Laser spectroscopy on nuclear ground states for charge radii and moments. Some new developments

Thanks to: Jon Billowes, Paul Campbell, Iain Moore, H.-J. Kluge

For a review up to 2002, see:
Laser Spectroscopy

The nucleus is not a point charge – the atomic energy levels are perturbed by the electric and magnetic fields at the nucleus (part per million effects)

Investigation of
  ➢ Hyperfine structure
  ➢ Isotope shifts
  ➢ Isomer shifts

provides **model-independent** data…

Optical techniques provide the sensitivity and precision required to measure these effects.
Isotope Shift (IS)  Hyperfine Structure (HFS)

Mean Square Charge Radii
\[ \delta \left< r^2 \right>^{AA'} \]

Nuclear Spin \( I \)
Magnetic Dipole Moment \( \mu_i \)
Electric Quadrupole Moment \( Q_s \)
Hyperfine Anomaly

Sample preparation is crucial…..
Nuclear reaction products must be slowed and thermalized quickly, efficiently, universally and selectively.

Thermal or discharge ion source
+ isotope separator

Gas stoppers and beam coolers
Introduction to laser spectroscopy

- Laser
- Ion source (40kV)
- PMT

Isotope Shifts
- $\delta \langle r^2 \rangle$ (Size)
- $\delta \langle \beta_2^2 \rangle$ (Shape)
- $\delta \sigma$ (Diffuseness)

Hyperfine Structure
- $\mu$
- $Q_s$ 
- $\langle \beta_2 \rangle$
Present status of laser spectroscopy measurements
Mass & decay spectroscopy
Collinear laser spectroscopy
RFQ cooler & buncher – optical manipulation techniques
Ion guide & laser ion source trap
FURIOS laser cabin
The IGISOL Beamline at JYFL
**Collinear Laser Spectroscopy with Bunching**

**IGISOL:**
\[ E \sim 40 \text{ keV}, \delta E \sim 100 \text{ eV} \]

**DC-cooler:** \[ \delta E < 1 \text{ eV} \]
transmission > 60%

**Buncher:**
Accumulation time 10 ms - 10 s

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**On-Line Ion Cooling and Bunching for Collinear Laser Spectroscopy**

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A new method has been developed for increasing the sensitivity of collinear laser spectroscopy. The method utilizes an ion-trapping technique in which a continuous low-energy ion beam is cooled and accumulated in a linear Paul trap and subsequently released as a short (10–20 µs) bunch. In collinear laser measurements the signal-to-noise ratio has been improved by a factor of \(2 \times 10^4\), allowing spectroscopic measurements to be made with ion-beam fluxes of \(\sim 50 \text{ ions s}^{-1}\). The bunching method has been demonstrated in an on-line isotope shift and hyperfine structure measurement on radioactive \(^{174}\text{Hf}\).
Cooler advantages

- Reduces energy spread of ion beam (100eV $\rightarrow$ 1eV)
- Improves emittance of ion beam
- Trap and accumulates ions – typically 100 - 500 ms
- Releases ions in a 10 μs bunch

Collinear Beams Laser Spectroscopy
Cooling for laser spectroscopy

- He buffer gas
- End plate

Energy spread: 100 → 1 eV
Less spectral broadening
Emittance: → 3 π mm.mrad
Better laser-ion overlap
Reduced peak skewing
Bunching for laser spectroscopy

Background suppression = \frac{\text{eg. 200ms accumulation}}{\text{20\mu s gate width}} \approx 10^4

Counts

5.25 hours 8000 ions/s

Before

Counts

48 minutes 2000 ions/s

After

100V

100
Some recent highlights – but first an older measurement

Zr charge radii measurement at IGISOL

\[ ^{96-102}\text{Zr} \]

\( \sim 3000 \text{ ions/s} \) \(^{100}\text{Zr} \)
\( \sim 500 \text{ ions/s} \) \(^{96}\text{Zr} \)

Deformed nucleus

\[ \langle r^2 \rangle = \langle r^2 \rangle_0 \left( 1 + \frac{5}{4\pi} \left( \langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + \ldots \right) \right) \]

Spherical nucleus

Droplet model


Radii predictions for $^{40}\text{Zr}$ from B(E2) values

(Very similar to $^{38}\text{Sr}$ behaviour)

\[
\langle \beta_\lambda^2 \rangle = \left( \frac{4\pi}{3ZeR_0^\lambda} \right) \sum_f B(E\lambda; J_{gs} \rightarrow J_f)
\]

Big discrepancies between B(E2) measurements and charge radii. But for A=96 to 100, nuclear spins are either 0 or ½: NO measureable quadrupole moments…..

….look at yttrium (+isomers).
$^{39}$Y isotopes and isomers

- Shape change at N=59
- 98m is well deformed
Yttrium charge radii
In some isotopes of yttrium the nuclear spin is uncertain. We can manipulate the atomic state to provide a better starting point for collinear work.

This is done by “optically pumping” the yttrium in the RF cooler – a new technique!
363.3nm pumping (40% transfer)

1pA of $^{89}$Y continuous beam

Indifference to bunching

Use broadband pulsed lasers with high repetition rates (10 kHz)
Laser spectroscopy of niobium

50% increase due to pumping ➔ 1 photon per 2700 ions
Principles of Resonance Ionization

- Non-resonant ionization
- Excitation of auto-ionizing states
- Field ionization of Rydberg-states

Ionization potential

~6 eV (5-9 eV)

First excited state

Higher excited states

Ground state

Energy

0 eV

Y. Kudryavtsev, - NIM B179 (2001) 412
M. Setwz, - PRL 90 (2003) 163002
Example on RILIS: Triple Isomerism in $^{70}$Cu (RILIS & ISOLTRAP)

Intensity ratio:
- $1^+$: 16%
- $6^-$: 80%
- $3^-$: 4%

$\omega_c = \frac{q}{m} \cdot B$

Unambiguous state assignment!

ME of ground state is 240 keV higher than literature value!

$R \approx 1 \cdot 10^7$, $\delta m/m \approx 4 \cdot 10^{-8}$

Full spectral coverage at a range of repetition rates, linewidths and powers….

Pulsed dye lasers, pumped by CVL (12 kHz) or by 50 Hz Nd:YAG

CW dye lasers

Ti:Sapphire lasers pumped by Nd:YAG (12 kHz)

Laser development for applications of in-source spectroscopy

A laser ion guide for heavy-ion fusion evaporation reactions
A laser ion guide for heavy-ion fusion evaporation reactions
Laser ion source trap technique at IGISOL

Laser spectroscopy at the dripline

Isotopes with small production rates at ISOL facilities

Heavy neutron rich isotopes

Next generation on-line facilities, SLOWRI at RIKEN and LASPEC at GSI. Much of the work can still be done at present facilities, eg at IGISOL, JYFL.

Laser spectroscopy at the dripline