Answering Questions of Nuclear and Astrophysics with Mass Measurements from ISOLTRAP

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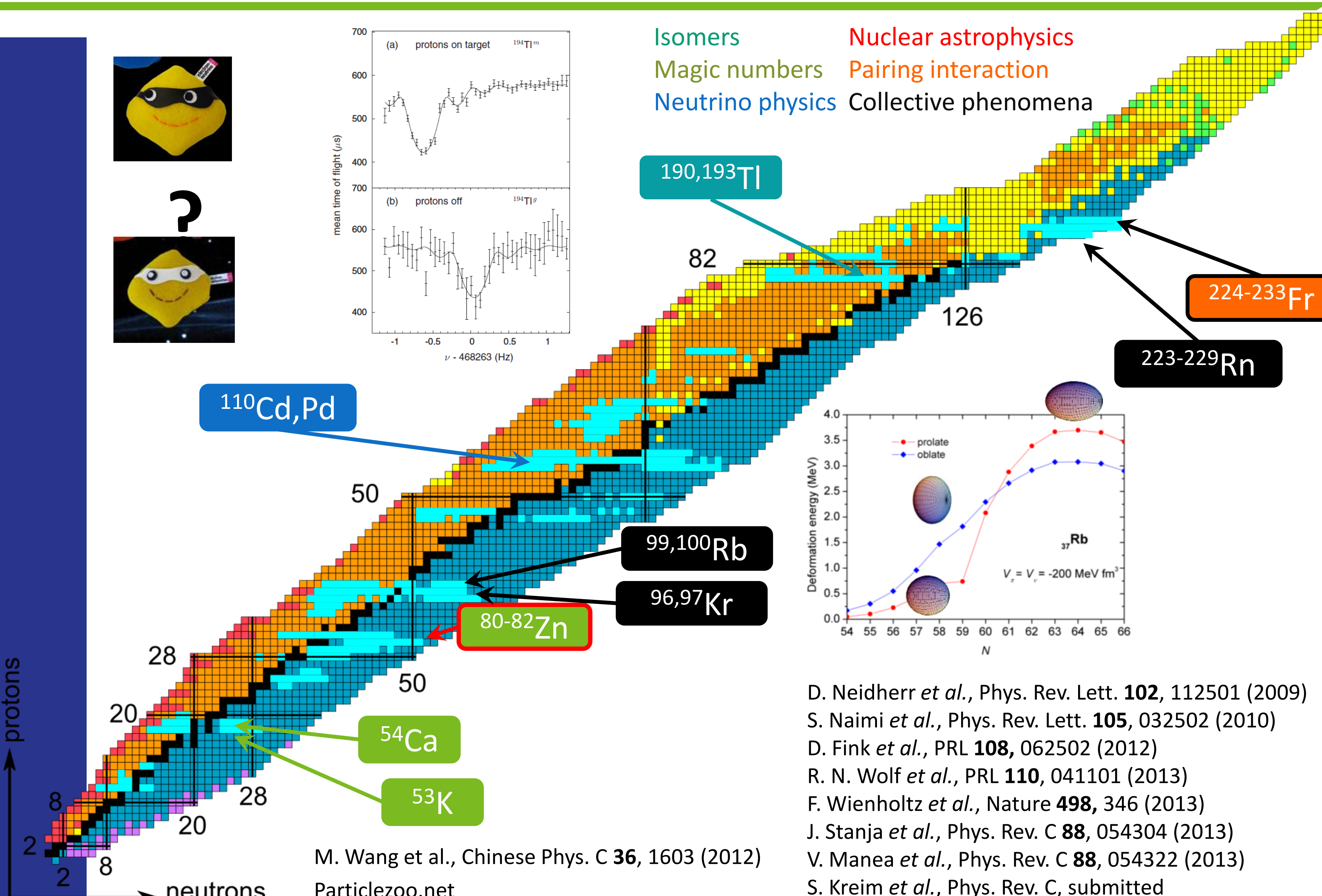
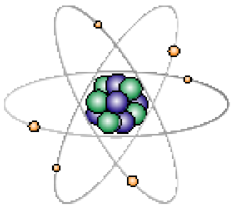
Physics with ISOLTRAP 2011-2014

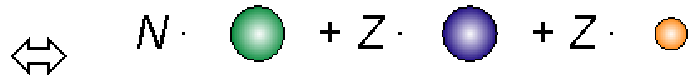


M. Wang et al., Chinese Phys. C **36**, 1603 (2012)
Particlezoo.net

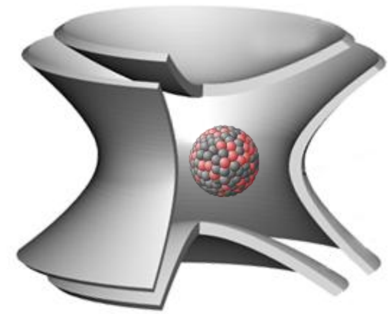
D. Neidherr *et al.*, Phys. Rev. Lett. **102**, 112501 (2009)
S. Naimi *et al.*, Phys. Rev. Lett. **105**, 032502 (2010)
D. Fink *et al.*, PRL **108,** 062502 (2012)
R. N. Wolf *et al.*, PRL **110**, 041101 (2013)
F. Wienholtz *et al.*, Nature **498,** 346 (2013)
J. Stanja *et al.*, Phys. Rev. C **88**, 054304 (2013)
V. Manea *et al.*, Phys. Rev. C **88**, 054322 (2013)
S. Kreim *et al.*, Phys. Rev. C, submitted

Overview



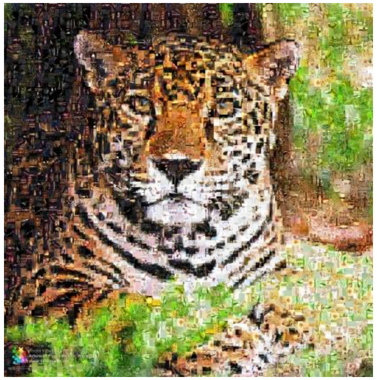


– binding energy



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

- Measurements with relative uncertainties of 10^{-6} required for insight into nuclear structre
  - Special tools needed
- Binding energy comprises information on all underlying interactions
  - How can we identify different contributions?
- Observations need interpretation
  - Examples ^{54}Ca, ^{53}K, ^{82}Zn, ^{233}Fr
- Nuclear theory for comparison and prediction (?)



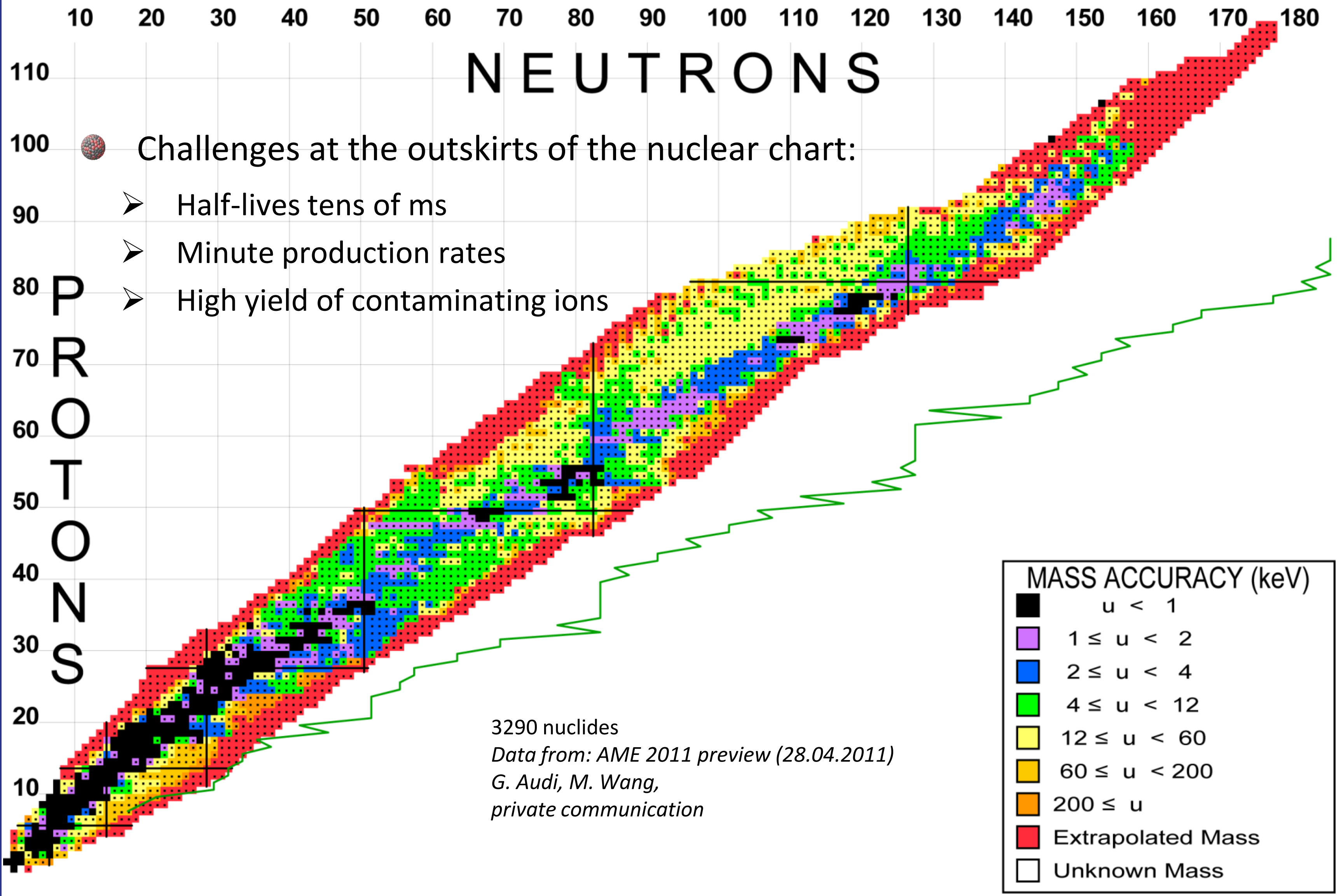
Penning alone in New York

- 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

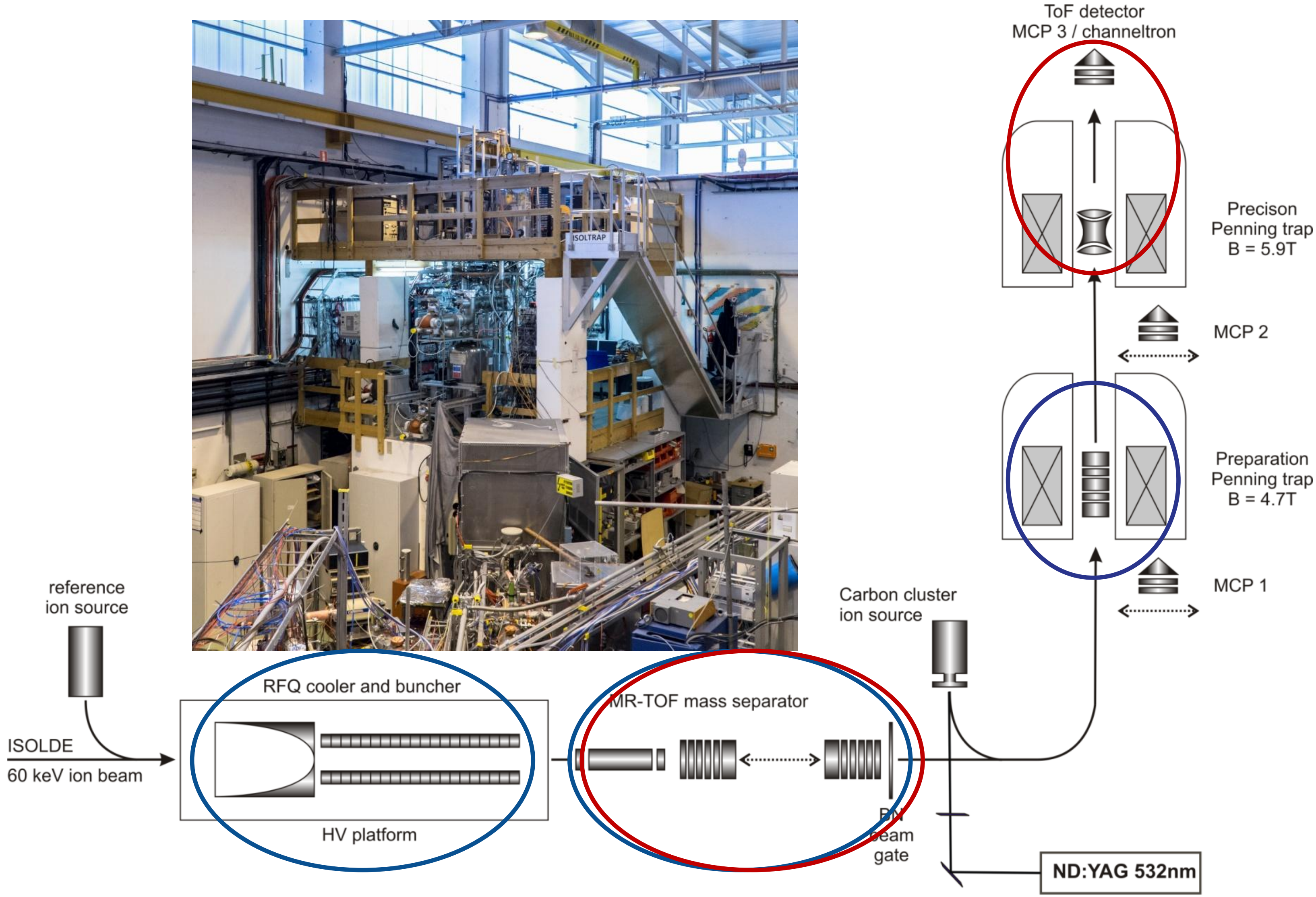
Challenges for Short-Lived Nuclides

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



3290 nuclides
Data from: AME 2011 preview (28.04.2011)
G. Audi, M. Wang,
private communication

The ISOLTRAP Experiment



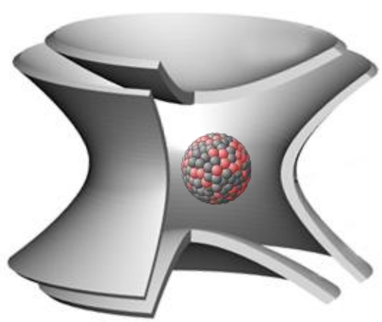
M. Mukherjee *et al.*, Eur. Phys. J A **35**, 1 (2008)

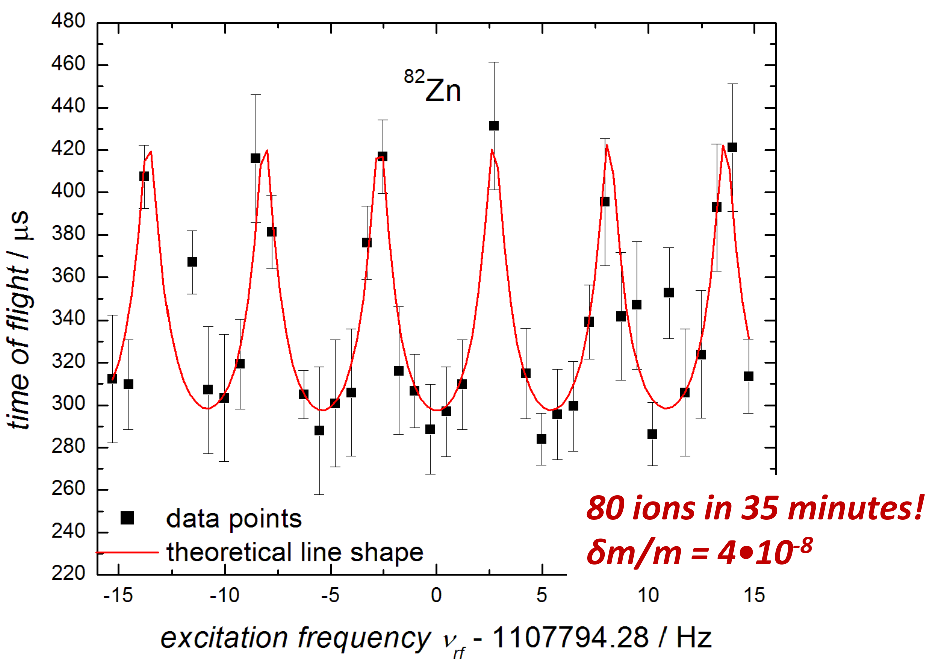
R. N. Wolf *et al.*, NIM A **686**, 82 (2012)

preparation measurement

Detection Techniques

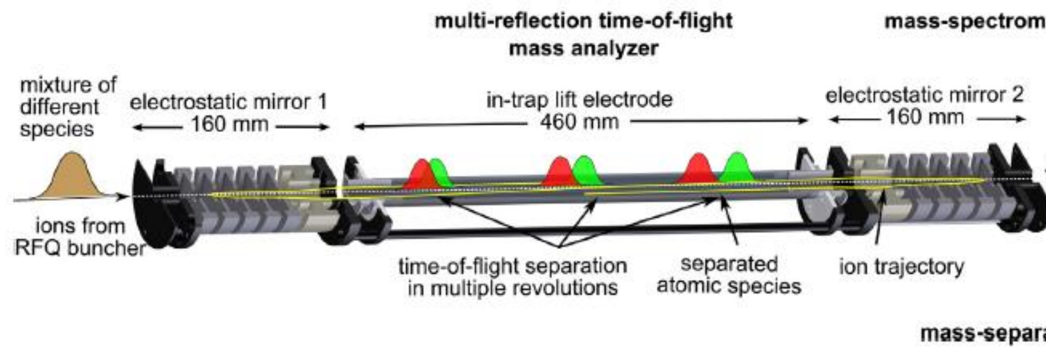
- Penning-trap mass spectrometry

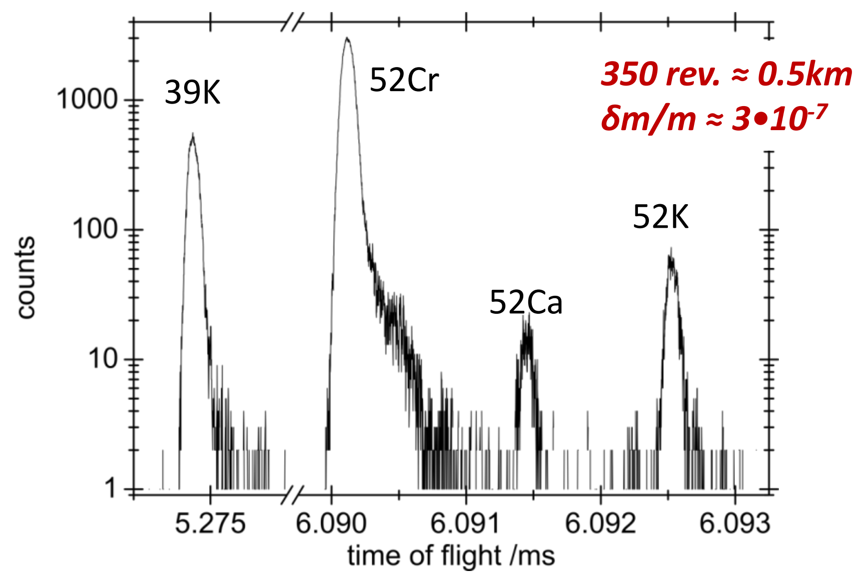




S. Kreim *et al.*, NIMB **317**, 492 (2013)

- Multi-reflection time-of-flight mass spectrometry

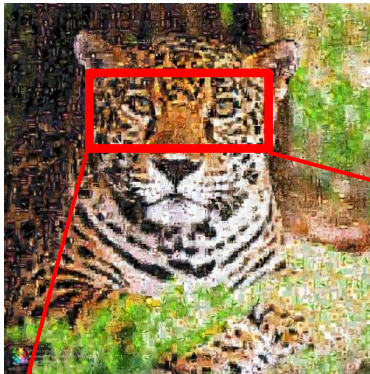




R. N. Wolf *et al.*, NIM A **686**, 82 (2012)

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

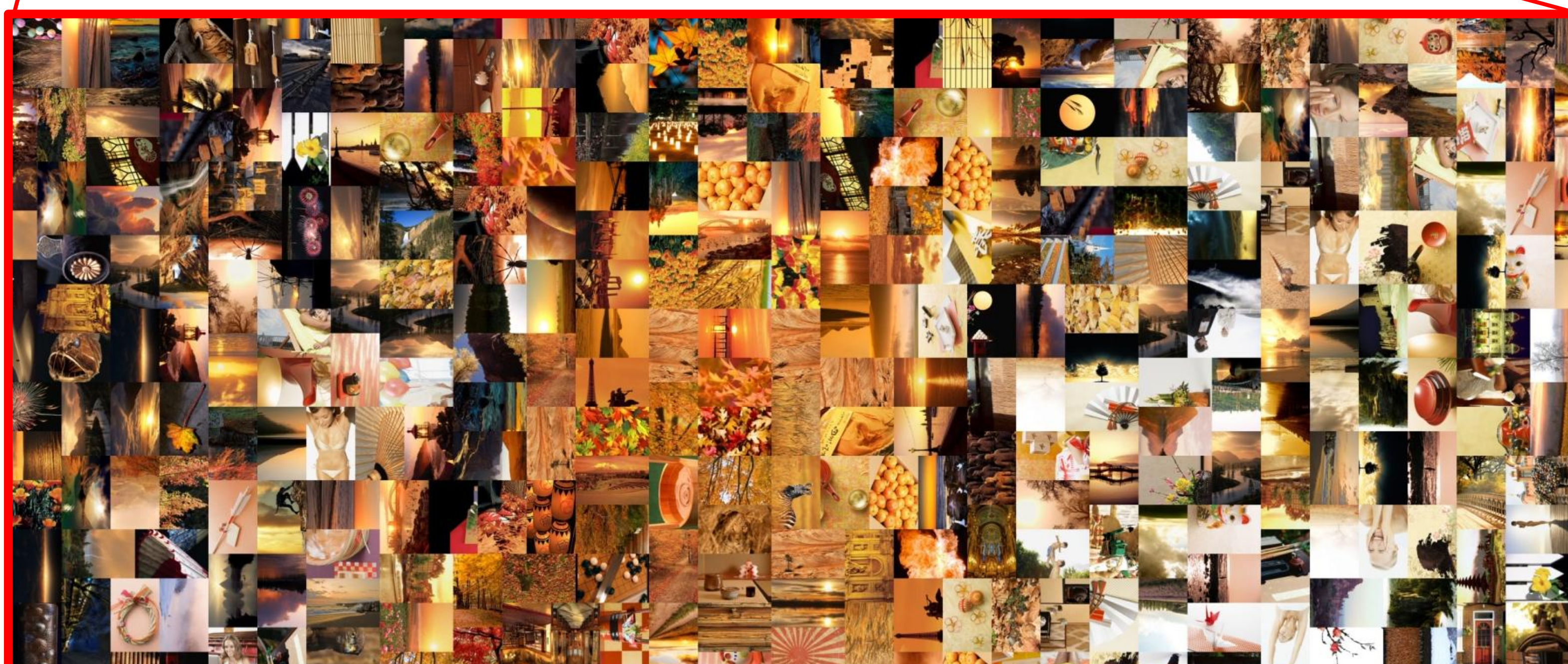
Physics from the Mass Surface



- Binding energy -> scale of GeV
  - Structural information hidden
- Apply filters -> most common two-neutron separation energy

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

  - Shell structure of nuclei
  - Identify different contributions of interaction



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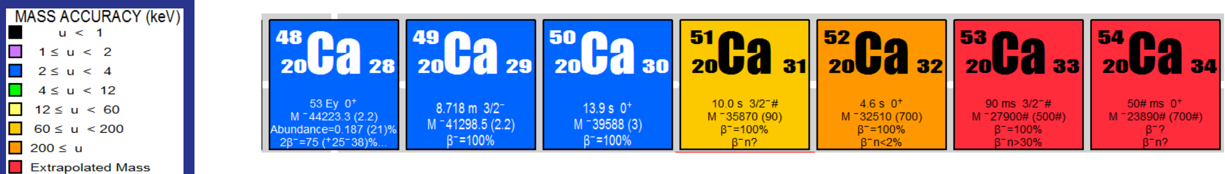
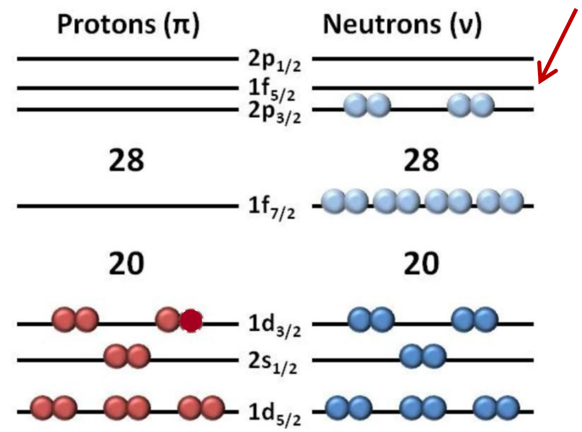
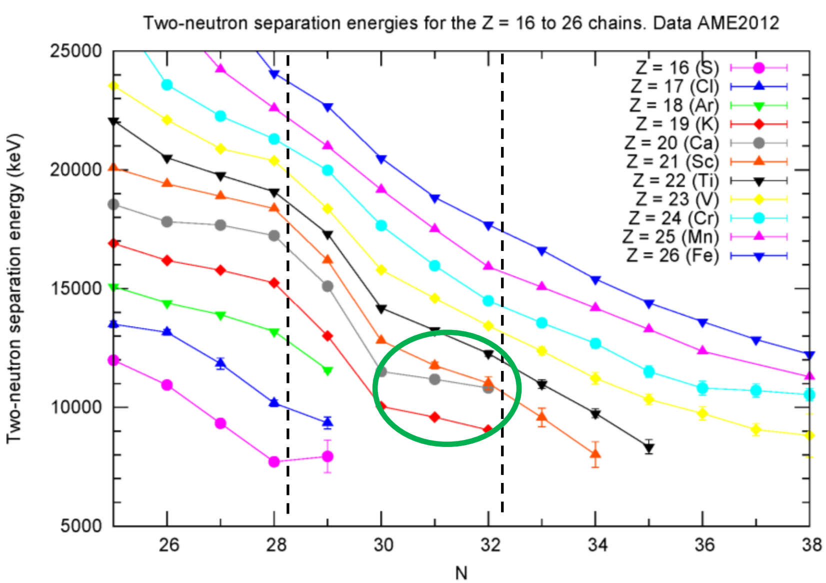
Neutron-Rich Calcium Isotopes

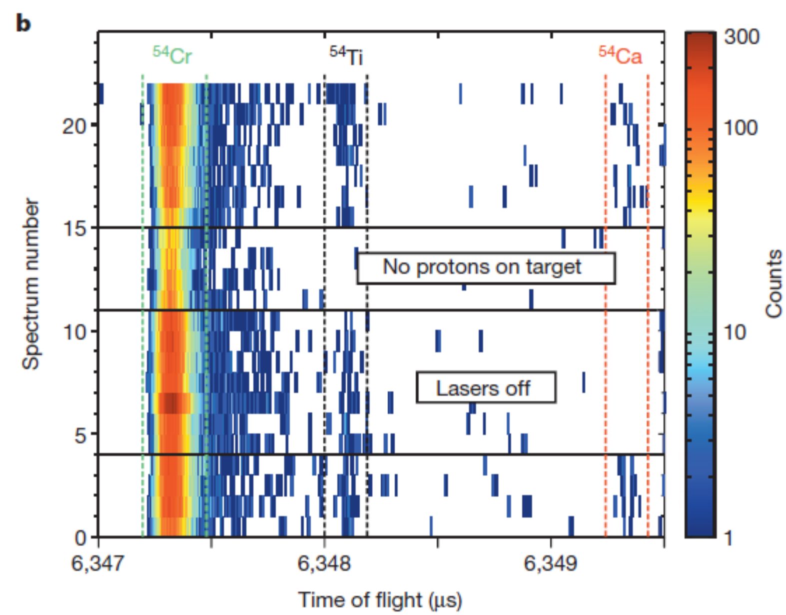




- On the mass surface, no clear signature for N=32 visible, only calcium and potassium chain show indication

- High-precision mass measurements of ^{53,54}Ca using ISOLTRAP's MR-TOF MS





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

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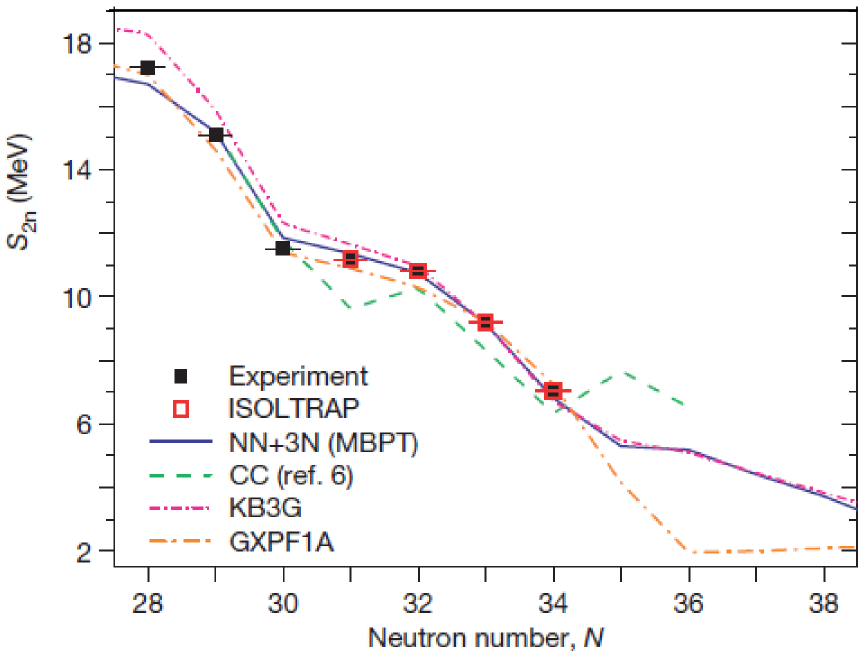
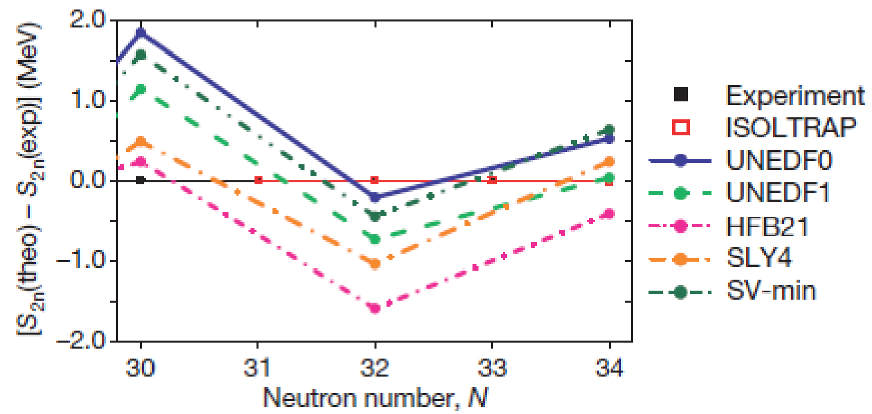
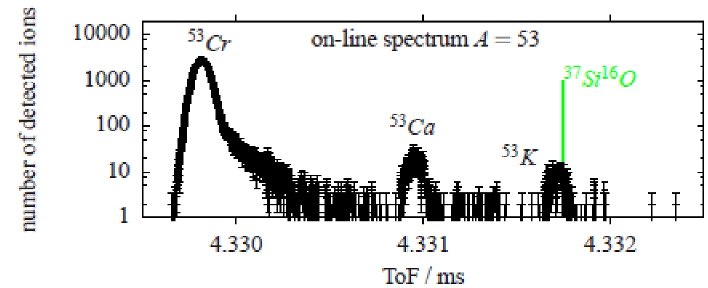




F. Wienholtz *et al.,* Nature **498,** 346 (2013)
J. Erler et al., Nature **486**, 509 (2012)
C. Forssén et al., Phys. Scr. T **152**, 014022 (2013)

Potassium Isotopes

- $^{51-53}$K masses determined with ISOLTRAP
- charge radii measured to ^{51}K
- Shell gap at *N*=32 confirmed
- Open-shell nuclei:
  - Coupled-cluster calculations predicted spin inversion and re-inversion up to ^{51}K
  - Gorkov-Green's function theory: 2- and 3-body interactions from chiral effective field theory fitted to few-body systems



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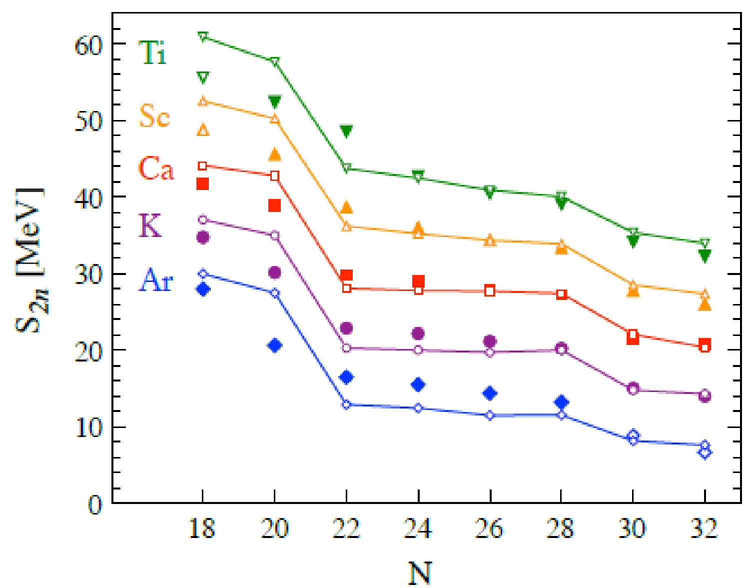
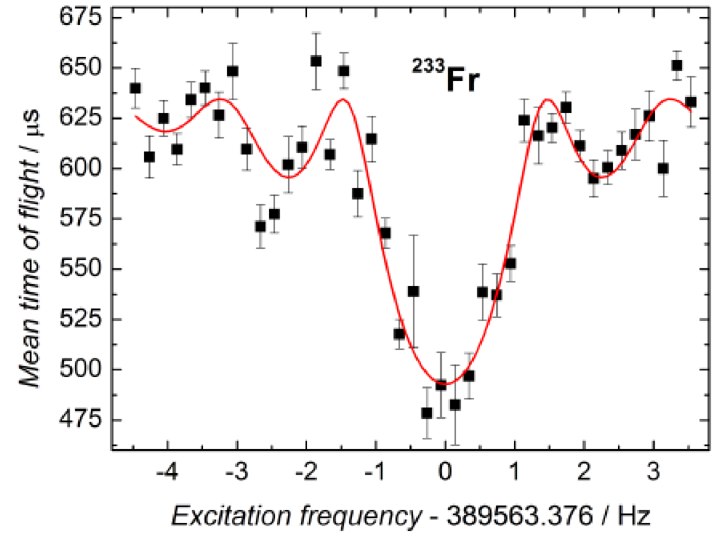


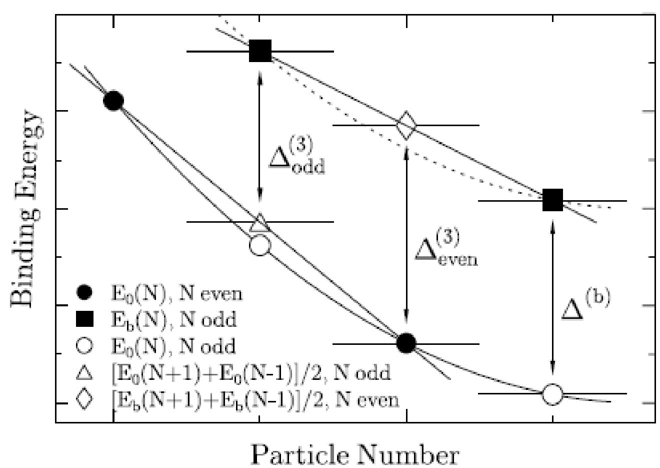
V. Somà *et al.*, arXiv:1312.2068v1 (2014)
G. Hagen , Private Communication (2013)
K. Kreim, PLB (2014)

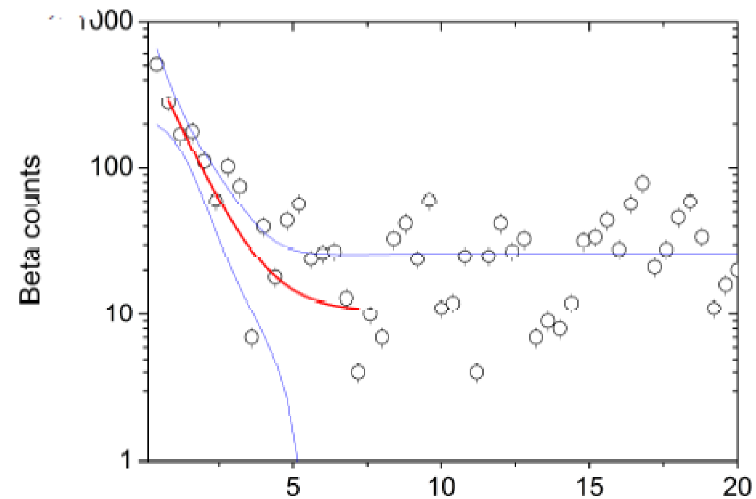
OES of Fr and Ra Isotopes

- $^{222,224,226\text{-}233}$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



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





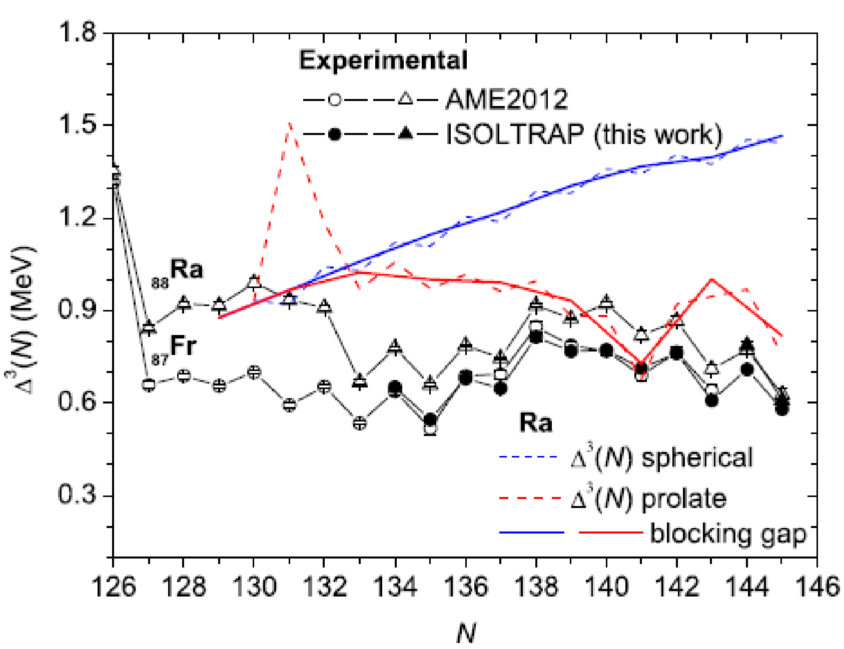
M. Bender *et al.*, EPJA **8**, 59 (2000)

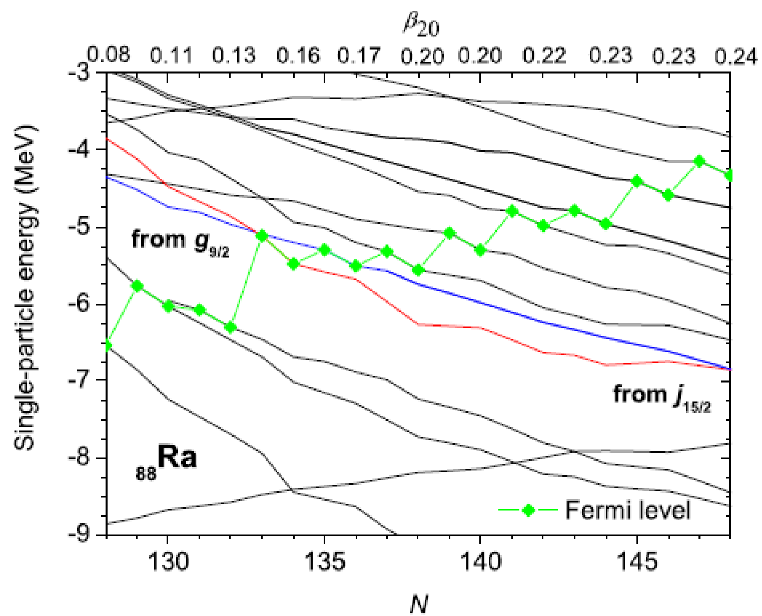
S. Kreim *et al.*, PRC (2014) submitted

Pairing Correlation and Deformation

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

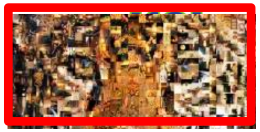
- Compare to calculations excluding pairing (HF) and including deformation (HFB) following ansatz from Satula *et al.*, PRL **81**, 3599 (1998)

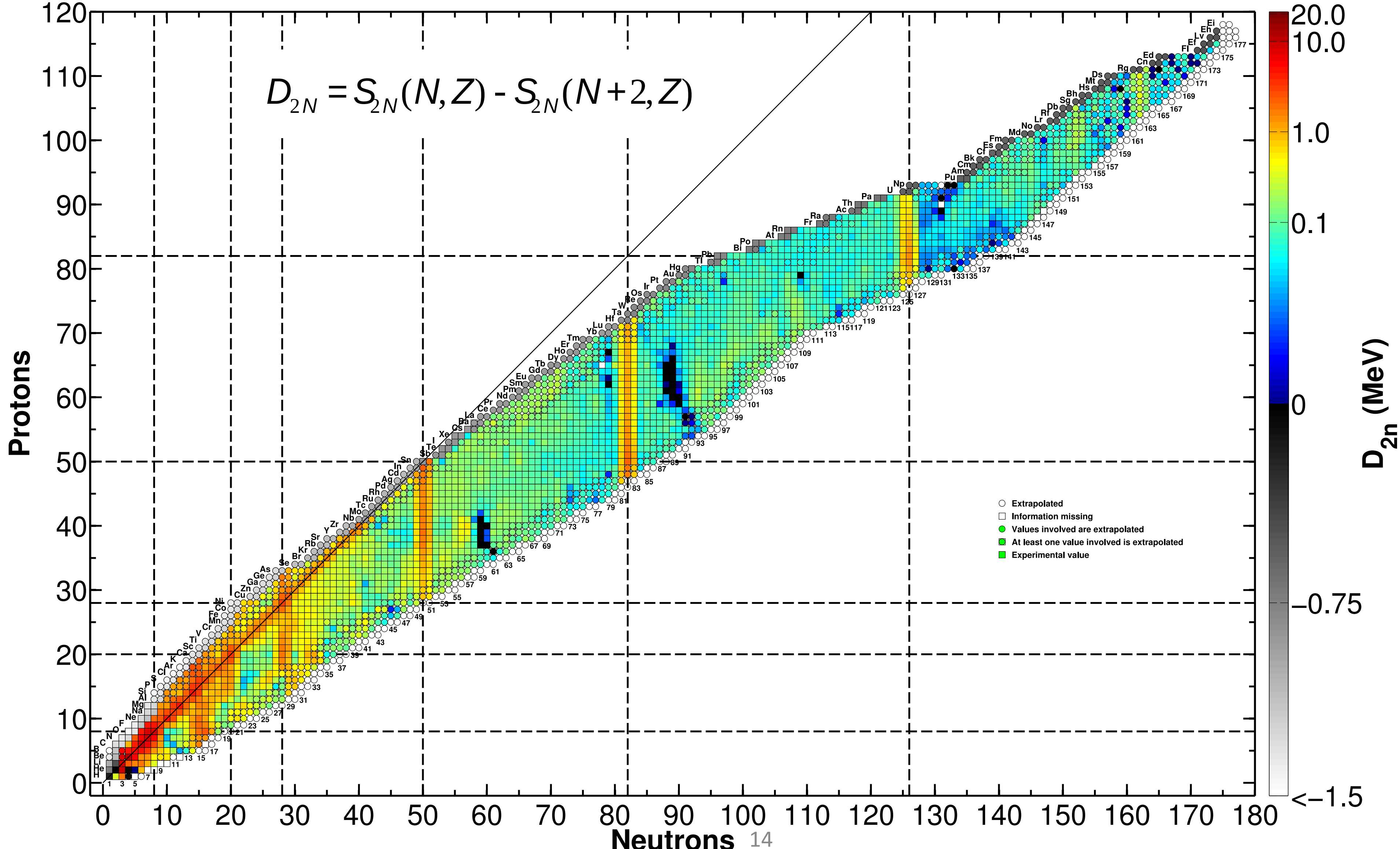




S. Kreim *et al.*, PRC (2014) submitted

Shell Gap Filter

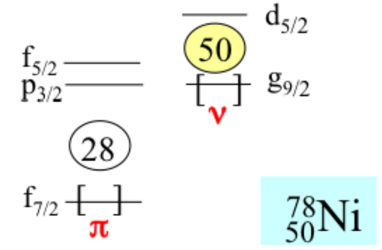


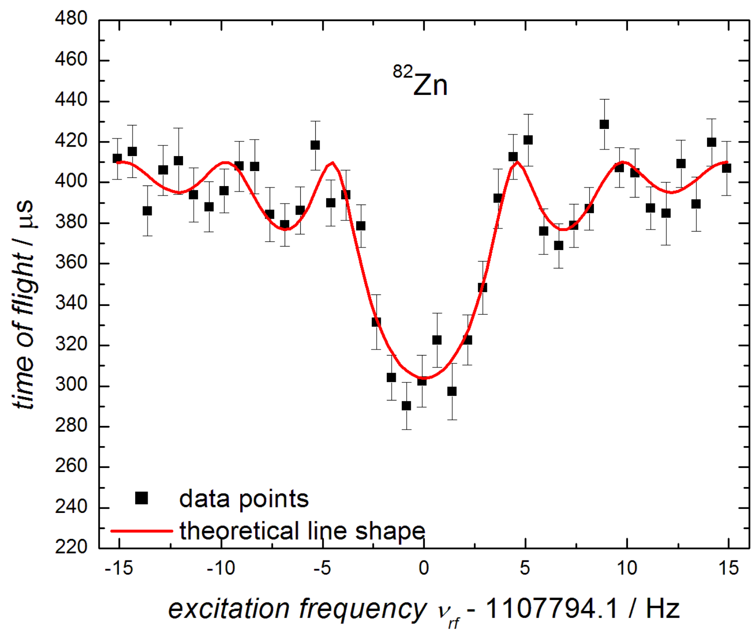


M. Wang et al., Chinese Phys. C **36**, 1603 (2012)

N=50 Shell Gap

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





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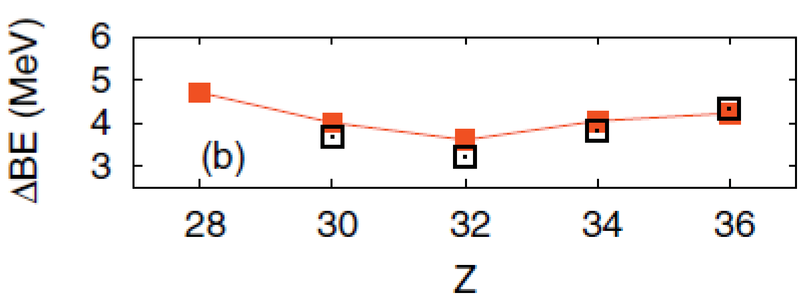
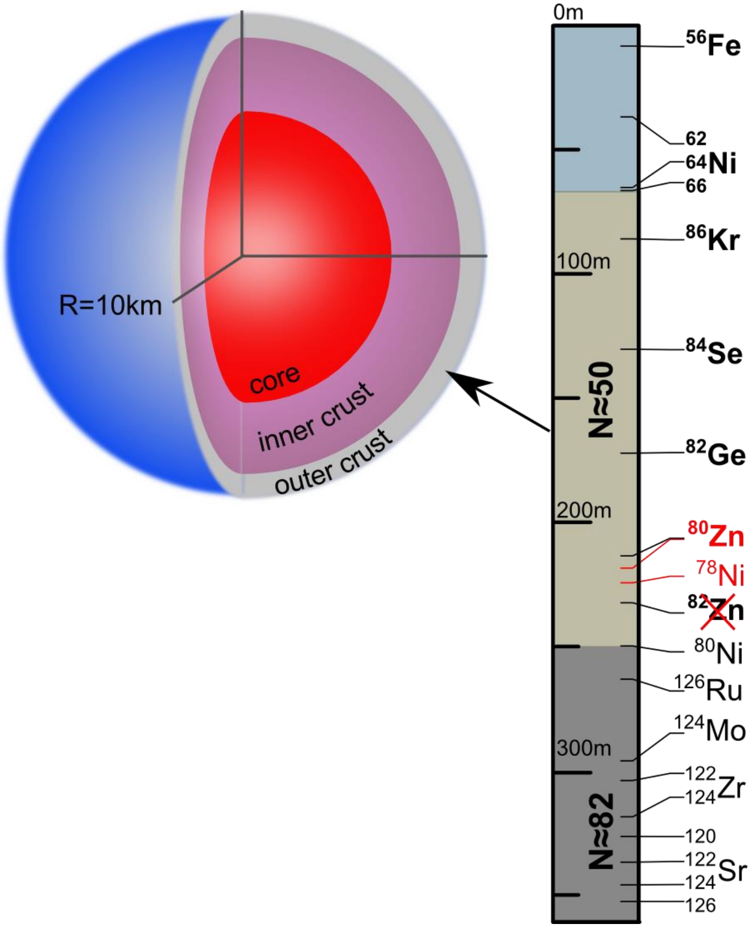


R.N. Wolf et al., PRL **100**, 041101 (2013)
K. Sieja and F. Nowacki, PRC **85**, 051301 (2012)

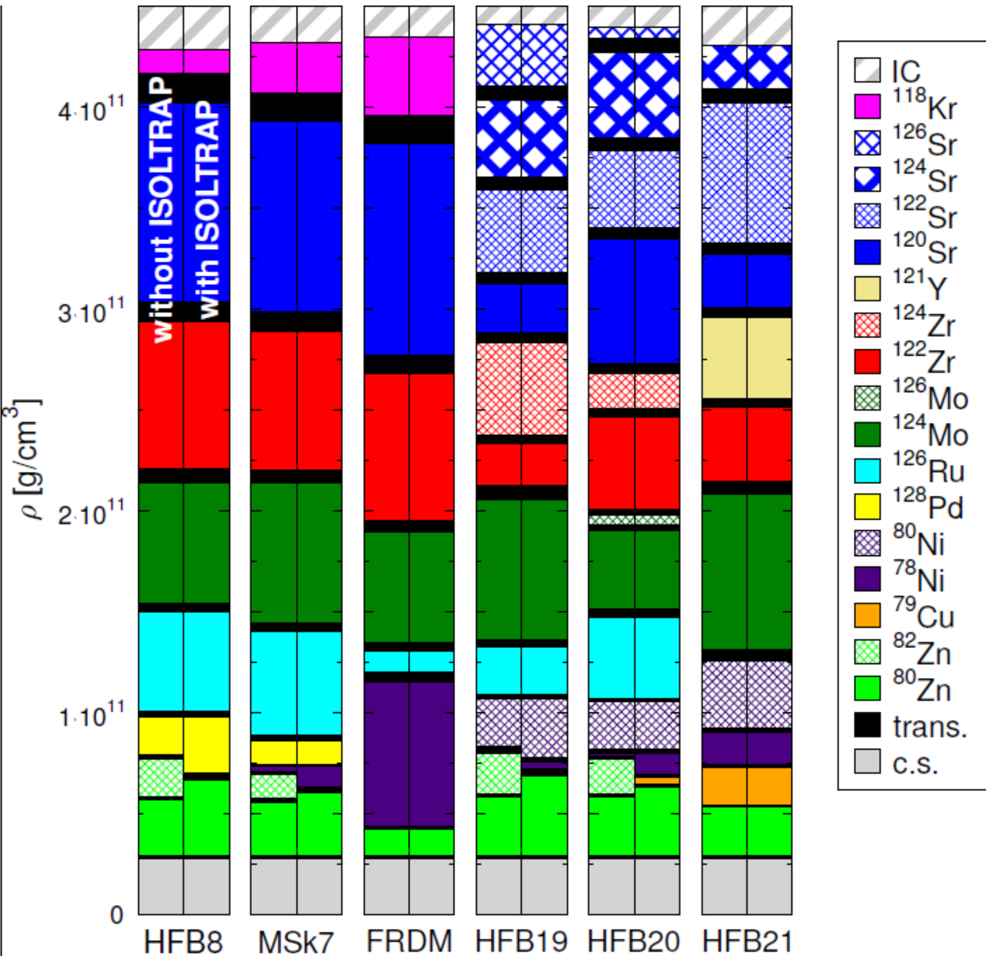
^{82}Zn and Neutron Stars

- Outer crust of neutron stars is a possible birthplace of the heavy elements
- At a given pressure, modeling composition depends mainly on the binding energy of the nucleus!
- Depth profile through experimental masses and mass models as input for equation of state
- ^{82}Zn most exotic nuclei measured for crustal composition excluded from crust
- Composition profile constrained deeper by experimental data



J. M. Pearson *et al.*, Phys. Rev. C **83** (2011)
R. N. Wolf *et al.*, PRL **110**, 041101 (2013)

Crustal Composition



- 25 different nuclear mass models have been tested and all now exclude ^{82}Zn from the outer crust of a neutron star
- Validate that up to a density of $5*10^{10}$ g/cm^3, the crustal composition is determined only by experimental data with ^{80}Zn being the corresponding nucleus
- Magic neutron shells *N*=50 and *N*=82 are the dominating effect of nuclear structure regarding the crustal composition

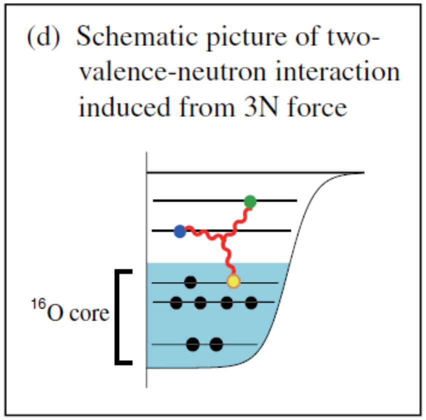
S. Kreim *et al.*, IJMS **349-350**, 63 (2013)

P. Ascher, D. Atanasov,
G. Audi, D. Beck, K. Blaum,
Ch. Böhm, G. Bollen,
Ch. Borgmann, M. Breitenfeldt,
R. B .Cakirli, T. E. Cocolios,
S. Eliseev, T. Eronen,
S. George, F. Herfurth,
A. Herlert, D. Kisler

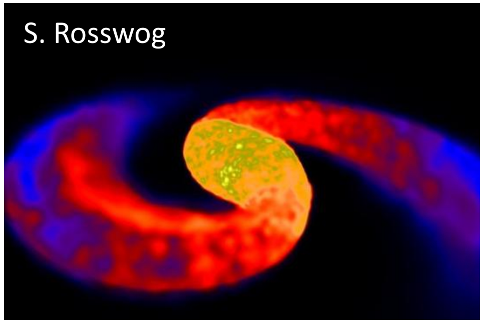
J. Kluge, M. Kowalska, S. Kreim,
Yu. A. Litvinov, D. Lunney,
V. Manea, E. Minaya Ramirez,
S. Naimi, D. Neidherr,
M. Rosenbusch, S. Schwarz,
L. Schweikhard, J. Stanja,
M. Wang, A. Welker,
F. Wienholtz, R. Wolf, K. Zuber

Conclusions

- Mass measurements with ISOLTRAP address topics of nuclear structure 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



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



- High-precision mass values constrain neutron-star models
  - ^{82}Zn most exotic nucleus yet
  - Further mass measurements desired, e.g. Pd isotopes

- The implementation of a MR-TOF MS has openend a wide range of possibilities at ISOLTRAP
  - Versatile device: mass spectrometry and in-source laser spectroscopy
  - Similar work at GSI and RIKEN

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