Physics opportunities with atomic physics techniques to probe nuclear ground-state properties and not only ...

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Outline

- Atomic physics techniques to study radionuclides (at ISOLDE and elsewhere)
- Laser spectroscopy, polarization and beta-NMR
- Ion traps
- New applications
- Summary and outlook
ISOLDE & atomic physics techniques

- 30-60 keV ion beam
- eV energy spread and small emittance
- Possibility to bunch beam (μs bunches)
- Many fixed and travelling setups
Laser spectroscopy

Lasers allow studying **ground-state (and isomeric) properties of nuclei**, based on:

- **Atomic hyperfine structure (HFS)** (interaction of nuclear and atomic spins)
  - HFS details depend on:
    - Spin -> orbit of last proton&neutron
    - Magnetic dipole moment -> orbits occupied by p&n
    - Electric quadrupole moment -> deformations

- **Isotope shifts (IS)** in atomic transitions (change in mass and size of different isotopes of the same chemical element)
  - IS between 2 isotopes depends on:
    - difference in their masses & charge radii

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Collinear laser spectroscopy

Detection method depends on the case => optimised for best S/N ratio:
Fluorescence photons (1e6 ions/s)
Ion-photon coincidence (1e3-1e4 ions/s)
Particles: betas, ions (1e2-1e4 ions/s)
Laser polarization and $\beta$-NMR

Spin polarization:
Circularly polarized laser light
Overlap with ion beam (collinear or traps – MR-TOF or Penning/Paul trap)
Polarizations of 10-90%

beta-detected NMR:
High polarization
High efficiency: beta-particles
=>Extreme sensitivity: $1e3$ ions/s

Applications:
- Measure precisely beta-asymmetry: probe Hamiltonian of Weak Interaction – fundamental studies (Measurement of the beta-asymmetry parameter in $^{35}$Ar with laser-polarized beam)
- Measure unknown e-m moments – nuclear structure
- Measure chemical shifts of resonances – material science and soon biology (e.g. my ERC grant starting in Oct15), Beta-NMR of Mg and Cu isotopes in ionic liquids
Collinear laser spectroscopy: nuclear structure

COLLAPS: Charge radii of Ne isotopes

Intrinsic density distributions of dominant proton FMD configurations

Open or data-analysis projects:
Ground-state properties of K-isotopes from laser and β-NMR spectroscopy
Laser Spectroscopy of Cadmium Isotopes: Probing the Nuclear Structure Between the Neutron 50 and 82 Shell Closures: discovery of ms isomers in 127,129Cd
Shell structure and level migrations in zinc studied using collinear laser spectroscopy: done up till 80Zn
Spins, Moments and Charge Radii Beyond 48Ca: preparations for 54Ca run
In-source laser spectroscopy

RILIS setup (ISOLDE Laser Ion Source):
pulsed lasers – high power, but large linewidth – best for heavy nuclei

Detection method depends on the case => optimised for best S/N ratio:
Ions - ISOLDE Faraday Cups (>1 pA) or ISOLTRAPs MR-TOF (> 10 ions)
Alphas: WINDMILL setup at LA1 or LA2 beamlines
In-source spectroscopy: nuclear structure

Changes in charge radii of heavy nuclei

Isotope shifts measured with RILIS setup (part of data shown):
Regions of deformation visible

Radii described well with mean field models

T.E. Cocolios et al., PRL 106 (2011) 052503
M. Seliverstov et al., EPJ A41(2009) 315
H. De Witte et al., PRL 98 (2007) 112502
In-source spectroscopy: atomic properties

Astatine: Last chemical element with unknown ionization potential (IP)
- atomic fingerprint, determines chemical properties

Ionization Potential determined with RILIS and detected in a Faraday cup

\[
\text{IP(At)} = 9.31751(8) \text{ eV}
\]

Outlook: improved IP predictions for element 117

S. Rothe et al., Nature Communications 4, 1835 (2013)
Ion traps

Penning traps – magnetic field
Paul traps – rf field
Cooler-buncher – rf field
Multireflection traps (electrostatic)

Ion manipulation with rf in Penning traps
Possibility of purifying the ion ensembles
ISOLTRAP: ISOLDE mass spectrometer

**From cyclotron frequency to mass**

\[
\nu_c = \frac{1}{2\pi} \frac{q}{m} B
\]

Relative mass uncertainty around 10\(^{-8}\)

**Determination of cyclotron frequency**

\((R = 10^7)\)

**Removal of contaminant ions**

\((R = 10^5)\)

**Bunching of the continuous beam**

10 ms, 1-10%

50 ms - 10 s,
100%

50 ms - 1 s,
100%

10-100 ms, >50%

**Beta- and gamma decay studies**
Multi-Reflection Time-of-Flight Mass Separator

TOF for ions of the same energy but different mass differs

Electrostatic potentials

Typical trapping time: 25-75 ms
Production: >10-100 ions/s
m/Δm (FW) > 10^5
Suppression factor 10^4
Mass uncertainty < 50 keV

**Multi-Reflection Time-of-Flight Mass Separator**

- **Lifetime measurements:**
  - Mass separation and observation of ion number vs trapping time (e.g. $^{82}\text{Zn}$)

- **Soon:** laser spectroscopy on trapped ions
  - Long laser-ion overlap
  - Space for in-trap photon and particle detectors
Masses: nuclear structure

Ion counts behind electrostatic trap

Ion purification by different time of flight


Two-neutron separation energy (MeV):
Sudden drop points to a shell closure

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Sudden drop points to a shell closure

Mass models
After several attempts at ISOLTRAP and elsewhere

- Combined ISOLDE technical know-how:
  - neutron-converter and quartz transfer line (contaminant suppression)
  - laser ionisation (beam enhancement)

Neutron-star composition:
- Test of models
- 82Zn is not in the crust

ISOLDE cooler-buncher ISCOOL

- Linear rf trap filled with He gas
  - Ion bunching
  - Lowering of ion emittance

- Increase in laser-spectroscopy sensitivity up to 1e4
  - Photon observation only when ion bunch arrives (e.g. K)

- Optical pumping with lasers
  - Change in atomic-state occupation – used for laser spectroscopy (e.g. Mn)
  - Soon: preparation of spin-polarized beams?
Trap- or laser-assisted decay studies

- Decay stations behind ISOLTRAP and CRIS
- Isobar and even isomer purification in an ion trap or by laser ionisation
- Studies of radionuclides suffering from contamination

Recent and open projects at ISOLTRAP:
Mass measurements and decay studies on isobarically pure neutron-rich Hg and Tl isotopes
Study of the odd-A, high-spin isomers in neutron-deficient trans-lead nuclei with ISOLTRAP
Trap-assisted studies of Po isotopes

Open projects at CRIS:
Purification and studies of Po isotopes
Summary and outlook

RIB (ISOLDE) atomic physics techniques

- Laser spectroscopy, polarization and beta-NMR:
  - Nuclear structure
  - Atomic properties
  - Material science and biology

- Ion traps
  - Masses – nuclear structure and astrophysics

- New (unexpected) techniques and applications:
  - Electrostatic traps
  - Beam purification and isomer-selectivity with lasers and traps

- More classical and new applications awaiting, e.g.
  - laser spectroscopy in electrostatic traps
  - beta-NMR in liquids for biological applications
Thank you for your attention
Laser and β-NMR Spectroscopy

Based on the hyperfine interaction between electromagnetic moments of the nucleus with internal or external electromagnetic fields

Atomic hyperfine structure
(interaction of nuclear and atomic spins)

\[ \Delta E_{\text{HFS}} = \frac{A}{2} K + B \left( \frac{3}{4} K(K+1) - I(I+1)J(J+1) \right) \]
\[ 2(2I-1)(2J-1)I \cdot J \]

where \( K = F(F+1) - I(I+1) - J(J+1) \)

\[ A = \frac{\mu_1 B_0}{IJ} \]
\[ B = e q V_{zz}(0) \]

Isotope shifts in atomic transitions
(change in mass and size of different isotopes of the same chemical element)

\[ \delta V^{A,A'} = K_{MS} \times \frac{m_A - m_{A'}}{m_A m_{A'}} + F \times \delta \langle r^2 \rangle^{A,A'} \]

Nuclear Magnetic Resonance – NMR
(Zeeman splitting of nuclear levels)

\[ \Delta E_{\text{mag}} = -m_i g_i \mu_N B_0 + e q V_{zz} \left( \frac{3m_i^2 - I(I+1)}{4I(2I-1)} \right) \]

Isotope shift

HFS

Isotope A Isotope A’

=> Probing single-particle and collective properties
Laser spectroscopy and nuclear physics

- **Spin** (orbital+intrinsic angular momentum), **parity** ($I^\pi$)
- Nuclear **$g$-factor** and **magnetic dipole moment** ($g_I$ and $\mu_I$)
- Electric quadrupole moment ($Q$)
- **Charge radius** ($\langle r^2 \rangle$)

**Give information on:**
- Configuration of neutrons and protons
- Size and form of the nucleus

<table>
<thead>
<tr>
<th>$I^\pi$</th>
<th>$g_I$ and $\mu_I$</th>
<th>$Q$</th>
<th>$\langle r^2 \rangle$</th>
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</thead>
<tbody>
<tr>
<td>$1/2^+$</td>
<td>$</td>
<td>l^p=2^+\mu = +0.54$</td>
<td>$Q=0$ spherical</td>
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<td></td>
<td>0d$_{3/2}$</td>
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<td>0d$_{5/2}$</td>
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<tr>
<td>$3/2^+$</td>
<td>$</td>
<td>l^p=2^+\mu = +1.83$</td>
<td>$Q&gt;0$ prolate</td>
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- Pairing
CRIS

Collinear Resonant Ionisation Spectroscopy

High sensitivity, lower resolution -> perfect for heavy ions

5. Ions deflected on to decay spectroscopy station

6. Alpha-gamma coincidences used to identify the decay of $^{204g, m}\text{Fr}$ to $^{200}\text{At}$

First physics experiment in 2011: HFS and decay of $^{207}\text{Fr}$

Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes
**Weak Interaction Trap for Charged particles** -> fundamental studies

**Goal:** determine $\beta\nu$ correlation for $^{35}\text{Ar}$ with $(\Delta a/a)_{\text{stat}} \leq 0.5\%$

-> energy spectrum of recoiling ions with a retardation spectrometer

Use a Penning trap to create a small, cold ion bunch

First high-statistics run in Nov 2011 (data analysis ongoing)

**Recent experiment:**

IS433: Search for new physics in beta-neutrino correlations using trapped ions and a retardation spectrometer

M. Tandecki et al., NIM A629 (2011) 396
S. Van Gorp et al., NIM A638 (2011) 192
Nuclei production at ISOLDE

$1 \text{ GeV } p$

$^{238} \text{U}$

$^{201} \text{Fr}$

$^{11} \text{Li}$

$^{143} \text{Cs}$

$^{201} \text{Fr}$

$^{11} \text{Li}$

$^{143} \text{Cs}$
Production process

- **Be14**: 4.35 ms
  - 0+
  - b, n, b 2n, ...

- **Li11**: 8.5 ms
  - 3/2-
  - b, n, b 2n, ...

- **Li12**: 0.3 MeV
  - 0+

- **He10**: 0.3 MeV
  - 0+

**Layout Diagram**
- **Hot Cell**
- **Robot Control**
- **Robots**
- **GPS Target**
- **Proton Beam**
- **GPS Separator**
- **Control Room**
- **HV Platform**
- **COLLAPS COMPLIS**
- **LITRAP**

**Time Table**
- **B13**: 17.36 ms
  - 3/2-
  - n

- **B14**: 13.8 ms
  - 2-
  - n

- **B15**: 10.5 ms
  - n

- **B16**: 200 Ps
  - 0-

- **B17**: 5.08 ms
  - 3/2-

- **Be12**: 23.6 ms
  - 0+
  - n

- **Li11**: 8.5 ms
  - 3/2-
  - b, n, b 2n, ...

- **Li12**: 0.3 MeV
  - 0+

- **He10**: 0.3 MeV
  - 0+

- **CN**: 5730 y
  - 0+
  - n

- **C13**: 2.449 s
  - 1/2+

- **C14**: 0.747 s
  - 0+

- **CN**: 193 ms
  - 0+

- **CN**: 95 ms
  - 0+

- **CN**: 46 ms
  - 0+
Facility photos
ISOLDE experimental setups
COLLAPS – laser spectroscopy
**RILIS**

- **Resonant Ionisation Laser Ion Source**: one way to ionise produced atoms
- Nd: YAG pumping dye or Ti:Sa lasers, with possibility of doubling to quadrupling
- Atomic physics: Used to determine ionisation schemes and ionising potential of chemical elements with no stable isotopes (e.g. polonium, astatine)
- Nuclear physics: laser spectroscopy -> electromagnetic ground state properties

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- Dye lasers with 2\textsuperscript{nd} harmonic generation and UV pumping option
- Narrow band dye laser for high resolution spectroscopy or isomer selectivity
- Nd:YAG laser for dye pumping or non resonant ionization
- Nd:YAG pump laser for the Ti:Sa lasers
- 3 Ti:Sa lasers
- Harmonic generation unit for Ti:Sa system
COLLAPS – laser spectroscopy

- Ion beam: $E_{\text{kin}} \approx 60$ keV
- Laser beam: fixed frequency
- Electrostatic deflection
- Electrostatic lenses for retardation
- Charge exchange cell (Na)
- Excitation & observation region
- Photo multiplier
Beta particles (e-, e+) can be used as a detection tool, instead of rf absorption (beams down to 1000 ions/s can be studied)

Measured asymmetry:

\[ A = \frac{N(0^\circ) - N(180^\circ)}{N(0^\circ) + N(180^\circ)} \]

Results:
Magnetic and electric moments of nuclei (position of last nucleons, shapes)