(Nuclear) Physics at ISOLDE-CERN (2/2)

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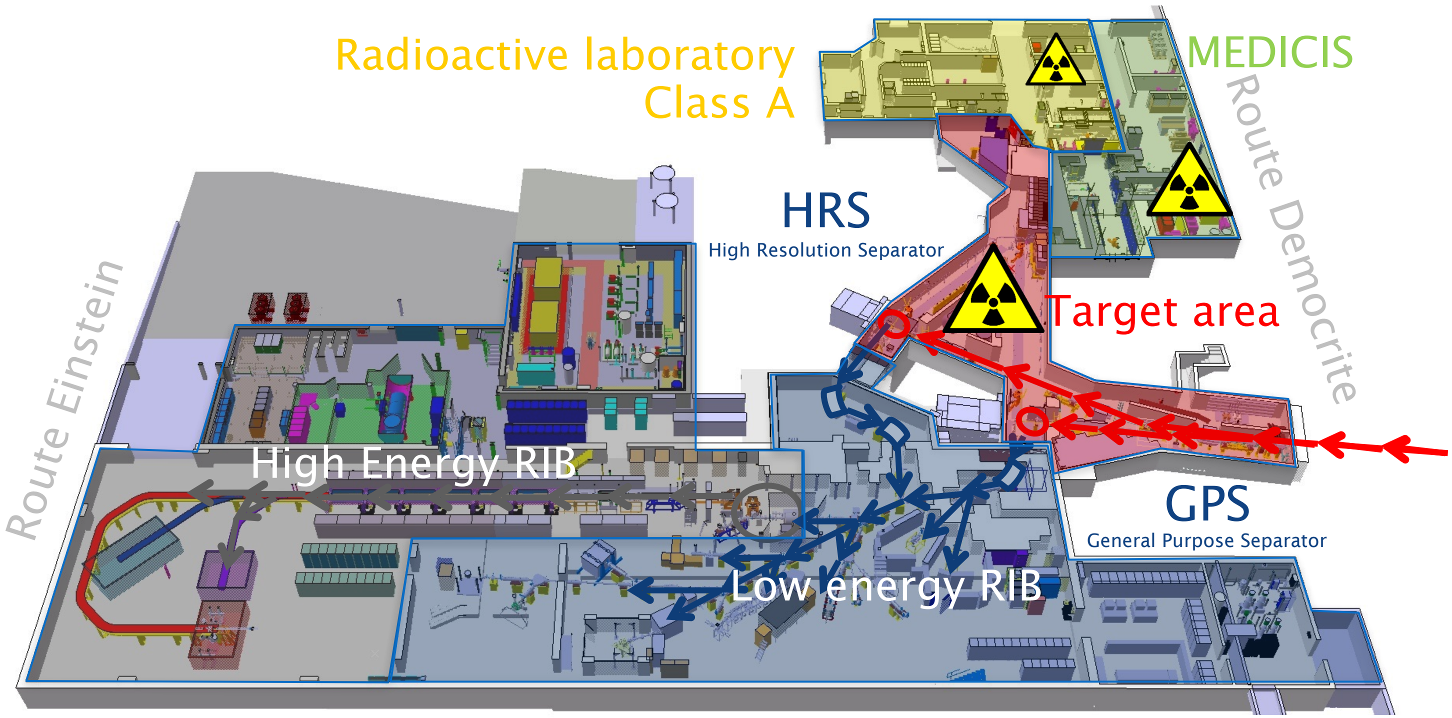
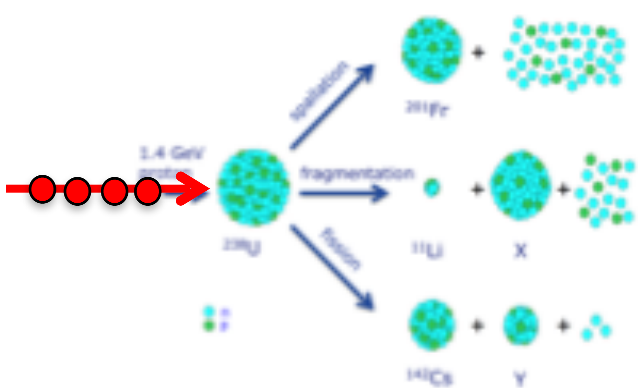
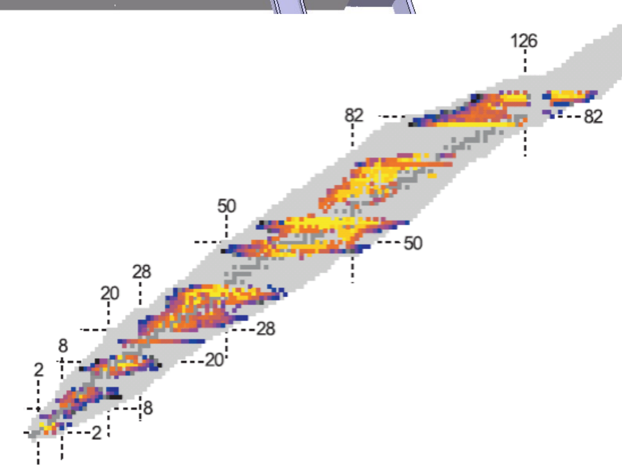
CERN, TRIUMF, and University of Toronto

on behalf of the ISOLDE-CERN group
http://isolde.web.cern.ch

The ISOLDE facility - recap







Homework

What factors determine ion beam intensity in your set-up?

ISOLDE

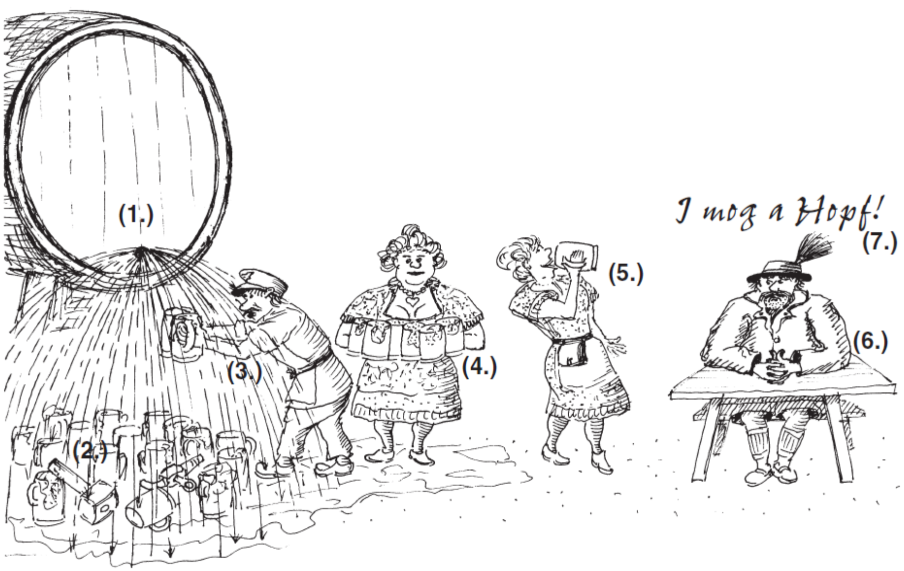
- 1.4 GeV protons
- 2 uA maximal proton intensity
- Isol facility

Homework

- Number of extracted ions (yield) is governed by:

$$r = \Phi \cdot \sigma \cdot N \cdot \varepsilon_{\text{target}} \cdot \varepsilon_{\text{source}} \cdot \varepsilon_{\text{sep}} \cdot \varepsilon_{\text{transp}} \cdot \varepsilon_{\text{det}} \cdot$$

primary particle flux x reaction cross section x number of target particles x efficiencies

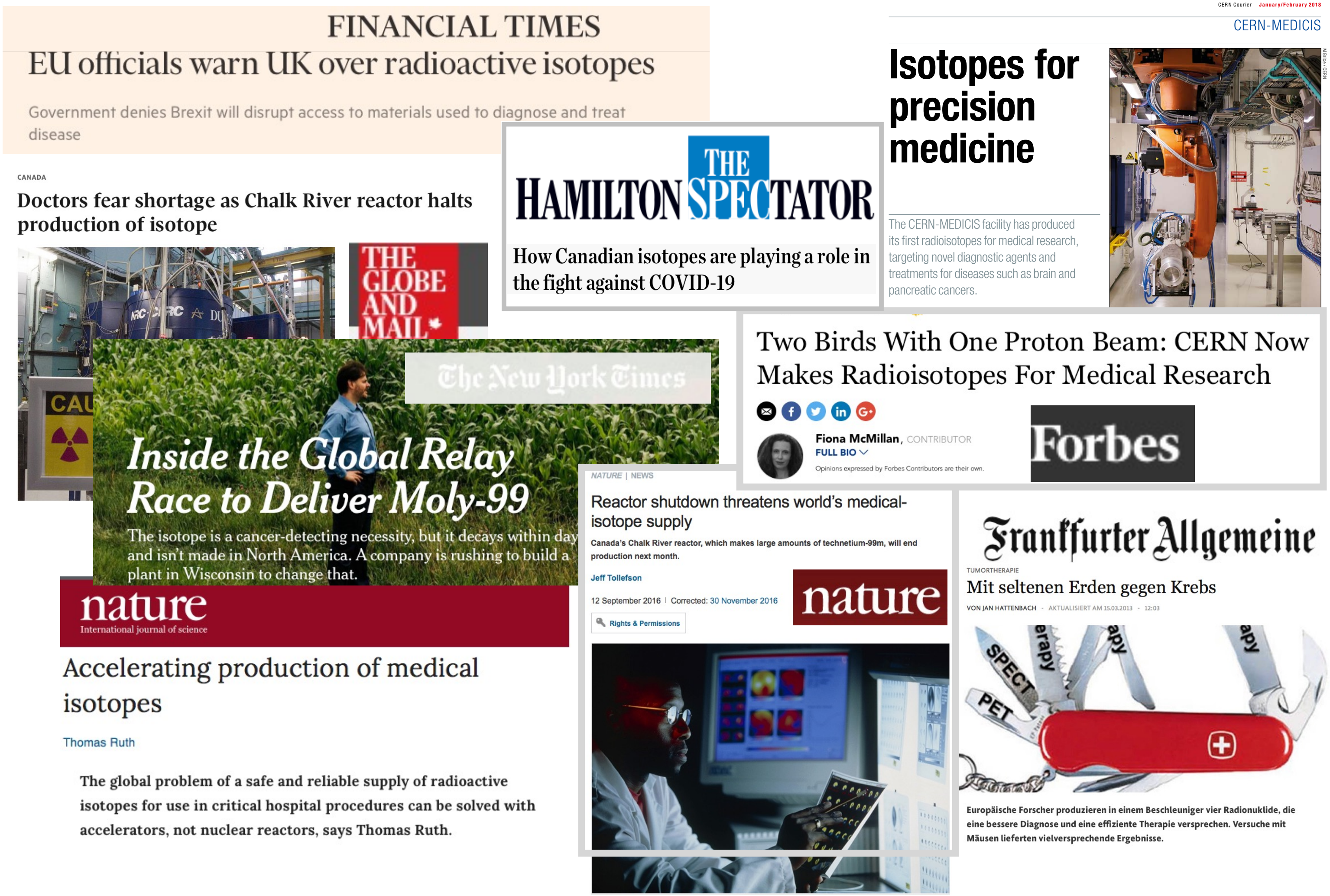


ISOLDE

- Energy loss of protons in thick target (σ(E))
- Secondary reactions in target
- Selectivity <> loss in yield
- Effusion/Diffusion out of target
- Release from target <> half-life
- How much time do we spend on optimizing (gain in intensity <> available beam time)
- ...

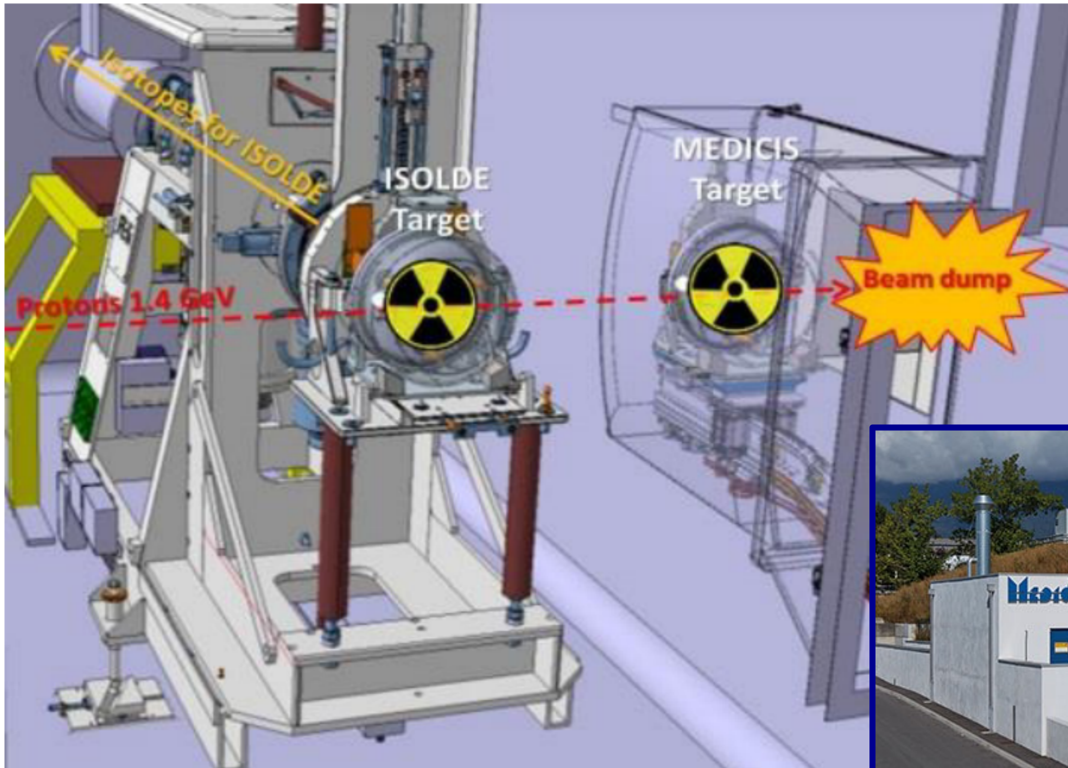
Outline

- Lecture 1: ISOLDE-CERN: radioactive ion beam production
- **Lecture 2**: Nuclear Physics and Applications at ISOLDE



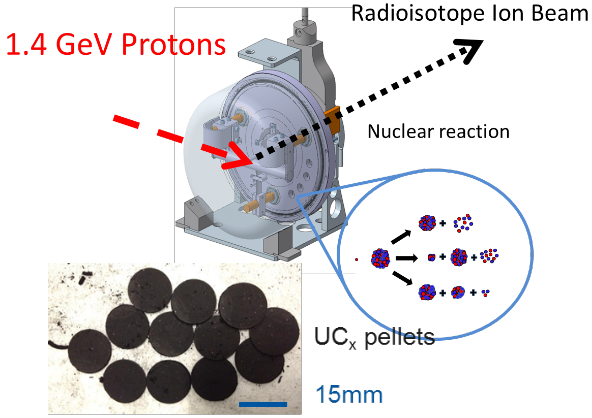
1. Medical Applications

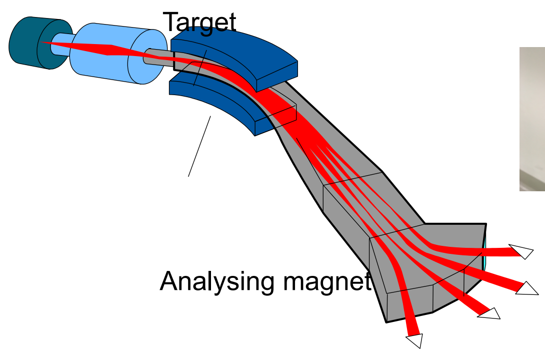
MEDICIS @ CERN

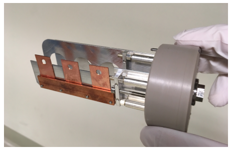


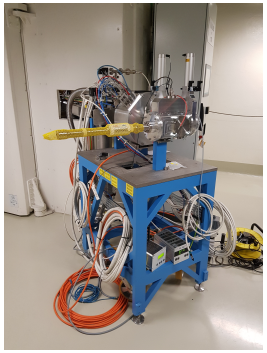
- MEDical Isotopes Collected from ISolde
- Production of non-conventional radioisotope for medical research
  - 80 – 90% of the proton beam goes through the ISOLDE target unaffected
  - Use these (free!) protons to create more radioisotopes
- Benefit from 50 years of ISOLDE experience

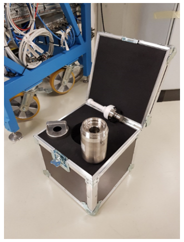
MEDICIS process

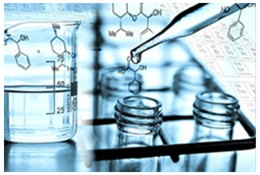


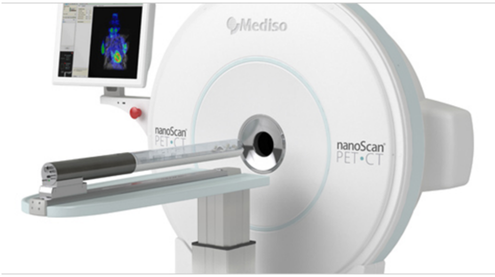


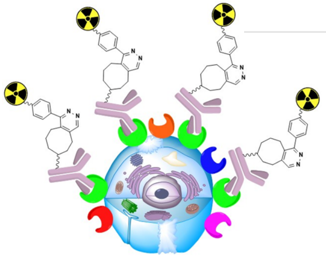




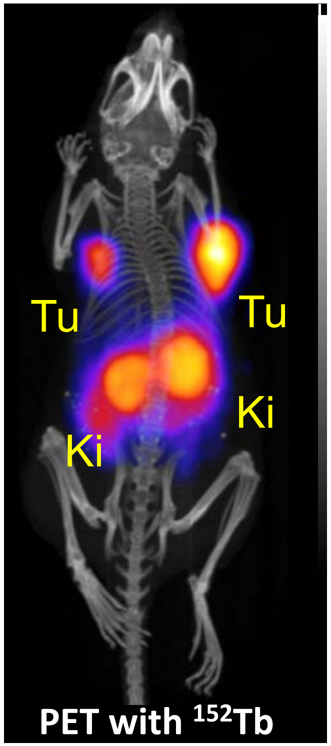


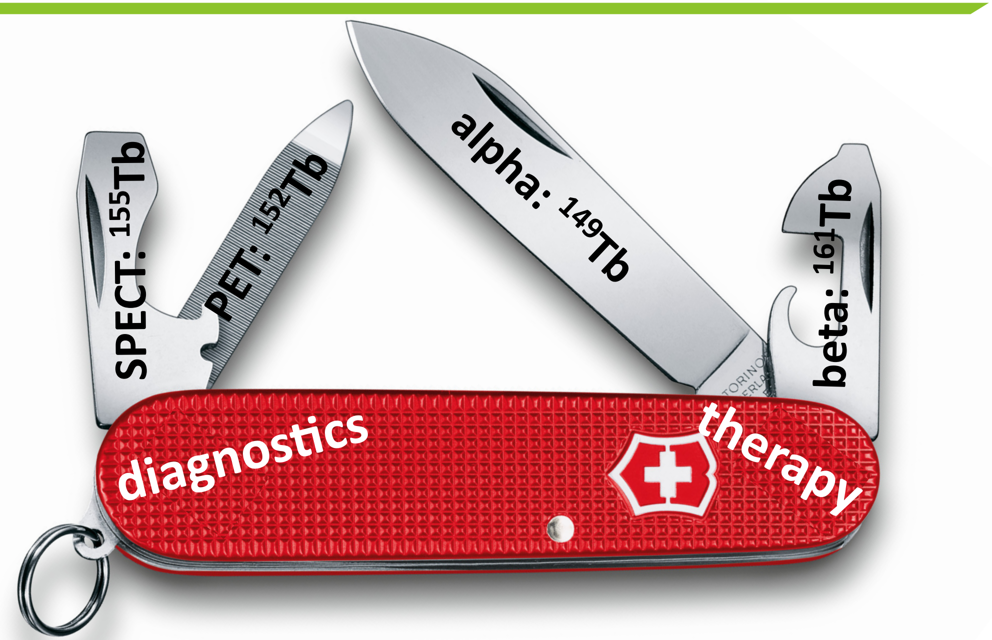




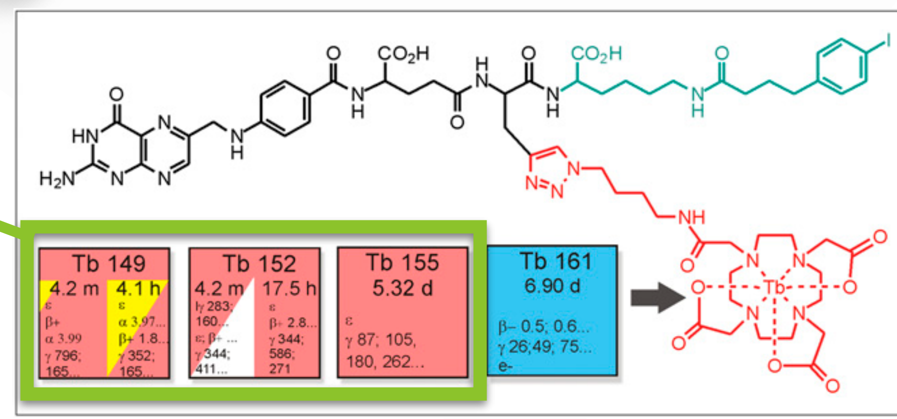


Tb as innovative medical isotopes



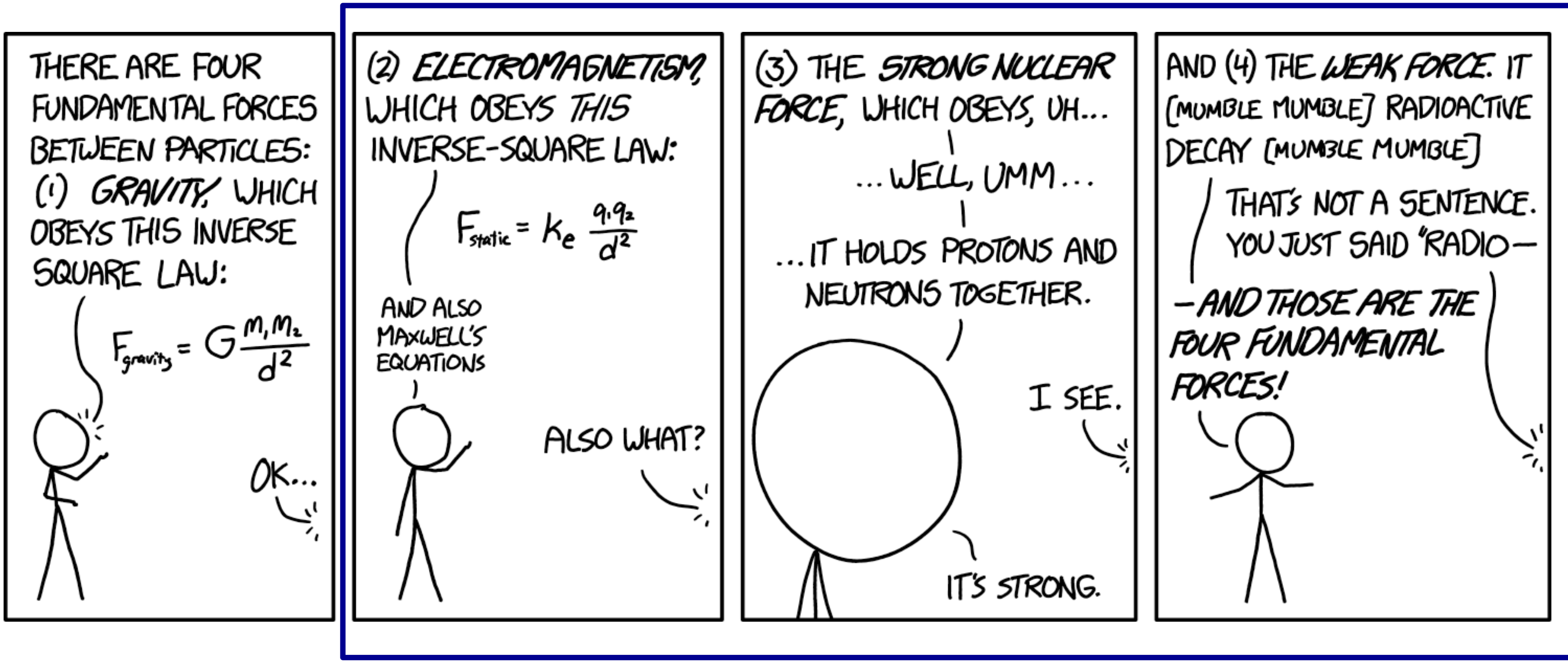


- synthesised at ISOLDE / CERN
  ➡ in fact: Dy, then β decay to Tb
- chemical separation
- In Vivo Studies



C. Müller et al., J. Nucl. Med. 53, 1951 (2012)
C. Müller et al., EJNMMI Radiopharm. Chem. 1, 5 (2016)

https://xkcd.com/1489/

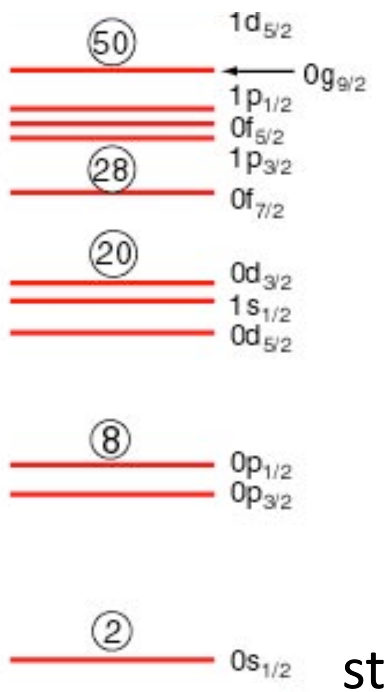


2. Nuclear physics

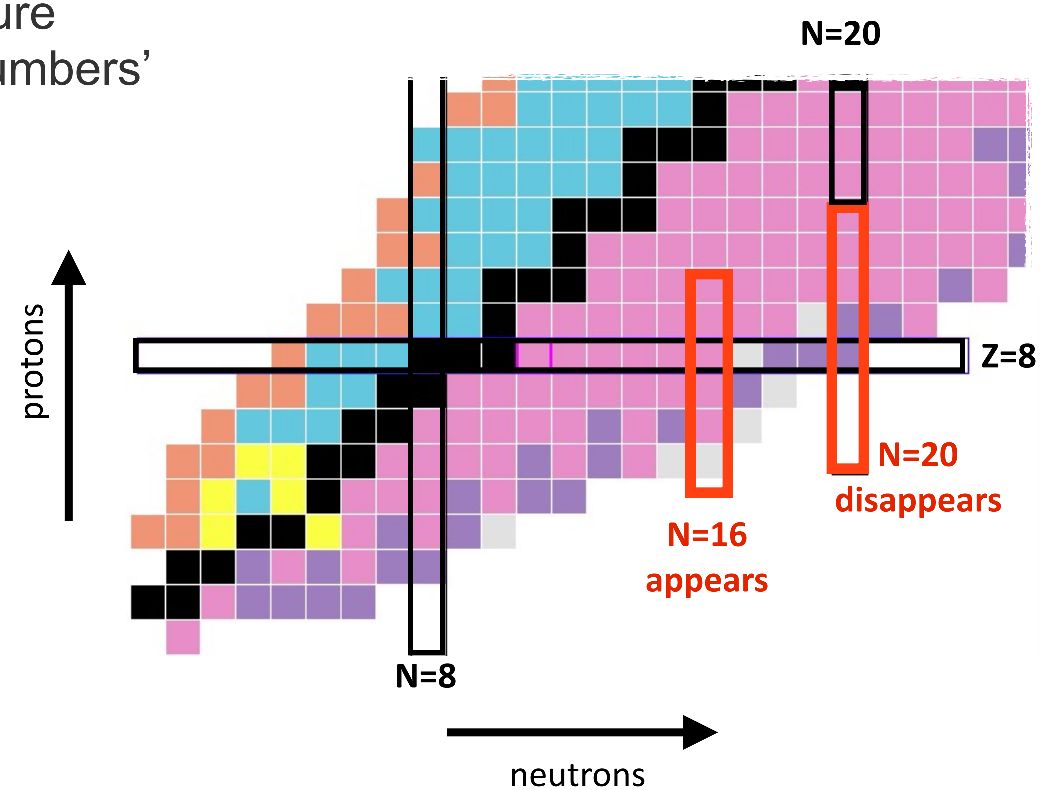
nuclear shell structure

Maria Goeppert Mayer
J. Hans D. Jensen
Nobel Prize 1963

shell structure
& 'magic numbers'



Shell Model of Nuclei



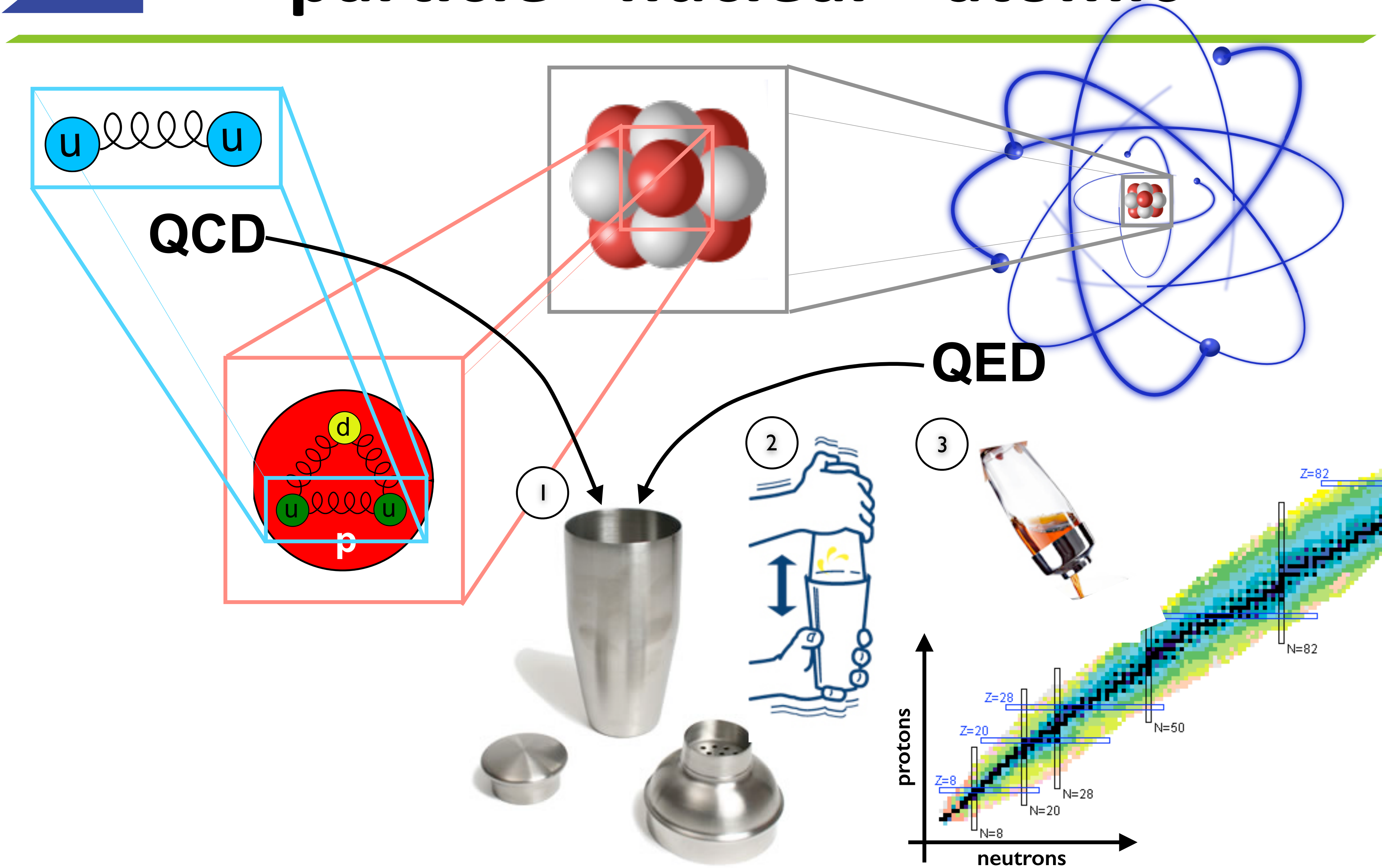
studies at modern radioactive ion beam (RIB) facilities

➡ disappearance of established shell closures

➡ emergence of new ones

explain this shell evolution from first principles

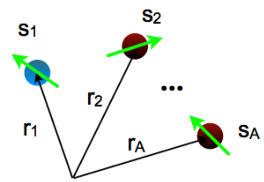
particle - nuclear - atomic



nuclear theory: the big challenges

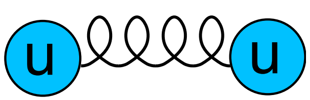
‘ingredients’ well understood, **<u>BUT</u>**

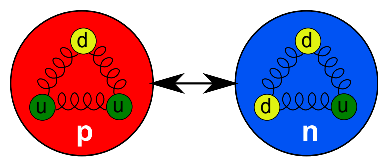
- neither a few nor a many body problem

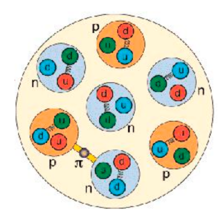


method

- nucleons composites of quarks: **force between nucleons?**



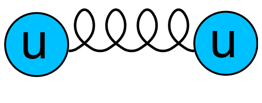




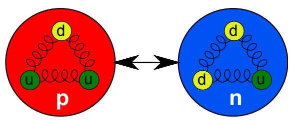
nuclear forces

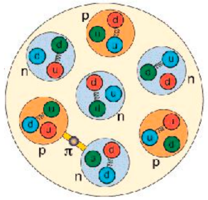
modern nuclear forces

quarks

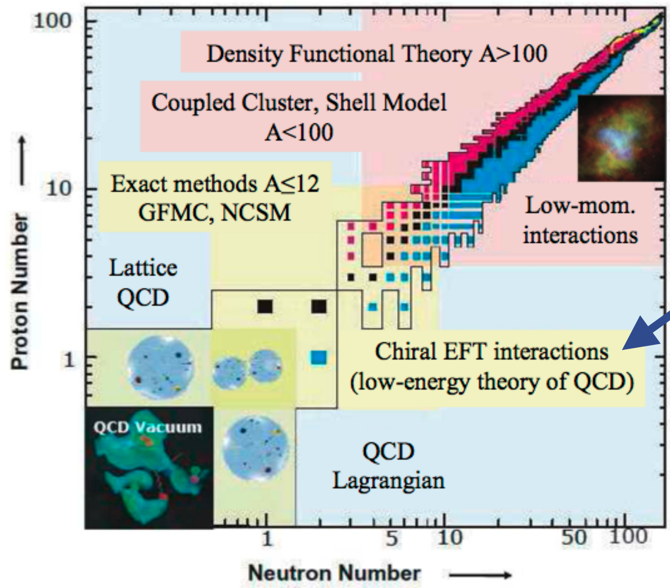


nucleons

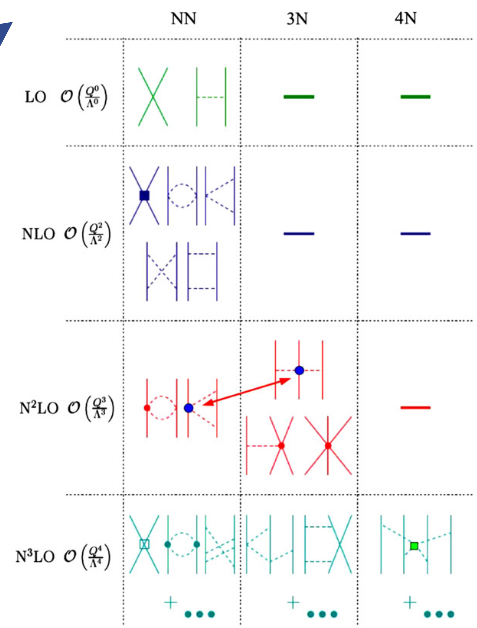




- bridge QCD to nuclear forces
- coupling constants fixed to (small) set of exp. data
- employ renormalisation methods
- 'one' nuclear potential used over whole nuclear chat
- potential employed in different few and many body methods

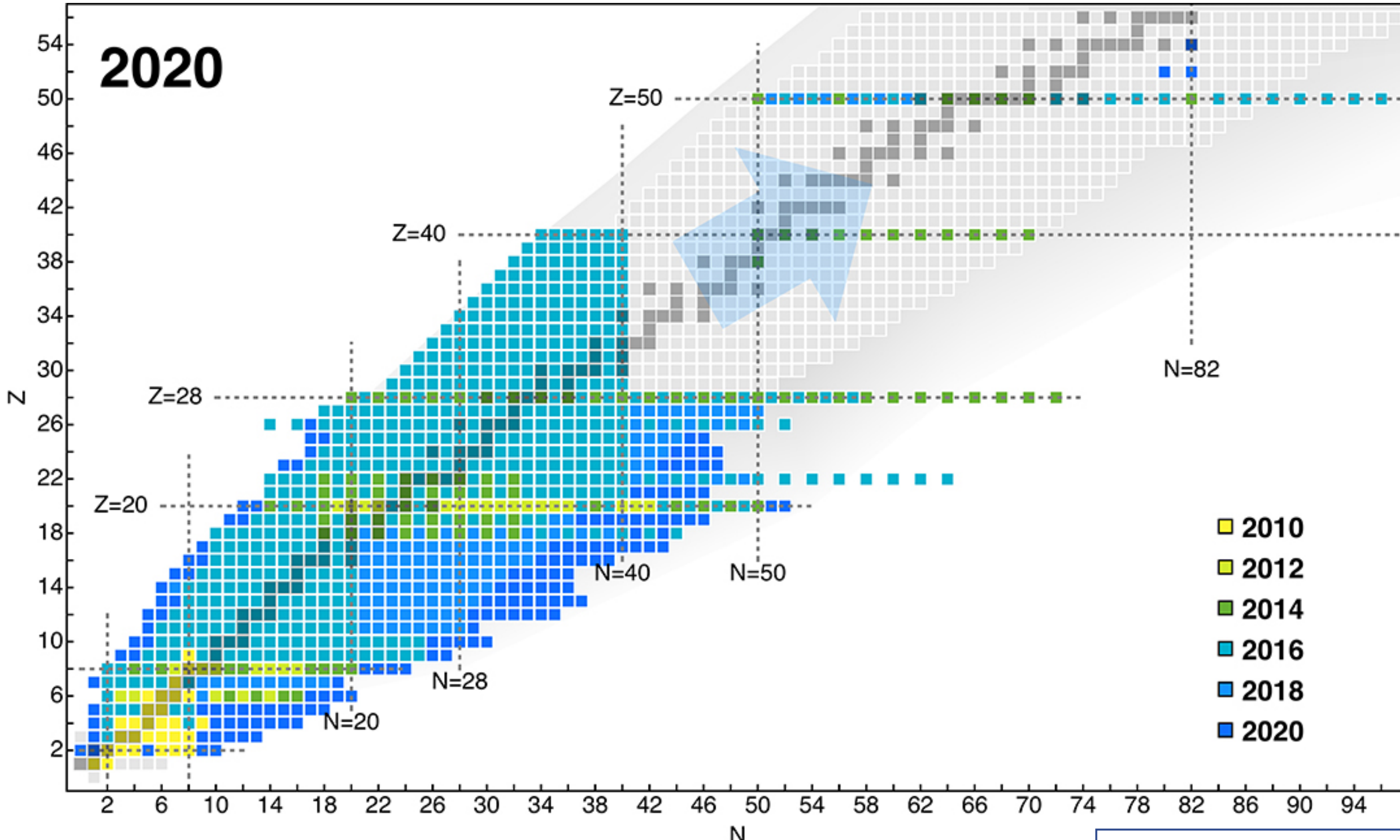


Chiral EFT



E. Epelbaum et al., Rev. Mod. Phys., 81, 1773 (2009)
S.K. Bogner et al., Prog. Par. Nuc. Phys., 65,94, (2010)
R. Machleidt and D.R. Entem, Phys. Rep. 503, 1 (2011)

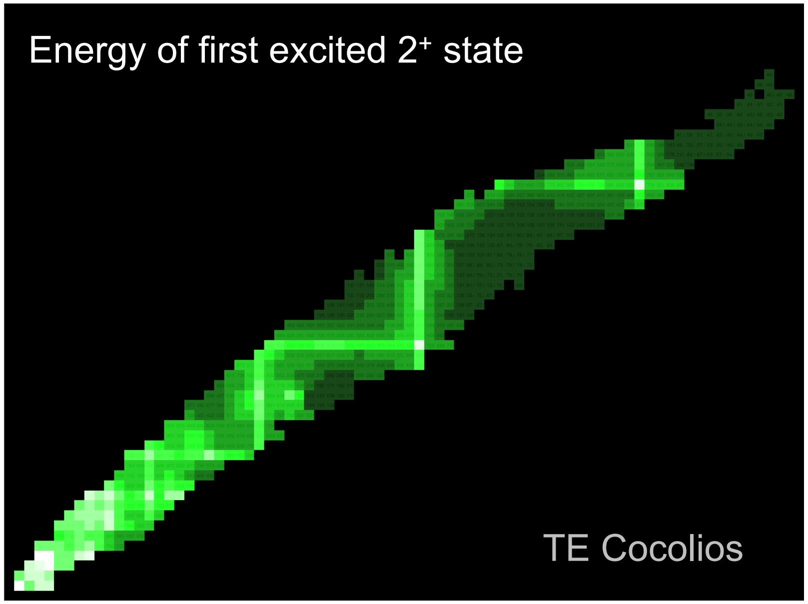
reach of ab-initio methods



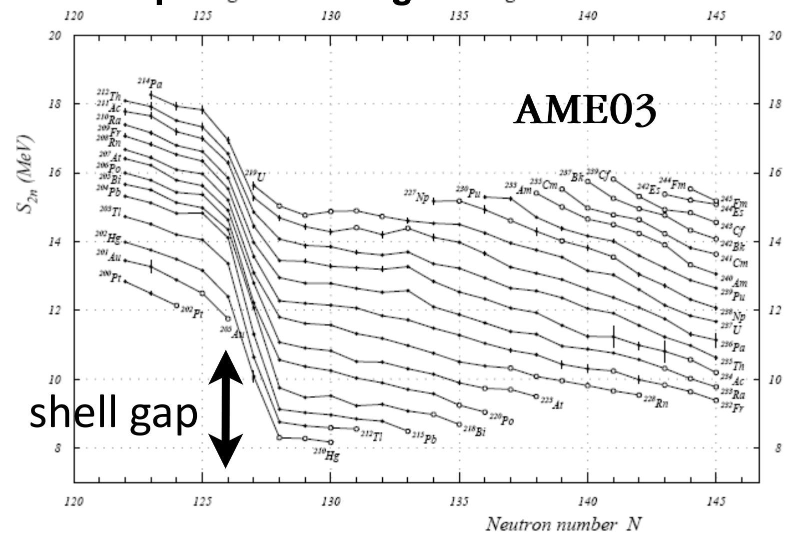
H. Hergert, Front. Phys. 8, 379 (2020)

requires experimental benchmark for nuclear theory

Examples for signatures of Shell Closures



Neutron separation energies & nuclear Masses



Beta decay energies

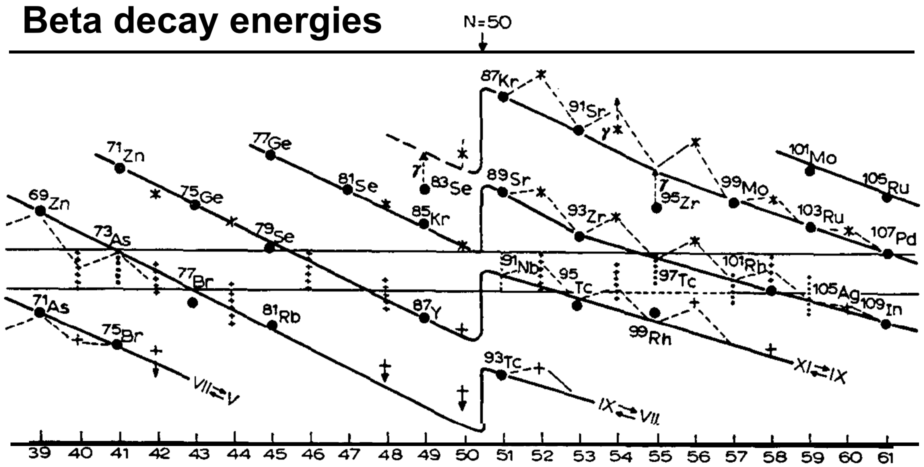
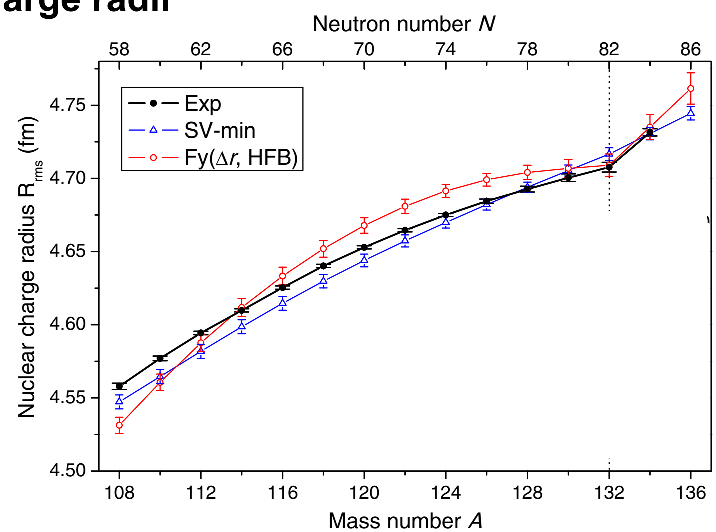


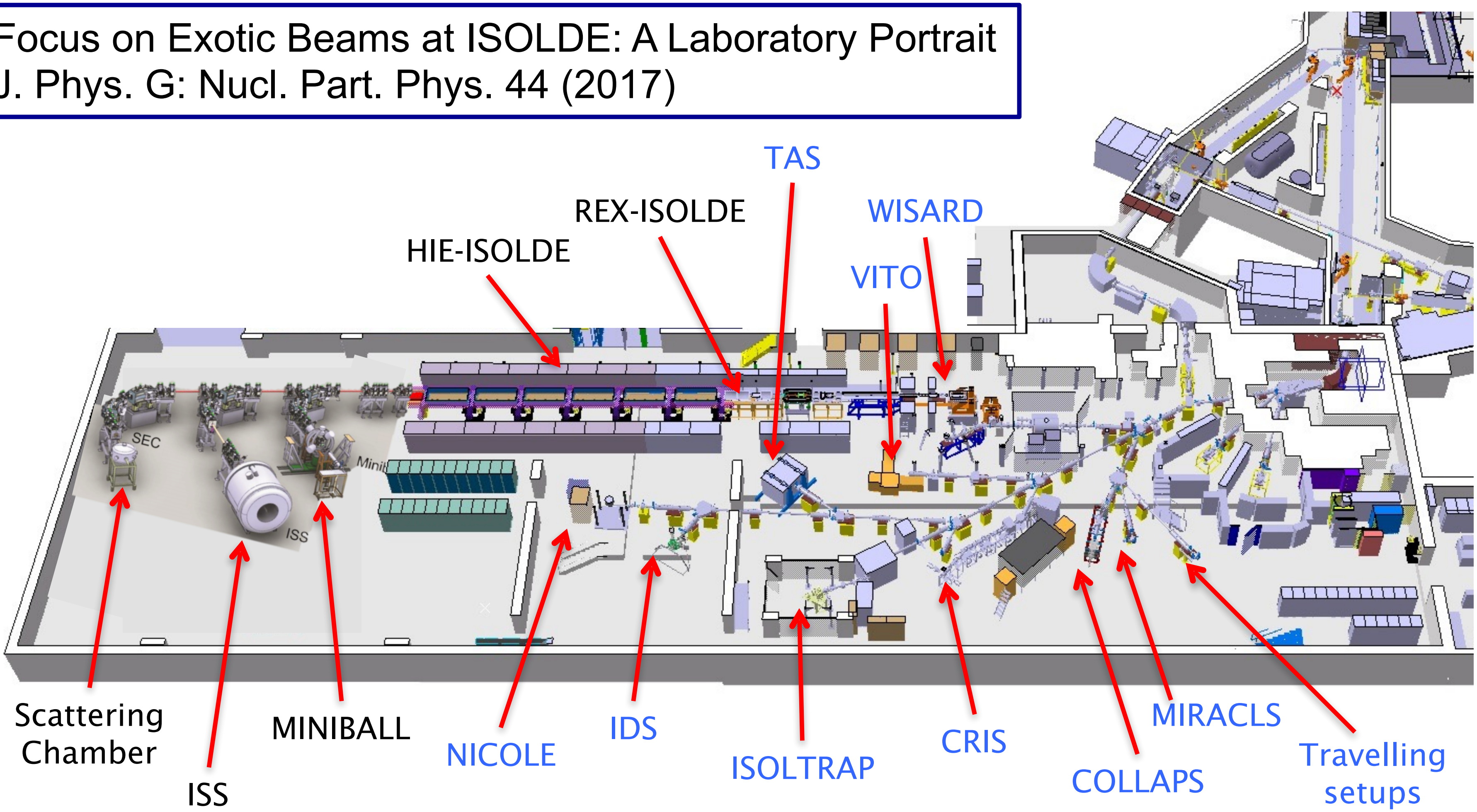
Fig. 3. Beta decay energies in the neighborhood of $N = 50$.

Charge radii



Experiments to probe nuclear structure

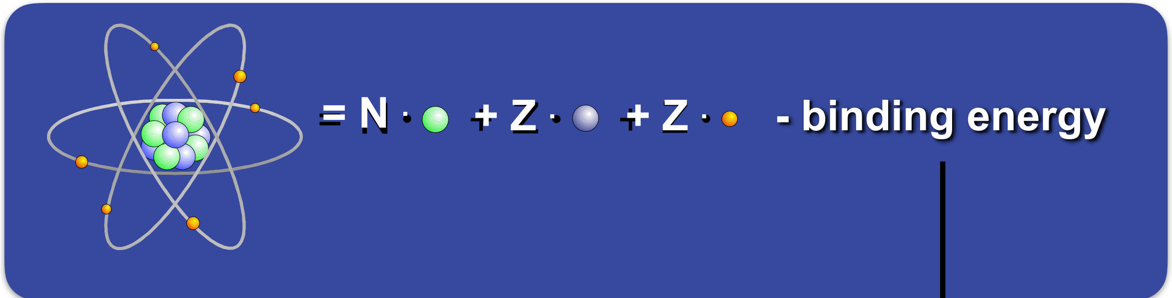
Focus on Exotic Beams at ISOLDE: A Laboratory Portrait
J. Phys. G: Nucl. Part. Phys. 44 (2017)



Low energy experiments
High energy experiments

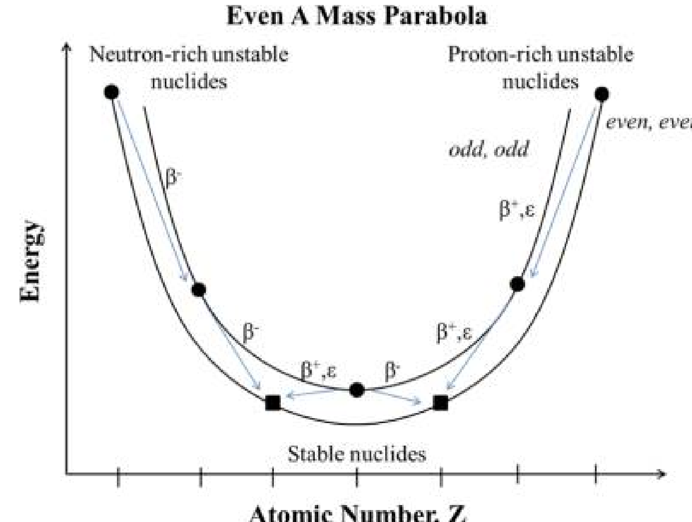
masses

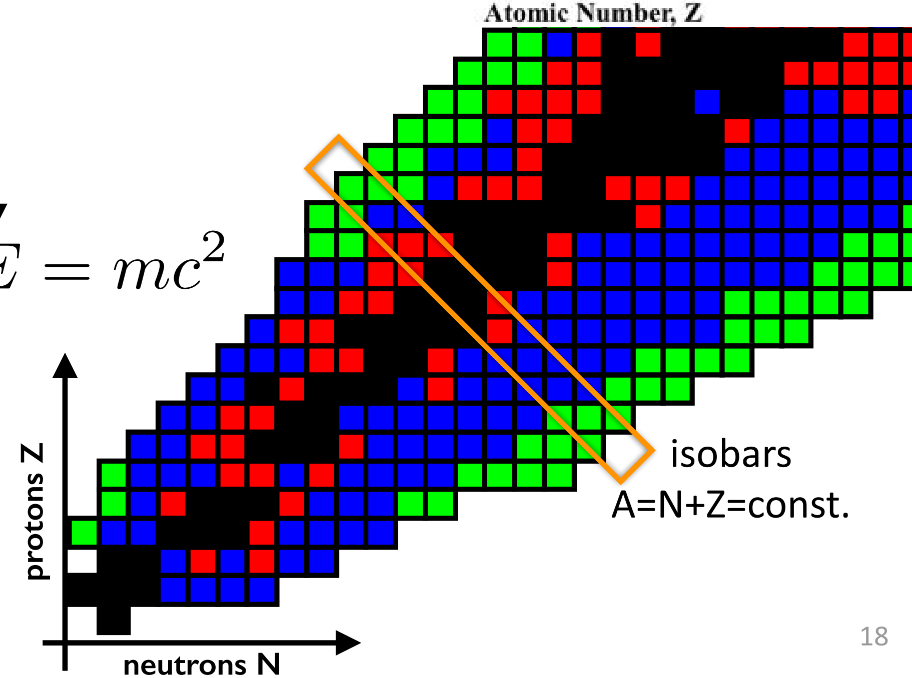
Atomic Masses



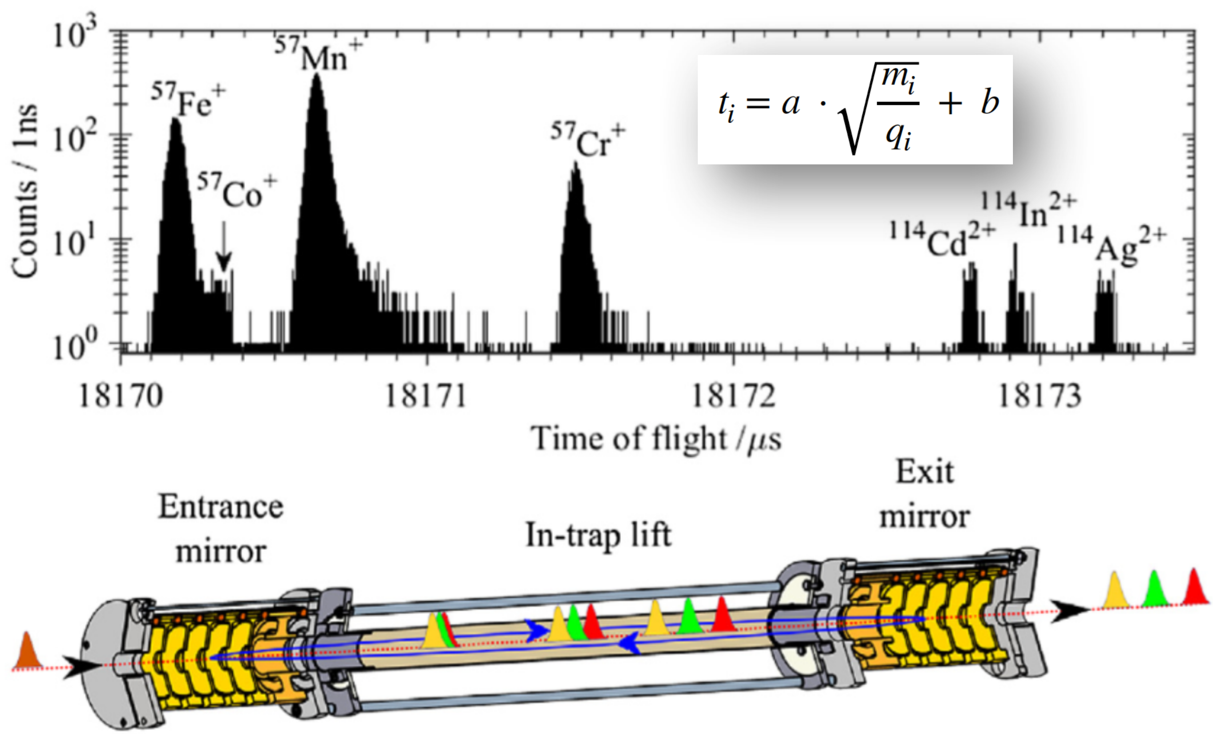
	Mass [MeV/c²]
neutron	939.565 420 52(54)
proton	938.272 088 16(29)
electron	0.510 99895000(15)
nuclear binding	≈8 per A
electron binding	0.000013 (Hydrogen) 0.115606 (inner e^- in U)

$$E = mc^2$$





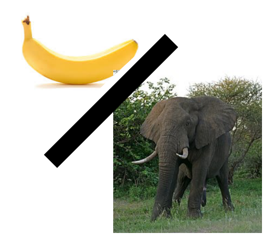
ISOLTRAP MR-ToF mass spectrometer



Multi-reflection Time-of-Flight (MR-ToF)

- Fold 1000s m of flight-path in device of ~1m
- Limitation
  - < 1 pps
  - 10 ms half-life
- Resolving power
  - 10^5 in ~20 ms

δm mass resolution / **m** mass ≈

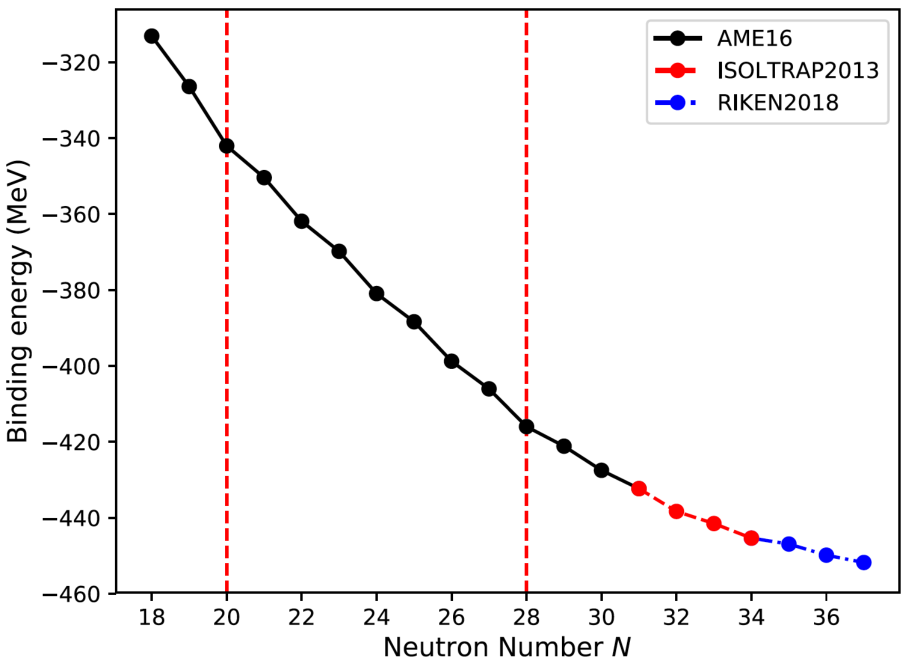


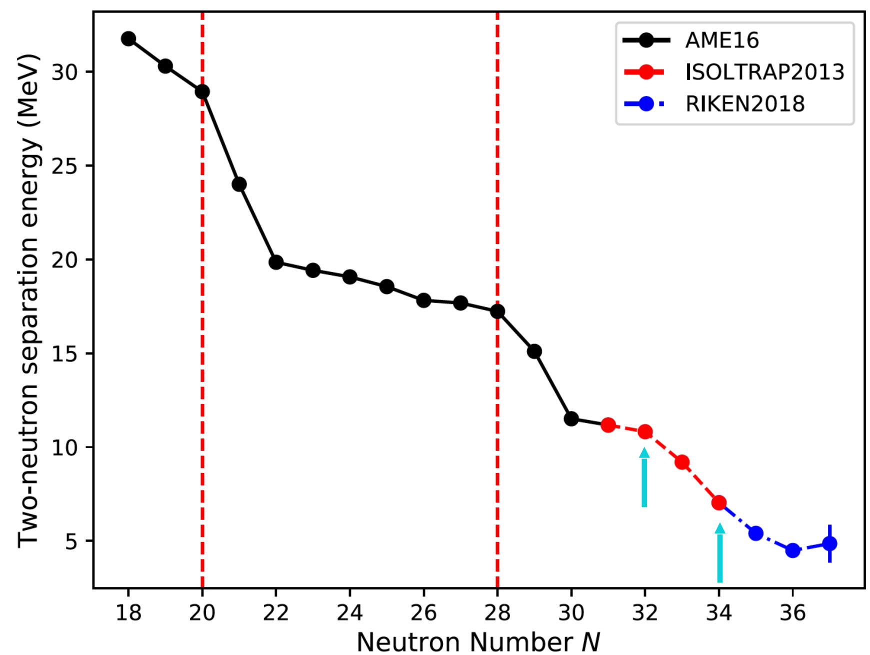
F. Wienholtz et al., Int. J. Mass Spectrom. 421, 285-293 (2017)

maxime.mougeot@cern.ch

ISOLTRAP mass spectrometer

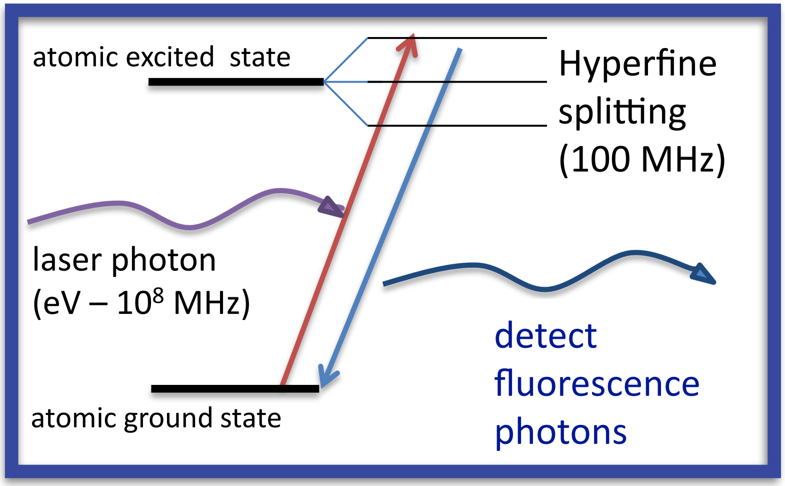
- Ca-isotopes
  - Z = 20 closed shell: benchmark for nuclear models
  - New magic numbers at N = 32 and N = 34?





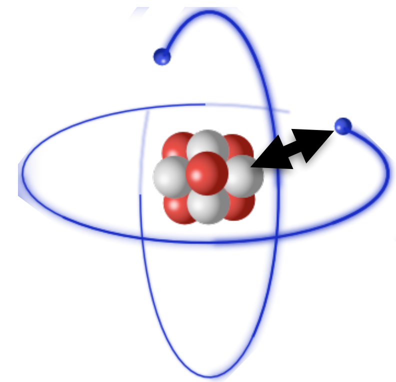
$$S_{2n}(Z,N) = E(Z,N-2) - E(Z,N)$$

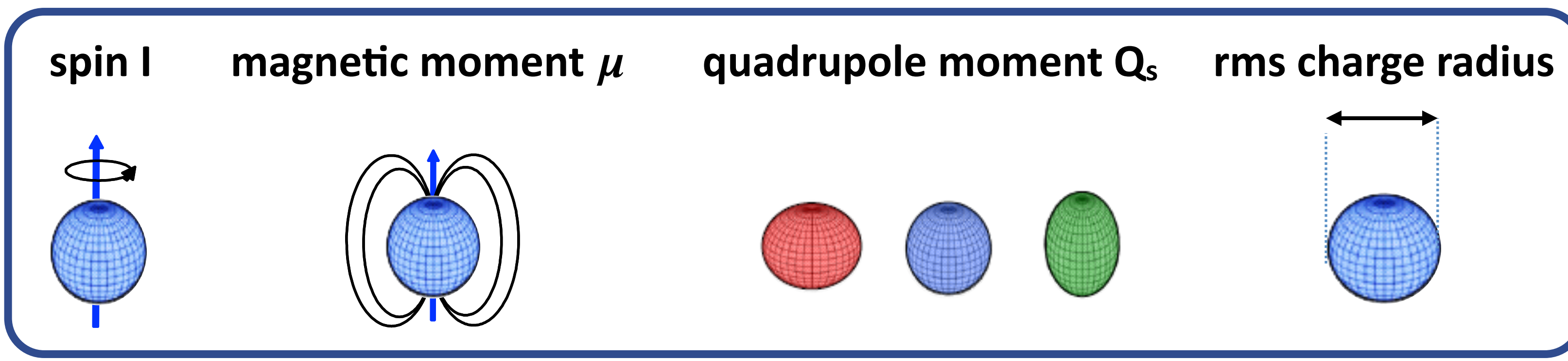
laser spectroscopy of radionuclides



nucleus - electrons interaction

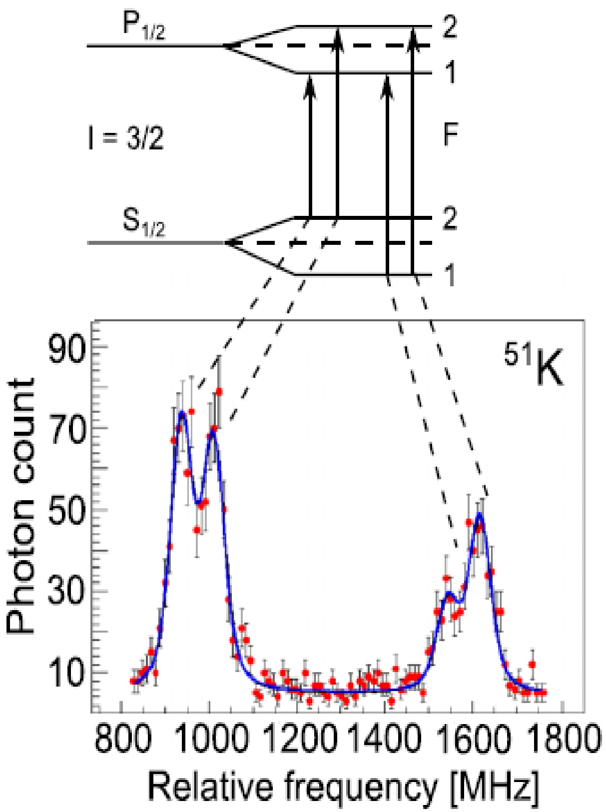
⇒ atomic hyperfine structure

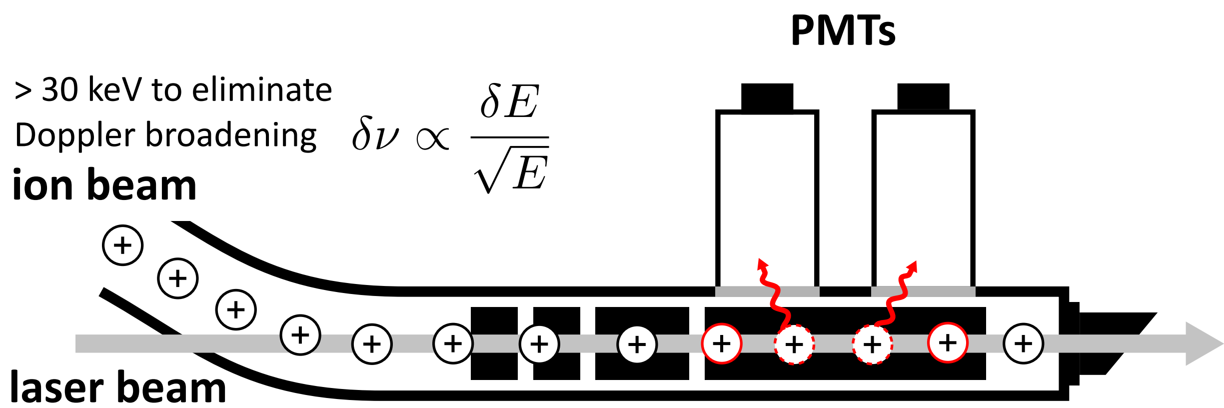




benchmark for modern nuclear structure theory

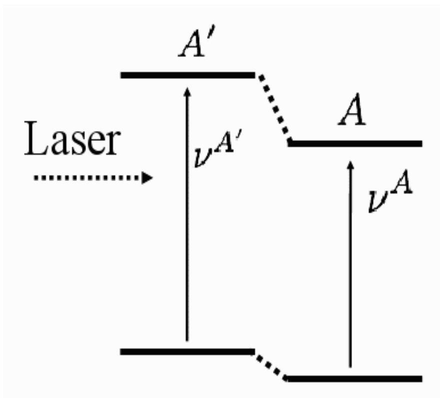
Collinear Laser Spectroscopy (CLS)





CLS and nuclear charge radii

isotope shift

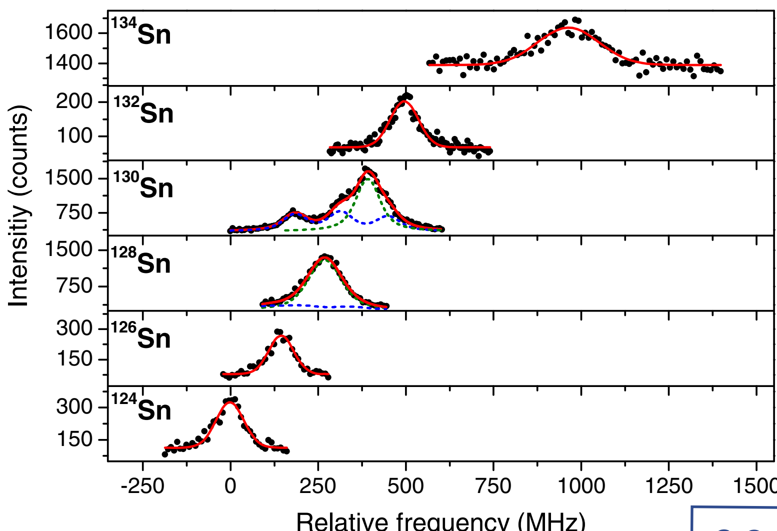


$$\delta\nu^{A,A'} = M\frac{A'-A}{A\cdot A'} + F\delta\langle r^2\rangle^{A,A'}$$

difference in ms charge radii

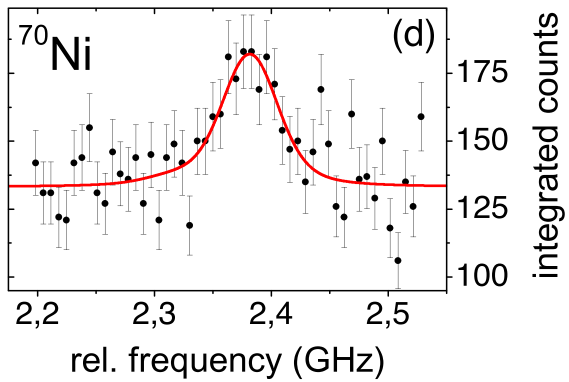
mass and field shift factors

- king-plot analysis of stable isotopes
- atomic theory



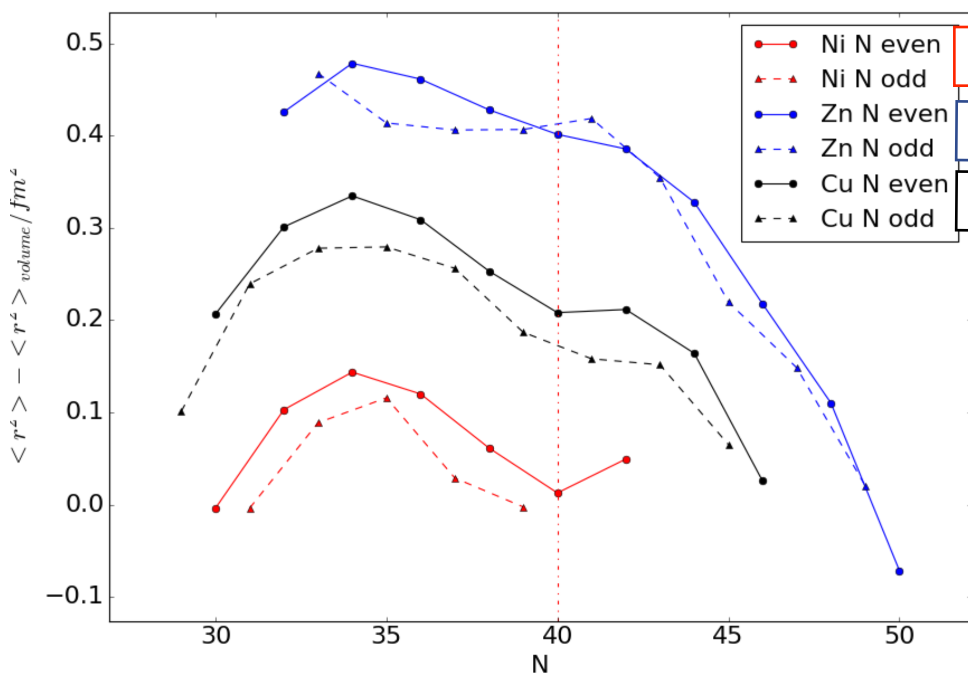
G. Gorges et al., PRL 122, 192502 (2019)

CLS of exotic Ni isotopes



Most exotic, studied Ni isotope: **^{70}Ni**

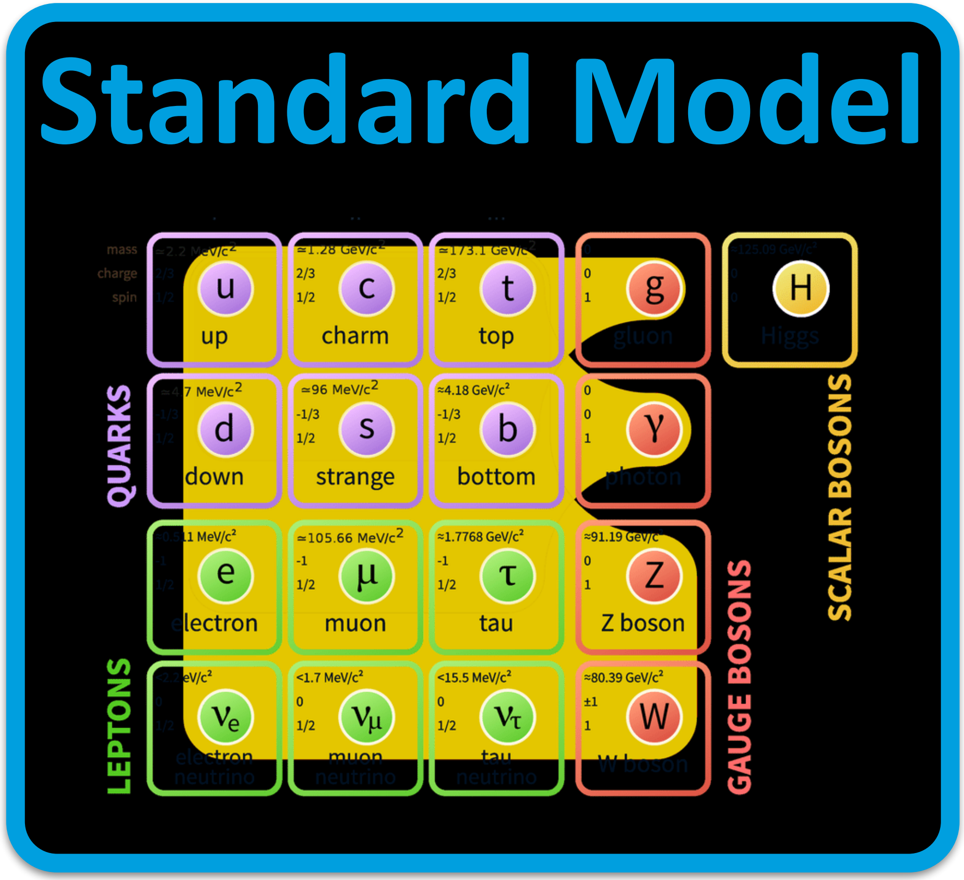
- $T_{1/2}$= 6 sec.
- typical ISOLDE yield 10^4 ions/sec
- ^{70}Ni : ^{70}Ga = 1 : 10^4



SME et al., Phys. Rev. Lett. 128, 022502 (2022)

L. Xie et al., PLB 797, 134805 (2019)

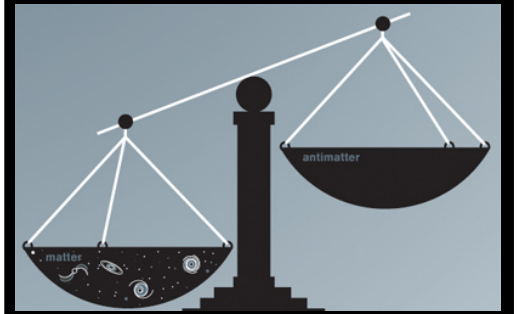
M. L. Bissell et al., PRC 93, 064318 (2016)



3. Radionuclides & Fundamental Symmetries of Nature

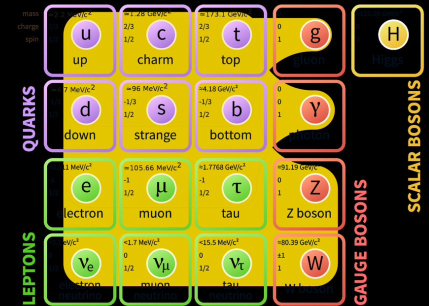
where is all the antimatter?

Macrocosmos



only matter

Microcosmos

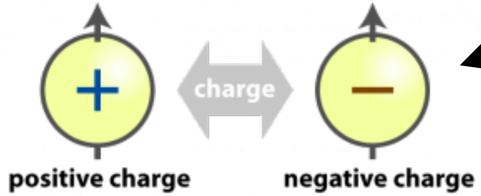


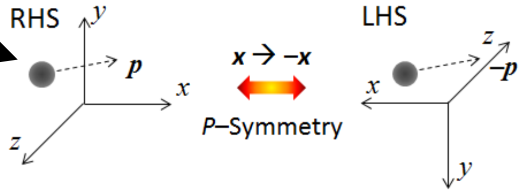
|matter|=|antimatter|

Sakharov, 1967

ingredient to resolve universe's matter-antimatter asymmetry:

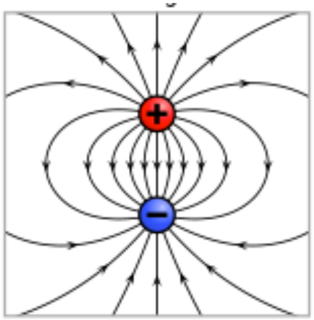
CP violation



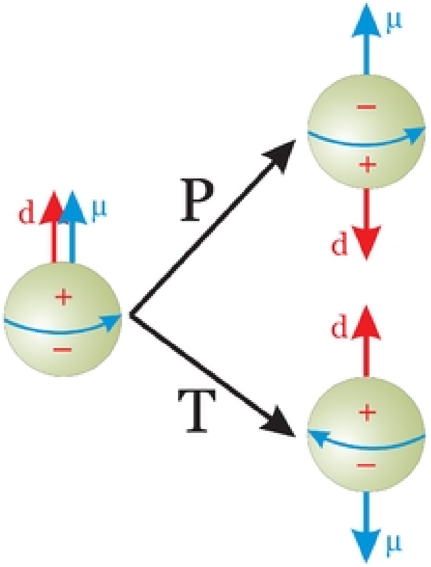


Permanent electric dipole moment

- local separation of the electric charge along a particle's spin axis

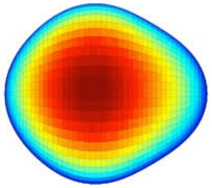


- implies time-reversal (T) violation ⇒ violation of CP symmetry (assuming CPT)



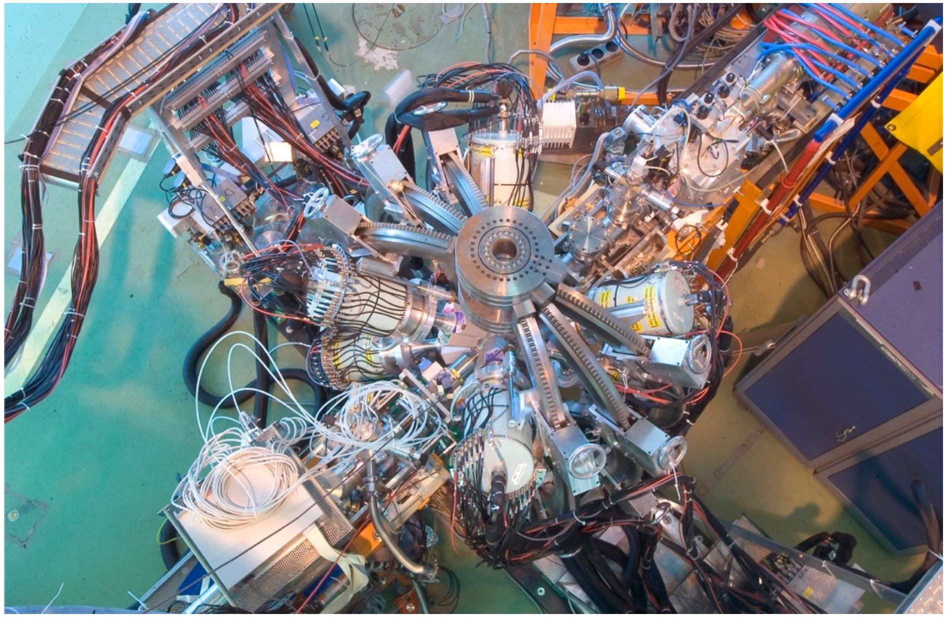
matter-antimatter asymmetry in the universe

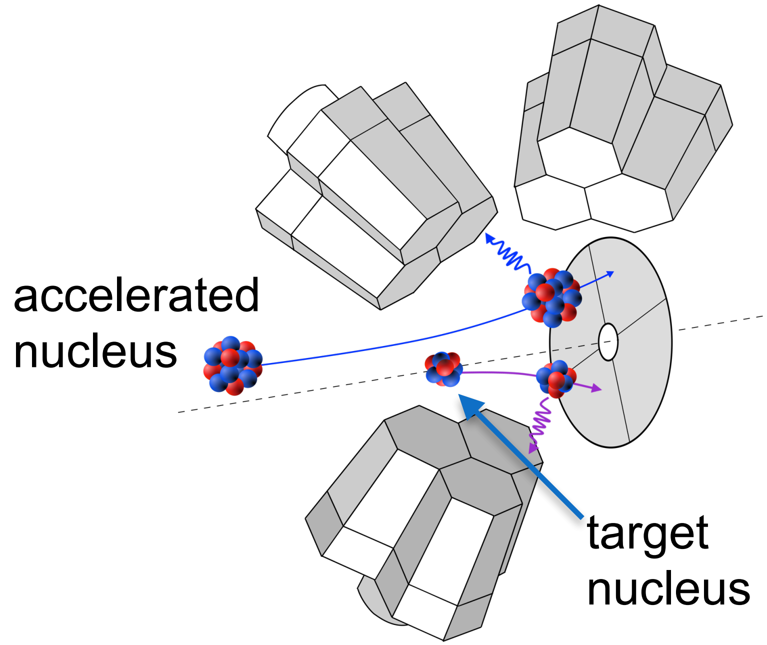
pear-shaped nuclei & 'nuclear EDM'



Schiff moment

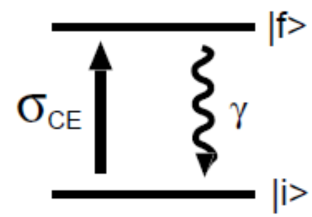
Miniball: Coulomb excitation





- Coulomb excitation
  - Inelastic scattering of nuclei with electromagnetic force only
  - Nuclei never collide

- Observables
  - Gamma-decay energies
  - Probability to excite to final state



Miniball: Coulomb excitation

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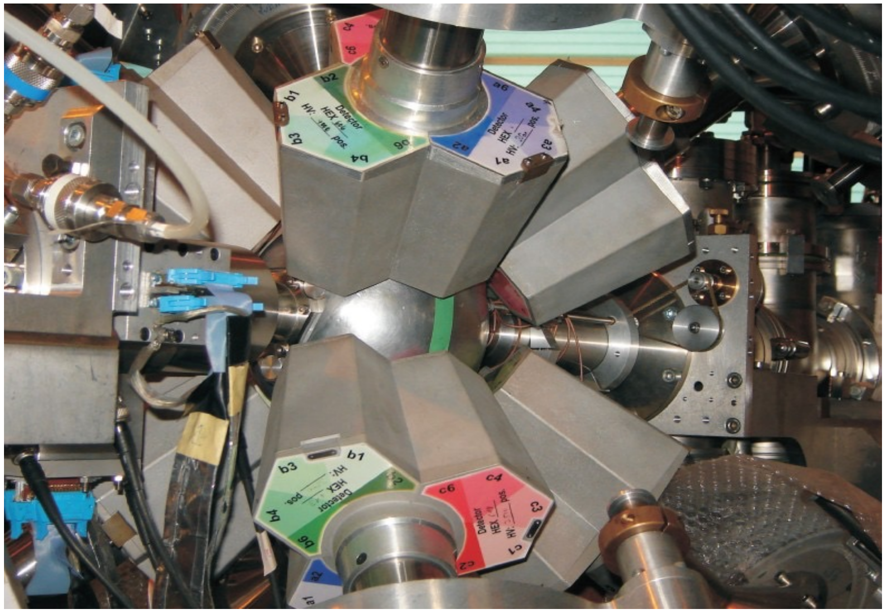
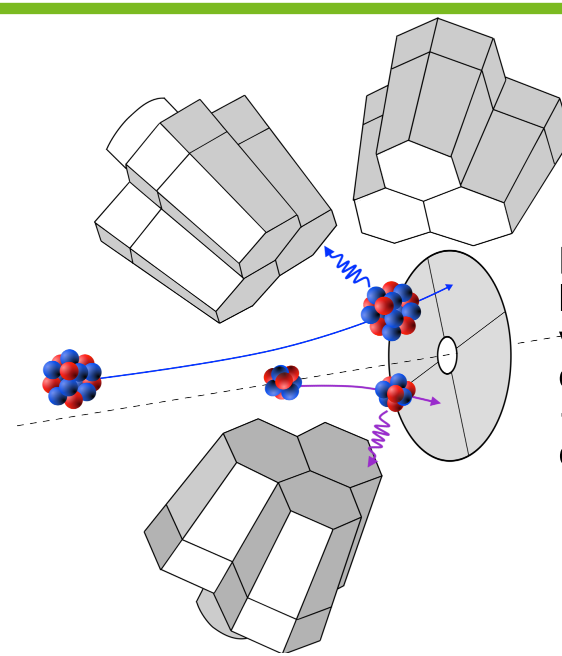
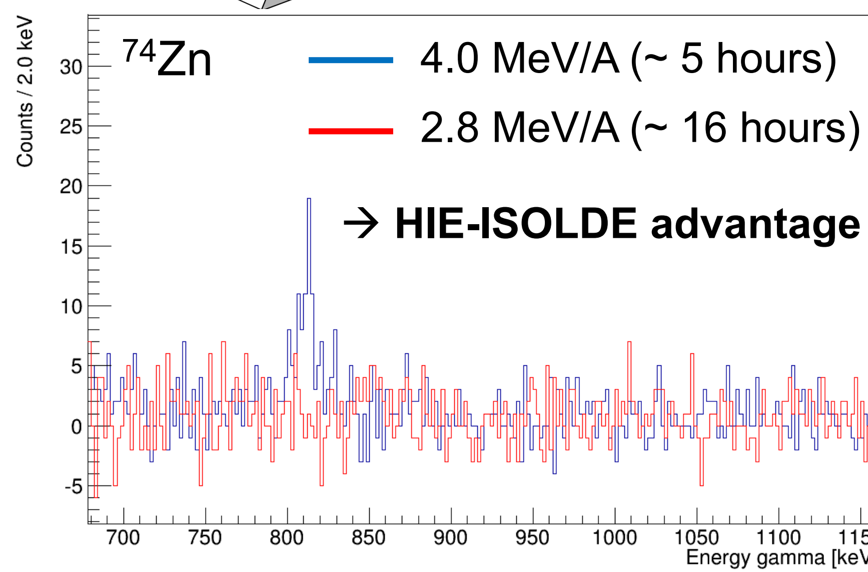


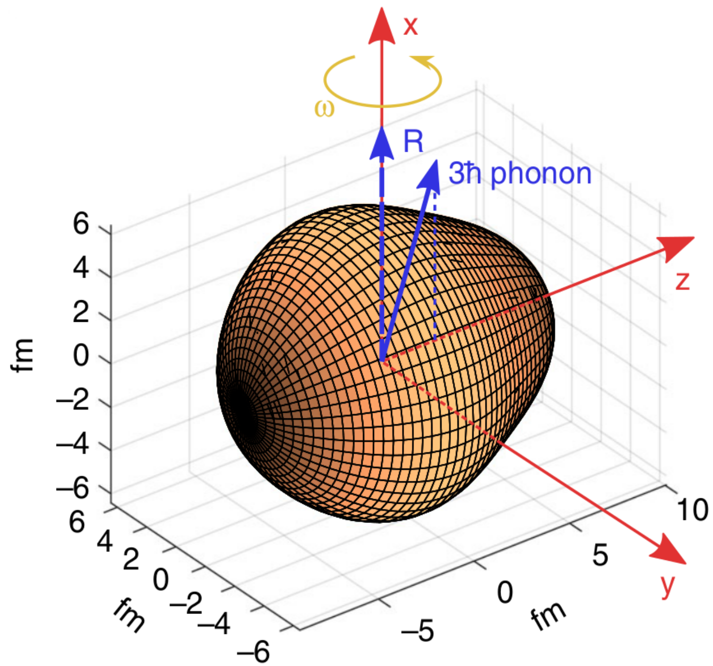


Detect scattered beam particle velocity and direction
→ Doppler correction



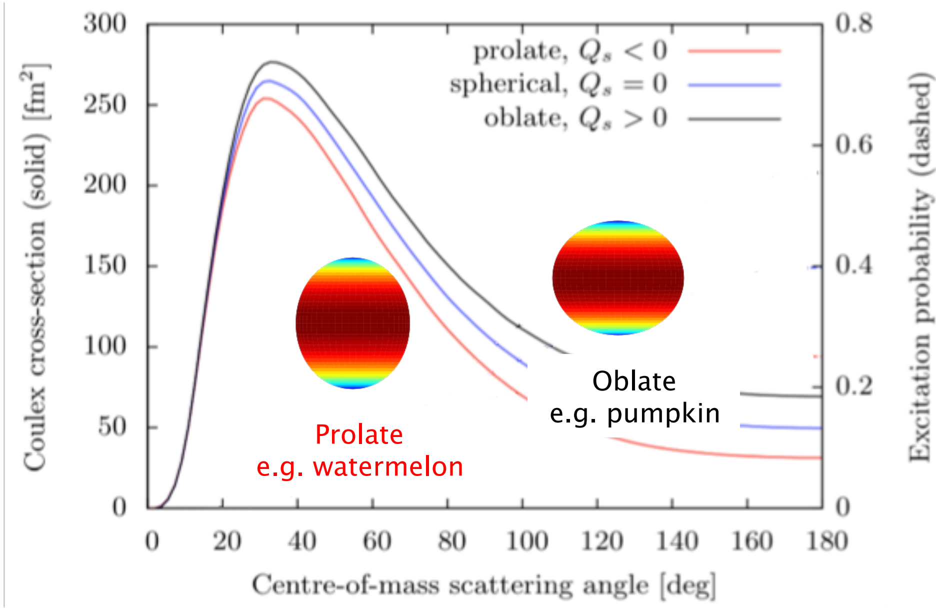
- Miniball set-up
  - Si detectors for particle identification
  - Ge detectors for efficient γ-ray detection
    - Compact and high-solid angle coverage
    - Segmented: position sensitive

Coulomb excitation

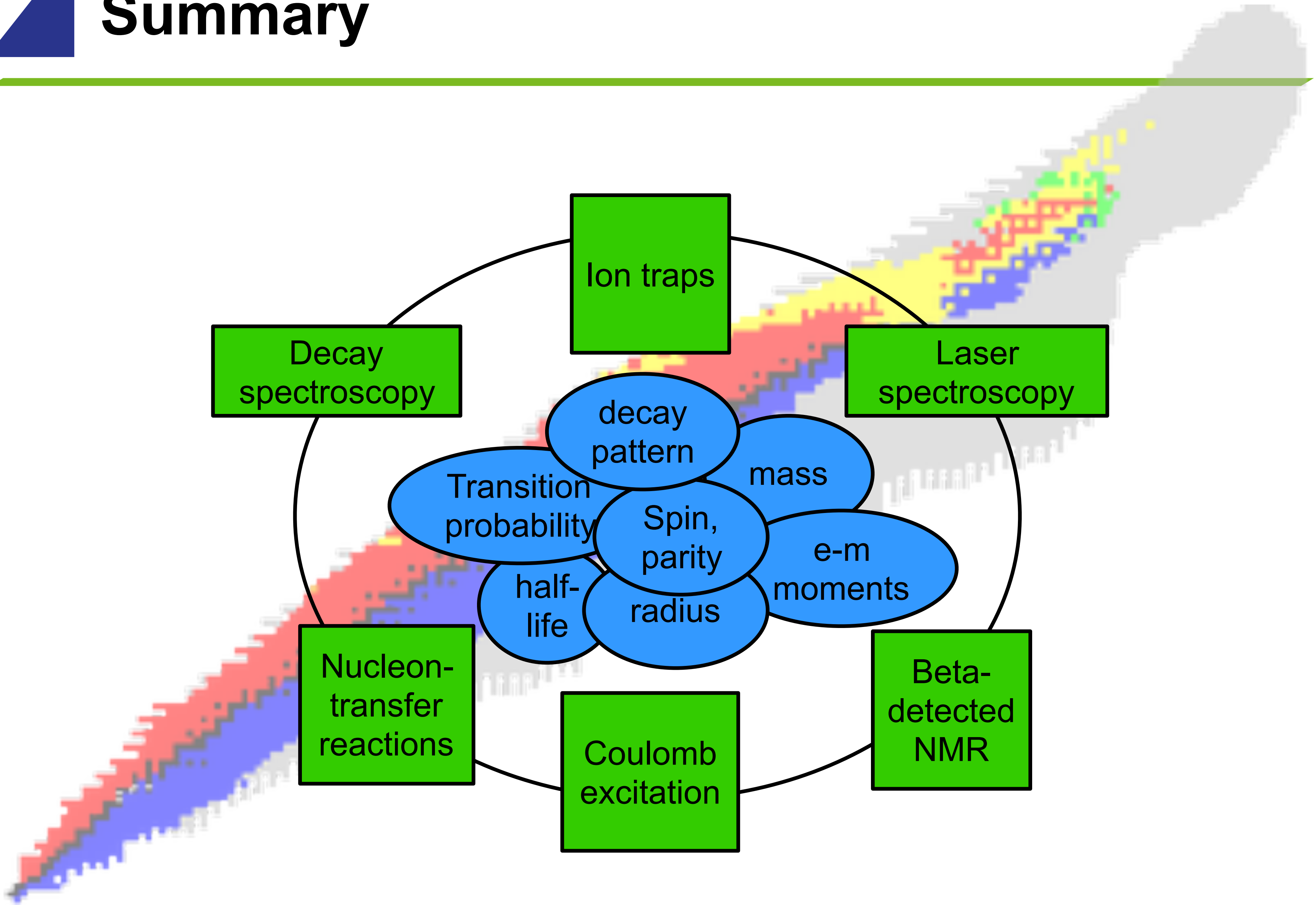


Observation of vibrating pear-shapes in radon nuclei
P.A. Butler *et al.*, Nature Comm. 10 (2019) 2473

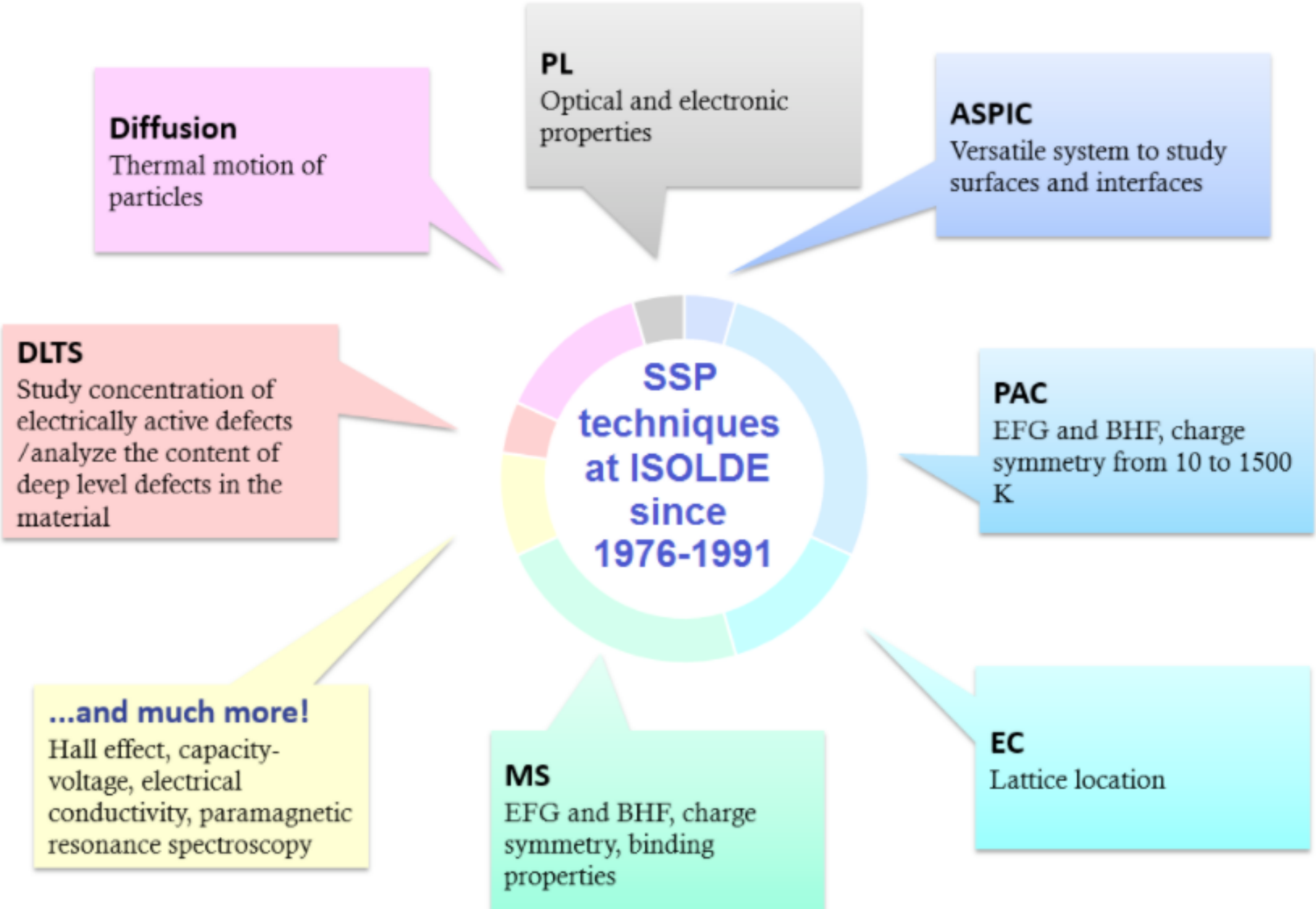
- Information
  - Level scheme
  - Nuclear shape of excited states



Summary



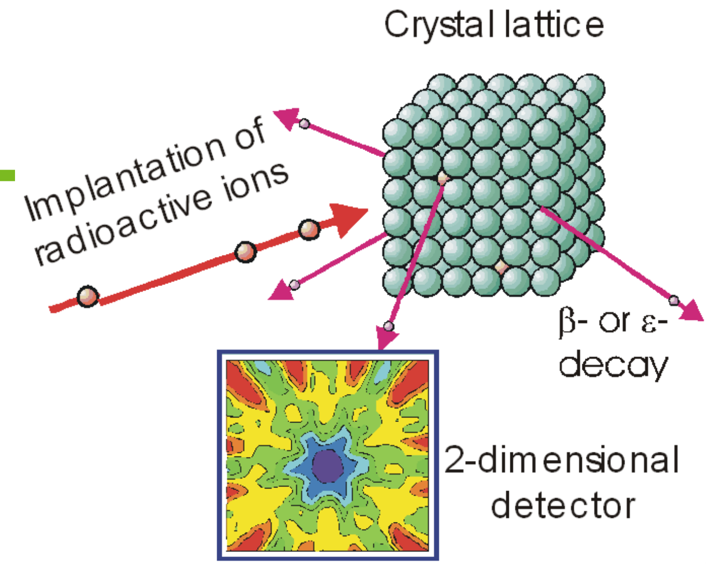
Ion traps
Decay spectroscopy
Laser spectroscopy
decay pattern
mass
Transition probability
Spin, parity
e-m moments
half-life
radius
Nucleon-transfer reactions
Beta-detected NMR
Coulomb excitation

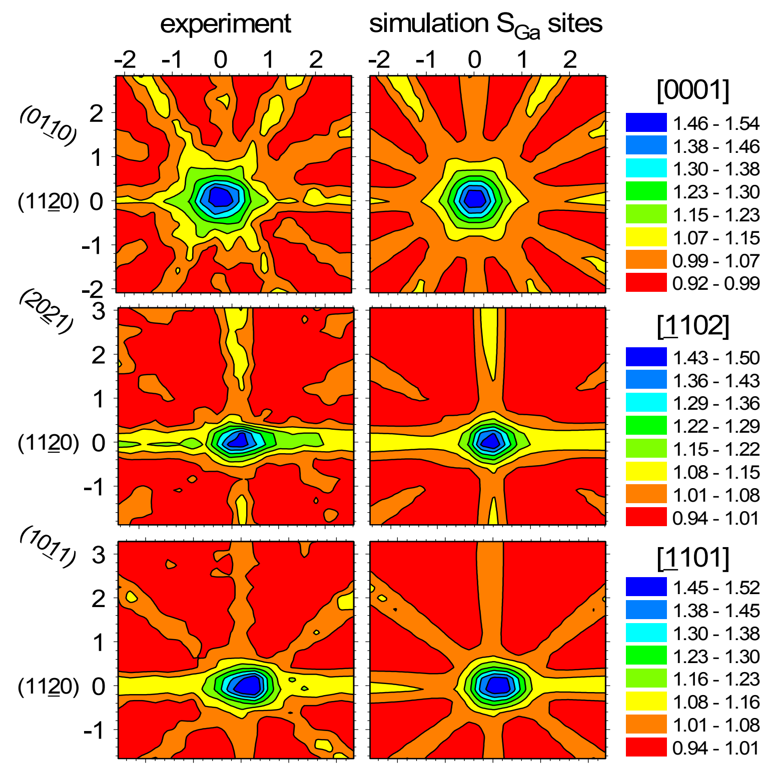


4. Research with radioactive isotopes

Emission channeling

- Information on:
  - Probe atom lattice site location as function of implantation/annealing temperature
  - Diffusion of probe atom
  - Annealing of implantation defects





Emission channelling pattern

Materials research with RIBs

- Use radioactive ion as **probe** to characterise different materials
  - Solid state physics
  - Biophysics

- Advantages from radionuclides
  - Wide variety of isotopes with different half-lives and decay properties
  - High detection efficiency for radiation
  - Low quantities need to be implanted (no interference with host)

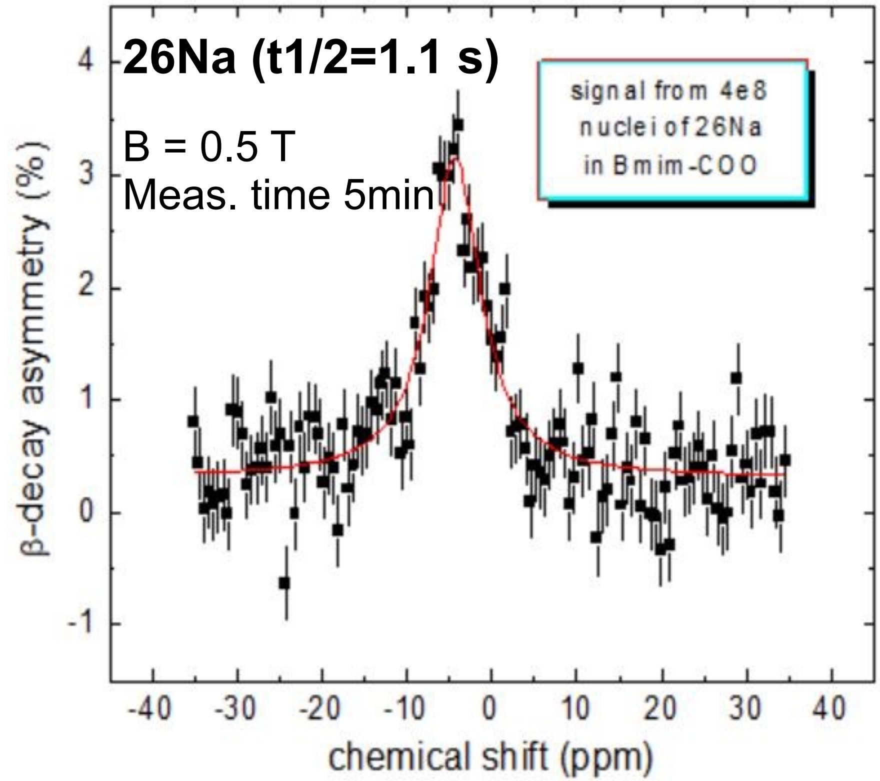
More info: J. Phys. G: Nucl. Part. Phys. 44 (2017) 104001

Beta-NMR at ISOLDE

- Metal ions in living organisms (Na, Mg, Cu, Zn …)
  - ➢ Right concentration crucial for correct functioning of cells
  - ➢ Very important but not very abundant
  - ➢ Difficult to study with techniques on stable isotopes (e.g. NMR)

- beta-NMR
  - ➢ Asymmetry in beta decay in space (due to parity non-conservation by weak interaction)
  - ➢ **Up to 10^{10} more sensitive than conventional NMR**
  - ➢ Structure and dynamic of the interaction of metal ions with biomolecules

1st Na beta-NMR signal in a liquid



Beta-NMR at ISOLDE

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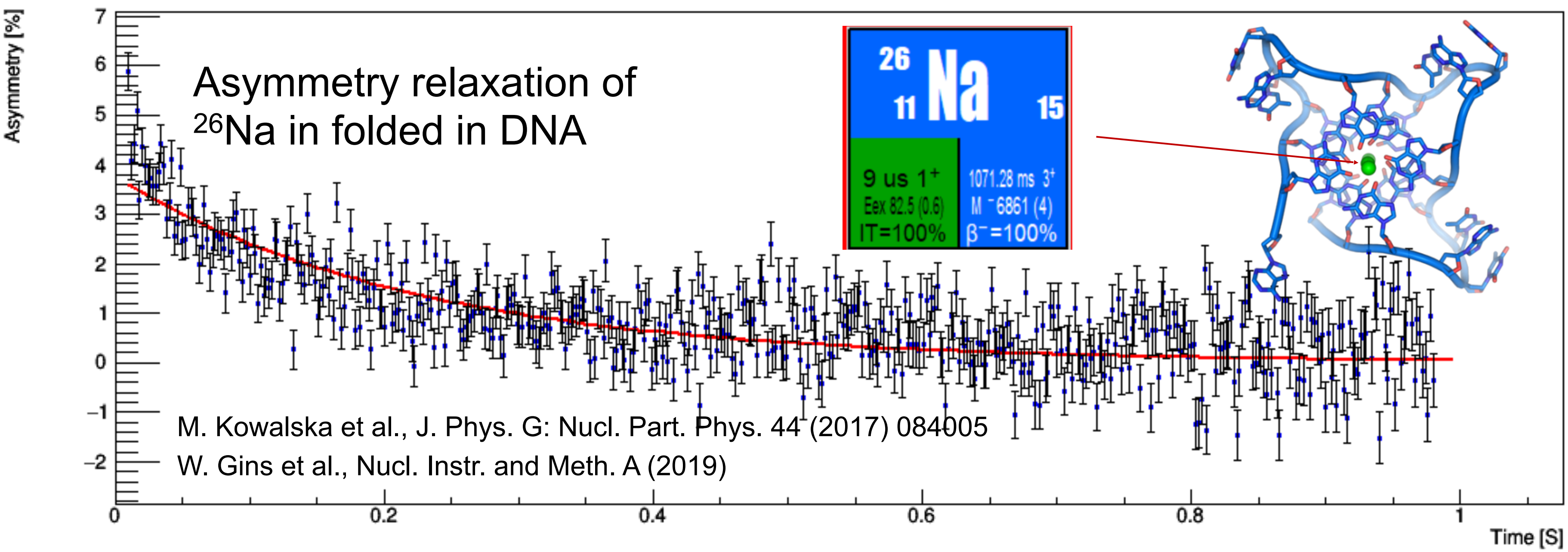

Summary

- ISOLDE is the world's first ISOL-type facility and is still a reference for radioactive ion beam production over 50 years later
- The upgrade of HIE-ISOLDE provides high-energy beams of up to 10 MeV/u
- ISOLDE is host to a dozen permanent experiments (and many travelling setups) studying:
  - Nuclear physics
  - Nuclear astrophysics
  - Solid state physics
  - Bio-physics
  - Fundamental physics
- The new facility MEDICIS produces radioactive isotopes dedicated to medical applications

Questions?

ISOLDE

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