Nuclear Parameters from Precision Measurements with ISOLTRAP

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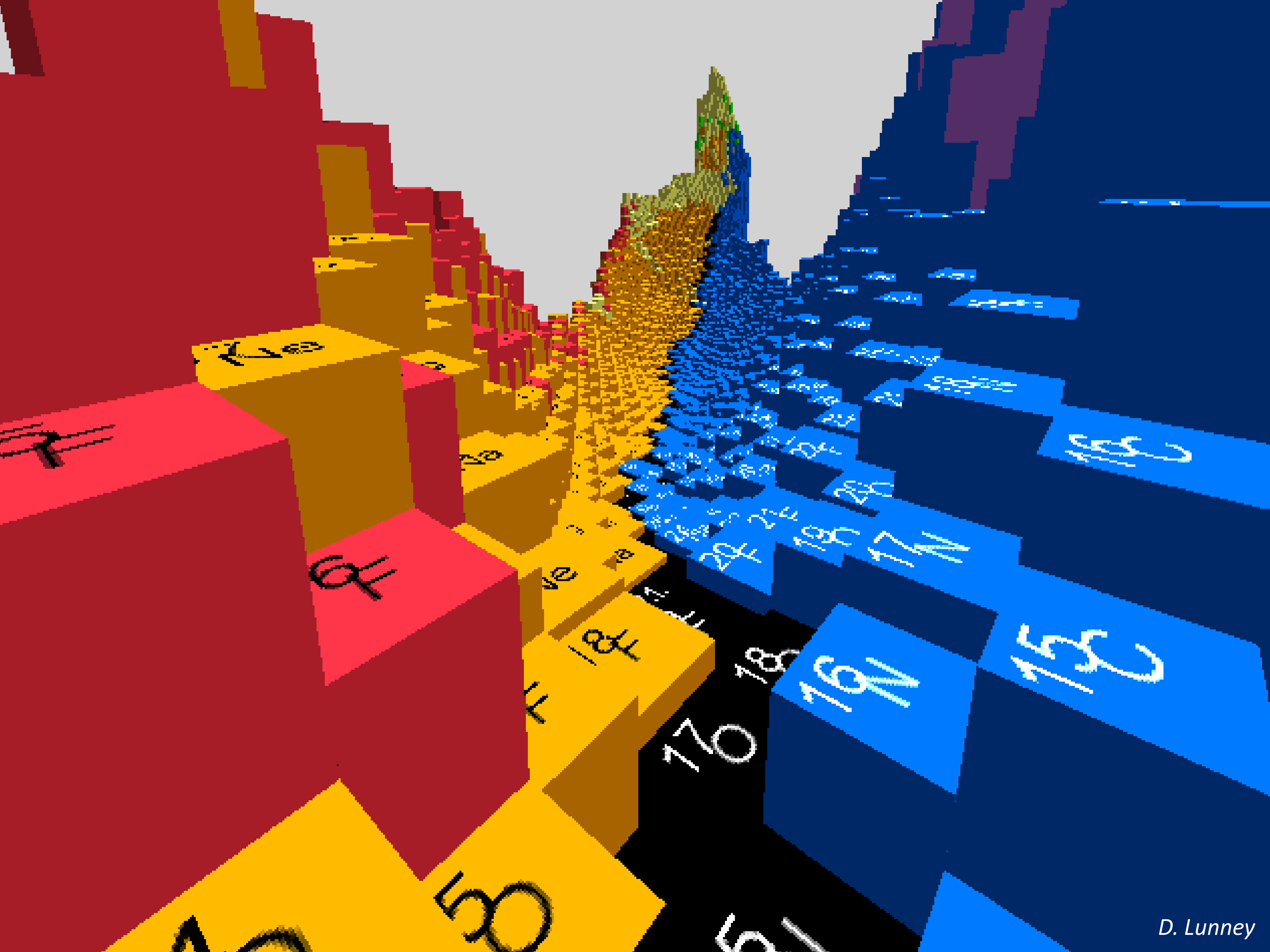
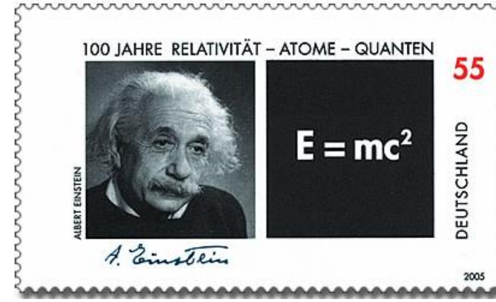


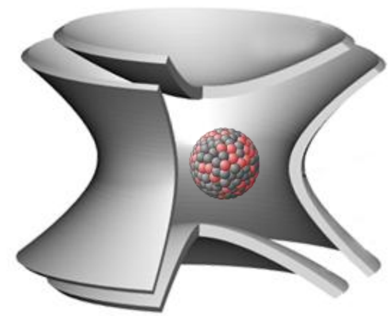
15C
16N
17N
17O
18F
20F
D. Lunney

Nuclear Masses

$$B(N,Z) = \left(Nm_n + Zm_p - m(N,Z)\right)c^2$$



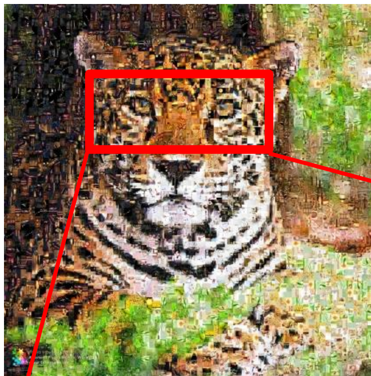
- A mass measurement yields the binding energy which comprises information on all underlying interactions
- Mass determination through frequency measurement of trapped, charged particles was invented by Paul and Dehmelt (Nobel Prize 1989)
- Measurements with relative uncertainties of 10^{-6} required for insight into nuclear structure



Distance Eltville – CERN

Measure to +/- 5mm

Physics from Nuclear Masses



- Binding energy -> scale of GeV
  - Structural information hidden
- Apply filters
  - Patterns across the nuclear chart
  - Identify different contributions of interaction

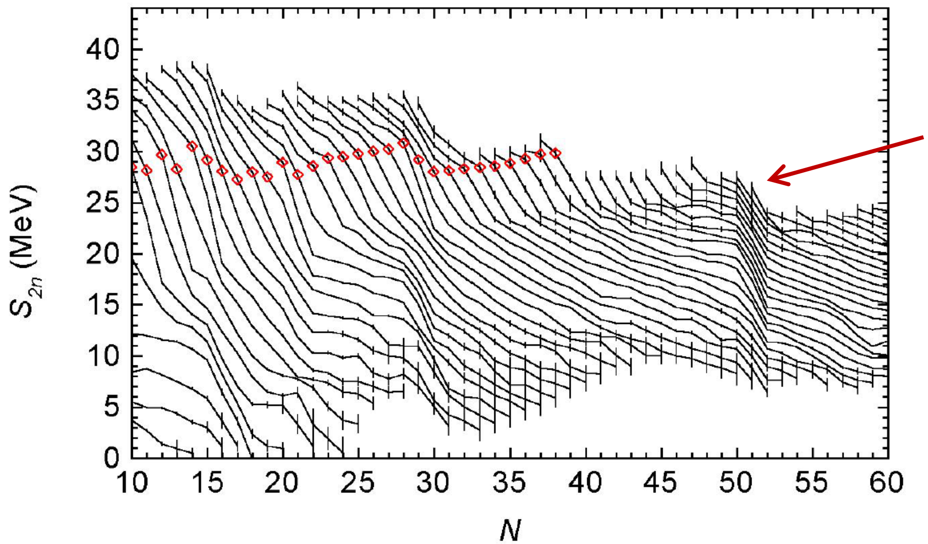
http://www.google.de/imgres?imgurl=http%3A%2F%2Fdownload2.artensoft.com%2Fartensoft_com%2FArtensoftPhotoMosaicWizard%2Fgallery%2FCat_3000Pieces_3000x3045.jpg&imgrefurl=http%3A%2F%2Fwww.artensoft.de%2FArtensoftPhotoMosaicWizard%2Fgallery.php&h=3045&w=3000&tbnid=3EnV8o5IysJMMM%3A&zoom=1&docid=BSnNtf8yXupoRM&ei=RL6AU8S2JsT34QTX8ICAAw&tbm=isch&iact=rc&uact=3&dur=1470&page=1&start=0&ndsp=27&ved=0CF4QrQMwAg

Nuclear Structure from the Mass Surface

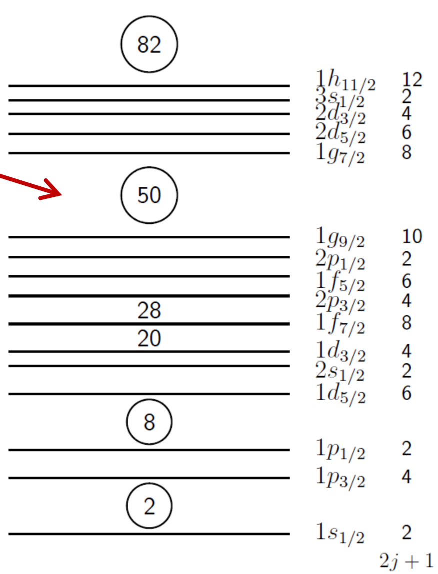
- Structural evolution via differential quantities
  - Two-neutron separation energy from mass excess ME = m – Au

$$S_{2n}(N,Z) = ME(N-2,Z) - ME(N,Z) + 2 \cdot ME(n)$$

  - Shell structure of nuclei

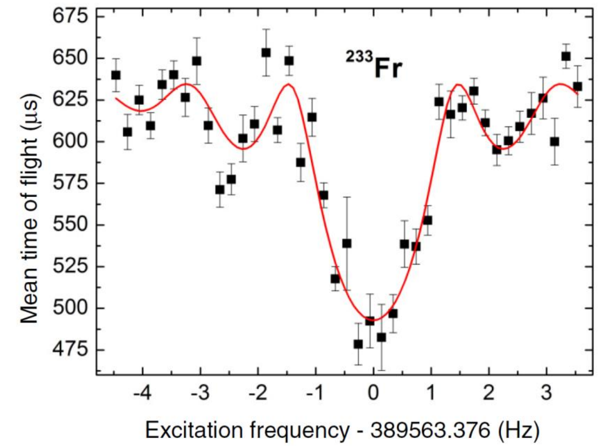


closed shell
high binding
„magic number“



Overview

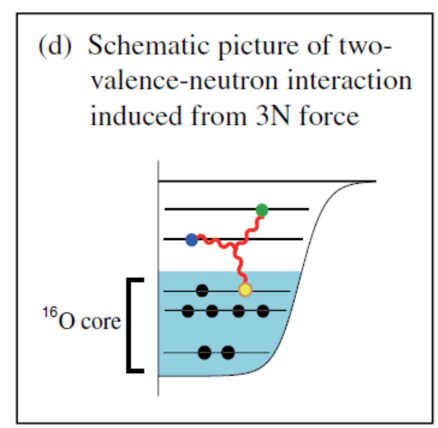
- Goal: Determination of nuclear parameters
  - Mass, radius, spin, moments
  - Half-lives and decay modes
  - Excitation spectra and isomers



- Method: High-precision mass spectrometry and decay spectroscopy of exotic radionuclides

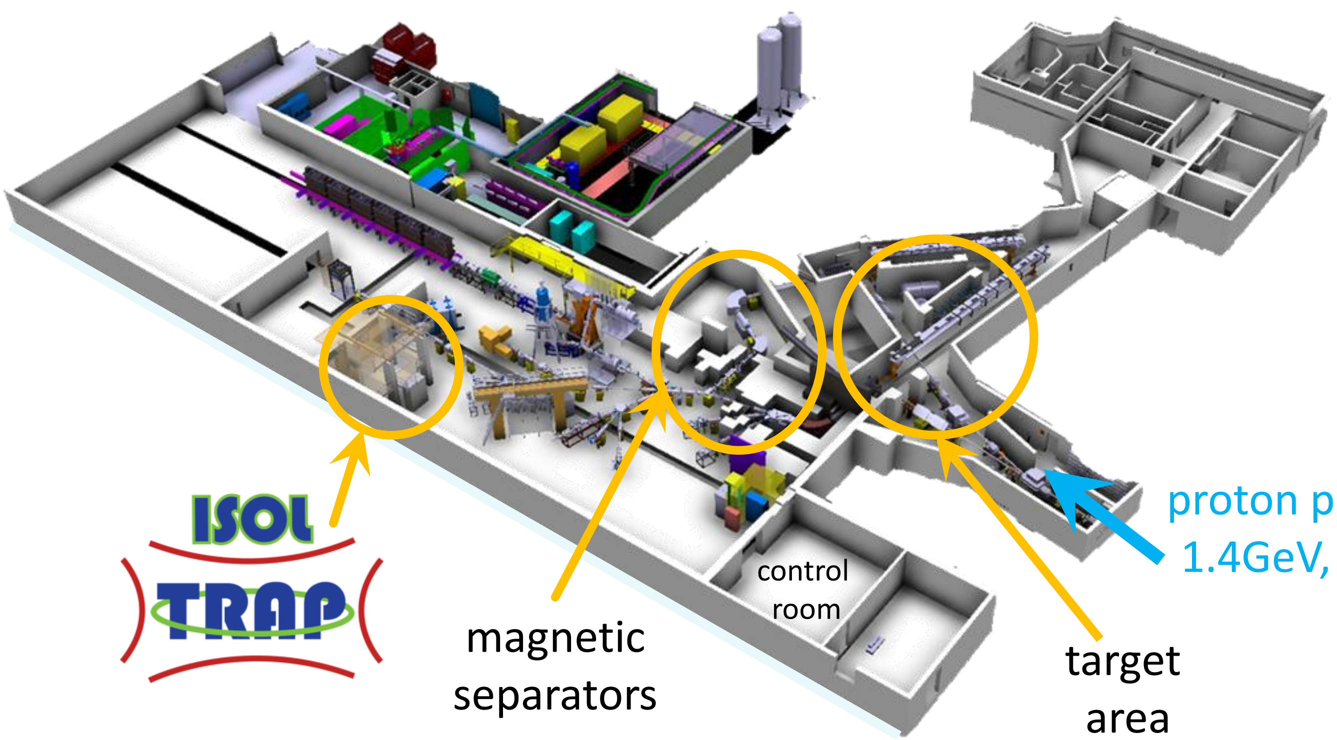
- Tool: Penning trap and multi-reflection time-of-flight mass spectrometry, β- and γ-decay station

- Application: atomic physics, nuclear (astro-) physics, fundamental and applied physics
  - Observation need interpretation
  - Theory for comparison and prediction (?)



T. Otsuka *et al.*, PRL **105**, 032501 (2010)

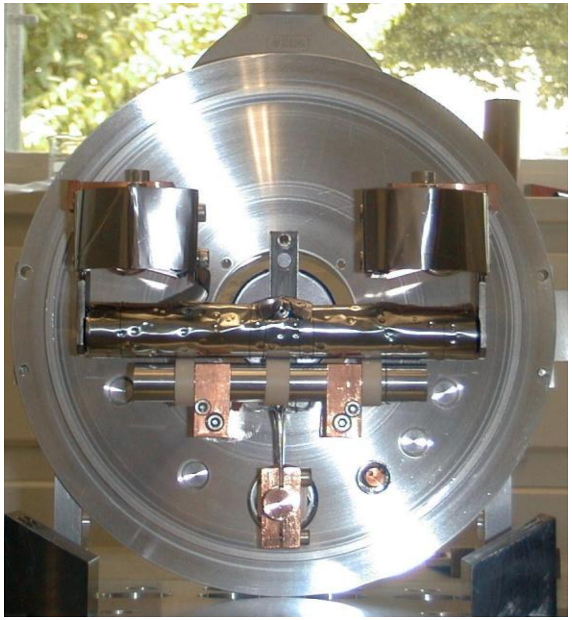
ISOLDE Hall

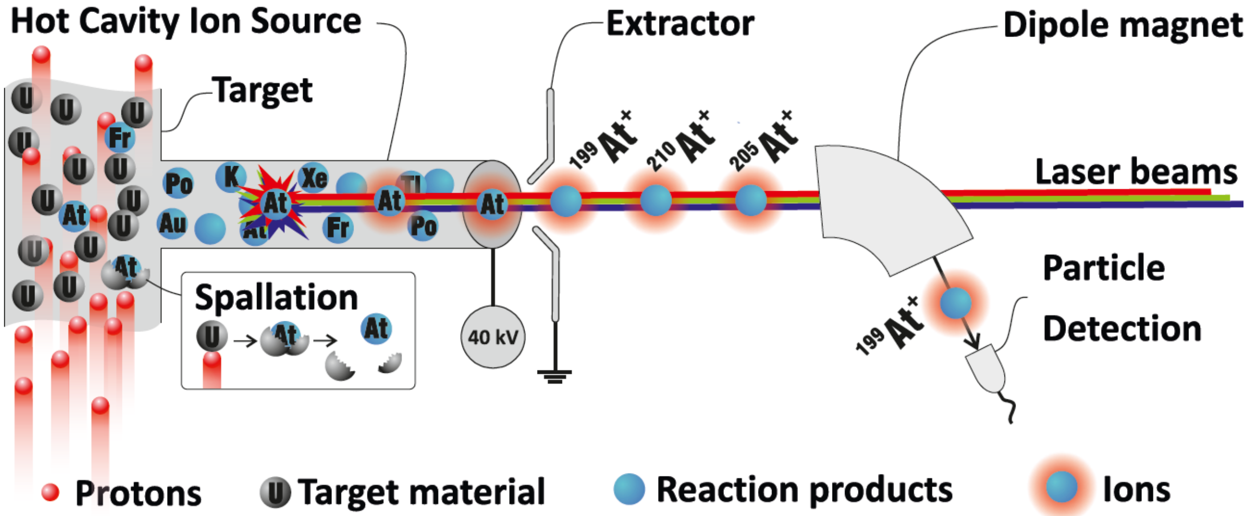


$$\frac{m}{\Delta m} \approx 5000$$

Radionuclides from ISOLDE/CERN

- Radioactive beam is provided by ISOL technique:
  - 1.4-GeV protons hit thick target material
  - Low-energy beam
  - Singly-charged ions
  - Isotopically pure beam
  - Mixture of isobars



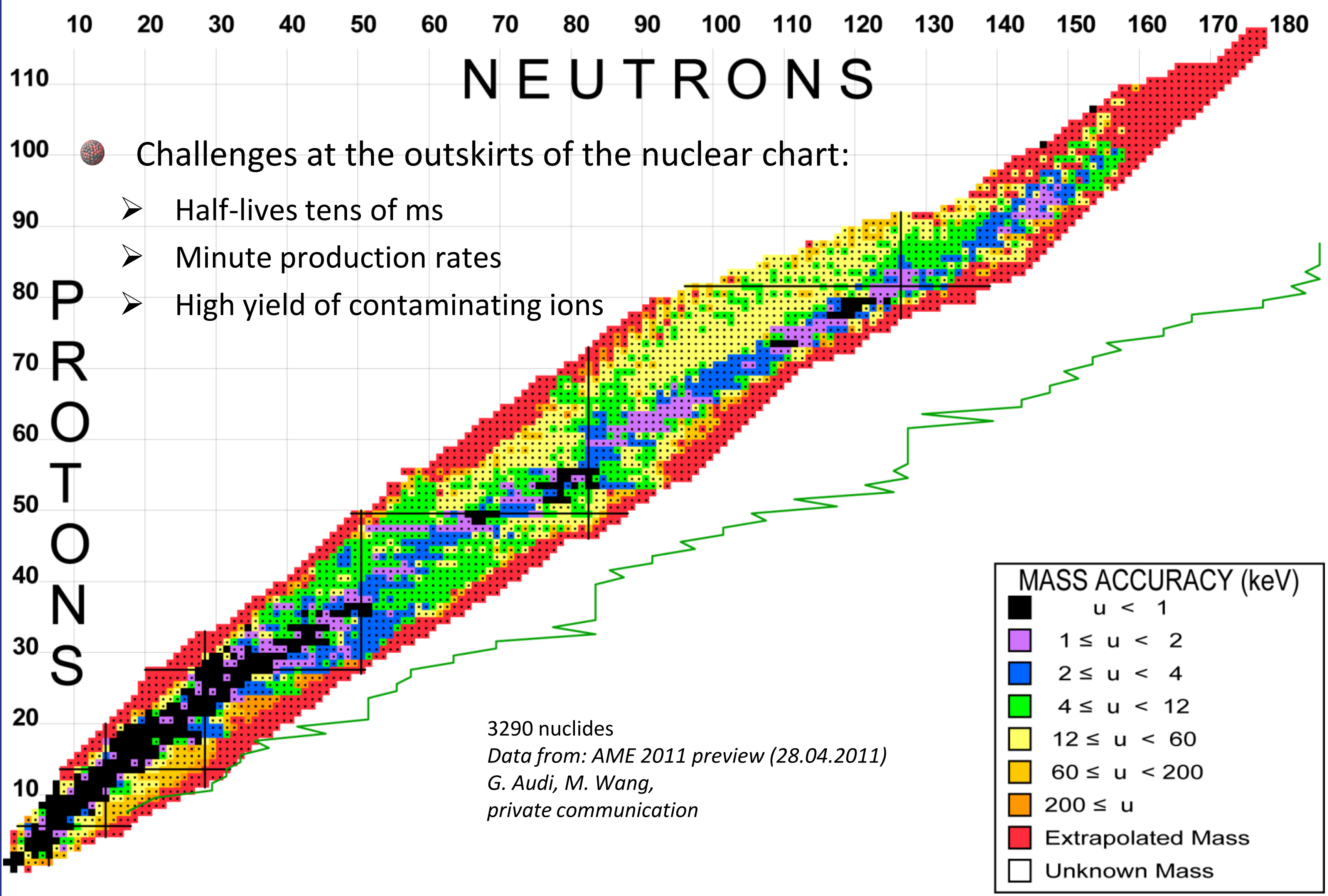


Courtesy Sebastian Rothe

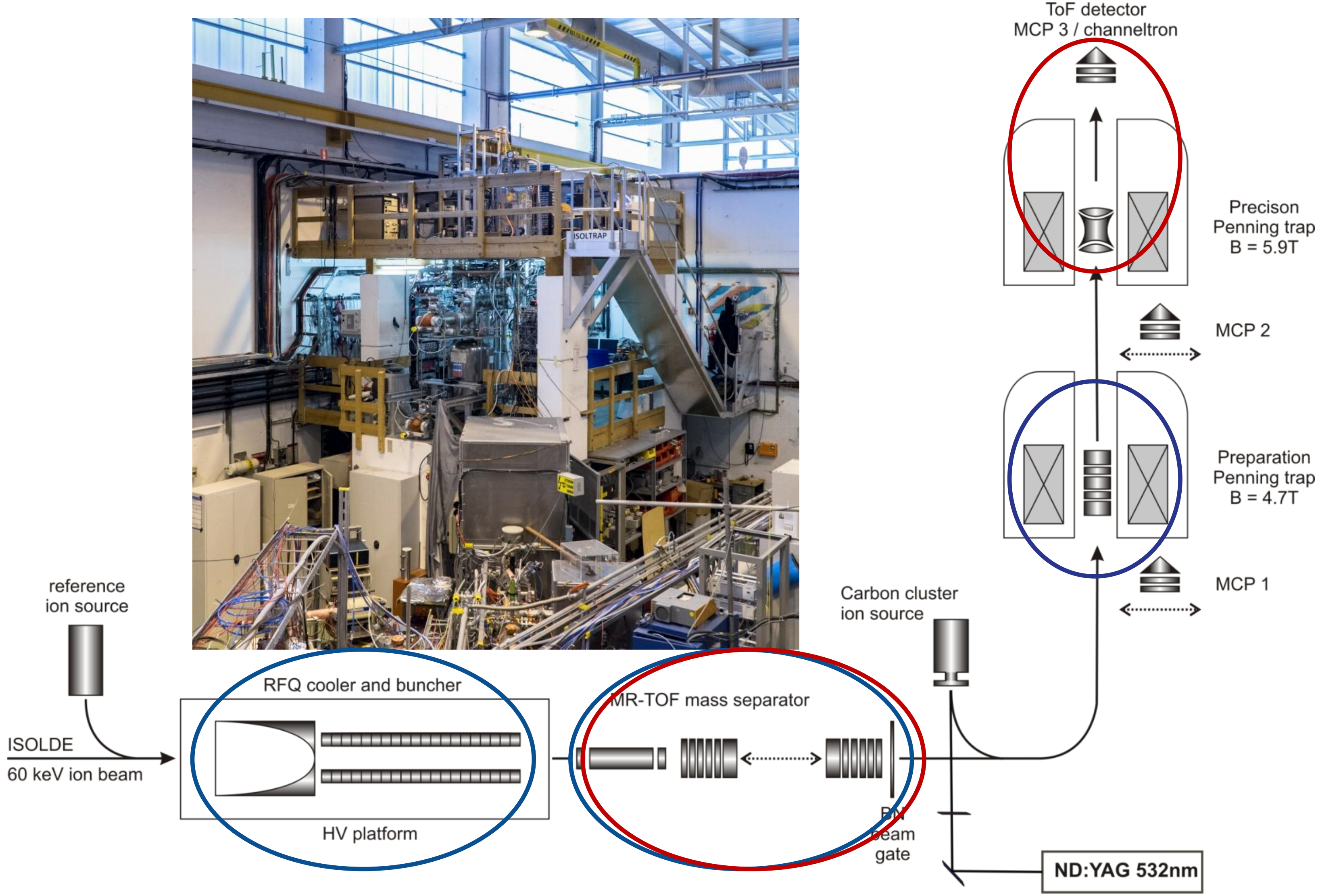
G. D. Alkhazov *et al.,* NIM B **69** (1992) 517, V. N. Fedosseev *et al.,* NIM B **266**, 4378 (2008), U. Koester *et al.,* Nucl. Phys. A **701**, 441 (2002)

Challenges for Short-Lived Nuclides

- Challenges at the outskirts of the nuclear chart:
  - Half-lives tens of ms
  - Minute production rates
  - High yield of contaminating ions



The ISOLTRAP Experiment

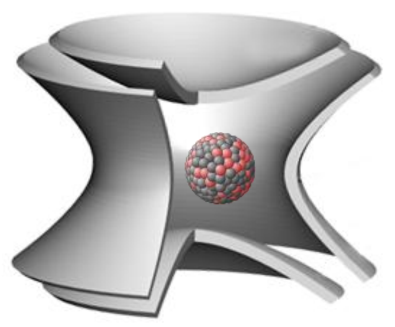


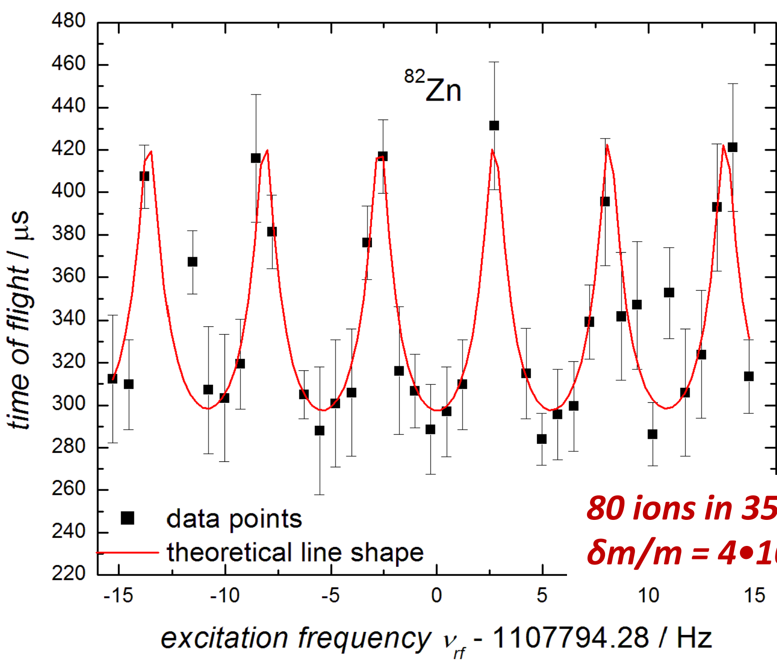
M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)
R. N. Wolf *et al.*, IJMS **349-350**, 123 (2013)

preparation measurement

Detection Techniques

- Penning-trap mass spectrometry



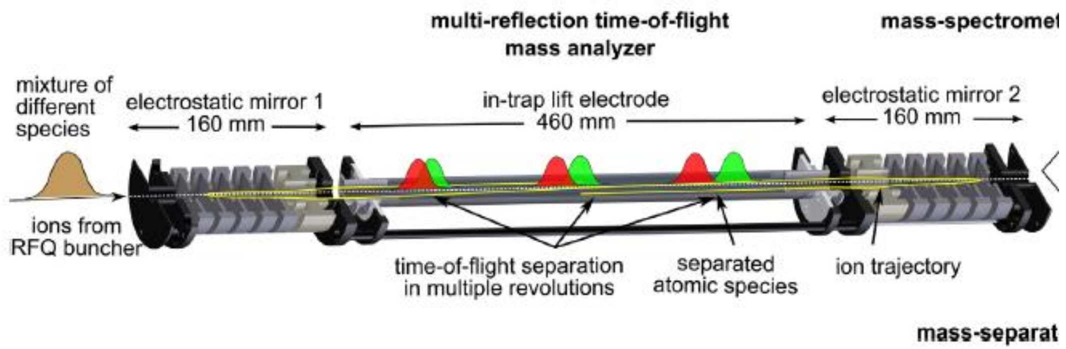


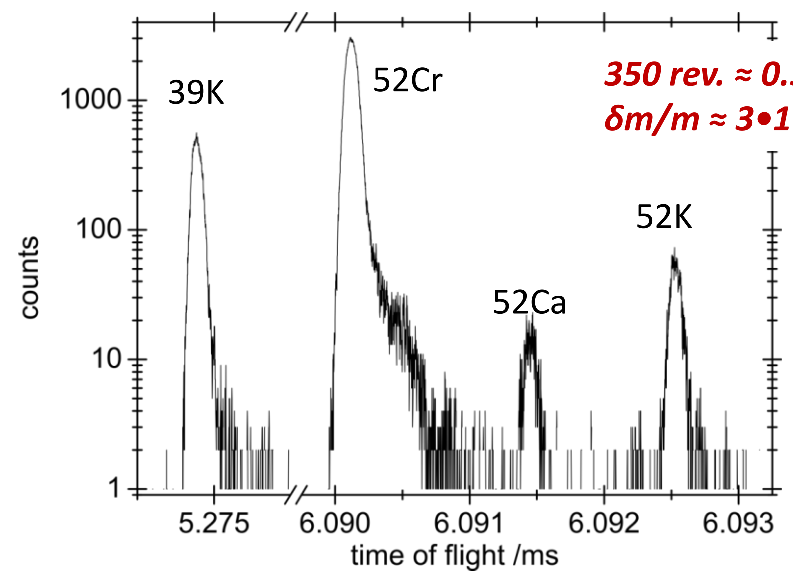
80 ions in 35 minutes!

δm/m = 4•10^{-8}

S. Kreim *et al.*, NIMB **317**, 492 (2013)

- Multi-reflection time-of-flight mass spectrometry





350 rev. ≈ 0.5km

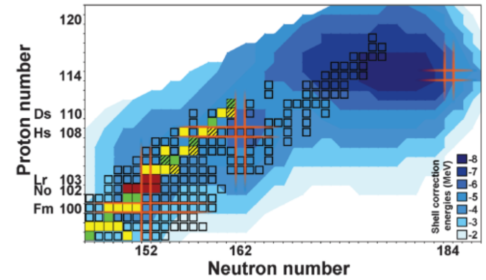
δm/m ≈ 3•10^{-7}

R. N. Wolf *et al.*, NIM A **686**, 82 (2012)

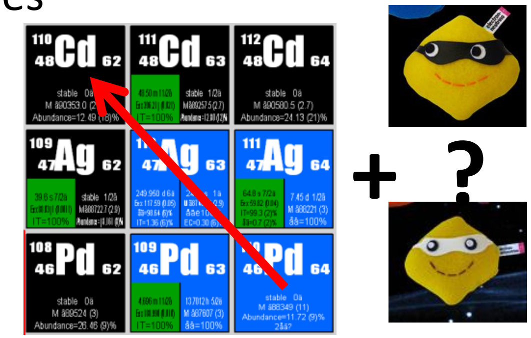
R. N. Wolf et al., IJMS **349-350**, 123 (2013)

Applications

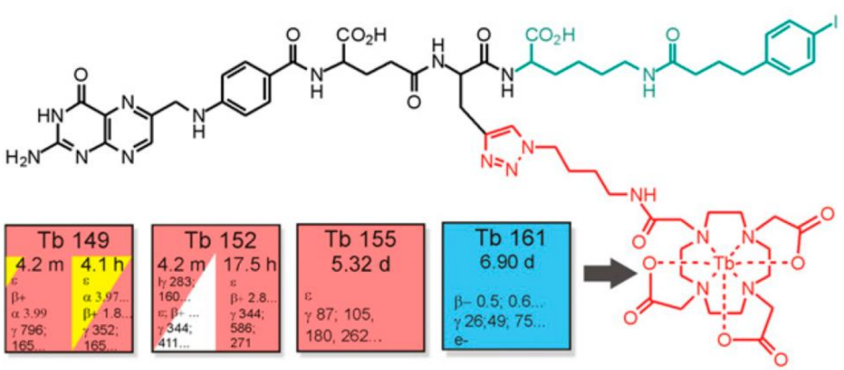
- Nuclear physics: structure of nuclei, exotic decay modes

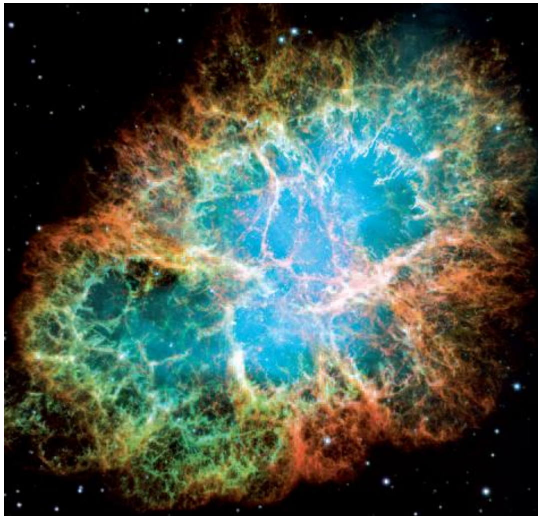


- Atomic physics: Radii, nuclear binding energies
- Nuclear astrophysics: element synthesis, stellar processes



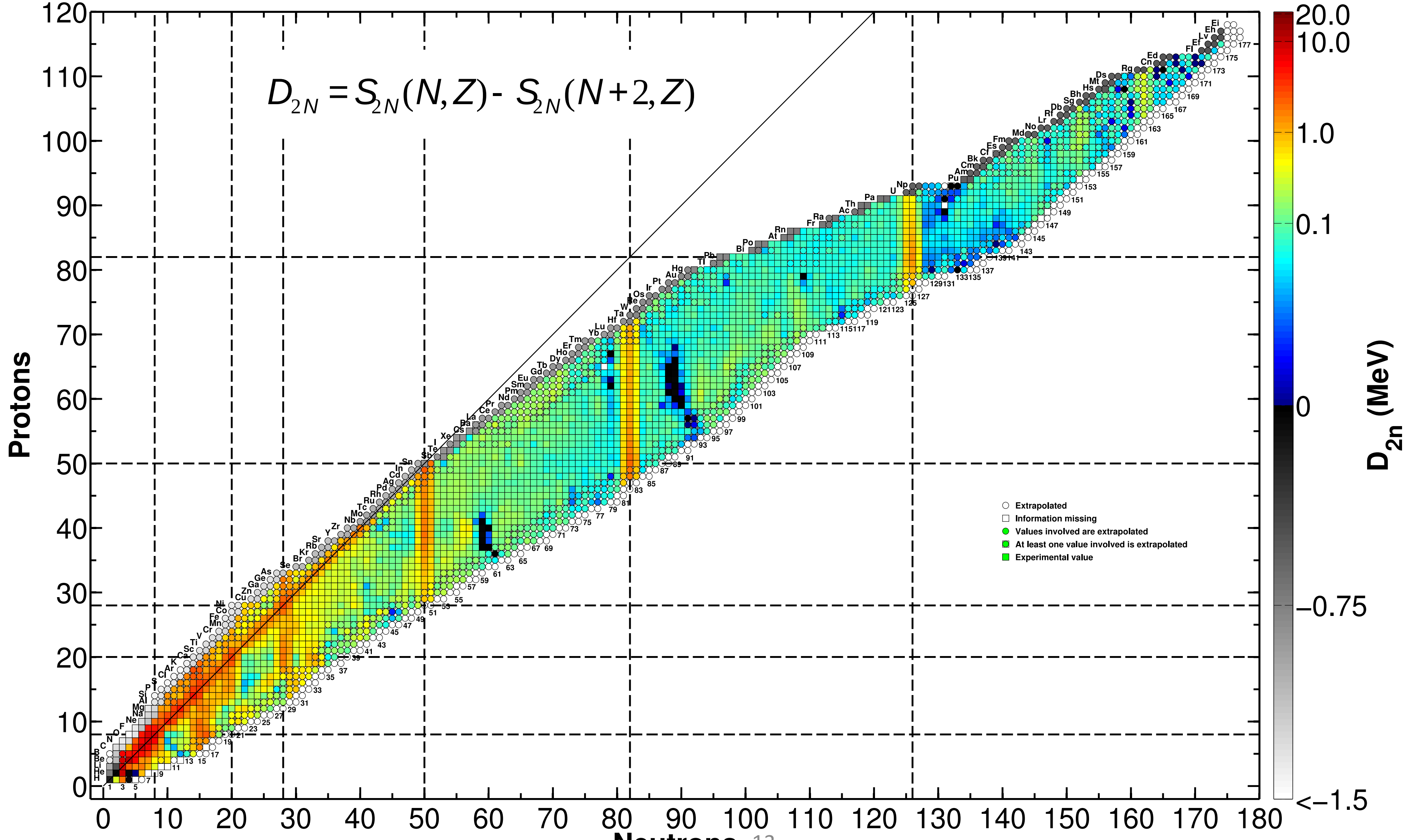
- Fundamental physics: CKM unitarity tests
- Applied physics: tailored isotopes for diagnosis and therapy





C. Müller, *et al.*, J. Nucl. Med. **53**, 1951 (2012)

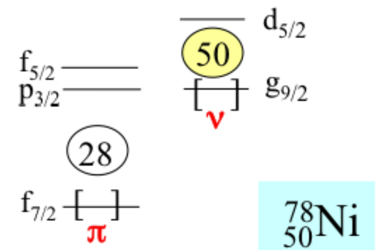
Shell Gap Filter



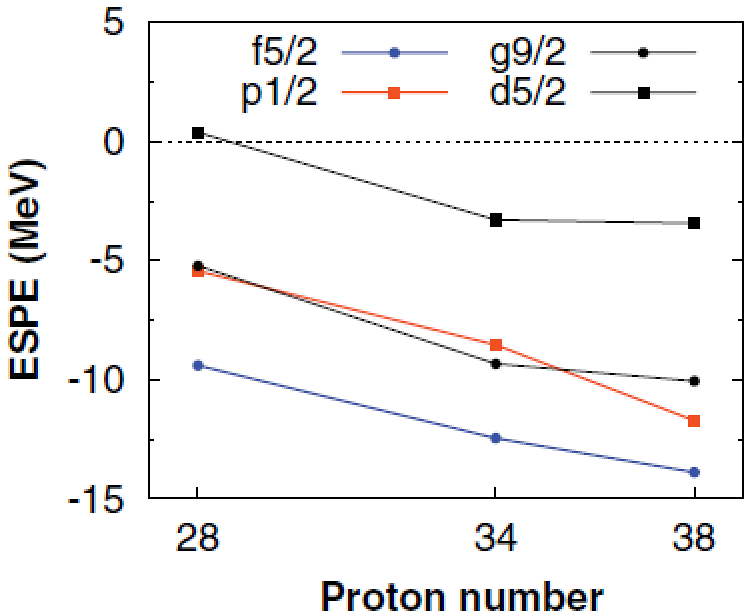
M. Wang et al., Chinese Phys. C **36**, 1603 (2012)

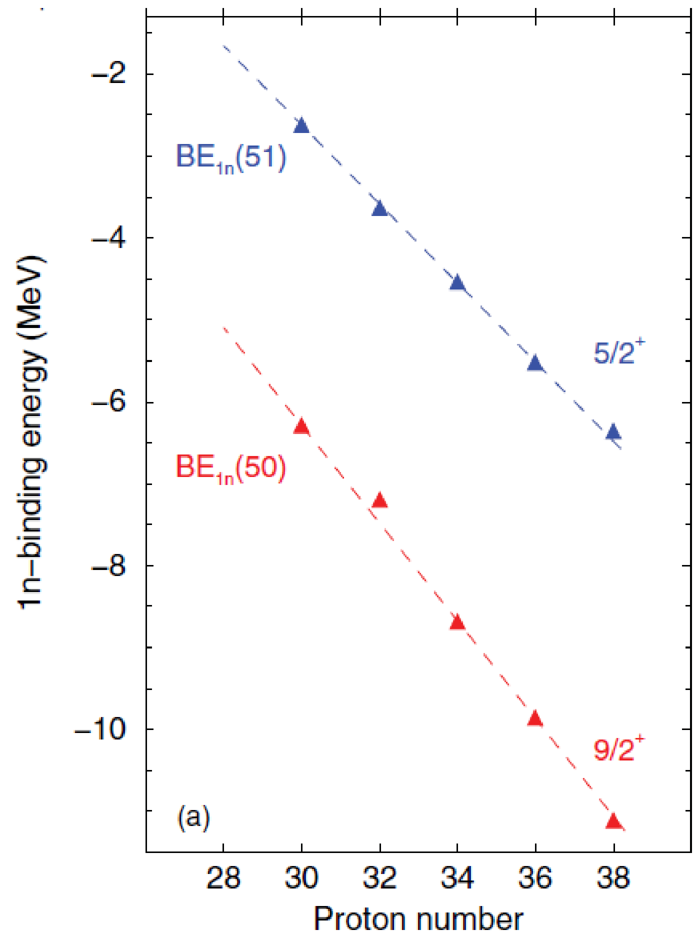
N=50 Shell Gap

- Size of N=50 shell gap for doubly-magic ^{78}Ni?
- Neutrons fill the $g_{9/2}$ orbit along the isotopic chain
- Trend of binding energies show quenching
- Shell-model predictions predict spherical shape



$$\Delta BE = BE(Z,N+1) + BE(Z,N-1) - 2BE(Z,N)$$





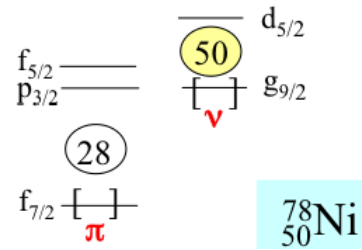
O. Sorlin and M.-G. Porquet, Phys. Scr. **T152**, 014003 (2012)

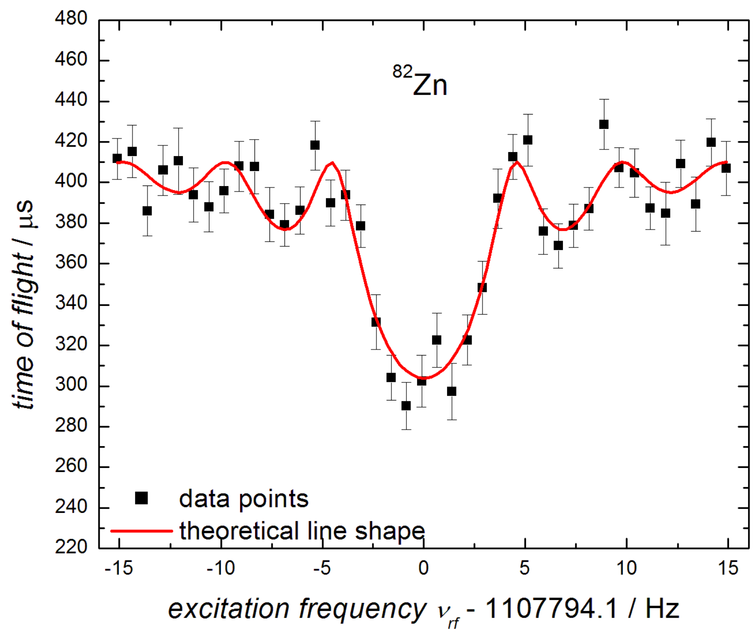
M.-G. Porquet and O. Sorlin, PRC **85,** 014307 (2012)

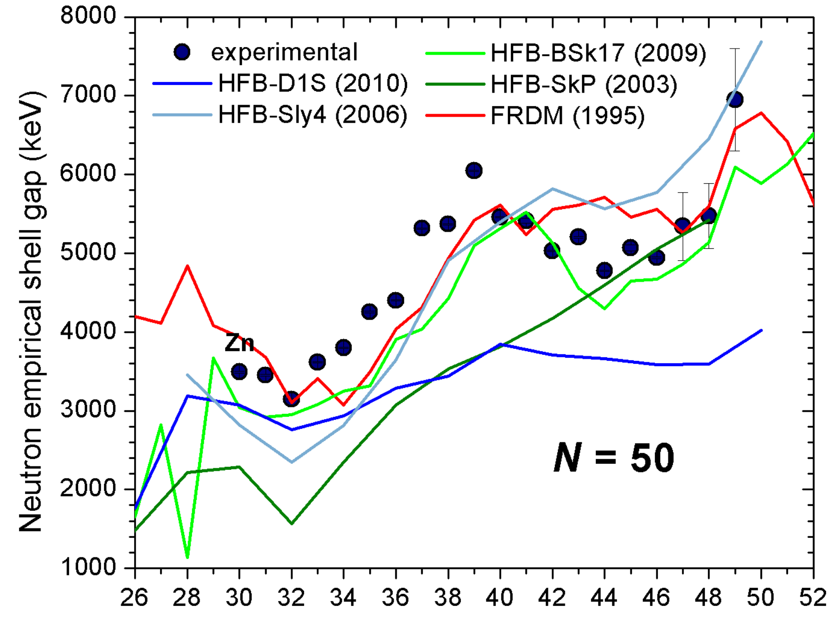
K. Sieja and F. Nowacki, PRC **85**, 051301 (2012)

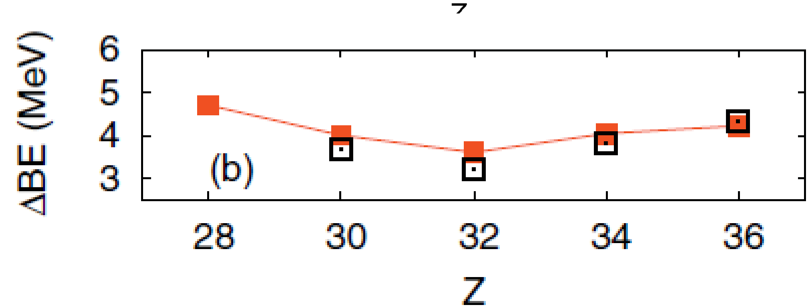
Most Exotic Test of Shell Gap

- Size of N=50 shell gap for doubly-magic ^{78}Ni?
- Mass of ^{82}Zn most exotic determination of shell gap
- Overall linear decrease
- Bumpy structure coming from correlations





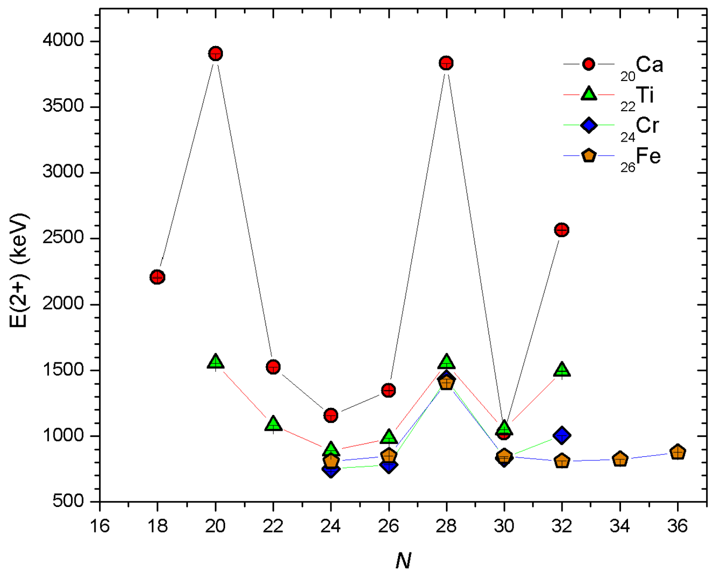


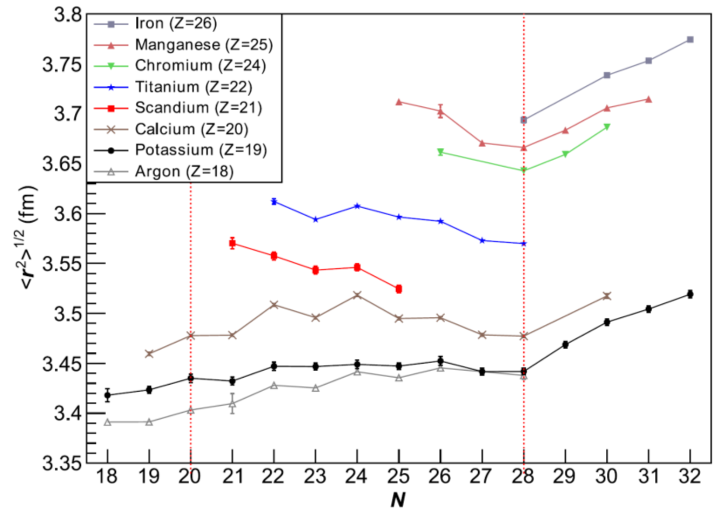


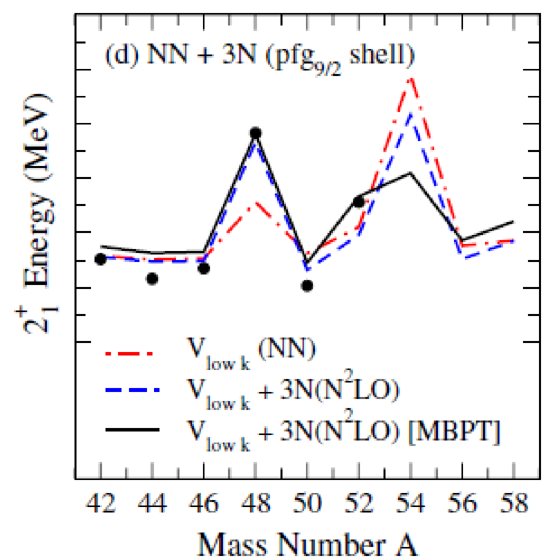
R.N. Wolf *et al.*, PRL **101**, 041101 (2013)

K. Sieja and F. Nowacki, PRC **85**, 051301 (2012)

Magic Neutron Number *N*=32?





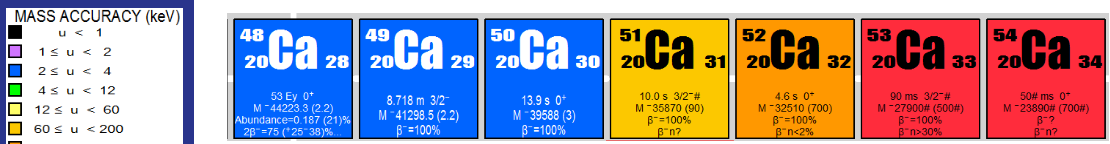


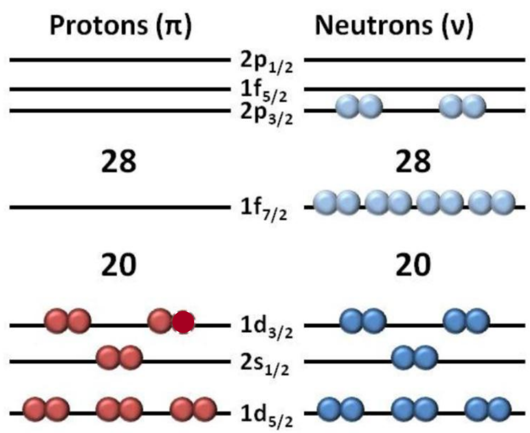
- Spectroscopic information available at *N*=32
- E(2+) energy particularly high in Ca
- Shell-model and beyond-mean-field calculations predict *N*=32 as magic number but disagree on *N*=34
- Calculations with 3-body forces correctly reproduce high E(2+) energy

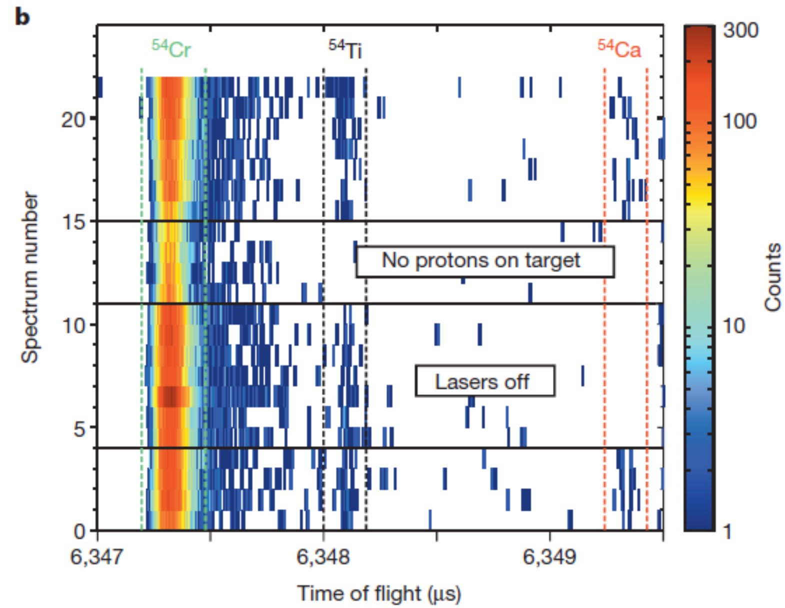
S. Raman, C. W. Nestor, P. Tikkanen, At. Data. Nucl. Data Tables **78**, 1 (2001)
R.V.F. Janssens *et al.*, Phys. Lett. B **546**, 55 (2002)

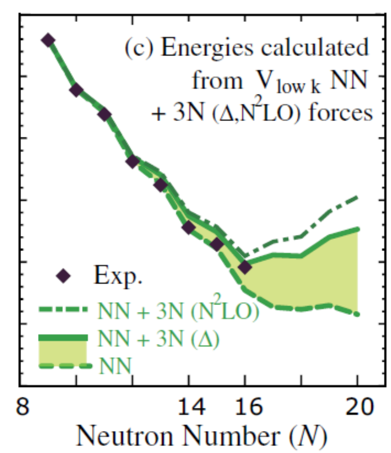
K. Kreim *et al.*, PLB **731**, 97 (2014)
J. D. Holt *et al.*, JPG **39**, 085111 (2012)

Heavy Calcium and 3-Body Forces









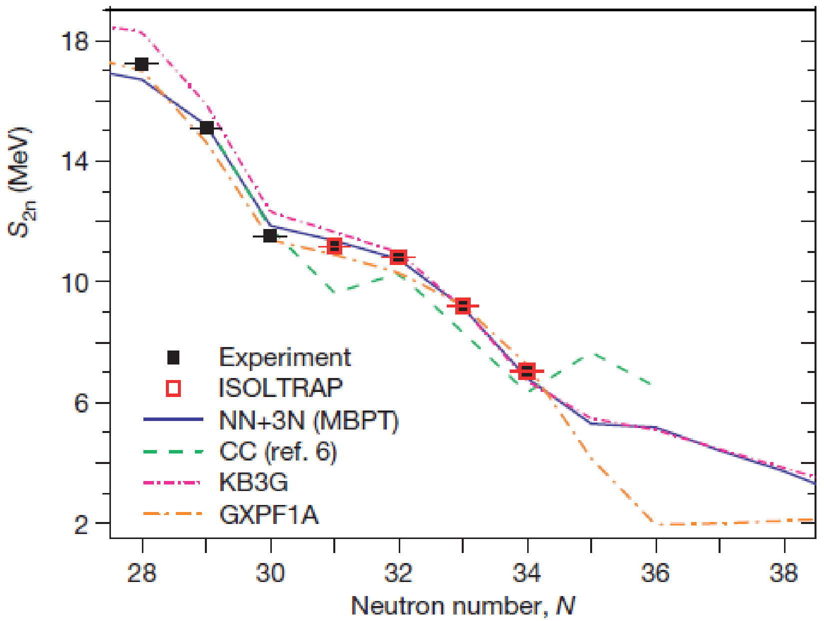
- Microscopic valence-shell calculations with three-nucleon forces (NN+3N) from chiral effective field theory
  - Semi-magic, medium-mass nuclei
  - Explain oxygen anomaly: repulsive interaction between valvence nucleons

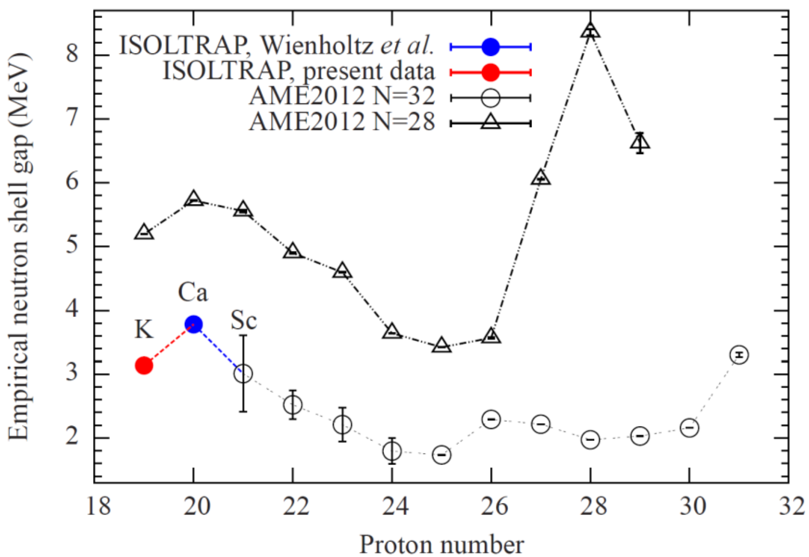
T. Otsuka *et al.*, PRL **105**, 032501 (2010)

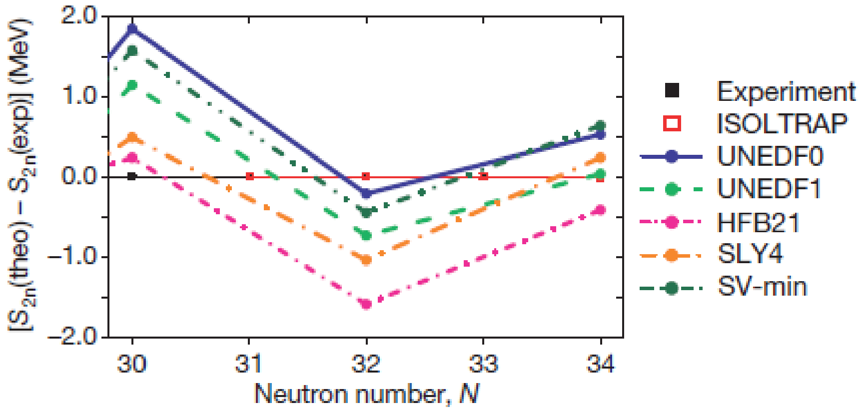
F. Wienholtz *et al.,* Nature **498,** 346 (2013)

Magic Number at *N*=32

- ISOLTRAP data on ground-state properties cleary establish *N*=32 magic number
- Agreement with predictions based on 3-body forces
  - EDF calculations cannot reproduce *N*=32 closure
- Highest shell gap of *N*=32 for calcium





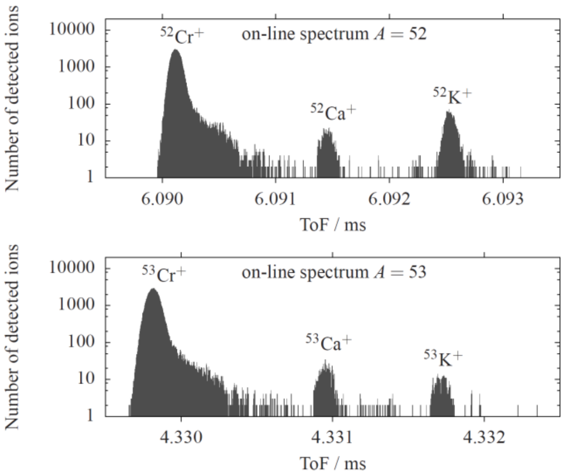


F. Wienholtz *et al.,* Nature **498,** 346 (2013)
J. Erler et al., Nature **486**, 509 (2012)
C. Forssén et al., Phys. Scr. T **152**, 014022 (2013)

Potassium Isotopes

- Open-shell nuclei calculations:
  - Coupled-cluster calculations predicted spin inversion and re-inversion up to ^{51}K
  - Ab-initio Gorkov-Green's function (GGF) theory:

    2- and 3-body interactions from chiral effective field theory fitted to few-body systems
    - ✓ First time N>32
- charge radii measured to ^{51}K
- $^{51\text{-}53}K$ masses determined with ISOLTRAP
- Shell gap at N=32 confirmed
  - weaker compared to Ca



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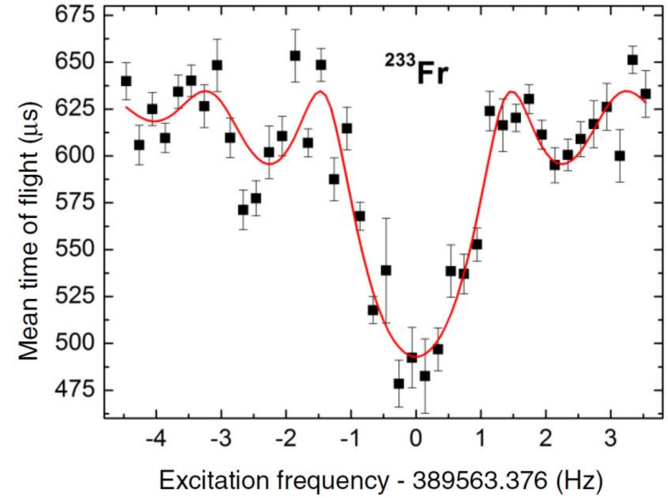
V. Somà *et al.*, PRC **84**, 064317 (2011)
V. Somà *et al.*, PRC **89**, 024323 (2014)

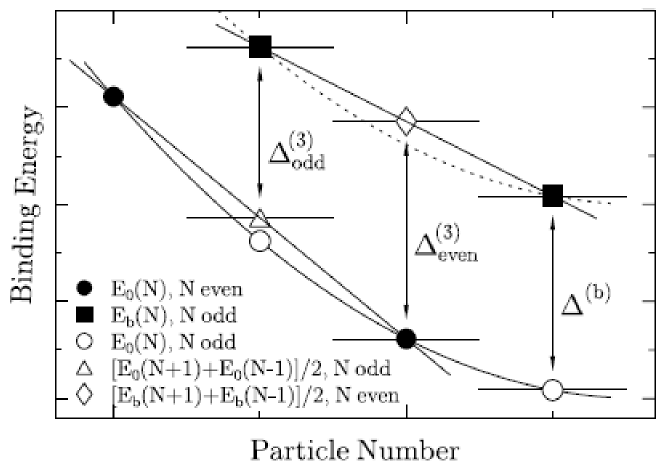
G. Hagen , Private Communication (2013)
K. Kreim *et al.*, PLB **731**, 97 (2014)

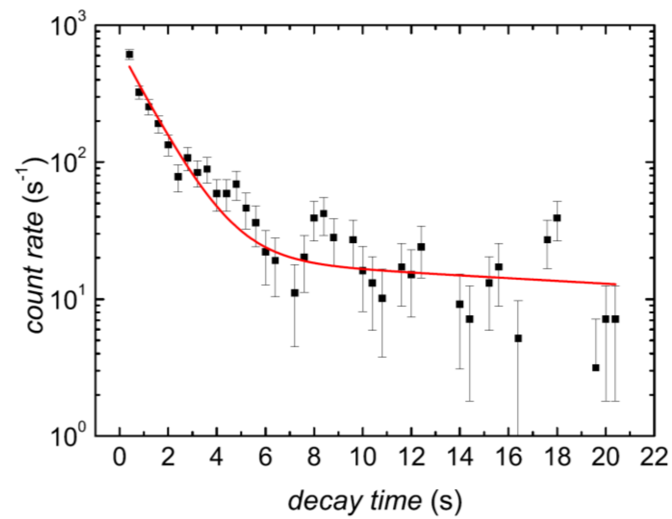
OES of Fr and Ra Isotopes

- $^{222,224,226\text{-}233}$Fr and ^{233,234}Ra measured
- Mass and half-life of ^{233}Fr for the first time
- Odd-even staggering of masses due to pairing interaction
  - Even nuclides more bound



$$\Delta^3(N_0) = \frac{(-1)^{N_0}}{2}\left[E(N_0-1) - 2E(N_0) + E(N_0+1)\right] .$$





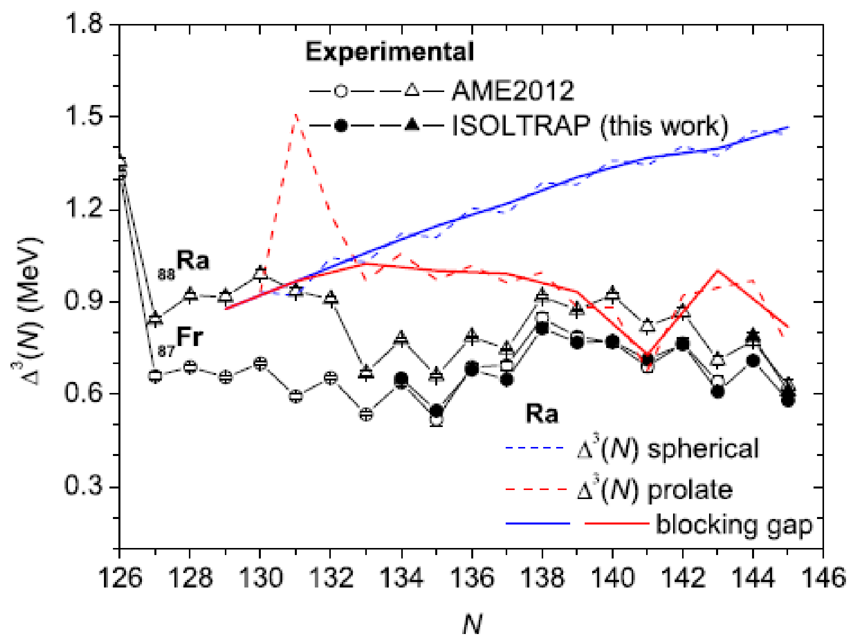
M. Bender *et al.*, EPJA **8**, 59 (2000)

S. Kreim *et al.*, PRC 90, 024301 (2014)

Pairing Correlation and Deformation

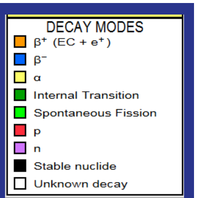
- Enhanced staggering of empirical pairing gap towards N=146
- Can contributions from pairing and deformation be disentangled?

- Compare to calculations excluding pairing (HF) and including deformation (HFB) following ansatz from Satula *et al.*, PRL **81**, 3599 (1998)

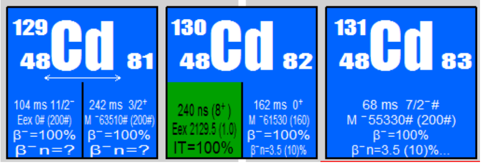


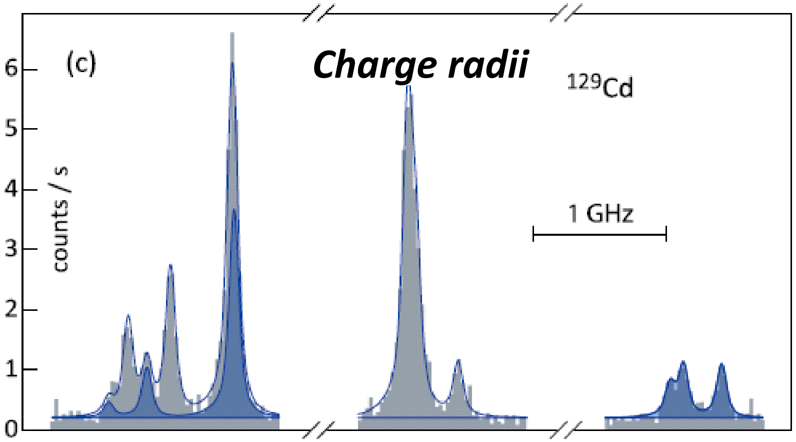
S. Kreim *et al.*, PRC **90**, 024301 (2014)

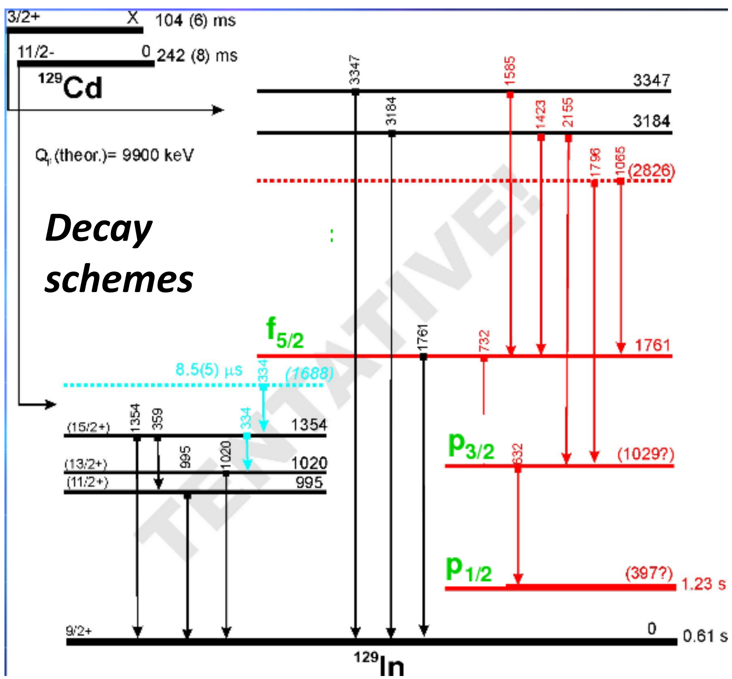
Neutron-rich Cd Isotopes

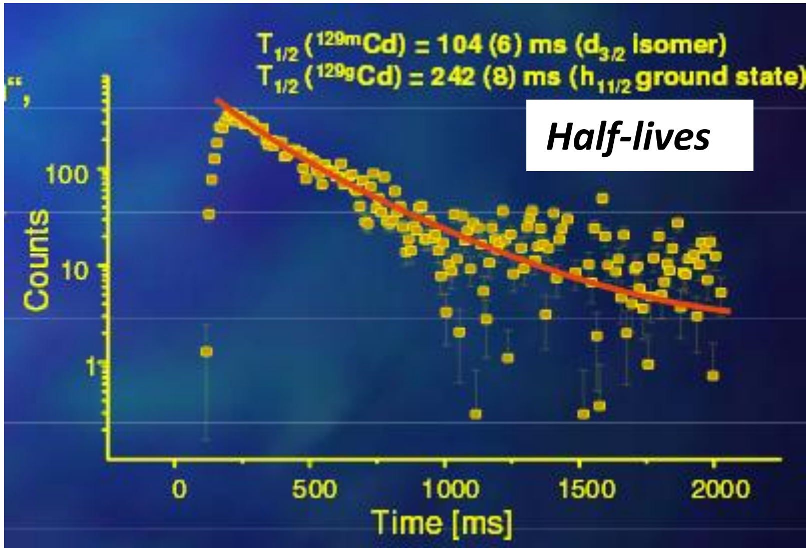


- Neutron-rich Cd isotopes in the vicinity of N=82 important for the rapid neutron-capture process of stellar nucleosynthesis
- Mass of „waiting point“ nuclide ^{130}Cd determined only through beta decay





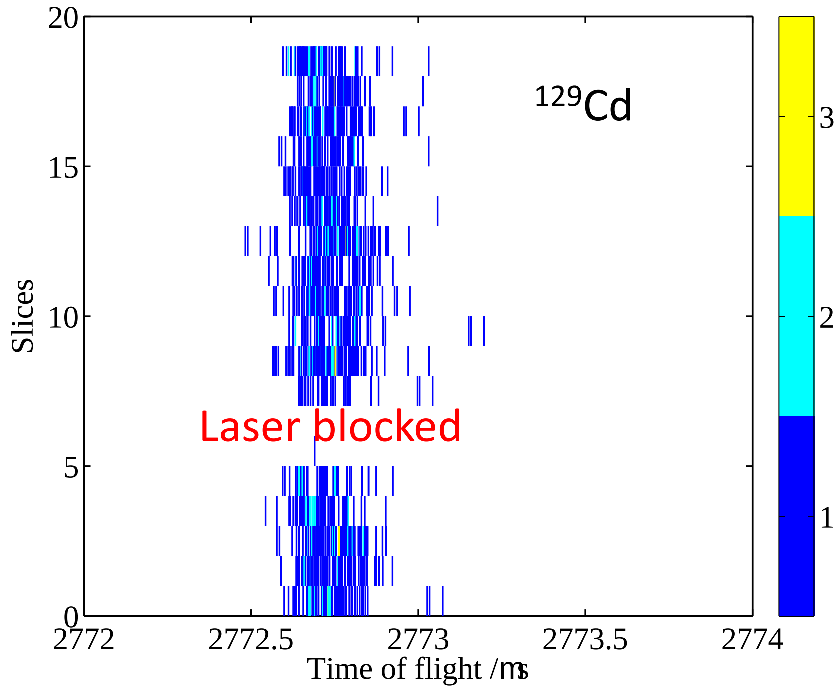




M. Hannawald *et al.*, PRC **62**, 054301 (2000)
I. Dillmann *et al.,* PRL **16**, 162503-1 (2003)
D.T. Yordanov *et al.*, PRL **110**, 192501 (2013)
M. Wang *et al.*, CPC **36** 1603 (2012)

N=82 Shell Gap

- ^{129}Cd after 100 revolutions in MR-ToF MS
  - 1539 ions → Δm/m≈1.2E-7



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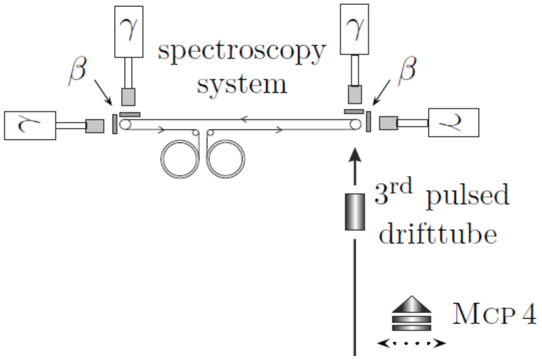
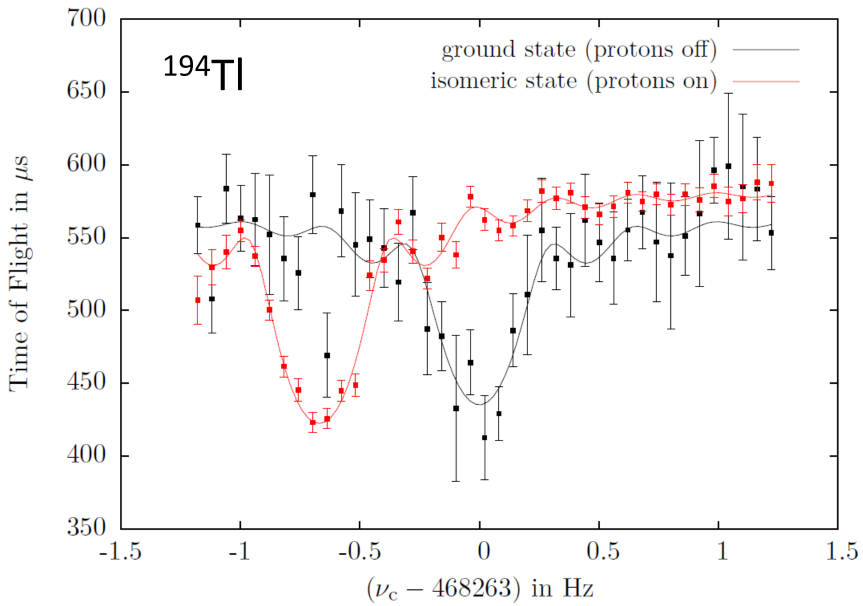
- Masses of $^{129-131}$Cd measured, deviations from known values seen
- The one-neutron shell gap agrees with the picture of a fast reduction (quenching) for $Z < 50$

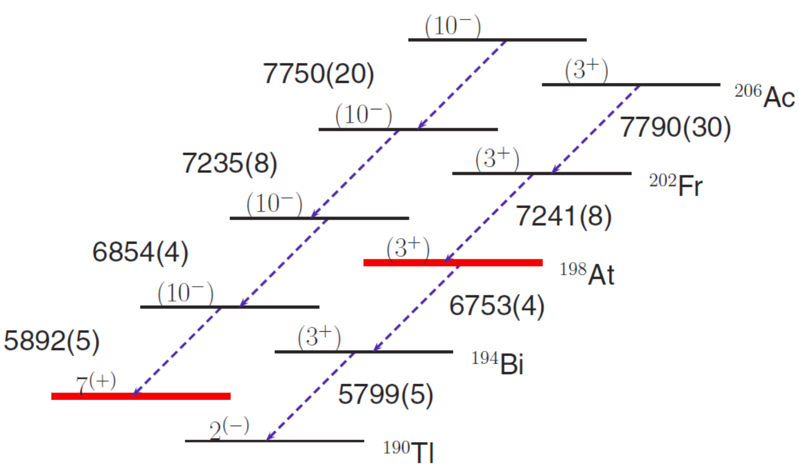
S. Goriely, *et al*., Phys. Rev. C **82**, 035804 (2010)
P. Möller, *et al.*, ADNDT **59**, 185, 1995.

Spectroscopy on Pure Samples

- Isomeric mixtures can be purified in the Penning trap
- Pure samples can be implanted on tape or guided to flexible spectroscopy station
  - Spin-state ordering in ^{194}Tl confirmed
  - Excitation energy determined
  - Mass, half-life, and excitation spectra of high-spin state in ^{190}Tl measured
  - State-ordering in ^{190}Tl determined through mass of ^{198}At



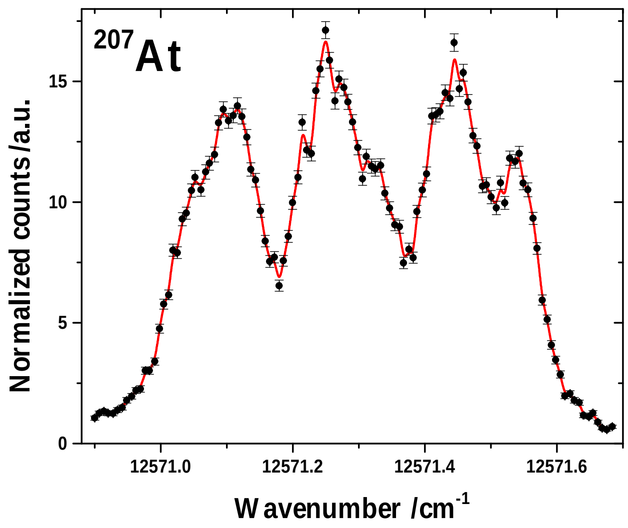


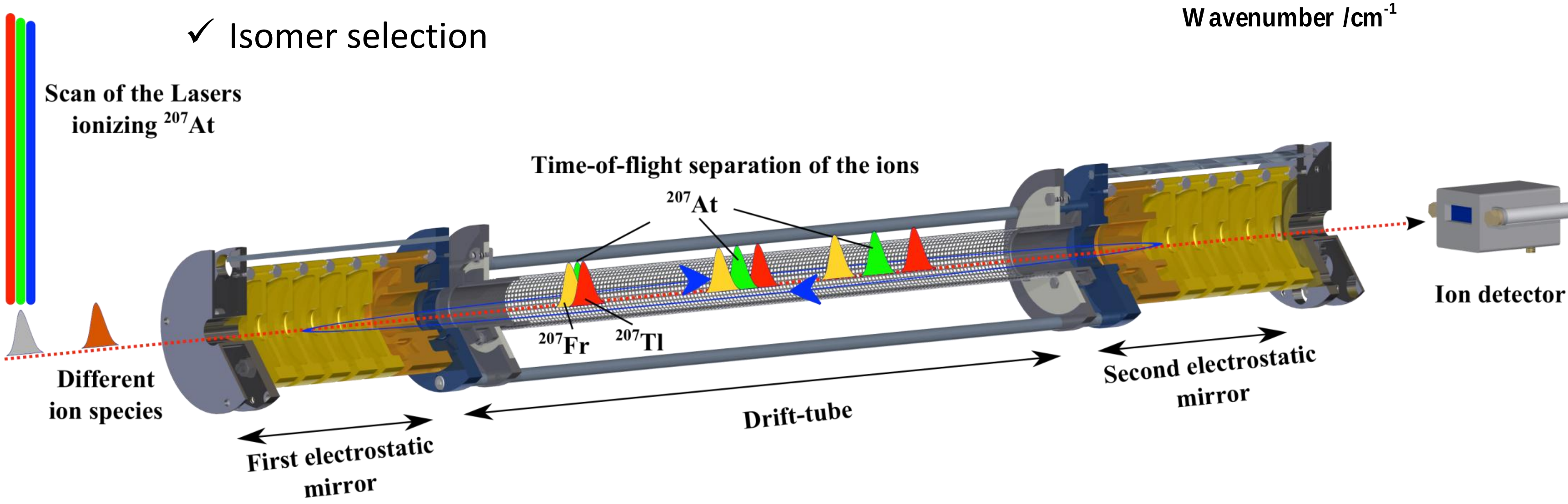


M. Kowalska et al., NIMA **689**, 102 (2012), J. Stanja *et al.*, PRC **88**, 054304 (2013)

In-Source Laser Spectroscopy

- In-source laser spectroscopy with RILIS
  - Investigate ionization efficiency for hyperfine-structure studies
- Two different techniques
  - Alpha spectroscopy using the Windmill setup
  - Selective single ion counting using MR-TOF MS of ISOLTRAP
    - ✓ Background suppression
    - ✓ Isomer selection





S. Kreim *et al.*, NIM B **317**, 492 (2013), R. N. Wolf *et al.*, IJMS **349-350**, 123 (2013), B. Marsh *et al.*, NIM B **317**, 550 (2013)


ISOL TRAP
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The University of Manchester
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ISOLDE
CSNSM
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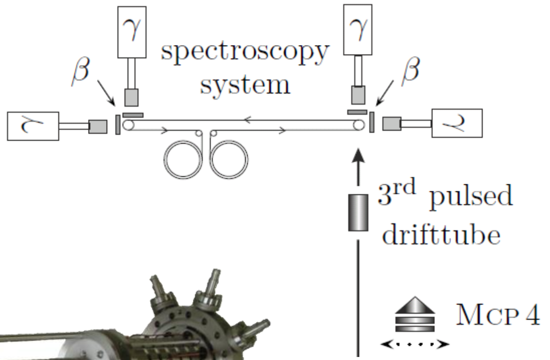
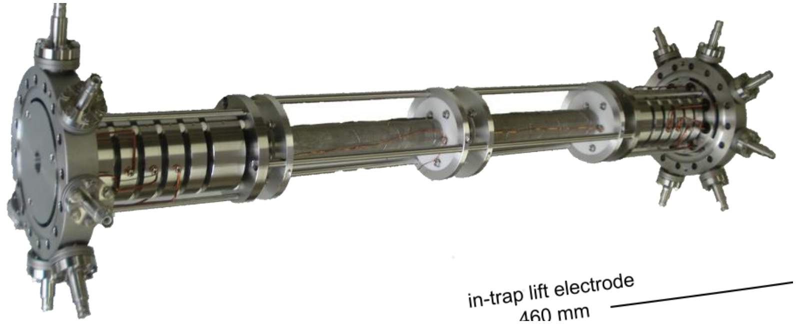
ERNST MORITZ ARNDT UNIVERSITÄT GREIFSWALD
KATHOLIEKE UNIVERSITEIT LEUVEN
CERN
Max-Planck-Institut für Kernphysik

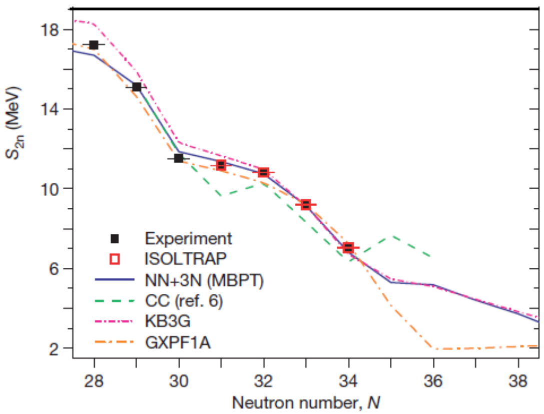
Conclusions



- Recent modifications at ISOLTRAP allow determination of different nuclear parameters
  - Mass (isotope discovery), excitation spectra (isomer selectivity), hyperfine structure



- Mass measurements with ISOLTRAP address topics of nuclear structure and astrophysics far away from stability
  - ^{54}Ca - test bench for calculations using 3-body forces
  - ^{53}K – test bench for open-shell calculations
  - ^{233}Fr – challenging to quantify contributions to OES
  - ^{130}Cd – waiting point nuclide challenging indirect mass determinations



- Complementary observables are required to interpret data consistently