Answering Questions of Nuclear and Astrophysics with Mass Measurements from ISOLTRAP

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June 3rd 2014

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Physics with ISOLTRAP 2011-2014

Isomers
Magic numbers
Neutrino physics
Pairing interaction
Collective phenomena

190,193Tl
224-233Fr
223-229Rn

54Ca
53K

50
80-82Zn
99,100Rb
96,97Kr

110Cd,Pd

82

50

126

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

D. Fink et al., PRL 108, 062502 (2012)
R. N. Wolf et al., PRL 110, 041101 (2013)
Overview

\[ B(N, Z) = (Nm_n + Zm_p - m(N, Z))c^2 \]

- Measurements with relative uncertainties of $10^{-6}$ required for insight into nuclear structure
  - 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

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

- Penning-trap mass spectrometry
- Multi-reflection time-of-flight mass spectrometry

80 ions in 35 minutes!
$\delta m/m = 4 \times 10^{-8}$

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

350 rev. ≈ 0.5 km
$\delta m/m ≈ 3 \times 10^{-7}$

R. N. Wolf et al., NIM A 686, 82 (2012)
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
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 $^{53,54}\text{Ca}$ using ISOLTRAP’s MR-TOF MS.
Magic Number at $N=32$

- ISOLTRAP data on ground-state properties clearly 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

Plot omitted from online version

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Potassium Isotopes

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

\[ \text{Plot omitted from online version} \]
OES of Fr and Ra Isotopes

- 222,224,226-233 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)
**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
\[ D_{2N} = S_{2N}(N, Z) - S_{2N}(N+2, Z) \]

M. Wang et al., Chinese Phys. C 36, 1603 (2012)
$N=50$ Shell Gap

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

R.N. Wolf et al., PRL 100, 041101 (2013)
K. Sieja and F. Nowacki, PRC 85, 051301 (2012)
**82Zn 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.

- 82Zn most exotic nuclei measured for crustal composition excluded from crust.

- Composition profile constrained deeper by experimental data.

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25 different nuclear mass models have been tested and all now exclude $^{82}\text{Zn}$ from the outer crust of a neutron star.

Validate that up to a density of $5 \times 10^{10}$ g/cm$^3$, the crustal composition is determined only by experimental data with $^{80}\text{Zn}$ 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)
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

- 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 opened a wide range of possibilities at ISOLTRAP
  - Versatile device: mass spectrometry and in-source laser spectroscopy
  - Similar work at GSI and RIKEN

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

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