Nuclear Parameters from Precision Measurements with ISOLTRAP

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Nuclear Masses

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

- 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
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

spallation, fission, fragmentation of UCx targets

proton pulses 1.4GeV, 2uA

target area

control room

magnetic separators

\[ \frac{m}{\Delta m} \approx 5000 \]
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

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

Detection Techniques

- Penning-trap mass spectrometry

- Multi-reflection time-of-flight mass spectrometry

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

350 rev. $= 0.5$ km

$\delta m/m \approx 3 \times 10^{-7}$

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

Shell Gap Filter

\[ D_{2N} = S_{2N}(N, Z) - S_{2N}(N+2, Z) \]

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

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

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

K. Sieja and F. Nowacki, PRC 85, 051301 (2012)
Most Exotic Test of Shell Gap

- Size of $N=50$ shell gap for doubly-magic $^{78}\text{Ni}$?
- 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 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

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

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

Potassium Isotopes

Open-shell nuclei calculations:
- Coupled-cluster calculations predicted spin inversion and re-inversion up to $^{51}\text{K}$
- 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 $^{51}\text{K}$
- $^{51-53}\text{K}$ masses determined with ISOLTRAP
- Shell gap at $N=32$ confirmed
  - weaker compared to Ca

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

- $^{222,224,226-233,234}$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 $^{130}\text{Cd}$ determined only through beta decay

M. Hannawald et al., PRC 62, 054301 (2000)
D.T. Yordanov et al., PRL 110, 192501 (2013)
M. Wang et al., CPC 36 1603 (2012)
$N=82$ Shell Gap

- $^{129}\text{Cd}$ after 100 revolutions in MR-ToF MS
  - 1539 ions $\rightarrow \Delta m/m = 1.2 \times 10^{-7}$

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

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 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

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