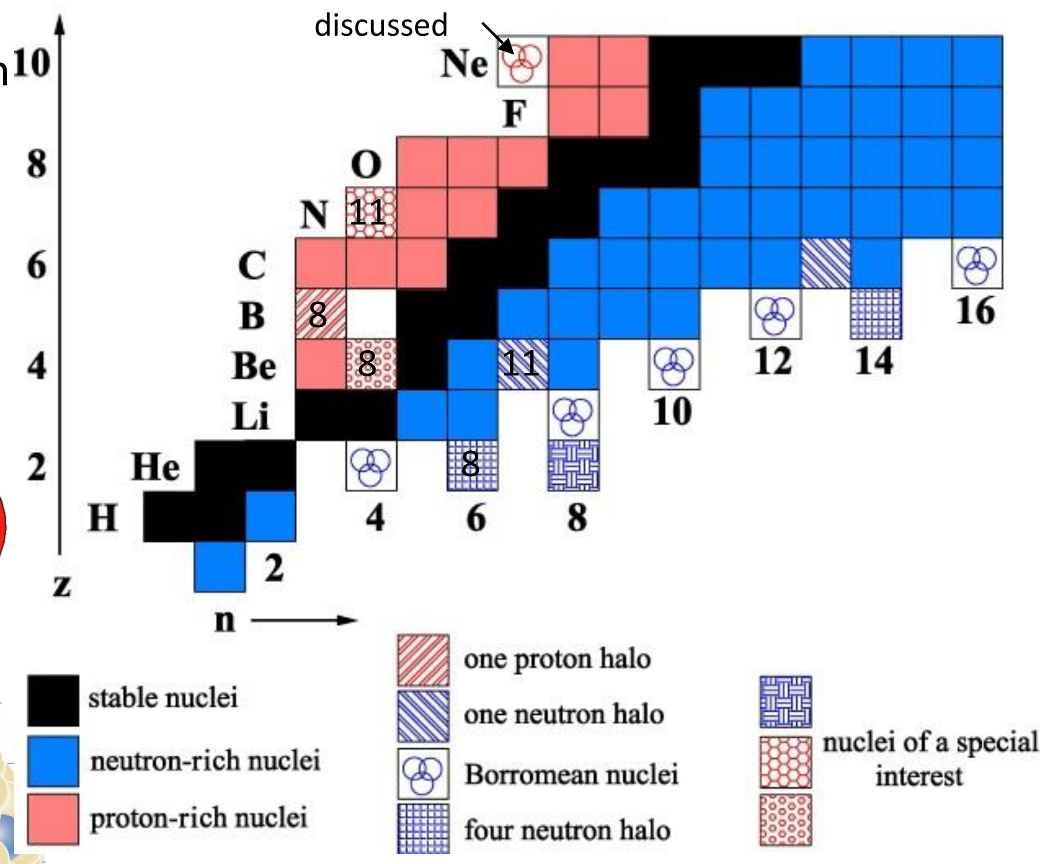
Halo: nucleus built from a core and at least one neutron/proton with spatial distribution much larger than that of the core

1985: first halo system identified: ^{11}Li
now: almost dozen other halos known

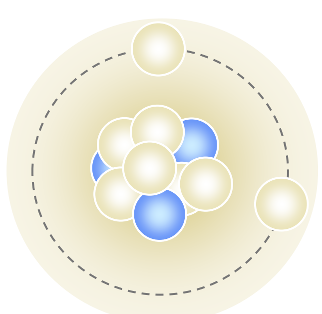
Nuclear structure and core-halo interaction still not well understood

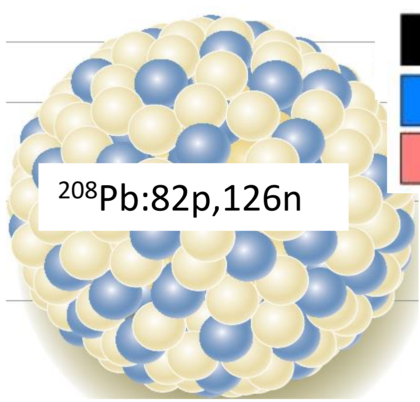
=> Crucial information:
Mass/binding energy
Spin-parity
Magnetic moment
Mass and charge radius
Quadrupole moment
Energy level scheme





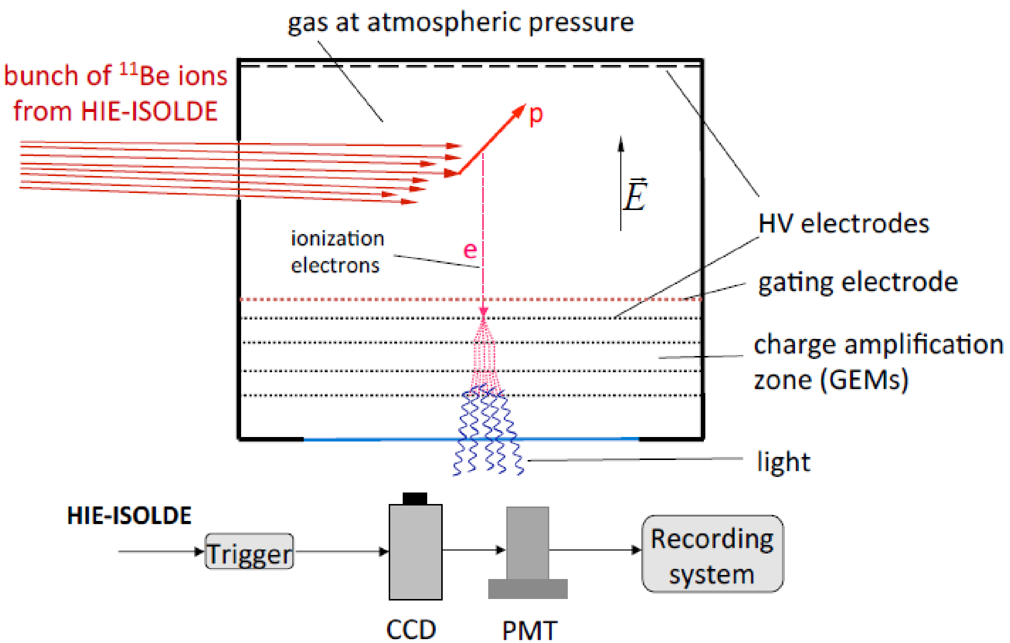
^{11}Li:3p,8n

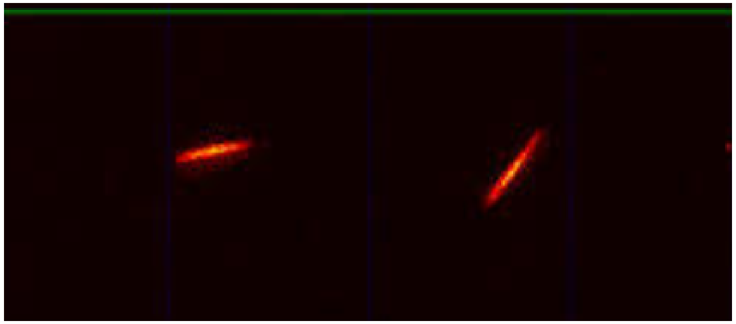


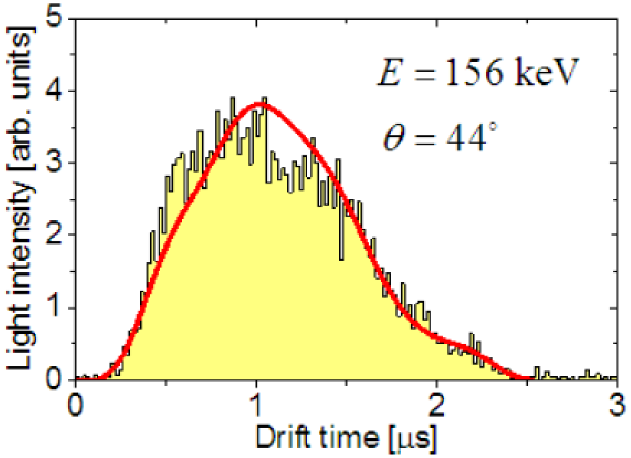


Proton emission from 11Be

- 2 experiments:
  - Appearance of 10B
  - Optical camera (publication under preparation)
- Rare decay, probability depends on mechanism -> interesting to measure





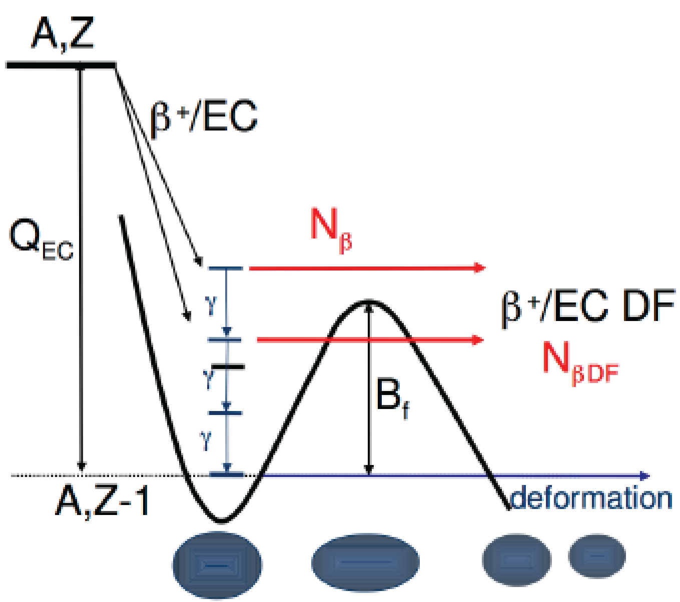


PHYSICAL REVIEW C **99**, 044316 (2019)

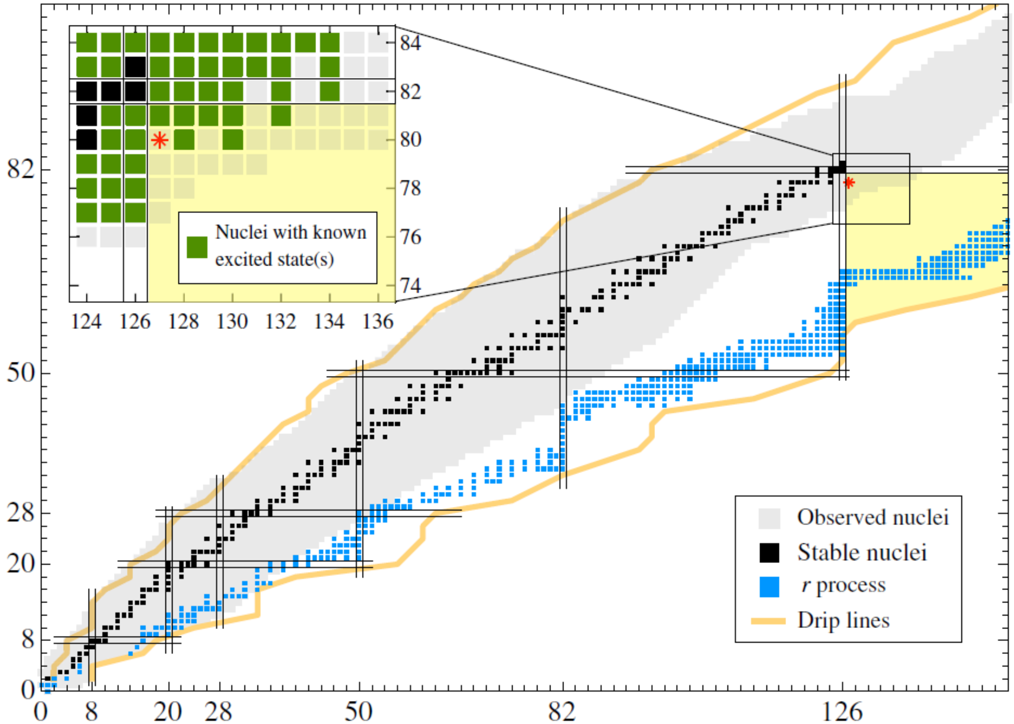
Other ISOLDE setups and studies

Decay spectroscopy

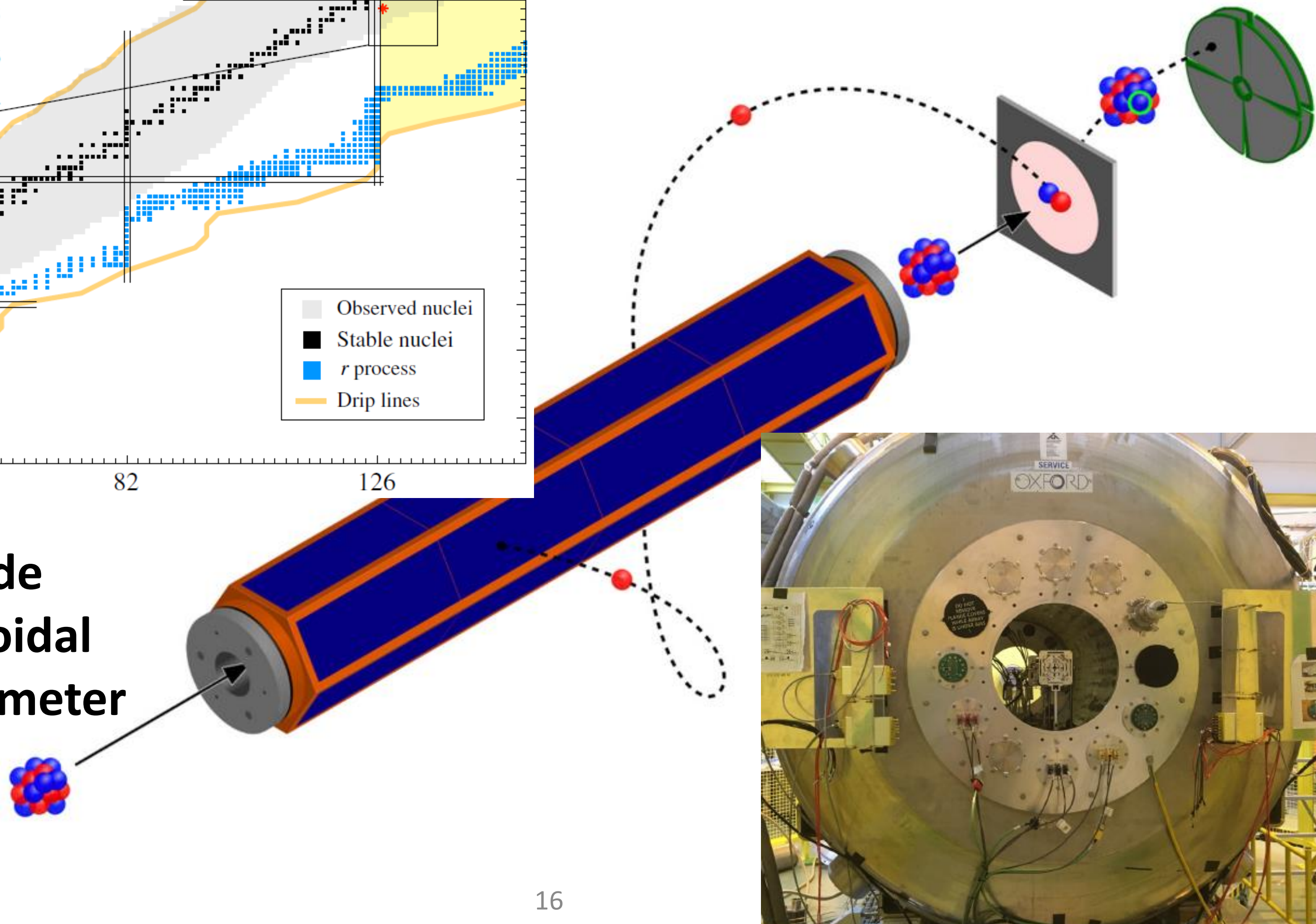
- Different detectors to sensitive to emitted:
  - Alpha particles
  - Beta particles
  - Gamma rays
  - Protons or neutrons
- Isolde Decay Station
- soon: polarised beams at VITO



Nuclear astrophysics at HIE-ISOLDE



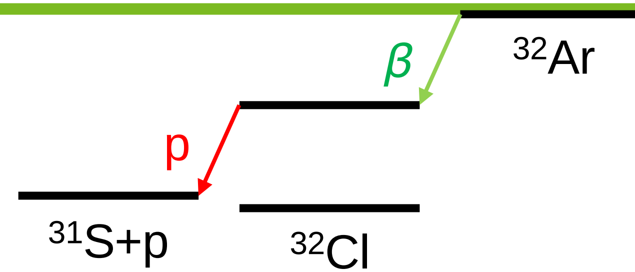
neutron excitations in ^{207}Hg by neutron-adding (d,p) reaction in inverse kinematics

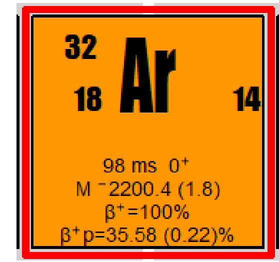


Isolde Solenoidal Spectrometer

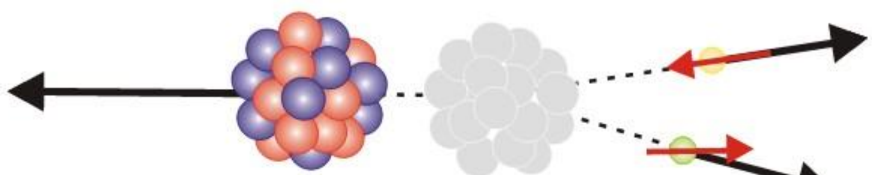
Scalar currents with ^{32}Ar

- Aim: search for scalar current contribution in predominantly vector current of β decay via β–ν correlation



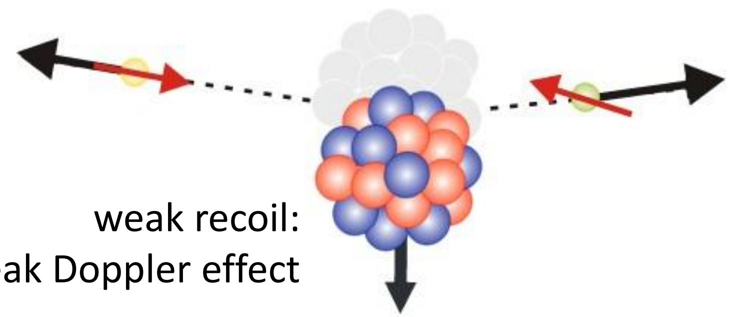


Vector current



strong recoil:
strong Doppler effect

Scalar current

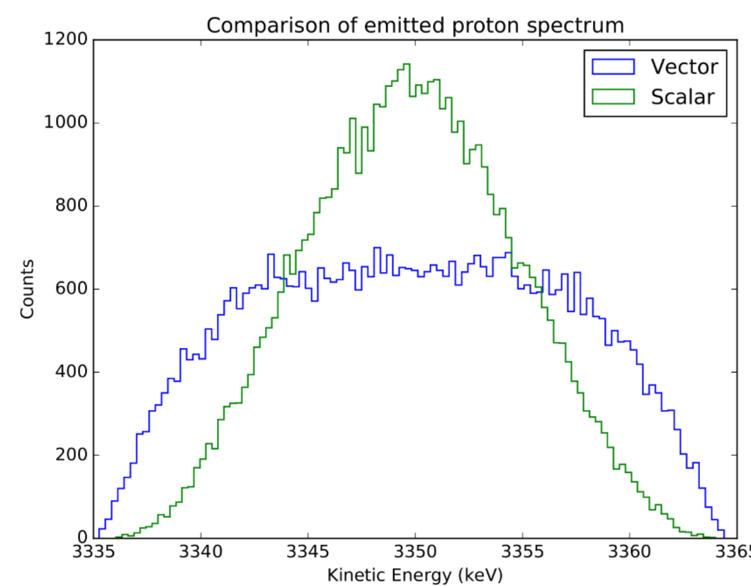


weak recoil:
weak Doppler effect

WISARD experiment

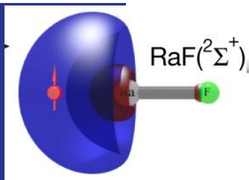
- Tool: β-delayed p decay of ^{32}Ar, Doppler effect on proton energy

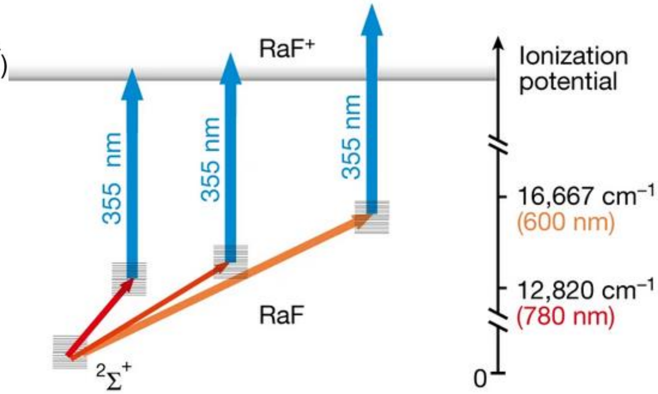
- Present limits on scalar current from βν correlation a_F = 0.65%

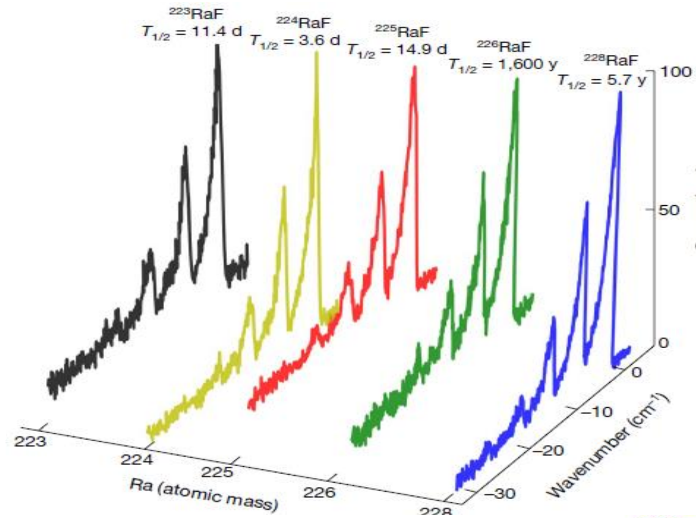


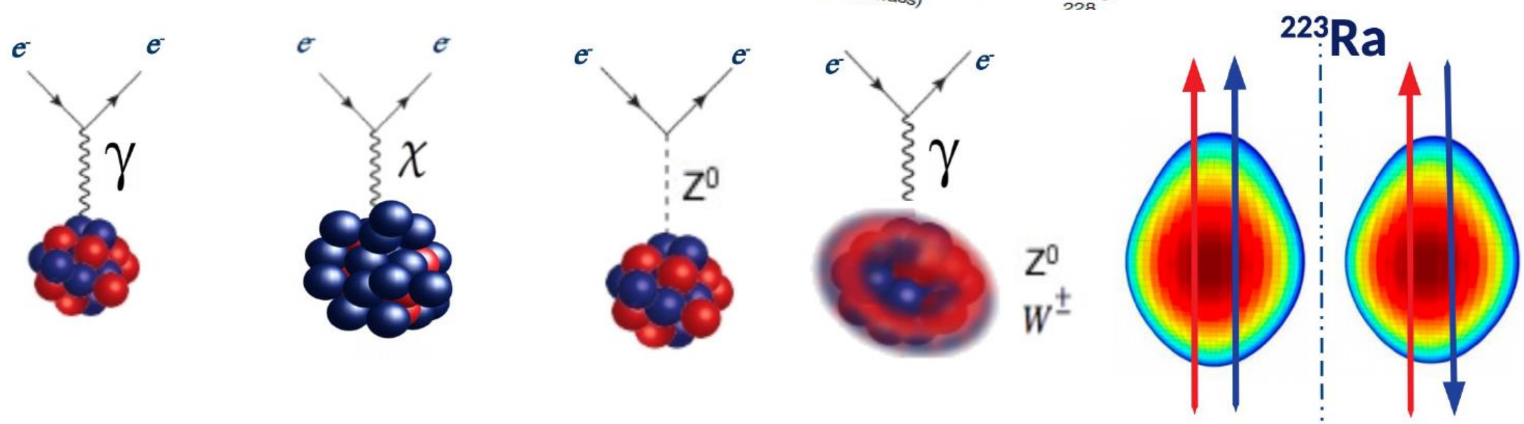
L. Hayen CRADLE++ (https://github.com/leenderthayen/CRADLE)

Radioactive molecules & Beyond SM









Low-energy SM tests | New e-N interactions? | P-violation | T-violation

- Nuclear matter
- Nuclear structure
- BSM searches

- Dark Matter properties?
- New forces?

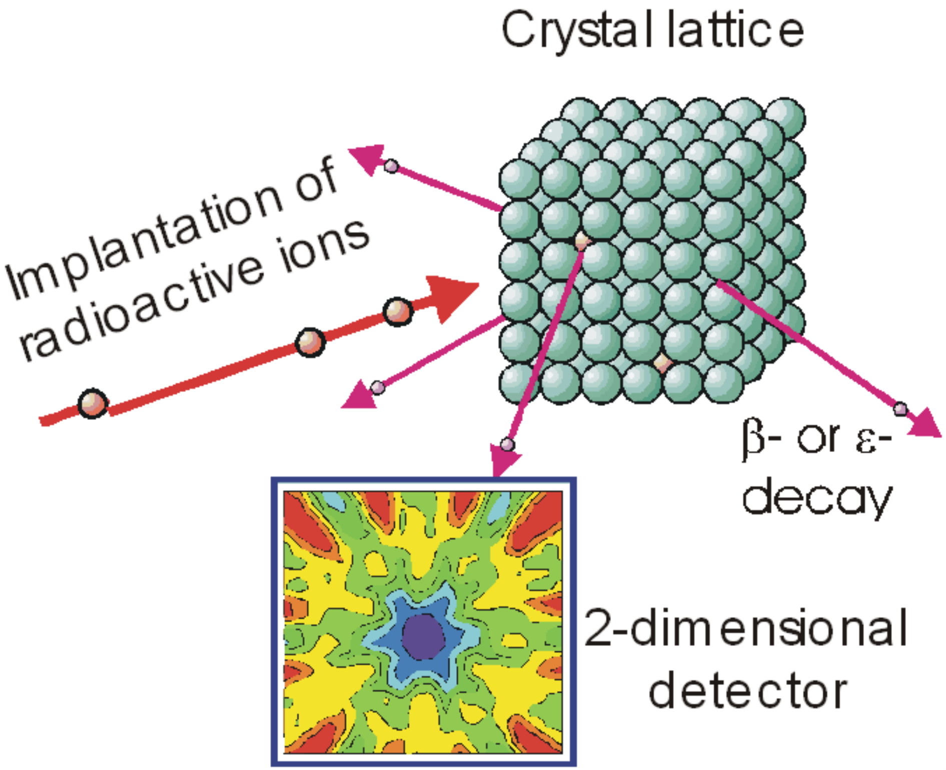
- Baryogenesis

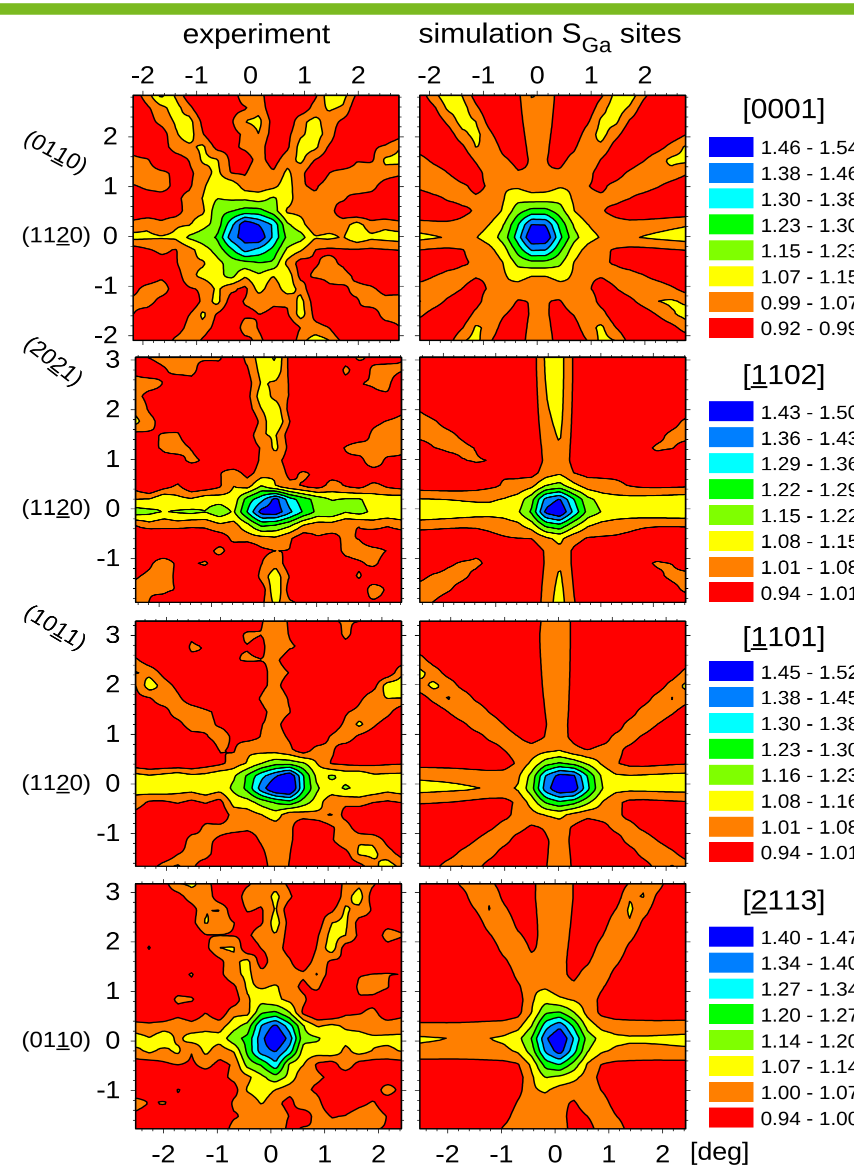
Nature 581, 396 (2020)

From M. Udrescu

Material science

- Emission channeling
  - ➢ Position of implanted ions



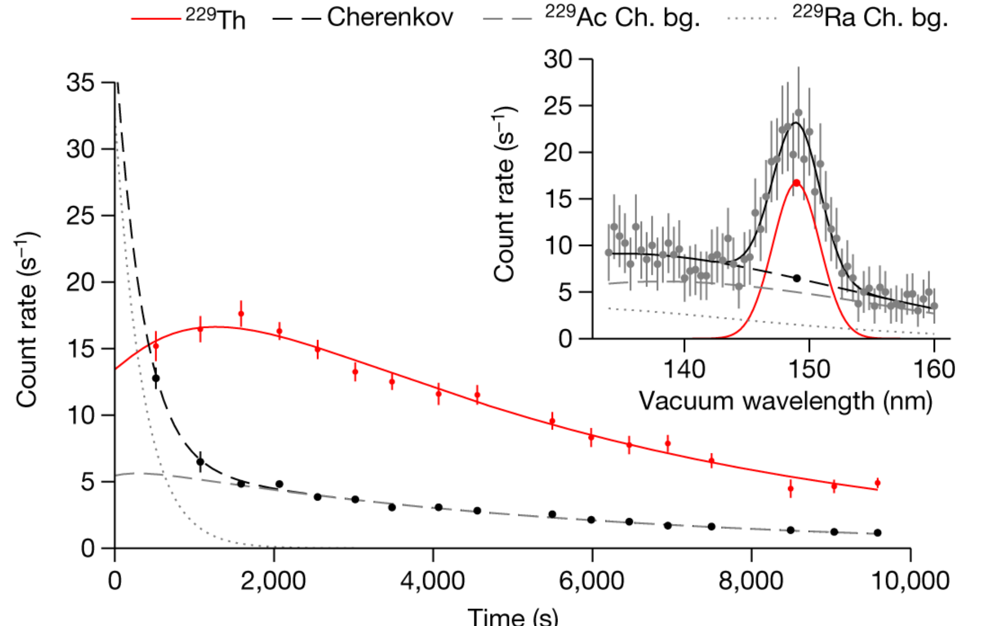


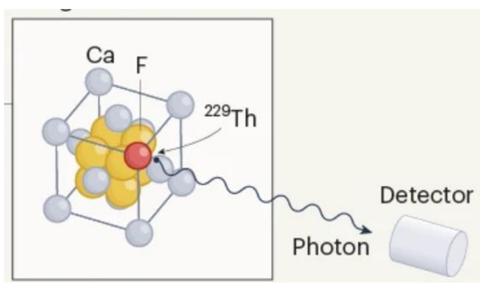
Emission channelling pattern

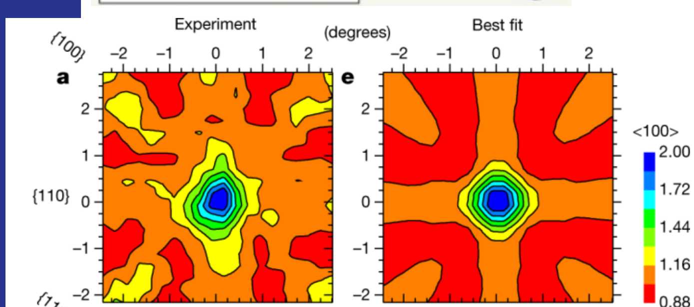
^{229m}Th: towards a nuclear clock with VUV and EC

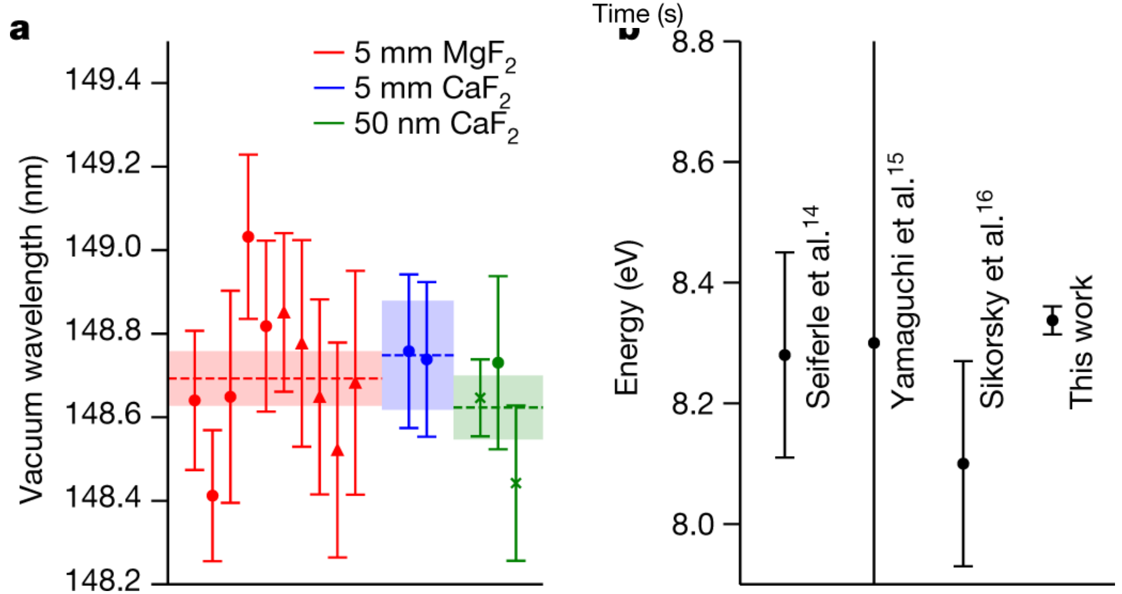
Determination of isomer energy with vacuum UV spectroscopy:

- 229Ac decay to 229mTh
- Internal conversion decay branch removed via study in a crystal
- CaF as host (wide band gap material)
- Implantation site verified with emission channeling









S Kraemer et al, *Nature* **617**, 706 (2023)

Video: https://videos.cern.ch/record/2297990

New medical isotopes

Collection at ISOLDE

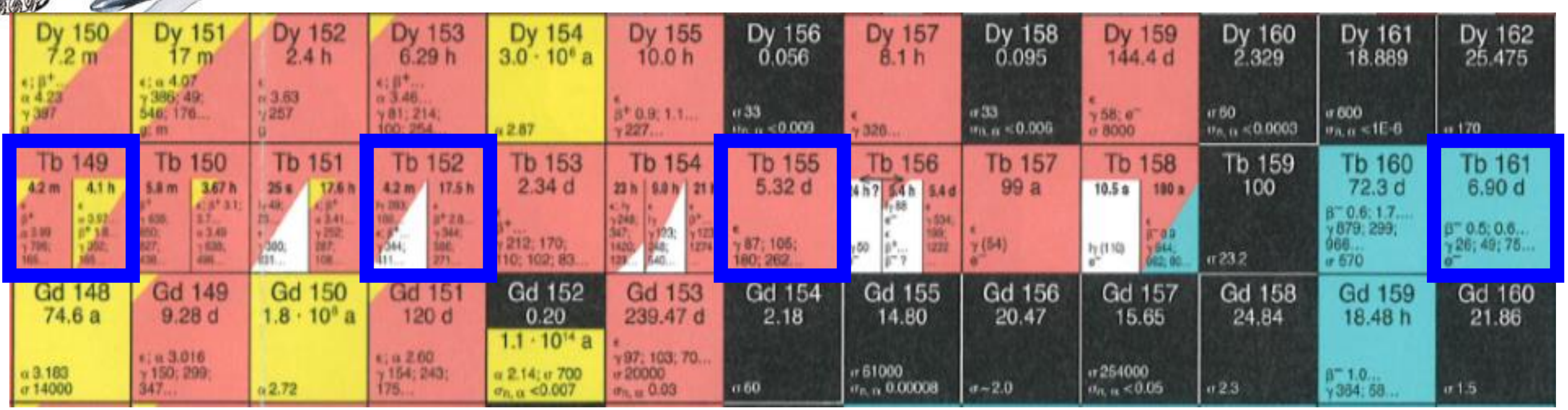
Radiochemical purification and labeling

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

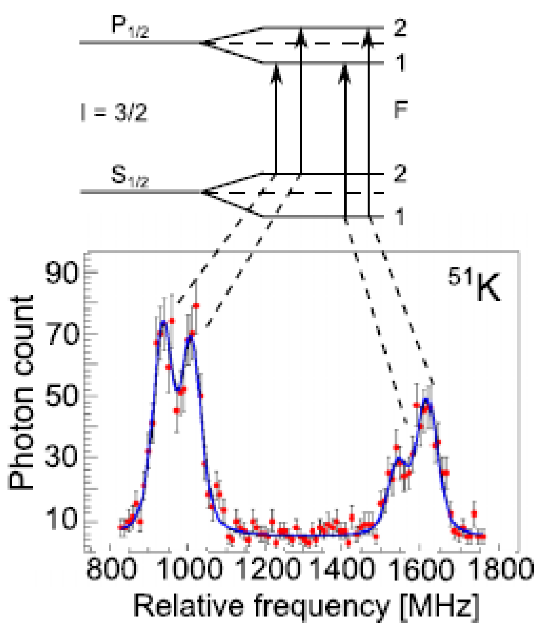
Nuclear structure from atomic transitions

Atomic transitions allow studying **ground-state (and isomeric) properties of nuclei**:

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 protons&neutrons
  - Electric quadrupole moment -> deformations

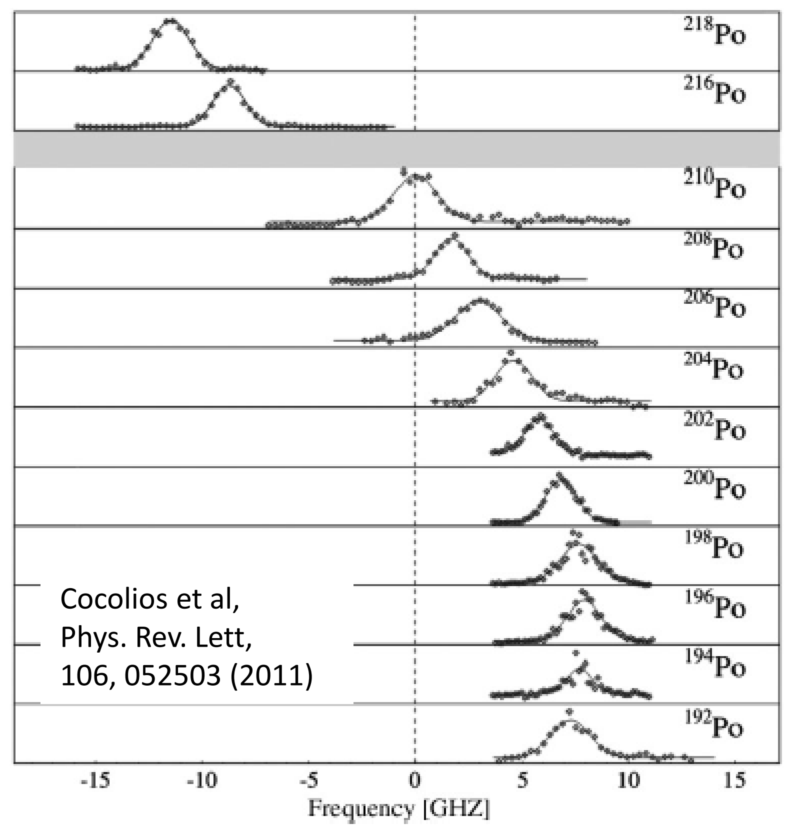


Yordanov et al, Phys. Rev. Lett., 110, 172503 (2013)

Isotope shifts (IS) in atomic transitions

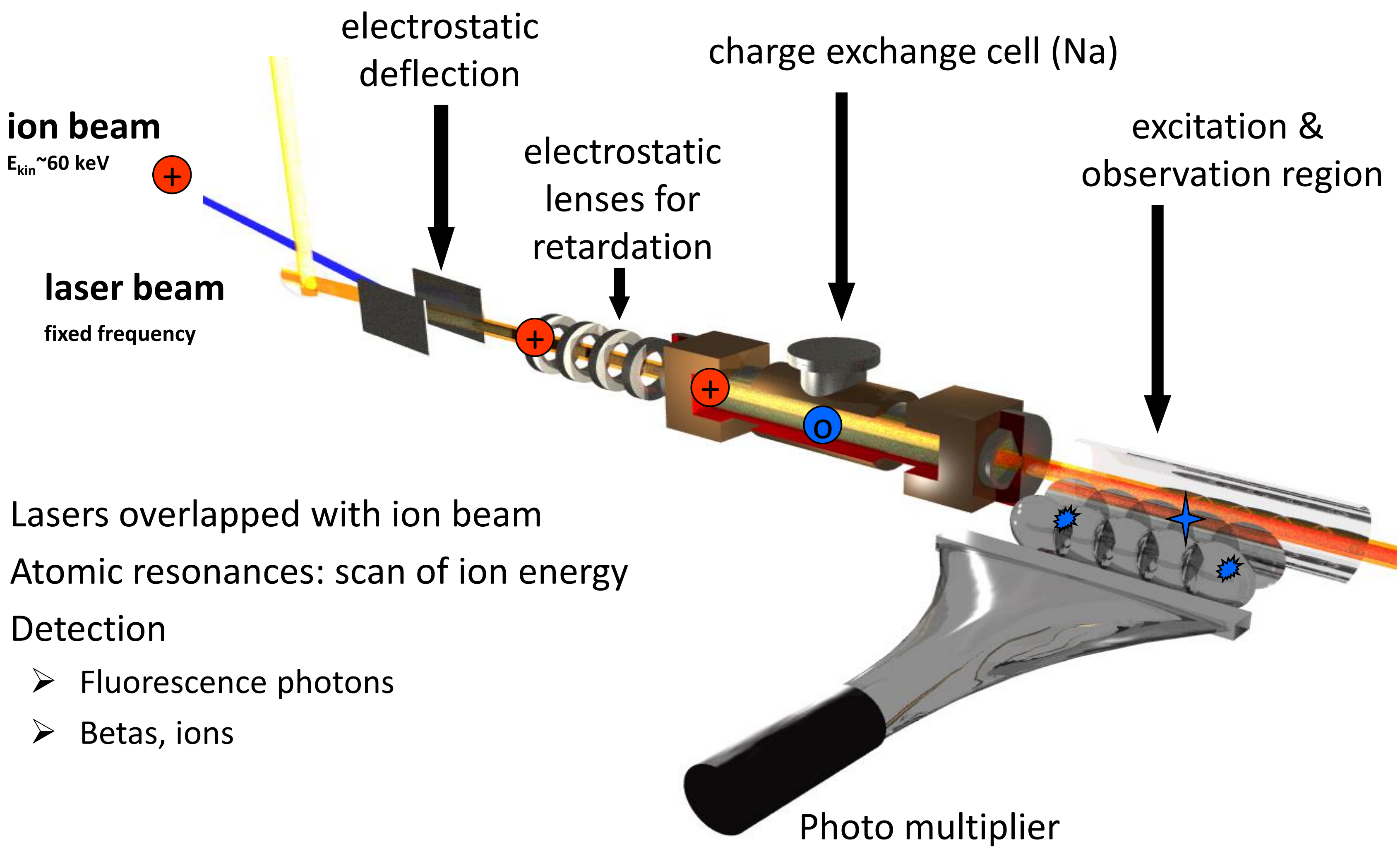
(change in mass and size of different isotopes of the same chemical element)

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



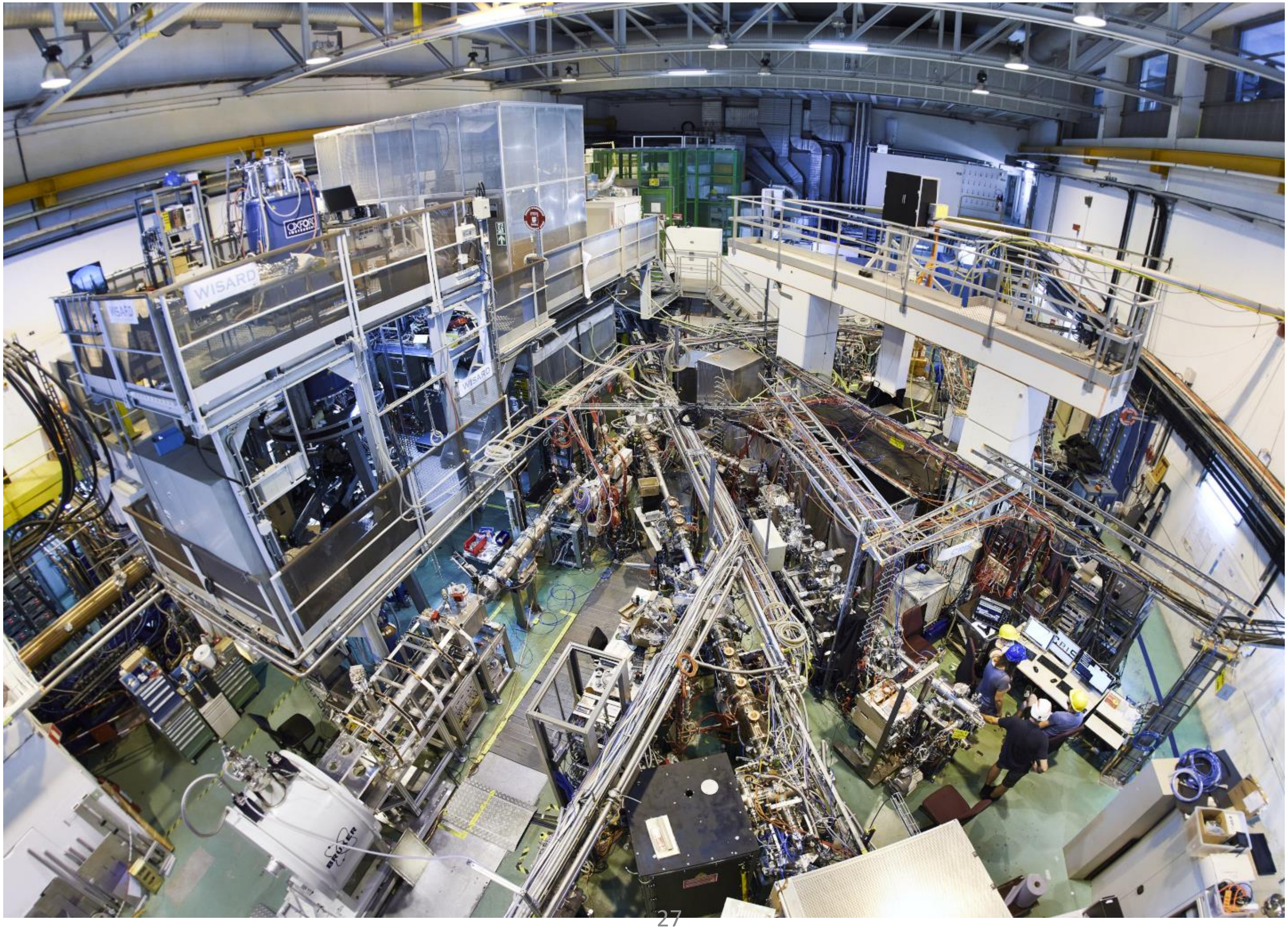
Cocolios et al, Phys. Rev. Lett, 106, 052503 (2011)

Collinear laser spectroscopy

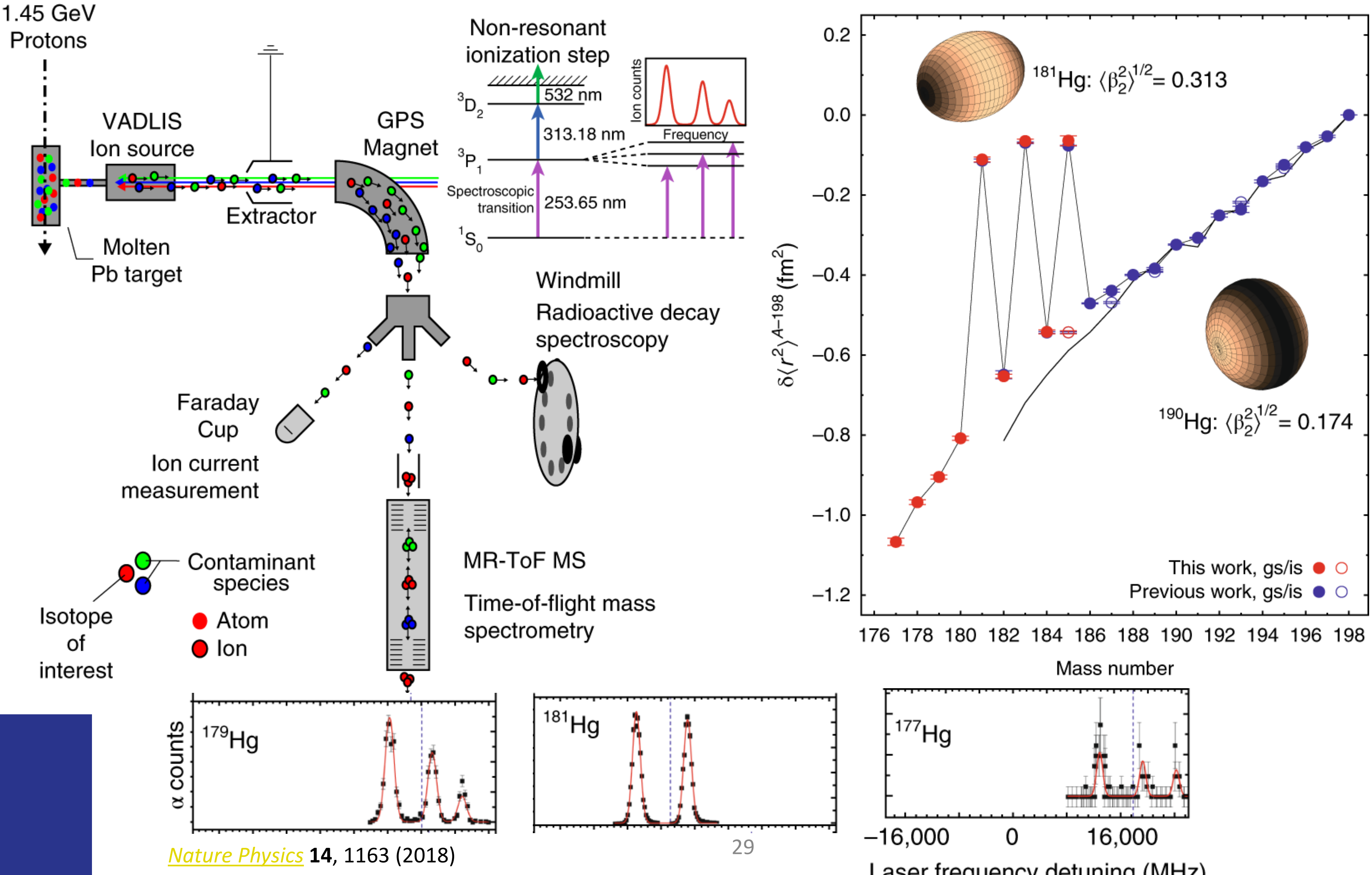


- Lasers overlapped with ion beam
- Atomic resonances: scan of ion energy
- Detection
  - Fluorescence photons
  - Betas, ions

ISOLDE experiments



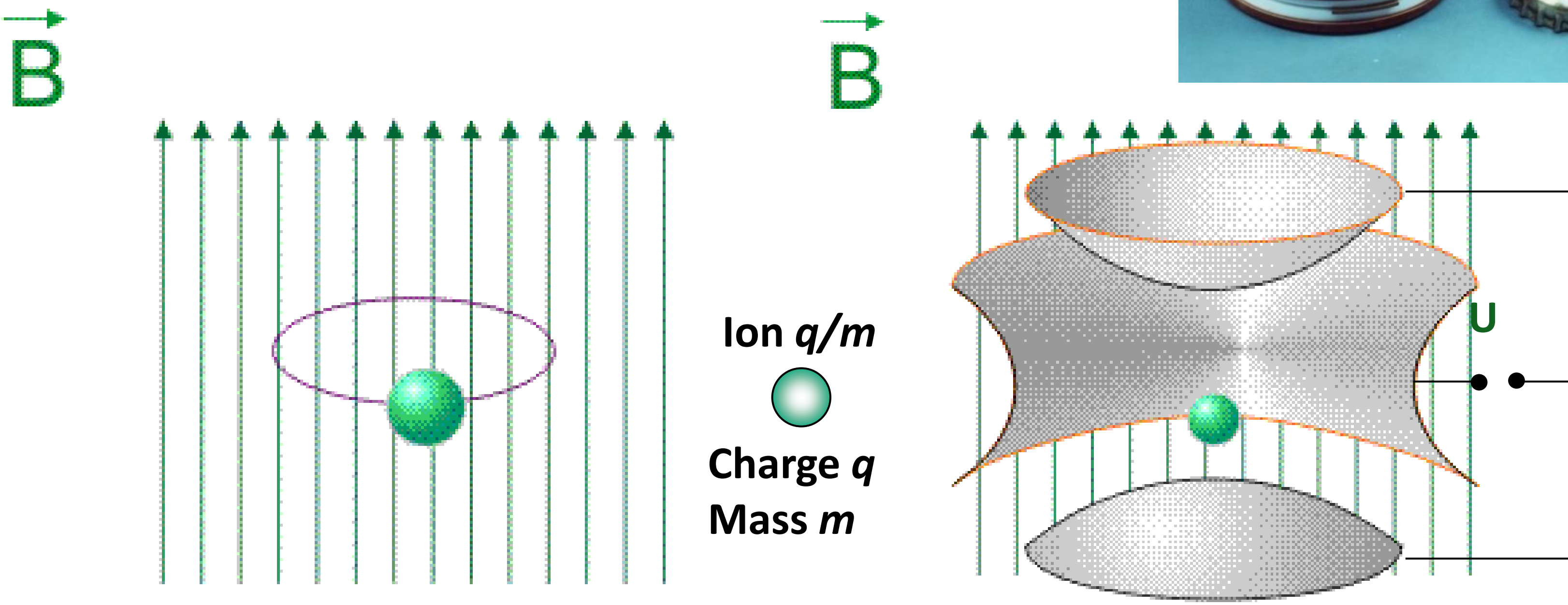
Shape staggering of mercury isotopes with RILIS



Nature Physics **14**, 1163 (2018)

Penning-trap mass spectrometry

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

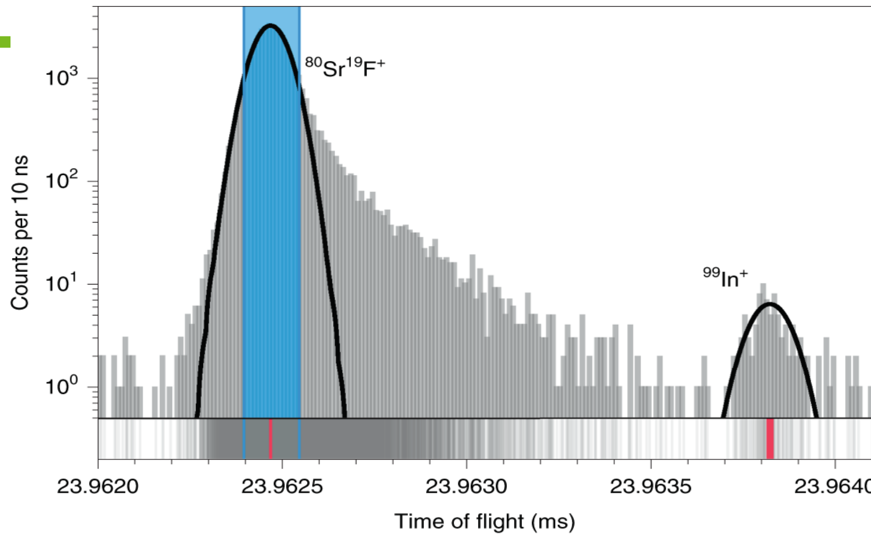


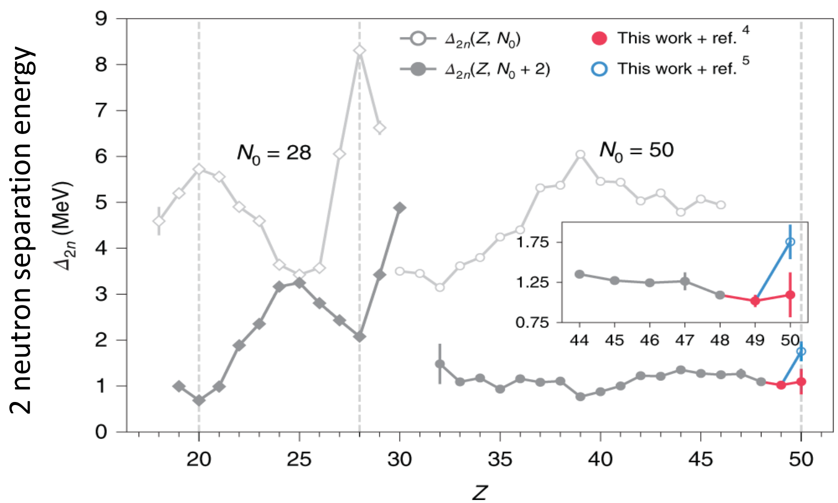
Free cyclotron frequency is inversely proportional to the mass of the ions!

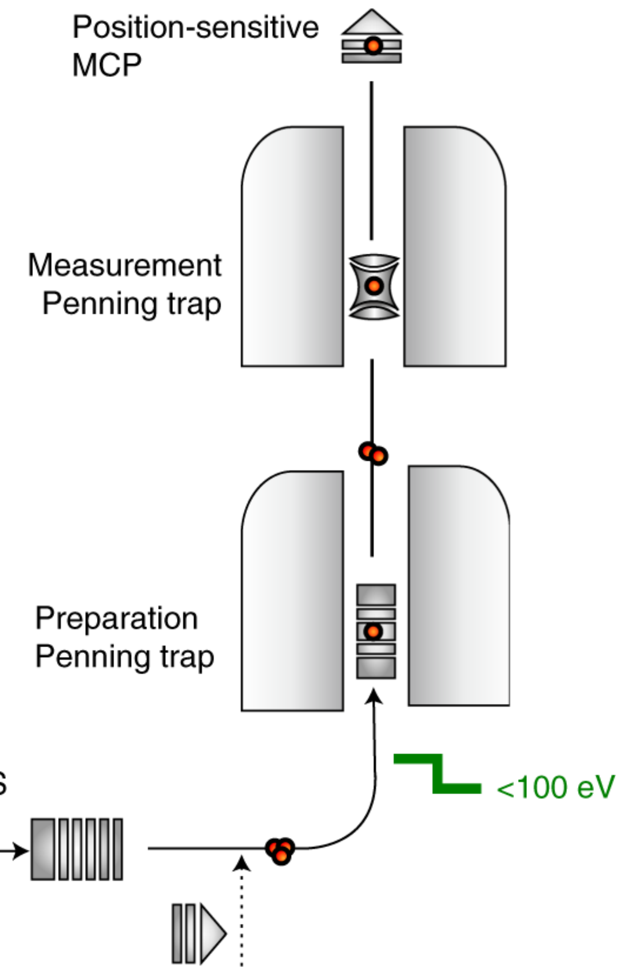
$$\omega_c = qB/m$$

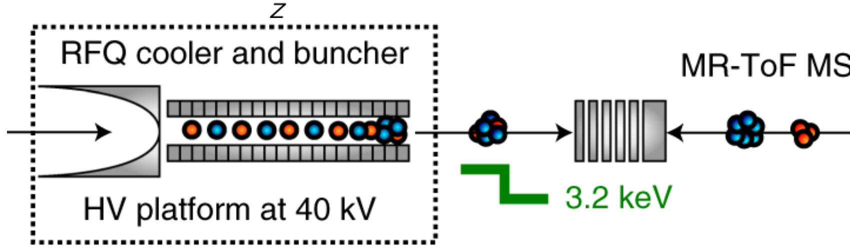
Masses around ^{100}Sn with ISOLTRAP

Nature Physics **17**, 1099 (2021)

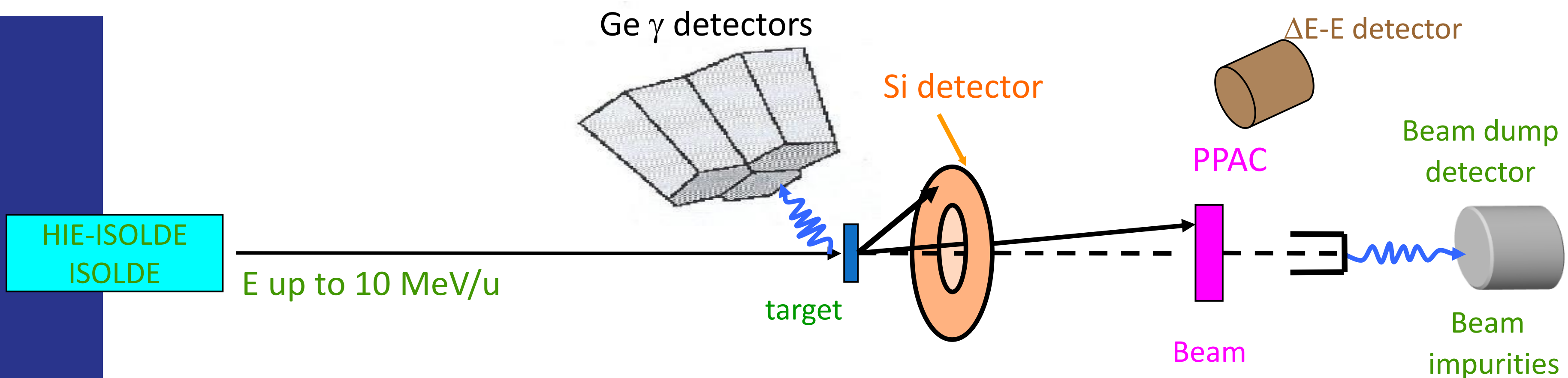




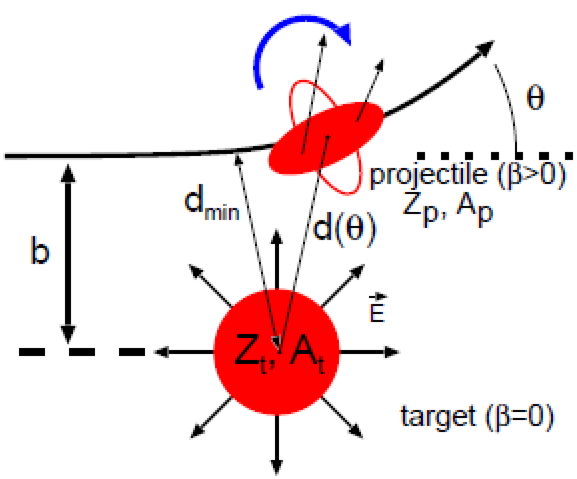


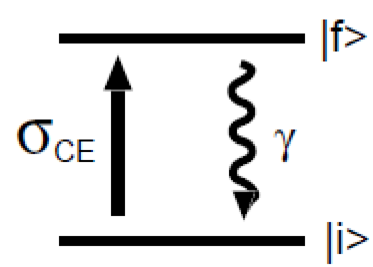


Coulomb excitation



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





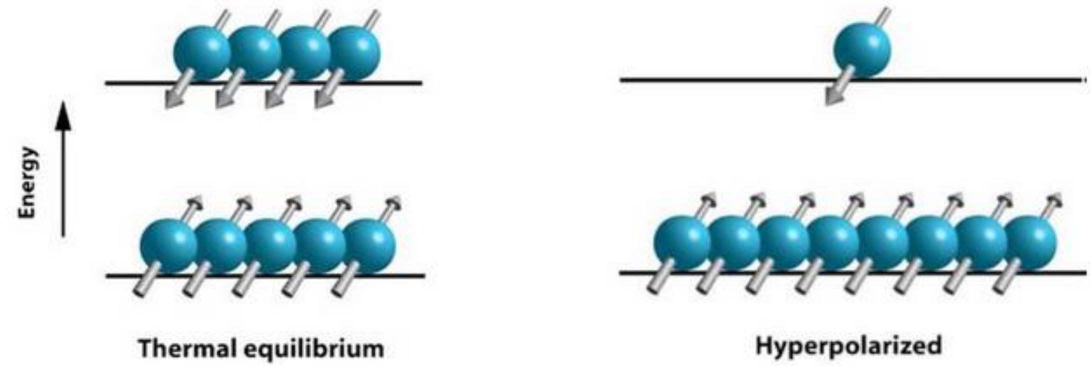
Observables: Transition energies and intensities

=> Determine new excited levels and study deformations

Beta-NMR in organic samples

Unstable probe nuclei with spin > 0 in magnetic field

Spin hyperpolarisation

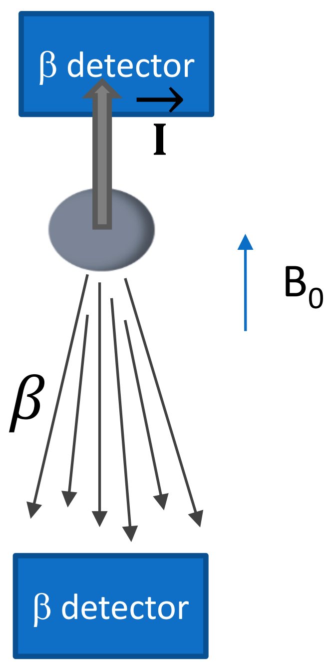


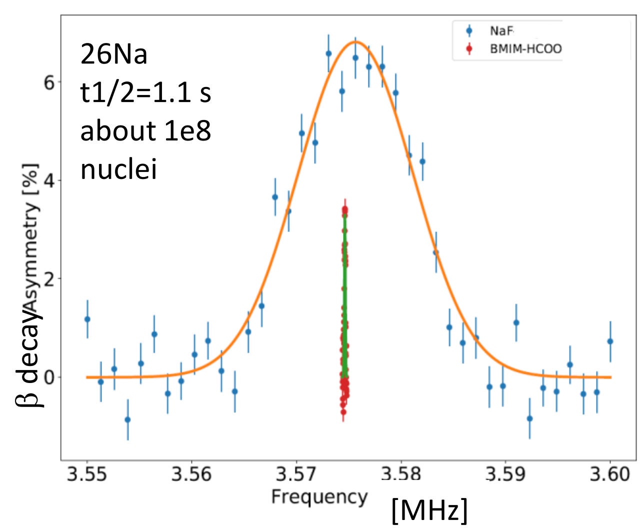
$P \approx 10^{-5} = \frac{1}{100{,}000}$ at 3T

$P \approx 50\% = \frac{50{,}000}{100{,}000}$

+ beta decay anisotropy

Beta decay, I>0





Up to 10 orders of magnitude more sensitive than conventional NMR,

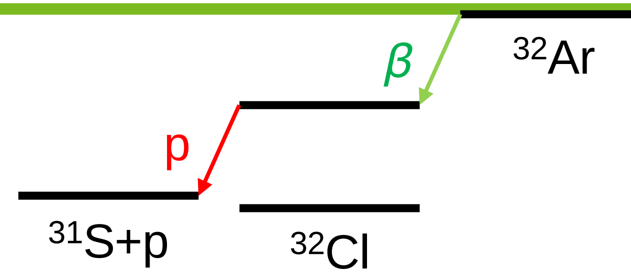
100 x more precise than solid state NMR

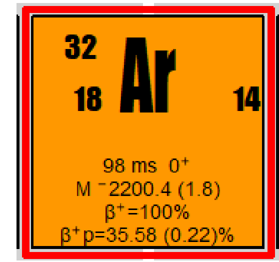
Applications in biology (metal ion interactions)
And nuclear physics: distribution of magnetisation

Phys. Rev. X 10, 041061 (2020)

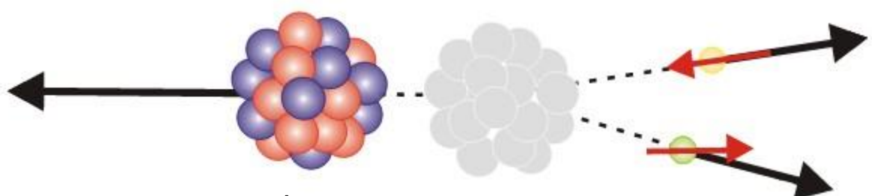
Scalar currents with ^{32}Ar

- Aim: search for scalar current contribution in predominantly vector current of β decay via β–ν correlation



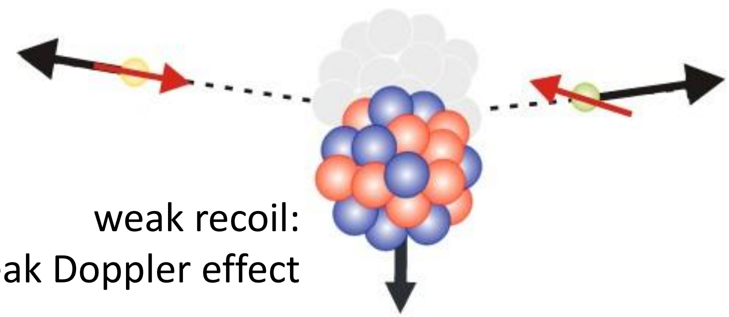


Vector current



strong recoil:
strong Doppler effect

Scalar current



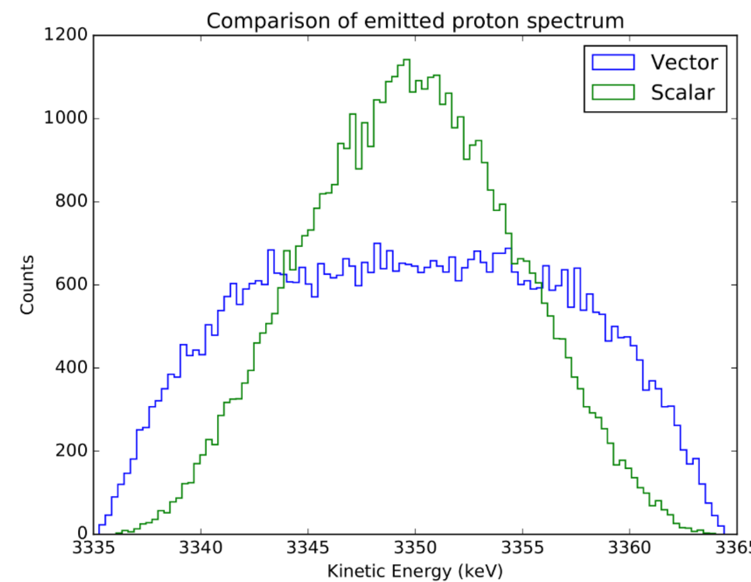
weak recoil:
weak Doppler effect

WISARD experiment

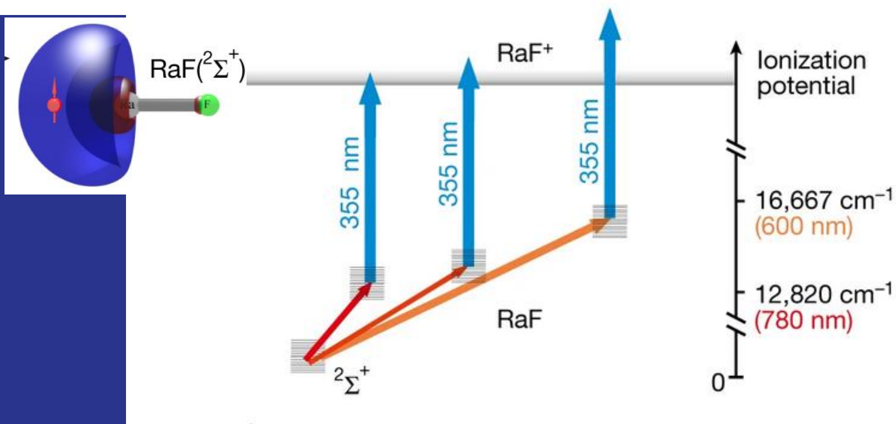
- Tool: β-delayed p decay of ^{32}Ar, Doppler effect on proton energy

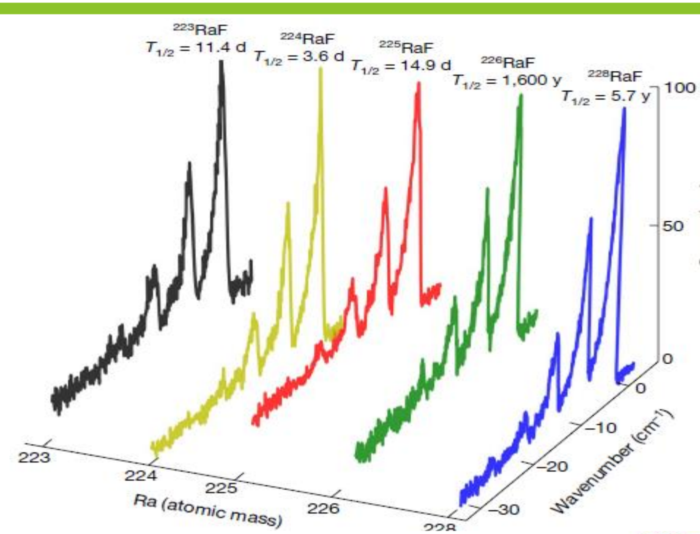
- Present limits on scalar current from βν correlation a_F = 0.65%

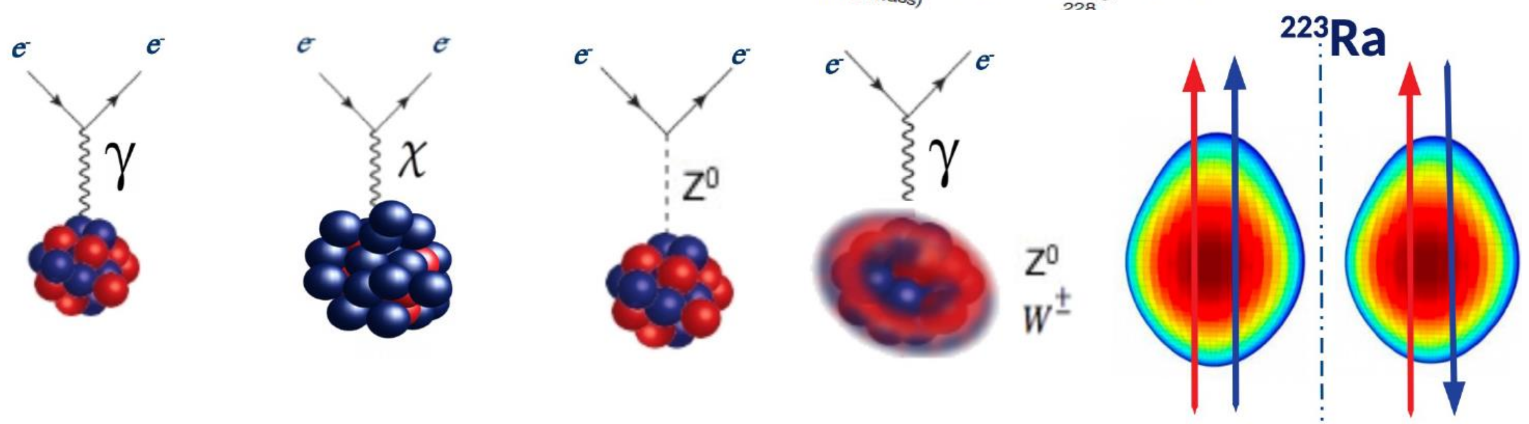
L. Hayen CRADLE++ (https://github.com/leenderthayen/CRADLE)



Radioactive molecules & Beyond SM







Low-energy SM tests

New e-N interactions?

P-violation

T-violation

- Nuclear matter
- Nuclear structure
- BSM searches

- Dark Matter properties?
- New forces?

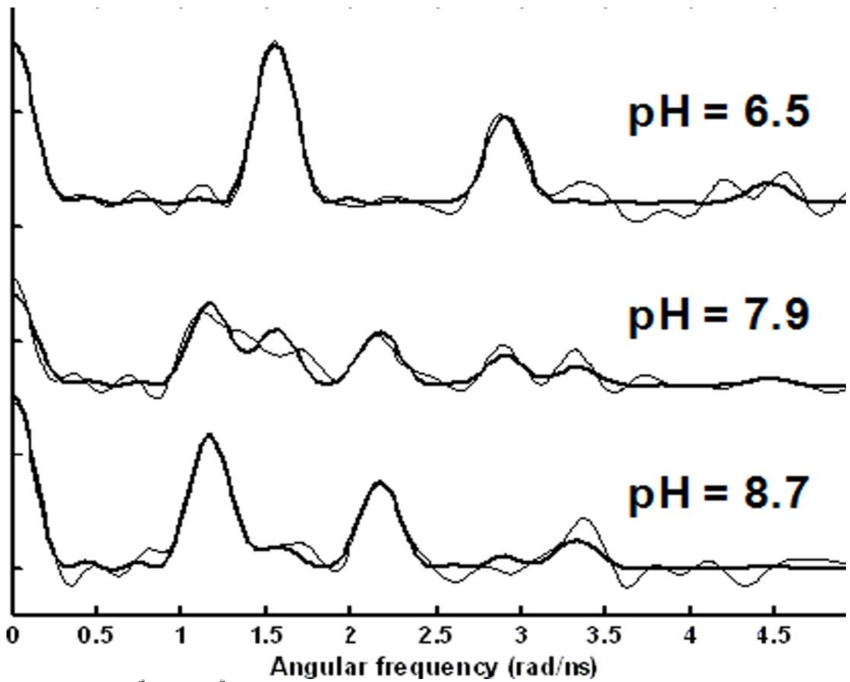
- Baryogenesis

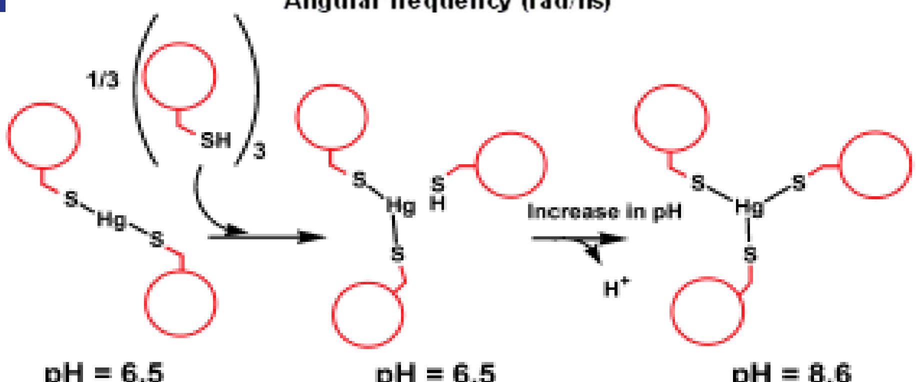
Nature 581, 396 (2020)

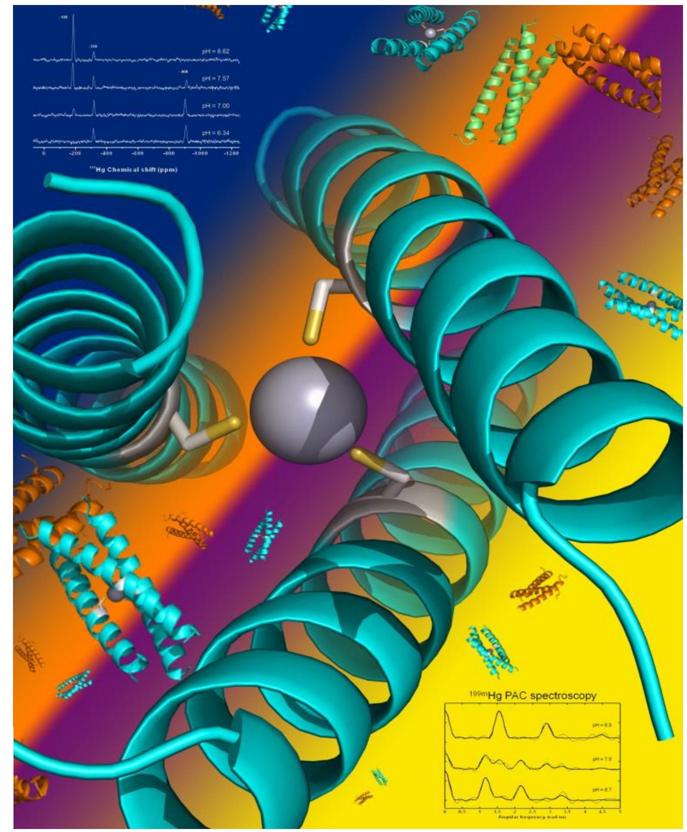
From M. Udrescu

Heavy-ion toxicity

- Studied with Perturbed Angular Correlation method



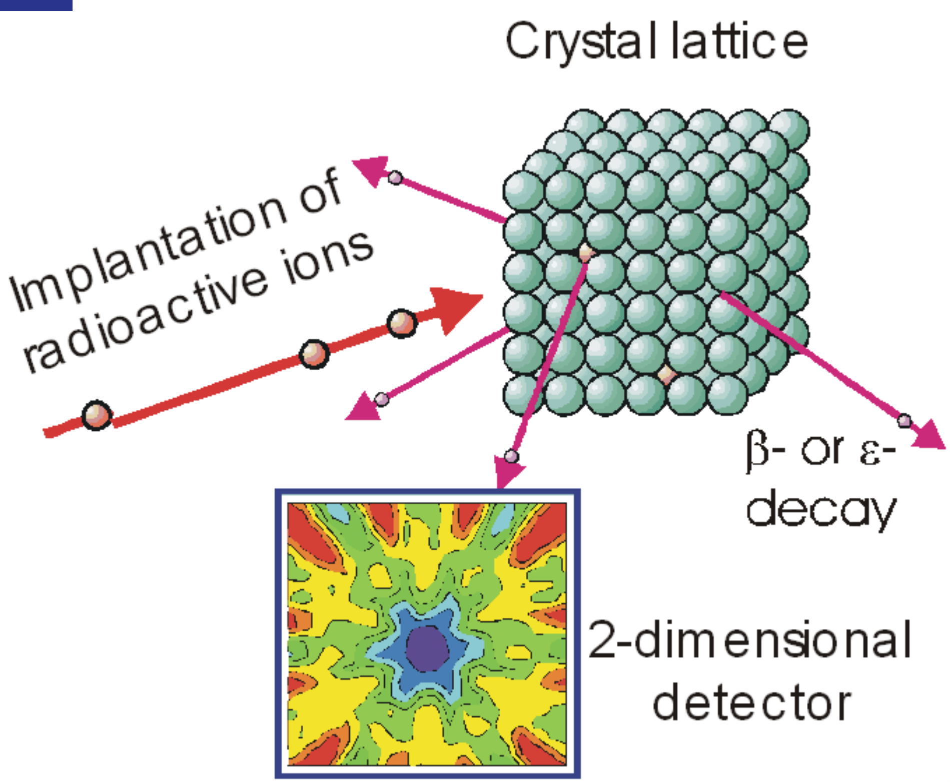


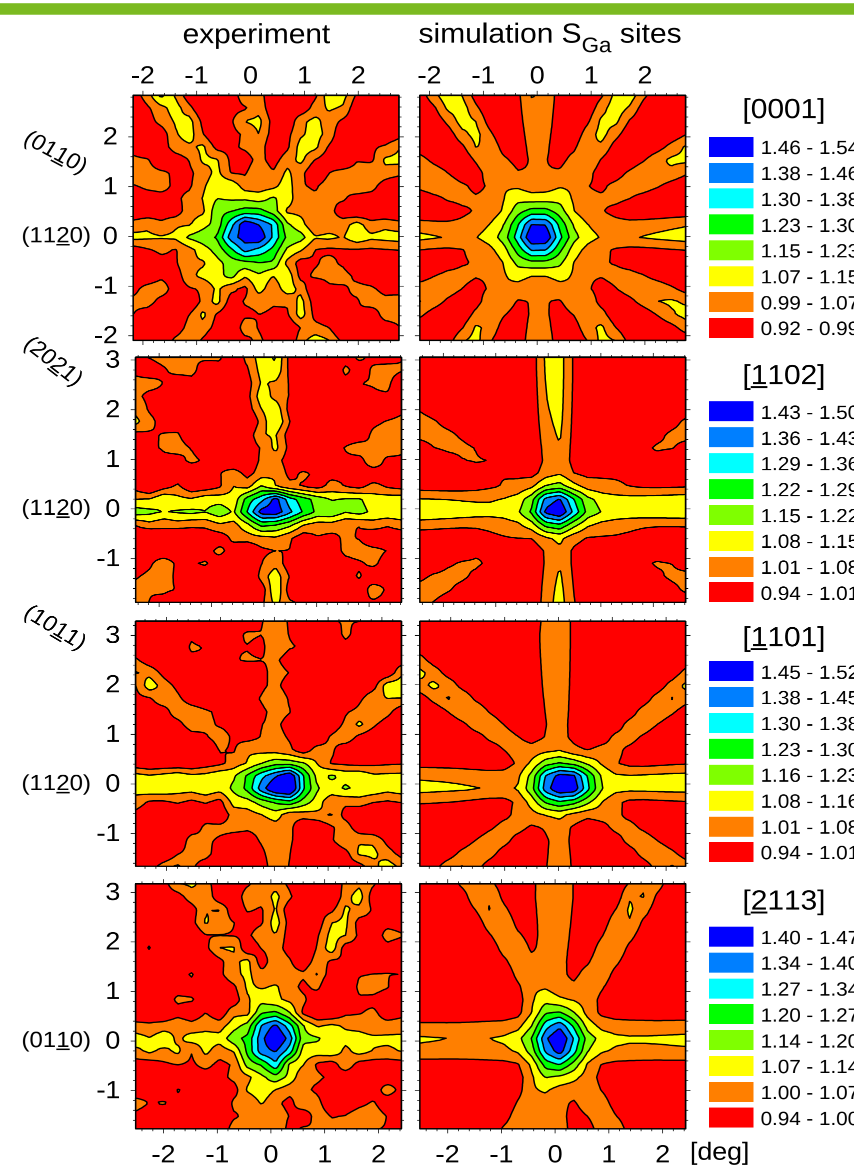


Vibenholt J et al, Inorg. Chem (2012)

Material science

- Emission channeling
  - ➢ Position of implanted ions



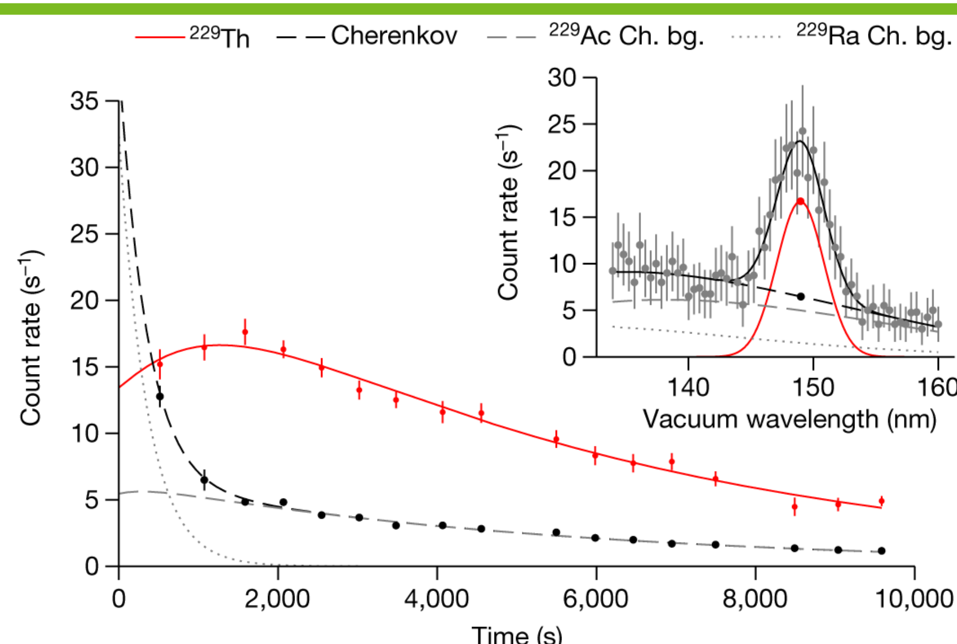


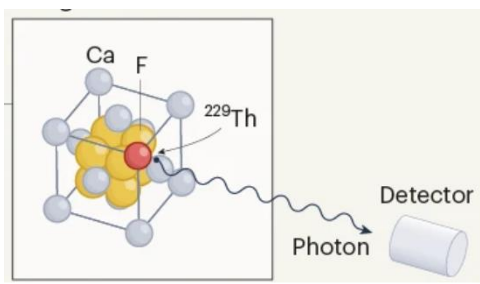
Emission channelling pattern

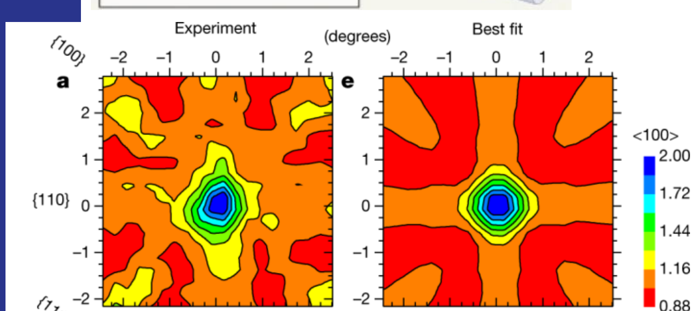
^{229m}Th: towards a nuclear clock with VUV and EC

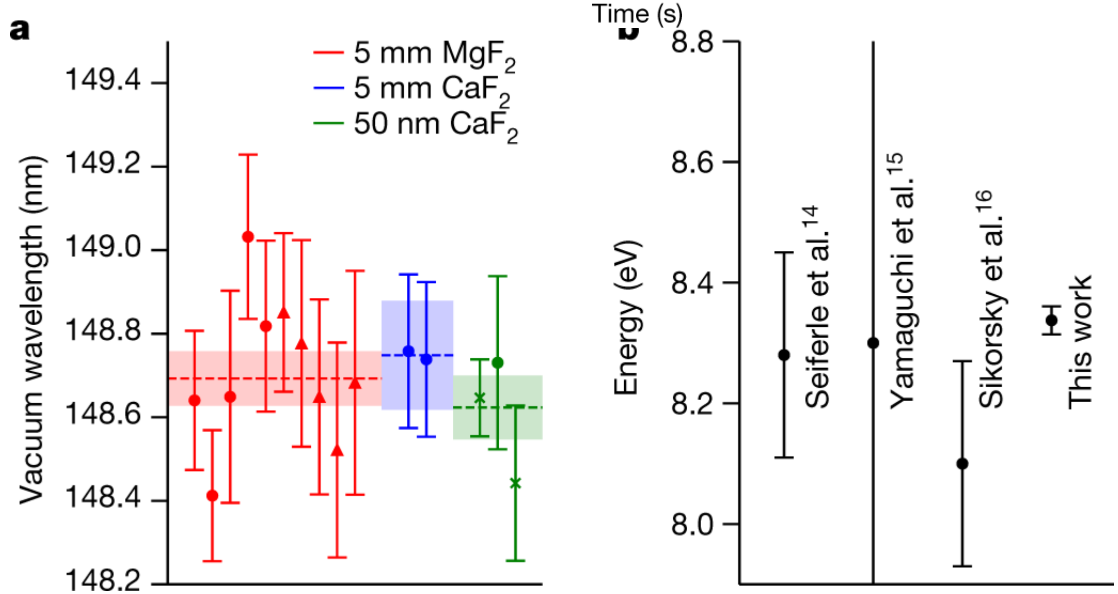
Determination of isomer energy with vacuum UV spectroscopy:

- 229Ac decay to 229mTh
- Internal conversion decay branch removed via study in a crystal
- CaF as host (wide band gap material)
- Implantation site verified with emission channeling









S Kraemer et al, *Nature* **617**, 706 (2023)

Video: https://videos.cern.ch/record/2297990

New medical isotopes

Collection at ISOLDE

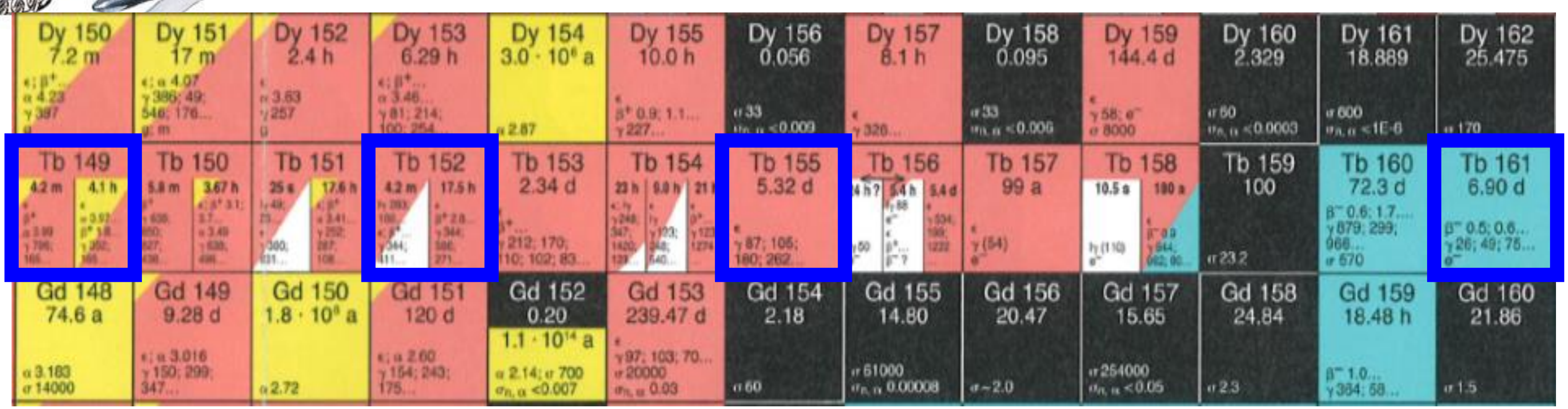
Radiochemical purification and labeling

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

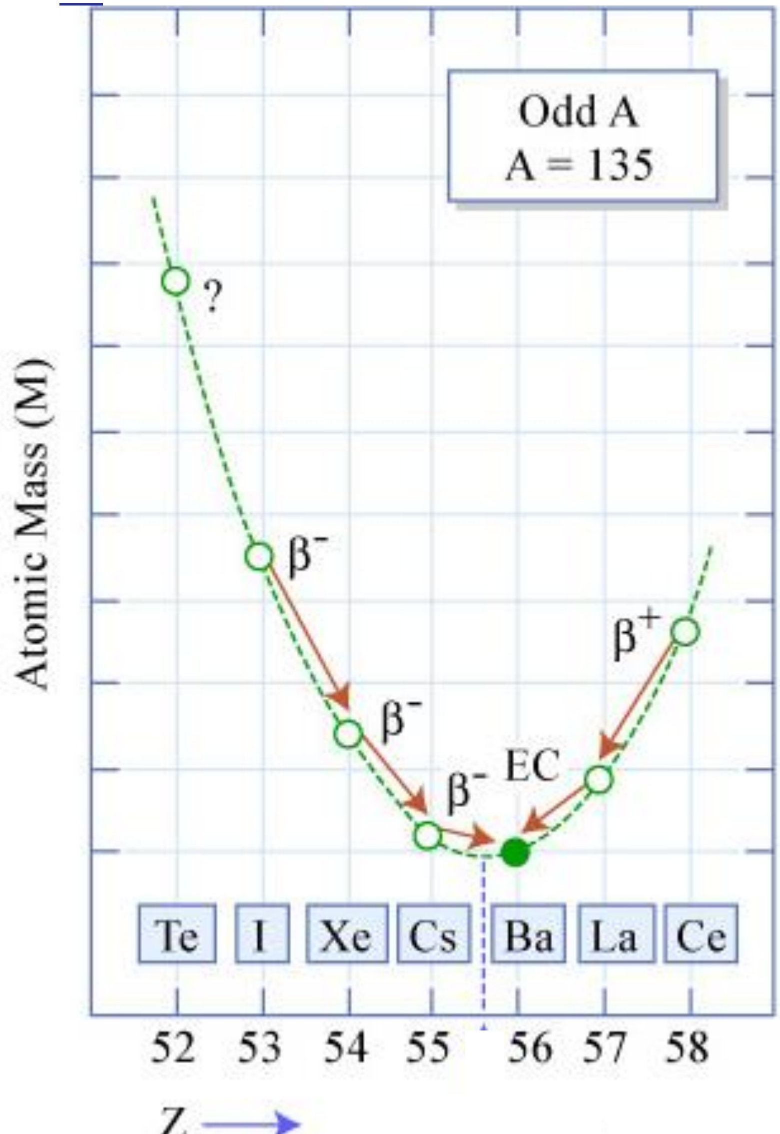


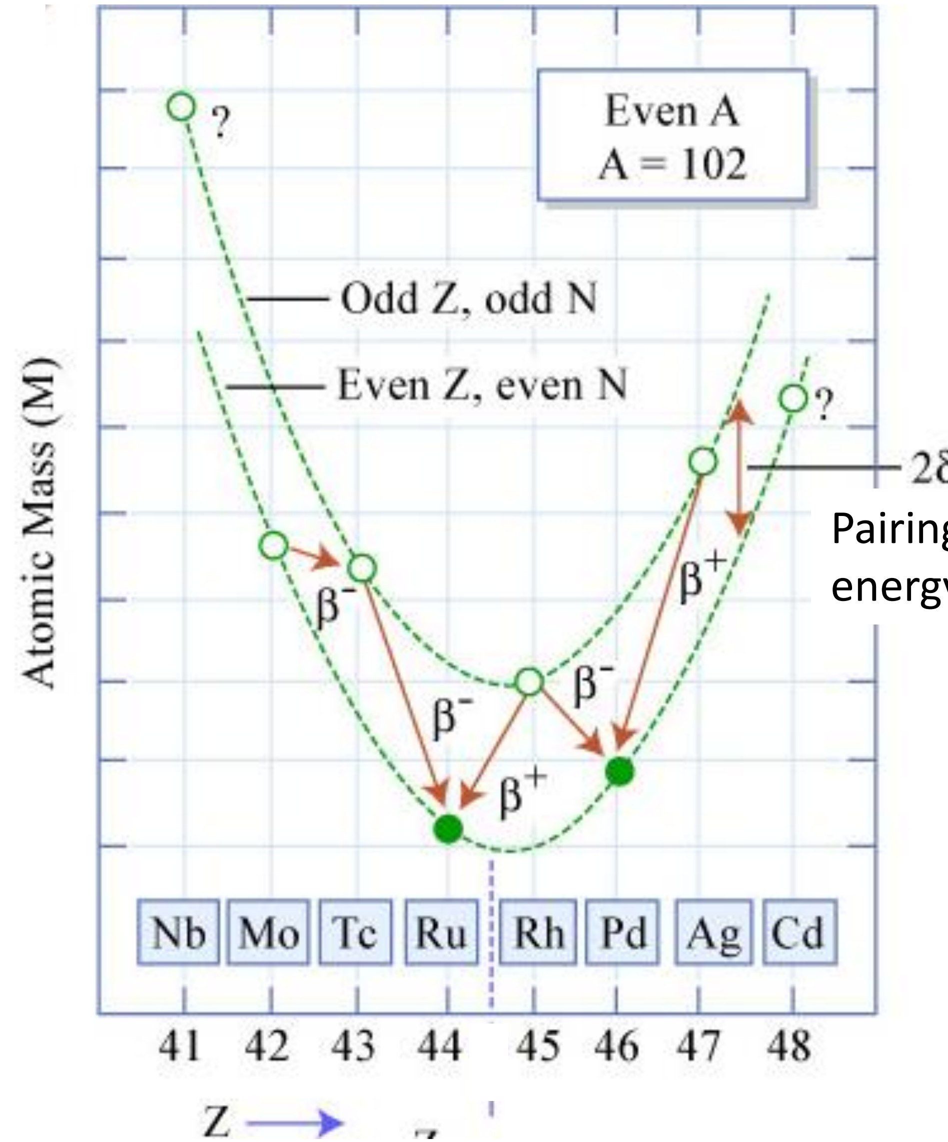
After U. Koster, C Müller et al. 2012 J. Nucl. Med. 53, 1951

Upcoming projects

- MIRACLS: laser spectroscopy in electrostatic trap (MR-TOF)
- PUMA: trapped antiprotons from AD to measure neutron skins
- BELAPEX: spin and parities of neutron emitting states with polarised nuclei
- Distribution of magnetisation and neutron halos

Nuclear pairing and masses



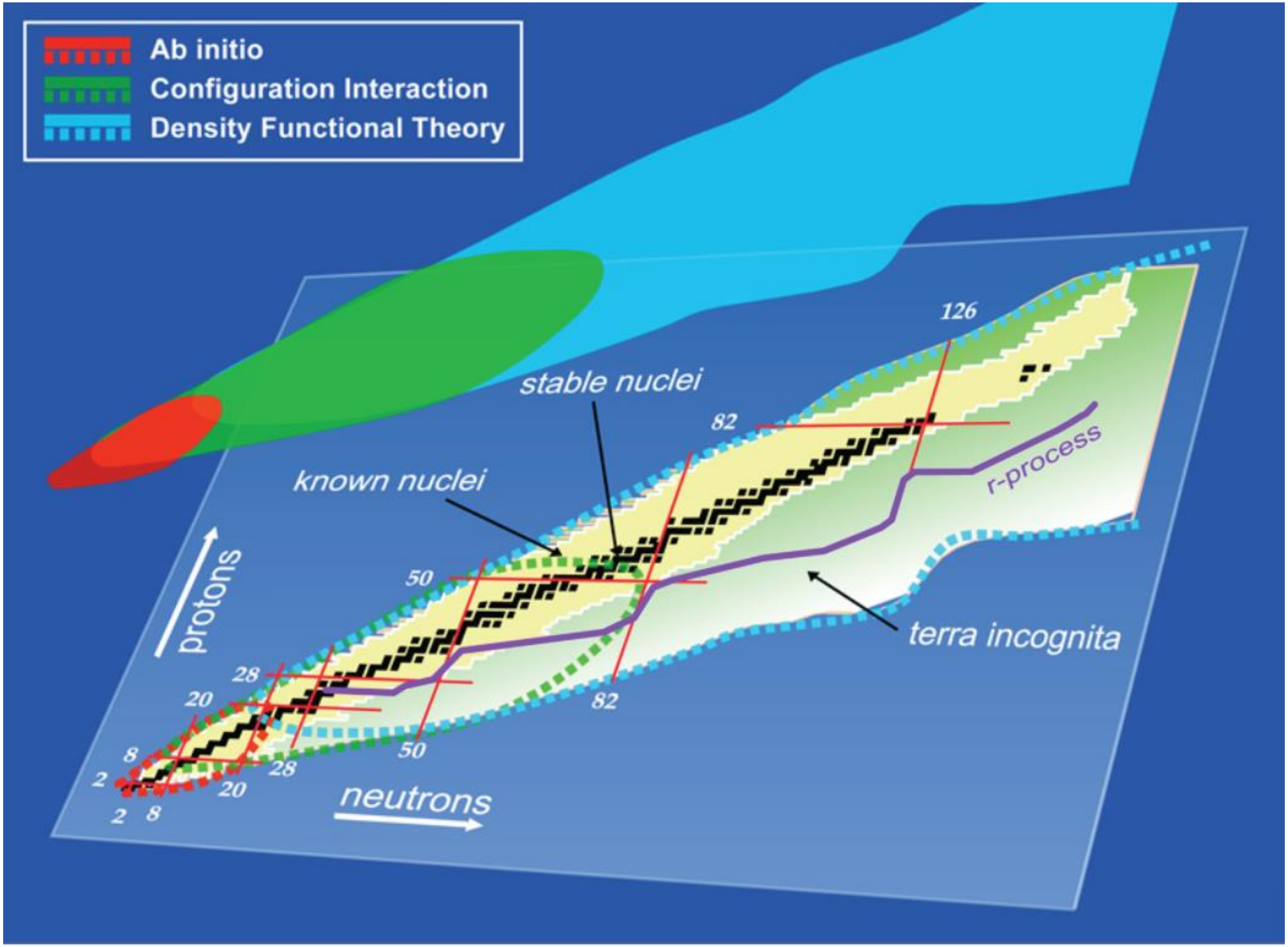


Pairing energy

Summary

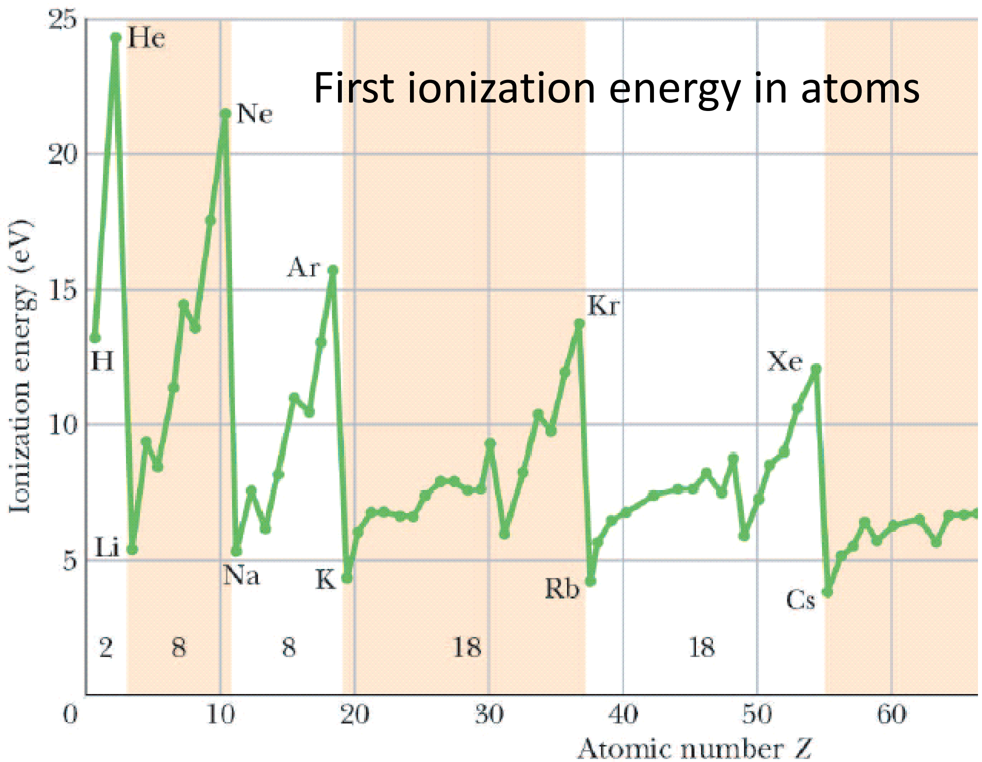
- Research topics with radionuclides:
  - Nuclear and atomic physics
  - Astrophysics
  - Fundamental studies
  - Applications
- Studied properties:
  - mass, radius, spin, moments, half-life, decay pattern, transition probabilities
- Examples of ISOLDE experimental techniques
  - Laser spectroscopy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

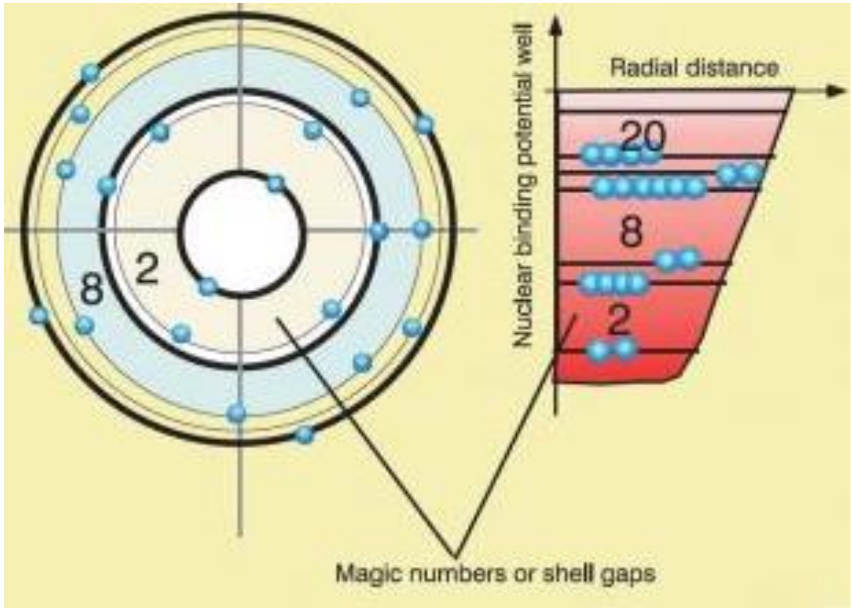
Nuclear models



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'



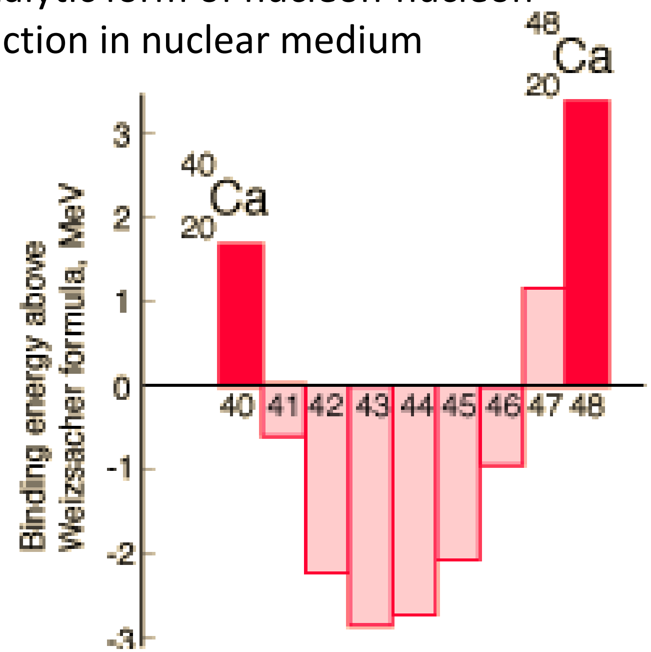


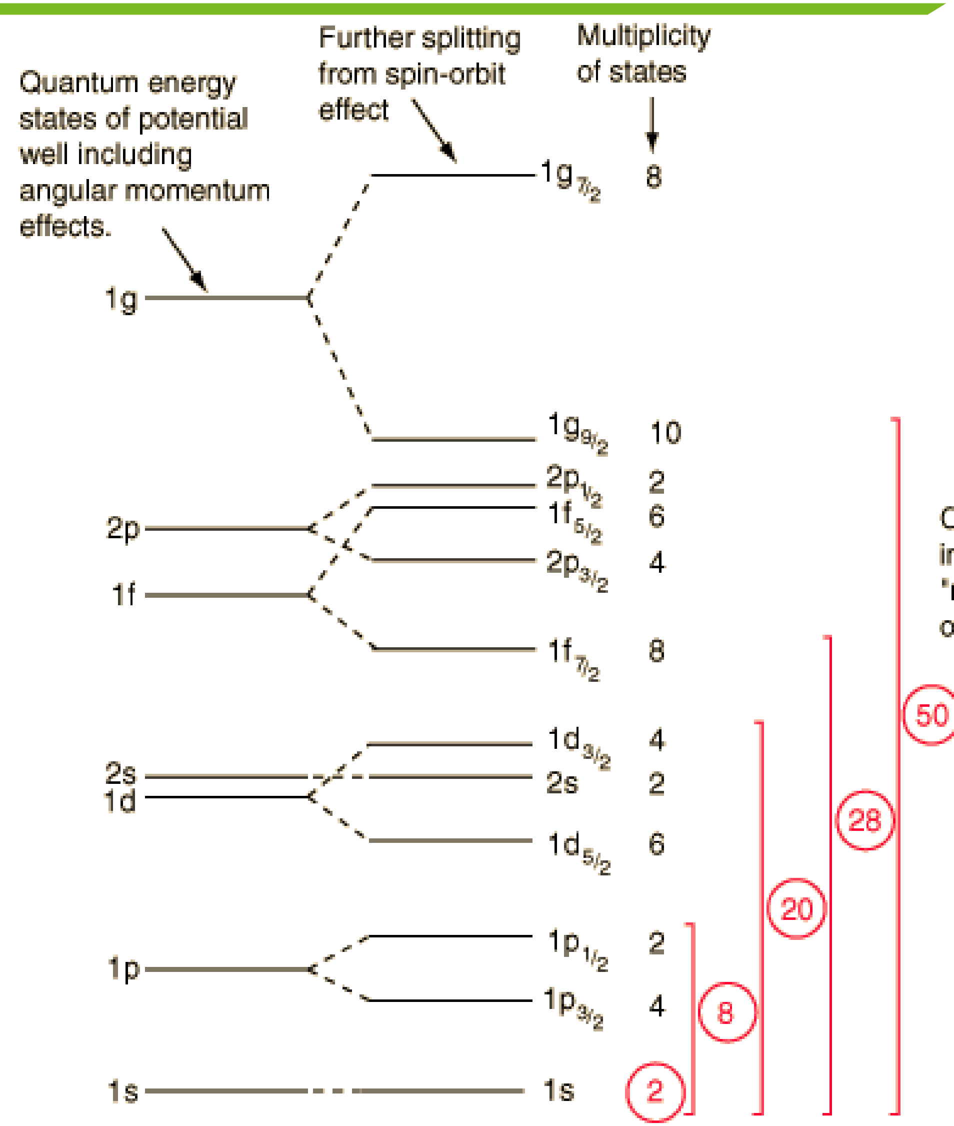
Challenge: created for stable nuclei, is it valid for radionuclides?

Nuclear shell model

Differences to atomic shell model

- No central potential but a self-created one
- Nucleon-nucleon interaction has tensor (non-central) components
- Two kinds of nucleons
- In ground state: all odd number of protons or neutrons couple to spin 0
- Strong spin-orbit coupling changes magic numbers: 8,20,28,50,…
- No analytic form of nucleon-nucleon interaction in nuclear medium





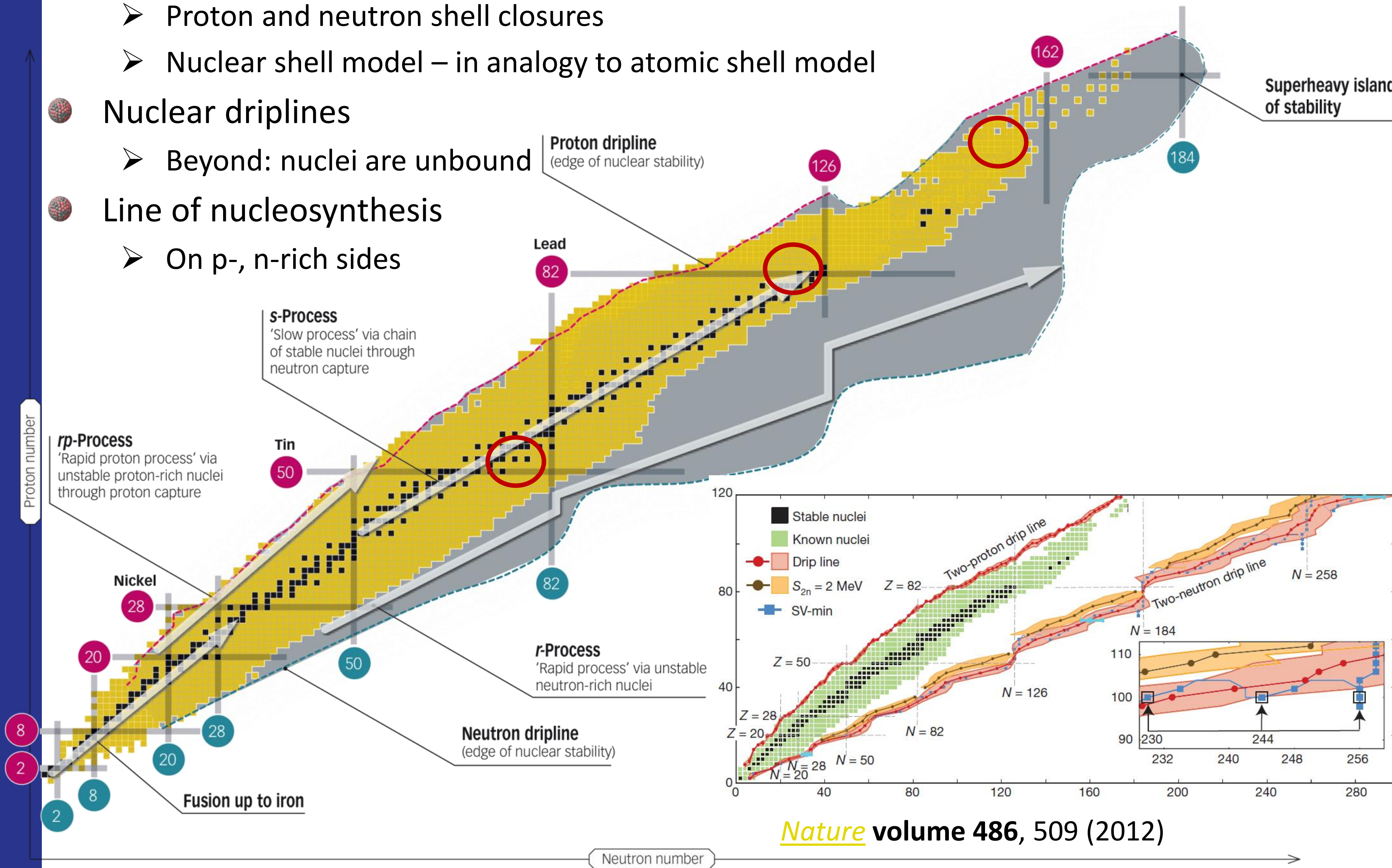
Summary

- Nuclear physics investigates the properties of nuclei and of the underlying nucleon-nucleon interaction
- Rich history and many nuclei discovered
- All 4 fundamental interactions at play
  - details of strong interaction are not known
- Nuclear landscape – over 3000 known nuclei and even more predicted
- Nuclear decays transform one nucleus into another
- Nuclear properties – reveal features of nuclear interaction
- Open questions in nuclear physics
  - How to describe various properties in with a fundamental interaction
  - How to make predictions
  - How do regular patterns emerge
- Nuclear models
  - Each is better in one respect and worse in another
  - Aim: describe known properties and predict new ones

- We are getting closer to the answers with radioactive ion beam facilities, such as ISOLDE -> Lecture 2 and 3

Chart of nuclei

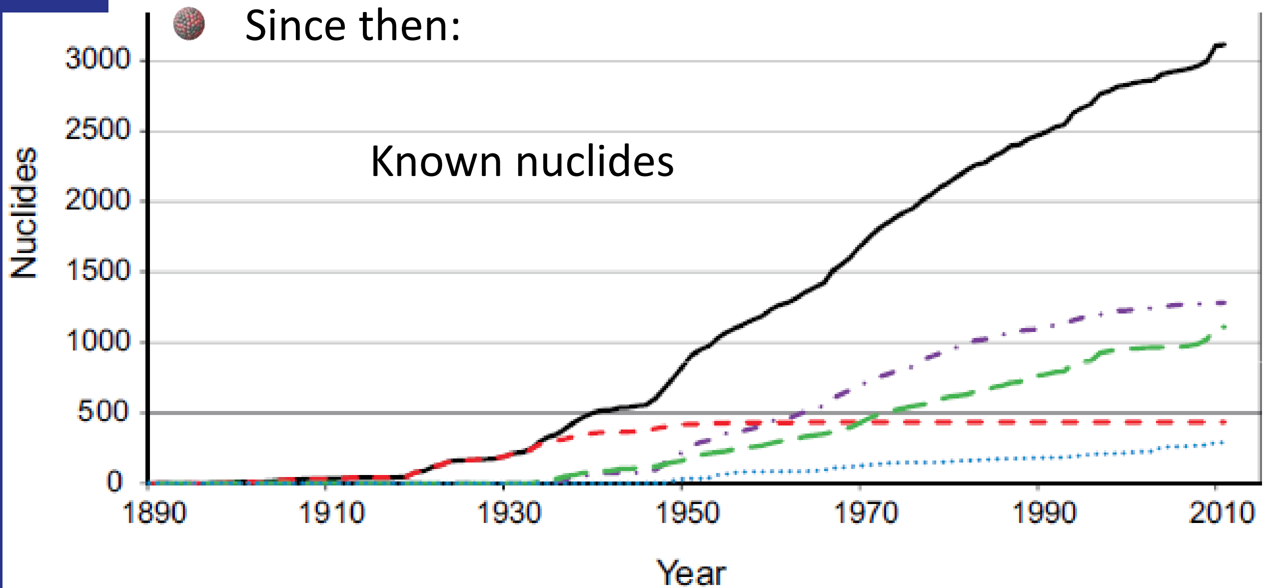
- Magic numbers:
  - Proton and neutron shell closures
  - Nuclear shell model – in analogy to atomic shell model
- Nuclear driplines
  - Beyond: nuclei are unbound
- Line of nucleosynthesis
  - On p-, n-rich sides



[Nature](#) **volume 486**, 509 (2012)

Key dates

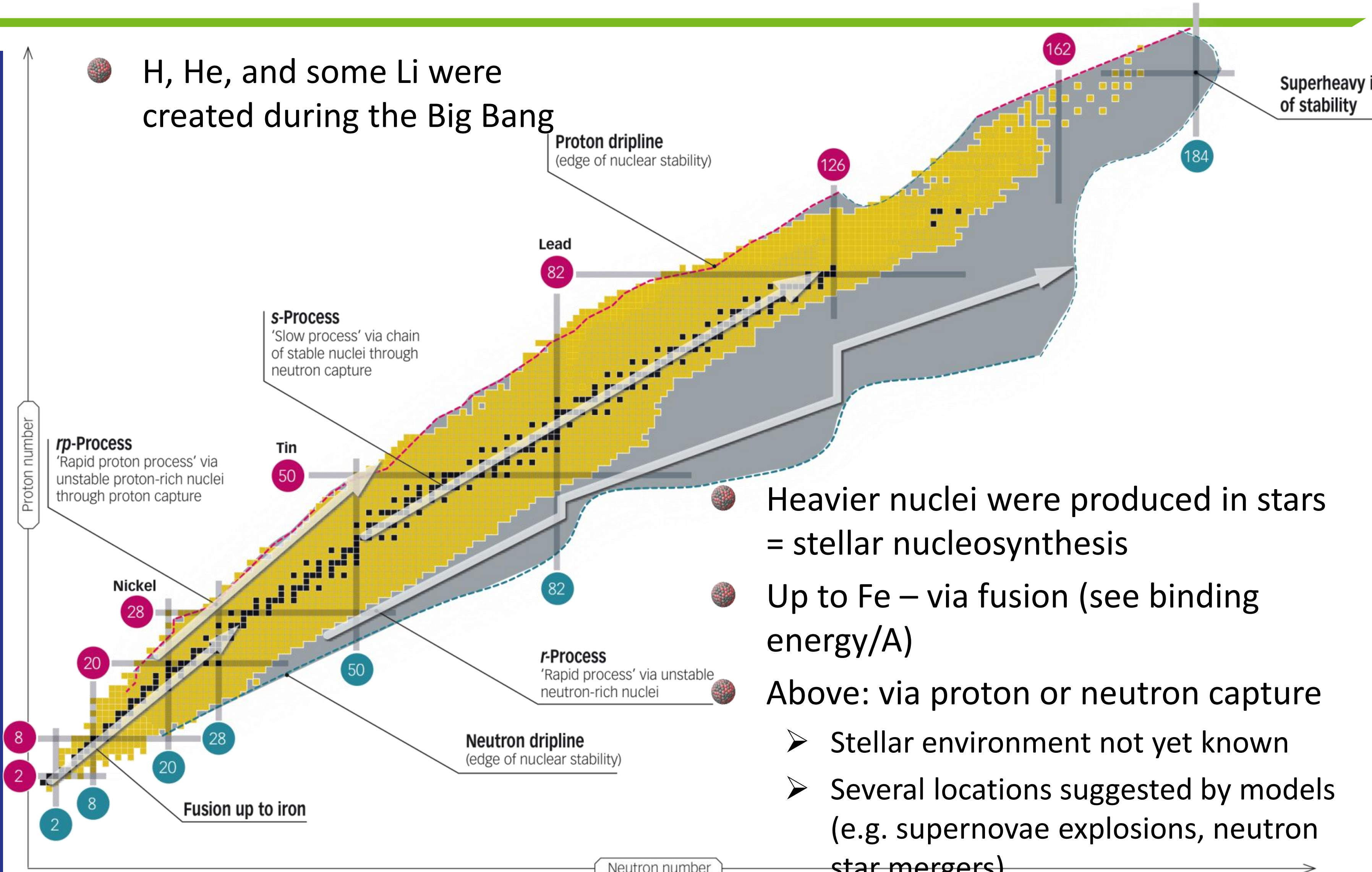
- 1896: Becquerel, discovery of radioactivity
- 1898: Skłodowska-Curie and Curie, isolation of radium
- 1911: Rutherford, experiments with α particles, discovery of atomic nucleus
- 1932: Chadwick, neutron discovered
- 1934: Fermi, theory of β radioactivity
- 1935: Yukawa, nuclear force mediated via mesons
- 1949: Goeppert-Meyer, Jensen, Haxel, Suess, nuclear shell model
- 1964: Gell-Mann, Zweig, quark model of hadrons
- 1960'ties: first studies on short-lived nuclei
- Since then:



Today: the exact form of the nuclear interaction is still not known, but we are getting to know it better and better with many dedicated facilities

Creation of nuclides

- H, He, and some Li were created during the Big Bang



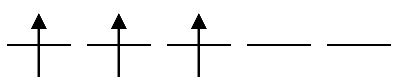
- Heavier nuclei were produced in stars = stellar nucleosynthesis
- Up to Fe – via fusion (see binding energy/A)
- Above: via proton or neutron capture
  - Stellar environment not yet known
  - Several locations suggested by models (e.g. supernovae explosions, neutron star mergers)
  - Need nuclear physics data to constrain models

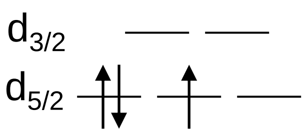
Binding energy

- Binding energy = mechanical energy required to disassemble a whole into separate parts
- Bound system = interaction energy is less than the total energy of each separate particle
  - Energy is needed to separate the constituents
  - Mass of constituents = mass of bound system + binding energy (positive)
- Atoms:
  - Mass of electrons + mass of nucleus > mass of the atom
- Nuclei:
  - Mass of protons + mass of neutrons > mass of the nucleus
  - E.g for 12C: 11.18 GeV > 11.27 GeV (difference of 90 MeV = binding energy)
- Nucleons:
  - It looks like mass of quarks < mass of nucleon (ca 10MeV < 1GeV)
  - But quarks don't exist as separate particles, thus 10MeV is a rest mass of quarks inside a nucleon. It would take an enormous energy to isolate quarks, so as separate particles they would be much heavier, so:
  - mass of constituents > mass of nucleon

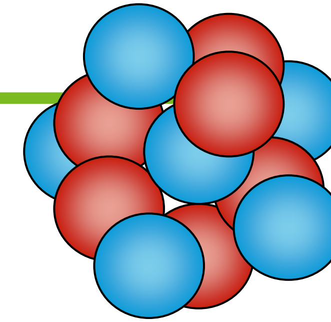
Atomic vs nuclear structure

Atoms		Nuclei
shell model: e^- fill quantized energy levels	**Description**	shell model (but not only): p and n separately fill quantized energy levels
n, *l*, m_ℓ, *s*, parity $(-1)^\ell$	**Quantum numbers**	*n*, *l*, m_ℓ, *s*, parity $(-1)^\ell$
max. *S* possible (due to Coulomb force): $J = L + S = \Sigma l_i + \Sigma s_i$ or $J = \Sigma j_i = \Sigma(l_i + s_i)$	**Lowest en. levels**	min. *S* possible (due to strong force pairing): $J = \Sigma j_i = \Sigma(l_i + s_i)$
weak	**Spin-orbit coupling**	strong
for 3 electrons in a *d* orbital		for 3 nucleons in a *d* orbital
calculated by solving Schrödinger equation with central potential dominated by nuclear Coulomb field	**Energy levels**	not easily calculated; nucleons move and interact within a self-created potential





Nuclear models



Nucleus = N nucleons interacting with strong force

The many-body problem
(the behavior of each nucleon influences the others)

Can be solved exactly for N < 10

For N > 10 : approximations

Shell model
• only a small number of particles are active

Approaches based on the mean field
• no inert core
• but not all the correlations between particles are taken into account

Nucleon-Nucleon force unknown
No complete derivation from the QCD

Different forces used depending on the method chosen to solve the many-body problem

Nuclear force and experiments

Our understanding of nuclear force is based on three types of experimental information:

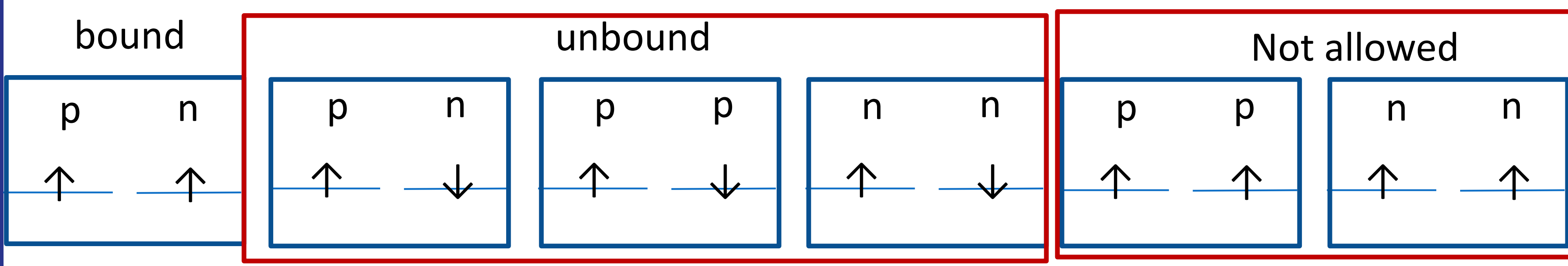
1. results of nucleon-nucleon (proton-proton, neutron-neutron, and proton-neutron) scattering experiments. Some of these experiments are conducted with spin-polarized projectiles/targets.
2. Nuclear binding energies and masses, especially for light nuclei.
3. Nuclear structure information, such as energies, spins, parities, magnetic and quadrupole moments, especially for light nuclei.

After http://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/LECTURE/Fraser/L5.pdf

Does di-neutron exist?

If nuclear force is charge independent, why does system with 1n and 1p exist (deuteron), but that with 2n and 2p, etc don't? And what binds neutrons in neutron stars?

- Nuclear force is charge independent, but it depends on the spin, i.e.
  - Spin-up to spin-up (↑ ↑) interaction of 2 protons is the same as for 2 neutrons
  - But ↑↓ interaction of 2p is different than ↑ ↑ for 2p or 2n
- And there is Pauli principle
- As a result => A system of n and p can form either a singlet or triplet state. The triplet state is bound, but not the singlet (we know it from deuteron). A system of 2n or 2p can only form a singlet (due to Pauli principle), so no bound state of 2p or 2n, etc, exists.



- Neutron stars exist thanks to gravity

See more details in http://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/LECTURE/Fraser/L5.pdf

Discovery of nuclei

- Discovery Project at MSU – documenting discoveries of nuclei

Discovery of Nuclides Project

Criteria

Home

Discovery criteria:

We decided on two main guidelines for the claim of discovery of a nuclide:
(1) Clean identification, either by decay curves and relationships to other known isotopes, particle or γ-ray spectra, or unique mass and Z identification.
(2) The discovery had to be reported in a refereed journal.

In most cases the discovery is easy to determine. However, there are many cases which are controversial for many different reasons.

We would appreciate any help in resolving the controversial cases. If you have any information that might be helpful or if you disagree with an assignment please send an email.

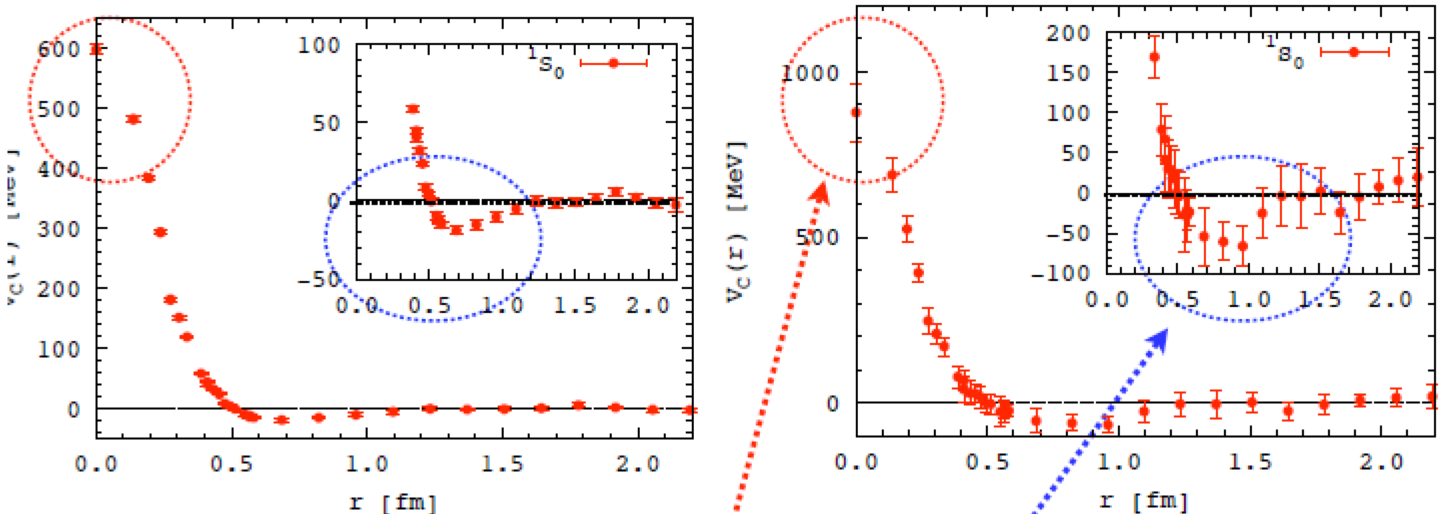
http://www.nscl.msu.edu/~thoennes/isotopes/criteria.html

Modelling nuclear interaction

1. Meson-exchange theory of Yukawa (1935)
2. Fujita-Miyazawa three-nucleon potential (1955)
3. First phase-shift analysis of *NN* scattering data (1957)
4. Gammel-Thaler, Hamada-Johnston and Reid phenomenological potentials (1957–1968)
5. Bonn, Nijmegen and Paris field-theoretic models (1970s)
6. Tuscon-Melbourne and Urbana *NNN* potential models (late 70's–early 80's)
7. Nijmegen partial wave analysis (PWA93) with $\chi^2/\mathrm{dof} \sim 1$ (1993)
8. Nijm I, Nijm II, Reid93, Argonne v_{18} and CD-Bonn (1990s)
9. Effective field theory (EFT) at N^3LO (2004–)
10. Can we constrain parameters in EFT from lattice QCD? In the mesonic sector, constraining EFT parameters from LQCD has been definitely demonstrated. With petascale and soon exascale, this will happen in the baryonic sector as well!

NN potential from QCD

$m_\pi \simeq 0.53$ GeV $\qquad$ $m_\pi \simeq 0.37$ GeV



- stronger repulsive core at short distance.
- a little stronger attraction at intermediate distance.

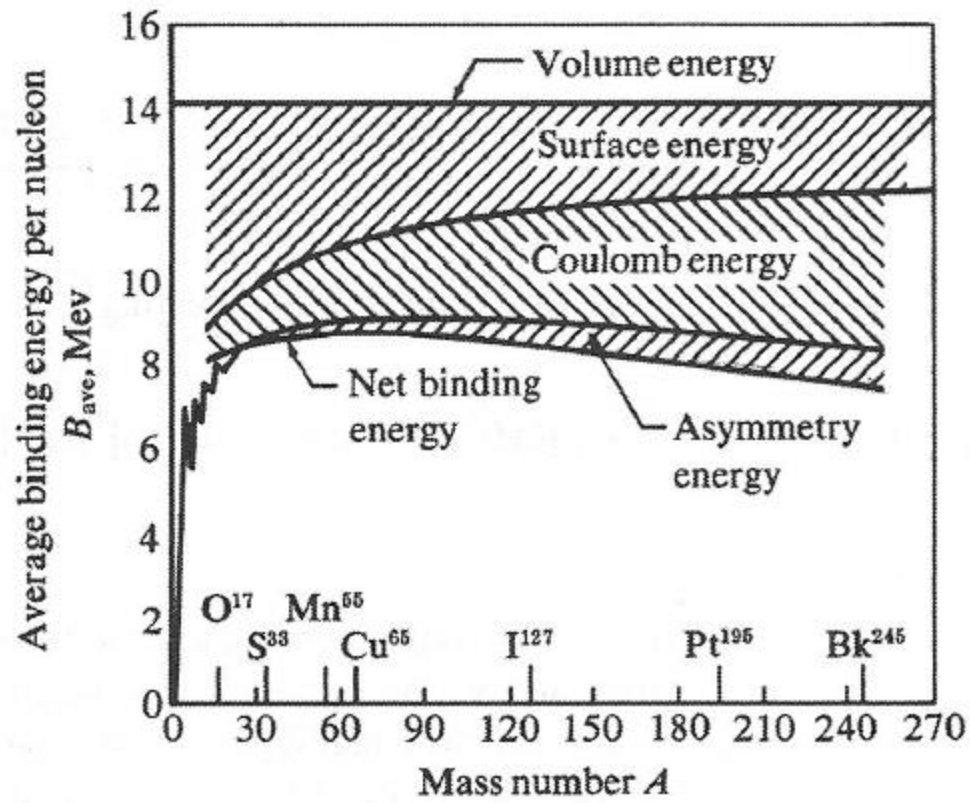
$m_\pi \simeq 0.13$ GeV ?

Aoki, Ishii, Matsuda

Liquid drop model

- The volume term coefficient $a_V = 15.56$ MeV.
- The surface term coefficient $a_S = 17.23$ MeV.
- The Coulomb term coefficient $a_C = 0.7$ MeV.
- The asymmetry term coefficient $a_V = 23.285$ M
- The pairing term

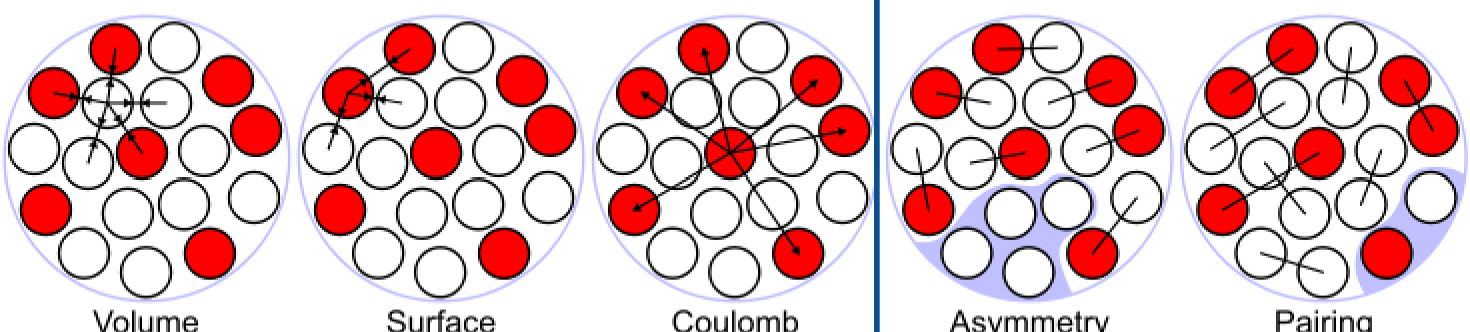
$$\delta = \begin{cases} -\frac{11}{\sqrt{A}} \text{ [MeV]} & \text{even-even nuclei} \\ 0 \text{ [MeV]} & \text{odd-even nuclei} \\ +\frac{11}{\sqrt{A}} \text{ [MeV]} & \text{odd-odd nuclei} \end{cases}$$



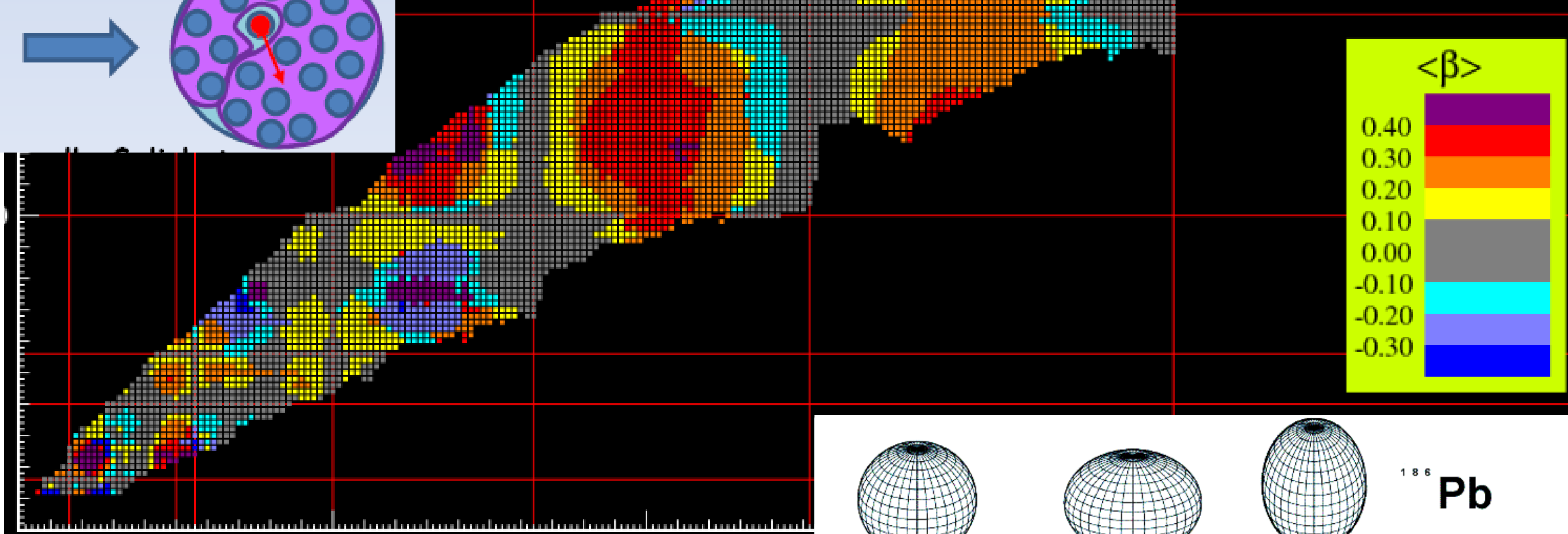
Liquid drop model

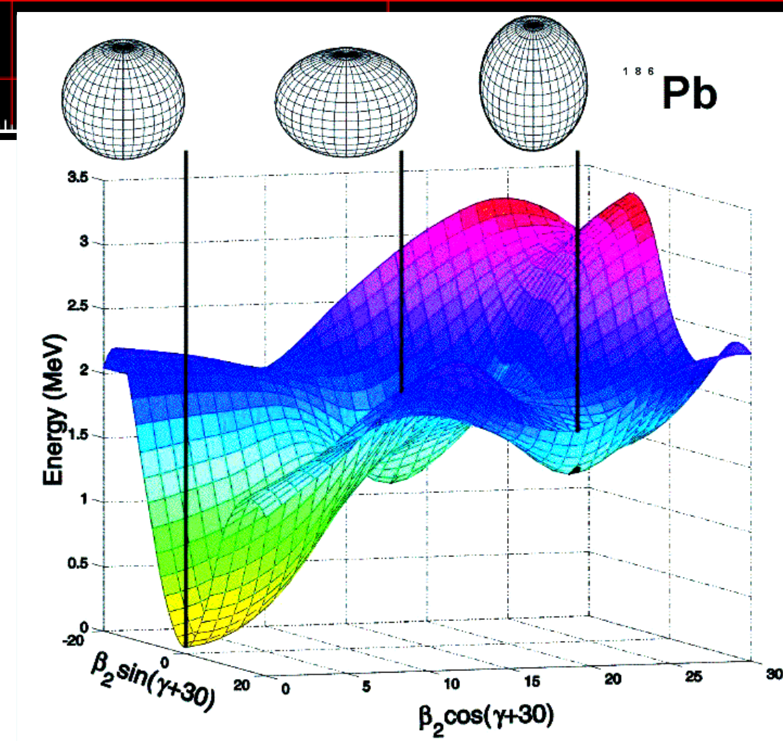
- Based on the experimental binding energy per nucleon
- Nuclei have nearly constant density => they behave like a drop of uniform (incompressible) liquid
- Forces on the nucleons on the surface are different from those inside
- Describes general features of nuclei, but not details
- $$B(Z,A) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(N-Z)^2}{A} + \delta(A,Z)$$

Additional terms -> shell model



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

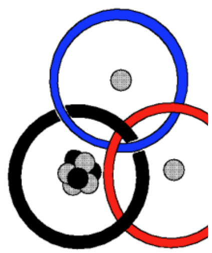
Halo nuclei

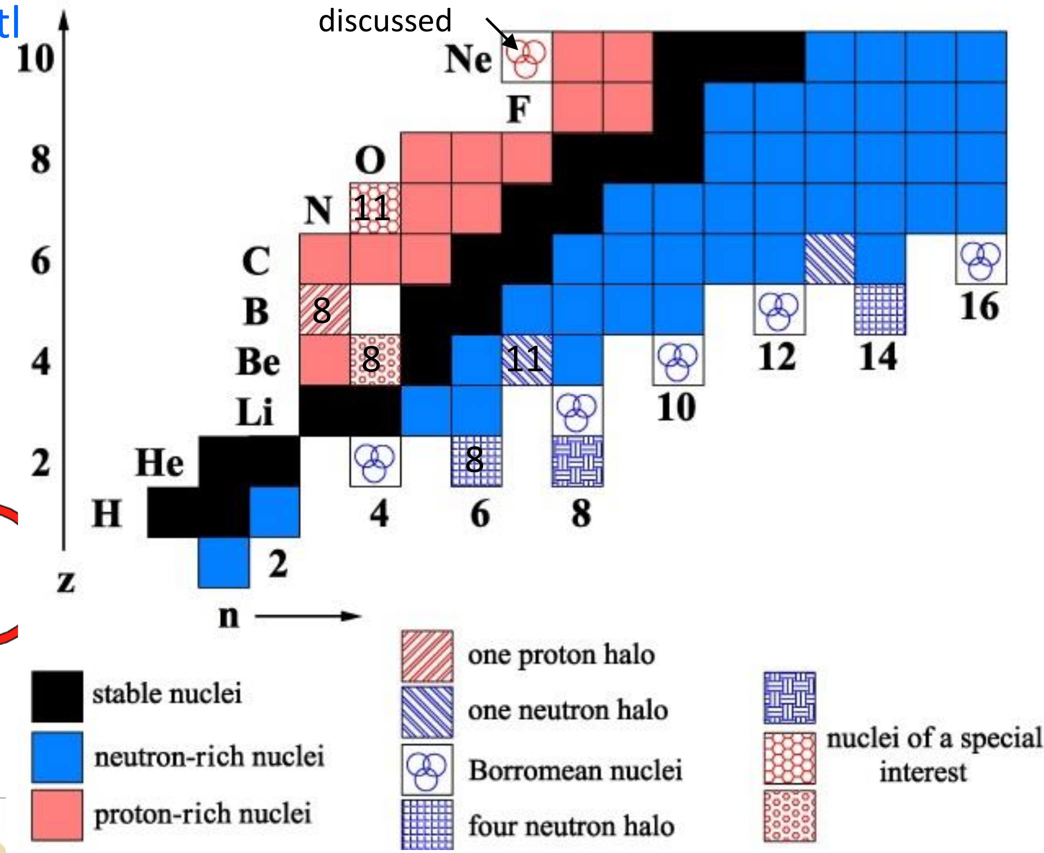
Halo: nucleus built from a core and at least one neutron/proton with spatial distribution much larger tl

1985: first halo system identified: ^{11}Li
2013: half-dozen other halos known

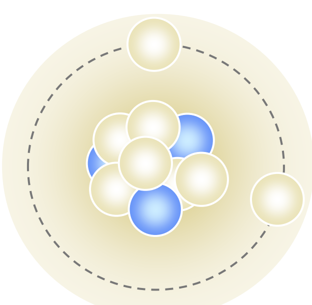
Nuclear structure and core-halo interaction still not well understood

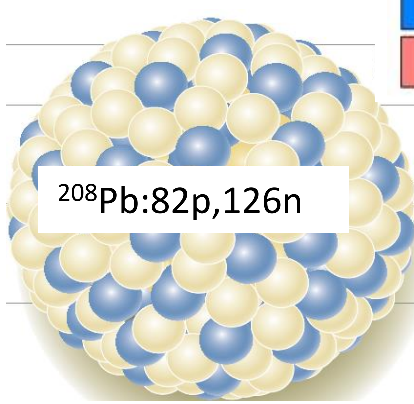
=> Crucial information:
Mass/binding energy
Spin-parity
Magnetic moment
Mass and charge radius
Quadrupole moment
Energy level scheme





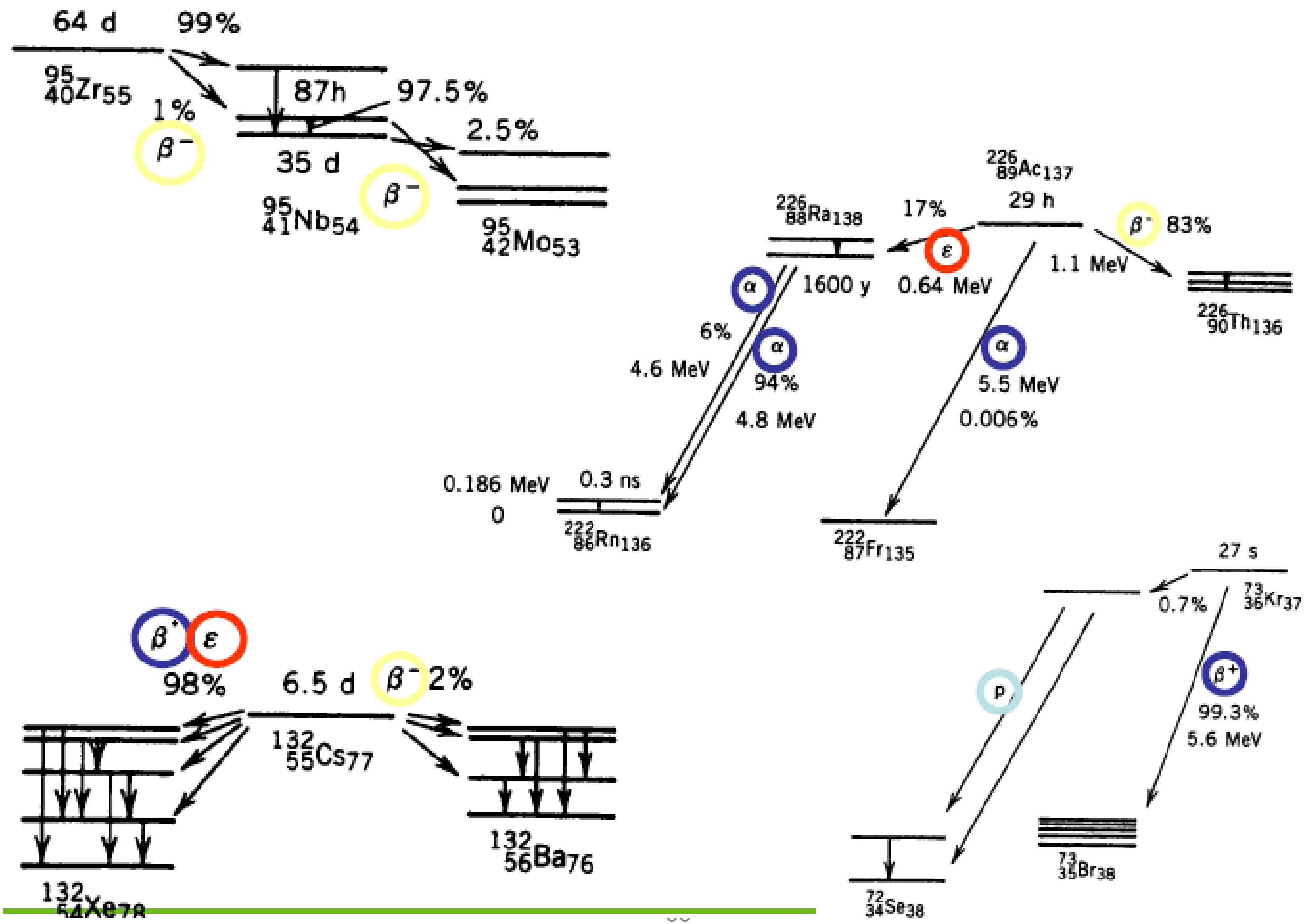
^{11}Li:3p,8n



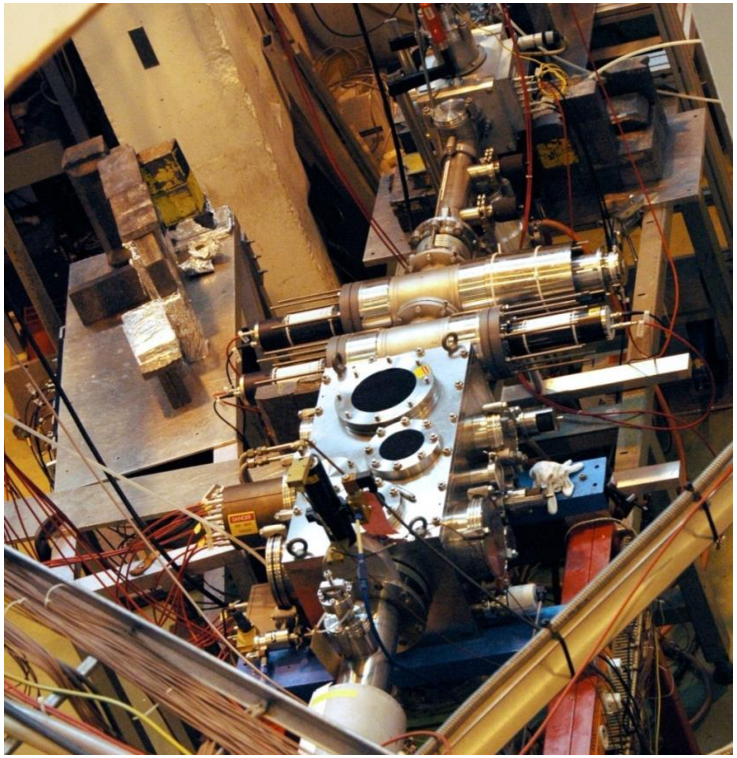


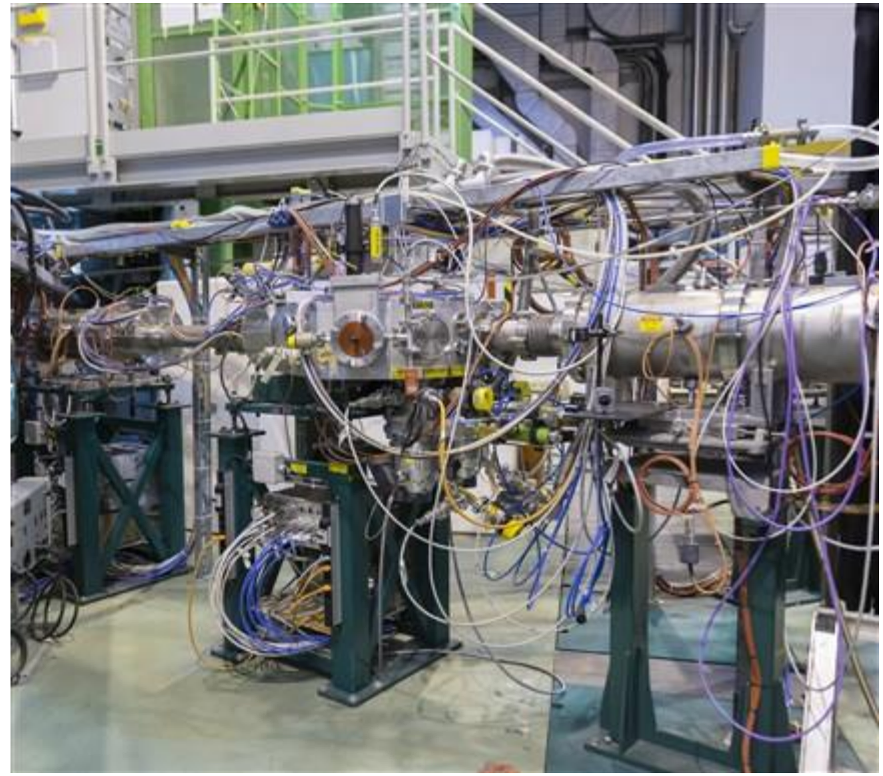
Recent achievements: charge radii of ^{11}Li (Uni Mainz/GSI), ^{6}He (Argonne)

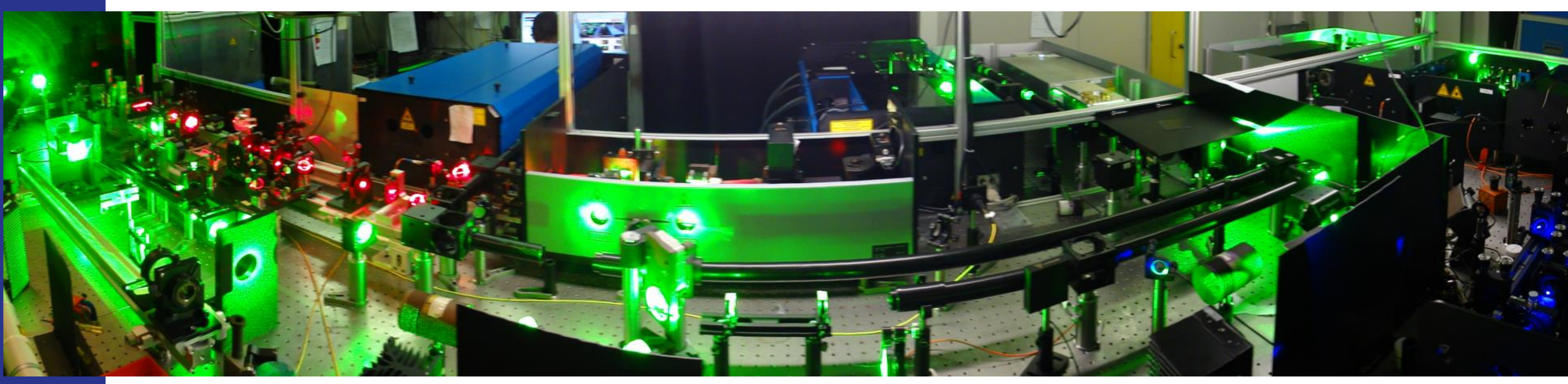
Examples of nuclear decays



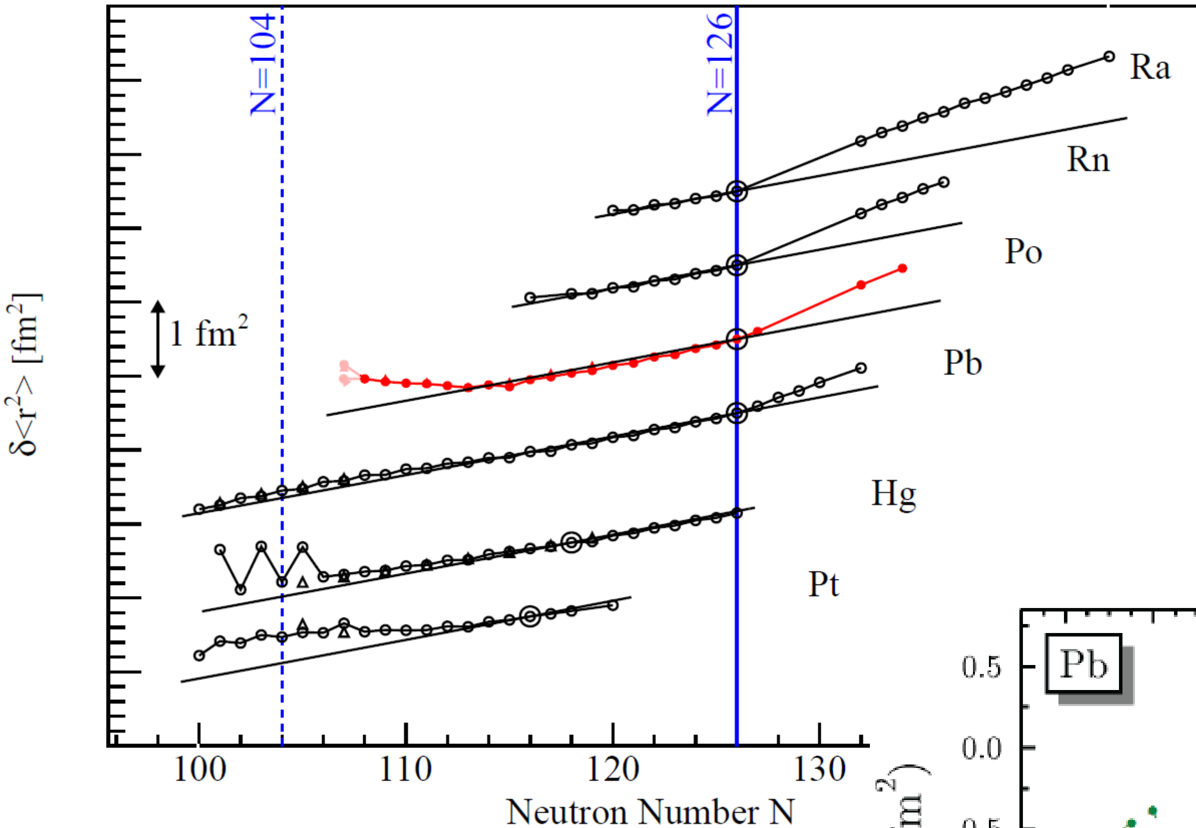
COLLAPS, CRIS, RILIS







Charge radii around lead

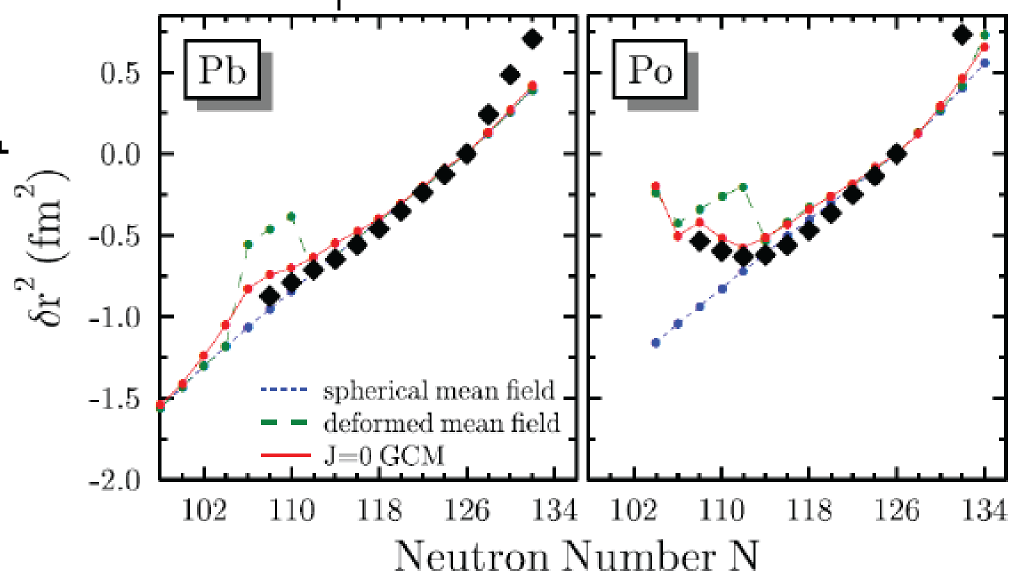


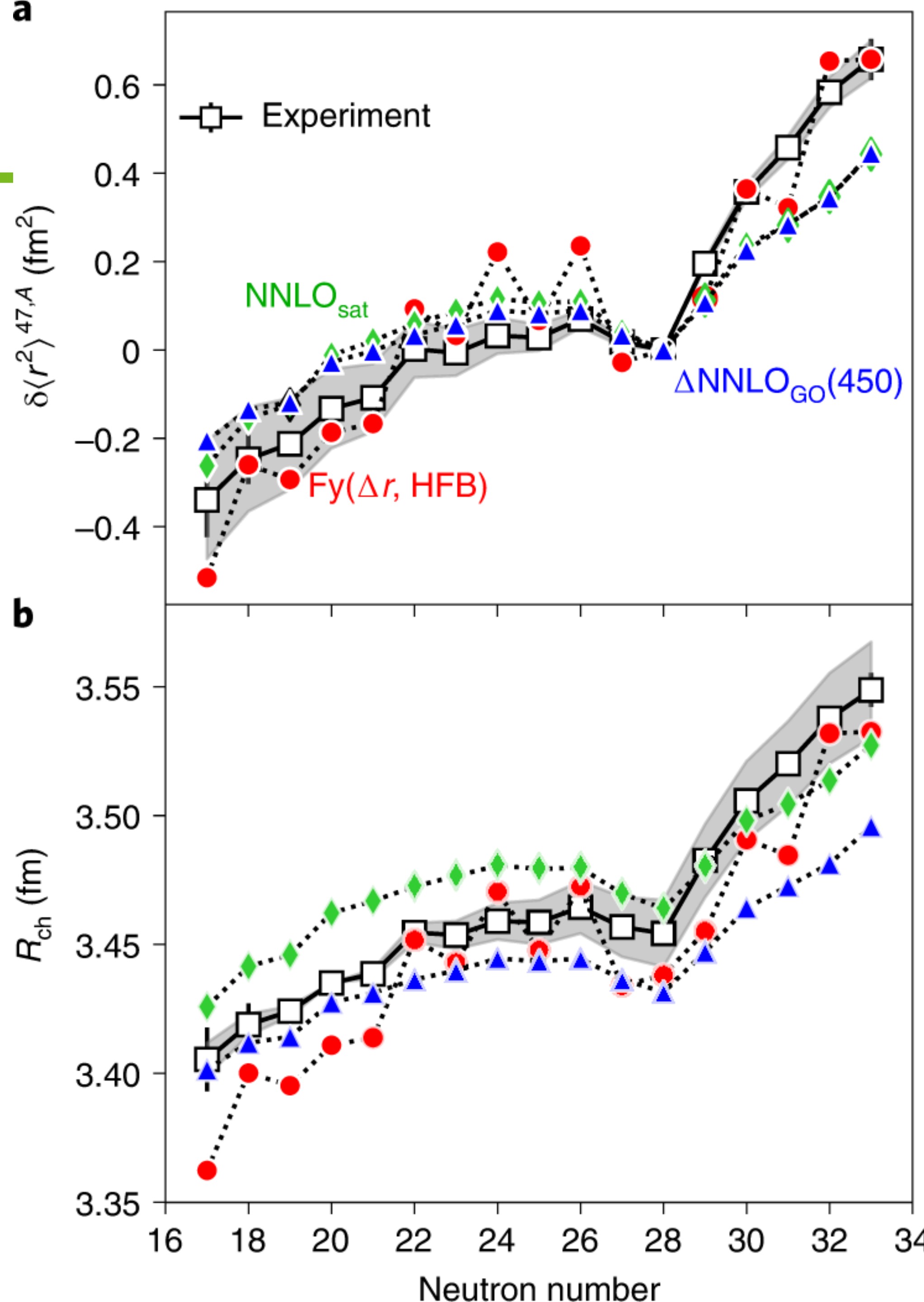
Isotope shifts measured with RILIS setup (part of data shown):

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

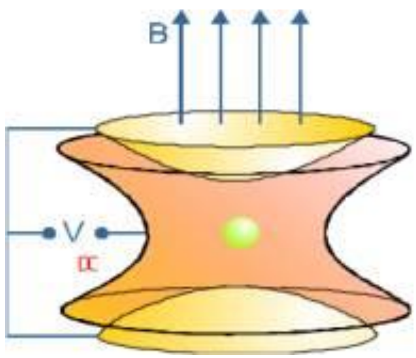
Radii described well with mean field models

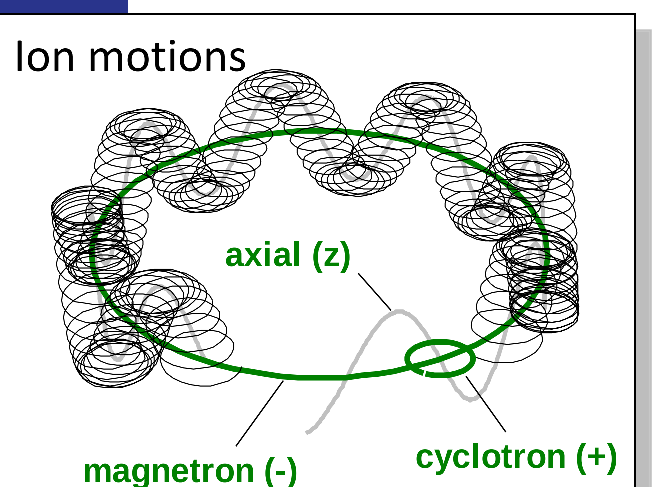


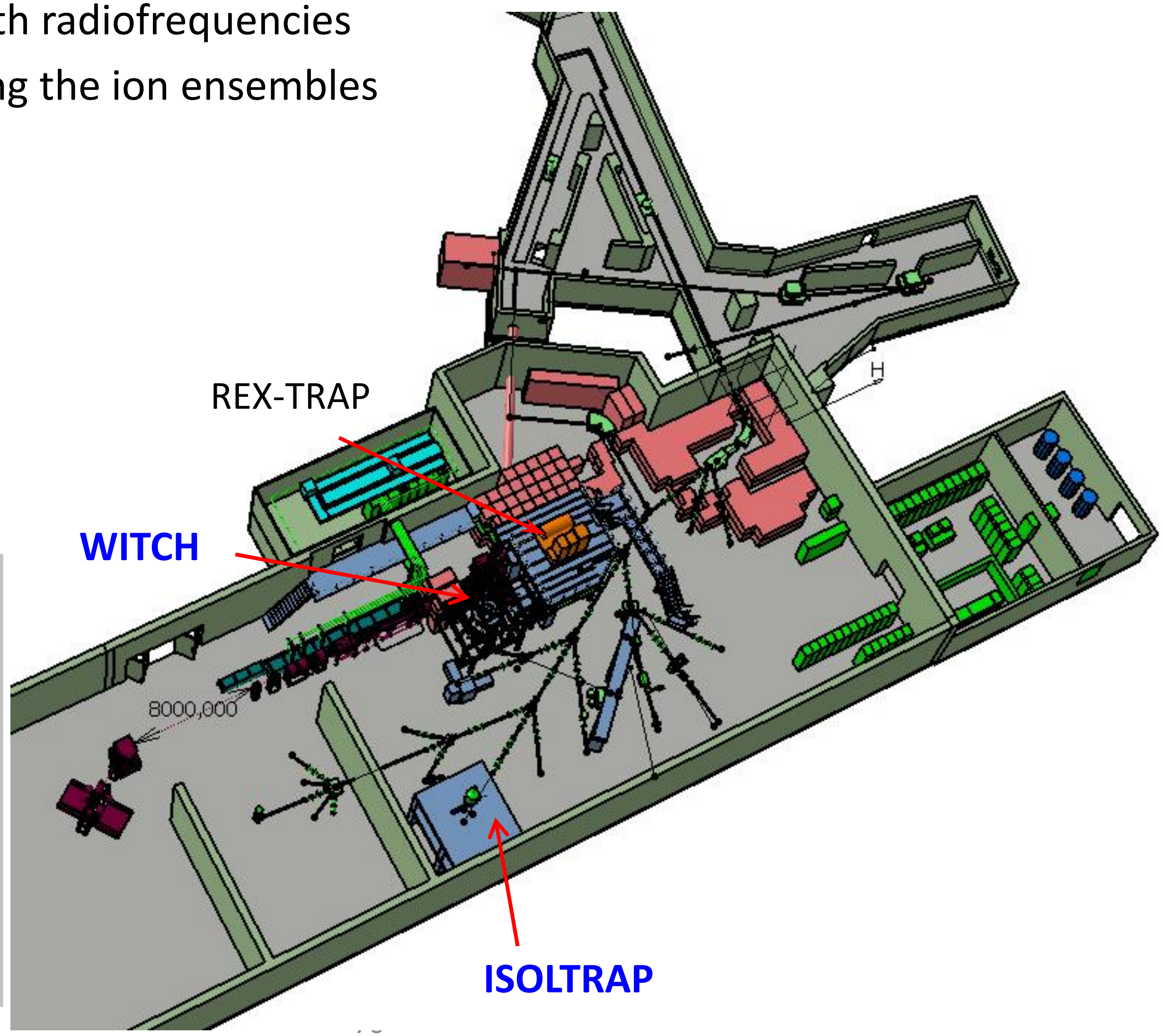

a
b
Experiment
NNLO$_{sat}$
ΔNNLO$_{GO}$(450)
Fy(Δr, HFB)
$\delta\langle r^2\rangle^{47,A}$ (fm^2)
R_{ch} (fm)
Neutron number
0.6
0.4
0.2
0
−0.2
−0.4
3.55
3.50
3.45
3.40
3.35
16
18
20
22
24
26
28
30
32
34

Studies with ion traps

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

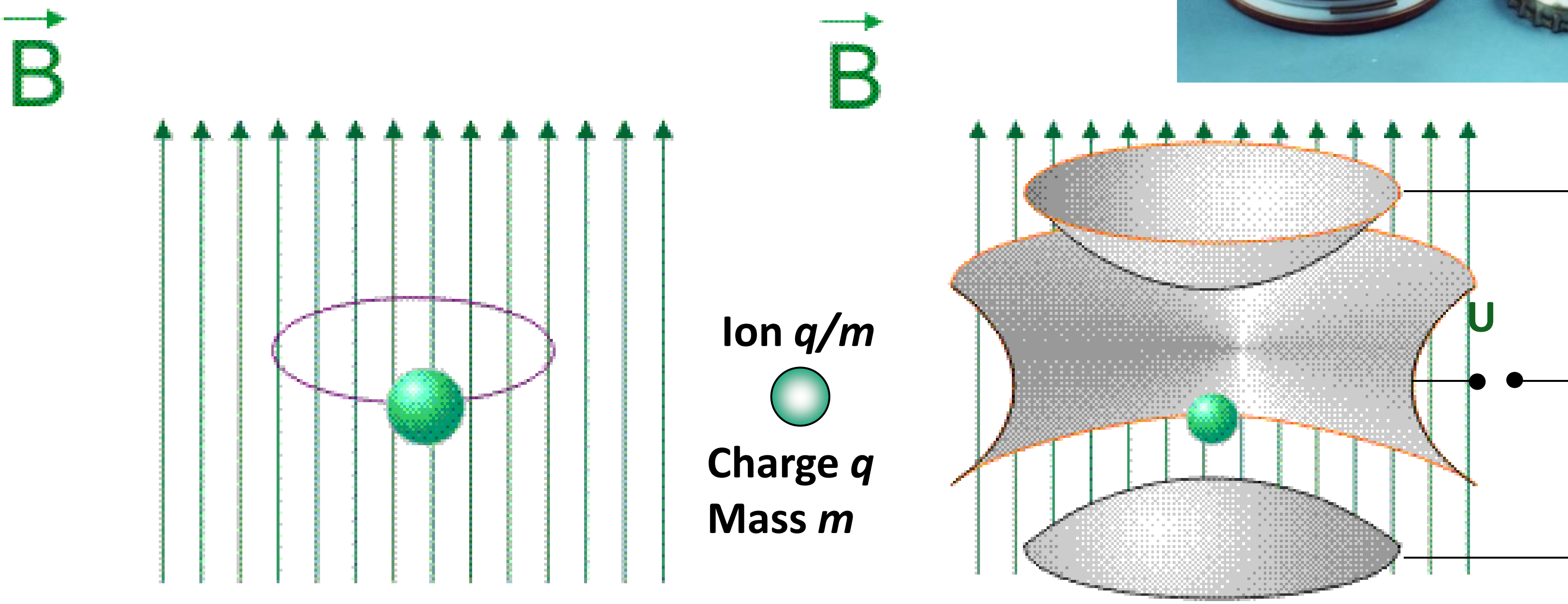






Penning-trap mass spectrometry

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



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

$$\omega_c = qB/m$$

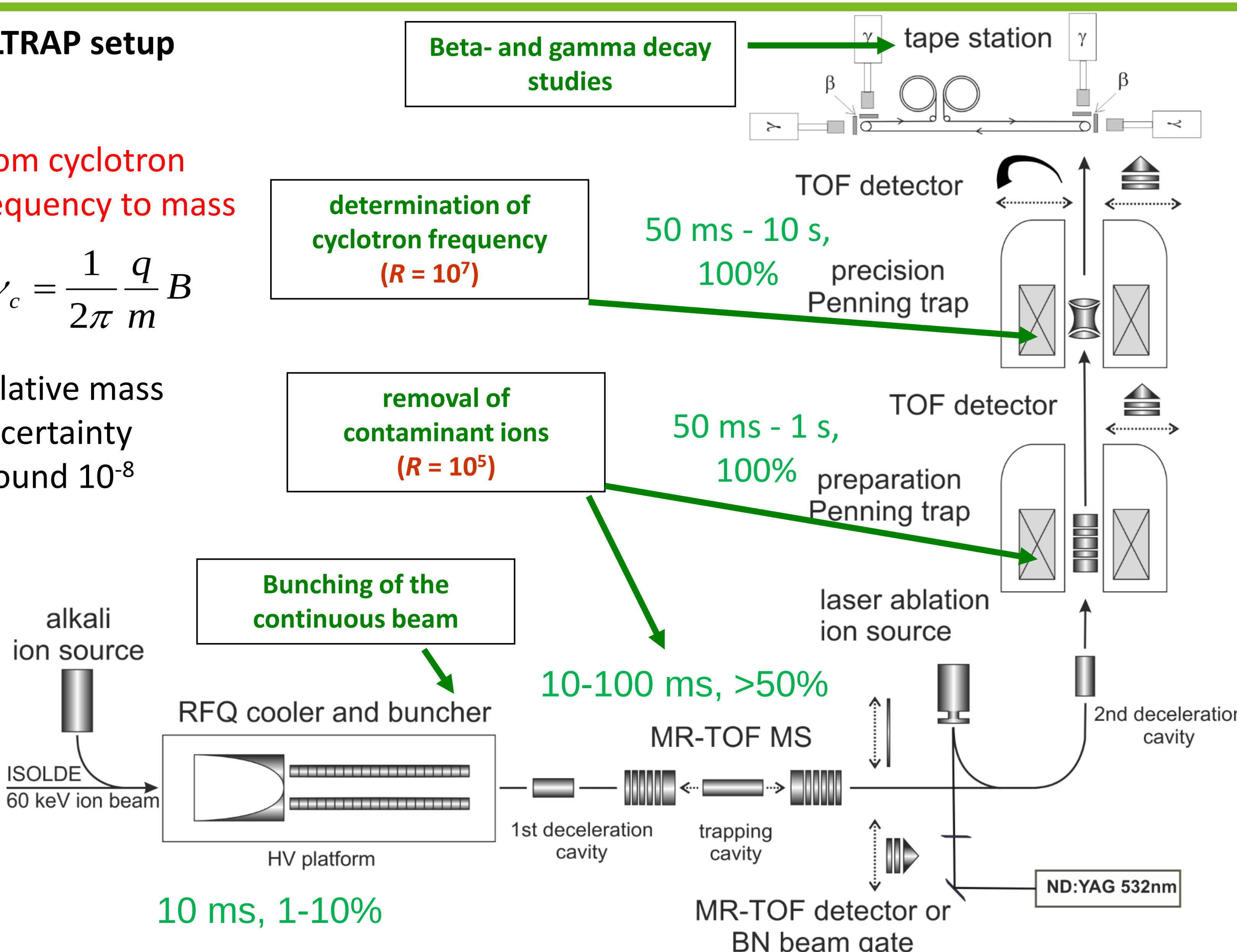
Penning-trap mass spectrometry

ISOLTRAP setup

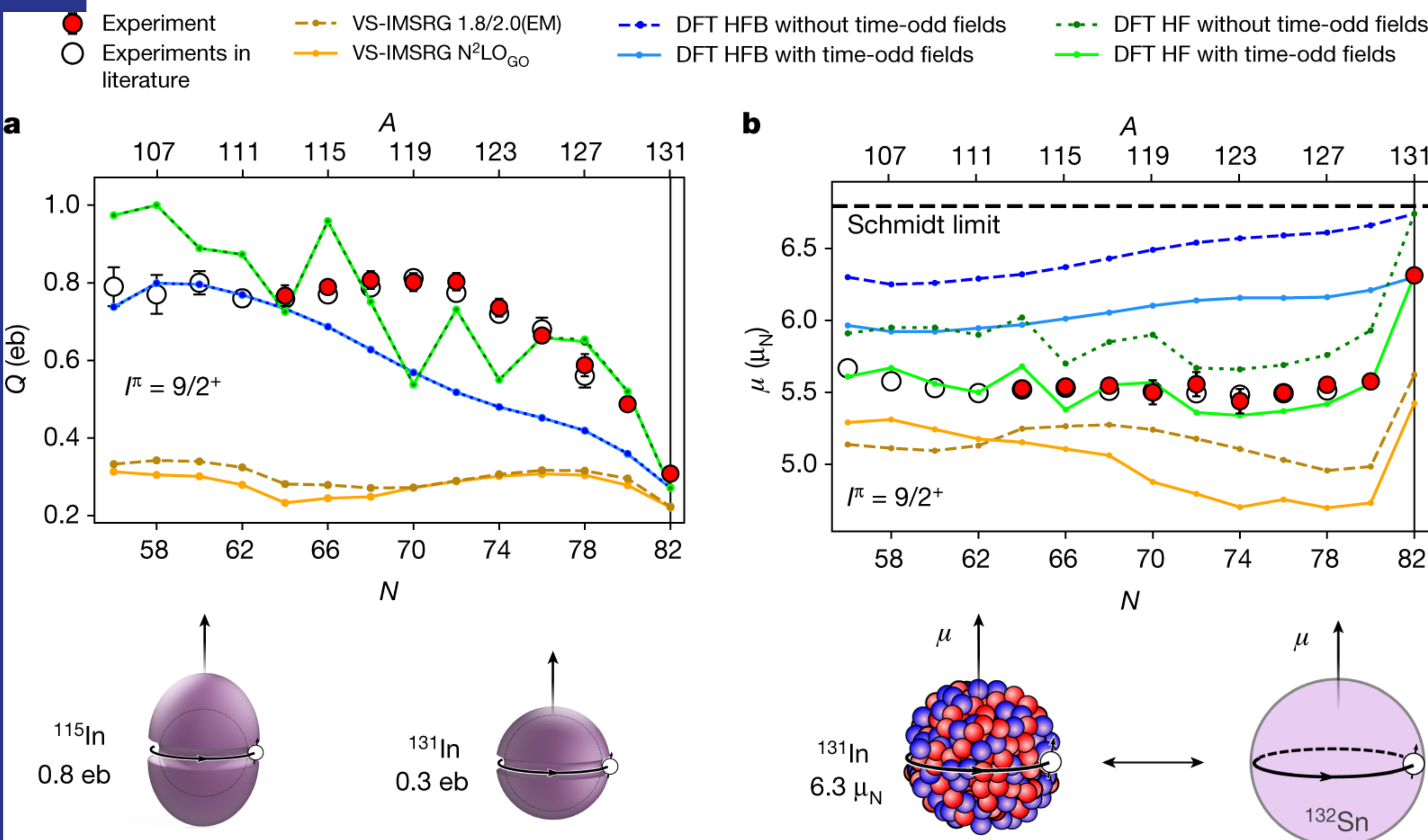
From cyclotron frequency to mass

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

Relative mass uncertainty around 10^{-8}



ISOLTRAP



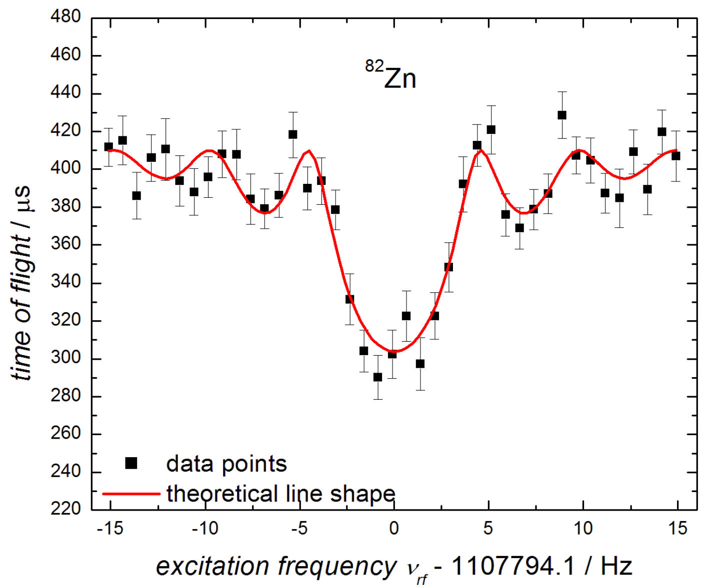
Experiment
Experiments in literature
VS-IMSRG 1.8/2.0(EM)
VS-IMSRG N2LOGO
DFT HFB without time-odd fields
DFT HFB with time-odd fields
DFT HF without time-odd fields
DFT HF with time-odd fields
a
A
Q (eb)
Iπ = 9/2+
N
b
Schmidt limit
μ (μN)
Iπ = 9/2+
N
115In
0.8 eb
131In
0.3 eb
μ
131In
6.3 μN
μ
132Sn

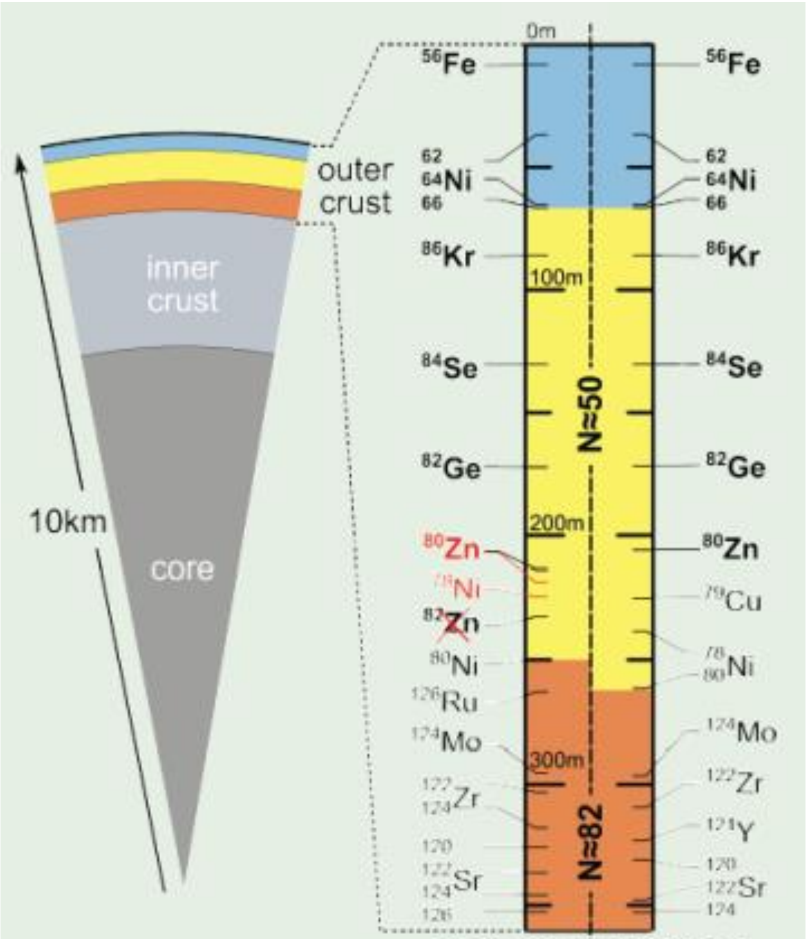
Mass of zinc-82

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)





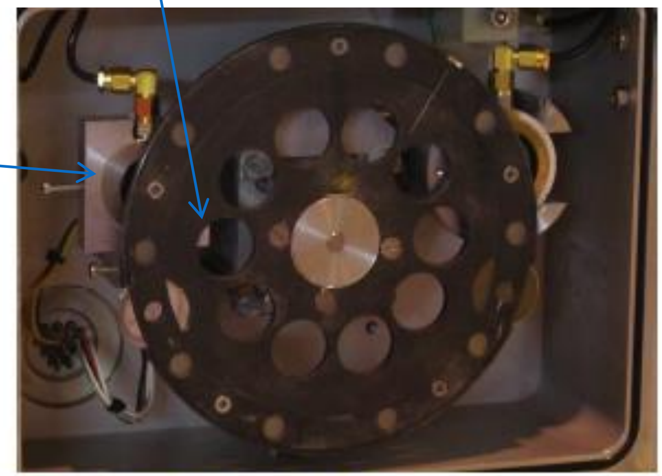
R.N. Wolf et al, Phys. Rev. Lett. 110, 041101 (2013)

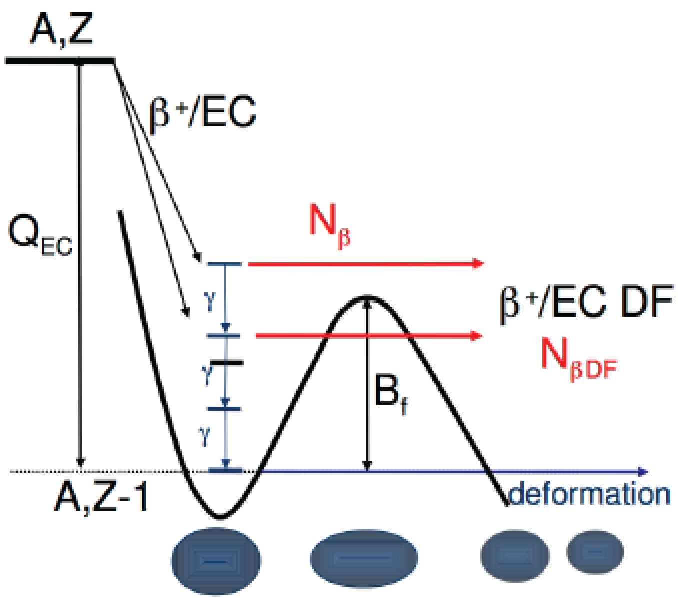
Decay spectroscopy

- 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)

C foil for implantation

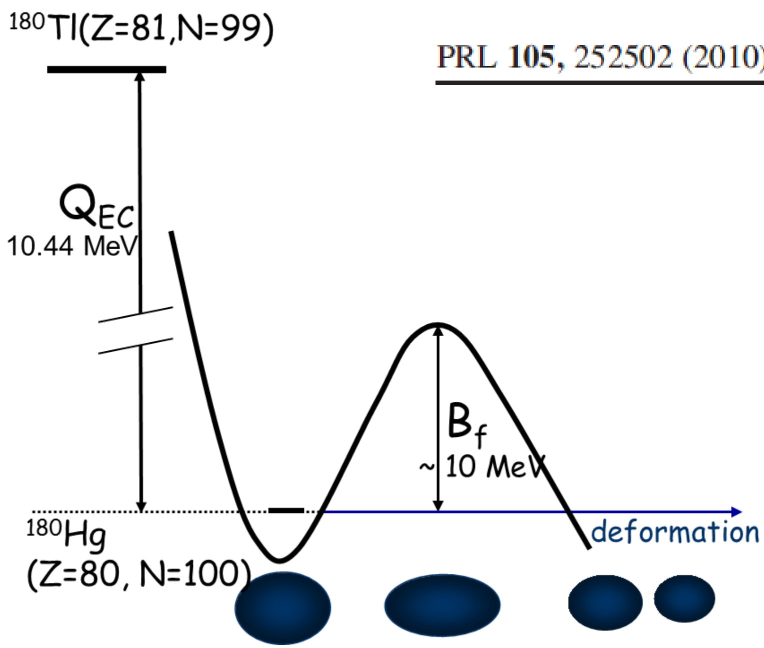
Si detector for alphas

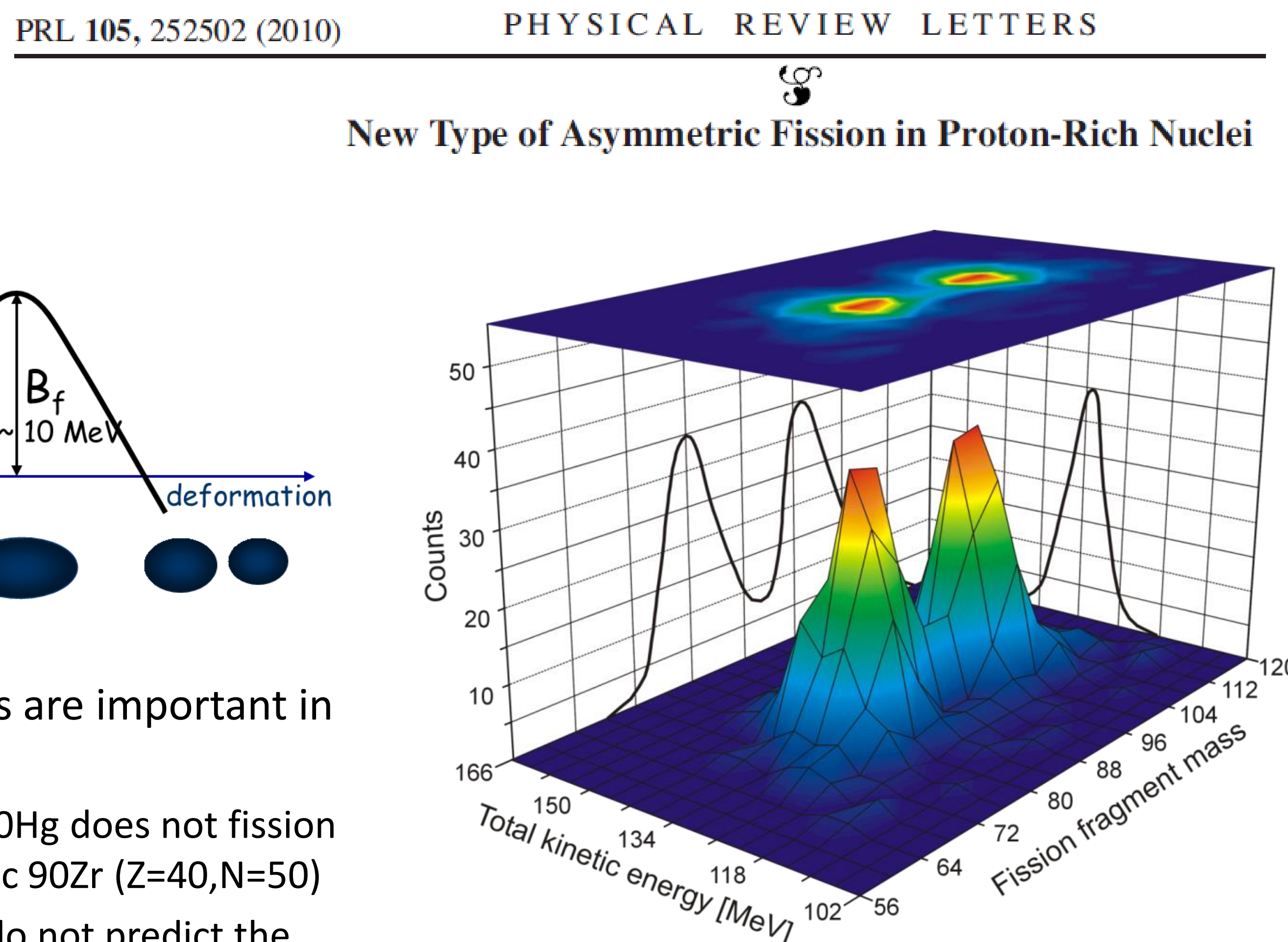




Beta-delayed fission of mercury-180

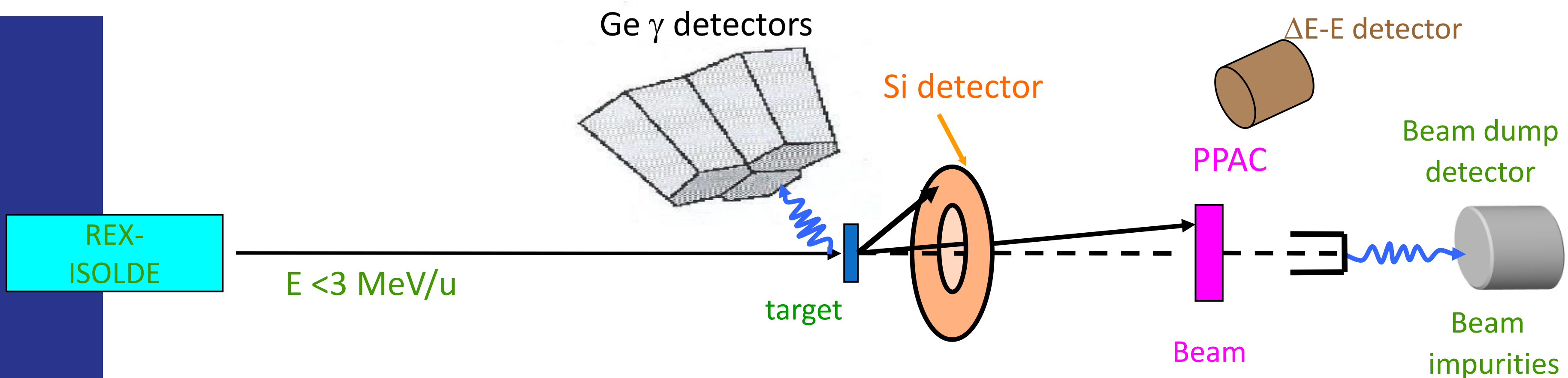
WINDMILL setup



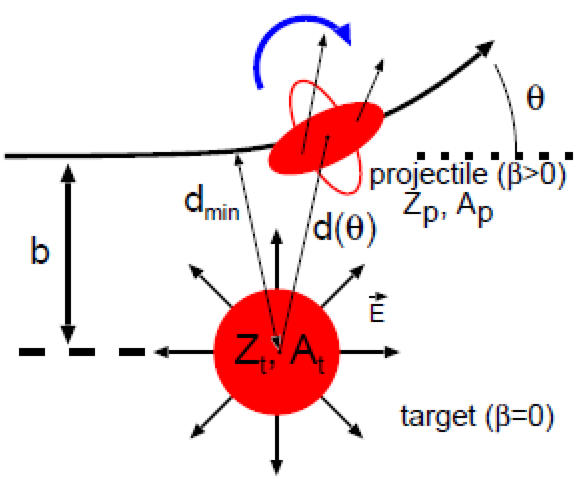


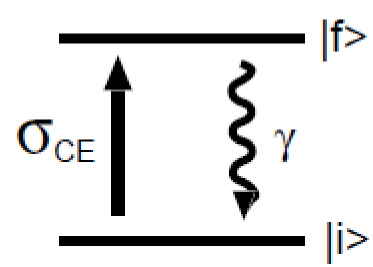
- Nuclear shell effects are important in fission, but:
  - Unexpectedly 180Hg does not fission in two semi-magic 90Zr (Z=40,N=50)
  - Fission theories do not predict the results correctly

Coulomb excitation



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

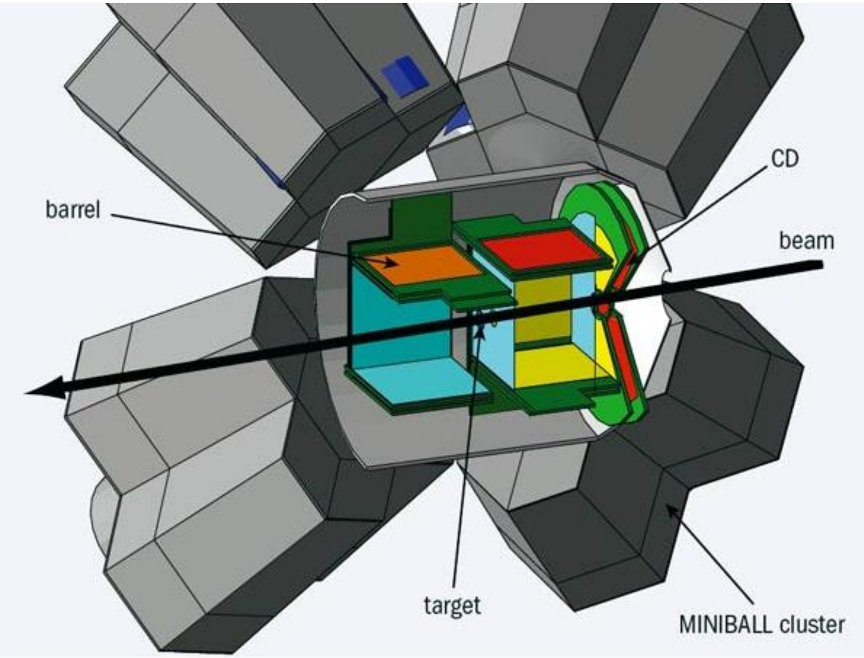




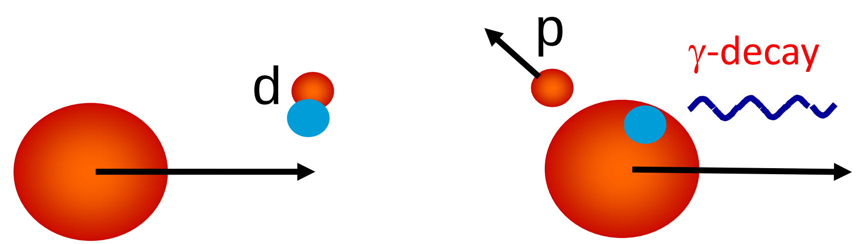
Observables: Transition energies and intensities

=> Determine new excited levels and study deformations

Nucleon-transfer reactions



Miniball + T-REX setup (Si detector barrel): gamma detectors and particle identification



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

Information:

Observables

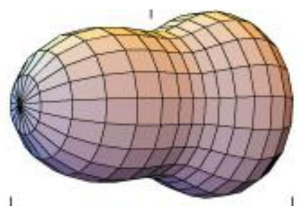
- energies of protons (+ E_g) — (single-particle) level energies
- angular distributions of protons (+ γ-rays) — spin/parity assignments
- (relative) spectroscopic factors — particle configurations

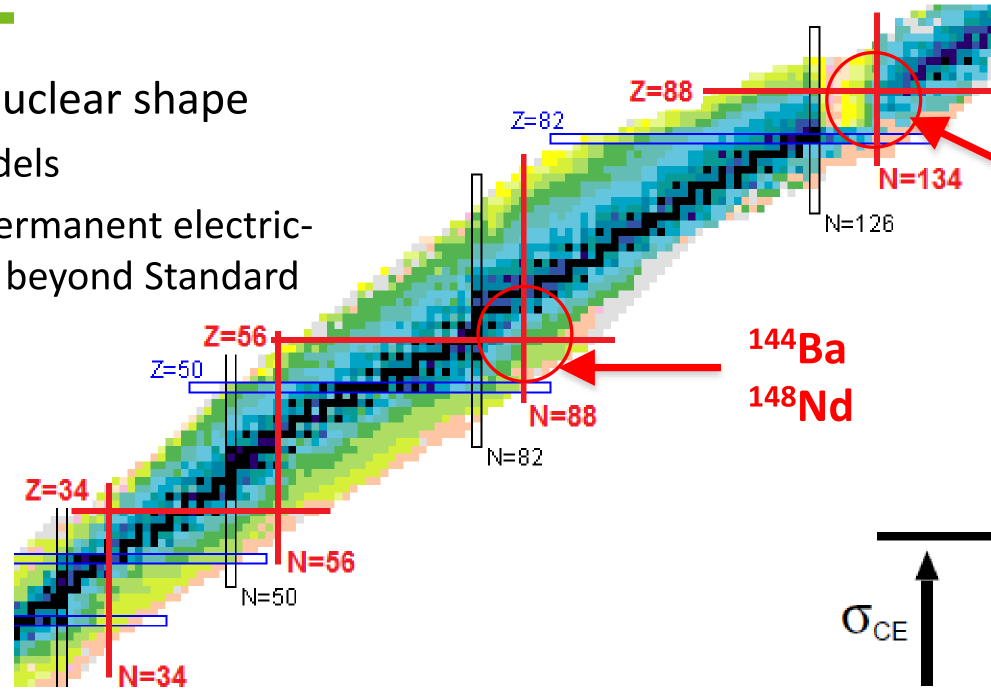
study single-particle properties of nuclei

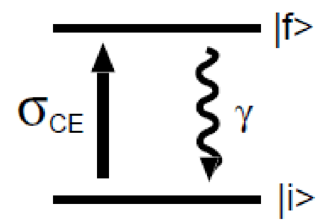
= > Similar configurations = large overlap of wave functions = Large probability of transfer reaction

Octupole deformation and MINIBALL

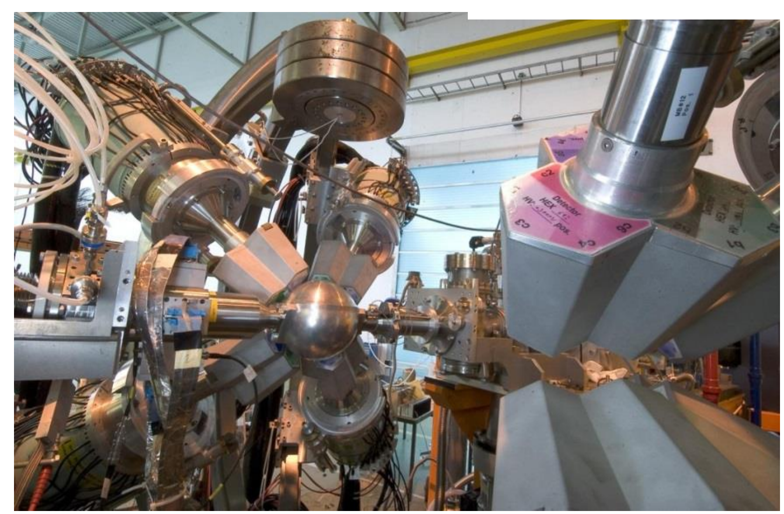
- Octupole shape – very rare nuclear shape
  - Test ground for nuclear models
  - Important in searches for permanent electric-dipole moments (EDM) – beyond Standard Model







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

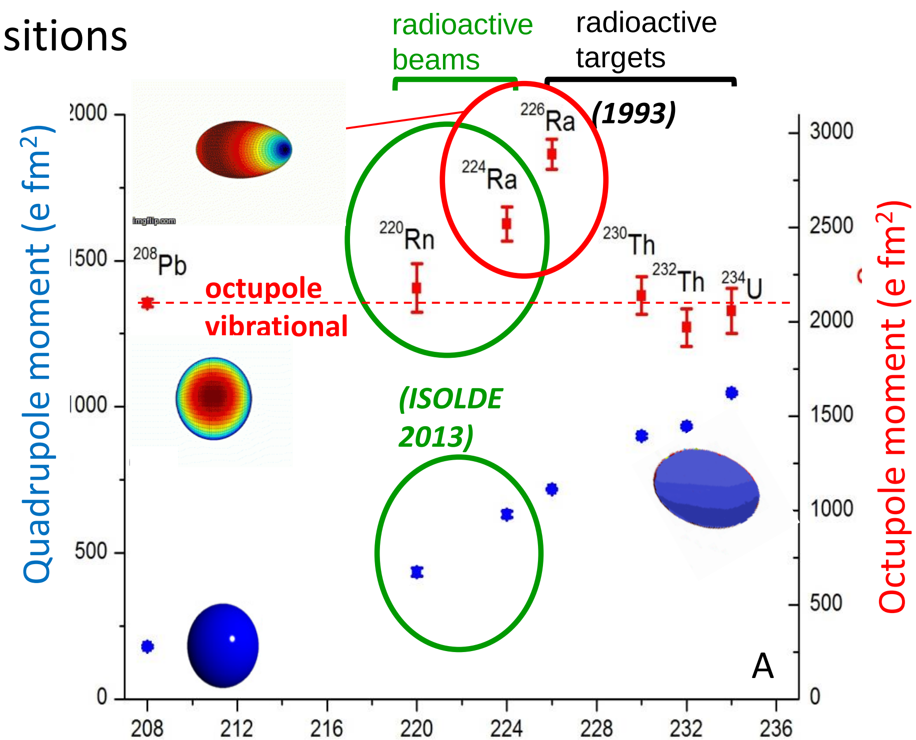


- Detection with MINIBALL gamma-array
  - Germanium detectors - high efficiency gamma detection
  - Silicon detectors for particle identification

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

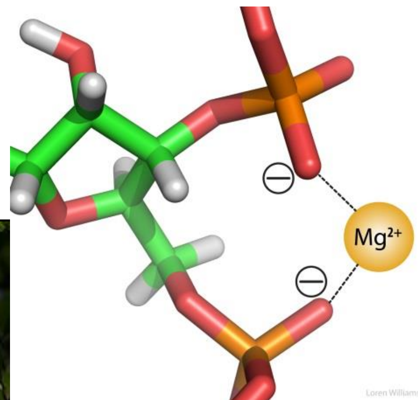
Biophysics and Parkinson disease

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

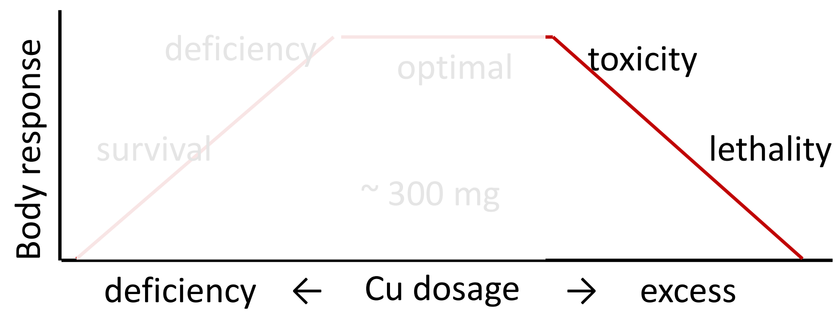
➢ Magnesium

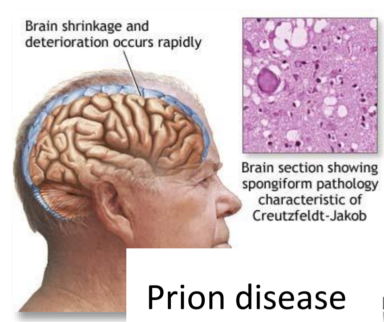
Catalysis in cellular energy transformations

Photosynthesis - component of chlorophyll



➢ Copper





- 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."

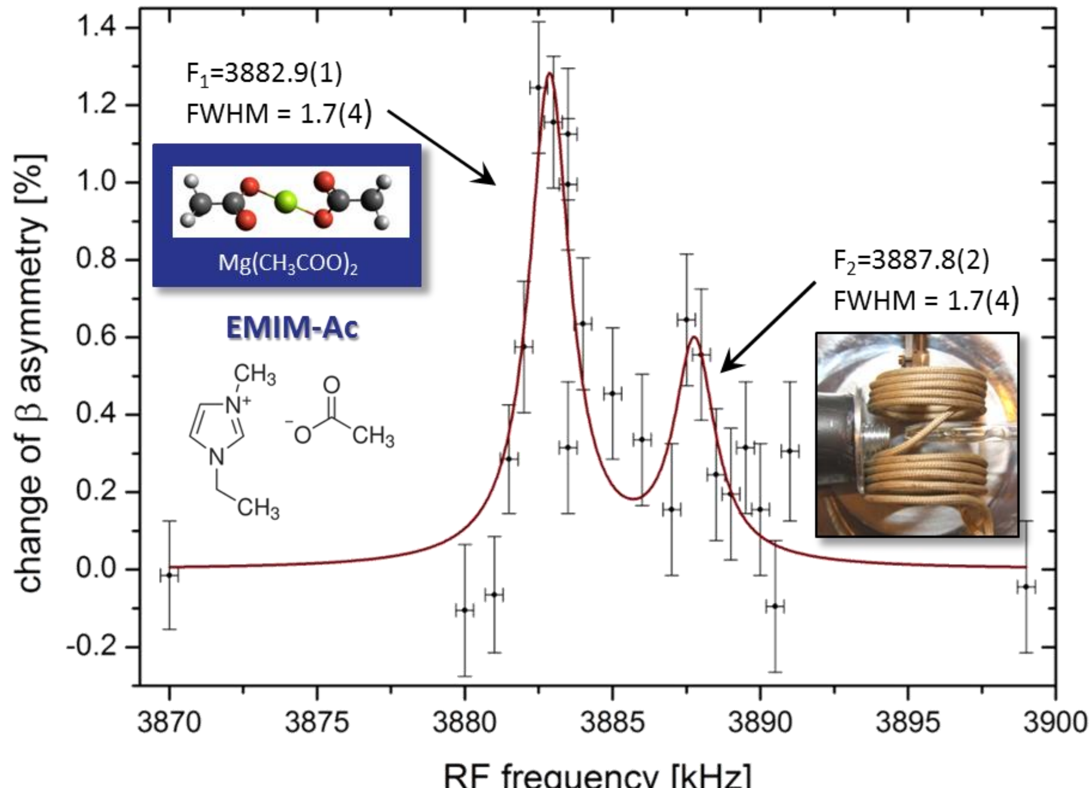
Metals in biology and beta-NMR

- 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

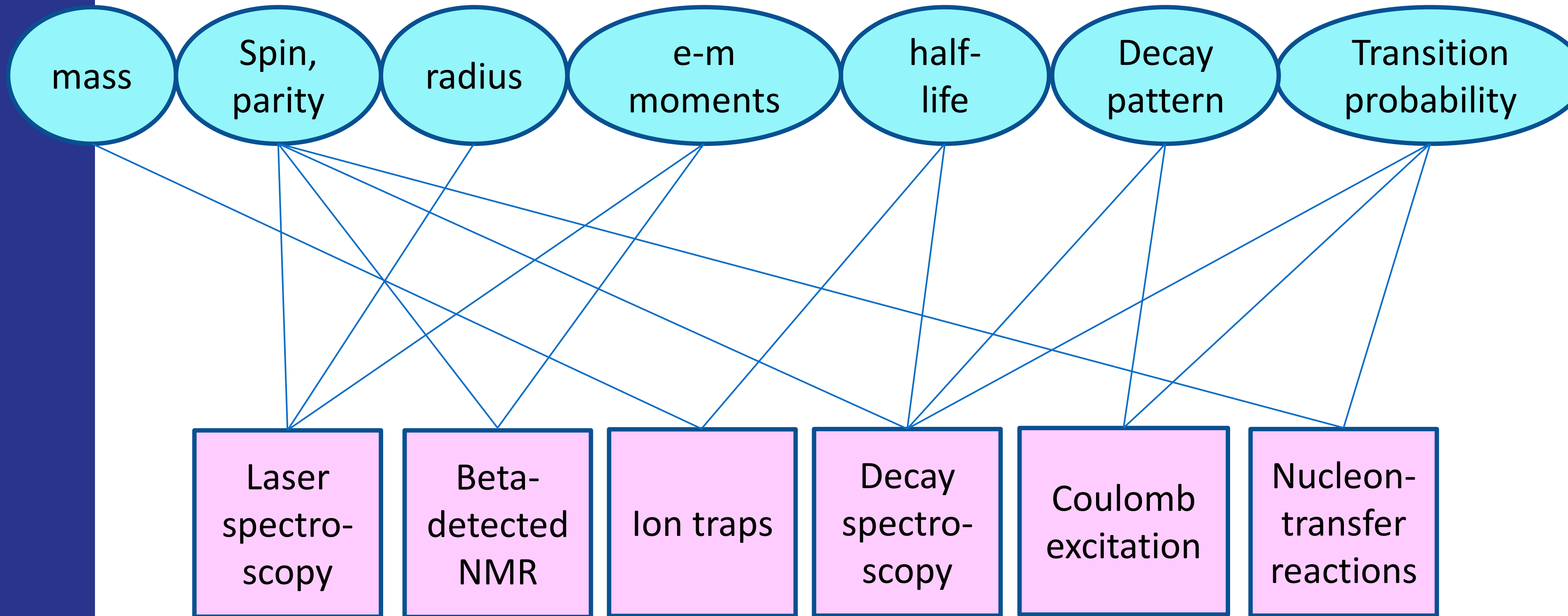


A. Gottberg, M. Stachura, M. Kowalska, et al, ChemPhysChem 15, 3929 (2014)

Soon be continued within MK'EU ERC Starting Grant

Studies of radioactive nuclides

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

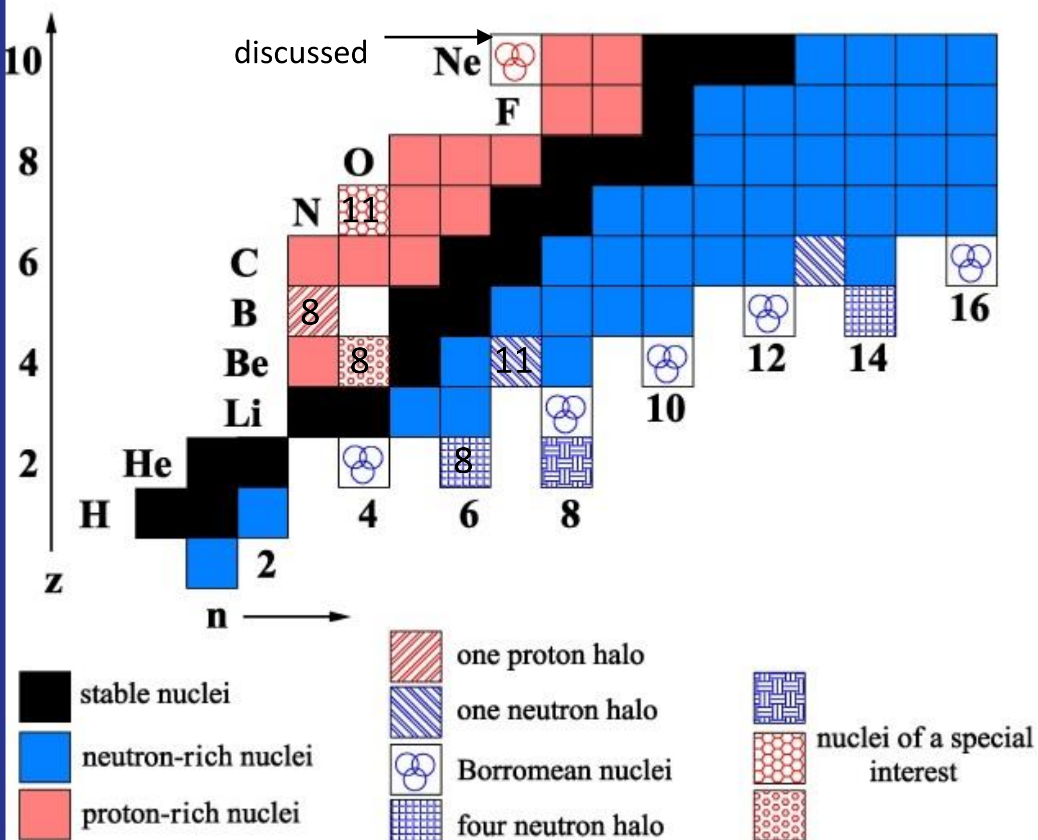


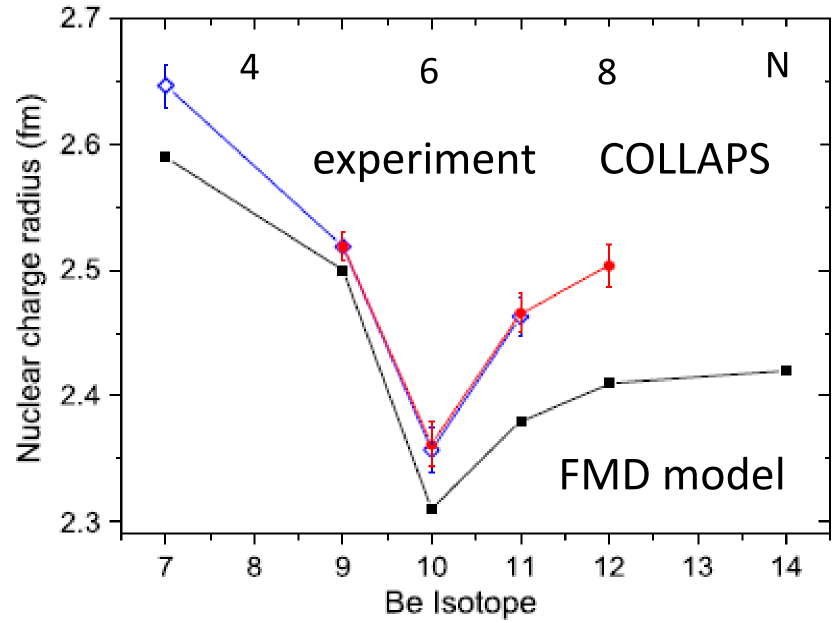
Techniques/ devices

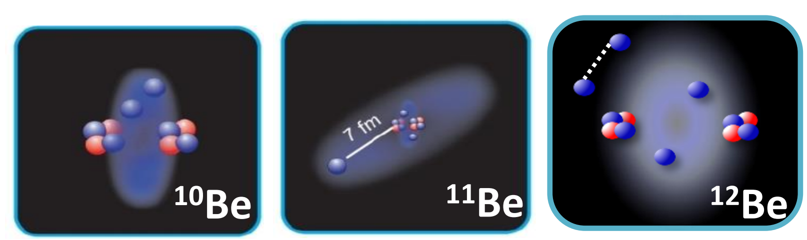
To obtain the full picture: need to study several properties and use several techniques

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



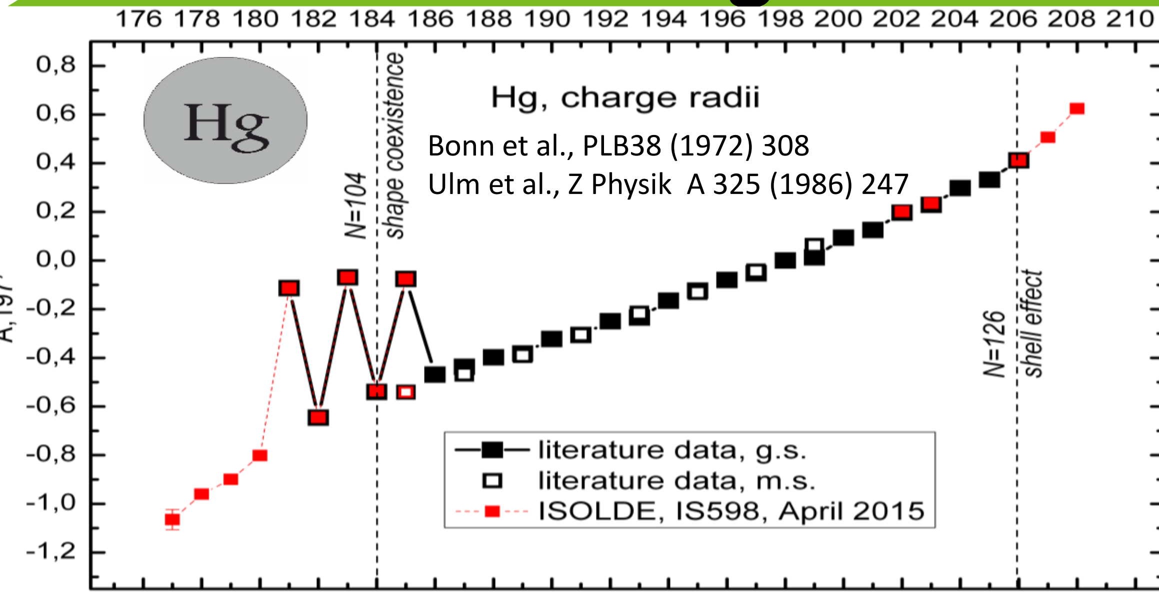




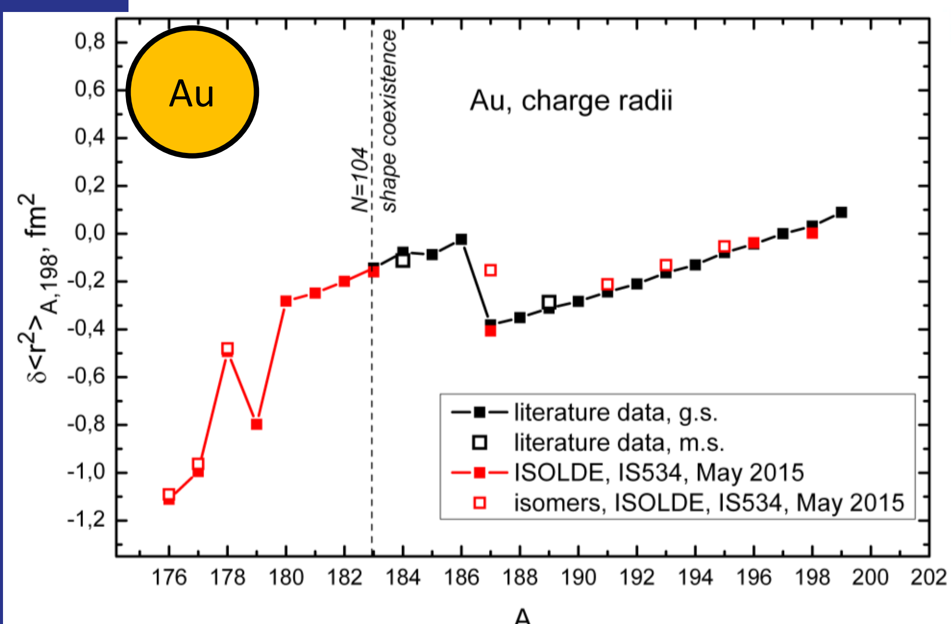
A. Krieger et al,
Phys. Ref. Lett. 108 (2012) 142501

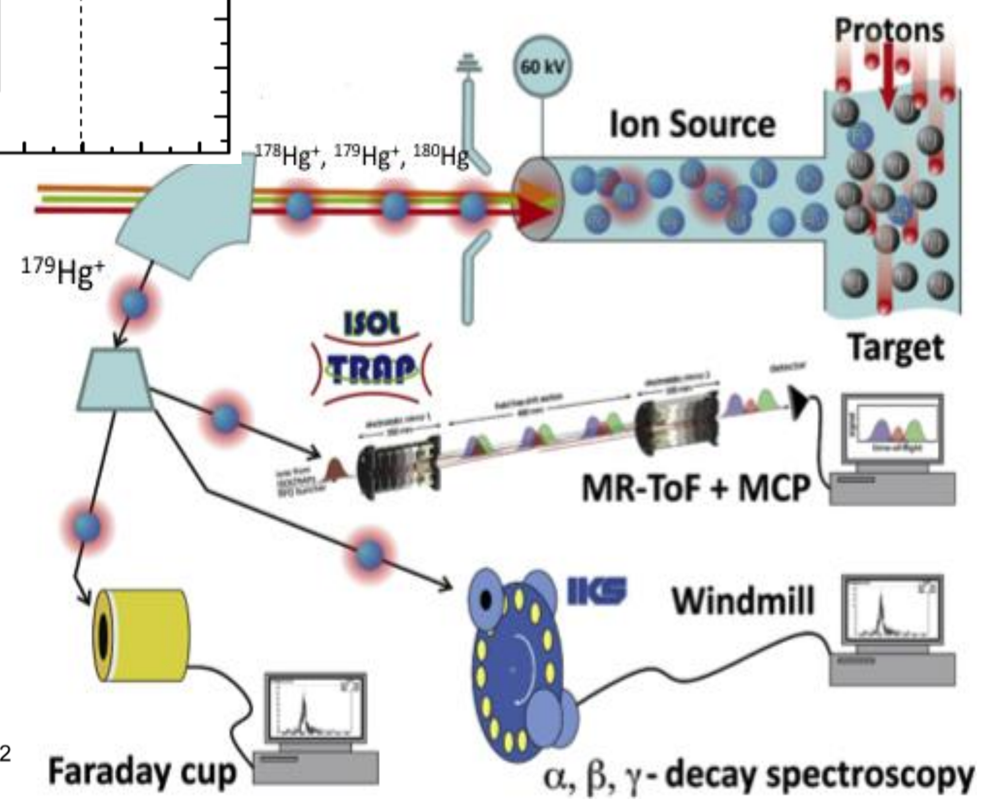
Combination of techniques: Charge radii of Hg & Au

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]

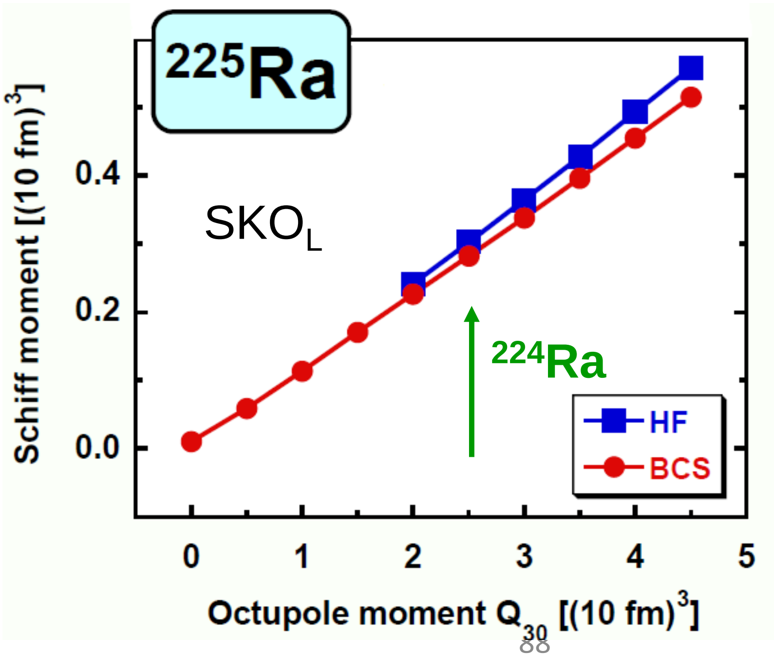
odd-*A* Ra [Argonne]

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

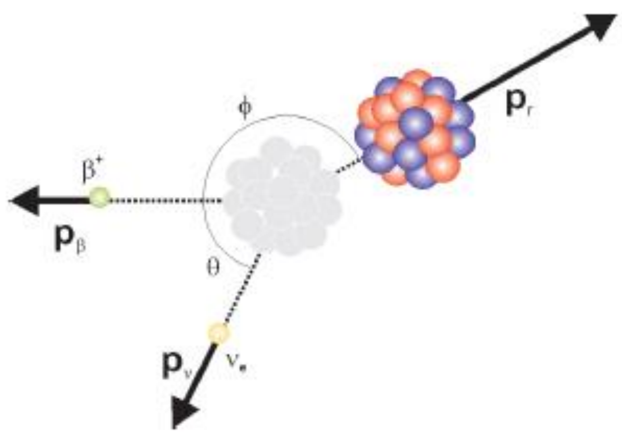
$$H_\beta = H_S + H_V + H_T + H_A + H_P$$

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

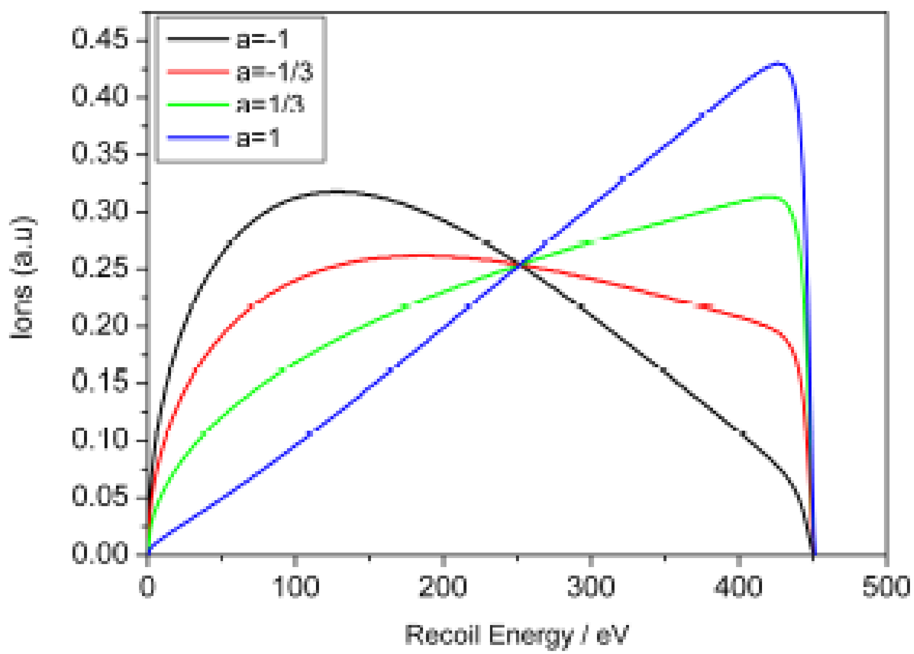
$$a \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

Angular distribution of β radiation

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



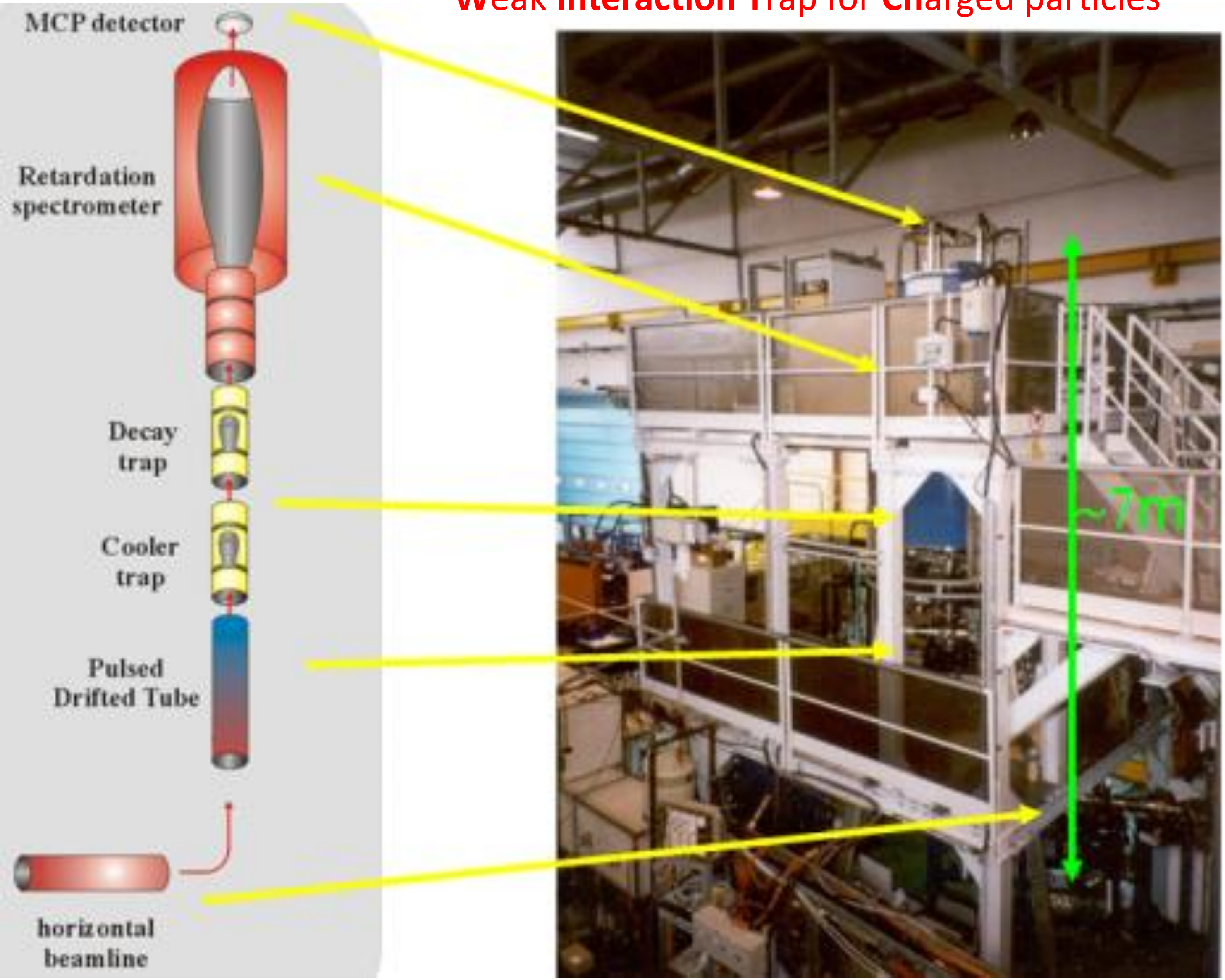
Simulated ion recoil for different *a*



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

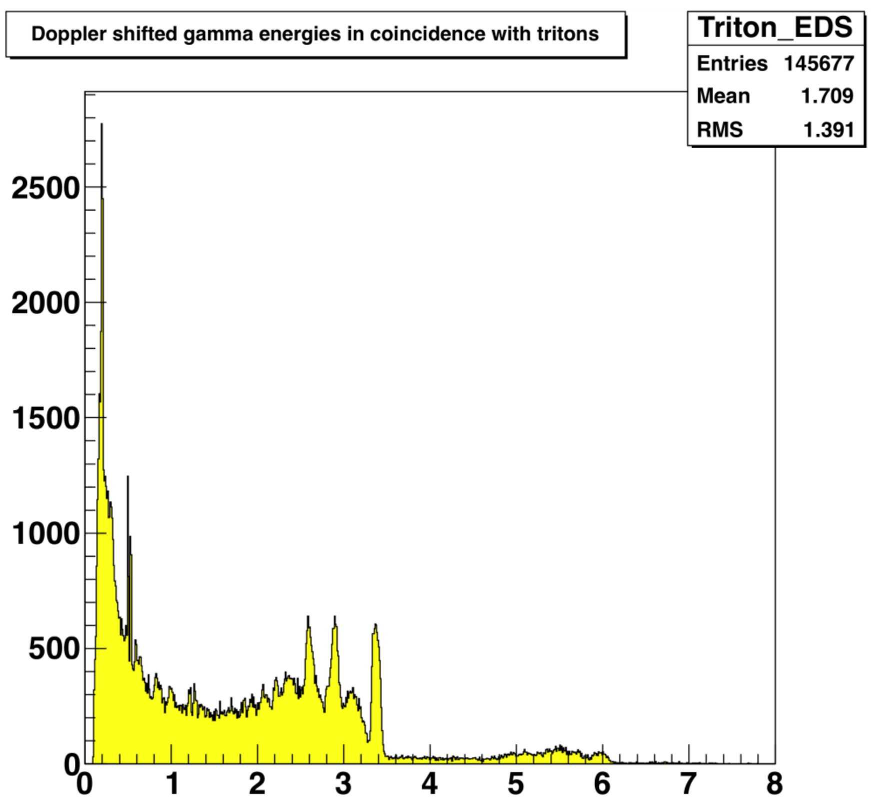
WITCH

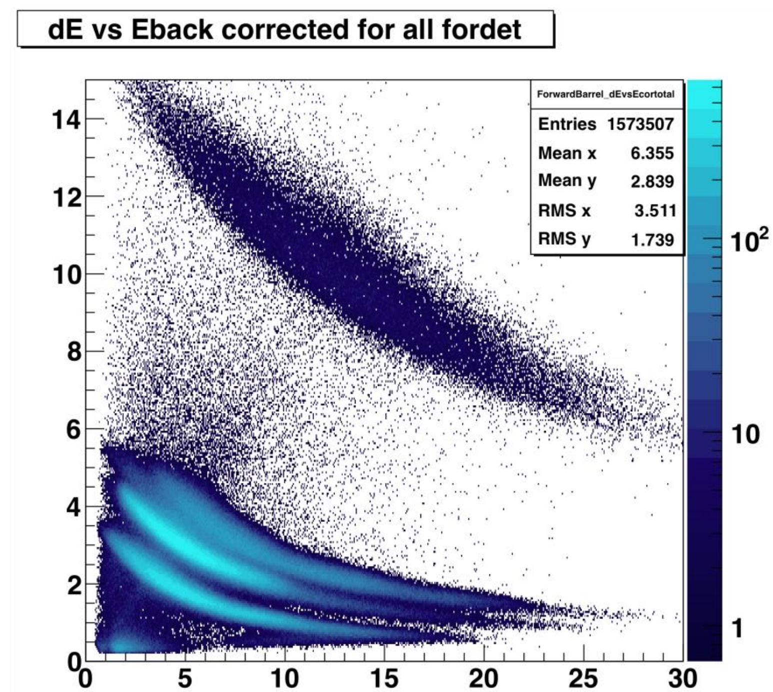
Weak **Interaction T**rap for **Ch**arged particles



Transfer reactions on beryllium-11

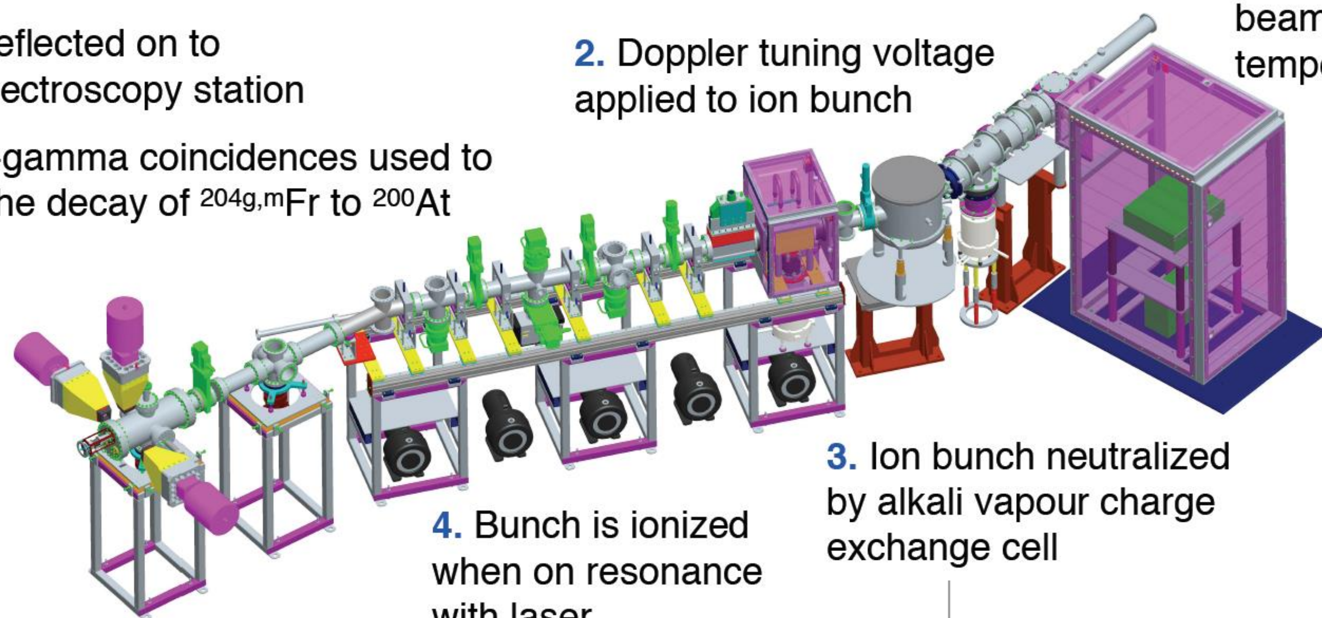
- 11Be:
  - Halo nucleus
  - Cluster structures in neighbours
  - N=8 broken in 12Be

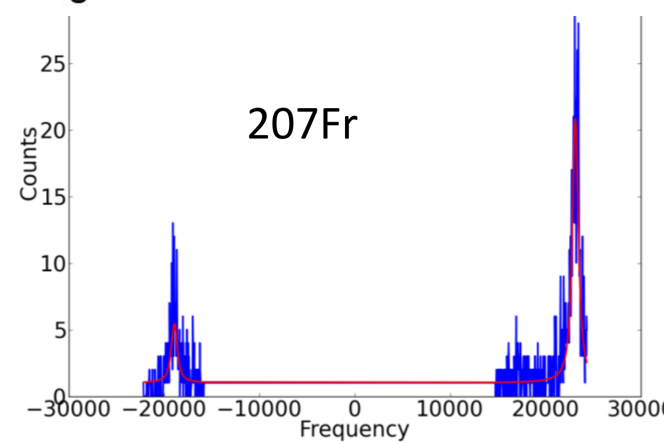




CRIS

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

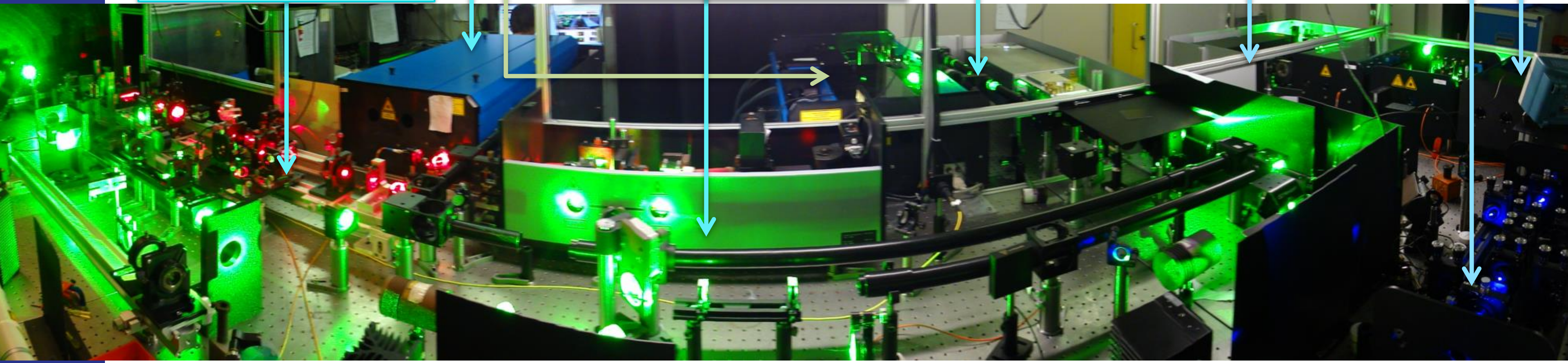




Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes

RILIS

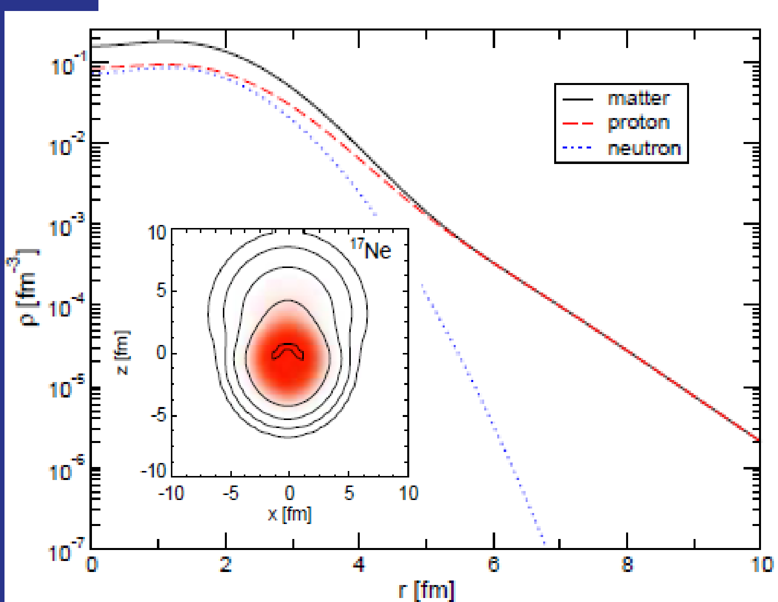
- Resonant Ionization Laser Ion Source

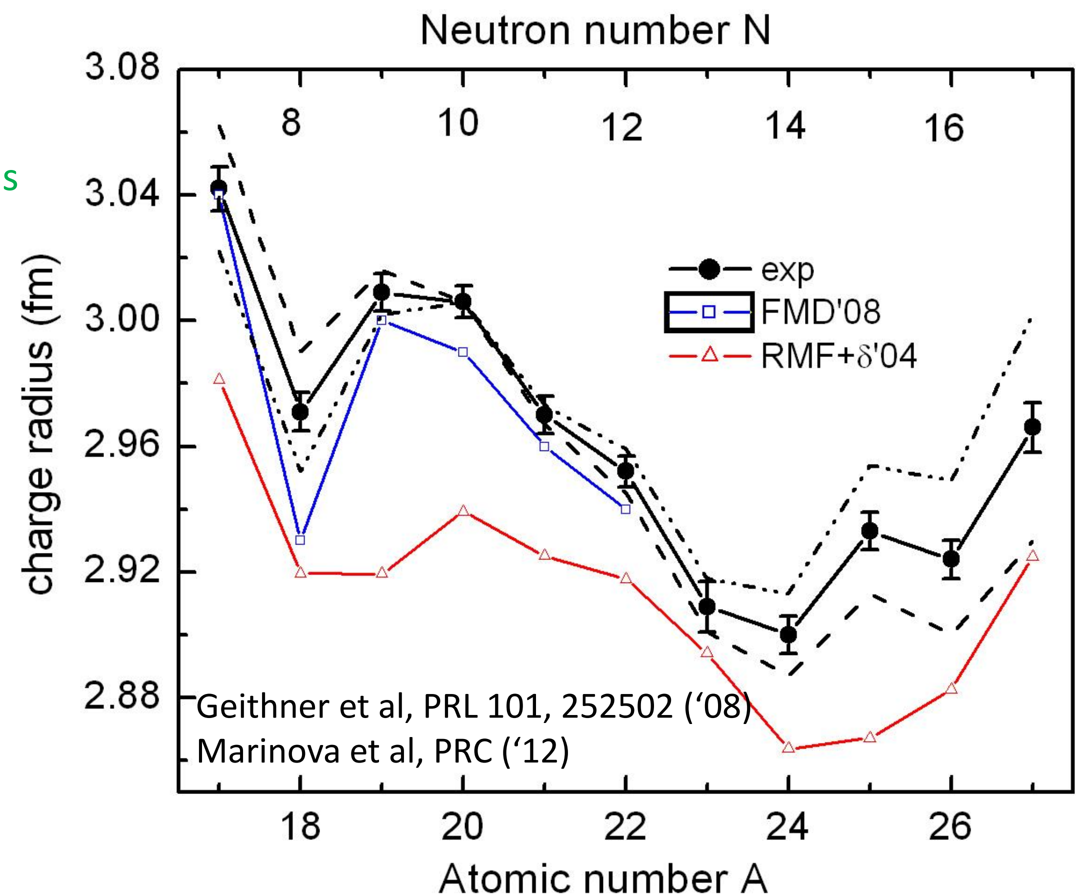


COLLAPS – Ne charge radii

Laser spectroscopy

Intrinsic density distributions of dominant proton FMD configurations

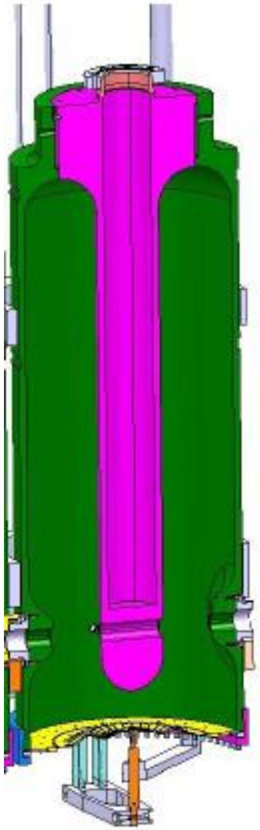




HIE-ISOLDE

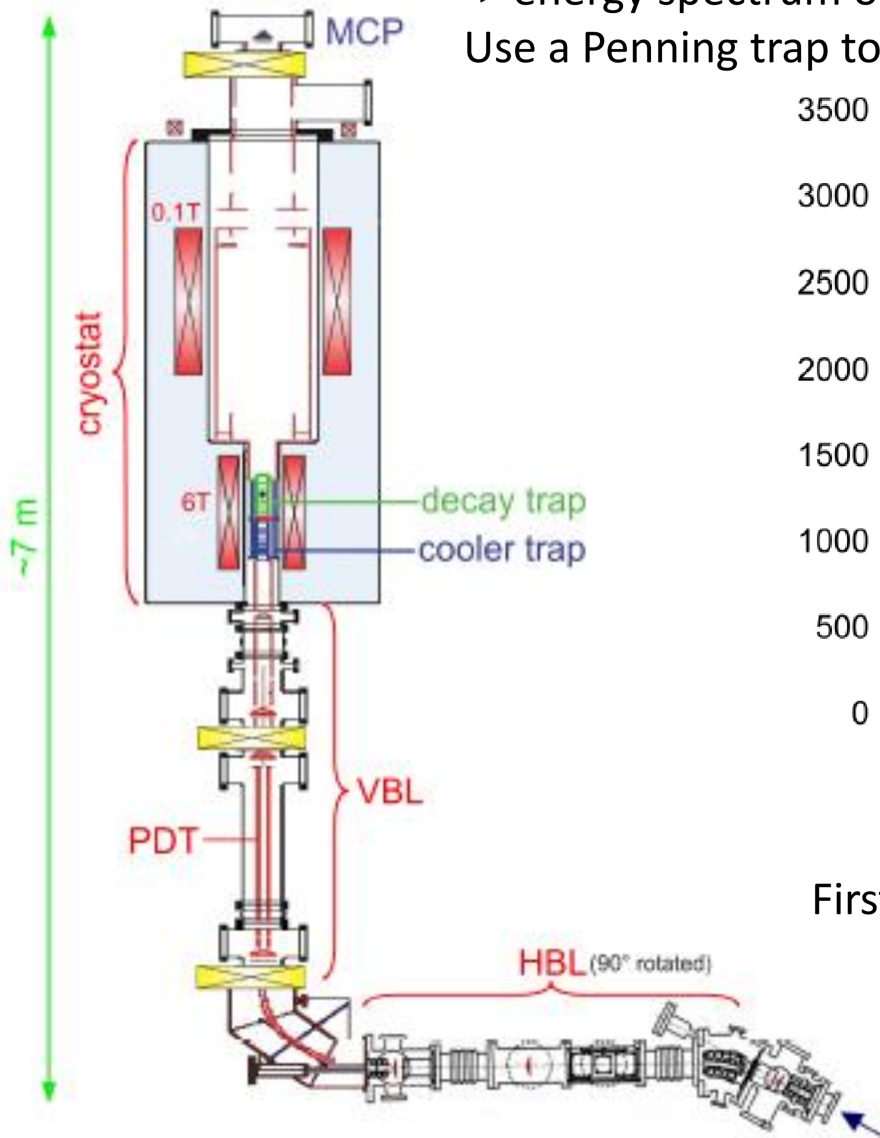
Quarter-wave resonators
(Nb sputtered)

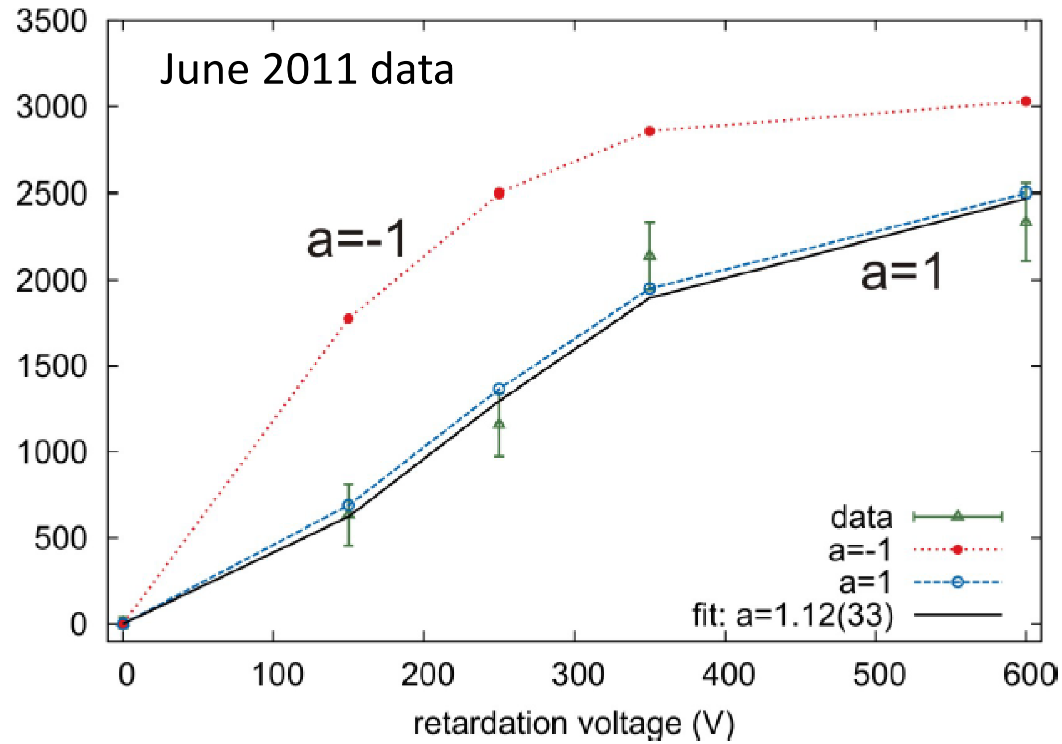
- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ β_0=10.3% and 12@ β_0=6.3%)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase fs= -20 deg
- 2.5<A/q<4.5 limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal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



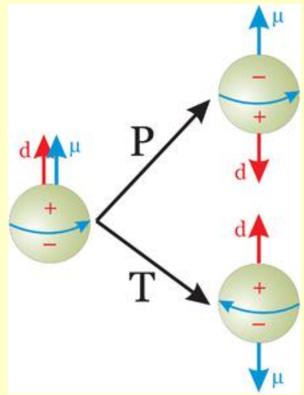


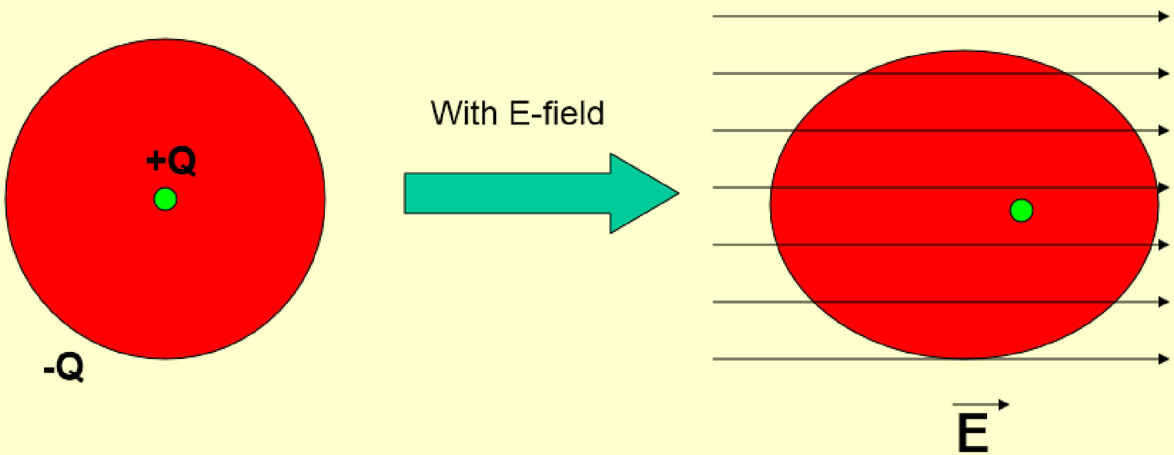
First high-statistics run in Nov 2011: under analysis

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

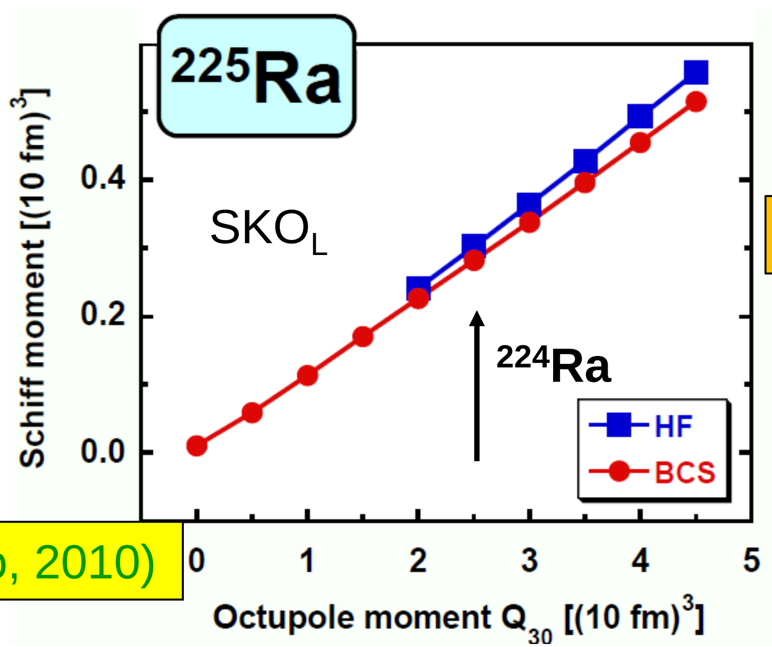
P,T-violating n-n interaction

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]

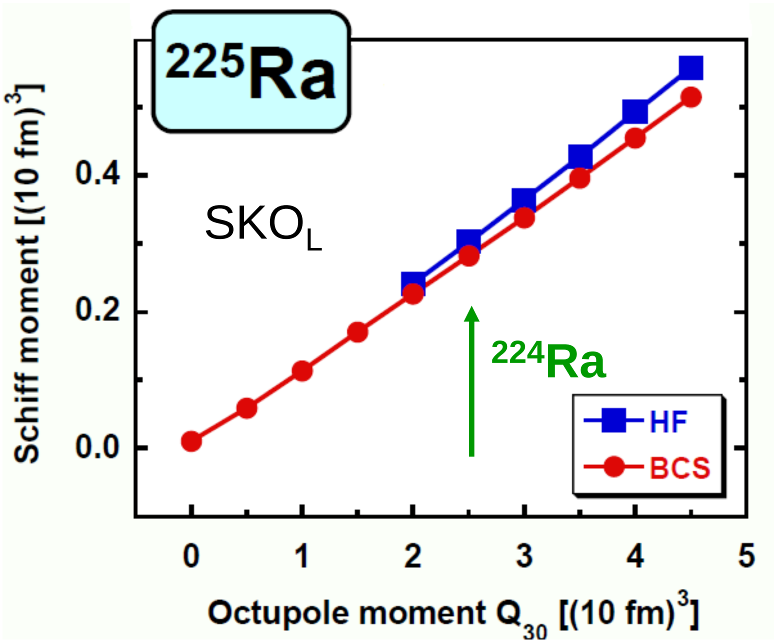
odd-*A* Ra [Groningen]

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:

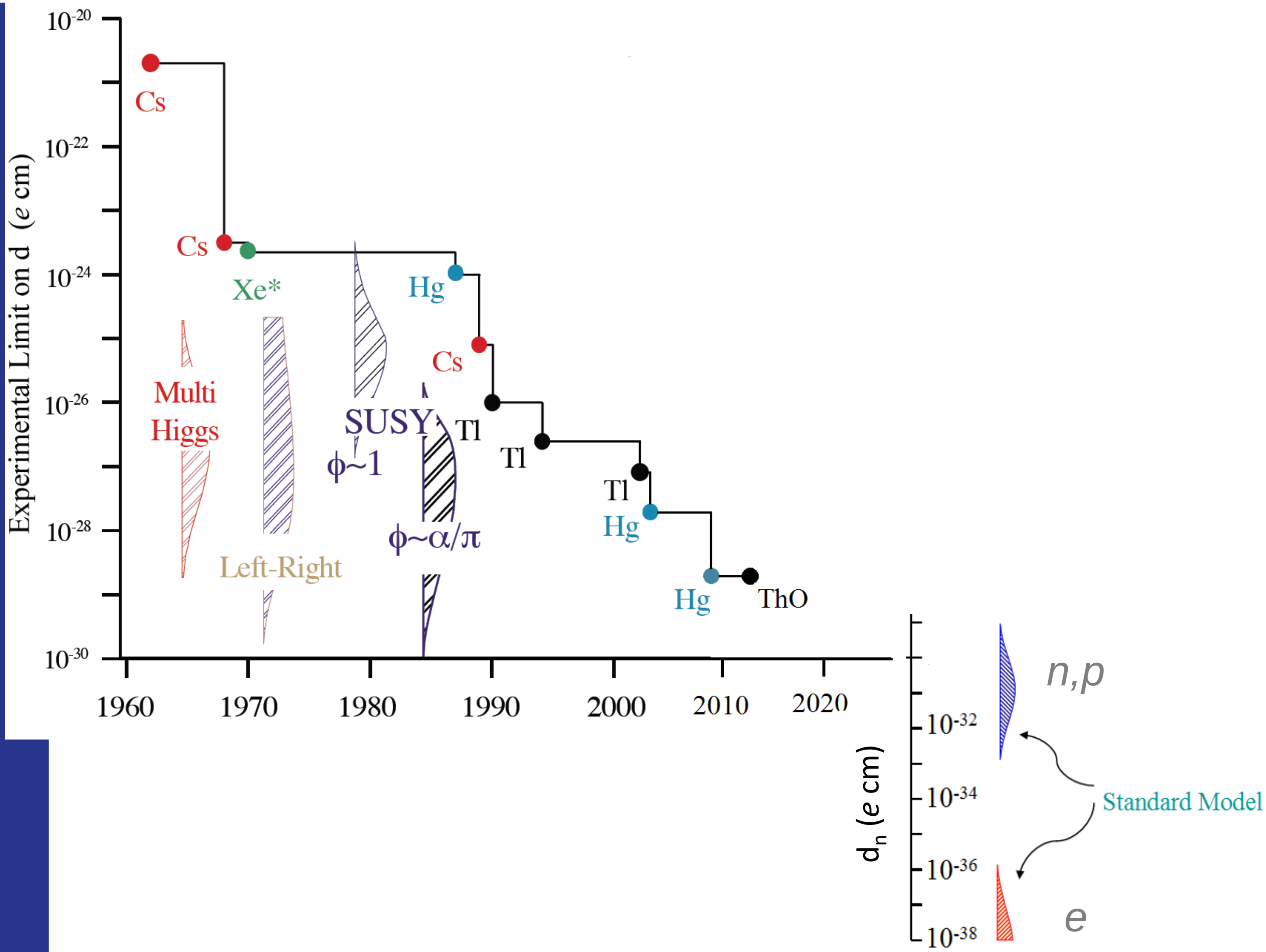
Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr$^+$ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma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

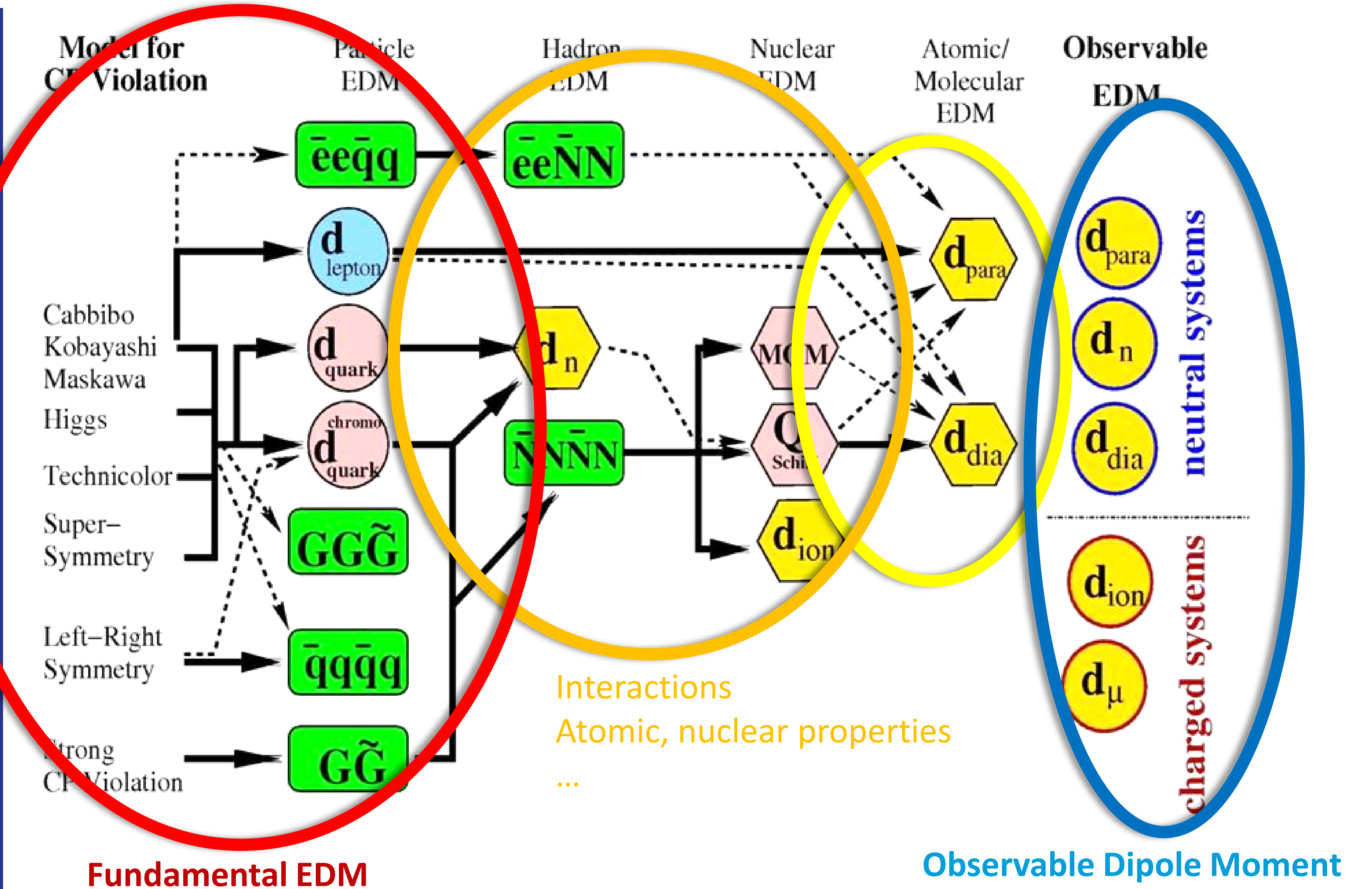
- Sakharov conditions require CP symmetry violation
- This violation is observed in electro-weak interaction, but probably cannot account for matter-antimatter imbalance
- No evidence for CP violation in strong interaction
- **$|d(n)| < 3.1\times10^{-26}$ e cm** ***(Baker et al PRL 97 (2006) 131801)***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



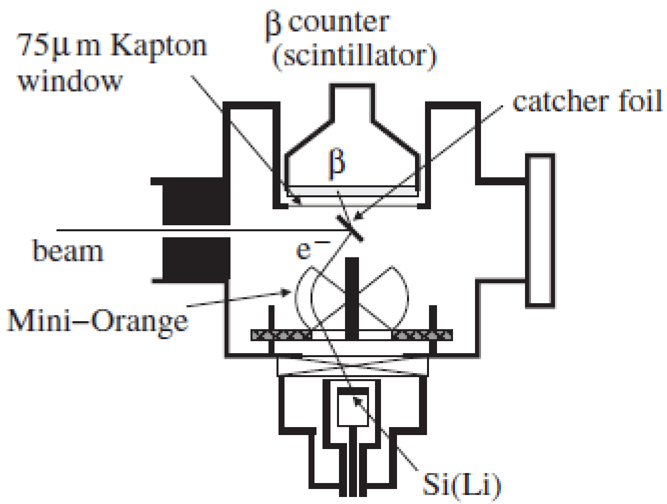
Experimental Limit on d (e cm)
10-20
10-22
10-24
10-26
10-28
10-30
Cs
Cs
Xe*
Hg
Cs
Tl
Tl
Tl
Hg
Hg
ThO
Multi Higgs
Left-Right
SUSY
ϕ~1
ϕ~α/π
1960
1970
1980
1990
2000
2010
2020
dn (e cm)
10-32
10-34
10-36
10-38
n,p
Standard Model
e

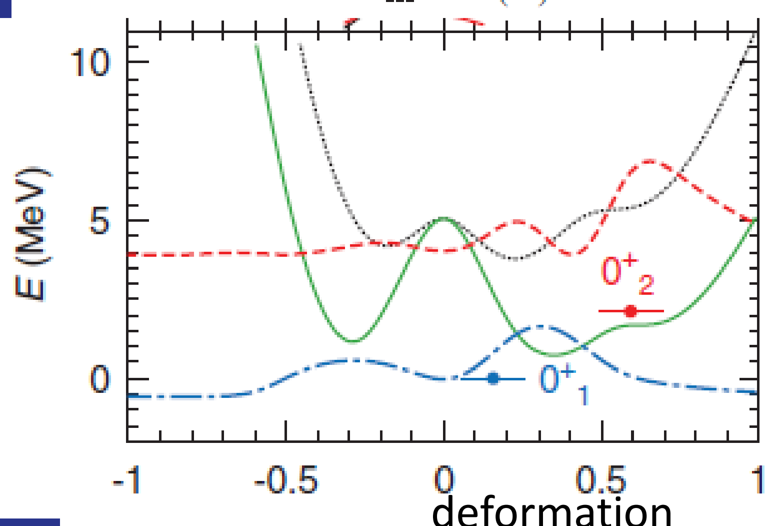


Model for CP Violation
Particle EDM
Hadron EDM
Nuclear EDM
Atomic/ Molecular EDM
Observable EDM
eeqq
eeNN
d lepton
d quark
chromo d quark
GGG̃
qqqq
GG̃
Cabbibo Kobayashi Maskawa
Higgs
Technicolor
Super–Symmetry
Left–Right Symmetry
Strong CP Violation
d n
NNNN
MQM
Q Schiff
d ion
d para
d dia
d para
d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

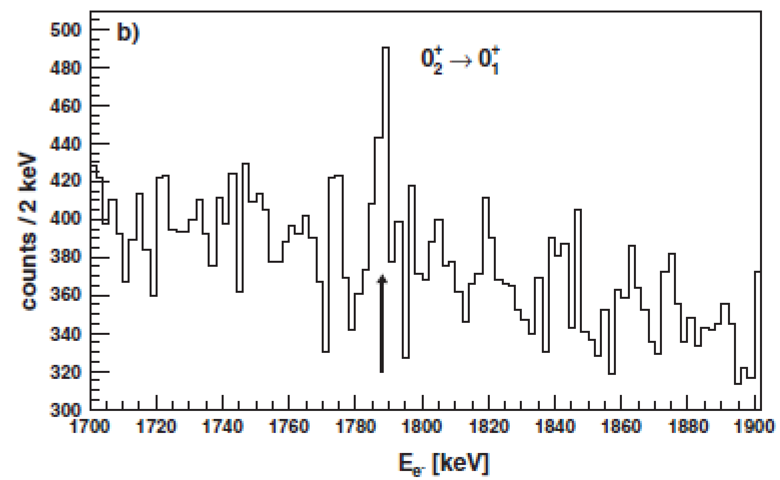
30Mg: E0 transition

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)

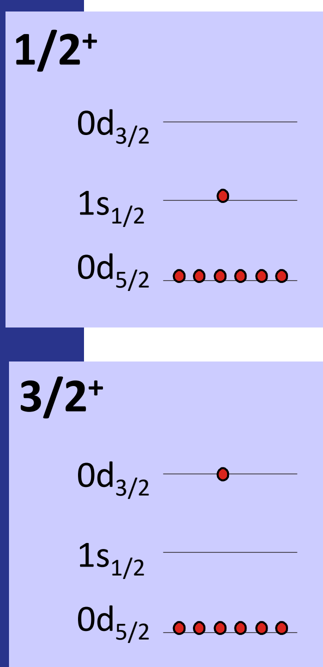
Laser spectroscopy and nuclear physics

- **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** ($\langle r^2 \rangle$)

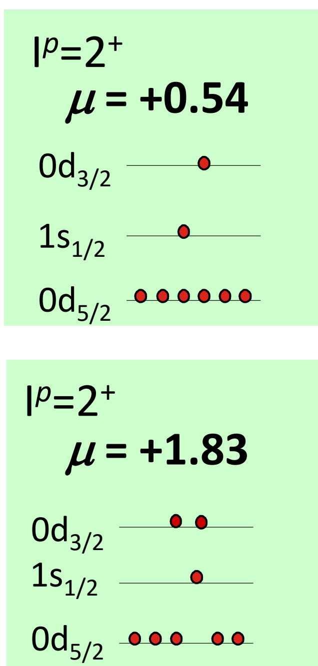
Give information on:

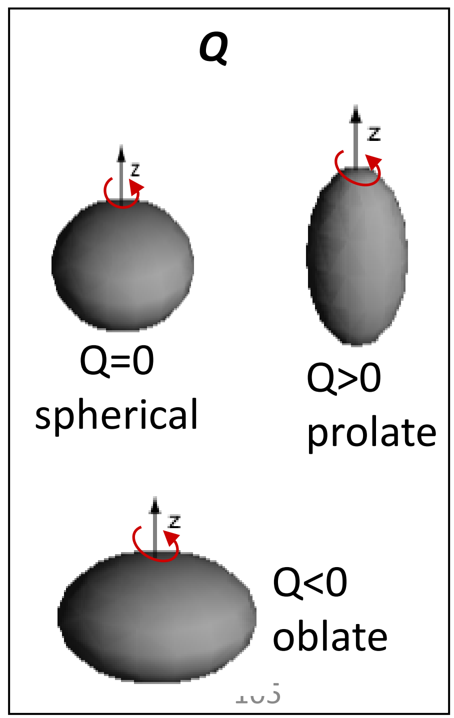
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

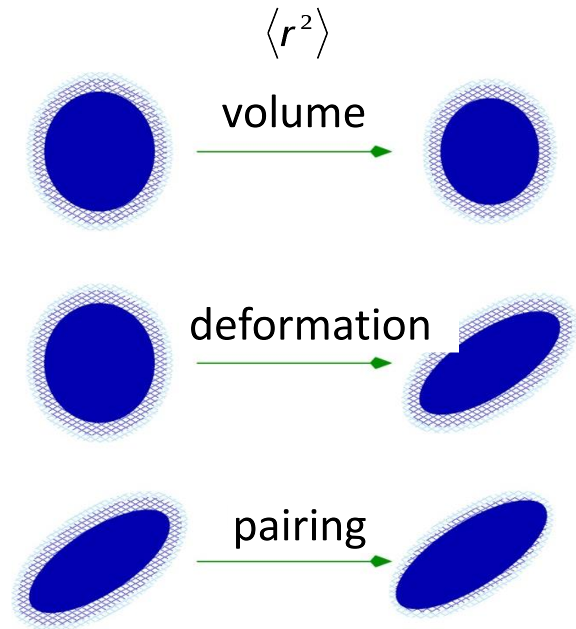
I^{π}



g_I and μ_I







Laser spectroscopy

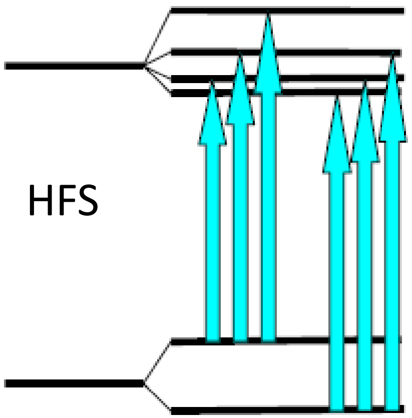
Atomic **hyperfine structure**

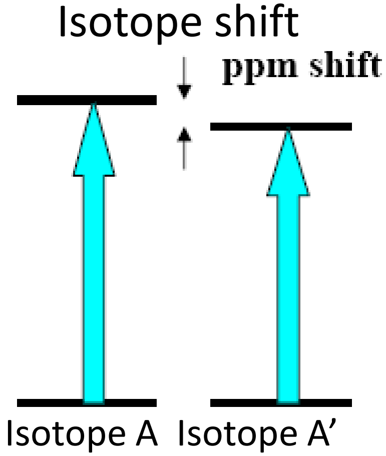
(interaction of nuclear and atomic spins)

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

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 shifts in atomic transitions

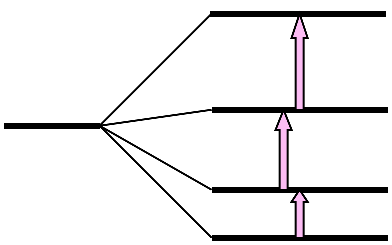
(change in mass and size of different isotopes of the same chemical element)

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

Nuclear Magnetic Resonance – NMR

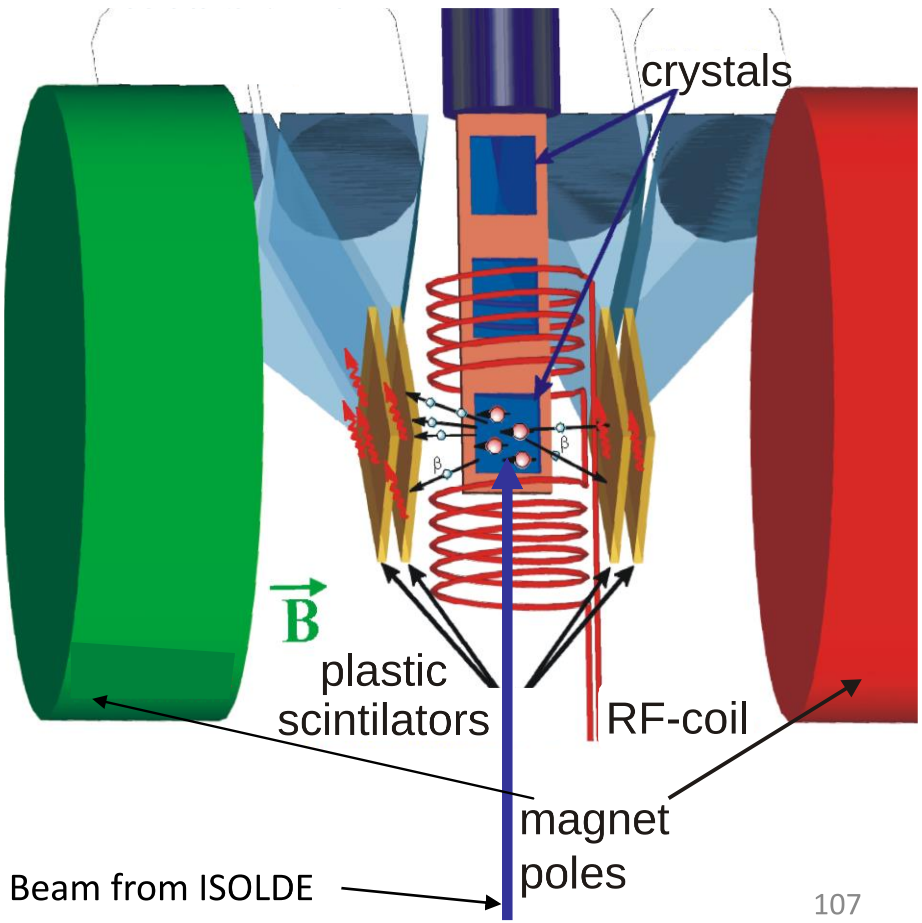
(Zeeman splitting of nuclear levels)

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



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)

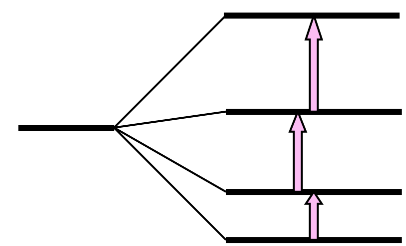


Measured asymmetry:

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

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

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



$B = 0$ $B \neq 0$

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