New Laser Spectroscopic Study for the Measurement of Nuclear Moments

Takeshi Furukawa
Department of Physics, Graduate School of Science, Osaka University

Collaborator
Y. Matsuo\textsuperscript{2}, A. Hatakeyama\textsuperscript{3}, Y. Fukuyama\textsuperscript{2}, T. Kobayashi\textsuperscript{2}, H. Izumi\textsuperscript{1}, and T. Shimoda\textsuperscript{1}

\textsuperscript{1}Dept. Phys., Osaka Univ., \textsuperscript{2}RIKEN, \textsuperscript{3}Inst. Phys., \textsuperscript{3}Univ. of Tokyo
1) Problems in measuring the nuclear moment
   - Low-yield, high-contamination, small-polarization of unstable nuclei

2) New laser spectroscopic method to cope with the problems
   - Double resonance method in He II
     - Laser spectroscopy & optical detection
     - Optical pumping in He II

3) Present status of the development
   - Long atomic spin relaxation time in He II
   - Magnetic resonance spectrum in He II

4) Summary and future prospect
Scientific Motivation

Unstable nuclei near the drip-line

- low-yield
- high-contamination
- small-polarization

Difficult to measure the nuclear moment

Laser spectroscopy & optical detection of RI atoms

Optical pumping in He II

Measure the hyperfine structure

Determination of nuclear moments

ex) $\beta$-NMR method

Polarized RI nucleus

Signals from RI

detector

stopper
Merit in Optical Detection

- low yield, high contamination
  - Laser spectroscopic method is suitable for unstable nuclei.
- Laser Induced Fluorescence (LIF) photon
  - The impurity atoms can not absorb the pumping laser.
    - Insensitive detection to the impurity atoms.
- Good S/N ratio
  - Useful to measure the unstable nuclei

Pumping the RI atoms repeatedly.
Detected the LIF photons repeatedly.
Double resonance method

Polarized atoms: Can not absorb circularly polarized laser light.

LIF Intensity \(\propto 1 - P_z\)
Double resonance method

Hyperfine Structure (J=1, I=3/2 case)

\[ \begin{align*}
J=1, I=3/2 & \quad F=1/2 \\
 & \quad F=3/2 \\
 & \quad F=5/2
\end{align*} \]

\[ A = \mu \frac{\langle B \rangle}{IJ} \quad B = eQ \langle V \rangle \]

\( I: \) nuclear spin, \( J: \) electronic angular momentum,
\( \mu: \) nuclear magnetic dipole moment,
\( eQ: \) nuclear electric quadrupole moment,
\( \langle B \rangle: \) magnetic field produced by the electrons
\( \langle V \rangle: \) electric field gradient produced by the electros

Measure the constant \( A, B \) of isotope \( mX \) and \( nX \)

\[ \frac{\mu_{mX}}{\mu_{nX}} = \frac{A_{mX} I_{mX}}{A_{nX} I_{nX}} \quad \frac{eQ_{mX}}{eQ_{nX}} = \frac{B_{mX}}{B_{nX}} \]
Double resonance method

Polarized atoms: Can not absorb circularly polarized laser light.

Measure the constant $A, B$ of isotope $mX$ and $nX$

$$
\frac{\mu_{mX}}{\mu_{nX}} = \frac{A_{mX} I_{mX}}{A_{nX} I_{nX}} = \frac{eQ_{mX}}{eQ_{nX}} B_{mX} - \frac{5}{4} B_{nX}
$$

Hyperfine Structure (J=1, I=3/2 case)

- $F=5/2$
- $F=3/2$
- $J=1, I=3/2$

$B=eQ<V>$

- Nuclear spin, $J$: electronic angular momentum,
- $\mu$: nuclear magnetic dipole moment,
- $eQ$: nuclear electric quadrupole moment,
- $<B>$: magnetic field produced by the electrons,
- $<V>$: electric field gradient produced by the electrons.

LIF intensity

Limited to alkali-like atoms.

Optical pumping is performed only alkali-like atoms.
**Optical pumping in He II**

In He II: possible to polarize various atoms with optical pumping

Optical spectrum of atoms is dynamically broadened due to the influence of the surrounding He atoms.

Possible to optically pump the atoms with complicated level structure using a single laser beam

Problem:
How fast spin relaxes in He II?
Spin polarization in He II

Long spin relaxation time are expected in He II!

How long the relaxation time?
We have measured $T_1$ of Cs atoms in He II.

Achieved polarization: $\sim 90\%$ in Cs.

He II is suitable to use with our method.

Optical pumping of the atoms other than alkalis is now in progress.

M.R. Spectrum in He II

Check the feasibility in He II

Double Resonance spectrum of Cs atoms in He II
(Zeeman sublevel transition, Magnetic field : ~ 3 G)

Peak frequency: 959.5(5) kHz

Energy level of g.s Cs atom

Zeeman transition

Hyperfine transition

F=4

F=3

6s_{1/2}

Peak frequency: 959.5(5) kHz
(preliminary)

Observing hyperfine resonance same as that

Nuclear moments can be determined precisely
### Summary and Future prospect

**Measurement Method for the nuclei near the drip-line**

**Double Resonance in He II**

### Problems
- low-yield
- high-contamination
- small-polarization

### Merit
- Detecting the LIF photons repeatedly
- Insensitive to the impurity atoms
- Long spin preservation, high polarization

- High polarization, long spin reservation, and precise resonance spectrum are confirmed in He II

### Future prospect

Optical detection from low-yield RI atoms

Optical pumping of various atoms other than alkalis (Mg, Al, ..)

Measure the moments of various nuclei ($^{22}\text{Al}$, $^{21}\text{Mg}$, ..)
Additional OHP
Double Resonance Method

Need more effective measurement method!

**Laser Double Resonance Method in He II**

is suitable for the measurement.

Double resonance method → a sort of laser spectroscopy
Hyperfine Interaction

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

\[ A = \mu <B>/IJ \quad B = eQ<V> \]

\(\mu\): nuclear magnetic dipole moment,
\(eQ\): nuclear electric quadrupole moment,
\(<B>\): magnetic field produced by the electrons
\(<V>\): electric field gradient produced by the electros

Measure the constant \(A\), \(B\) of isotope \(^mX\) and \(^nX\)

\[ \frac{\mu_{mX}}{\mu_{nX}} = \frac{A_{mX} I_{mX}}{A_{nX} I_{nX}} \quad \frac{eQ_{mX}}{eQ_{nX}} = \frac{B_{mX}}{B_{nX}} \]
Bubble Model

Atoms in He II: repel the surrounding helium atoms (by Pauli repulsion)

Like as bubble

Energy levels in the ground state and excited state as a function of bubble radius.
Physics motivation

$^{22}\text{Al}$ : proton halo?

$^{22}\text{Al} = ^{21}\text{Mg} + \text{p}$

$^{21}\text{Mg}$ : Isospin symmetry?

$^{21}\text{Mg} - ^{21}\text{F}$ mirror pair in $T = 3/2$

$^{35}\text{Ca}$ : $Z=20$ magic?
Optical Pumping of Metastable Mg atoms

Observable resonance line (Assume $I = 5/2$)

$3s3p \, ^3P_2 \ F=9/2 \leftrightarrow F=7/2$

\[ [\text{h.f.s} = (9/2)A + (27/40)B] \]

$F=7/2 \leftrightarrow F=5/2$

\[ [\text{h.f.s} = (7/2)A + (7/40) B] \]

( $3s3p \, ^3P_1 \ F=7/2 \leftrightarrow F=5/2$ )
Relaxation in the Dark Method

- Laser excitation of atoms into the $^2P_{1/2}$ state.
- Laser is turned off, allowing for polarization relaxation.
- Spin-relaxed atoms absorb light and re-emit LIF photons.

**Key Points:**
- Atoms polarized completely.
- Polarization relax.
- Spin-relaxed atoms absorb the light.
Timing chart

Sputtering laser on and off: 2s

Cw pumping laser width: 5ms

Count gate width: 100μs

Photon counts

$\tau$: 0-1400 ms

OP1, OP2, OP3, OP4
Experimental Setup
Measured LIF intensity

- $\tau = 100$ ms
- $\tau = 700$ ms
- $\tau = 1400$ ms

Photon count rate (cps) vs. Time (ms)
Measured LIF intensity

100msec spin relaxation

700msec spin relaxation

1400msec spin relaxation

no polarization at pump1
Spin Relaxation Mechanism

Sphere-state electron(s) \( (^2S_{1/2} \) electron in Cs,Rb)

magnetic interaction \( \sigma \cdots \approx 10^{-19-26} \text{cm}^2 \)

\( \text{ex) Cs} \ ^2S_{1/2} : 2.5 \times 10^{-24} \text{cm}^2 \)

\( J>1 \) electron(s) \( (^3P \) electrons in Mg)

electrostatic interaction \( \sigma \cdots \approx 10^{-14-15} \text{cm}^2 \)

\( \text{ex) Hg} \ ^3P_1 : 1.1 \times 10^{-15} \text{cm}^2 \)

\( ^2P_{1/2} \) electron(s) \( (^2P_{1/2} \) electron in Cs,Rb)

virtual transition to \( ^2P_{3/2} \) & electrostatic interaction \( \sigma \cdots \approx 10^{-16-17} \text{cm}^2 \)

\( \text{ex) Tl} \ ^2P_{1/2} : 6.0 \times 10^{-19} \text{cm}^2 \quad \text{Cs} \ ^2P_{1/2} : 2.1 \times 10^{-16} \text{cm}^2 \)

\( 2^P_{1/2} - 2^P_{3/2} \Delta E : 7793 \text{cm}^{-1} \quad 554 \text{cm}^{-1} \)