Mass Measurements with ISOLTRAP for Nuclear Structure and Astrophysics

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January 31st 2013

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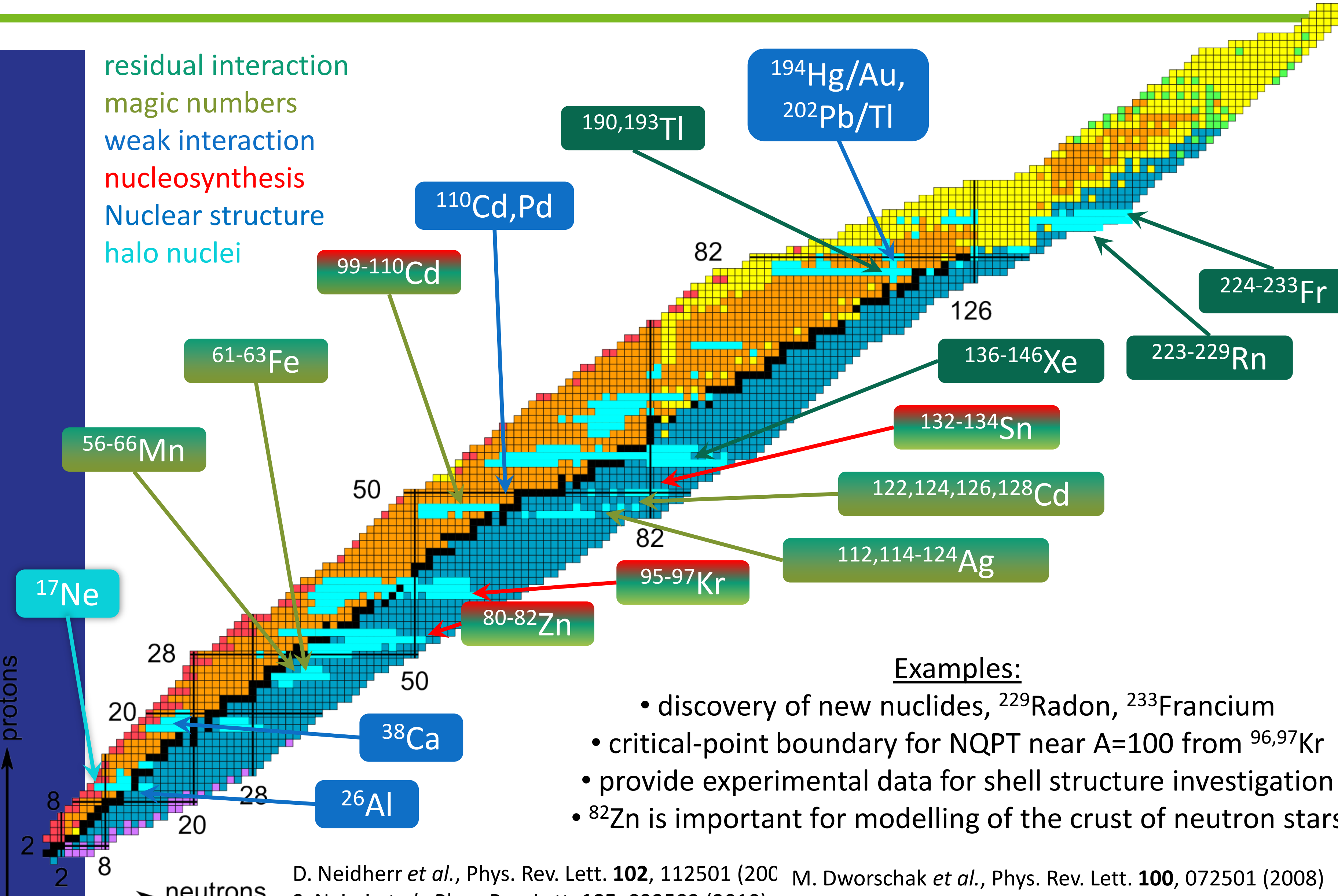
Penning alone in New York

- 8 million inhabitants
- many with the similar weight

- Goal: identify the few with exactly the same mass, evacuate all others
- Measure their mass with high precision

Physics with ISOLTRAP 2004-2012



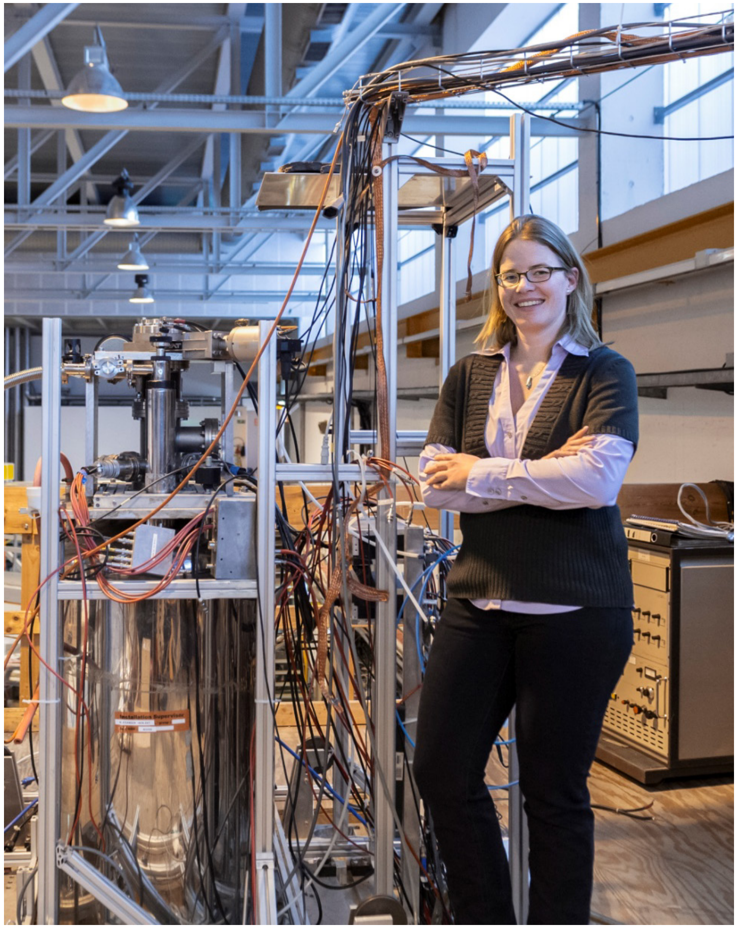
Examples:

- discovery of new nuclides, ^{229}Radon, ^{233}Francium
- critical-point boundary for NQPT near A=100 from ^{96,97}Kr
- provide experimental data for shell structure investigation
- ^{82}Zn is important for modelling of the crust of neutron stars

D. Neidherr *et al.*, Phys. Rev. Lett. **102**, 112501 (200
S. Naimi *et al.*, Phys. Rev. Lett. **105**, 032502 (2010)
M. Dworschak *et al.*, Phys. Rev. Lett. **100**, 072501 (2008)
R. N. Wolf *et al.*, PRL **110**, 041101(2013)

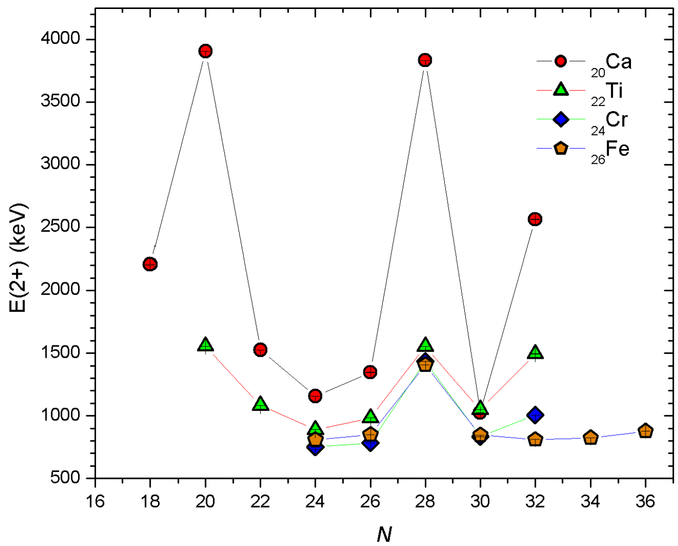
Overview

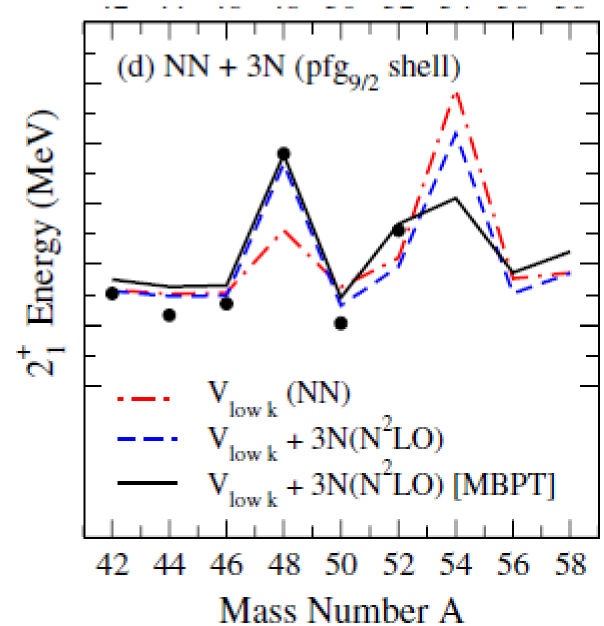
- 3 Examples far from stability
  - ^{54}Ca – structural evolution close to dripline
  - ^{82}Zn - nuclear and astrophysics
  - ^{233}Fr - structure of heavy nuclei
- Penning-trap mass spectrometry
  - Production of radioactive nuclei
  - Purification and measurement
- Future possibilities
  - K isotopes
  - Pd isotopes
- Summary



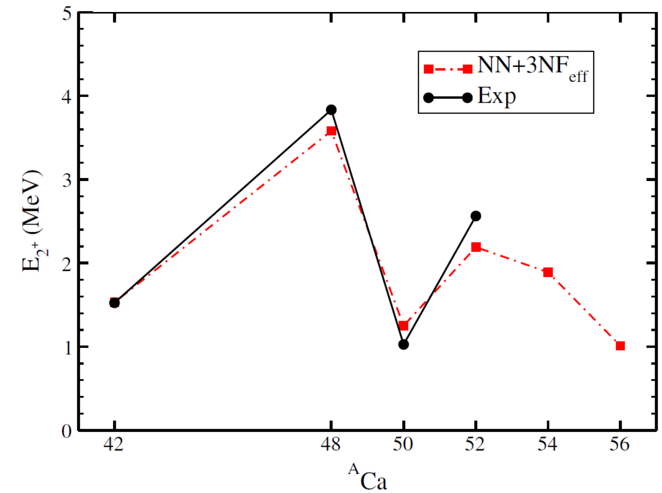
Taken from: „Longer-Faster-Purer“ CERN Bulletin, 18.1.2013
cern.ch/bulletin

Magic Neutron Number *N*=32?





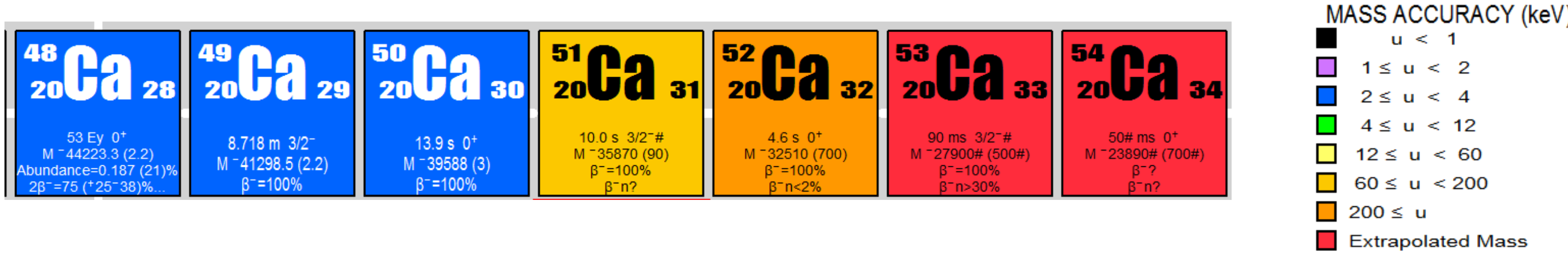
- Spectroscopic information available at *N*=32
- E(2+) energy particularly high in Ca
- Shell-model and beyond-mean-field calculations predict *N*=32 as magic number but disagree on *N*=34
- Calculations with 3-body forces correctly reproduce high E(2+) energy



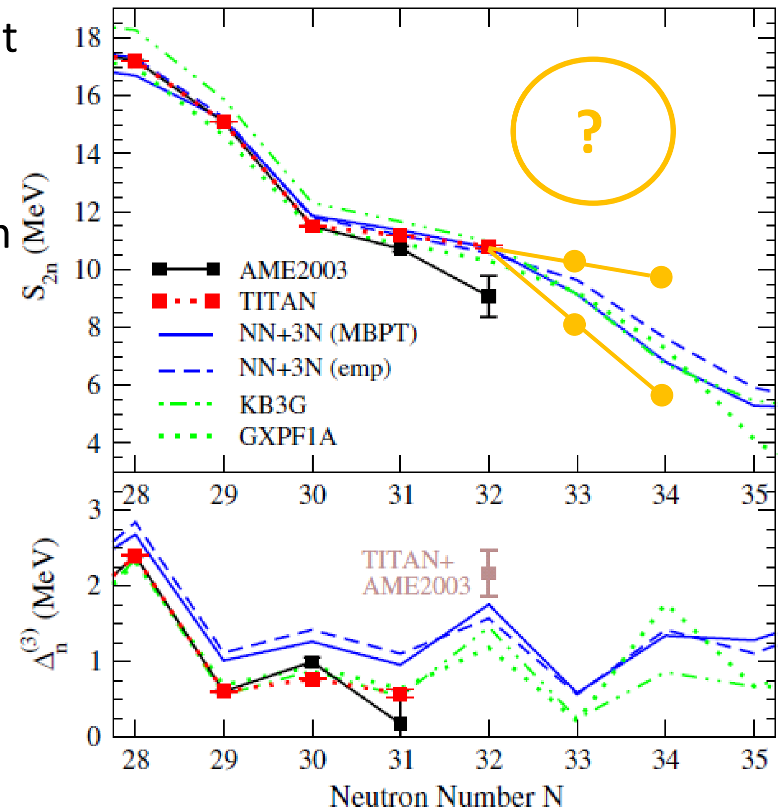
S. Raman, C. W. Nestor, P. Tikkanen, At. Data. Nucl. Data Tables **78**, 1 (2001)
R.V.F. Janssens *et al.*, Phys. Lett. B **546**, 55 (2002)

G. Hagen et al., PRL 109, 032502 (2012)
J. D. Holt et al., JPG 39, 085111 (2012)

Neutron-Rich Calcium Isotopes



- Ground-state properties (masses, radii) at *N*=32 missing
- TITAN measurements of ^{51,52}Ca
- Calculations including 3-body forces from chiral effective field theory
  - Agreement with phenomenological approaches
  - Agreement with TITAN
  - Prediction of Ca masses beyond ^{52}Ca
- ISOLDE proposals
  - S. Kreim et al., INTC-P-317 (2011)
  - M. Bissel et al., INTC-P-XXX (2011)



A. T. Gallant *et al.,* PRL **109**, 032506 (2012)

Shell gap at *N*=32

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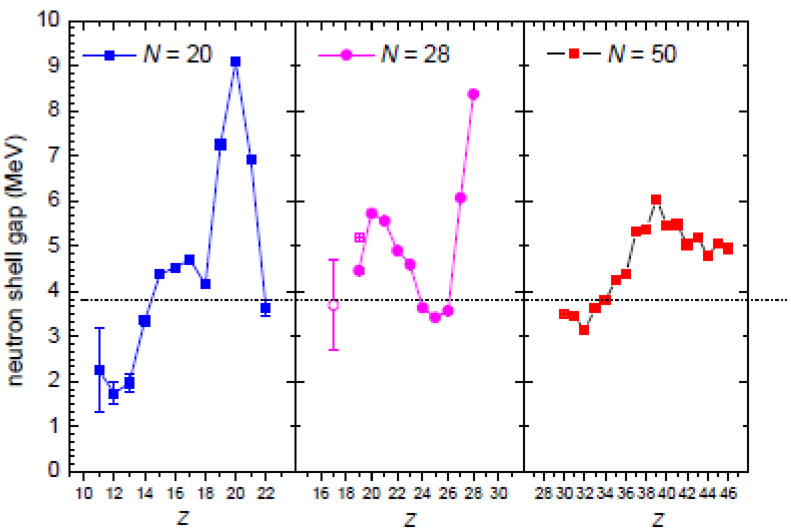
- ^{53,54}Ca mass values determined
- ^{51,52}Ca confirmed
- Excellent agreement of new mass values and model predictions
- Strong evidence for magic number *N*=32 also from masses
- Highest shell gap of *N*=32 for calcium



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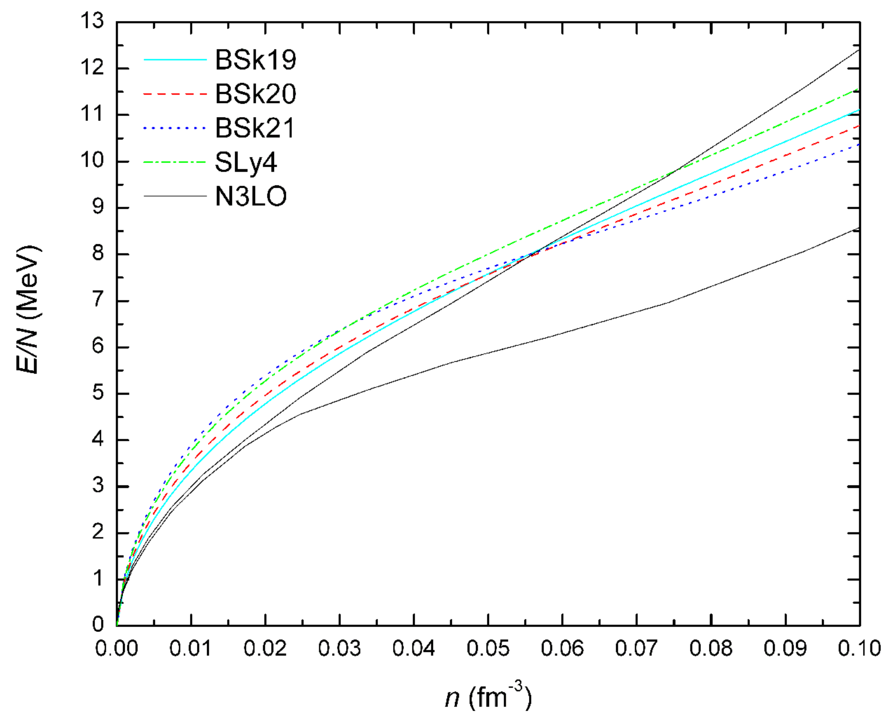
Equation of State

- 3-body forces from chiral effective field theory also applicable to neturon matter
- First N^3LO calculations of neutron matter energy
- Mass predictions at present limited to A~60

- Effective Skyrme forces calculated with HFB method
- BSk19-21 provide consistently EOS and nuclear mass tables
- HFB19-21 predict composition of outer crurst of neutron stars



J. M Pearson *et al*, PRC **83**, 065810 (2011)

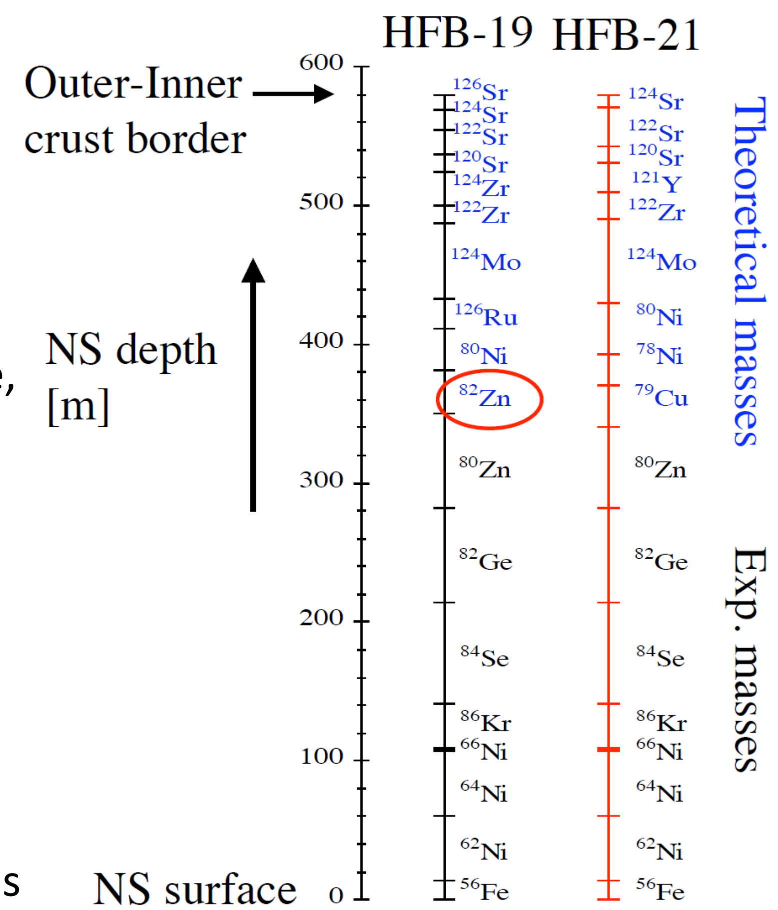
P. Haensel and B. Pichon, Astron. Astrophys. **283,** 313 (1994)

J. M Pearson *et al*, PRC **85**, 065803 (2012)

I. Tews *et al*., PRL **110**, 032504 (2013)

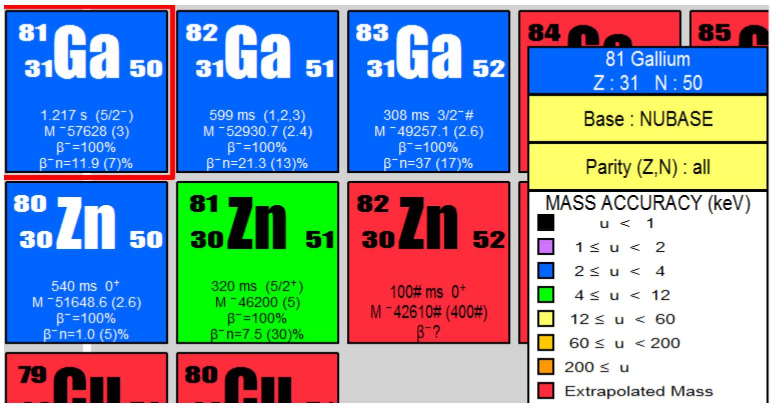
Modelling of Neutron-Star Crust

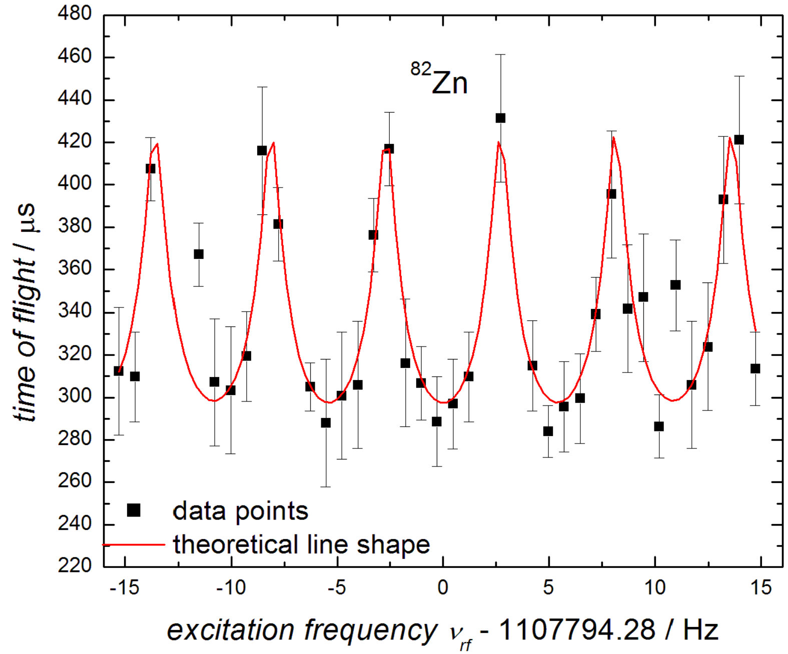
- Outer crust of neutron stars is a possible birthplace of the heavy elements
- To determine the composition, the principle of minimisation of the Gibbs free energy is used. For a given pressure, this will depend mainly on the binding energy of the nucleus!
- Nuclear structure remains crucial: nuclei cluster around *N*=50 and *N*=82
- Depth profile of a neutron star by using experimental masses and mass models as input for equation of state



J. M. Pearson *et al.*, Phys. Rev. C **83** (2011)

Mass Measurement of ^{82}Zn



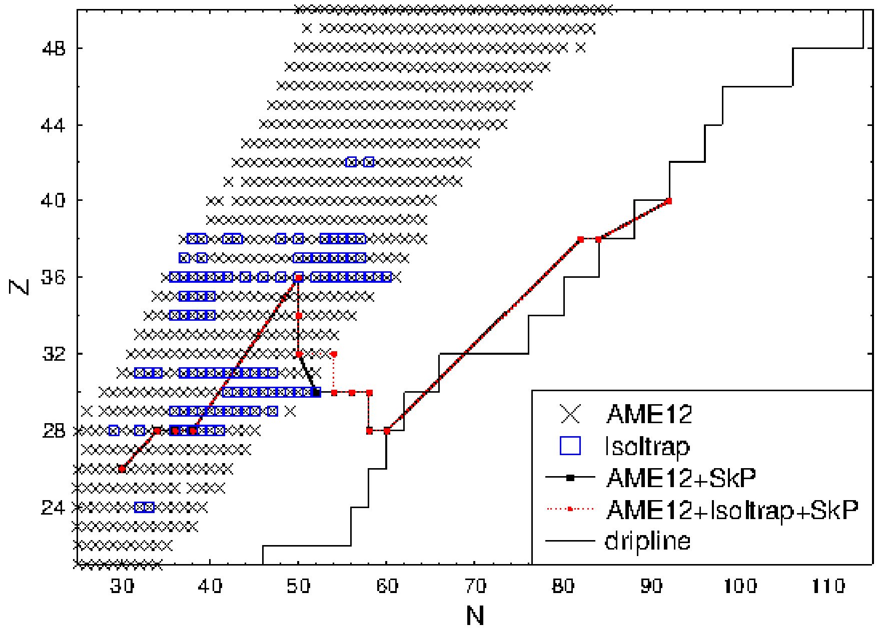


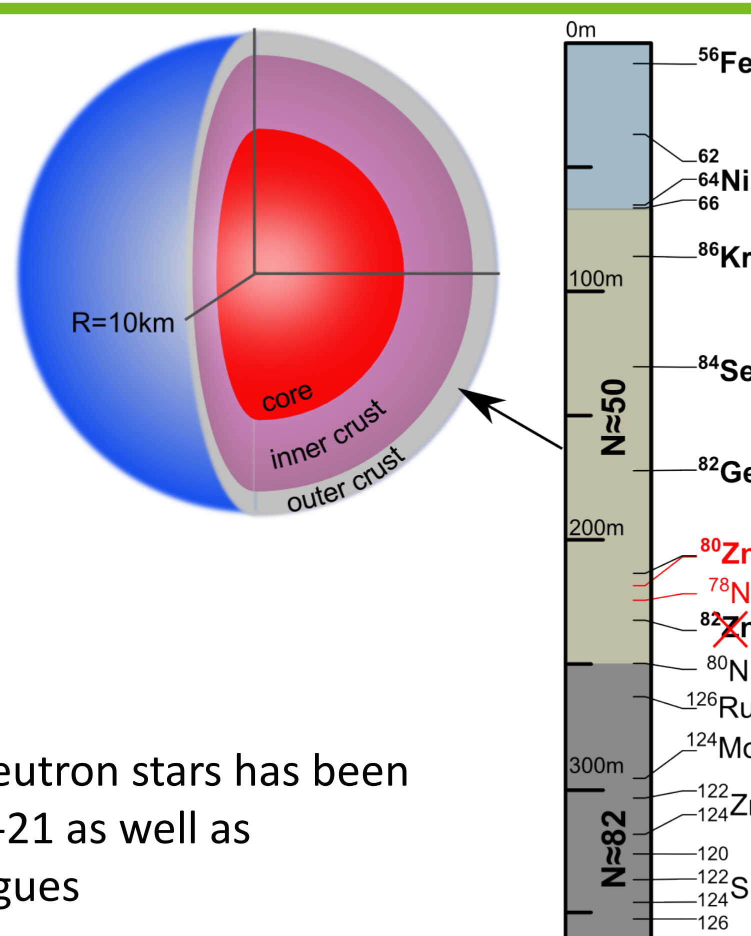
80 ions in 35 minutes!

- Before only AME extrapolation with 400keV uncertainty
- Mass excess ME(^{82}Zn) = m – Au = -42.314(3) MeV/c^2
  - Uncertainty δm/m = 4•10^{-8}
- Most exotic nuclei measured for neutron-star crustal composition

G. Audi and M. Wang, private communication (2011)
R. N. Wolf *et al.*, PRL **110**, 041101 (2013)

Crustal Composition





- Sequence of nuclei in the outer crust of neutron stars has been determined using BRUSLIB models HFB19-21 as well as calculations from Dobaczweski and colleagues
- In all models, the prior predicted nucleus is ruled out from the experimental ^{82}Zn value!

R. N. Wolf *et al.*, PRL **110**, 041101 (2013)
S. Kreim, M. Hempel *et al.*, in preparation

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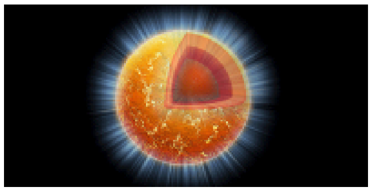
Synopsis: Weighing Models of Neutron Stars



NASA/CXC/M. Weiss

Plumbing Neutron Stars to New Depths with the Binding Energy of the Exotic Nuclide ^{82}Zn

R. N. Wolf, D. Beck, K. Blaum, Ch. Böhm, Ch. Borgmann, M. Breitenfeldt, N. Chamel, S. Goriely, F. Herfurth, M. Kowalska, S. Kreim, D. Lunney, V. Manea, E. Minaya Ramirez, S. Naimi, D. Neidherr, M. Rosenbusch, L. Schweikhard, J. Stanja, F. Wienholtz, and K. Zuber

Phys. Rev. Lett. **110**, 041101 (2013)

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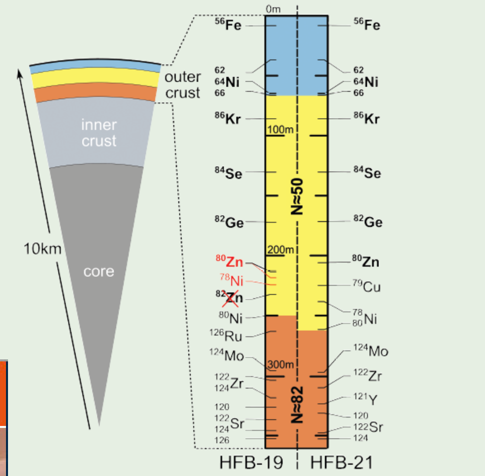

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Paris, le 24 janvier 2013

Peser le noyau de zinc-82

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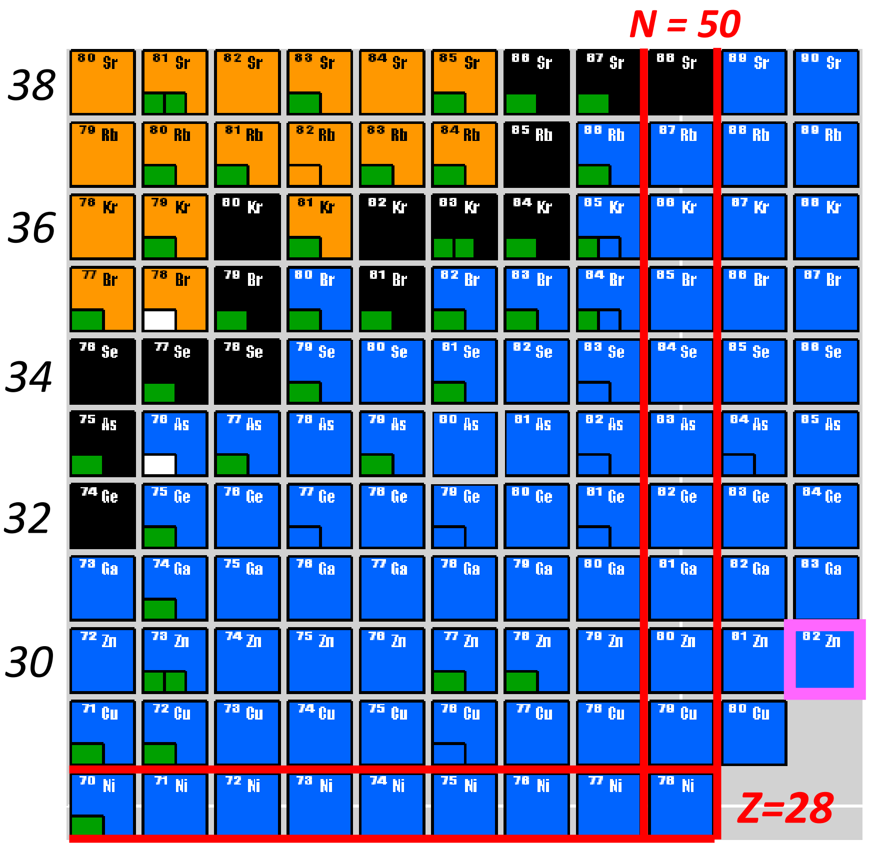
An atom sheds light on neutron stars | Atom & Cosmos

N=50 Shell Gap

- How does the N=50 shell gap evolve towards doubly-magic ^{78}Ni?
- Models make different predictions
- Mass of ^{82}Zn constitutes the most exotic determination of shell gap



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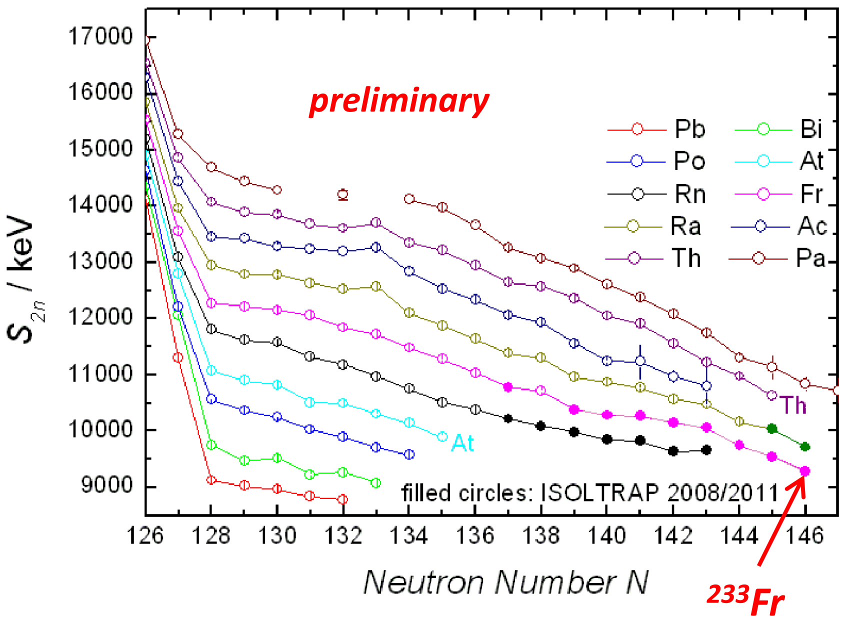
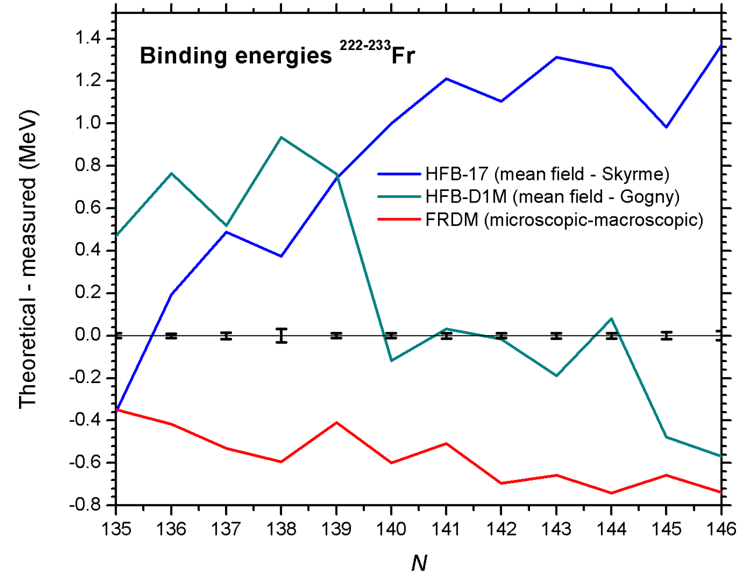
Nuclear Structure Above ^{208}Pb

- Two-neutron separation energies

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





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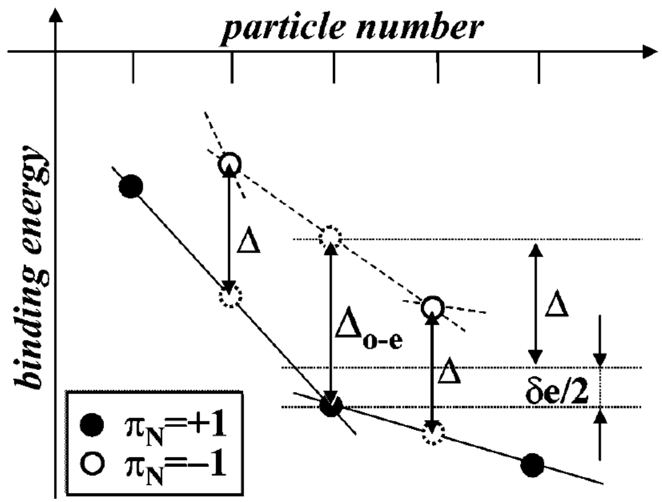
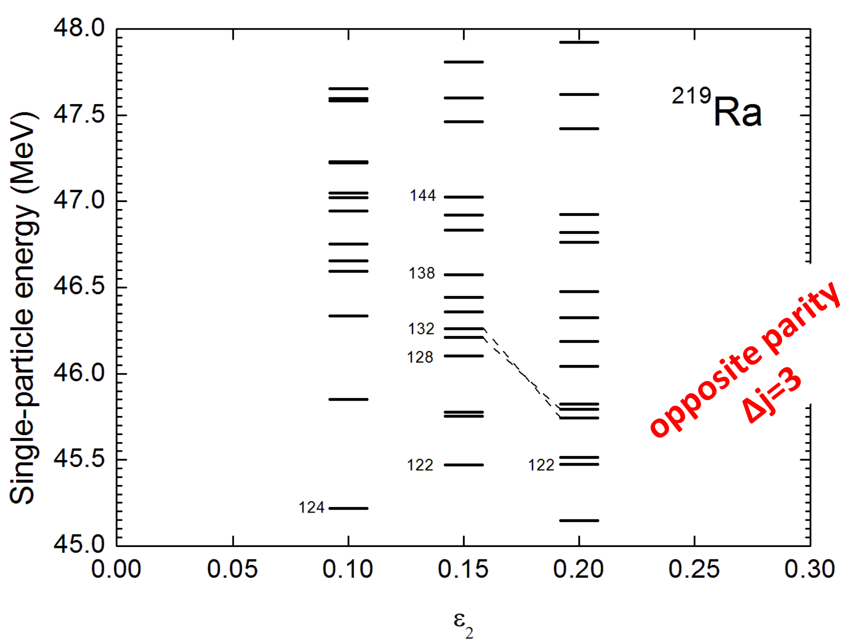
D. Neiherr *et al.*, PRL **102**, 112501 (2009)
H. Alvarez-Pol *et al.*, Phys. Rev. C 82, 041602(R) (2010)
S. Kreim *et al.,* INTC-P-299, IS 518 (2011)
S. Goriely *et al.*, PRL **102**, 152503 and 242501 (2009)
P. Moller, *et al.*, Data and Nucl. Data Tables 59, 185 (1995)

Odd-even Staggering



- Describe subtle structural effects from ground-state properties describe?
- Single particle energies from OES in neutron empirical pairing gap
- Compare to Nilsson orbitals



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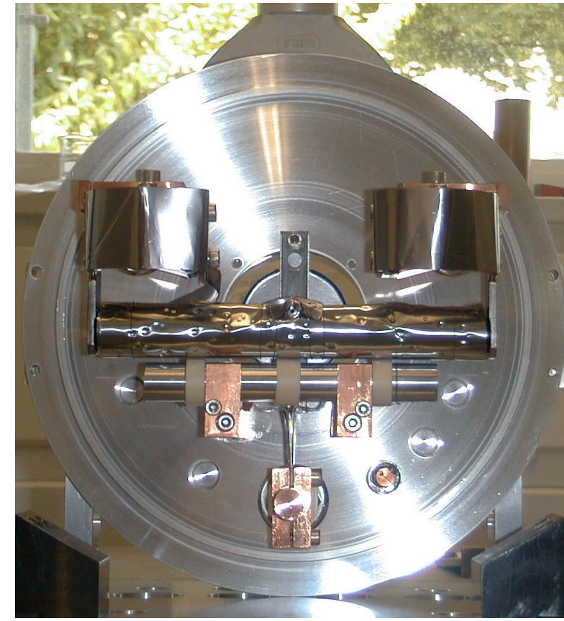
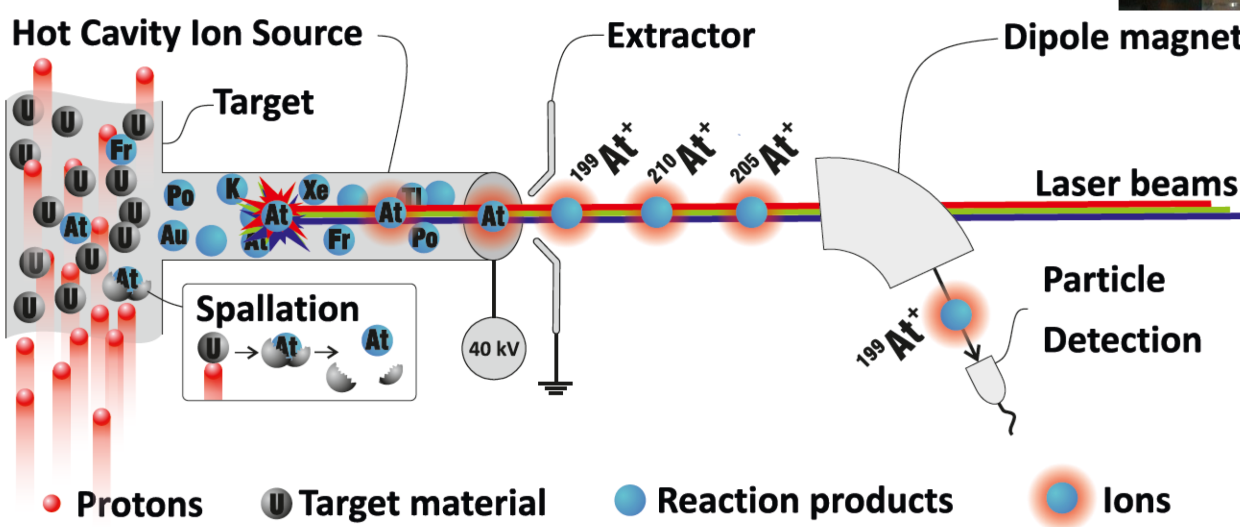
W. Satula *et al.*, PRL **81**, 3599 (1998)

ISOLTRAP at 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



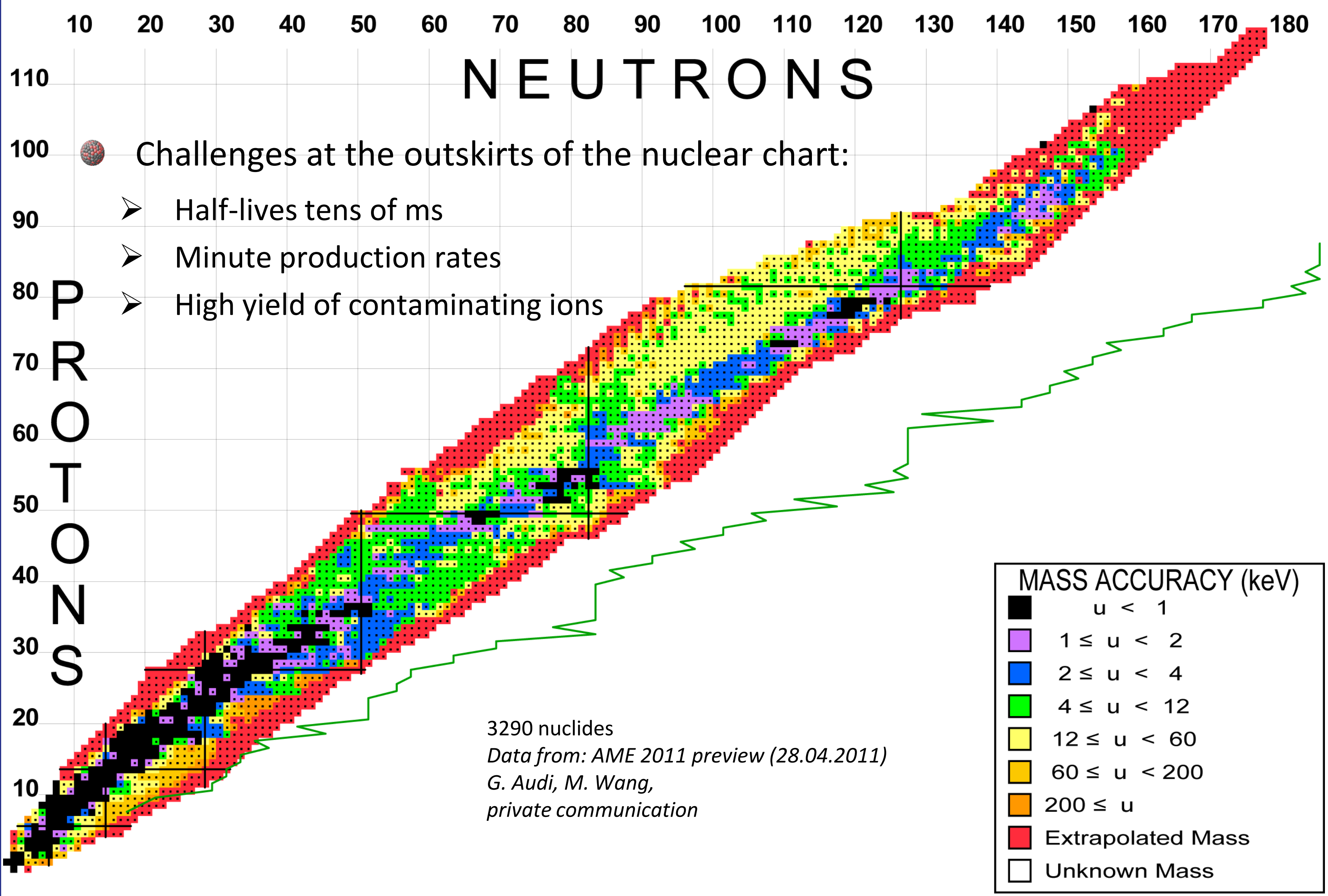


Courtesy Sebastian Rothe

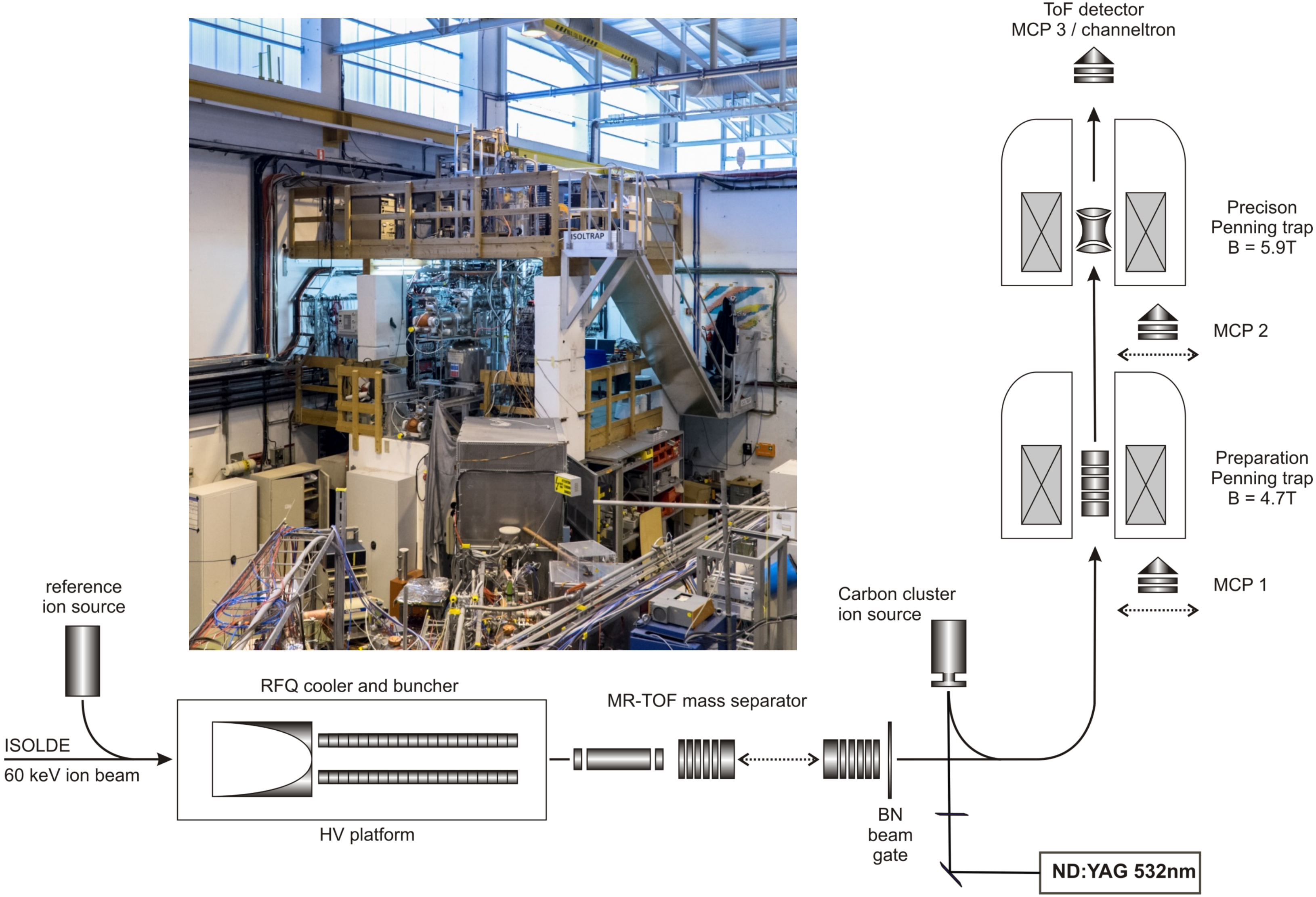
G. D. Alkhazov *et al.,* NIM B **69** (1992) 517, V. N. Fedosseev *et al.,* NIM B **266**, 4378 (2008), U. Koester *et al.,* Nucl. Phys. A **701**, 441 (2002)

Challenges for PTMS

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



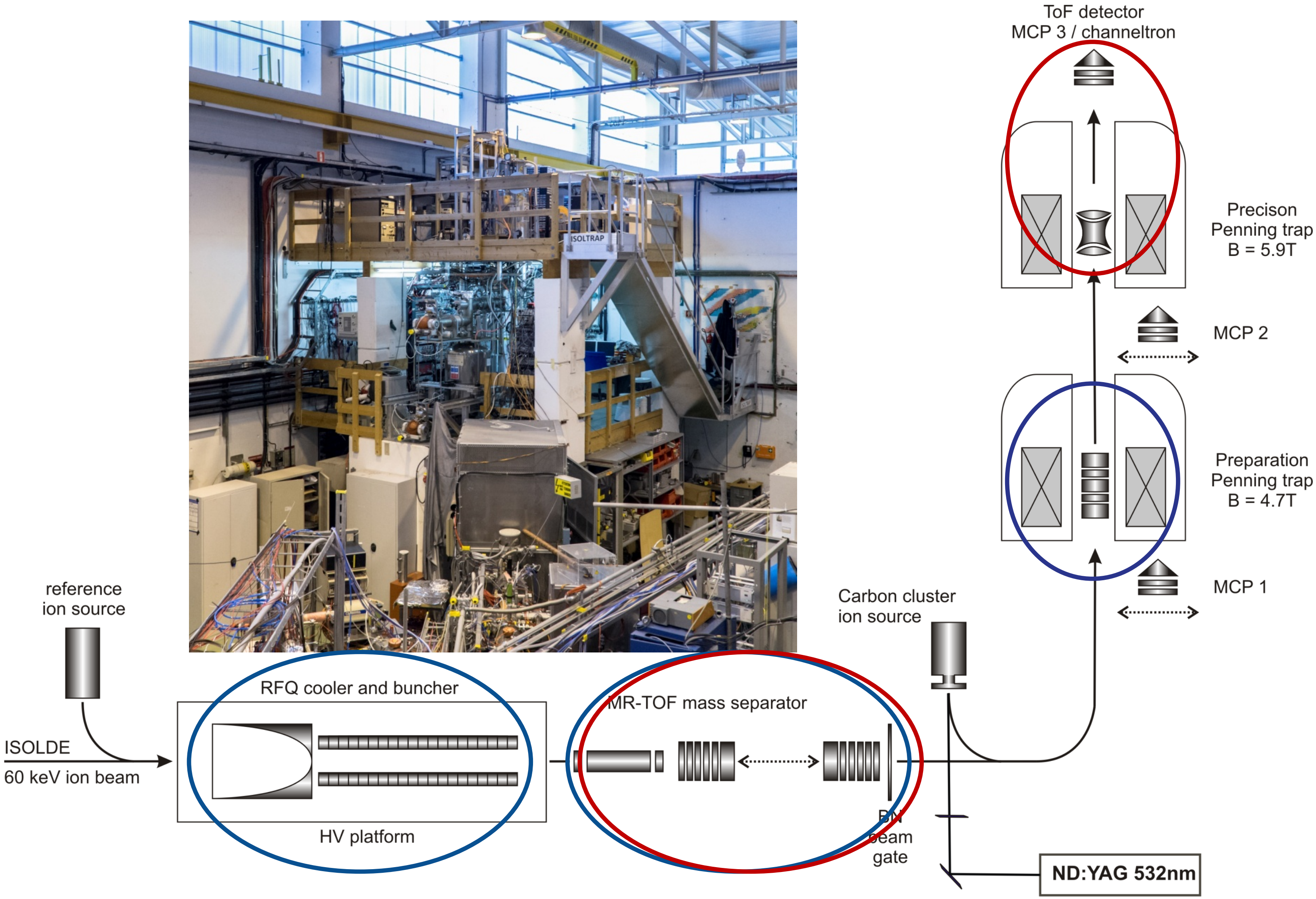
The ISOLTRAP Experiment



M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

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

The ISOLTRAP Experiment



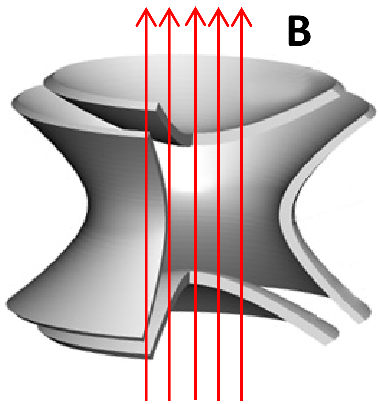
M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

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

preparation measurement

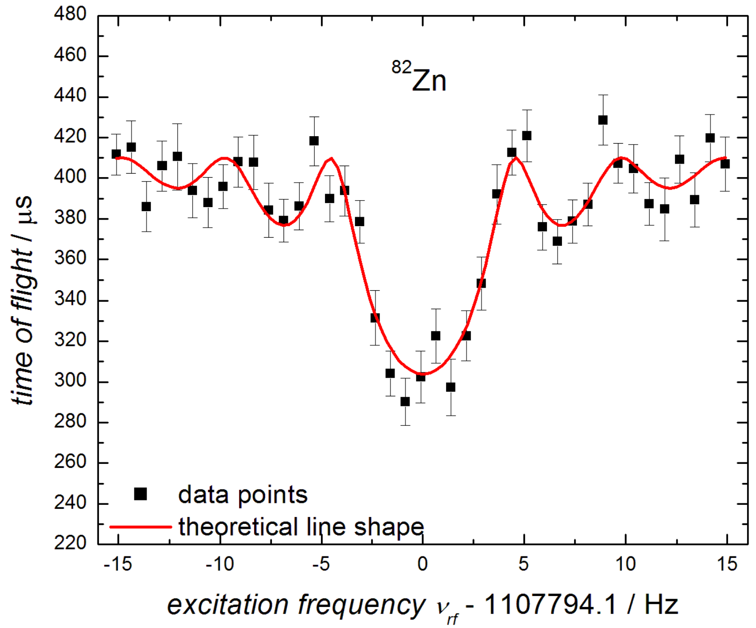
Detection Principle

- Charged particle stored by superposition of strong homogeneous magnetic field in z direction and weak, electrostatic potential for axial confinement
  - Frequency measurement
  - Long storage times
  - Single-ion sensitivity
  - High precision



- Frequency measurement: eigenmotion in the trap can be used to determine mass

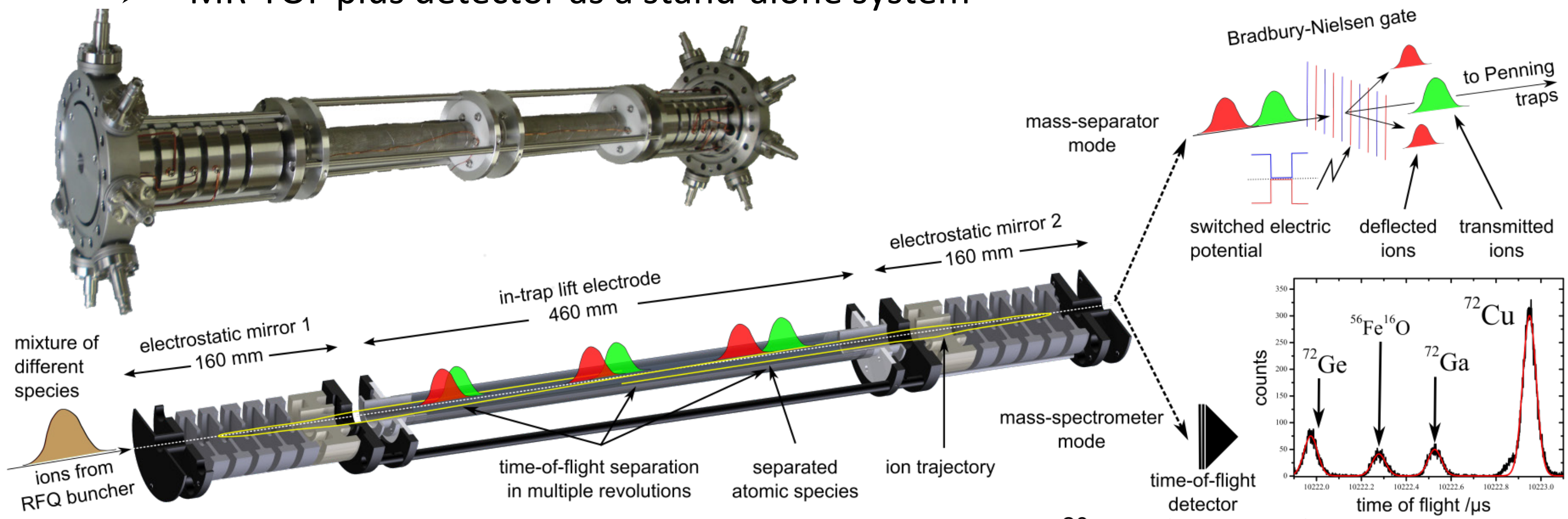
$$\nu_c = \nu_+ + \nu_- \quad \Rightarrow \quad \nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



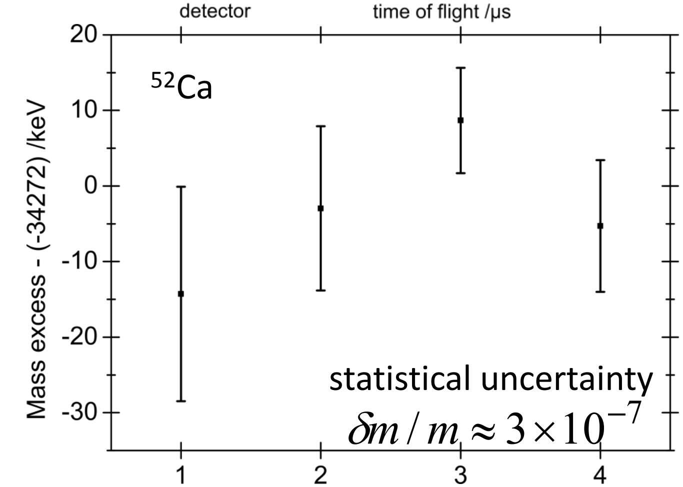
L. S. Brown and G. Gabrielse , Rev. Mod. Phys. **58**, 233 (1986)

MR-TOF Measurements

- Implementation of multi-reflection time-of-flight mass separator (MR-TOF MS) opened a wide range of possibilities
  - Support Penning-trap mass spectrometry on fast time scales
  - MR-TOF plus detector as a stand-alone system

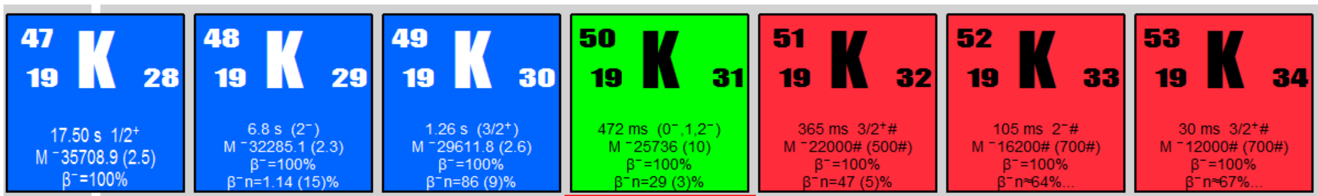


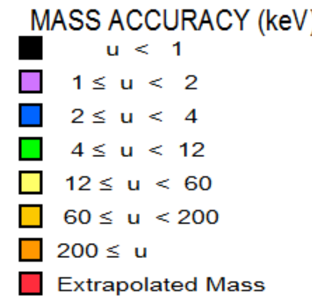
- Versatile tool allows for:
  - Higher contamination yield – 10^6:1
  - lower production yield – 10/s
  - lower half-lives – tens of ms
  - High repetition rate – 20Hz



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

Potassium Isotopes





- $^{51-53}$K masses determined with ISOLTRAP
- *N*=32 also prominent sub-shell closure
- Shell gap at *N*=32 decreased compared to Ca chain
- Bench mark for state-of-the-art calculations
  - Coupled-cluster already provide spins (talk by G. Hagen)
  - Gorkov self-consistent Green's function approach

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Ab-initio Calculations

- Gorkov-Green's function theory: 2- and 3-body interactions from chiral effective field theory fitted to few-body systems.
- Method accounts for pairing correlations
  - able to address open-shell systems / whole isotopic chains “ab-initio”
- calculations of the odd-even Ca and odd-odd K ongoing

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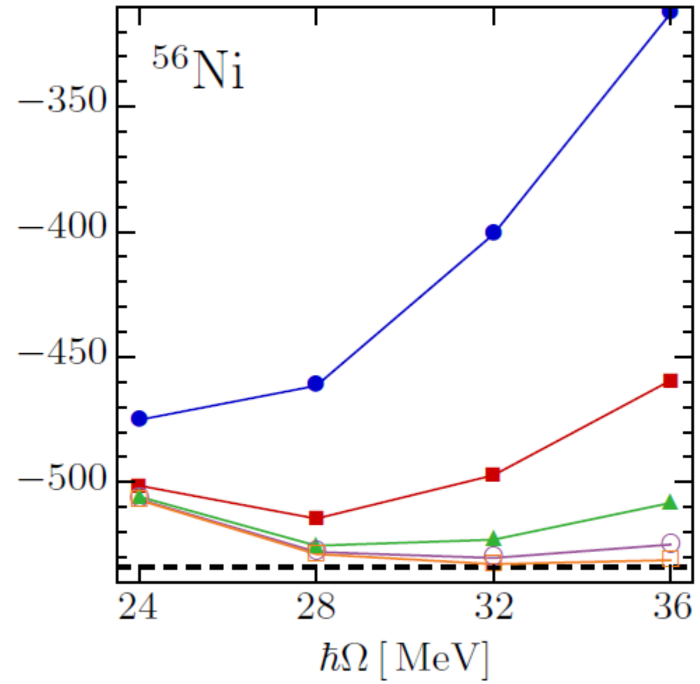
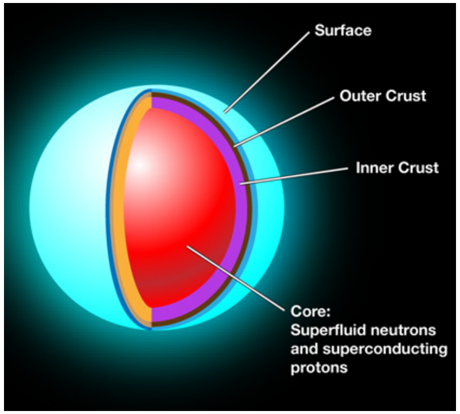
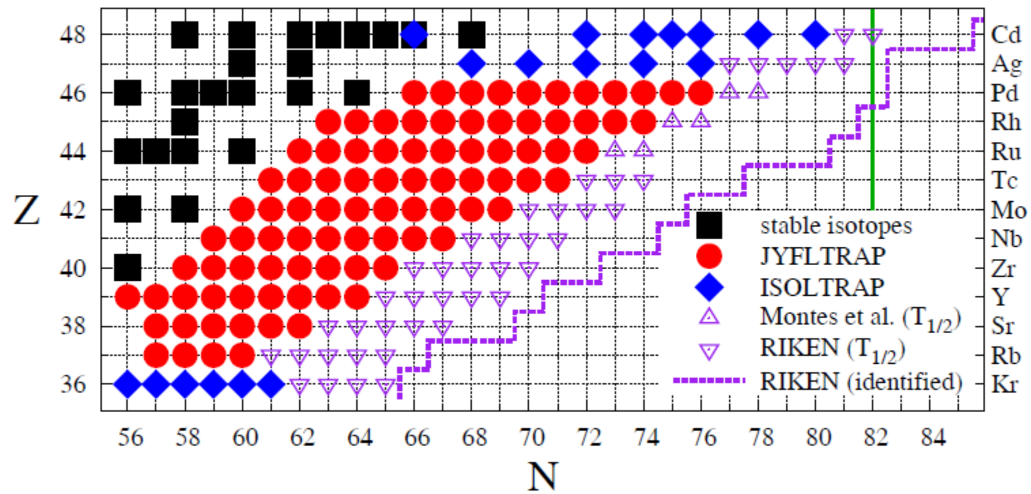


S. Kreim *et al.*, V. Somà *et al.*, in preparation

H. Hergert *et al.*, ArXiv 1212.1190 (2012)

Pd Isotopes





- Some models predict ^{46}Pd to be part of the *N*=82 nuclei constituting the outer crust of neutron stars
- Masses of nuclei measured up to ^{122}Pd, half-life of ^{128}Pd measured at RIKEN
- Upgrades of radioactive beam facilities will provide neutron-rich Pd beams
- Laser-ionization schemes are under development
  - Collaboration with Klaus Wendt (Mainz)

J. Hakala *et al.*, EPJA **47**, 129 (2011)

ISOLTRAP Collaboration

D. Atanasov, K. Blaum, Ch. Böhm, Ch. Borgmann, R. B. Cakirli, S. Eliseev

S. George, M. Rosenbusch, R. Wolf, L. Schweikhard, F. Wienholtz

G. Audi, D. Lunney, M. Wang, V. Manea

D. Beck, F. Herfurth, J. Kluge, Y. Litvinov, E. Minaya-Ramirez, D. Neidherr

J. Stanja, K. Zuber

M. Kowalska, S. Kreim

S. Schwarz, G. Bollen

M. Breitenfeldt

S. Naimi

T. Cocolios

Summary

- Mass measurements with ISOLTRAP address topics of nuclear structure as well as astrophysics
  - ^{54}Ca - as test bench for calculations using 3-body forces
  - ^{82}Zn - one mass value changes crustal composition as compared to core-collapse supernovae r-process scenarios
  - ^{233}Fr – structural evolution of neutron-rich Fr isotopes hard to describe with state-of-the-art mass models

- The implementation of a MR-TOF MS has openend a wide range of possibilities at ISOLTRAP
  - Versatile device: mass spectrometry and in-source spectroscopy
  - Similar work at GSI and RIKEN
  - Other Penning-trap facilities can profit from these achievements