22nd International Spin Symposium

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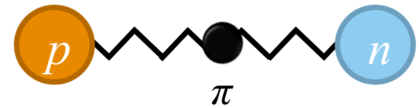
Measurement of analyzing powers for $p-{}^{3}\mathrm{He}$ scattering with polarized ${}^{3}\mathrm{He}$ target

Department of Physics, Tohoku University, Japan

Atomu Watanabe

Introduction

2-Nucleon Forces



first formulated by H. Yukawa → **meson exchange picture**

Proc. Phys. Math. Soc. Jpn **17**, 48 (1935)

1960's~ performed many *NN* scattering exp. throughout the world

1990's **realistic *NN* potentials** (AV18, CD-Bonn, Nijmegen I&II)

→ precisely reproduced many *NN* scattering data ($N_{\mathrm{data}} \sim 4000, \chi^2 \sim 1$)

A≧3 system

- scattering observables (d+p)
- binding energies (^{3}H, ^{3}He)
- equation of state of nuclear matter

only *NN* potential

reproduced by **Three-Nucleon Forces (3NFs)**

Experimental study of 3NFs

Property of Nuclear Force

- momentum dependence
- spin dependence
- isospin dependence

→ **Few-Nucleon Scattering** is a good approach

direct comparison

precise data ⇔ rigorous theoretical calc.

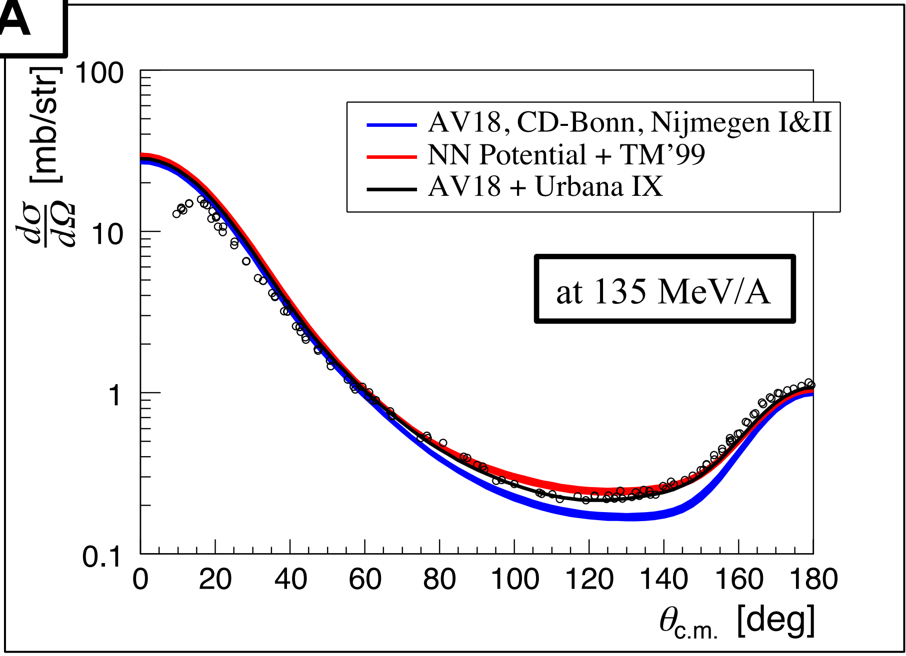
→ **quantitative discussion of 3NFs**

***d*+*p* elastic scattering at 70~300 MeV/A**

$$\frac{d\sigma}{d\Omega},\ A_{ij}$$

↓ precise data ↓

The first signatures of 3NFs
in 3-nucleon scattering system
(at intermediate energy)



K. Sekiguchi *et al.*, PRC **65**, 034003 (2002)

3NFs effect in 4-nucleon system

Our Next Step

- ◆ 3NFs effects in the A≧4 system
- ◆ isospin dependence of 3NFs

➡ we focus on p+^{3}He system

- theoretical calculation (at low energy)
- the appearance of 3NFs at intermediate energy…?

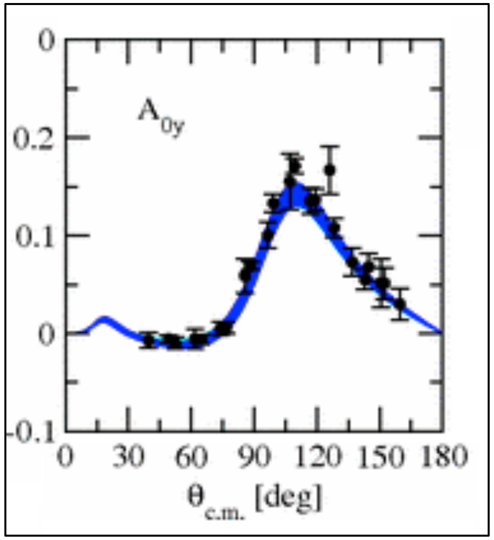
Planning the measurement in p-^{3}He scattering system (at 70 MeV)

$$\frac{d\sigma}{d\Omega}, \ A_y(^3\text{He and } p)$$

^{3}He analyzing power (spin observable)

➡ need to develop **the polarized ^{3}He target**

A_y^{3He} calculation at E_p = 5.54 MeV

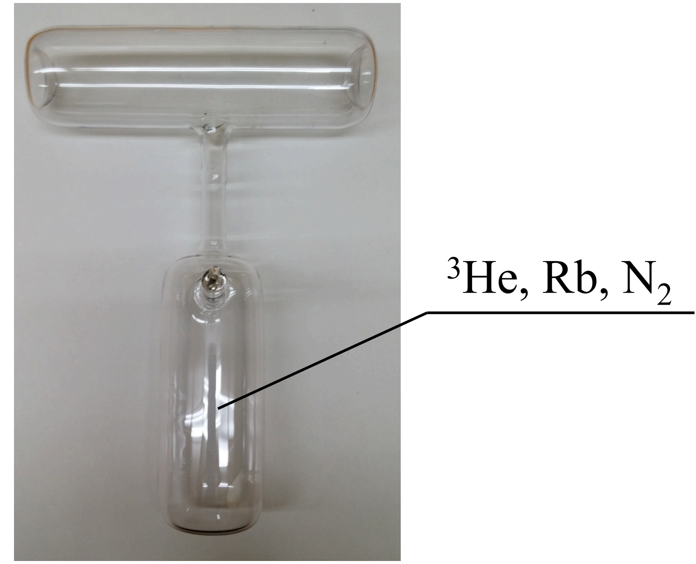


M. Viviani *et al.*, PRL **111**, 172302 (2013)

Polarized ^{3}He target

Requirement for our exp.

- high polarization (> 20 %)
- high density (~3 atm at room temp.)
- measuring polarization during scattering exp.

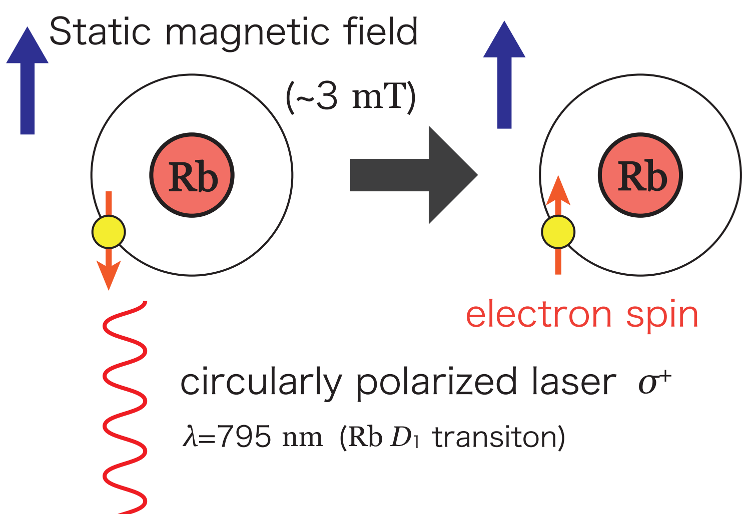


target glass cell

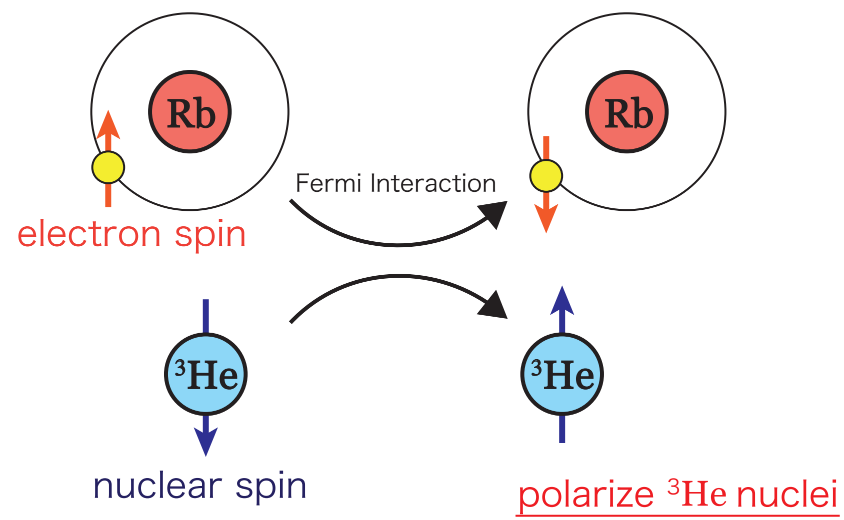
How to polarize ^{3}He gas

Method : **Spin Exchange Optical Pumping (SEOP)**

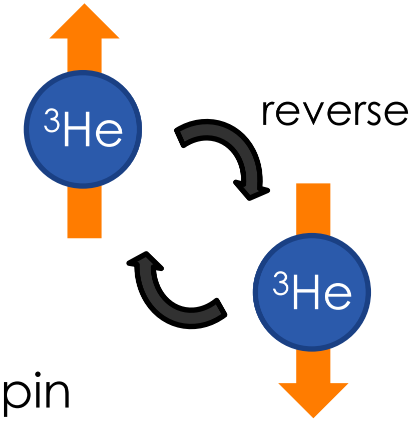
① Polarization of Rb atom



② Spin-Exchange

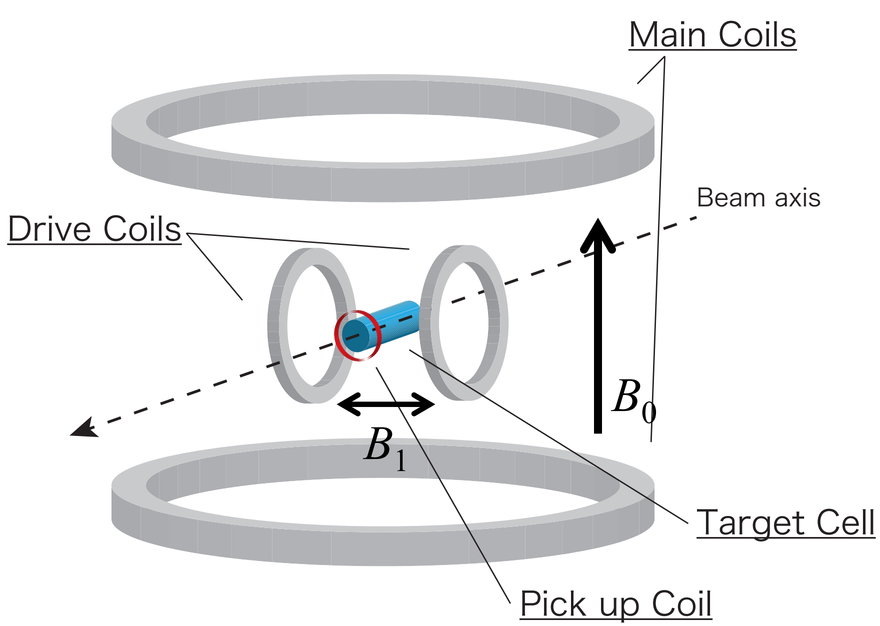


^{3}He polarization measurement

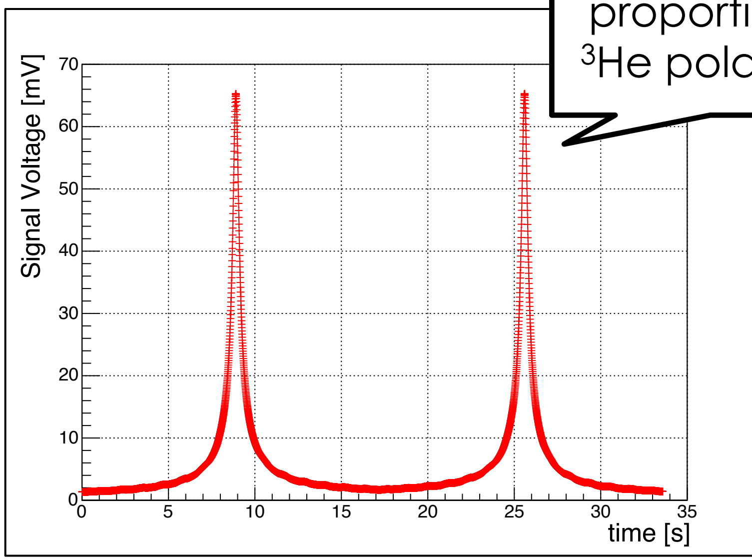


AFP-NMR method

- RF + sweeping magnetic field ➡ reverse ^{3}He nuclear spin
- detect induced voltage by pick-up coil



Schematic view of NMR system



NMR signal is proportional to ^{3}He polarization

Typical NMR signal

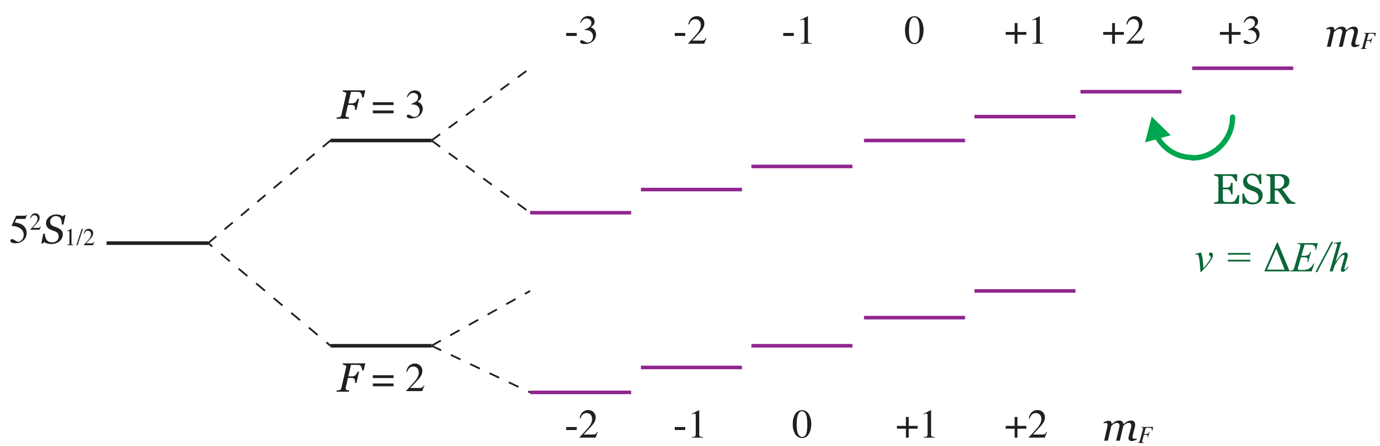
This method does not give **the absolute ^{3}He polarization**

Calibration of NMR signal

Rb-ESR

Ref. : See, e.g., M. V. Romalis and G. D. Cates, Phys. Rev. A **58**, 3004 (1998)

- in the presence of magnetic field, energy levels of Rb are split (**Zeeman effect**)
- because of the presence of polarized ^{3}He, ESR frequency shift comes about
- ESR freq. shift is proportional to ^{3}He polarization



Energy levels of ^{85}Rb

Hyper fine structure

Zeeman spliting

Calibration of NMR signal

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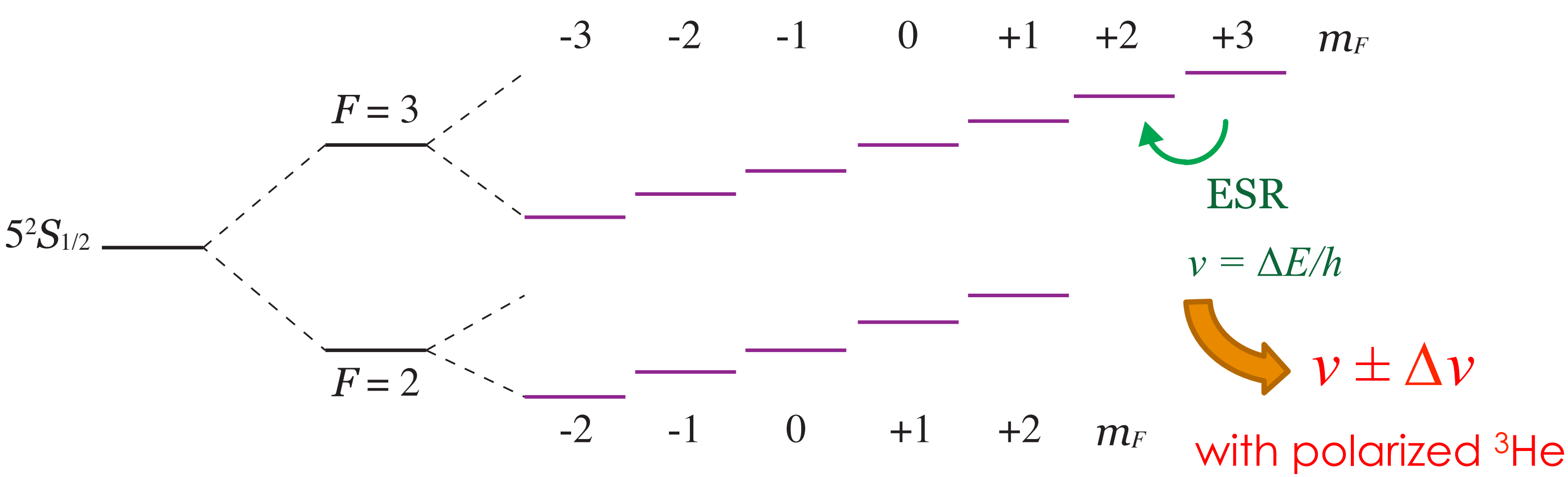
➡ **obtaining the absolute ^{3}He polarization** and **calibration of NMR signal** are possible



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Calibration of NMR signal

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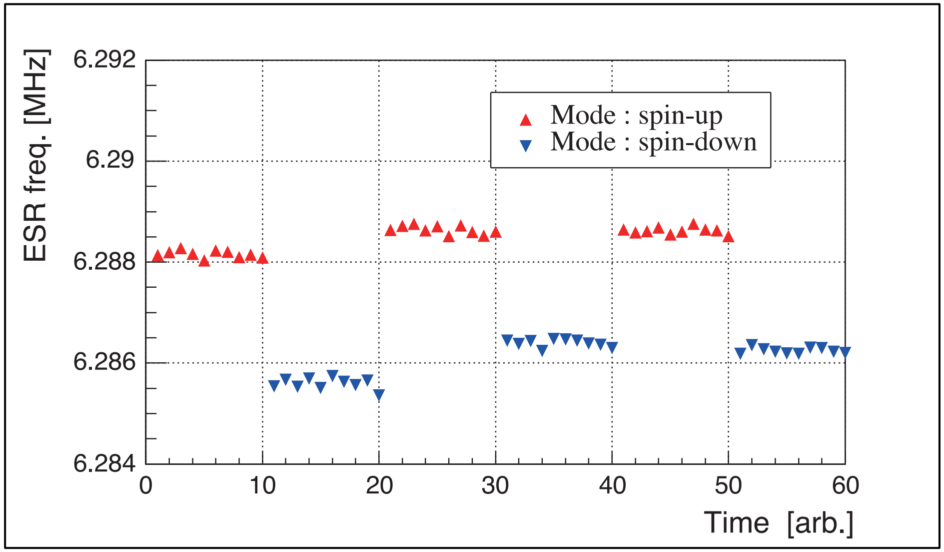
- in the presence of magnetic field, energy levels of Rb are split (**Zeeman effect**)
- because of the presence of polarized ^{3}He, ESR frequency shift comes about
- ESR freq. shift is proportional to ^{3}He polarization

⇒ **obtaining the absolute ^{3}He polarization** and **calibration of NMR signal** are possible

- measure ESR freq. in ^{3}He nuclear spin-up and down
- ESR freq. shift between spin-up and down is **a few kHz**

as a result…

the value of ^{3}He polarization is ~10 %



Typical result of ESR freq. measurement

p-^{3}He elastic scattering exp.

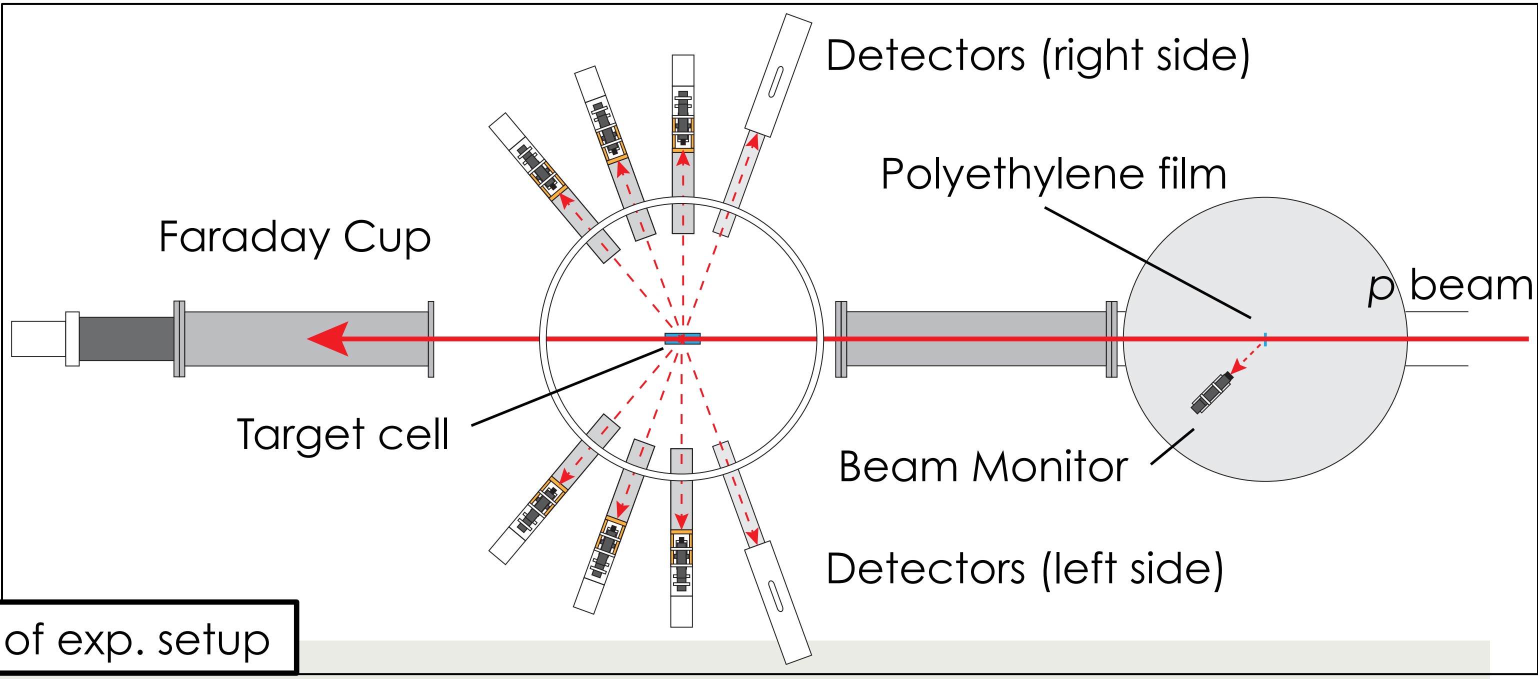
@CYRIC, Tohoku Univ.

Setup

- beam : 70 MeV proton (~ 5nA)
- target : polarized ^{3}He gas (~3 atm, 2.98 mg/cm^2)
- detector : ΔE-E detector (PID by ΔE-E coincidence)
- measured angles : 50°, 70°, 90°, 110° (lab. system)

plastic(1 mm)
+
plastic (50 mm) or
NaI(Tl) (50 mm)

solid angle : ~0.4 msr



Schematic view of exp. setup

p-^{3}He elastic scattering exp.

@CYRIC, Tohoku Univ.

- beam intensity is measured by Faraday Cup and Beam Monitor
- reverse ^{3}He nuclear spin direction by AFP-NMR method
- detect protons scattered by ^{3}He nuclei
- and compare yields before and after reverse ^{3}He nuclear spin direction

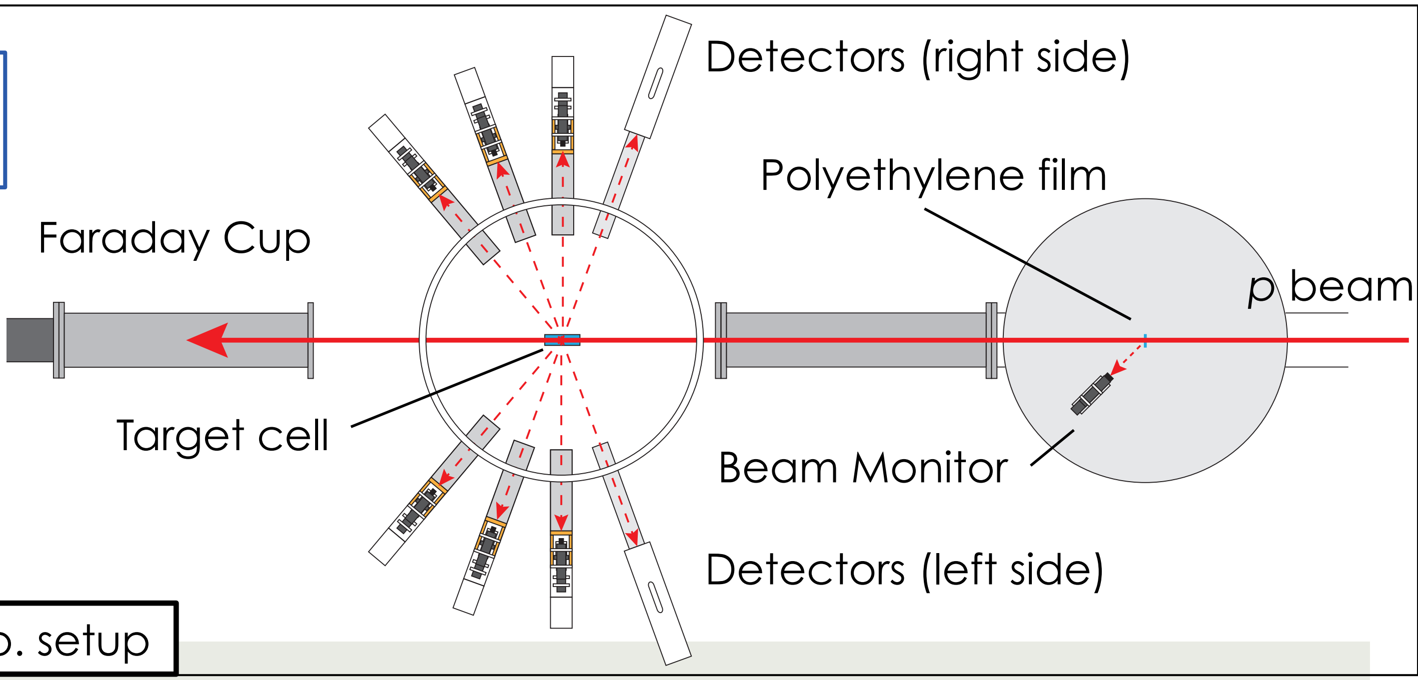
⇨ "**asymmetry**" of yields ∝ ^{3}He analyzing power

$$p_y A_y^{^3\mathrm{He}} = \frac{N_+ - N_-}{N_+ + N_-}$$

$N_\pm$: Yield (± : spin-up or down)

p_y : ^{3}He polarization

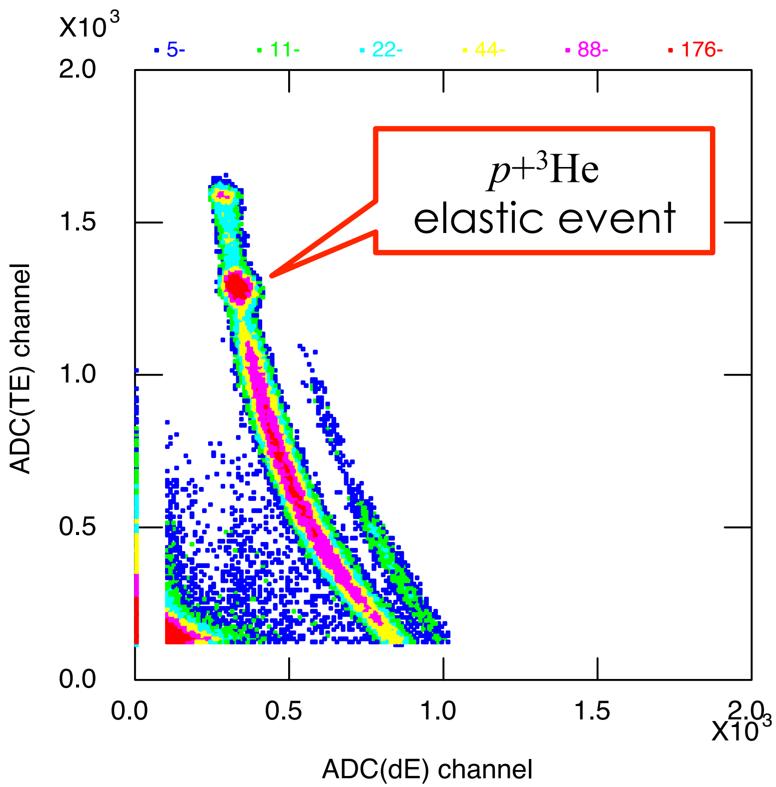
$A_y^{3\mathrm{He}}$: ^{3}He analyzing power



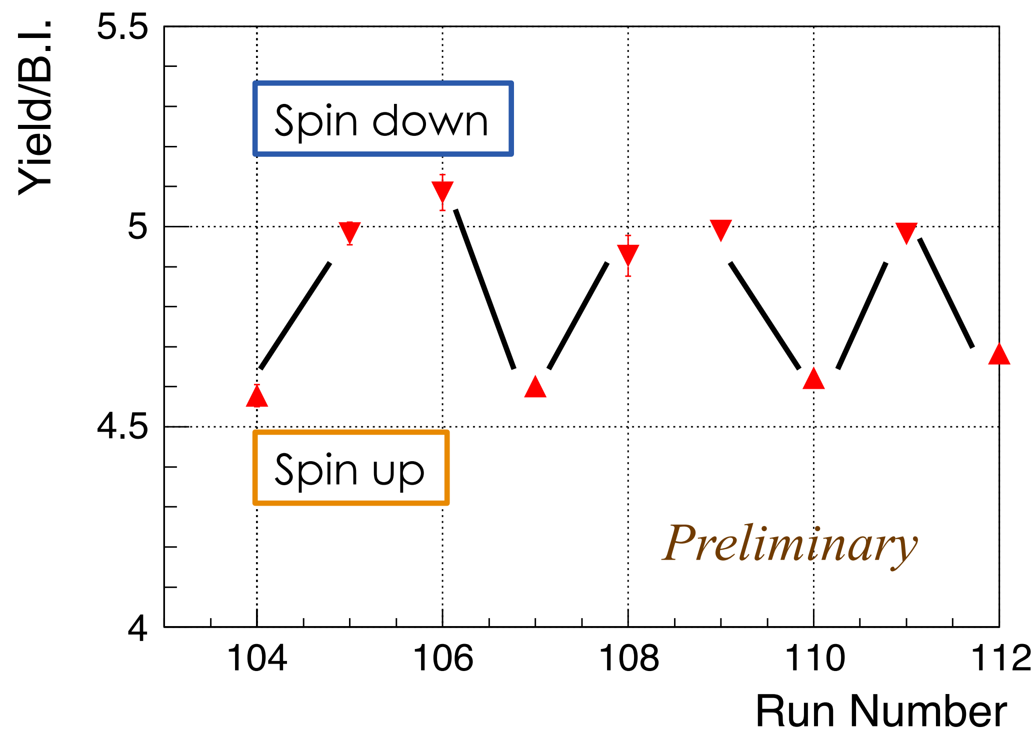
Schematic view of exp. setup

Results of exp.

at left-side 50° detector



PID spectrum (ΔE vs. E)



Yield of elastic proton event

asymmetry of yield/B.I. was confirmed
at forward angles(50°, 70°)

Results of exp.

110° detector

- energy of scattered proton is low
- thus, PID spectrum spread (right figure)

➡ need to develop detector

- low statistics for elastic events

➡ need to improve ^{3}He polarization

statistical error : $\delta A_y^{^3\mathrm{He}} = \dfrac{1}{\sqrt{N p_y}}$

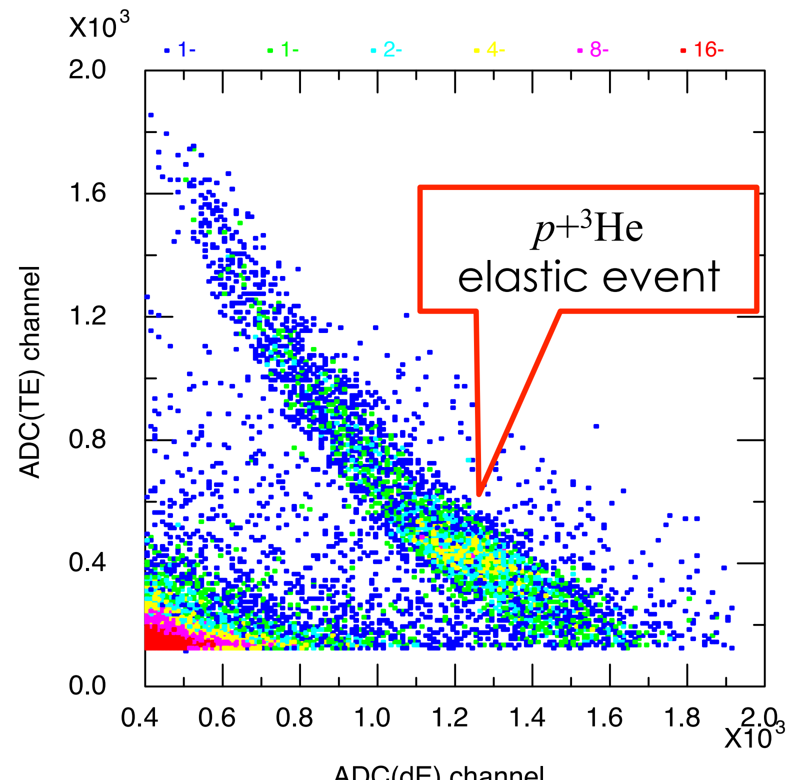
N : Yield of detected protons

p_y : ^{3}He polarization

$A_y^{3\mathrm{He}}$: ^{3}He analyzing power

Energies of scattered proton

θ_{lab} [deg]	$\theta_{c.m.}$ [deg]	E_p' [MeV]
50	65.5	50.9
70	89.0	41.1
90	110.2	32.1
110	128.9	25.1



PID spectrum (ΔE vs. E) at 110°

Summary

- Recently, importance of **3NFs** has been indicated
- In order to explore **3NFs**, we are planning the measurement in p-^{3}He system at intermediate energy
- We have performed the measurement of ^{3}He analyzing power for p-^{3}He scattering at CYRIC, Tohoku Univ.
- Future plan
  - **improve ^{3}He polarization**
    → improve process of gas-filling and glass cell cleaning
  - **develop detectors** for measurement at backward angles
  - measure ^{3}He analyzing power **at the other angles**

Collaborators

Department of Physics, Tohoku Univ.

A. Watanabe, K. Sekiguchi, K. Miki, Y. Wada, Y. Shiokawa, D. Eto, T. Akieda, H. Kon, S. Nakai, T. Mukai

CYRIC, Tohoku Univ.

M. Itoh

RIKEN, Nishina Center

T. Uesaka

NIRS

T. Wakui

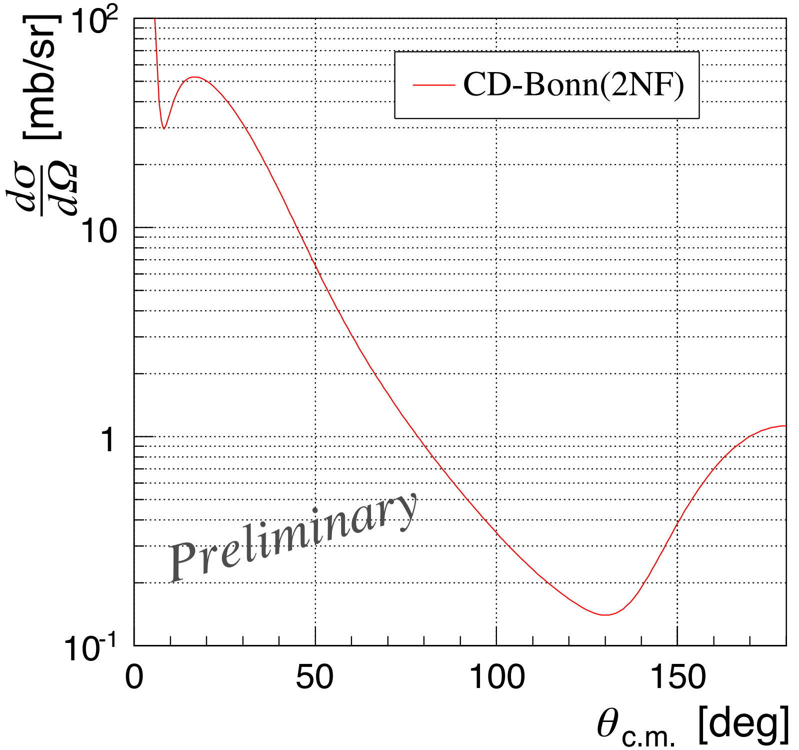
KEK

T. Ino

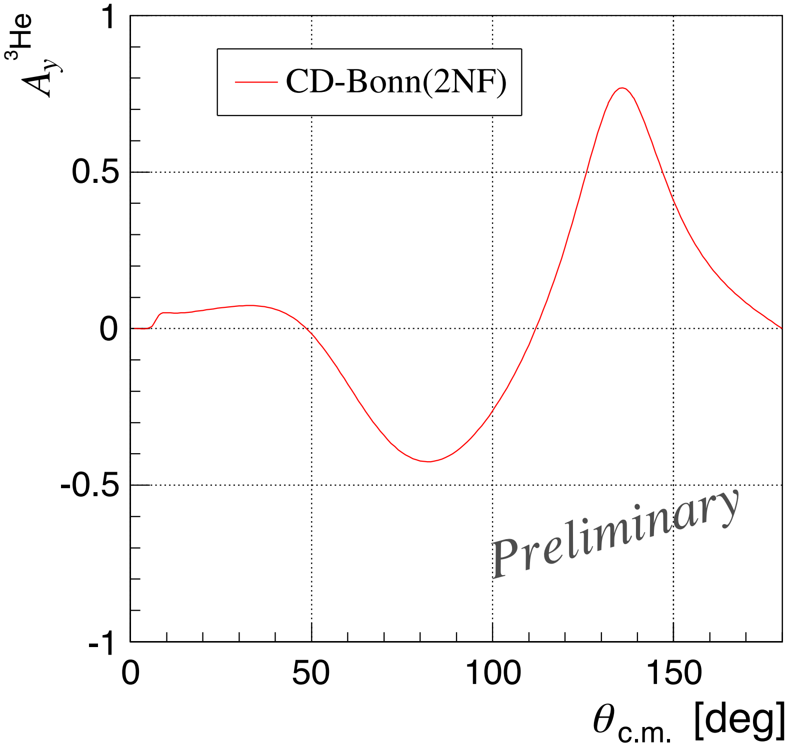
Thank you for your attention.

$p+^3$He theoretical calc. @70 MeV

by A. Deltuva (private communication)

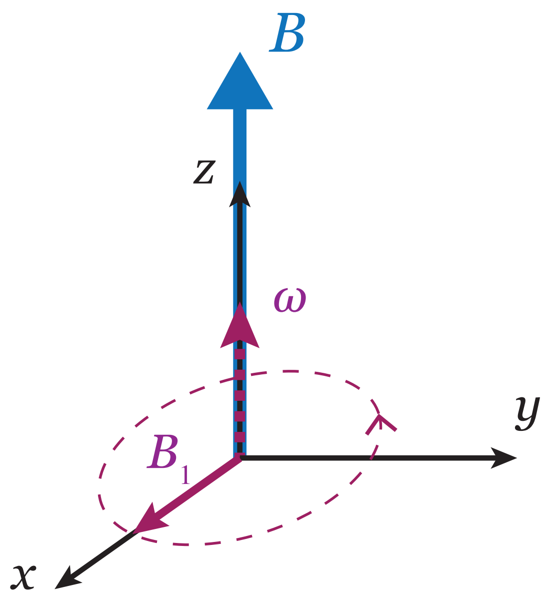


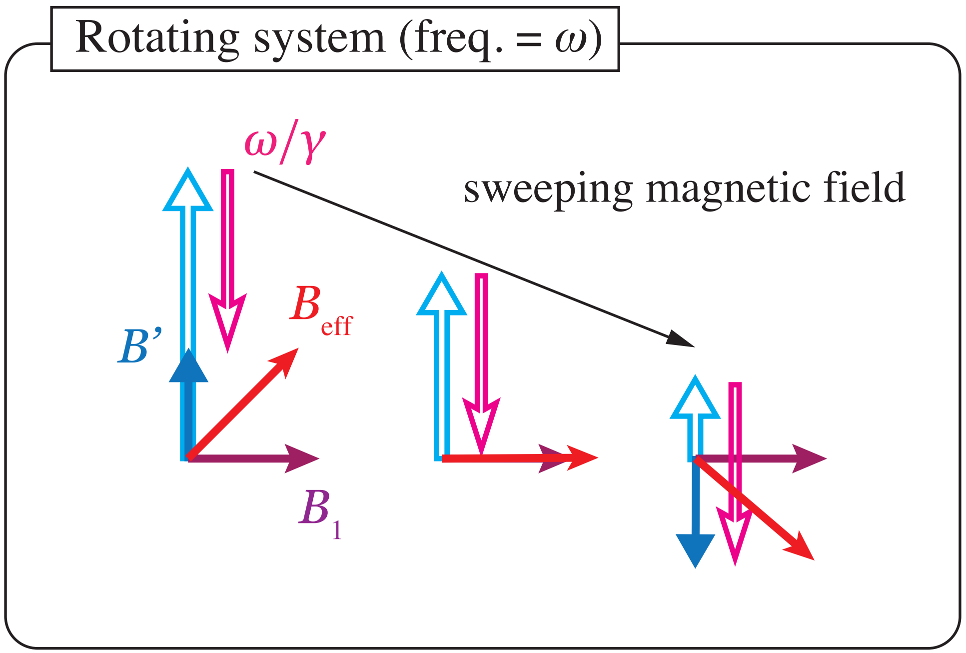
differential cross section



^{3}He analyzing power

AFP-NMR





B : static magnetic field
B_1 : RF magnetic field
B_{eff} : effective magnetic field

$$\boldsymbol{B}_{\mathrm{eff}} = \left(B + \frac{\omega}{\gamma_{^3\mathrm{He}}} \right) \boldsymbol{e}_z + B_1 \boldsymbol{e}'_x$$

Rb-ESR

ESR frequency shift

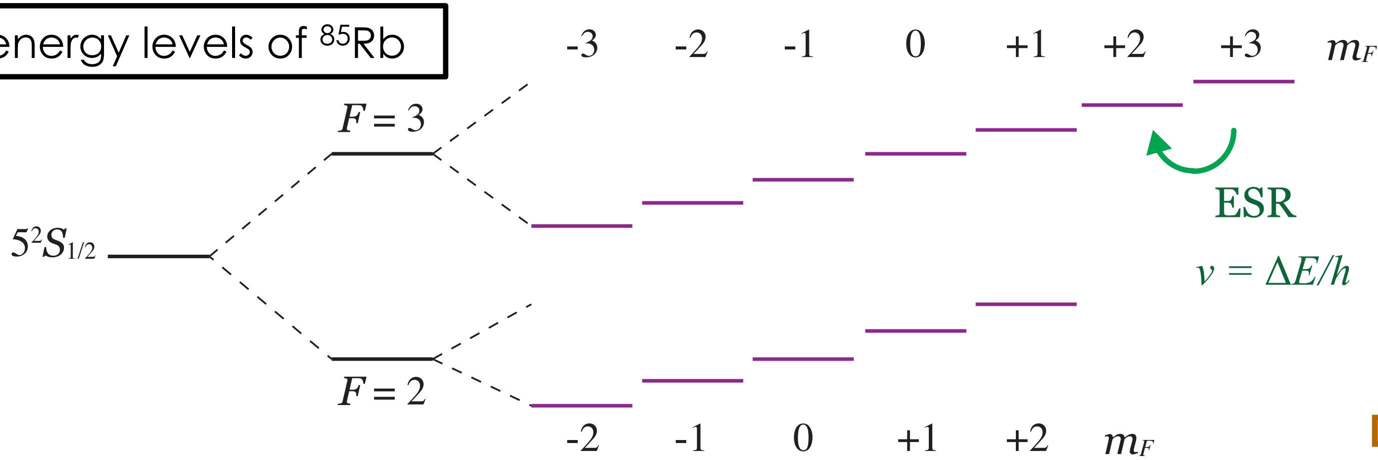
M. V. Romalis and G. D. Cates, Phys. Rev. A **58**, 3004 (1998)

$$\Delta\nu(m_F = \pm F) = \underbrace{\frac{2\mu_0}{3}\frac{\mu_B g_e}{h(2I+1)}\left(1 \mp \frac{8I}{(2I+1)^2}\frac{\mu_B g_e B_0}{h A_{\mathrm{hfs}}}\right)\kappa_0 \mu_K [^3\mathrm{He}]}_{\text{constant}} P_{^3\mathrm{He}}$$

constant

(κ_0 is coefficient depending on temp.)

energy levels of ^{85}Rb



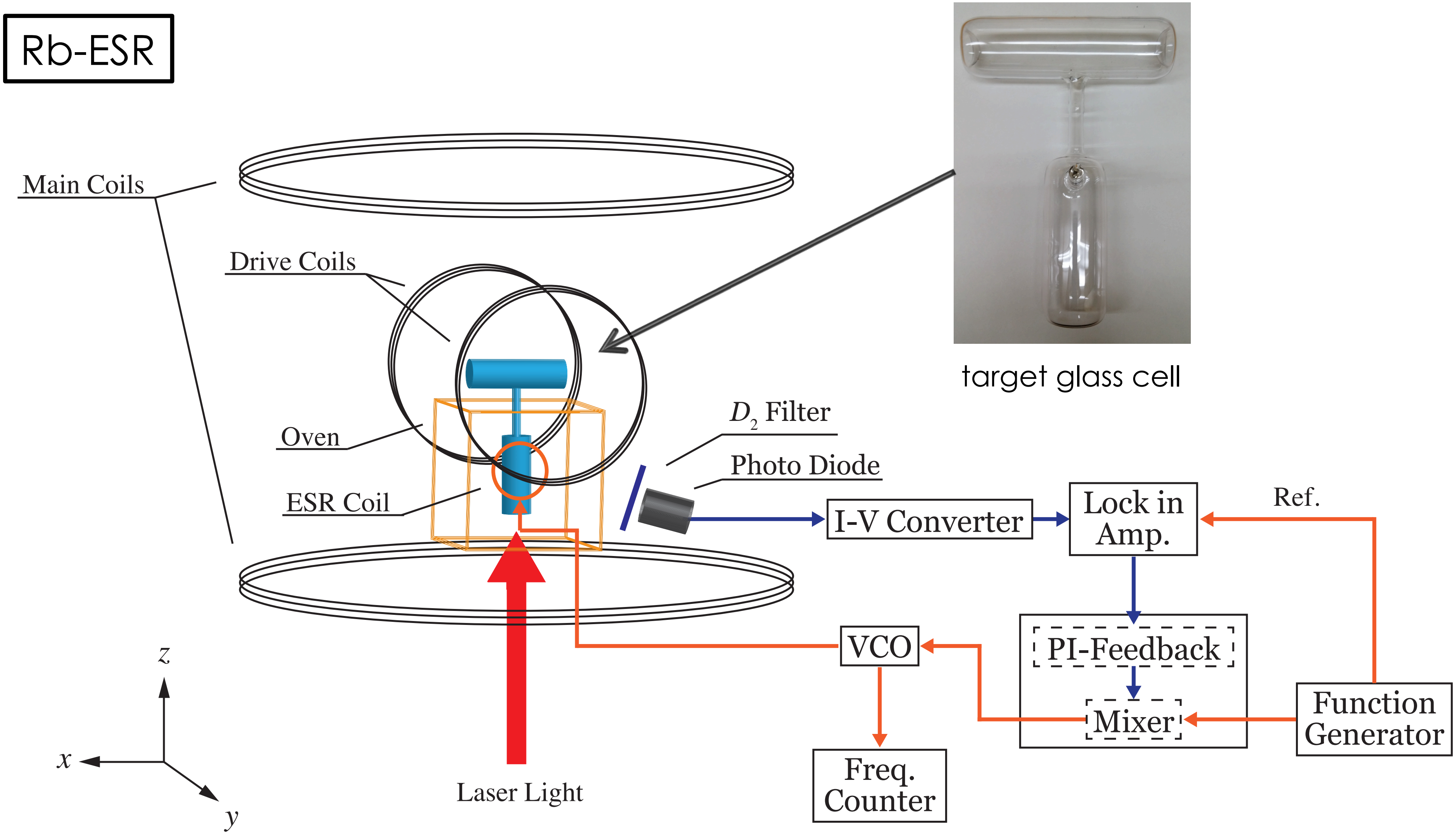
$\nu \sim 6$ MHz
$@B_0 \sim 1.20$ mT

⇒ $\Delta\nu \sim$ few kHz

Hyper fine structure

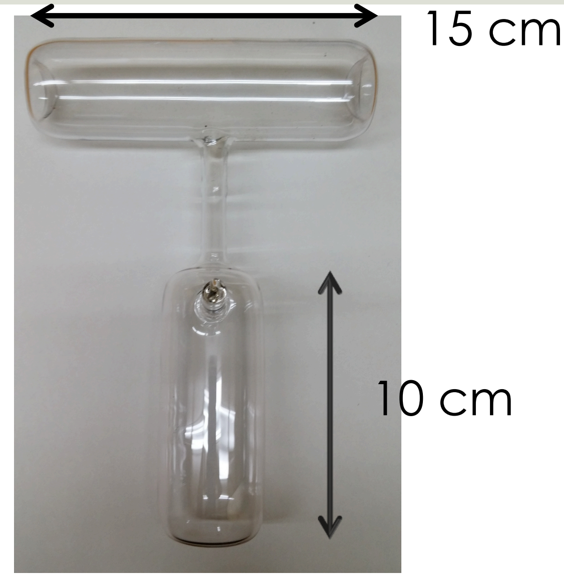
Zeeman spliting

Rb-ESR



Setup of ESR measurement

Our target system design



Pumping laser

power : 40 W
wavelength : 794.7 nm (FWHM : 0.2 nm)

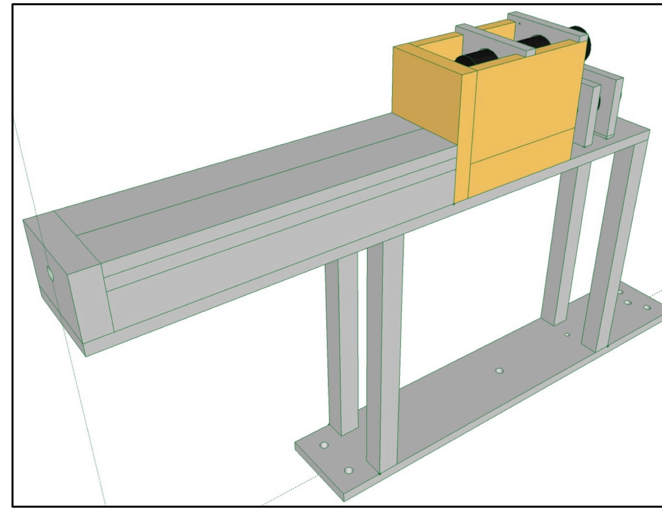
Target glass cell

structure : double-cell
material : GE180
gas pressure : ^{3}He gas -> 3 atm, N_2 gas -> 100 torr
typical relax. time : ~8 hour (@160℃), ~10 hour (@room temp.)

NMR

static magnetic field : ~3 mT
RF magnetic field : ~5 μT, 87 kHz

Detector design



ΔE-E detector

50°,70°,90° detector

plastic + NaI(Tl) +PMT

ΔE detector : plastic (1 mm)

E detector : NaI(Tl) (50 mm)

solid angle : 0.4 msr

110° detector

plastic +PMT

ΔE detector : plastic (1 mm)

E detector : plastic (50 mm)

solid angle : 0.5 msr

Beam Monitor

plastic +PMT

ΔE detector : plastic (2 mm)

E detector : plastic (35 mm)

solid angle : 4.3 msr

target : CH_2 (20 μm)

For improvement of ^{3}He polarization

$$P_{^3\mathrm{He}} = \bar{P}_{\mathrm{Rb}} \frac{\gamma_{\mathrm{SE}}}{\gamma_{\mathrm{SE}} + \Gamma_{^3\mathrm{He}}}$$

$P_{3\mathrm{He}}$: ^{3}He polarization

P_{Rb} : average of Rb polarization

γ_{SE} : spin-exchange rate between ^{3}He nucleus and Rb atoms

$\Gamma_{3\mathrm{He}}$: relaxation rate of ^{3}He polarization

- impurities in the ^{3}He gas ⇐ we focused on
- inhomogeneity of magnetic field
- dipole interaction between two ^{3}He nucleus

⇒ develop the vacuum system for cell-construction