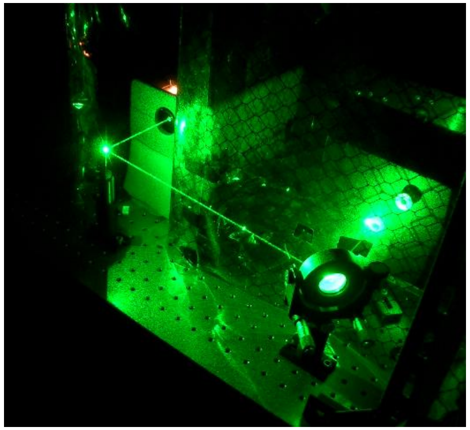
Spin Polarization of Radioisotope Atoms with Optical Pumping in Superfluid Helium for the Measurement of Nuclear Spins and Electromagnetic Moments



Tokyo Metropolitan University

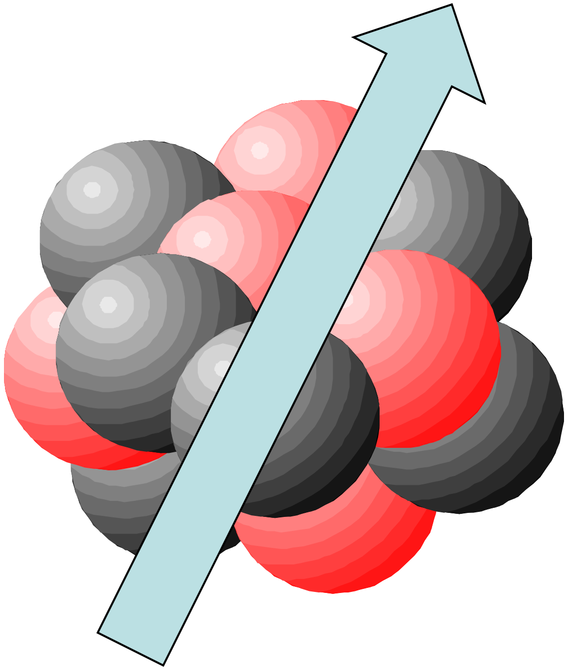
Takeshi Furukawa

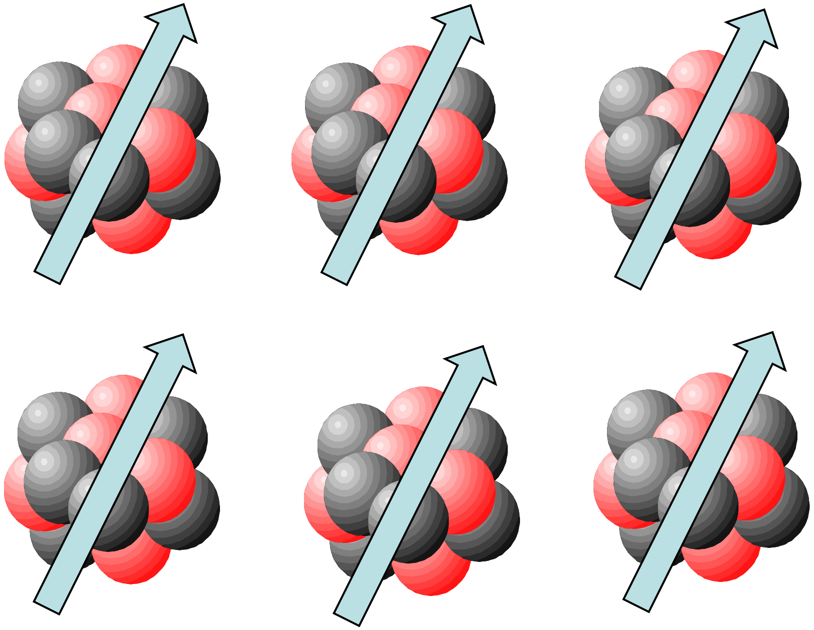
SPIN2014 @ Beijing, China 2014 Oct. 20-24

Production of spin polarization

Nuclear spin :

Unique quantity which determine the direction of an nucleus





Spin-polarized nuclei :

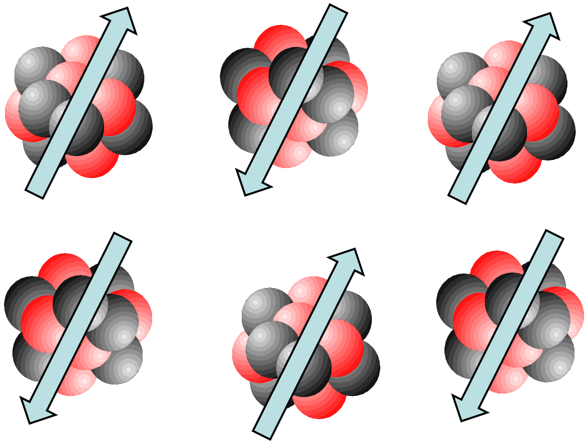
Sensitive and effective tool for the study of,

not only nuclear physics but also many fields of sciences

Production of spin polarization

Based on two ways in principle

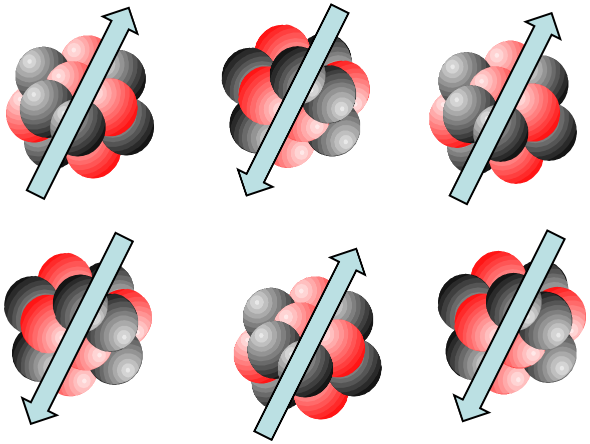
Selection of the m-quantum number



- Selection of reaction angle in the nuclear reactions
  - Projectile fragment reaction
  - Pick-up / Knock out reaction

- Selection of atomic substate with magnetic field gradient
  - Stern-Gerlach method

Control of the m-quantum number



- Transfer angular momenta from surrounding electrons
  - (Direct) Optical Pumping (OP)
  - Spin Exchange OP
  - Dynamical Nuclear polarization

- Boltzmann distribution
  - Low Temp. Nuclear Orientation

Production of spin polarization

Two ways in principle

Selection of the m-quantum number

Advantage/Disadvantage for low-yield exotic RIs

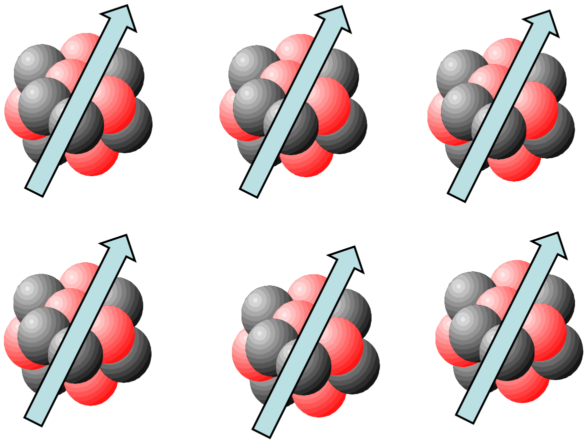
☺ Large polarization

☺ Easy to use

☹ Need slow/stopped RIs

☹ Depend on elements
(Only alkali-like)

Control of the m-quantum number



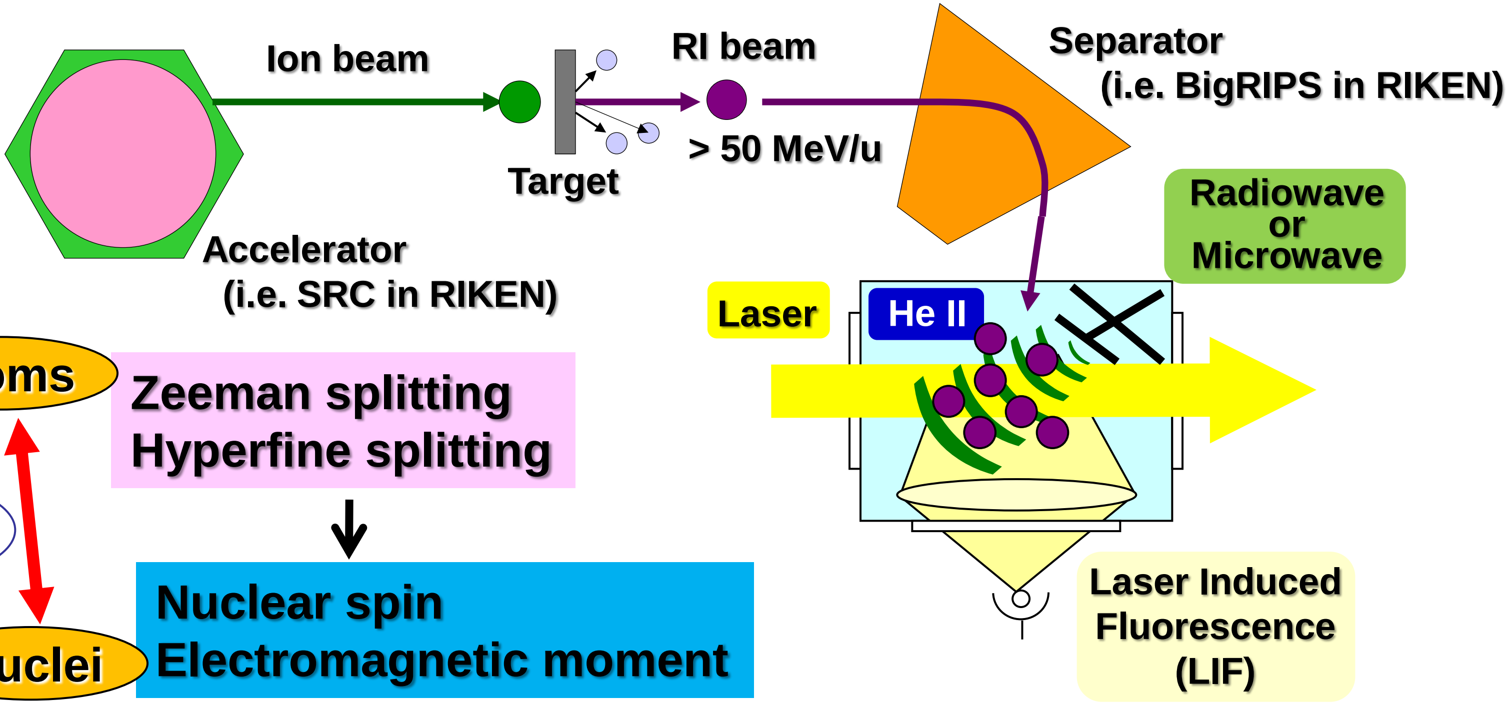
- Transfer angular momenta from surrounding electrons
  - (Direct) Optical Pumping (OP)
  - Spin Exchange OP
  - Dynamical Nuclear polarization

- Boltzmann distribution
  - Low Temp. Nuclear Orientation

Laser spectroscopy of atoms in He II

“OROCHI”

Optical **R**I-atom **O**bservation in **C**ondensed **H**elium as **I**on-catcher



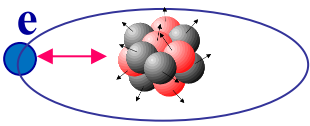
Atoms

Zeeman splitting
Hyperfine splitting

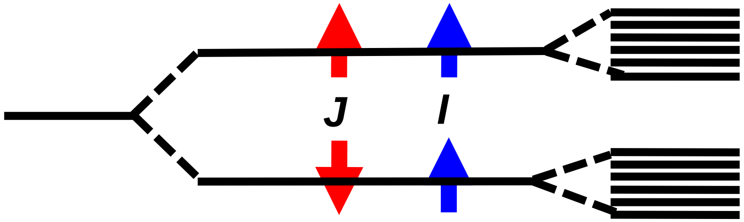
↓

Nuclei

Nuclear spin
Electromagnetic moment



Interaction between
nuclear moments
and electrons



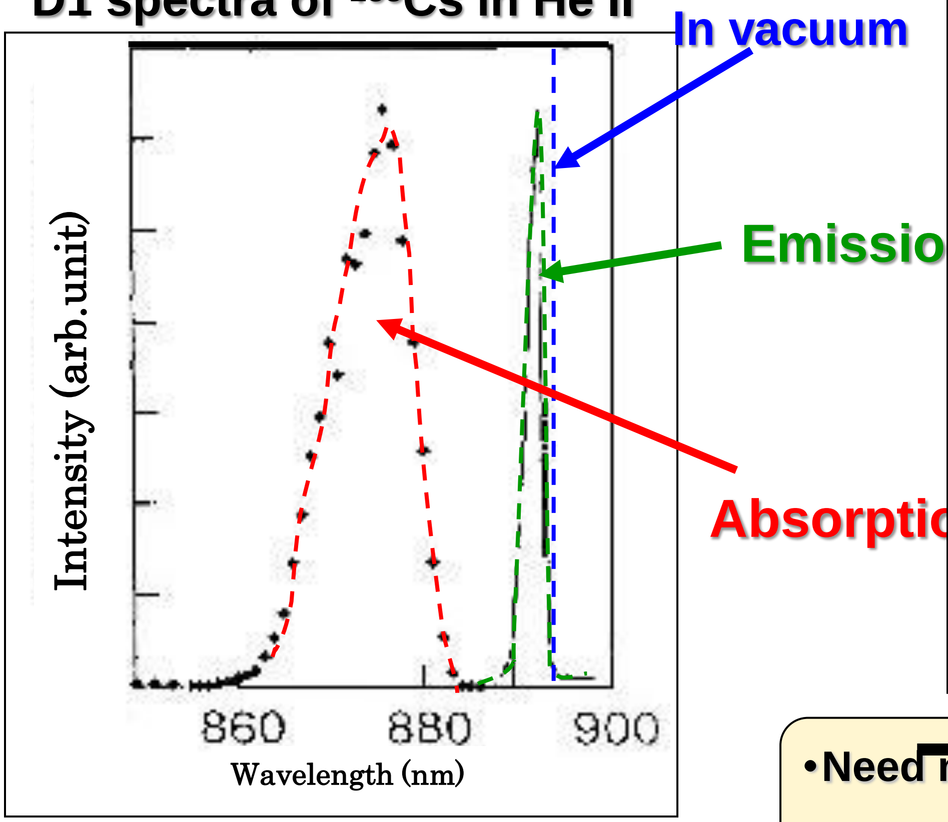
Interaction between
atomic spin m_F and
external magnetic field

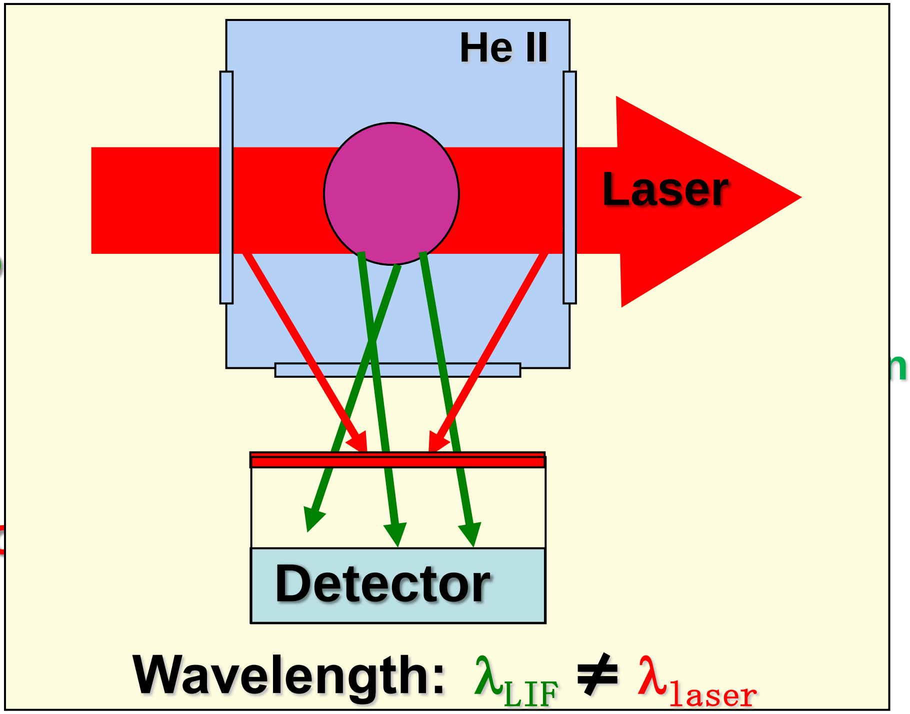
Advantage in He II

We use He II to trap the atoms efficiently,
also to reduce the b.g. photons.

Atomic absorption spectra in He II (① Largely blue-shifted
② Widely broadened

D1 spectra of ^{133}Cs in He II





Wavelength: $\lambda_{LIF} \neq \lambda_{laser}$

- Need more
- Different a

Suppress background count

Reduction: expected as10^{-9}

Double resonance spectroscopy

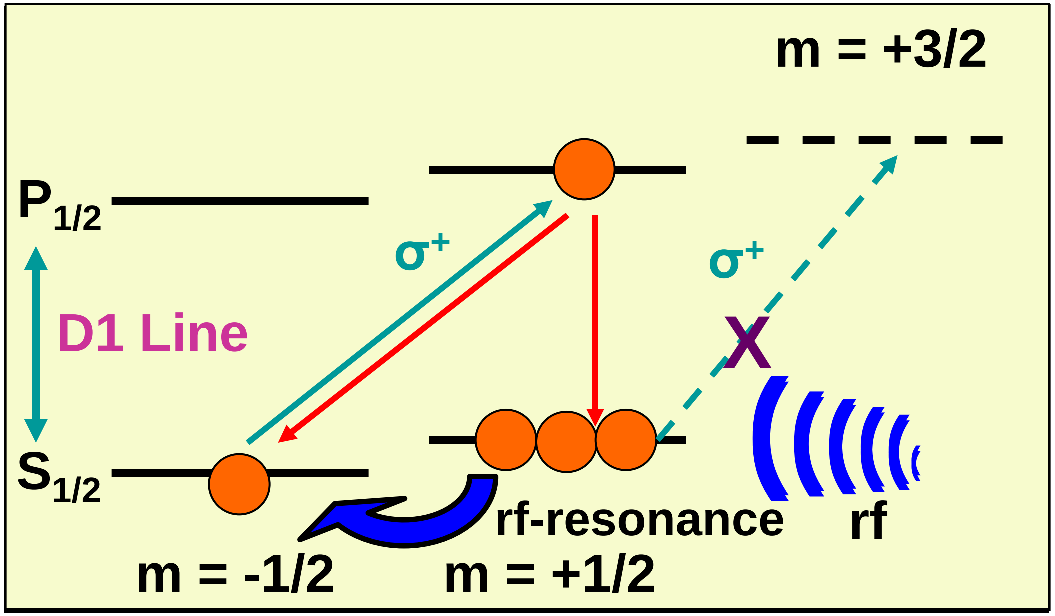
Owing to the slow diffusion of atoms in He II:

- Measurement of double resonance spectroscopy

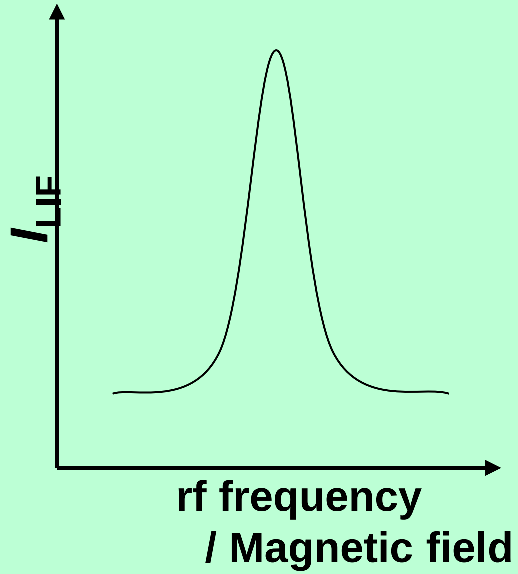
In the case of Zeeman splitting in alkali atoms

1st step: optical pumping

2nd step: double resonance



Expected spectrum



LIF Intensity…

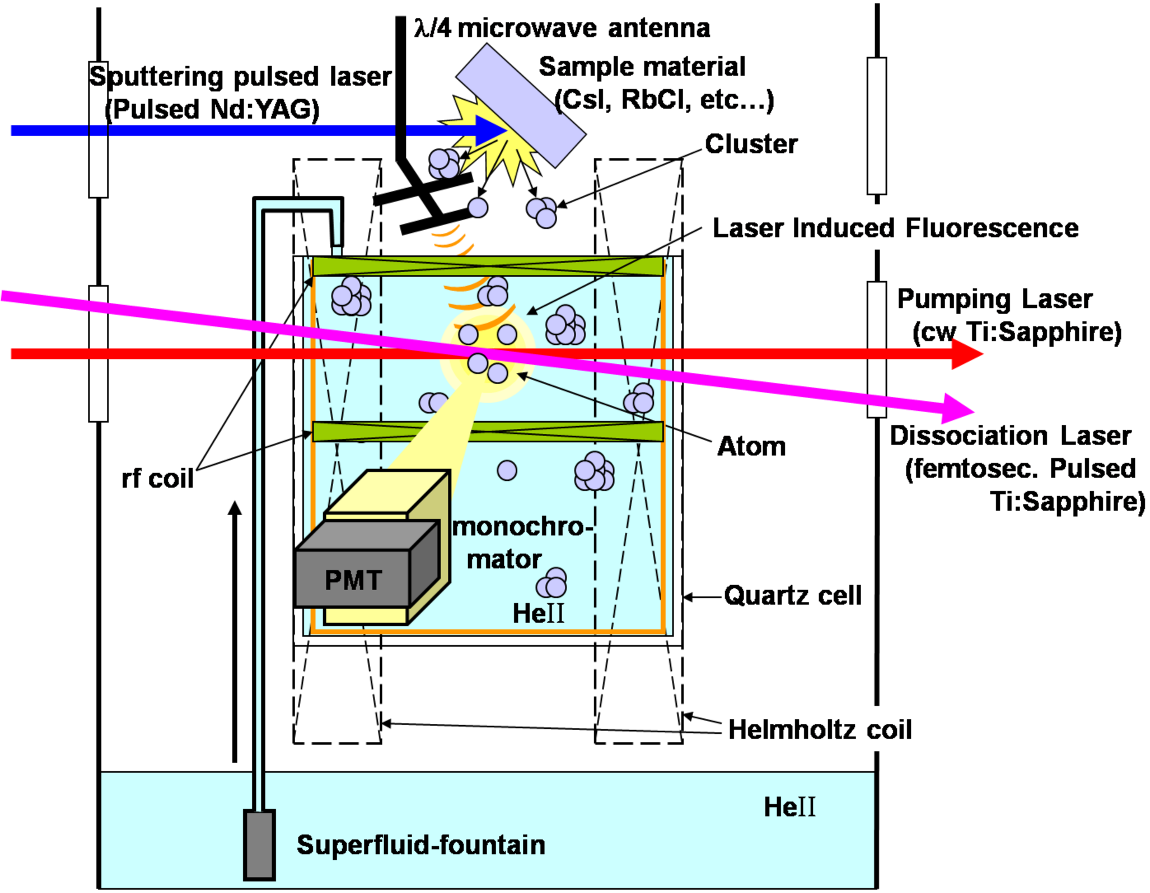
Decreased gradually

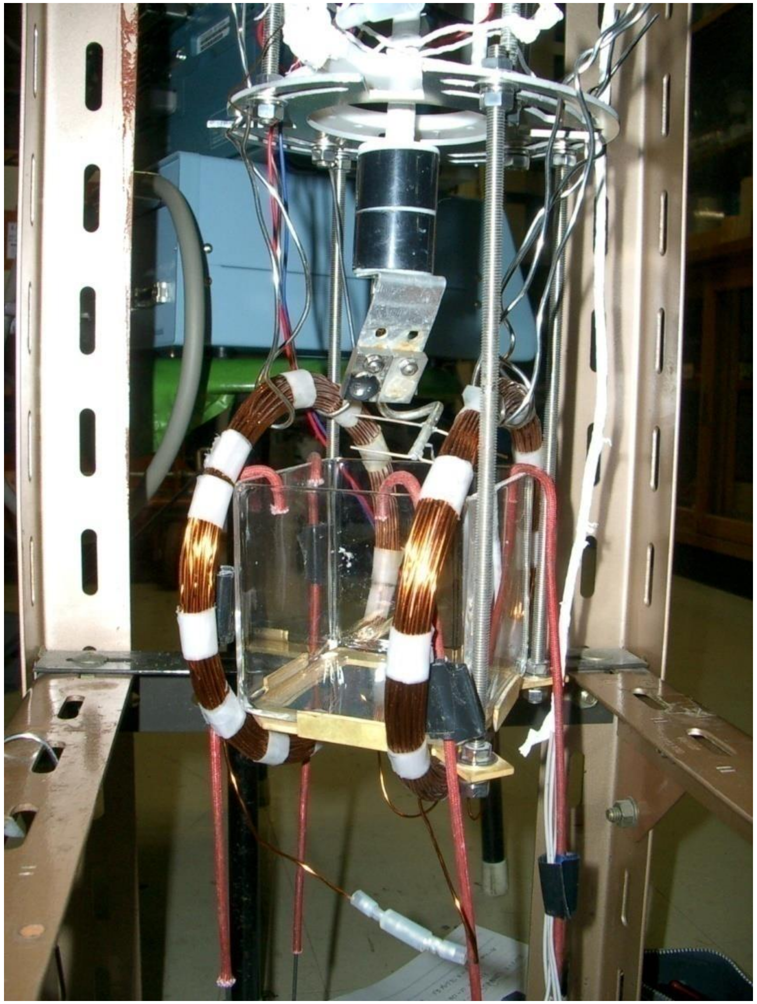
$$[I_{\mathrm{LIF}}] \propto 1 - P_z$$

Setup for off-line development

Introducing atoms in He II by laser sputtering

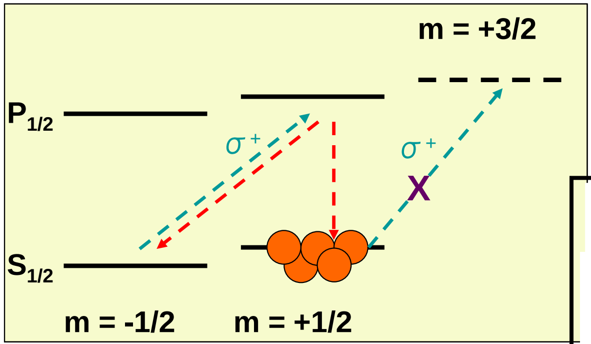
Stable isotopes of Rb, Cs, and so on





Optical pumping in He II

Produce the polarization on stable isotopes in He II

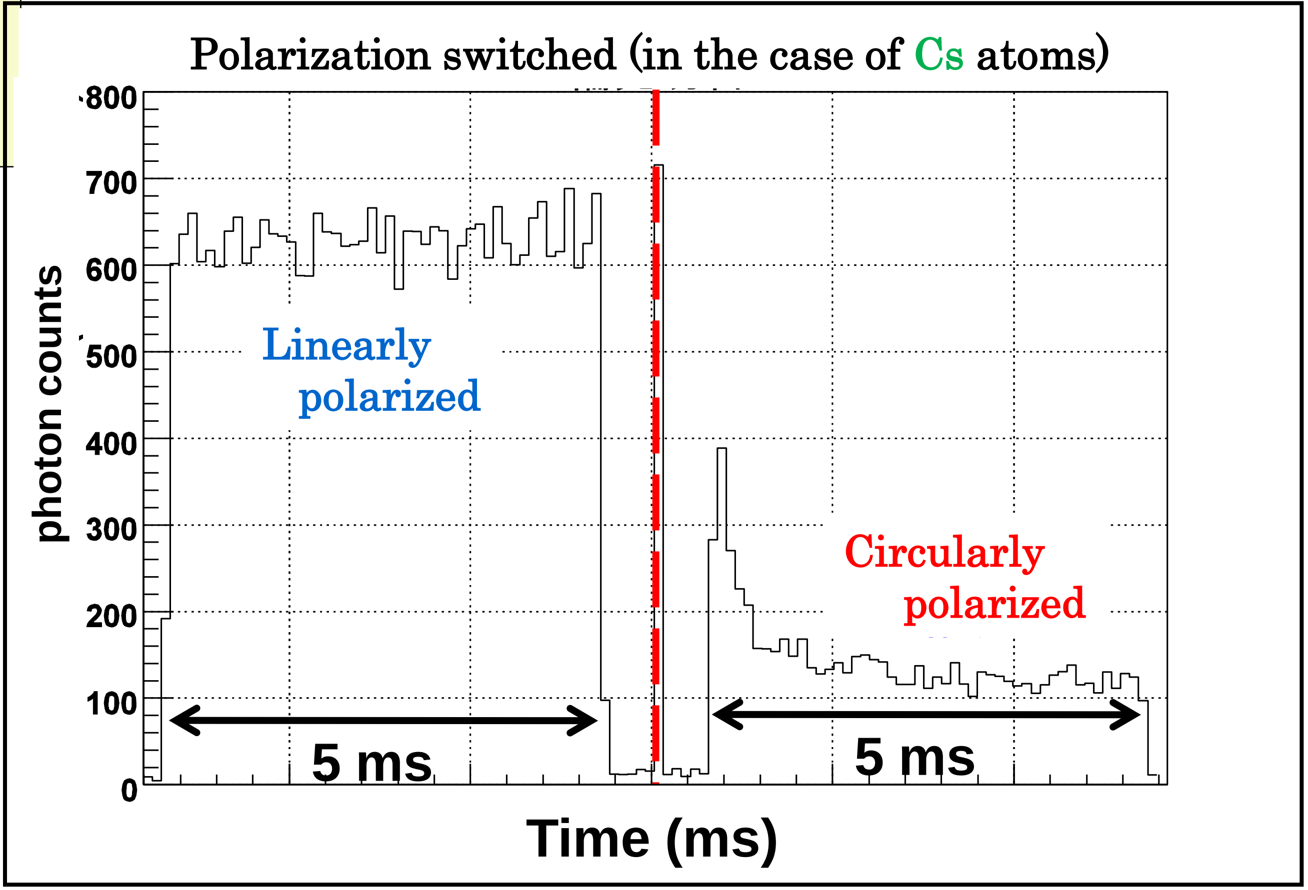


Polarization : -90% (Cs), -40%(Rb)

Polarization: Increased

LIF intensity: Decreased

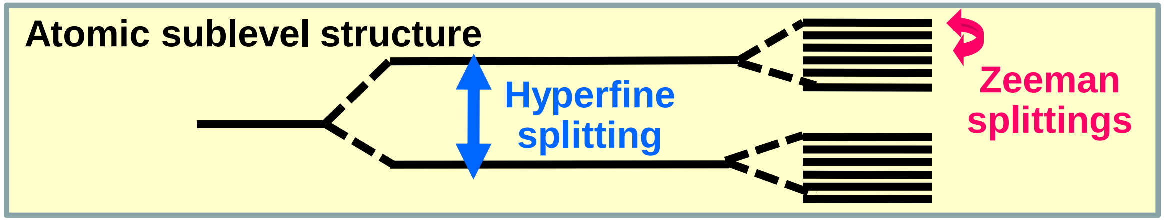
$$[I_{\mathrm{LIF}}] \propto 1 - P_z$$


Polarization switched (in the case of Cs atoms)

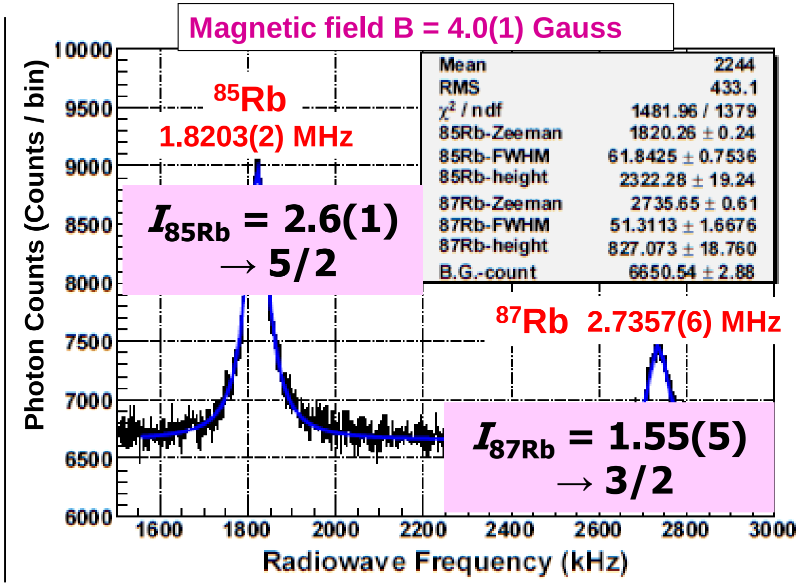
T. Furukawa *et al.*, Phys. Rev. Lett. 96, 095301 (2006)

T. Furukawa *et al.*, Physica E 43, 843 (2011)

Nuclear spin & moment determination



Zeeman resonance of Rb isotopes

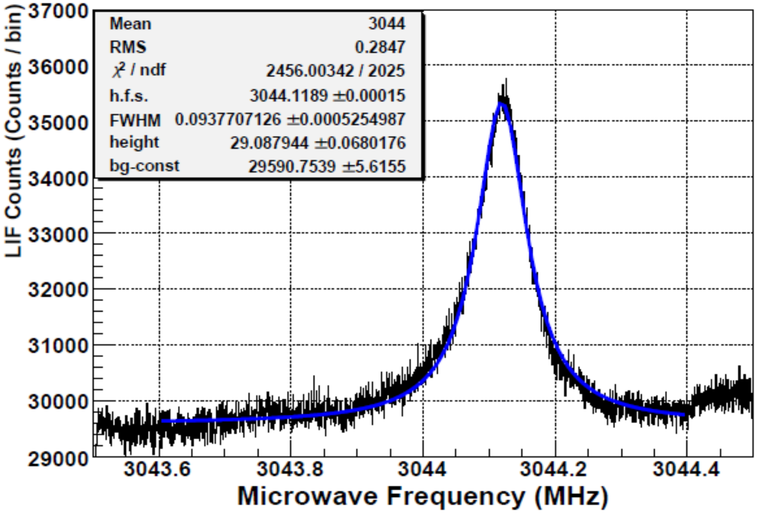


$$\Delta\nu_{Zmn} = g_F\, m_B\, B/h$$

$$= \frac{2.8\,(\text{MHz}) \times B\,(\text{Gauss})}{(2\underline{I}+1)}$$

Nuclear spin

Hyperfine resonance of ^{85}Rb

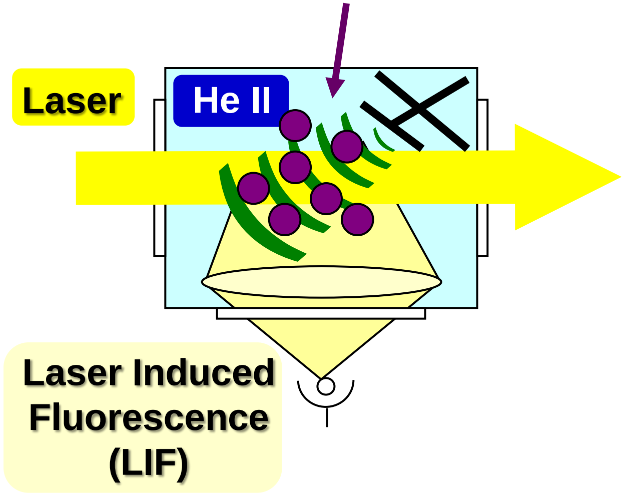


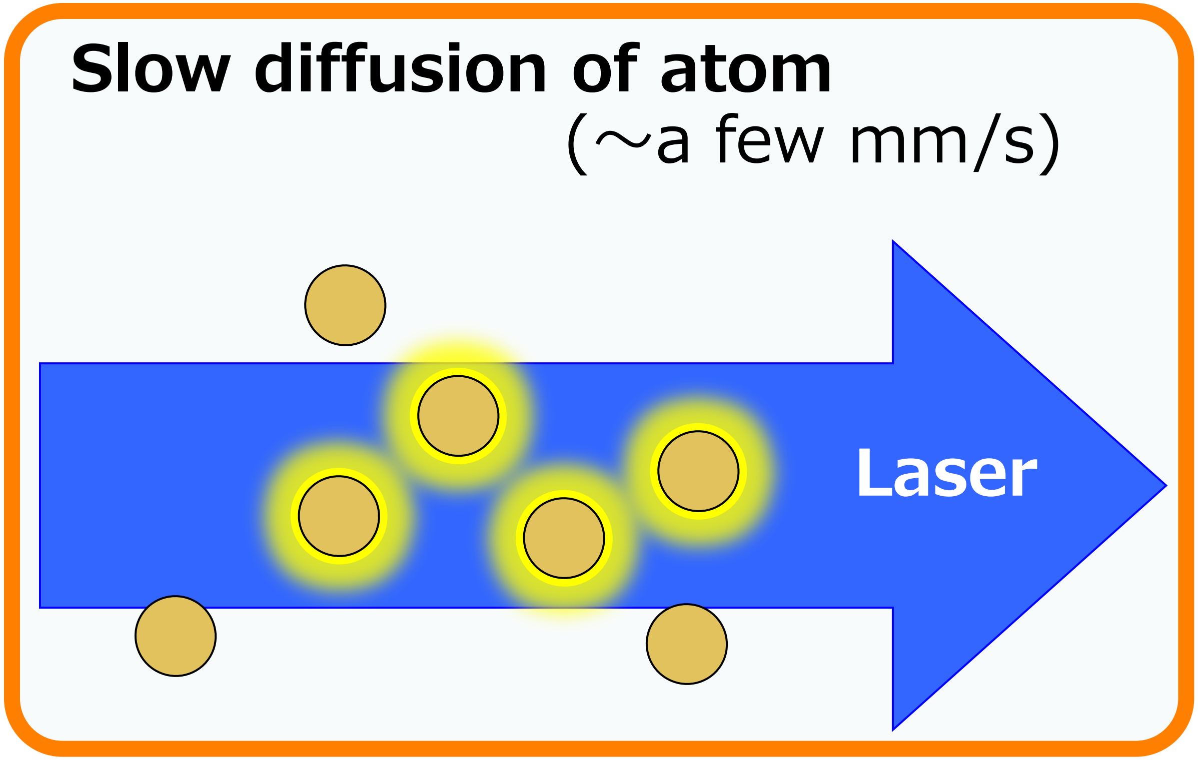
	$\mu_I^{85\text{Rb}}$ (μ_N)
This work (from A_{HeII})	1.357 83 (7) μ_N
Evaluated (from A_{vacuum})	1.358 071(1) μ_N
Literature value (NMR)	1.353 351 5 μ_N

T. F., Hyperfine Interactions 196, 191 (2009)

T. F. Doctoral thesis, Osaka Univ. (2007)

Optical pumping of Ag and Au in He II





Slow diffusion of atom

(~a few mm/s)

Possible to excite same atoms repeatedly before atoms escape with "pulsed laser"

Easy to prepare wide variety of laser wavelength including ultra violet region

Optical pumping of Ag and Au in He II

Atomic spin polarization

$$P_z\,\sigma = \left(1 - \frac{I_{pol}}{I_{unpol}}\right)\times 100(\%)$$

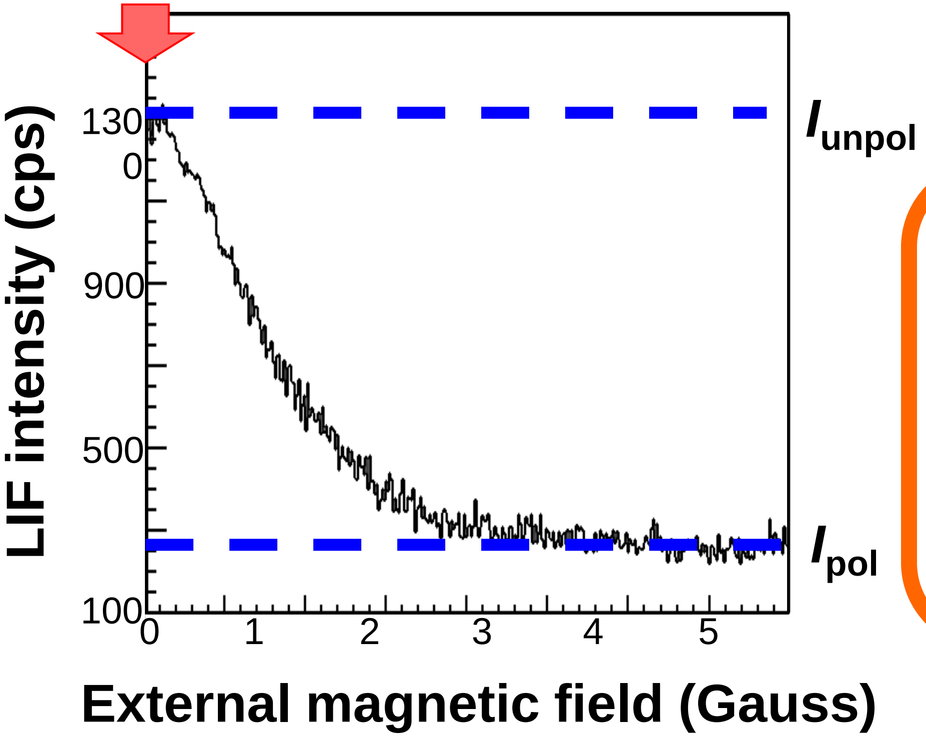
σ : Circular polarization degree of laser

I_{pol} : LIF intensity from polarized atoms

I_{unpol} : LIF intensity from un-polarized atoms

Sweeping external magnetic field

B =0 : No conservation of atomic spin polarization



Achieved polarization

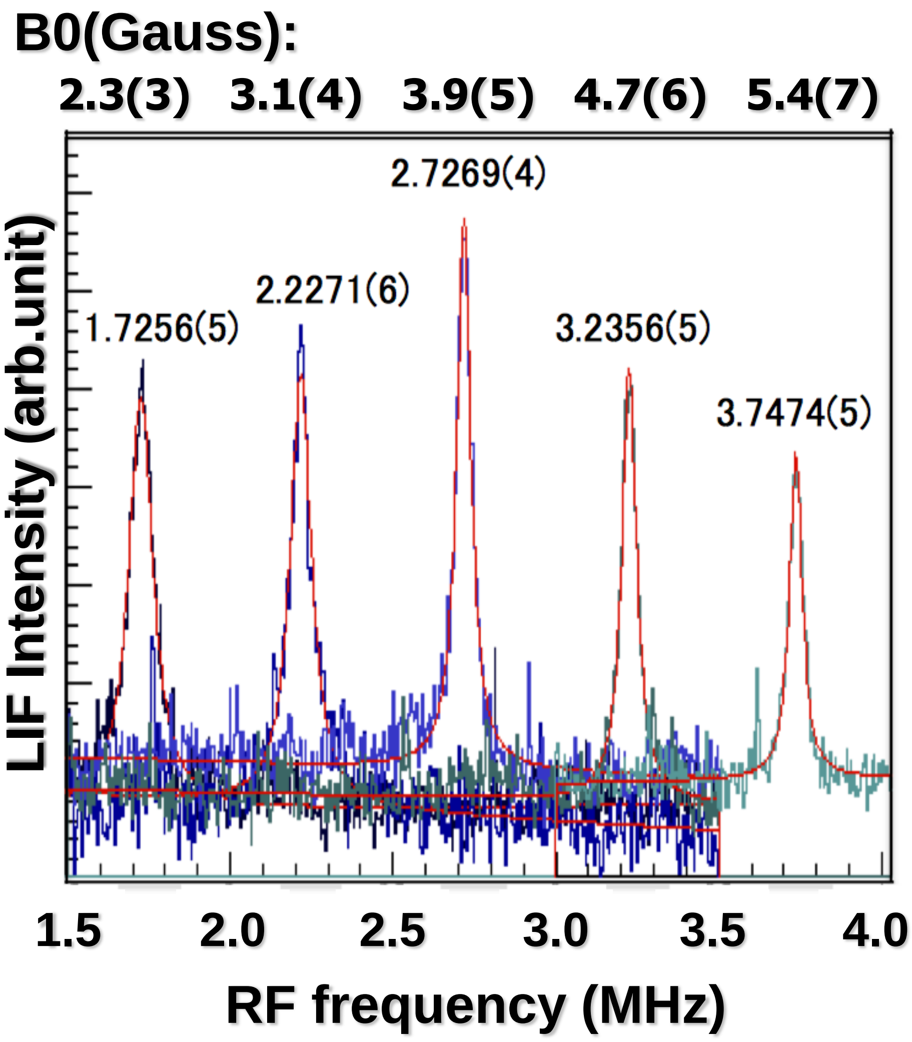
-85% (both Ag and Au, preminiary)

Incomplete polarization

⇨ **Imperfect circular polarization**

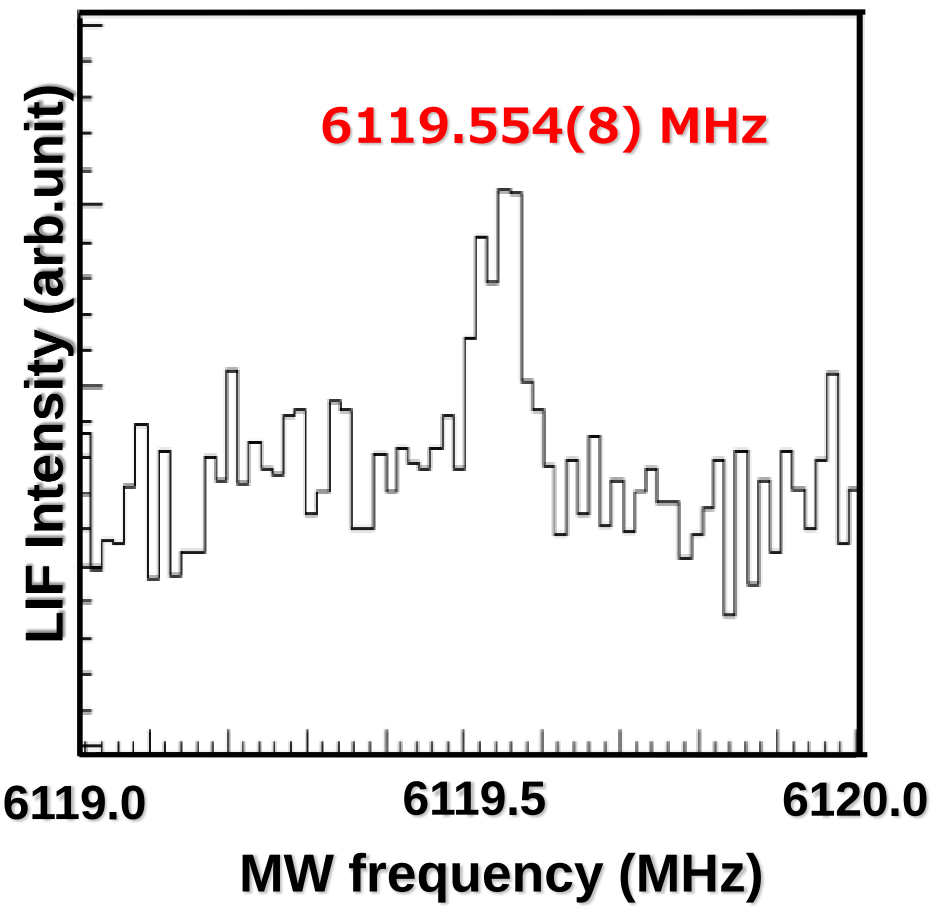
Sublevel structure measurement of Au

Zeeman resonance



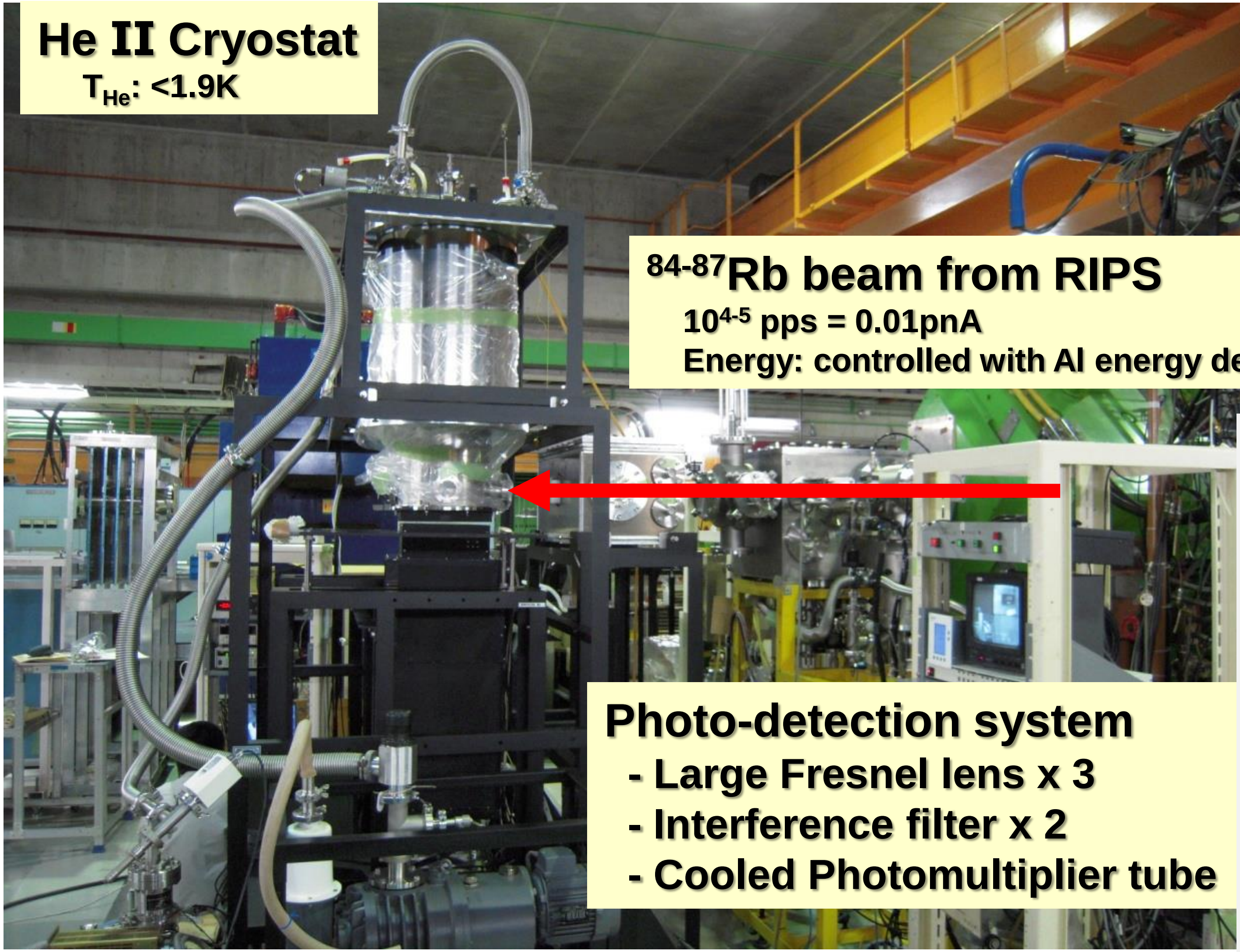
Hyperfine resonance

Observed with σ- pumping laser



Setup for on-line experiment

The experiment with $^{84\text{-}87}$Rb (< 60 MeV/u) from RIKEN RIPS beam line



He II Cryostat

T_{He}: <1.9K

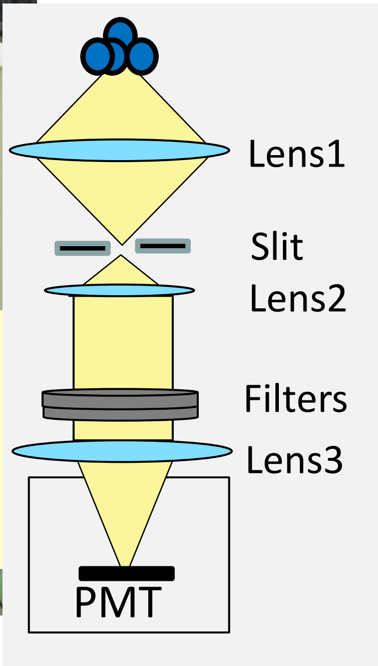
$^{84\text{-}87}$Rb beam from RIPS

$10^{4\text{-}5}$ pps = 0.01pnA

Energy: controlled with Al energy degraders

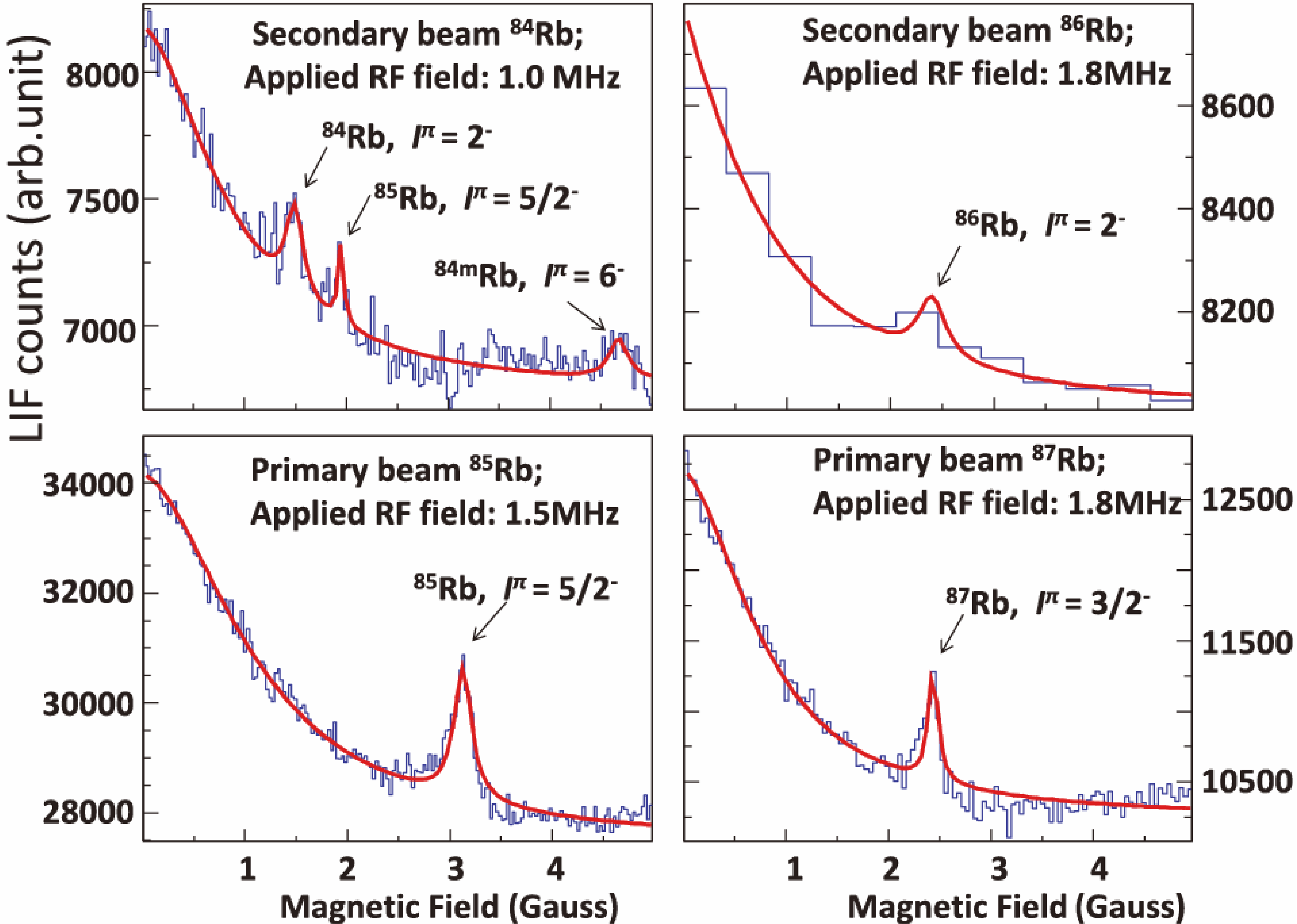
Photo-detection system

- Large Fresnel lens x 3
- Interference filter x 2
- Cooled Photomultiplier tube

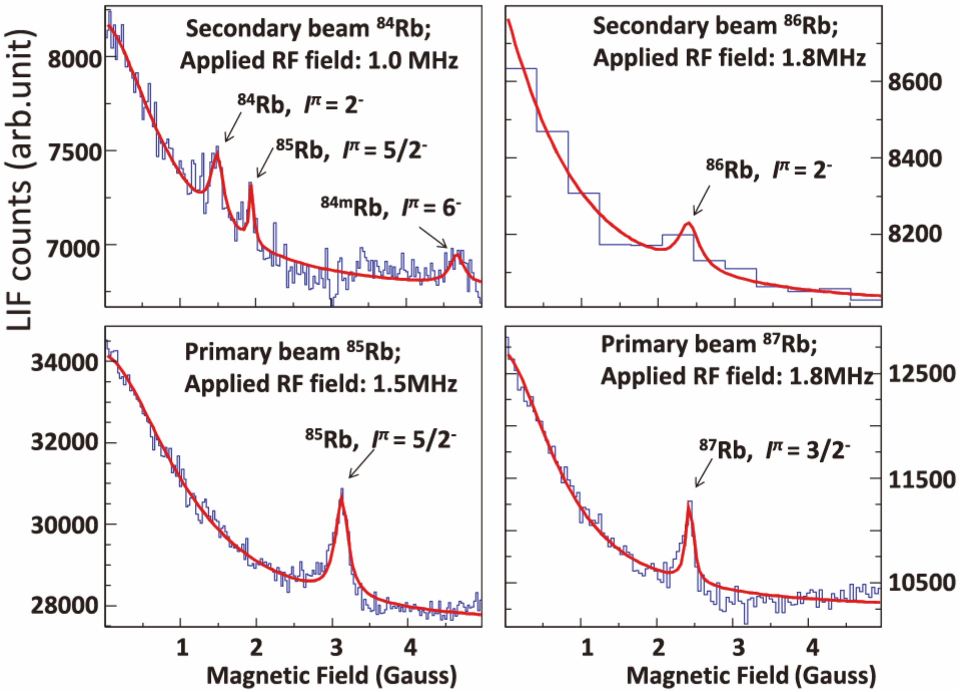


Zeeman resonance spectra

Beam intensity : up to 1.0 x 10^4 pps



Zeeman resonance spectra



Fitting with Bell–Bloom equation

$$P_z(B_0, B_\perp) = P_\infty \frac{1 + (aB_0/\gamma_2)^2}{1 + (aB_0/\gamma_2)^2 + aB_\perp^2/\gamma_1\gamma_2}$$

$$I_{LIF} = I_0\,(1 - P_z)$$

Optical pumping in longitudinal and transverse external magnetic field (B_0 and $B_\perp$, respectively).

*C. Thibault, et al., PRC 23 (1981) 2720.

$$I = \frac{\mu_B B}{\nu} - \frac{1}{2}$$

Isotopes	Nuclear spin value	
	This work	Literature value*
^{84}Rb	1.9(1)	2-
^{84m}Rb	6.2(2)	6-
^{85}Rb	2.5(1)	5/2-
^{86}Rb	1.9(2)	2-
^{87}Rb	1.53(6)	3/2-

X.F.Yang et al., submitted to PRA (2014).

Summary & Future

"OROCHI"

Optical **R**adioisotope-atom **O**bservation in **C**ondensed **H**elium as **I**on-catcher

- To perform the optical pumping with various elements of low yield RIs, we have developed the new laser spectroscopy method "OROCHI", which is based on the optical pumping of atoms in superfluid helium (He II).

- Not only the alkali Rb and Cs atoms, we have successfully performed the optical pumping and following double resonance spectroscopy to Ag and Au isotopes owing to characteristic properties of atoms in He II.

- We have also successfully demonstrated the feasibility with energetic RI beams. Zeeman and hyperfine resonances from $^{84\text{-}87}$Rb (up to 10^4 pps) have been observed, respectively.

- Further improvements of our instruments, i.e. the efficiency of photo-detection system are going on. After them, we will perform this OROCHI to exotic nuclei, such as neutron deficient ^{175}Au and ^{94}Ag isotopes.

Collaboration

Spokesperson:

Takeshi Furukawa (Tokyo Metropolitan University), **Yukari Matsuo** (Hosei University)

Email: takeshi@tmu.ac.jp

RIKEN Nishina Center:

X. F. Yang, Y. Ichikawa, H. Ueno, Y. Ishibashi, M. Wada, T. Sonoda, Y. Ito , T. Kobayashi, S. Nishimura, M, Nishimura, K. Yoneda, S. Kubono

CYRIC, Tohoku Univ.:

T. Wakui, T. Shinozuka

Meiji Univ.:

K. Imamura, Y. Mitsuya

Osaka Univ.:

T. Fujita, T. Shimoda

Tokyo Gakugei Univ.:

Y. Ebara, M. Hayasaka, S. Kishi, T. Sagayama

Tokyo institute of Technology:

H. Shirai, T. Suzuki, T. Sato, Y. Otomo, Y. Kojima, K. Asahi, Y. Kondo

Tokyo Univ. of Agriculture and Tech.:

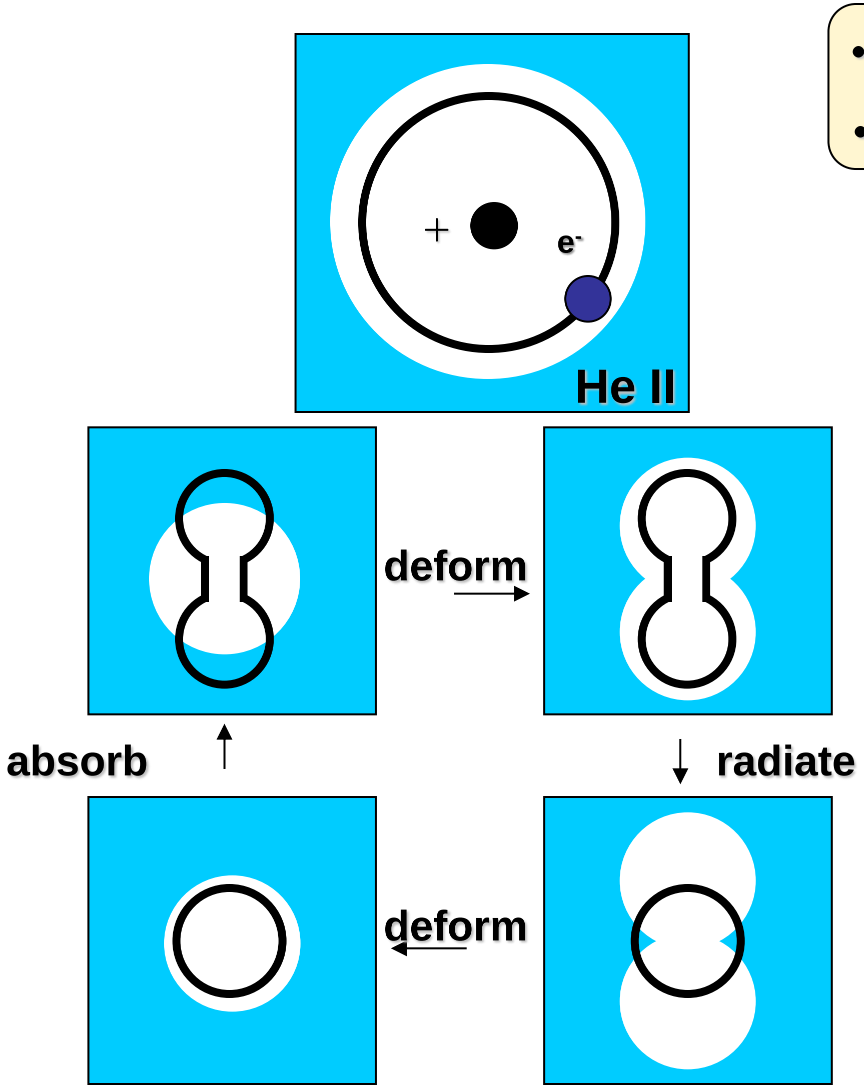
A. Hatakeyama

CNS, Univ. Tokyo:

Y. Oshiro

Atomic Spectra in He II

- Need more energy → blue shifted abs. spectrum
- Different atom-He distance → broadened spectra



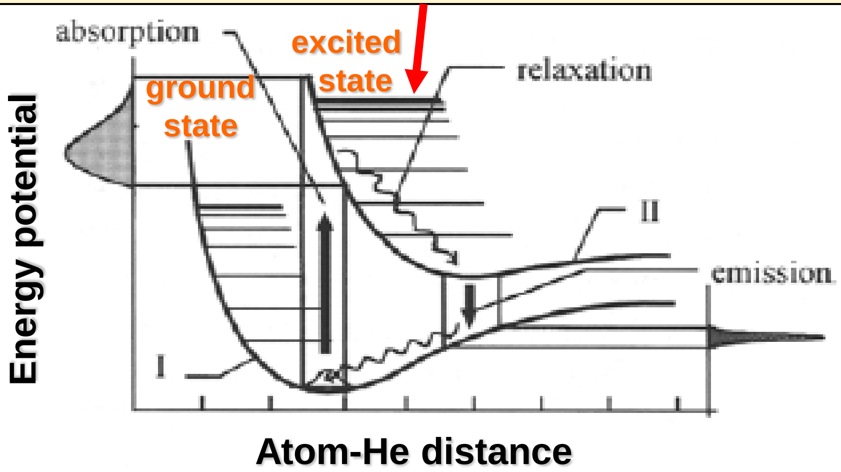
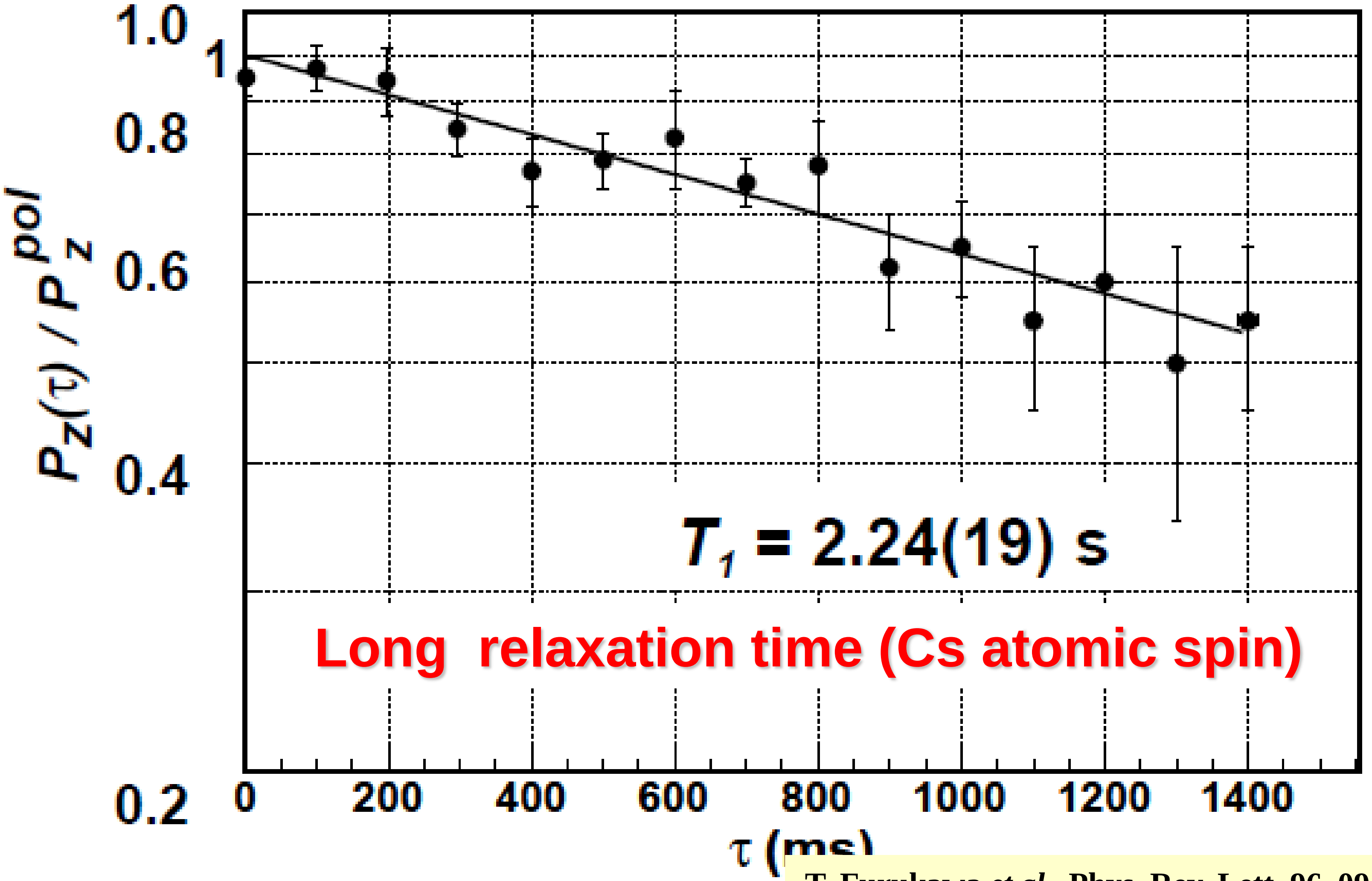


Fig. 11. Schematic configuration coordinate diagram for the ground (I) and the first excited state (II) of an atom trapped in a bubble in liquid helium. The absorption-emission cycle is accompanied by a change of the defect size due to the different equilibrium radii for both states I/II. Since the optical transitions are much faster (10^{-15} s) than the vibrational relaxation of the bubble (10^{-12} s) absorption and emission are vertical in this scheme (Franck Condon principle). Energy dissipation into the liquid during the relaxation of the bubble is the reason for the considerable wavelength shift between excitation and emission.

Long spin relaxation of ^{133}Cs in He II

Long relaxation time of atoms in He II

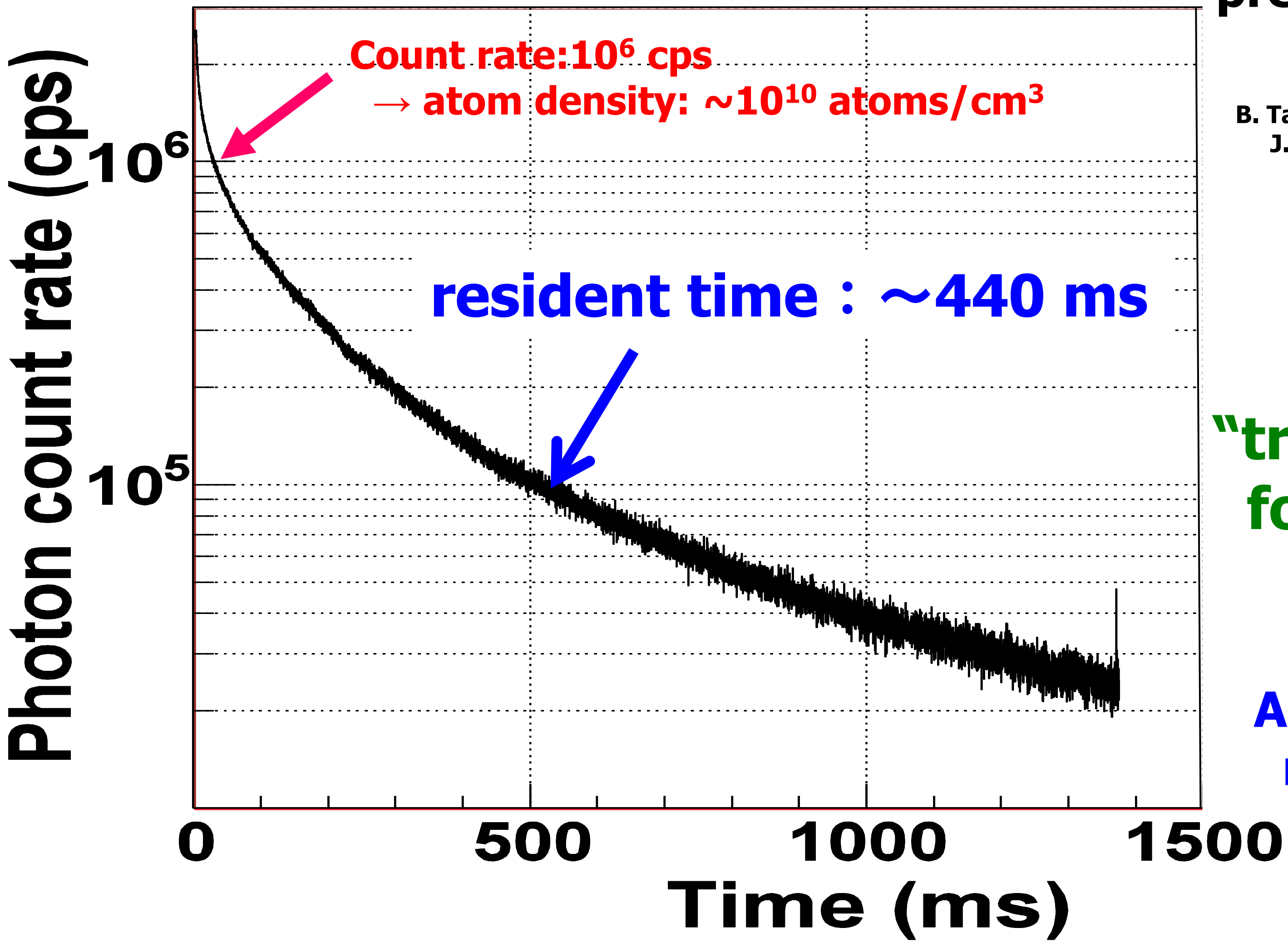
1) Spinless , 2) Small polarizability, 3) Low temperature



Long relaxation time (Cs atomic spin)

T. Furukawa *et al.*, Phys. Rev. Lett. 96, 095301 (2006)

Slow diffusion of atoms in He II



Count rate: 10^6 cps
→ atom density: ~10^{10} atoms/cm^3

resident time : ~440 ms

previous method:

~10 ms

B. Tabbert *et al.*,
J. Low Temp. Phys. 109, 653 (1997)

"trap" the atoms
for a long time

Applicable to
many experiment

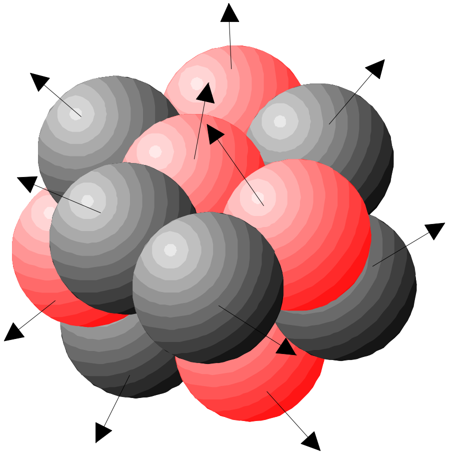
Hyperfine interactions

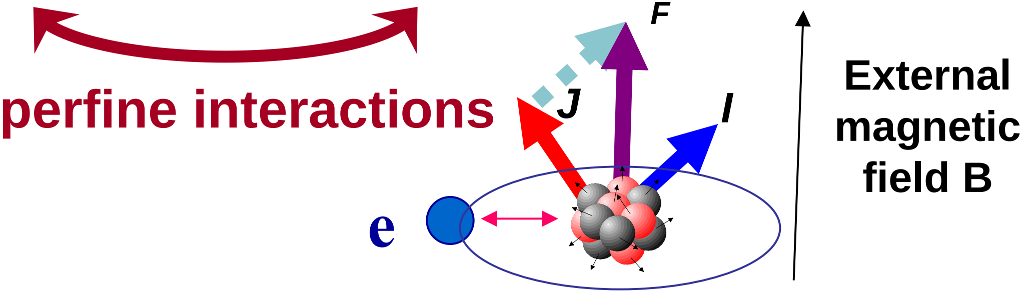
Nuclear structure

Laser spectroscopy

Nuclear spins ↔ **Zeeman splittings**

Electromagnetic moments ↔ **Hyperfine structures**



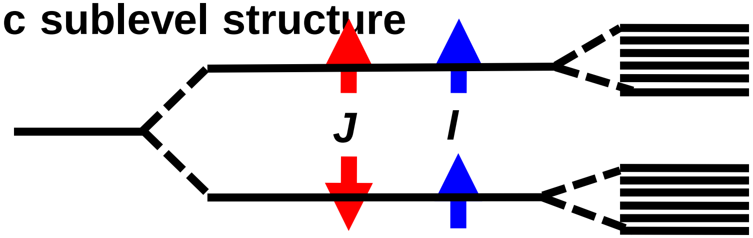


Hyperfine interactions

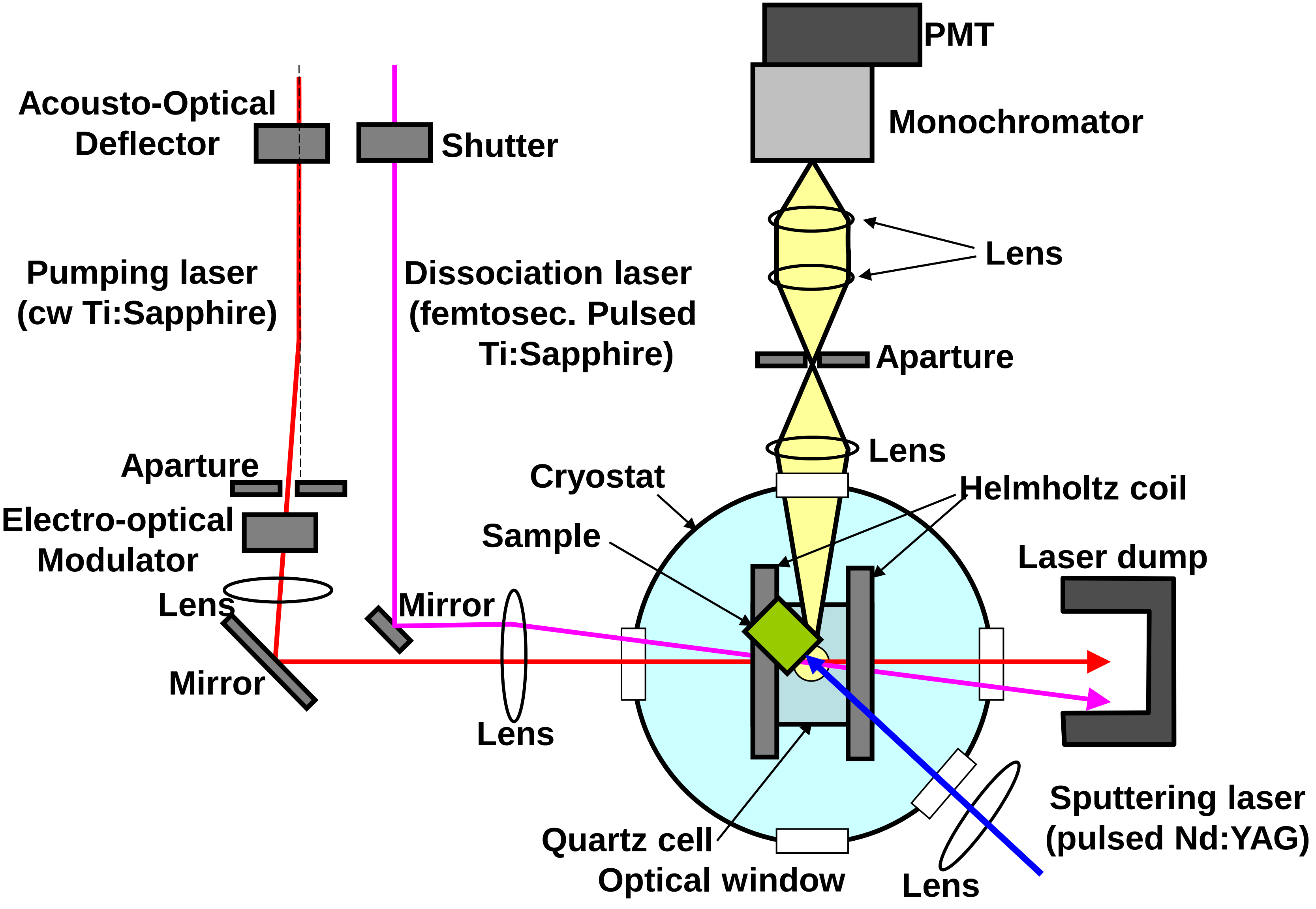
Interaction between nuclear moments and electrons

Interaction between atomic spin m_F and external magnetic field

Atomic sublevel structure

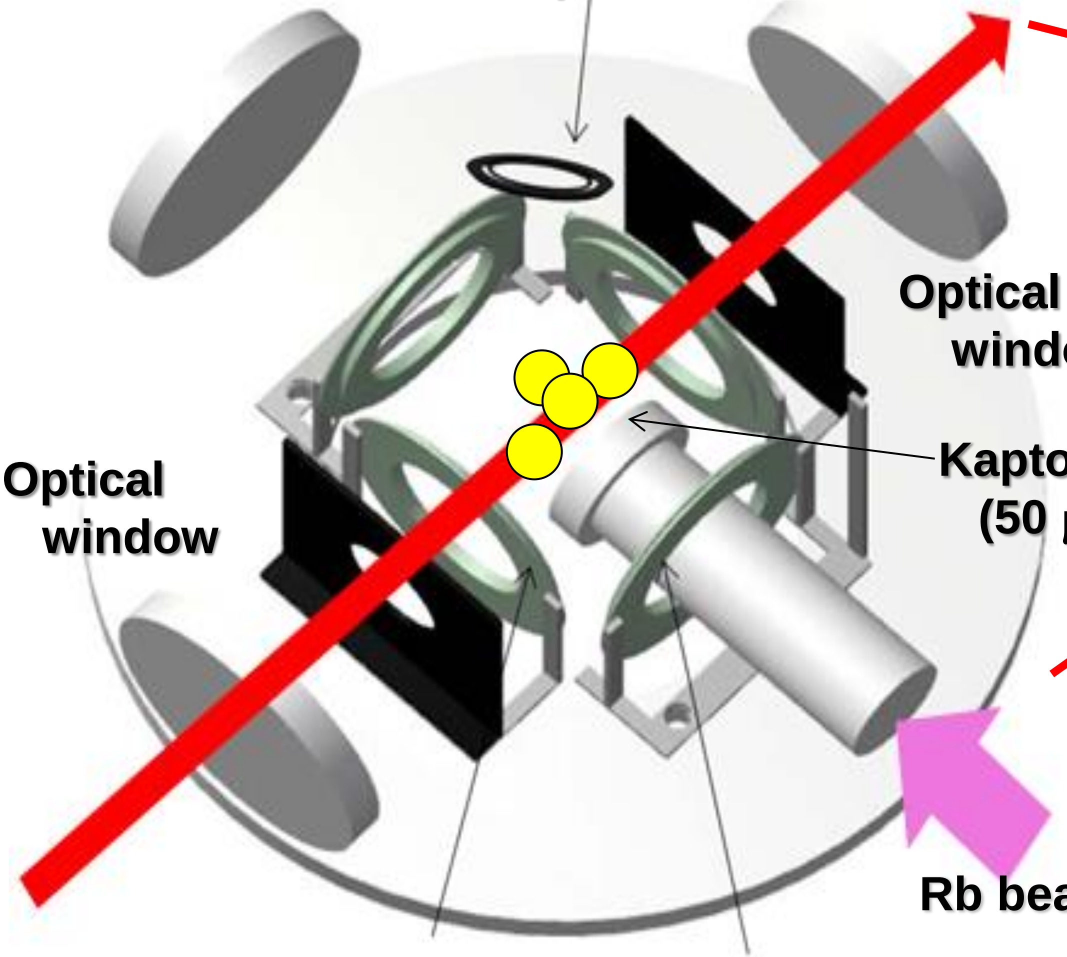


Optical apparatus



Inside of Cryostat

T_{He} = 1.8 K



MW loop antenna

Ti:Sapphire Laser
780 nm, 100 mW

Optical window

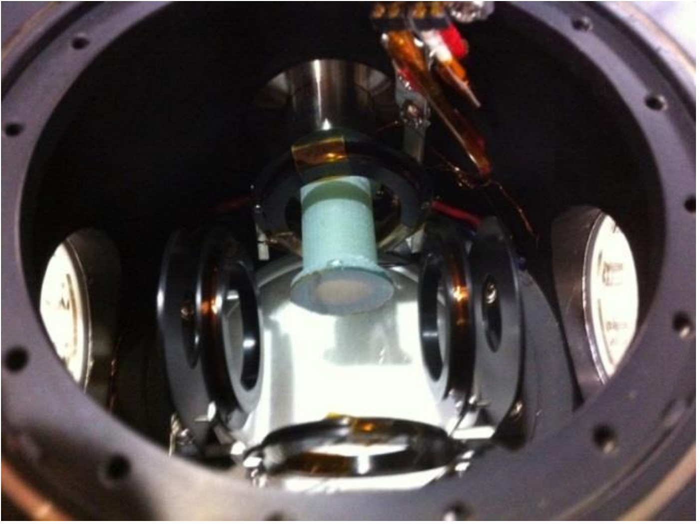
Optical window

Kapton foil
(50 μm)

Rb beam

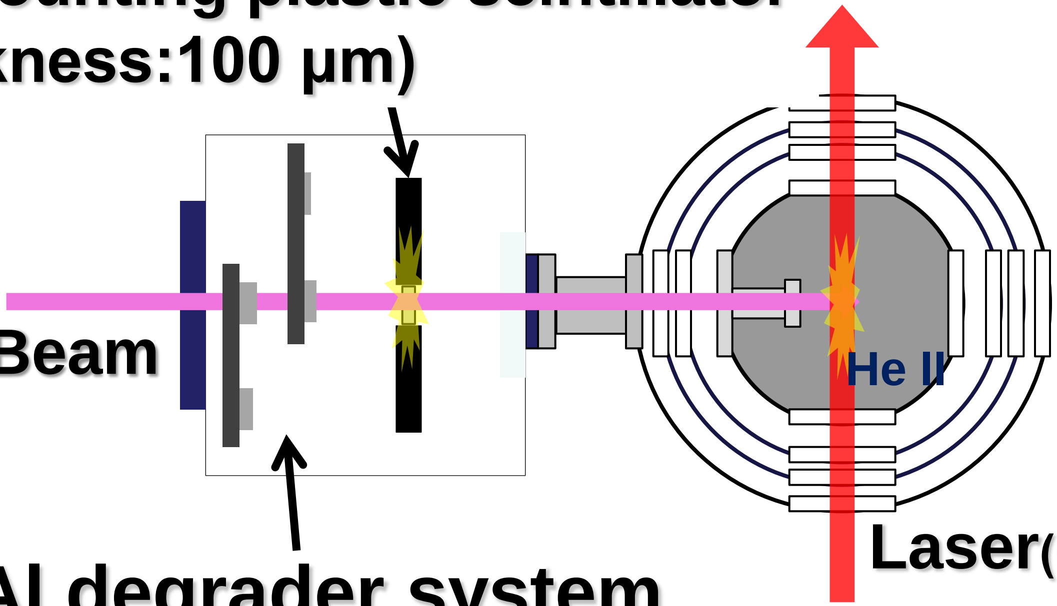
Helmholtz Coil
B_0: up to 10 Gauss

RF coil
ν : up to 3 MHz



Optimization of beam stop position

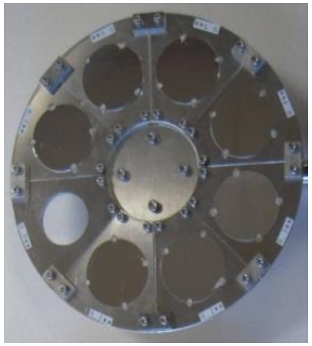
Beam counting plastic scintillator
(thickness:100 μm)



Beam

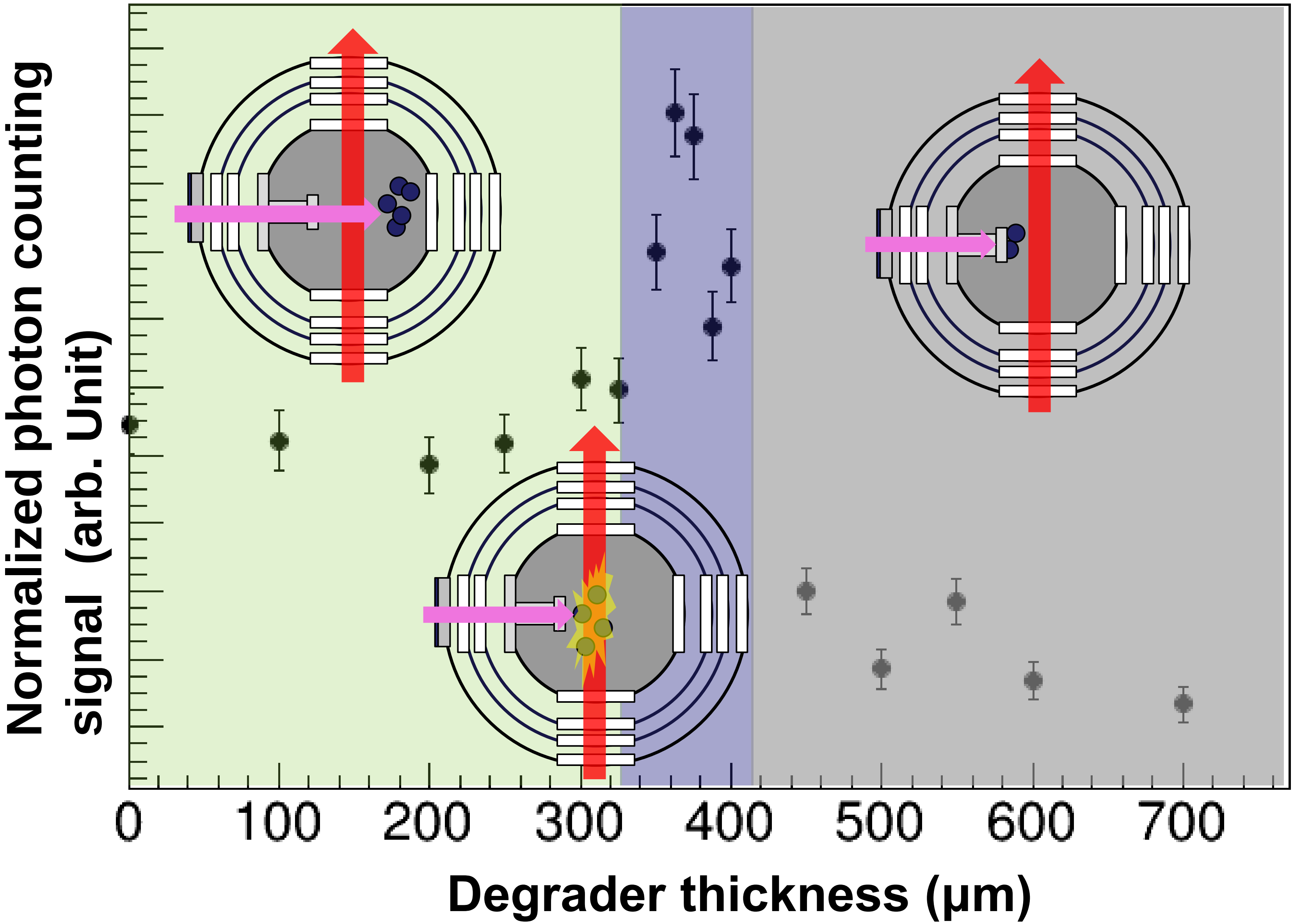
Al degrader system

Laser(Φ2 mm power:100 mW)



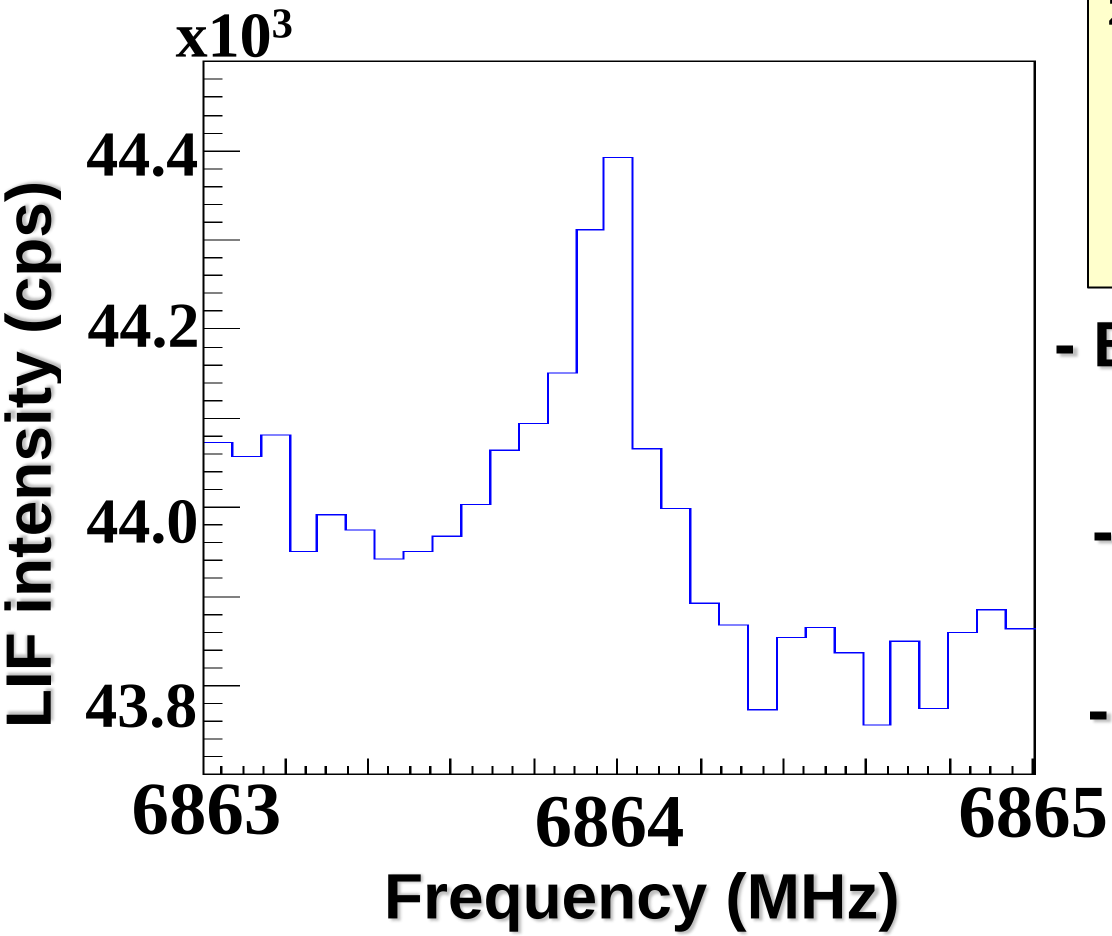
- 2 sets of Al degraders
- Available from 0 μm to 800 μm
  with 12.5 μm step.

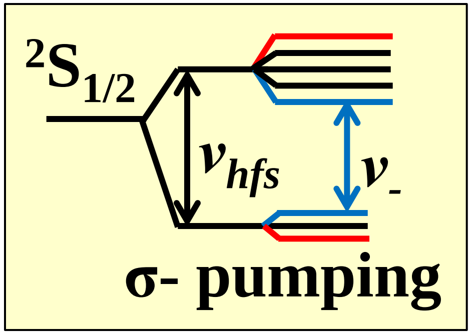
Optimization of beam stop position



HFS measurement of ^{87}Rb

HFS resonance of ^{87}Rb injected into He II





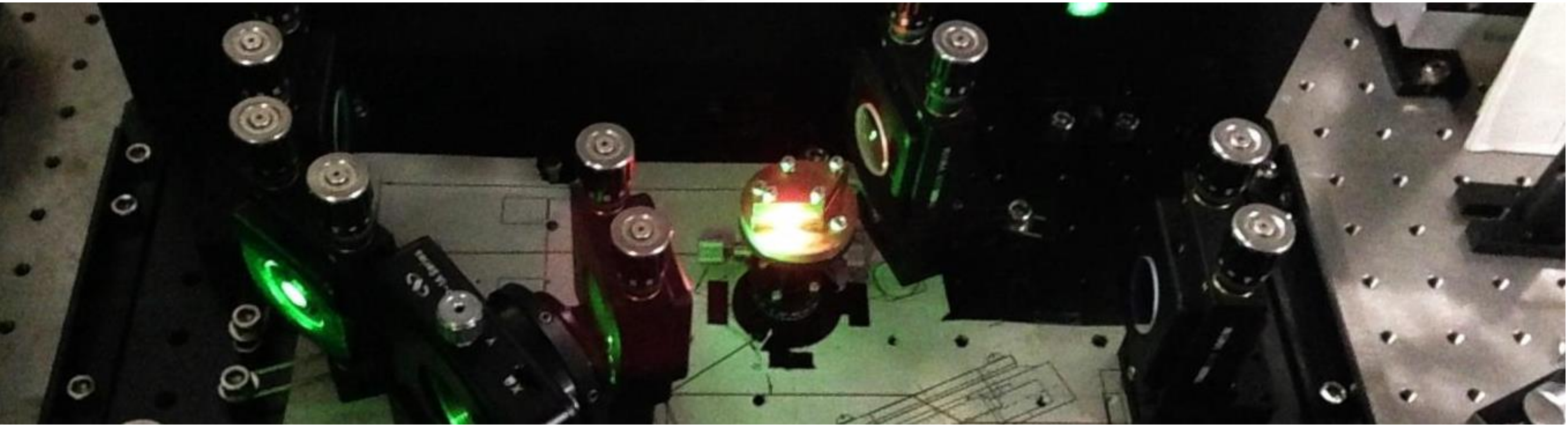
- Beam Intensity:
  8.5 × 10^3 particles / sec.
- Data acquisiting time:
  within 36 min.
- Applied magnetic field :
  2.2(1) G

New laser system

Perform optical pumping
with high rep. pulsed laser

→ More intense & tunable
pulsed Ti:Sa laser system

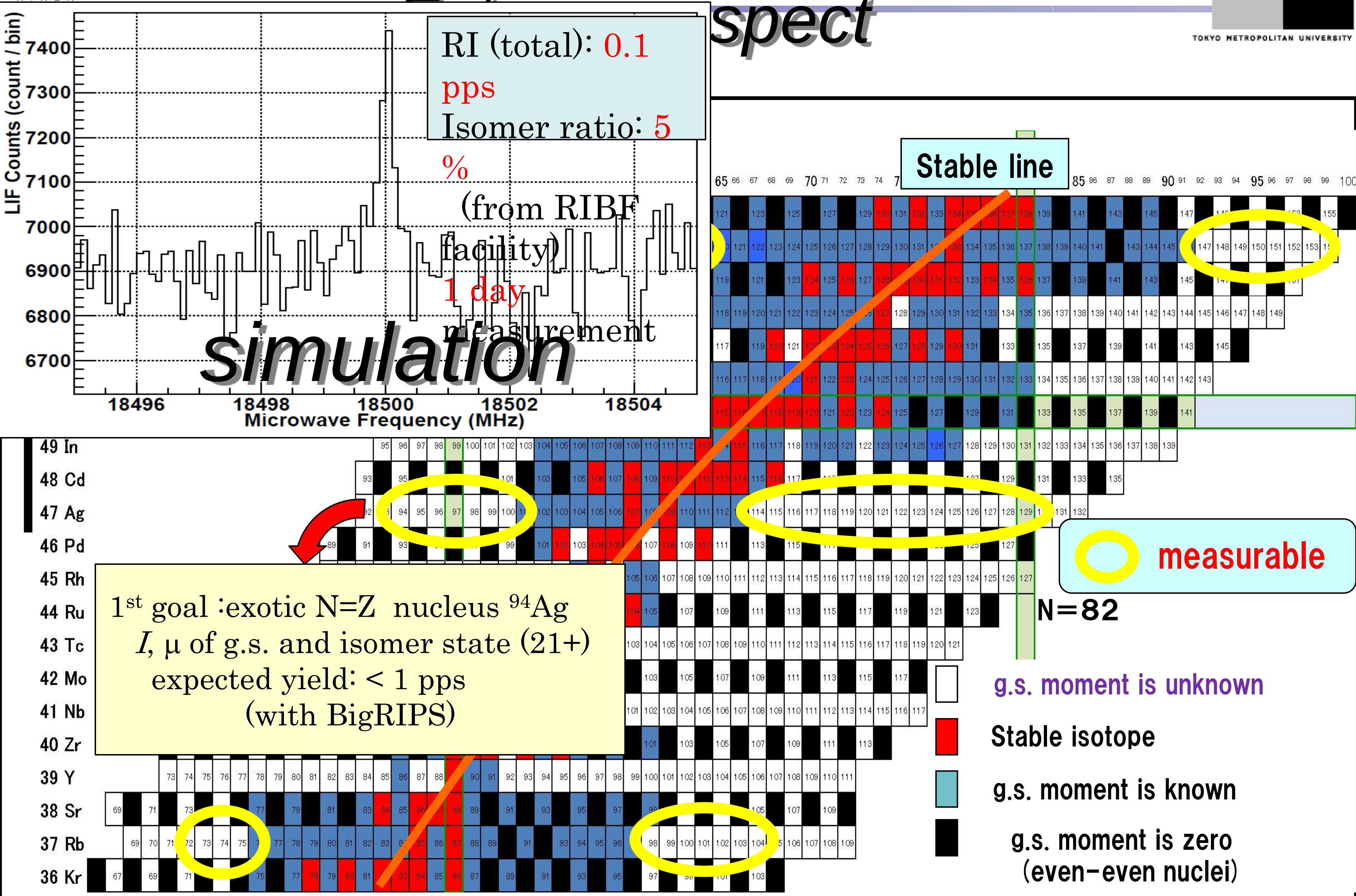
M. Hayasaka et al.,
To be presented
in Saturday afternoon.
[ML.04]



~Expected performance~

- Wavelength : 690 – 950 nm (fundamental)   Rb, Cs, Fr, ….
  350 – 470 nm (2nd harmonics)   In,
- Repetition : 1-10 kHz
- Output power : 200 mW @ 780 nm, 3 kHz rep.

spect

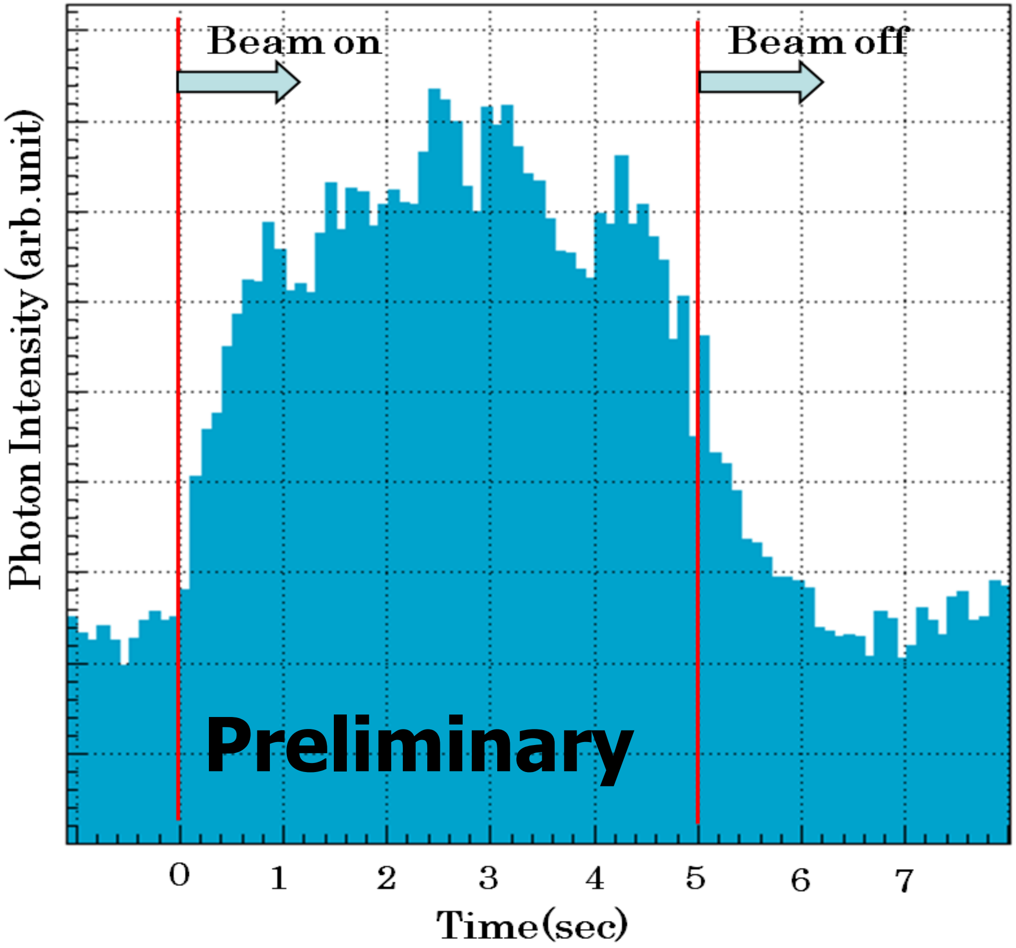


RI (total): 0.1 pps
Isomer ratio: 5 %
(from RIBF facility)
1 day measurement

1st goal :exotic N=Z nucleus ^{94}Ag
I, μ of g.s. and isomer state (21+)
expected yield: < 1 pps
(with BigRIPS)

N. J. Stone, At. Nucl. Data Tab.

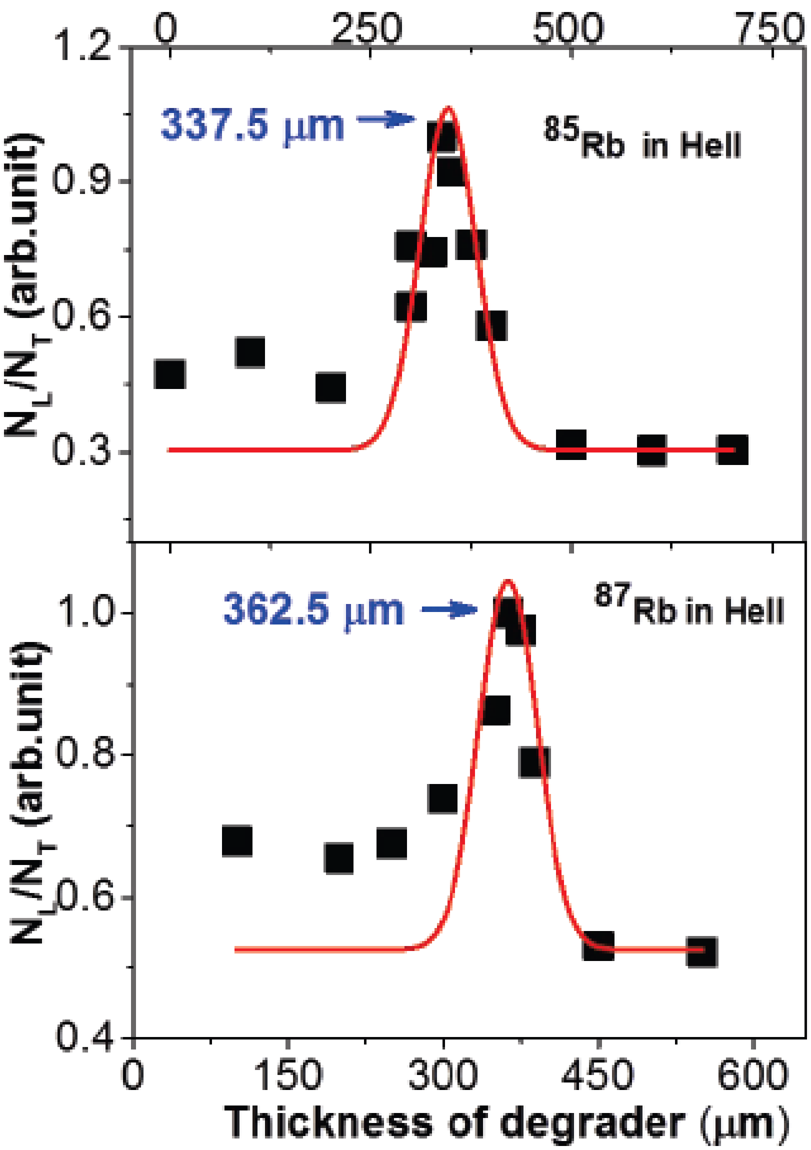
Time evolution of LIF intensities

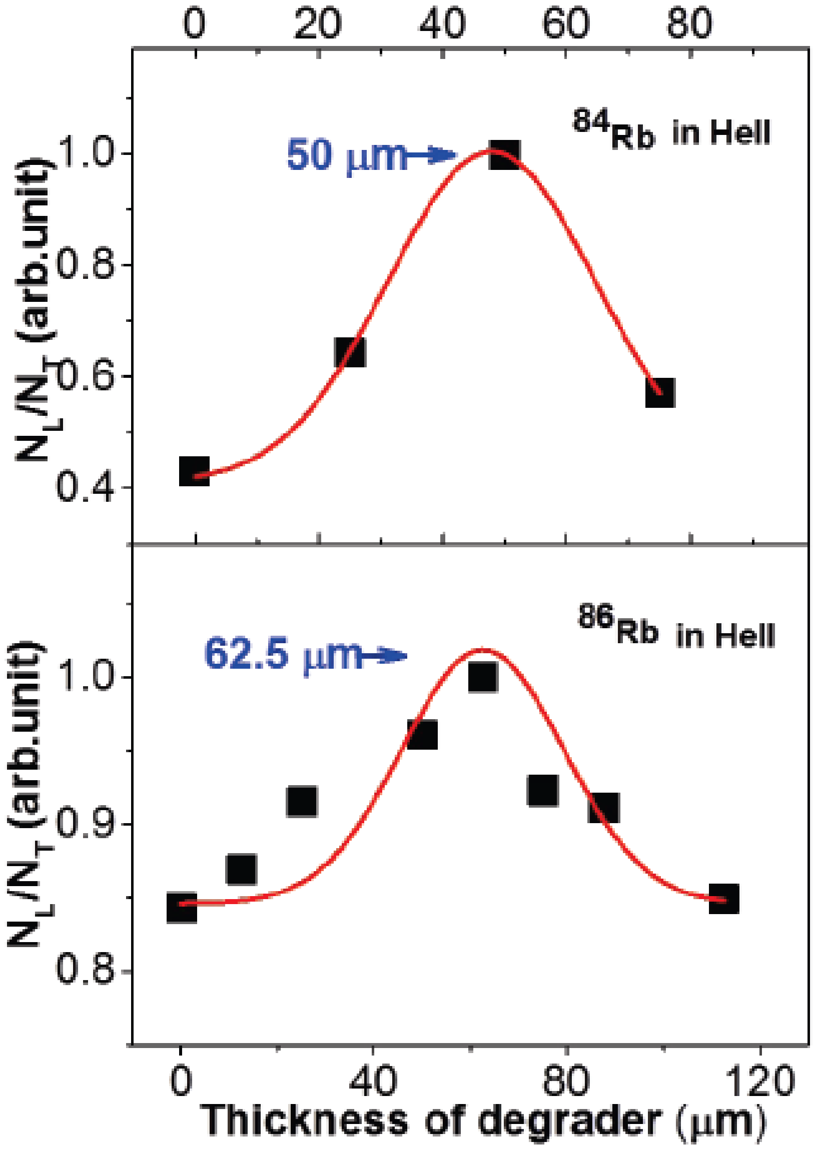


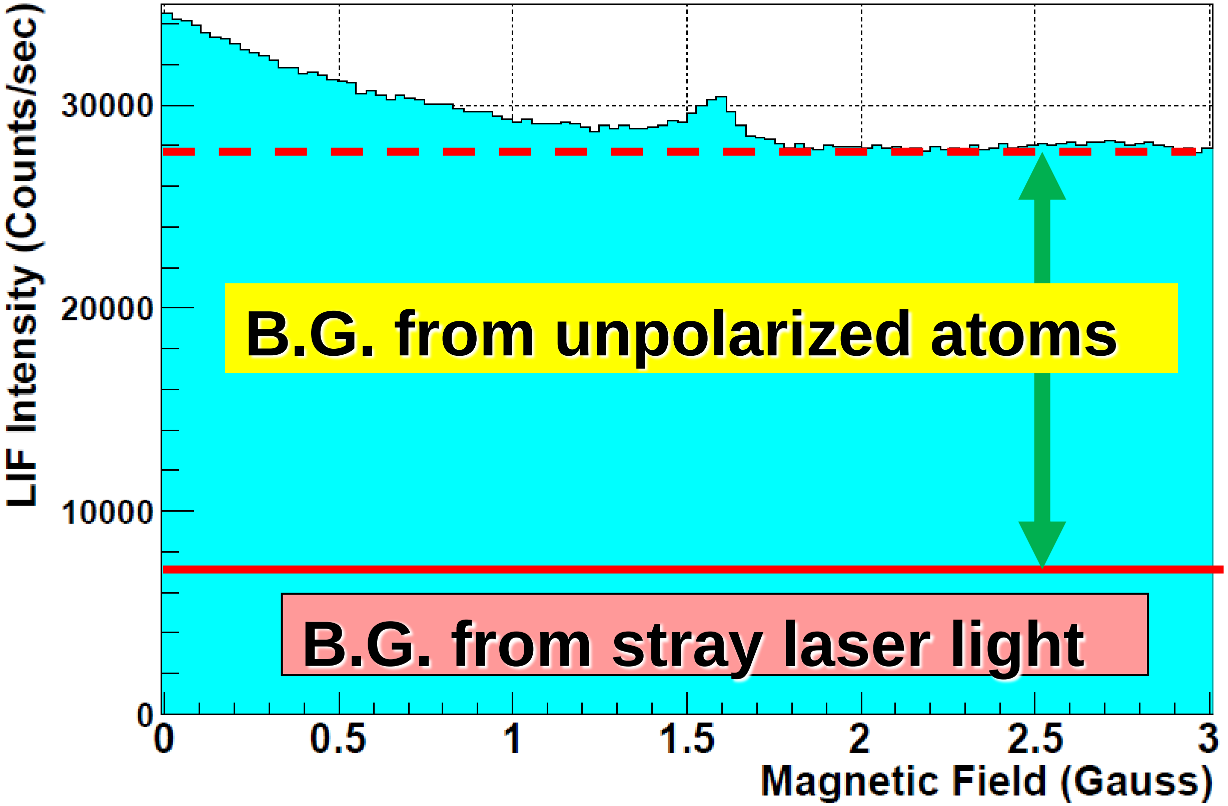
- injected Rb atoms: 1.7 x10^5 pps

- observed LIF photons: 0.8 x10^5 pps

Stopping position of atoms in He II







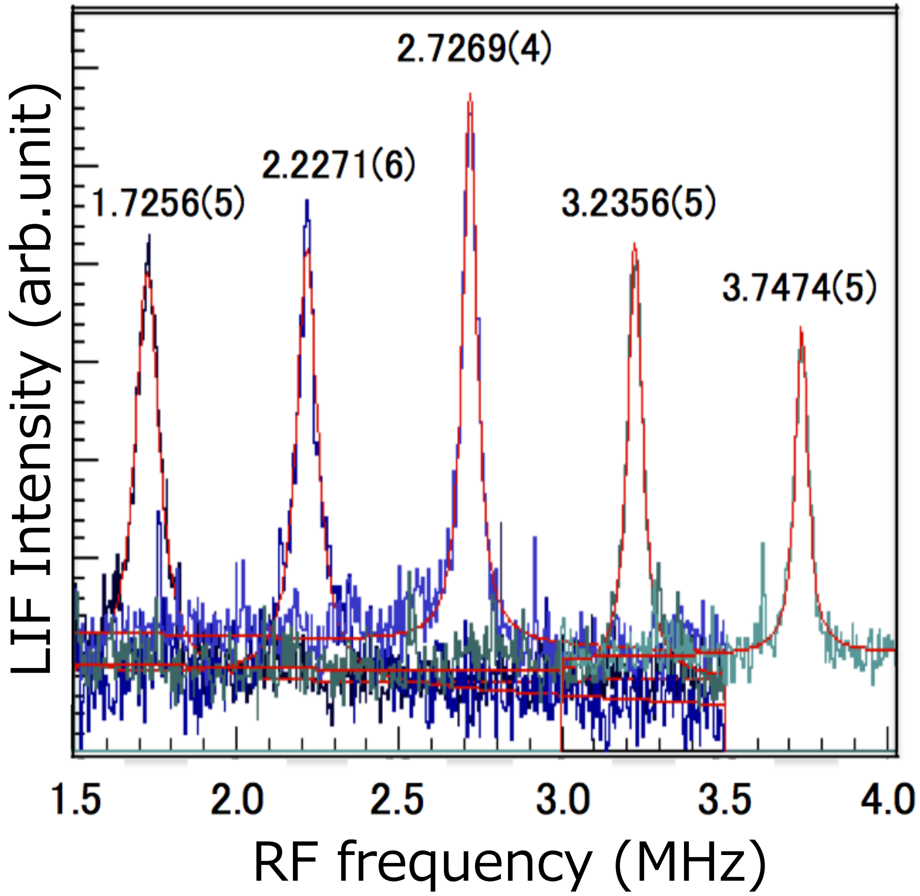
B.G. from unpolarized atoms

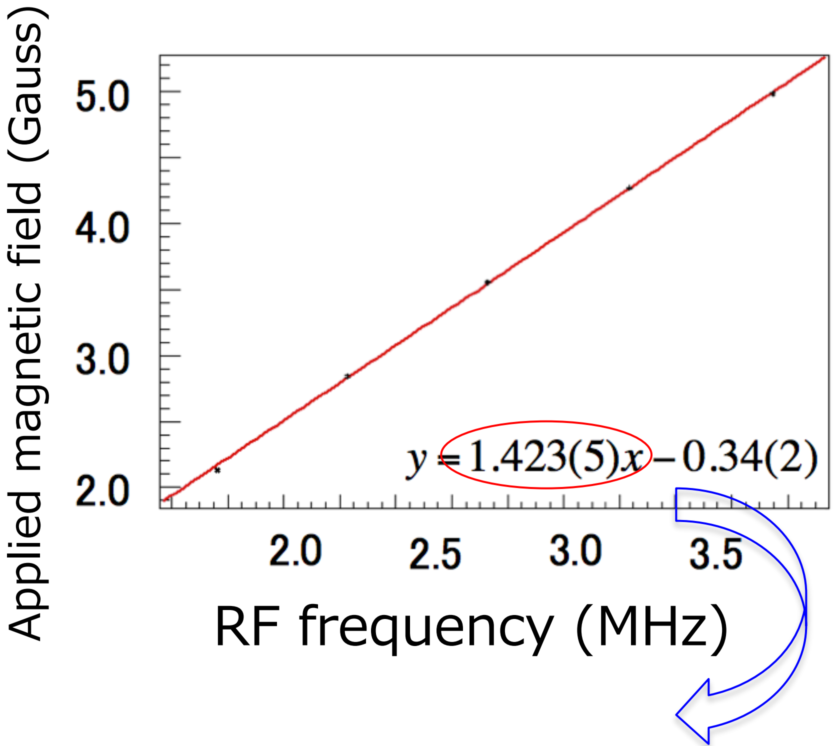
B.G. from stray laser light

Preliminarily

- Increase polarization of atoms
- Increase rf power
- Reduce remaining stray laser light
- Reduce stray magnetic field
- Reduce convection flow in He II

Zeeman splitting of ^{197}Au

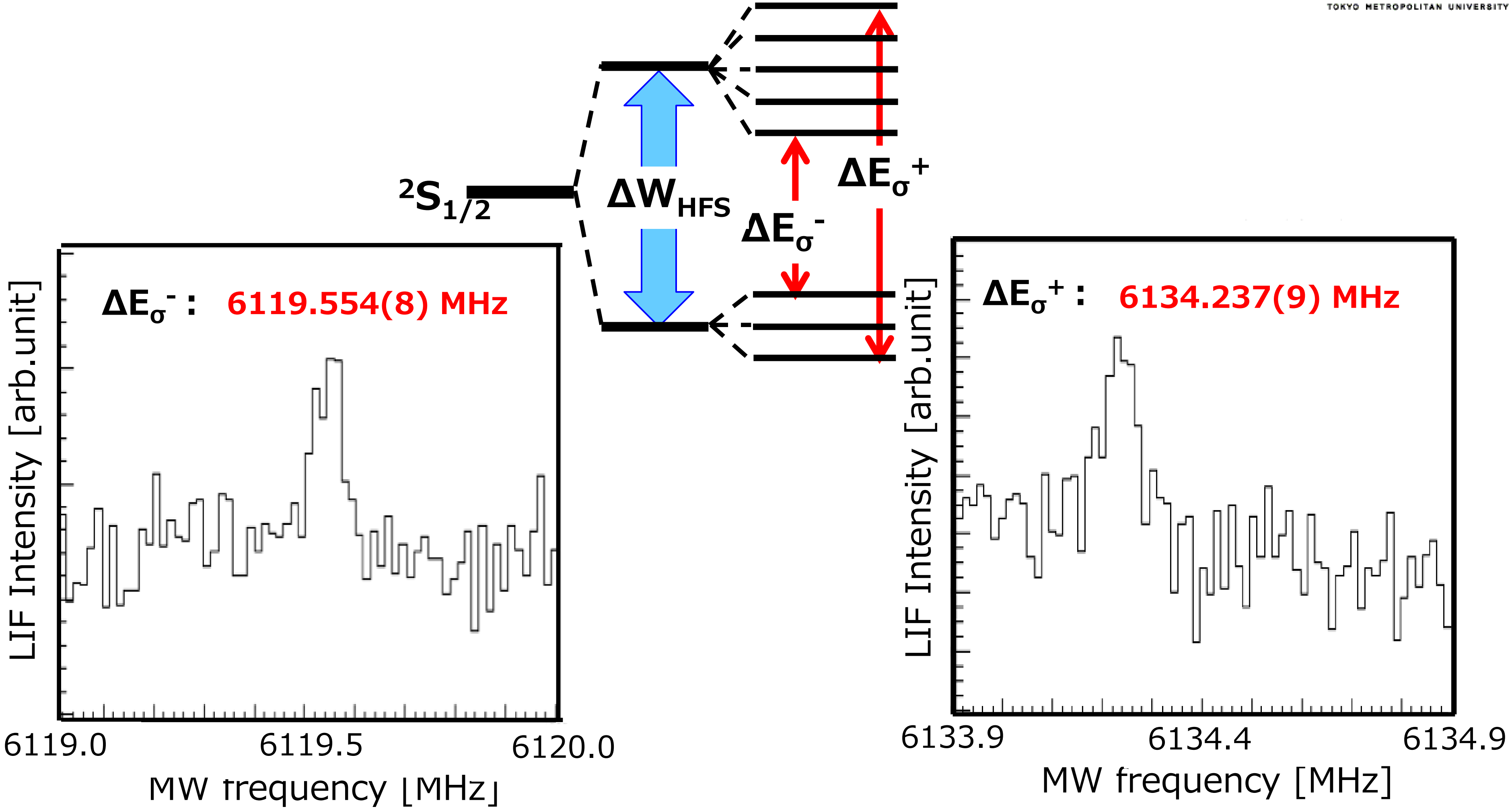




$$I \cong \frac{1}{2}\left(2.8029\frac{B}{\nu_{zeeman}} - 1\right)$$

$$I = 1.49(7)$$

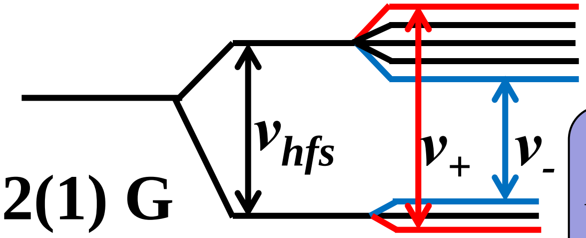
HFS of ^{197}Au



The deduced HFS ΔW_{HFS} from the results :

$$\Delta W_{HFS} = 6126.896(6)\ \text{MHz}$$

Experimental result



σ+ pumping

σ- pumping

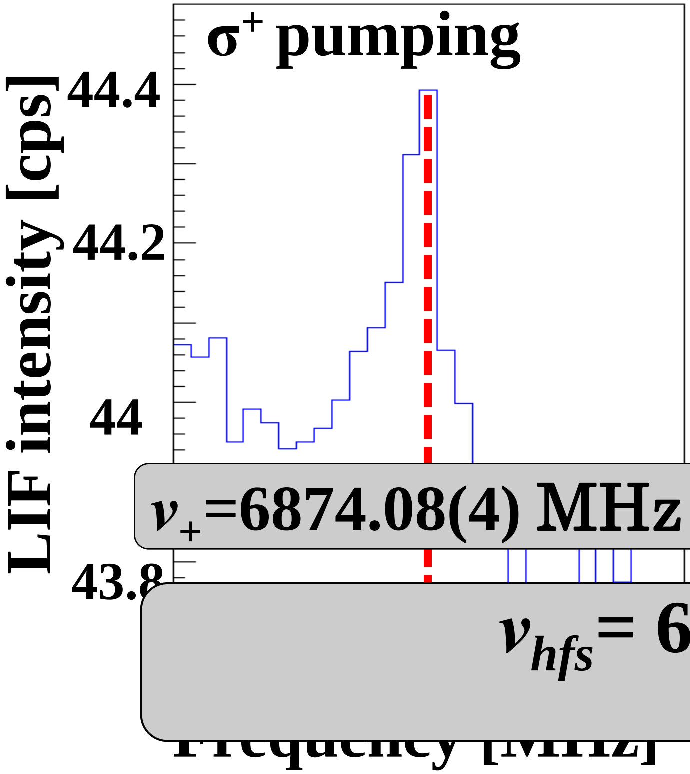
$\nu_{hfs}=(\nu_+ + \nu_-)/2$

ν: Transition frequency

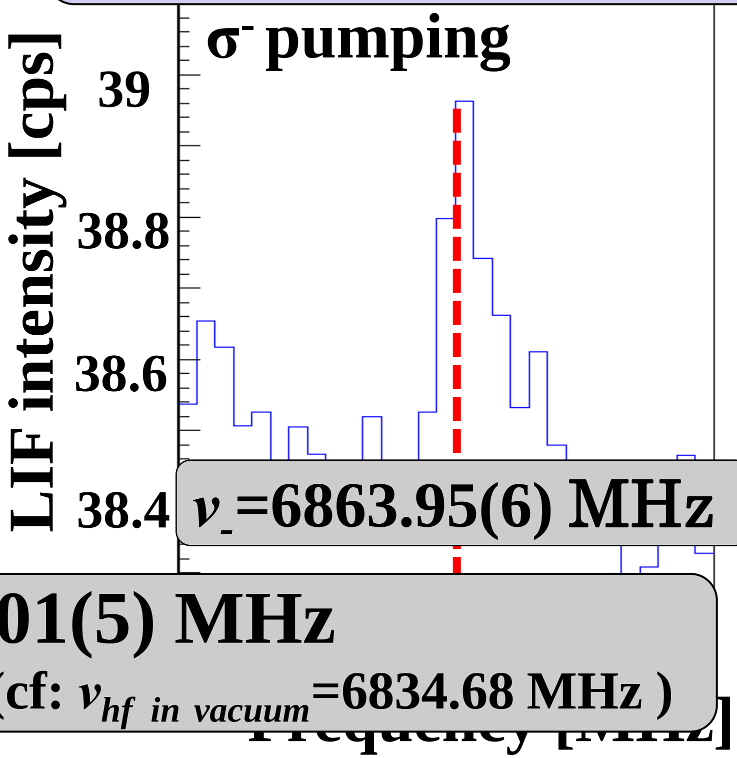
The applied magnetic field : 2.2(1) G

8.5×10^3 particle par sec.,
Measurement time:36 min.

1.0×10^4 particle par sec.,
Measurement time:36 min.



ν_+=6874.08(4) MHz

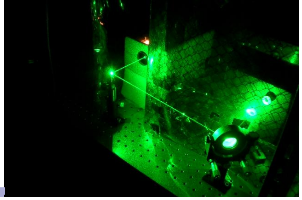


ν_-=6863.95(6) MHz

ν_{hfs}= 6869.01(5) MHz

(cf: $\nu_{hf\ in\ vacuum}$=6834.68 MHz)

Laser spectroscopy of Ag and Au



T. Furukawa, K.Fujikake, Y. Matsuura *et al.*, to be published…

Apply to noble metal Ag and Au atoms

Broadened absorption spectra in He II.

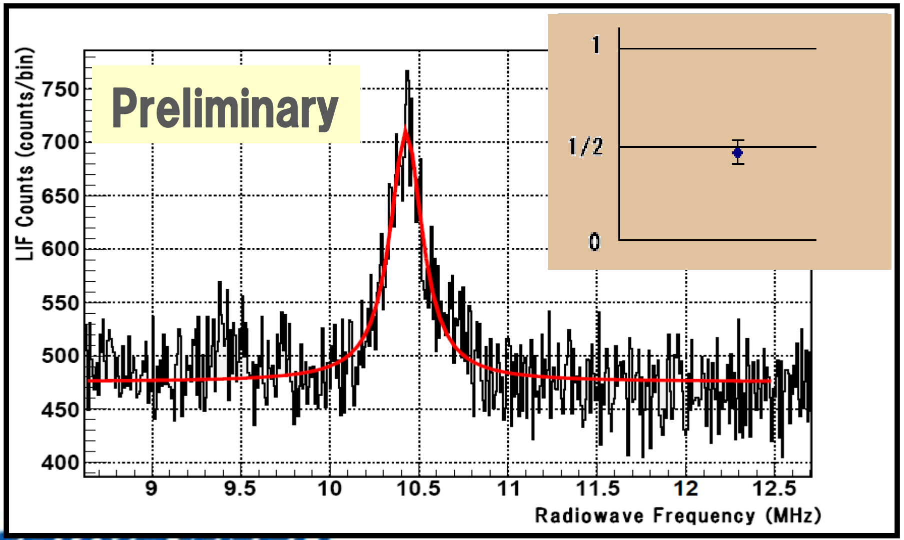
→ feasible to optically pumping various atomic species

(less limitation of laser wavelength)

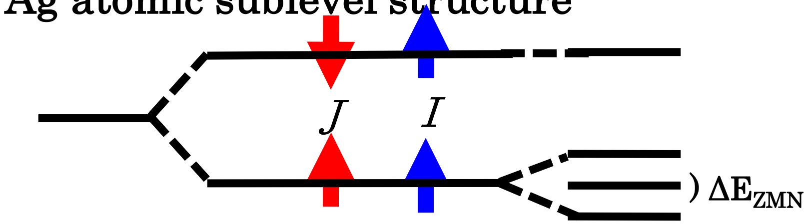
polarization: ~85% (both Ag and Au)

incomplete polarization is due to imperfect circular polarization of laser

Zeeman splitting of stable ^{107,109}Ag isotopes (both I=1/2)

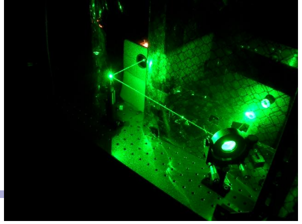


Ag atomic sublevel structure

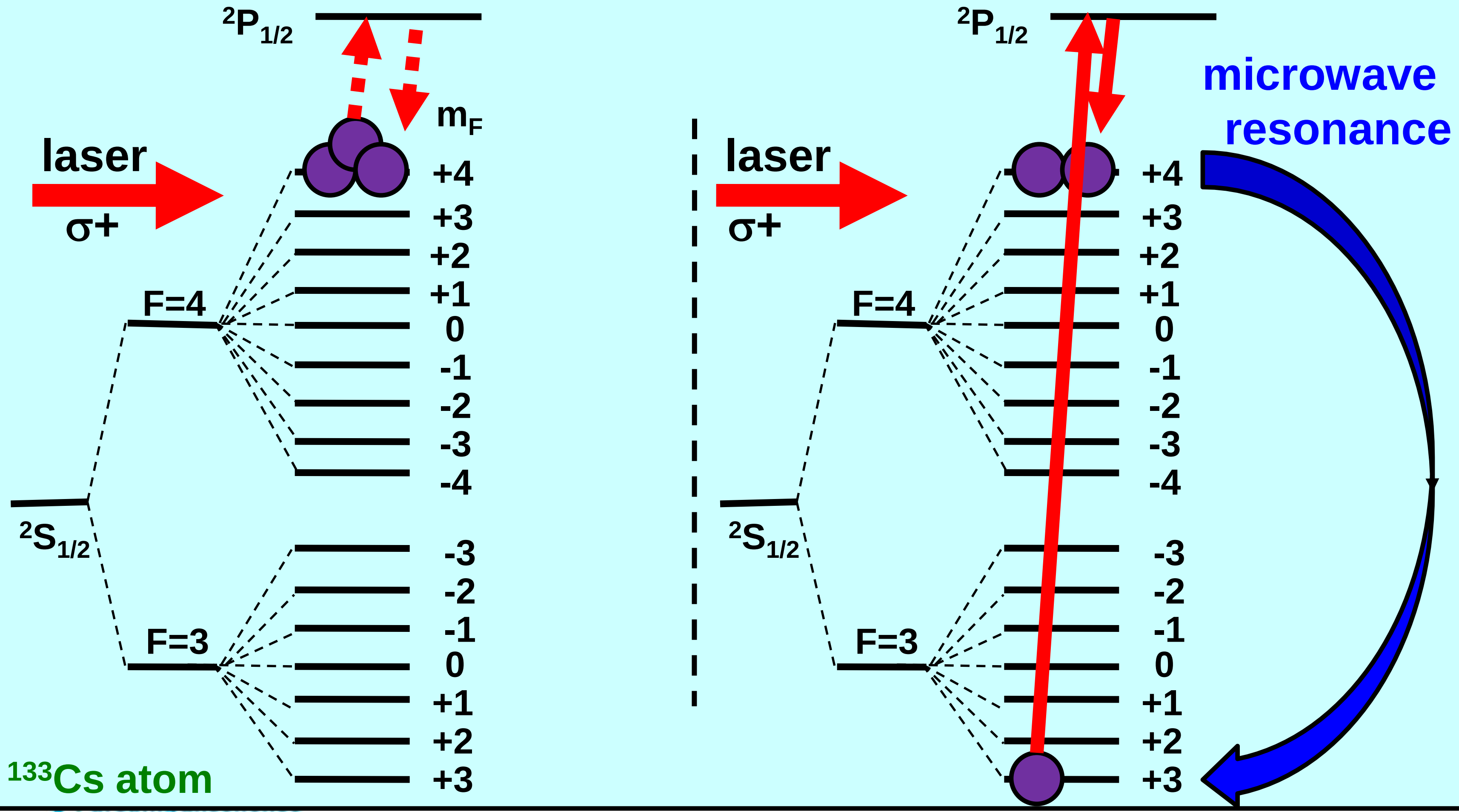


Nuclear spin I=1/2
can be deduced clearly.

Laser Spectroscopy

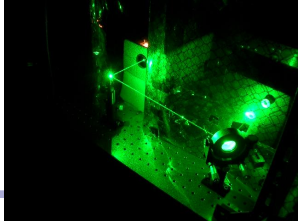


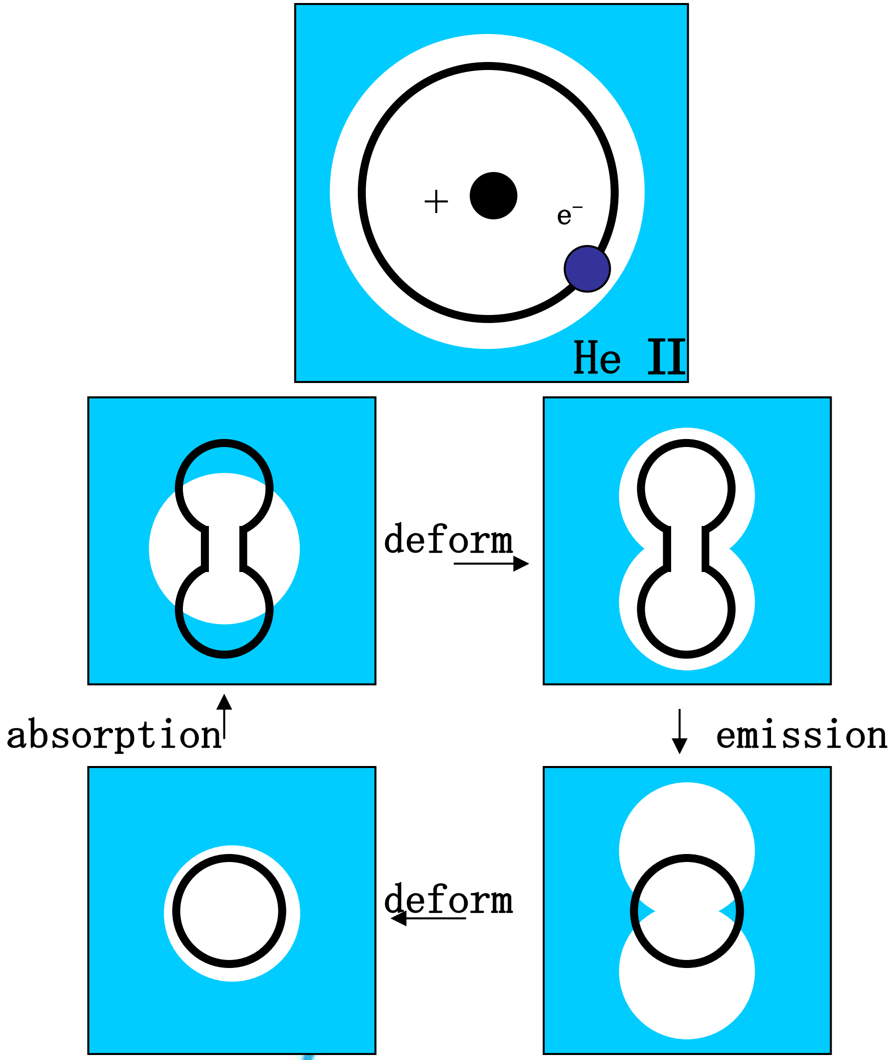
laser-microwave double resonance
hyperfine splitting energy → nuclear moments determination



^{133}Cs atom

Atomic Spectra in He II





- need more energy → blue shifted abs. spectrum
- different atom-He distance → broadened spectra

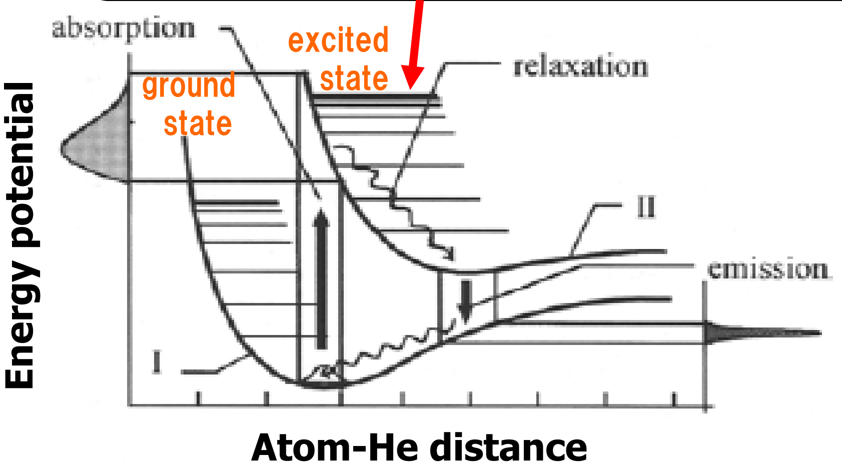
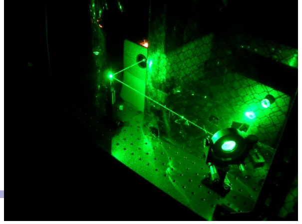
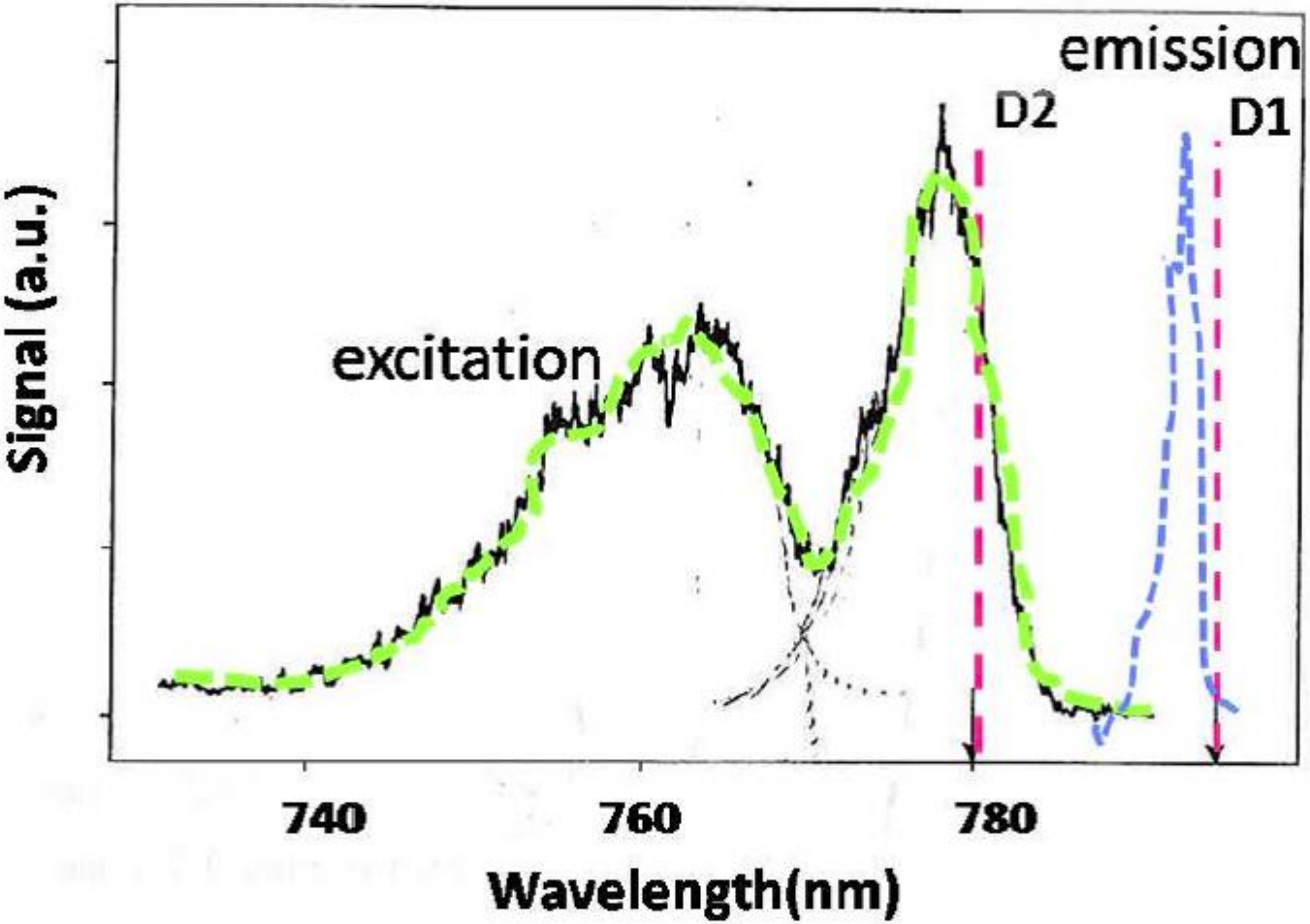


Fig. 11. Schematic configuration coordinate diagram for the ground (I) and the first excited state (II) of an atom trapped in a bubble in liquid helium. The absorption-emission cycle is accompanied by a change of the defect size due to the different equilibrium radii for both states I/II. Since the optical transitions are much faster (10^{-15} s) than the vibrational relaxation of the bubble (10^{-12} s) absorption and emission are vertical in this scheme (Franck Condon principle). Energy dissipation into the liquid during the relaxation of the bubble is the reason for the considerable wavelength shift between excitation and emission.




emission
D2
D1
excitation
Signal (a.u.)
740
760
780
Wavelength(nm)