Nuclear structure studies via precision mass measurements

Anu Kankainen
Nuclear structure via mass measurements

- Evolution of shell gaps
- Onset of deformation
- Nucleon pairing energies
- IMME, isospin symmetry
- Single-particle energies
- Shape coexistence
- ISOMERS

IGISOL facility in the JYFL Accelerator Laboratory
JYFL Accelerator Laboratory

FOUR ACCELERATORS

K-130 CYCLOTRON

MCC-30/15 CYCLOTRON

1.7 MV PELLETRON

VARIAN eLINAC2100

University of Jyväskylä (JYU)
Jyväskylä, Finland

JYU. 2 FAST 4 JYU? #jyflacclab

JYFL Accelerator Laboratory
@jyflacclab
IGISOL facility at JYFL Accelerator Laboratory
IGISOL (Ion Guide Separator On-Line)

- a fast and universal method to produce radioactive beams

J. Ärje, J. Äystö et al., PRL 54 (1985) 99

PRODUCTION METHODS:
- Fusion-evaporation
- Heavy-ion fusion-evaporation
- Proton/deuteron-induced fission
- Multinucleon transfer (in progr.)

IGISOL-4:

JYFLTRAP – a cylindrical double Penning trap at IGISOL

(1) PURIFICATION TRAP - Selecting the ions

Mass-selective buffer gas cooling technique

Ion’s cyclotron resonance frequency:

\[ \nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m} \]

B with a reference ion:

\[ m = \frac{\nu_c^{\text{ref}}}{\nu_c} (m_{\text{ref}} - m_e) + m_e \]

(2) PRECISION TRAP - Mass measurements

Time-of-Flight Ion Cyclotron Resonance (TOF-ICR) technique

\[ v_c = \nu_+ + \nu_- = \frac{qB}{2\pi m} \]

mass
Nuclides measured with JYFLTRAP

JYFLTRAP:
- Over 340 nuclides measured
  ~100 neutron-deficient
  ~220 neutron-rich
  ~20 stable
- More than 50 isomeric states
- Typical precisions: ~10 ppb
Neutron-rich rare-earth isotopes
Neutron-rich rare-earth isotopes

- 21 rare-earth isotopes measured
- 14 masses measured for the first time
- Mainly TOF-ICR, recently also PI-ICR
- Campaign I: M. Vilén et al., PRL 120, 262701 (2018)
- Campaign II: in preparation

Motivated by the rare-earth abundance peak in the astrophysical r process
Local maximum at $N=100$ - deformed shell closure?

$^{164}\text{Gd}$ ($N=100$) more rigid than $^{160,162}\text{Gd}$

Change in structure at $N=98$?
Two-neutron separation energies $S_{2n}$

Onset of deformation

No change at N=100

No clear indication of a subshell closure at N=100 based on two-neutron separation energies

$^{163}\text{Gd g.s. measured}$

M. Vilén et al., PRL 120, 262701 (2018)
Neutron separation energies $S_n$

Less odd-even staggering (weaker pairing) than predicted by the models

Lower for $N = 96, 98, 100, 102$
Higher for $N = 97, 99, 101$
Neutron pairing

\[ D_n(N) = (-1)^{N+1}[S_n(Z, N + 1) - S_n(Z, N)] = 2\Delta^3(N) \]

Empirical neutron pairing gap or odd-even staggering parameter

Experimental **neutron pairing weaker** than predicted by theoretical models when approaching the midshell!

M. Vilén et al., PRL 120, 262701 (2018)
Nuclei close to $^{78}\text{Ni}$
Mass measurements close to N=40 and N=50

Measured several new isotopes close to N=40 and N=50 at JYFLTRAP

L.C. Canete, S. Giraud, A. Kankainen, B. Bastin et al., in preparation
Phase-Imaging Ion Cyclotron Resonance technique (PI-ICR): resolving low-lying isomers

**JYFLTRAP: PI-ICR, t\textsubscript{acc} = 200 ms**

**JYFLTRAP: TOF-ICR, T\textsubscript{RF} = 1120 ms**

**JYFLTRAP: estimate for T\textsubscript{1/2}**

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There are two states!

**76\textsuperscript{Cu}**

<table>
<thead>
<tr>
<th>NUBASE 2016</th>
<th>(J^\pi = (1,3))</th>
<th>(T\textsubscript{1/2} = 1.27(30)) s</th>
<th>(E^* = 0#(200#)) keV</th>
</tr>
</thead>
</table>

| Mass of 76\textsuperscript{Cu} (638 ms state; ISOLTRAP): C. Guenaut et al., PRC 75, 044303 (2007); A. Welker et al., PRL 119, 192502 (2017). | | | |

**JYFLTRAP: estimate for T\textsubscript{1/2}**

- **Two half-lives (TRISTAN):** J. A. Winger et al, PRC 42, 954 (1990).
### Systematics of Cu isotopes

*Vingerhoets et al., PRC 82 (2010) 064311*

<table>
<thead>
<tr>
<th></th>
<th>68 Cu&lt;sub&gt;39&lt;/sub&gt;</th>
<th>70 Cu&lt;sub&gt;41&lt;/sub&gt;</th>
<th>72 Cu&lt;sub&gt;43&lt;/sub&gt;</th>
<th>74 Cu&lt;sub&gt;45&lt;/sub&gt;</th>
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<tbody>
<tr>
<td>6-826</td>
<td>6-722</td>
<td>3-564</td>
<td>(3-) 611</td>
<td>6-451</td>
</tr>
<tr>
<td>3-563</td>
<td>3+443</td>
<td>1+573</td>
<td>645 2-</td>
<td>2+662</td>
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<tr>
<td>6-92</td>
<td>6-290</td>
<td>1+297</td>
<td>1+438</td>
<td>2+538</td>
</tr>
<tr>
<td>2+90</td>
<td>2+162</td>
<td>3+101</td>
<td>2+264</td>
<td>(2) 452</td>
</tr>
<tr>
<td>2+ GS JUN45</td>
<td>2+ GS jj44b</td>
<td>3- GS JUN45</td>
<td>6-GS Expt.</td>
<td>1+62</td>
</tr>
</tbody>
</table>

76 Cu?
Shape coexistence in the $^{78}\text{Ni}$ region: $^{79}\text{Zn}^m$

Isomeric state with an exceptionally large root-mean-square radius and spin $1/2^+$

Collinear laser spectroscopy at ISOLDE

Excitation energy from masses:
$$E_x = [m(\text{isomer}) - m(\text{g.s.})]c^2$$

JYFLTRAP TOF-ICR measurements

X. F. Yang et al. PRL 116, 182502 (2016)
Systematics of N=49 isotones

Shell evolution when moving further away from stability

\[ N = 49 \text{ Isotones} \]

- low-lying intruder states (2h-1p)

\[ \begin{align*}
1/2^+ & \quad 1100(150) \\
1/2^- & \quad 896 \\
5/2^+ & \quad 711 \\
5/2^- & \quad 679 \\
5/2^+ & \quad 582 \\
1/2^+ & \quad 540 \\
1/2^- & \quad 228 \\
1/2^+ & \quad 1430 \\
5/2^+ & \quad 1140 \\
1/2^- & \quad 304 \\
1/2^- & \quad 388
\end{align*} \]

\[ \begin{align*}
9/2^+ & \quad 0 \\
79^{30}_{49} \text{Zn} & \quad 81^{32}_{49} \text{Ge} \\
9/2^+ & \quad 0 \\
83^{34}_{49} \text{Se} & \quad 85^{36}_{49} \text{Kr} \\
9/2^+ & \quad 0 \\
87^{38}_{49} \text{Sr} & \quad 0
\end{align*} \]

X. F. Yang et al., PRL 116, 182502 (2016)
N=40 subshell closure

- Measurements of $^{67}$Fe and $^{69,70}$Co at JYFLTRAP
- N=40 subshell closure below $^{68}$Ni weak
- Previous measurements of $^{68}$Co and $^{69}$Co [Izzo et al., PRC 97, 014309 (2018)] most likely measured the isomer, not the ground state → anomaly in the $S_{2n}$ plot
- Ground and isomeric states determined for $^{69}$Co at JYFLTRAP → location of the 1/2- intruder state at N=42

L. Canete, S. Giraud, A. Kankainen, B. Bastin et al., submitted
Nuclei close to $^{132}$Sn
Neutron-rich silver isotopes

**ENSDF**

<table>
<thead>
<tr>
<th>State</th>
<th>Energy (keV)</th>
<th>Half-life (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6⁻)</td>
<td>129.8</td>
<td>9.3</td>
</tr>
<tr>
<td>(3⁺)</td>
<td>47.9</td>
<td>20</td>
</tr>
<tr>
<td>(0⁻)</td>
<td>0</td>
<td>230</td>
</tr>
</tbody>
</table>

$^{116}$Ag

- $Z=40$ subshell closure
- Comparison to shell model predictions

**Measurement campaign at the IGISOL facility 2018 - 2019**

→ Excitation energies and more accurate ground-state mass values (PI-ICR)
→ Spins of the states (laser spectroscopy)
\( ^{128}\text{In} \) and \( ^{130}\text{In} \) studied with TOF-ICR and PI-ICR

Close to \(^{132}\text{Sn}\)

\[
^{130}\text{In}: (\pi 0 g_{9/2})^{-1} (\nu 0 h_{11/2})^{-1} \\
^{128}\text{In}: (\pi 0 g_{9/2})^{-1} (\nu 0 h_{11/2})^{-3}
\]

All three states in \(^{130}\text{In}\) resolved and measured with PI-ICR
Isospin symmetry
Isobaric Multiplet Mass Equation at A=52

Charge-independence

\[ T_z = \pm \frac{1}{2} \]

JYFLTRAP: 
52Co (g.s.+m)  
52Fe, 52Mn

\[ d = 6.0(32) \text{ keV} \]

Conclusions: Compatible with \( d=0 \)
No big changes above \( A=40 \)

Isospin symmetry in the heavier mass region

- Precision measurements of $T_Z=+1$ nuclei: $^{82}$Zr, $^{84}$Nb, $^{86}$Mo, and $^{88}$Tc
- $^{88}$Tcm and $^{89}$Ru ($T_Z=+1/2$) measured for the first time
- $^{89}$Ru more bound than predicted in AME16
- MDE predictions for $^{82}$Mo and $^{86}$Ru also more bound and more precise than AME16 extrapolations

M. Vilen et al., to be submitted
Summary and outlook

- Penning traps are versatile tools to study nuclear structure via nuclear binding energies
- PI-ICR method opens new possibilities to study low-lying isomeric states unreachable with other techniques
- MR-TOF to be installed before JYFLTRAP later this year → decay spectroscopy with purified beams (MONSTER) → mass measurements
Acknowledgements

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