Development of Light Manipulation Techniques for the Laser Spectroscopy Experiment at TRIUMF

IOP 2015

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• Improving laser spectroscopy measurements
• Physics motivation for studying Rb and Fr
• Laser spectroscopy experiment at TRIUMF
  • Light manipulation techniques
  • Demonstration of techniques
Laser Spectroscopy Measurements

• Coupling of nuclear spin with total electron angular momentum produces hyperfine structure.

• Measurement of nuclear spin, magnetic and electric moments.

• Optical pumping limits experiments
Scientific Value

- Single particle behaviour in n-def francium isotopes
  - Francium +5 protons & 126-N fewer neutrons than $^{208}$Pb core.
    - Deviation from Pb in charge radii
    - Deviations in magnetic moments.
  - Spin measurements vital.
• Shape coexistence in A = 100 region:
  • Region characterised by sudden onset of deformation at N = 60
  • Interest in rubidium and strontium (which is fed by beta decay of rubidium)

Charge radii - laser spectroscopy

2n separation energies - mass measurements
Scientific Value

- Shape coexistence in $A = 100$ region:
  - Region characterised by sudden onset of deformation at $N = 60$
  - Interest in rubidium and strontium (which is fed by beta decay of rubidium)

Charge radii - laser spectroscopy

2n separation energies - mass measurements
• Proposed ms isomeric states in $^{98}\text{Rb}$. No direct observation experimentally.
• Spin assignment important in both cases.
ISAC at TRIUMF

ISAC-I and ISAC-II Facility

RFQ  TITAN  TRINAT  LEBT  High Resolution Mass Separator  Target Stations  500 MeV Protons  Cyclotron

EMMA  TIGRESS

Development of Light Manipulation Techniques at TRIUMF
Experiment

TITAN

Taken from O. Shelbaya presentation 2012

Development of Light Manipulation Techniques at TRIUMF
Experiment

TITAN

DC Ion Beam

RFQ

Ion Bunch

Charge Exchange Cell: Hot Sodium Gas

PMT

Focussing Lenses

Doppler Tuning Voltage

Neutral Atom Bunch

Laser Pulses
Laser Lab
Optical Pumping

Charge Exchange Cell

Atom/Ion Beam

3 us
Optical Pumping
Optical Pumping
Fast Chopping

Electro-Optical-Modulation - EOM

Fast Chopping (up to 1 MHz) of laser light

Acts like fast-switching half wave plate
Fast Chopping (333 kHz) of laser light

Fr atomic transition nat. lifetime ~ 20 ns
Fast Chopping

CW Laser Light
Fast Chopping

333 kHz ~ 1 pulse per 3 us
Fast Chopping
Fast Chopping
Fast Chopping
Fast Chopping
Fast Chopping
Fast Chopping
Fast Chopping
Fast Chopping
Demonstrated on $^{208}$Fr

A. Voss PRL 2013
However, a lot of time where atoms aren’t seeing any light
Frequency Flipping

Fr nat. linewidth ~ 8 MHz

more light pulses seen by each ion bunch

\[ \nu_0 - \text{RF} \quad \nu_0 + \text{RF} \]
Frequency Flipping

x3 -> 1 MHz ~ 3 pulses per 3 us
Frequency Flipping

Acousto-Optical-Modulation - AOM

Fast Switching (1 MHz) between frequencies

Laser Frequency $\nu_0$

RF = 100 MHz

$\nu_0 + 2*RF$

$\nu_0 + RF$

$\nu_0$

$\nu_0 - RF$

$\nu_0 - 2*RF$
Frequency Flipping

Output = +/- 20 MHz
RF = +/- 10 MHz
Frequency Flipping

Acousto-Optical-Modulation - AOM

Fast Switching (1 MHz) between frequencies

\[ \nu_1 \]
\[ \nu_2 \]
\[ \nu_3 \]
\[ \nu_1 \]

\[ \nu_0 - 20 \text{ MHz} \]
\[ \nu_0 \text{ MHz} \]
\[ \nu + 20 \text{ MHz} \]
\[ \nu_0 - 20 \text{ MHz} \]
Frequency Flipping
Frequency Flipping

• Obtain 3 individual scans for each frequency pulse
• Tune laser power to optimal power
• Efficiency improved by ~50% measured on 208Fr
• Technique used to measure isomer in 206Fr.
Scans performed on second isomer in $^{206}\text{Fr}$ (thousands per s)

Results allow spin assignment to be made
Spin measurements allow single particle properties such as magnetic moments to be investigated.

Charge radii also measured for all states.
• Observation of two states in $^{98}\text{Rb}$: High-spin and low-spin.

• Cannot confirm which is ground state
Hartree-Fock-Bogoliubov

Lhersonneau et al. propose the configuration of the I=3 high-spin state to arise from the prolate $\pi[431]3/2^+ \otimes \nu[411]3/2^+$ coupling. Both states fall in line with deformation of $^{97}\text{Rb}$ ($\pi[431]3/2^+$). Low-spin state I=0, therefore cannot confirm prolate or oblate. No signs of shape coexistence.
Summary

- Fast chopping method demonstrated on n-rich Rb
- Fast chopping and frequency flipping demonstrated on Fr
- Minimising optical pumping assists in extracting nuclear properties from data
- Fully investigate techniques for experimental effects and to extend reach of measurements
Thank you! Merci!
Isomeric State in 98Rb

- Low-spin state confirmed as $I = 0$
- High-spin state tentatively assigned $I = 3$ based on these data and gamma decay data.

<table>
<thead>
<tr>
<th>$A$</th>
<th>$N$</th>
<th>$I$</th>
<th>$\mu$ ($\mu_N$)</th>
<th>$Q_s$ (b)$^a$</th>
<th>$\langle \beta_2 \rangle^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{98}_{\text{HS}}$</td>
<td>61</td>
<td>(3)</td>
<td>+1.785(1)$^b$</td>
<td>+1.431(32)$^b$</td>
<td>+0.126</td>
</tr>
</tbody>
</table>

$^a$ Calculated from hyperfine coefficients published in Reference [7]
$^b$ This work

Prolate Deformation

$$Q_0 \approx \frac{5Z \langle r_{\text{sph}}^2 \rangle}{\sqrt{5\pi}} \langle \beta_2 \rangle (1 + 0.36 \langle \beta_2 \rangle),$$
• Measured lifetimes by varying injection times in RFQ.

• Results in close agreement with those from gamma results.
Charge Radii

\[ \delta <r^2>_{N=50} \text{ (fm}^2\text{)} \]

- Combined Analysis Charge Radii (Ground State)
- Optical Charge Radii (Ground State)
- Optical Charge Radii (Isomer)
- \(^{88}\text{Rb High-spin}\)
- \(^{88}\text{Rb Low-spin (offset)}\)

Neutron Number, \(N\)

\(\beta_{\text{rms}} = 0.43\)

\(\beta_{\text{rms}} = 0.0\)
As seen in practice

PMT by beam line

Light time structure
S1552, September 2014

- All Frequencies (offset by 140)
- Frequency 1 (110MHz)
- Frequency 2 (100MHz)
- Frequency 3 (90MHz)

Counts per 5ns bin

Photodiode in laser lab

- CH1 5.00V
- CH2 5.00V
- CH3 5.00V
- CH4 50.0mV

M 500ns 4–Sep–14 13:30
CH2 2.00V

2.2065kHz
Dynamic nature of nucleus remains constant across $N = 60$ shape shape

“Hardening” of nucleus at $^{98}\text{Rb}$ (high-spin). Observed in other elements in this region.
Shape Behaviour

- Example of shape coexistence in mercury isotope chain.
- Competing oblate and strong prolate shapes.
- Isomer shift due to coexisting competing shapes

Isotope Shift between $^{85}$Rb and $^{87}$Rb.

$$\delta \nu_{IS}^{A,A'} = -K_{MS} \frac{m_{A'} - m_A}{m_A^A m_A^A} = F_{el} \delta \langle r_{ch}^2 \rangle^{A,A'}$$

$$K_{MS} = +201(44) \text{ GHz.amu.}$$

Muonic Radii of $^{85}$Rb and $^{87}$Rb.

$$+0.042(18) \text{ fm}^2$$

$$-568 \text{ MHz/fm}^2$$

$Ab\ initio$ calculations. Relativistic Hartree-Fock method.


Mass Shift

- Normal Mass Shift.
  - Exactly calculable.
- Specific Mass Shift.
  - Difficult to calculate.
The volume shift component

Ab initio calculations look into overlap of electron wave functions with nuclear potential

\[ \delta E = \frac{Ze^2}{6\varepsilon_0} \left| \psi(0) \right|^2 \delta \langle r^2 \rangle^{A,A'} \]

electron density at the nucleus
Scientific Value

• Mass Measurements