High-Resolution Laser Spectroscopy for the Study of Exotic Nuclear Properties

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Nuclear structure of exotic isotopes

- Exotic phenomena near dripline
- Nuclear astrophysics
- Super heavy element

- Radioactive ion beam
- Experimental investigation
- Theoretical development

Nuclear Reaction; Decay spectroscopy; Mass measurement; laser spectroscopy...
World-wide laser spectroscopy setups

- **VITO**: M. Kowaska (28081)-Mon
- **CRIS**: K. Flanagan (28014)-Tue

**Nuclear properties**
- Nuclear properties

**Laser ion source**
- Laser ion source

**Application**
- Application

**Operation**
- operation

**Under construction/test**
- under construction/test

**Planned**
- planned
Achievements until Now

- **Exotic phenomenon** (halo, shell evolution, deformation…)
  
  - Predicted nuclei
  - Observed nuclei ($T_{1/2}>500\text{us}$)
  - Nuclei studied with laser spectroscopy
  - Stable nuclei

*Radioactive molecules*

- **Heavier mass**
- **Heavier mass**
- **Deformation N=60**
- **Deformed 1/2+ intruder g.s in $^{31}\text{Mg}$**
- **Deformed 1/2+ intruder isomer in $^{79}\text{Zn}$**
- **New isomers in $^{101}\text{In}$ -- coming soon**

- **ISOLDE, IGISOL, GSI, TRIUMF, ATLAS, GANIL, NSCL, RIKEN, …….**

- **Shapes (Pb)**

- **No: M. Block: plenary(27116)-Thu**
- **Hg: S. Sels (27990)-Thu**
- **Ir: S. Mukai(27328)-Mon**

- **Halo**
- **B: B Maß (27368) - Thu**
Contents

◆ Hyperfine structure
  - Ground state properties
  - Link to nuclear structure

◆ High precision laser spectroscopy at ISOLDE
  - Collinear laser spectroscopy
  - Collinear resonance ionization spectroscopy

◆ Recent highlights in different mass region
  - Ca region ($^{52}$K at CRIS)
  - Ni region ($^{79}$Zn at COLLAPS)
From Atoms to Nuclei

### Electronic energy level structure

<table>
<thead>
<tr>
<th>THz</th>
<th>eV</th>
<th>GHz</th>
<th>eV</th>
<th>MHz</th>
<th>eV</th>
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<td>~508</td>
<td>2.1</td>
<td>~500</td>
<td>~10^{-3}</td>
<td>~200</td>
<td>~10^{-6}</td>
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</tbody>
</table>

Only in HFS precision level, nuclear information are involved

\[ l \quad J = l + s \quad F = J + I (nuclear spins) \]
Atomic hyperfine structure

\[ \Delta E = A \cdot \frac{K}{2} + B \cdot \left\{ \frac{3K(K+1)}{4} - I(I+1)J(J+1) \right\}/\{2(2I-1)(2J-1)IJ\}, \quad K = F(F+1)-I(I+1)-J(J+1) \]

**Atomic parameters**

- Magnetic dipole HF parameter
  \[ A = \frac{\mu_i B_j}{IJ} \]

- Electric quadrupole HF parameter
  \[ B = eQV_{zz} \]

- Centroid \( \nu_0 \) => Isotopes shift
  \[ \delta \nu^{AA'} = M \frac{A'-A}{AA'} F \delta <r^2>^{AA'} \]

**Fine structure**

\[ J = l + s \]

**Hyperfine structure**

\[ F = J + I (\text{nuclear spins}) \]

\[ ^3S_1 \]

\[ ^3P_2 \]

\[ I = 3/2 \]

All quantities are deduced (nuclear) model-independently
Observables from laser spectroscopy
---and its link to nuclear information

Spin
Parity

Shell evolution/Magicity

Magnetic
Moment

Correlations/deformation

Quadrupole
Moments

Halo, astrophysics...
PRL 112, 162502 (2014); PRL 119(2017)122502

Charge
Radii

Input for nuclear theories

Providing complementary nuclear information!
Laser spectroscopy methods

- Single laser beam
  - Photon detection

- Multiple laser beams
  - Ion detection

- Collinear laser spectroscopy
- Laser spectroscopy of trapped atoms

MIRACLE: S. Sels’ Poster (27991)-Thu

HELIOS: S. Franchoo (27365)-Tue

RILIS: S. Wilkins (27534)-Thu

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Collinear Laser spectroscopy at ISOLDE

http://isolde.web.cern.ch/

Collinear resonant ionization spectroscopy

Polarized RI beam using laser techniques

beams produced using laser ion sources

Collinear laser spectroscopy
Collinear laser spectroscopy (COLLAPS)

- Collinear: High resolution
- Photon detection: Sensitivity $10^3$ pps

http://collaps.web.cern.ch/

$$\delta \nu_D = \nu_0 \frac{\delta E}{\sqrt{2eVmc^2}}$$

**Diagram:**
- RFQ Bunched Ion beam
- Laser beam
- Neutralization by charge exchange cell
- Doppler Tuning
- PMTs for photon detection
- Gated PMT signal, $10^4$ times background suppression

**Equations:**

$$\nu_{\text{transition}} = \nu_{\text{laser}} \frac{1 - \beta}{\sqrt{1 - \beta^2}}$$

$$\beta = \sqrt{1 - \frac{M_0^2c^4}{(Uq + M_0c^2)^2}}$$
Collinear ionization laser spectroscopy (CRIS)

Collinear: High resolution

Ion detection: Higher sensitivity


R.P. De Groote et al., PRL C96(2017)041302(R)
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Research interests (COLLAPS/CRIS)

Sn: PRL122(2019)192502
Cd: PRL121(2018)102501
In: PRX8(2018)041005
Cd: PRL116(2016)032501

100,132Sn: In, Sn, Sb...

68,78Ni: Ni, Cu, Zn, Ga, Ge...

48,52,54Ca: K, Sc, Ca

Zn: PLB(2019)accepted;
Cu: PRC96(2017)041302(R);
Zn: PLB771(2017)385;
Zn: PRL116(2016)182502;

Ca: NP12(2016)594;
Ca: PPC750(2015)041304(R);
K: PRL113(2014)052502;
K: PLB731(2014)97;

- http://collaps.web.cern.ch/people
- With strong collaboration with theoretical collages
Research interests (COLLAPS/CRIS)

100,132Sn: In, Sn, Sb…

68,78Ni: Ni, Cu, Zn, Ga, Ge…

48,52,54Ca: K, Sc, Ca

Unpublished
- ISOLDE
- BECOLA
- IGISOL

79\text{Zn}_{49}

52\text{K}_{33}

32\text{Ca}_{34}

Ca/Sn/In: R. F. Garcia Ruiz (29005)-Tue
In: C. Ricketts’s poster (27375)-Thu
52K @ CRIS, ISOLDE-CERN ($N=32$ magic?)

K, Ca ($Z = 19,21$): $S_{2n}$

- Rosenbusch et al., PRL, 2015

Ca ($Z = 20$): $E(2^+)$

- Steppenbeck et al., Nature 2013
- Garcia Ruiz et al., Nat.Phys (2016)
- K. Kreim et al., PLB (2014)

K, Ca ($Z = 19,21$): $\delta r^2$

- AME2012
- Meisel et al.

\[ \text{\textit{Two-neutron separation energy (MeV)}} \]

\[ \text{\textit{Neutron number}} \]

\[ \text{\textit{E(3^-)}} \]

\[ \text{\textit{E(2^+)}} \]

\[ \text{\textit{\langle r^2 \rangle (fm)}} \]

\[ \text{\textit{Neutron Number}} \]

\[ \text{\textit{K, Ca (Z = 19,21): $\delta r^2$}} \]

\[ \text{\textit{52K}} \]

- $\sim 200$ ions/s
- $\sim 10^8$ ions/s
Charge radius of $^{52}$K ($N=32$ magic?)

Cross $N = 32$ for the first time!!


The increased radii at $N = 32$ has similar trend for open-shell e.g. Mn (no magicity expected)
Theoretical development and $N = 32$ magic?

- **Ab initio CC (NNLOsat)**
  Fitting to the data of binding energies and radii of selected nuclei up to mass number $A = 25$.

- **SRG1 and SRG2**
  Fitting only to properties of $A \leq 4$

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New development is on going (G. Hagen)

- Fitting only to properties of $A \leq 4$
New isomer observed!!

79Zn @COLLAPS, ISOLDE-CERN

Few hundreds ms half life!!
Intruder isomer!!

$^{79}\text{Zn}$ Intruder isomer!!

Spins, moments!!

$79\text{Zn}$ Intruder isomer!!

A3DA-m

$^{40}\text{Ca}$

L.Xie, X.F. Yang et al., PLB(2019) Accepted

C.Wraith, X.F.Yang et al., PLB771 (2017) 385

X.F Yang et al PRL 116(2016)182502;
Shape coexistence near $^{78}$Ni

Deformation

- Quadrupole moment of $9/2^+$ gs
  => soft spherical shape
- Larger isomer shift of the $1/2^+$ state
  => a larger deformation

Shape coexistence in $^{79}$Zn!!

X.F Yang et al PRL 116(2016)182502
Structure feature near $^{78}\text{Ni}$

2016

EDITORS' SUGGESTION
Shape Coexistence Near $^{78}\text{Ni}$

Two different experiments observe nuclei with excited nuclear states that differ in shape from their ground states, so called shape coexistence. These nuclei lie close to the neutron-rich doubly-magic $^{78}\text{Ni}$ region of the nuclear chart.

X.F. Yang et al.  A. Gottardo et al.

2017

Physics Viewpoint: Doubly Magic Nickel

Two independent experiments on the isotope copper-79 confirm that its nuclear neighbor nickel-78 is indeed a doubly magic nucleus.

A. Welker et al.  L. Olivier et al.

2019

A doubly magic nucleus that has two faces

The neutron-rich nickel nucleus $^{78}\text{Ni}$ is difficult to excite and, once excited, has competing spherical and deformed shapes. These intriguing properties make $^{78}\text{Ni}$ a valuable testing ground for nuclear theory. See Article p.53

When atomic nuclei have particularly stable configurations with fully occupied energy shells, their nucleon numbers are said to be magic. However, experiments suggest that the shell-closure criterion need not apply for magic nuclei with vastly different proton and neutron numbers. The $^{78}\text{Ni}$ isotope has 28 protons and 50 neutrons — both magic numbers — making it a unique testbed to investigate this question.

Ryo Taniuchi and colleagues studied $^{78}\text{Ni}$ spectroscopically at the Radioactive Isotope Beam Factory, confirming predictions of its doubly magic nature and spherical shape despite asymmetric nucleon numbers. What came as a surprise was that the spherical shape competes with a prolate deformation. As a result, heavier nickel isotopes with 28 protons or lighter isotones with 50 neutrons should not have spherical shapes despite their magicity. The onset of shape deformations in these neutron-rich nuclei may influence the synthesis of elements heavier than iron via rapid neutron capture in the Universe.

https://doi.org/10.1038/s41567-019-0558-9
Summary and outlook!!

- Laser spectroscopy is a powerful tool to access multiple nuclear properties of exotic isotopes.
- Continues efforts are still ongoing toward a higher resolution and higher sensitivity.
- For the exotic nuclear structure study in different mass region of nuclear chart.
- Important benchmark for the test and development of state-of-art nuclear theory.

Potentially have many aspects of applications using RI beams.
“An atomic nucleus is an elephant”

Prof. Jacek Dobaczewski
Thanks for your attention!