2021/02/24
日本のスピン物理学の展望

偏極標的を用いた三核子力の研究

~散乱実験に向けた偏極^{3}He標的の開発~

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2NF and 3NF

Theoretical Discription of Nucleon-Nucleon (*NN*) Force

1935 **Meson exchange picture** by H. Yukawa Proc. Phys. Math. Soc. Jpn **17**, 48.

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

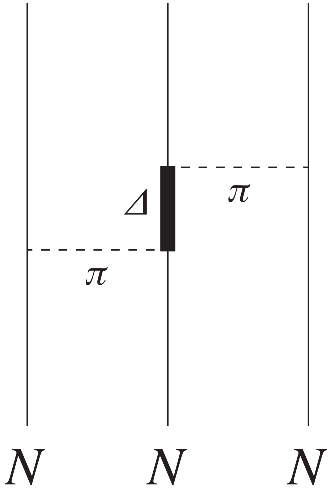
→ precisely reproduce 3000–4000 *NN* scattering data (χ^2/datum~1).

Three-Nucleon Force (3NF)

First theoretical insight by **Fujita & Miyazawa** → 2π-exchange 3NF

Prog. Theor. Phys. **17**, 360 (1957).

- ✓ Main ingredient of 3NF models (TM'99, Urbana IX, …).
- ✓ 3NFs play important roles to nuclear properties ($A \geq 3$).



Δ-isobar excitation

$$(J^P, I) = \left(\frac{3}{2}^+, \frac{3}{2}\right)$$

2π-exchange 3NF diagram

3*N*, 4*N* B.E. [MeV]

	AV18	AV18+TM	Exp.
^{3}H	7.628	8.478	8.482
^{3}He	6.917	7.733	7.718
^{4}He	24.25	28.84	28.30

A. Nogga *et al.*, PRC **65**, 054003 (2002).

Few-Nucleon Scattering

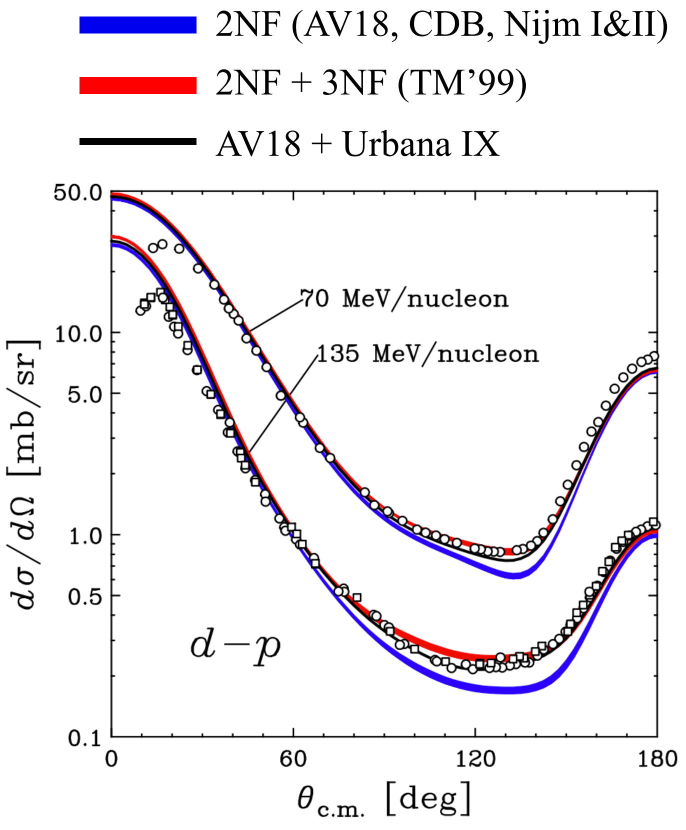
A good probe to study the dynamical aspects of 3NFs.
- ✓Momentum dependence
- ✓Spin & Iso-spin dependence

Direct Comparison

- **Theory** : **Faddeev (-Yakubovsky) eq.**, etc…
  Rigorous numerical calc. for 3, 4N system
  w/ 2NF, 3NF inputs
- **Exp.** : **Precise Data**
  Cross section, Spin observables ($\boldsymbol{A_i}$, $\boldsymbol{C_{ij}}$, $\boldsymbol{K_{ij}}$)

d + *p* Elastic Scattering at 70–300 MeV/u

- Differential Cross Section $d\sigma/d\Omega$
  - 3NFs are clearly needed.
- Spin Observables (iT_{11}, T_{20}, T_{21}, T_{22}, $K_{ij}^{l'}$)
  - The data are partially reproduced by including 3NFs.
  - Spin dependent parts of 3NFs are less known.



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

Solid basis to explore the 3NF properties

3NF Study via p-^{3}He Scattering

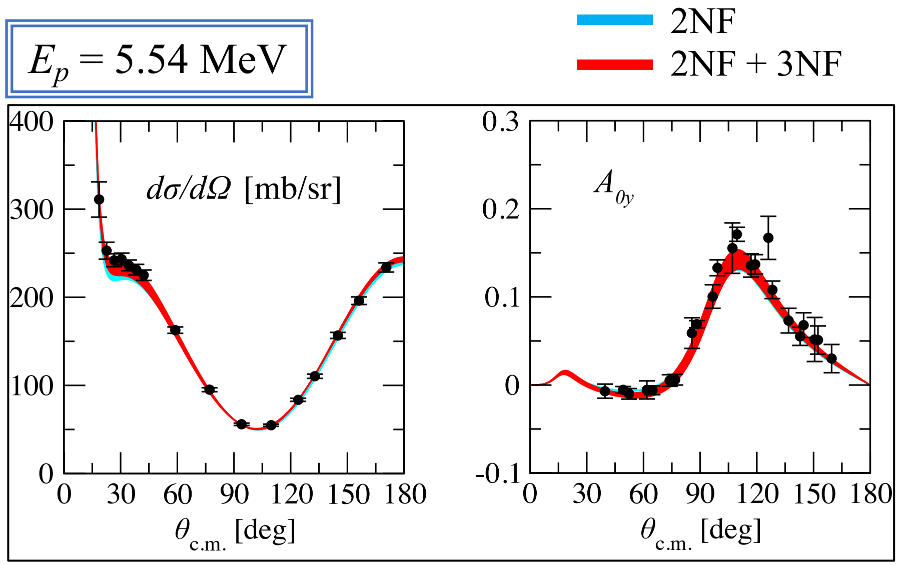
The measurement of p + ^{3}He system ($E_p \geq 65$ MeV)

Observables

Cross section,
Analyzing powers,
Spin correlation coefficients.

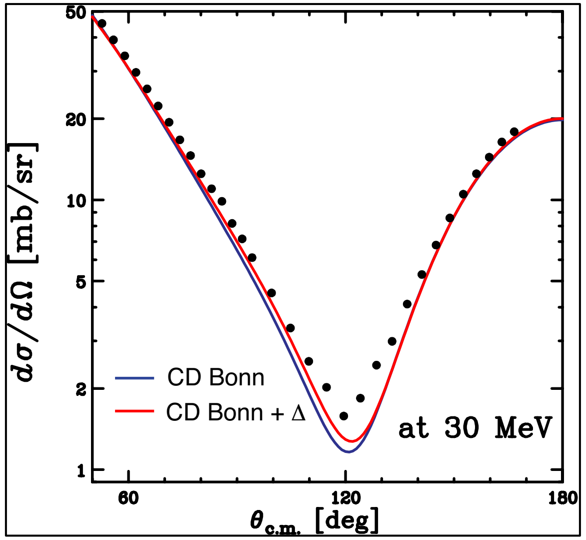
- First Step from Few to Many
  - ✓ Verifying 3NFs determined from *Nd* scattering system.
- Approach to isospin $T = 3/2$ of 3NFs
- Theory in progress…

$E_p = 5.54$ MeV



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

up to 30 MeV



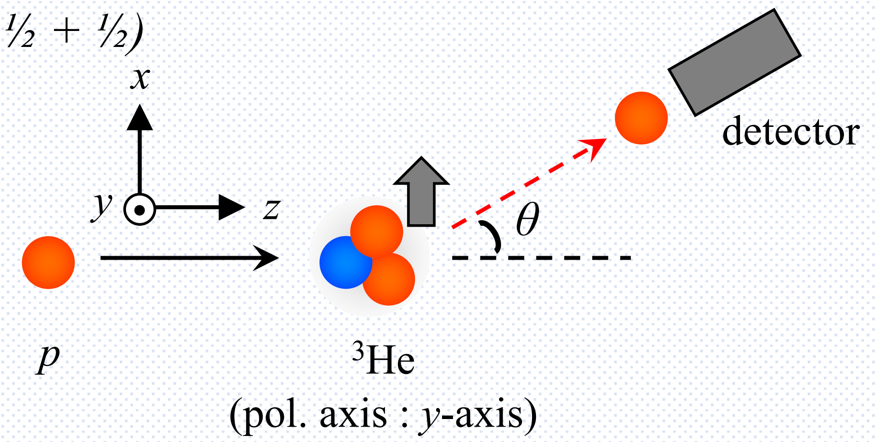
A. Deltuva and A. C. Fonseca,PRC **87**, 054002 (2013).

Why do we need a polarized ^{3}He target?

differential cross section with polarized beam or target (spin ½ + ½)

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + p_y A_y)$$

p_y : Polarization A_y : Analyzing power



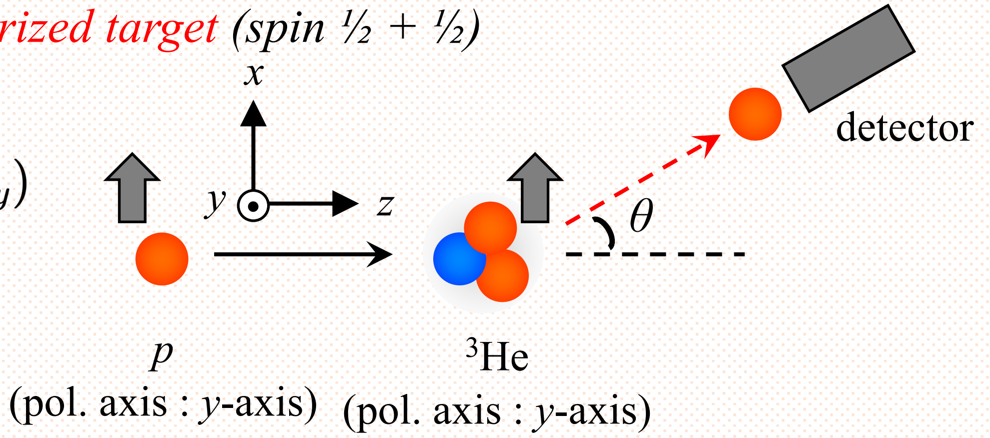
differential cross section with polarized beam and polarized target (spin ½ + ½)

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + p_y A_y + p_{0y} A_{0y} + p_y p_{0y} C_{y,y})$$

p_y : Beam polarization p_{0y} : Target polarization

A_y, A_{0y} : Analyzing power

$C_{y,y}$: Spin-correlation coefficient



Polarized ^{3}He Target

~for measurements of spin-observables~

Polarization Method

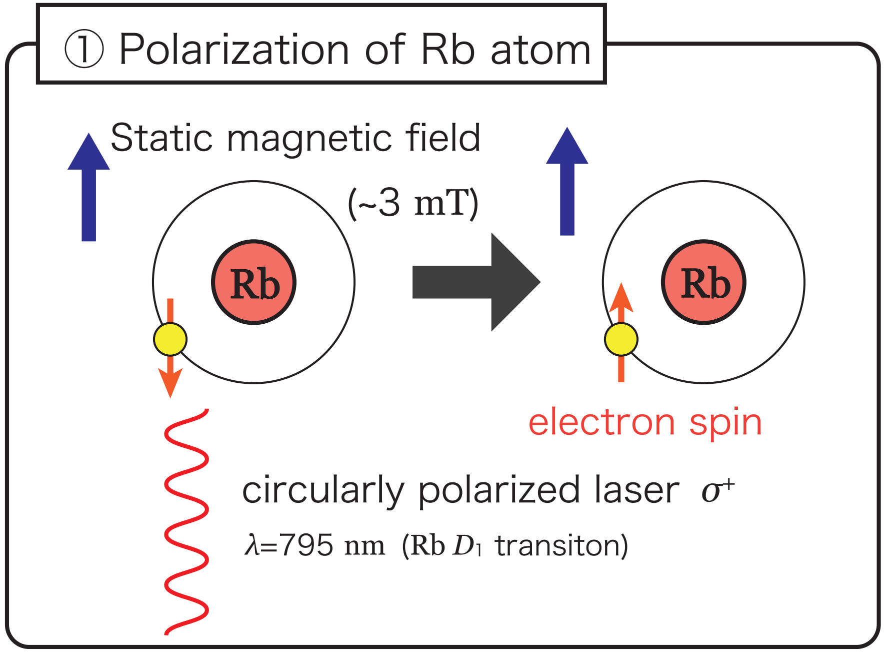
Spin-Exchange Optical Pumping (SEOP)

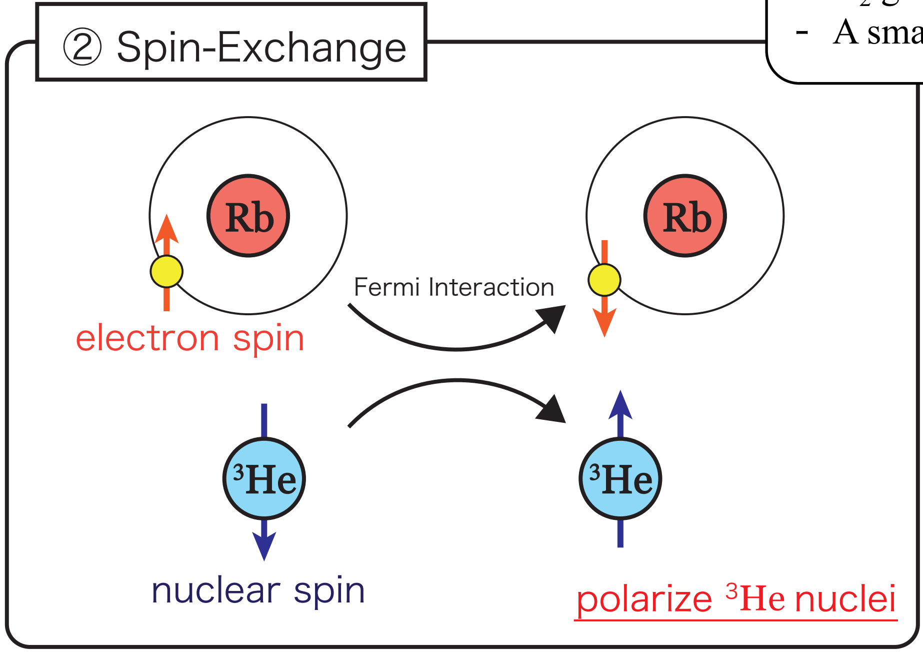
- Optical pumping by diode-laser → Rb polarization
- Polarization transfer (Spin-exchange) : Rb atoms → ^{3}He nuclei
- Mixture of **Rb & K** → high-polarization efficiency (“***Alkali-Hybrid*** ”)

150 mm

Target glass cell

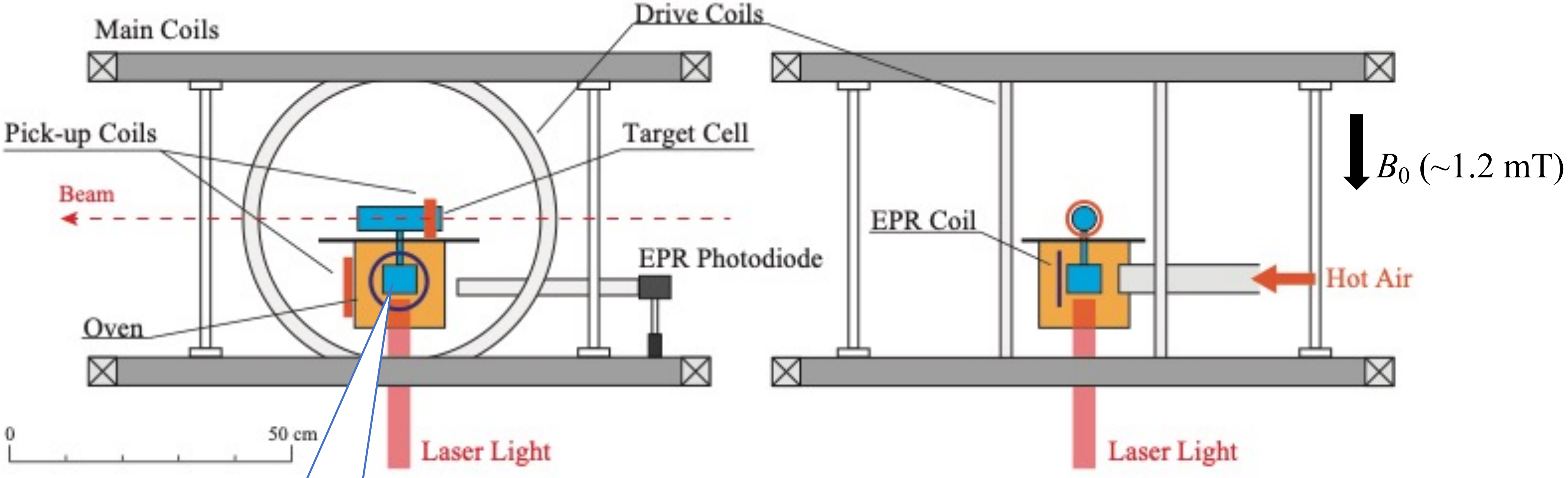
- ^{3}He gas ： 3 atm, ~2 mg/cm^2
- N_2 gas ： ~ 0.1 atm
- A small amount of Rb, K





Polarized ^{3}He Target System

Side View **Front View**



Laser System

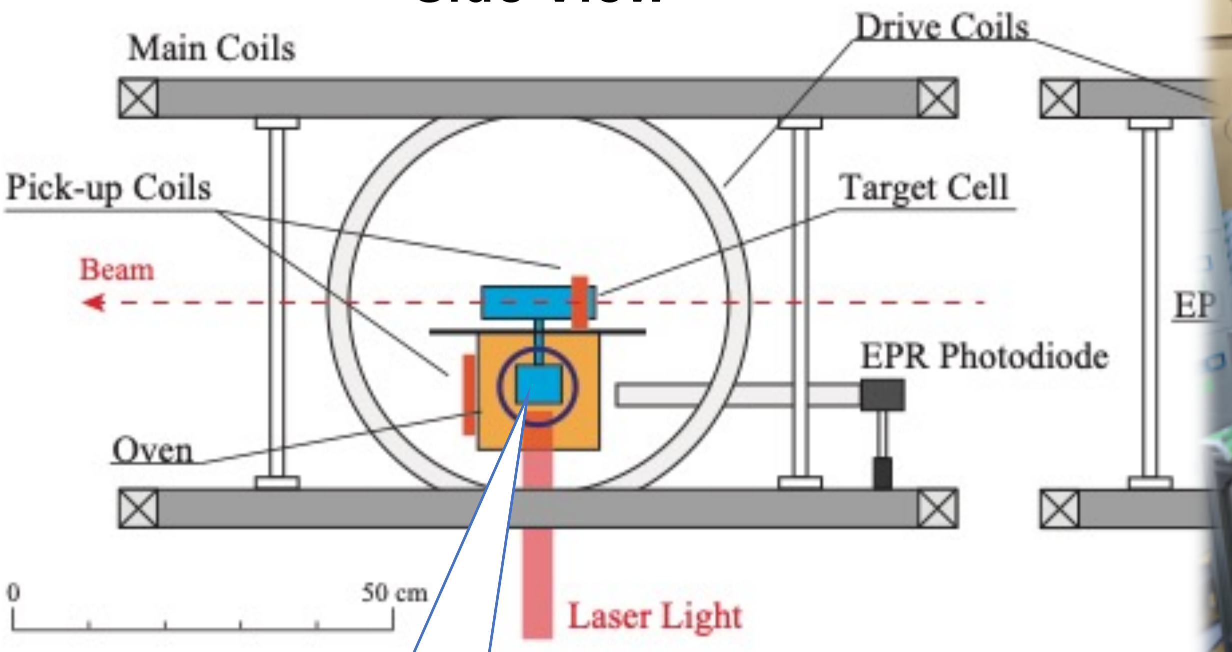
Diode laser + VBG (Volume Bragg Grating)

- Power : ~80 W (Max)
- Wavelength : 794.7 nm
- Width : 0.2 nm (FWHM)

Optics system (lens, mirror, …)

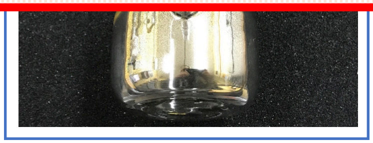
Polarized ^{3}He Target System

Side View



Typical ^{3}He polarization : **50%**

Pol. relaxation time : **39 hrs**



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Diode l

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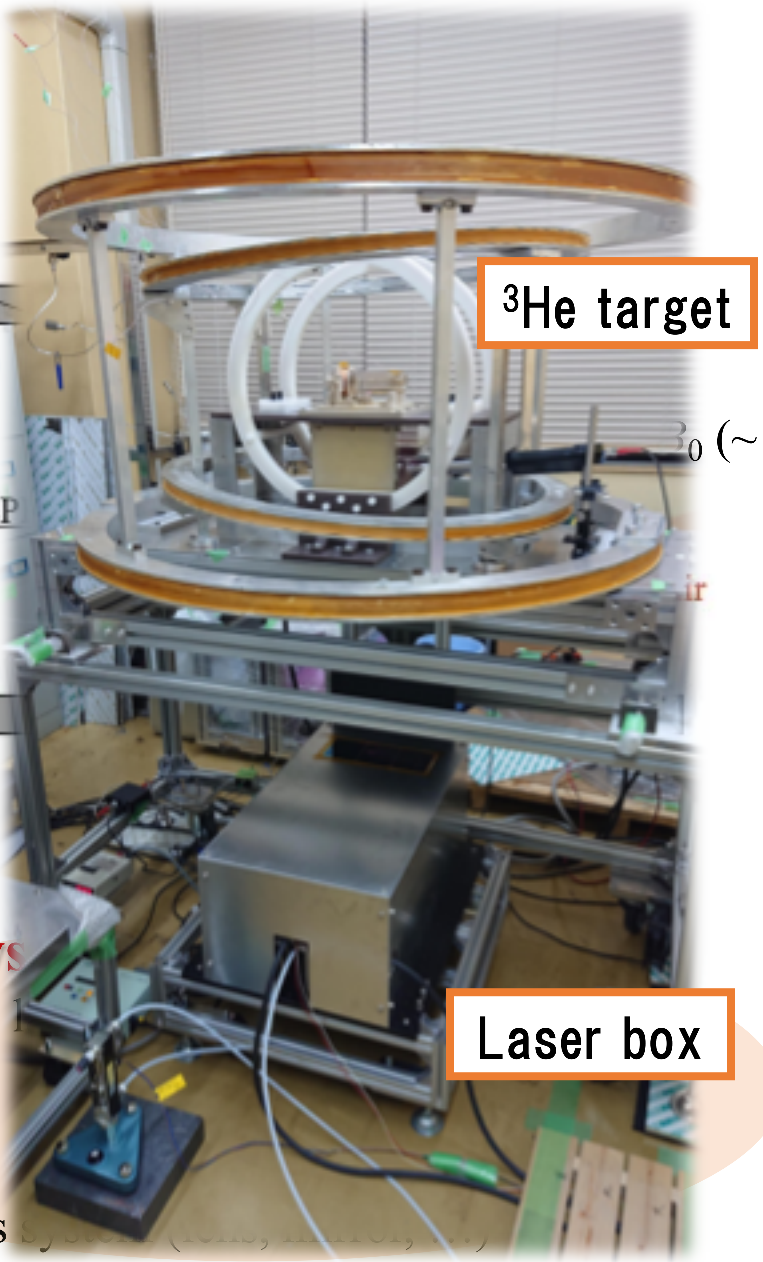
Optics



$_0$ (~1.2 mT)

ir

^{3}He Polarimetry

AFP-NMR

- Reverse polarization direction.
- Measurement of relative ^{3}He polarization.
- Monitoring ^{3}He polarization during the scattering experiment.

EPR of alkali-metals

- Measurement of **absolute** ^{3}He polarization*1.
- Calibration of AFP-NMR.

*1 The value of ^{3}He number density is needed.

Neutron transmission

- Measurement of **absolute** ^{3}He polarization.
- Calibration of AFP-NMR.
- ***Cross-check*** for EPR.

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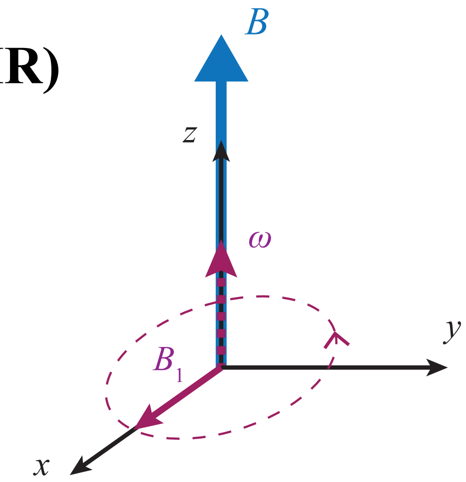
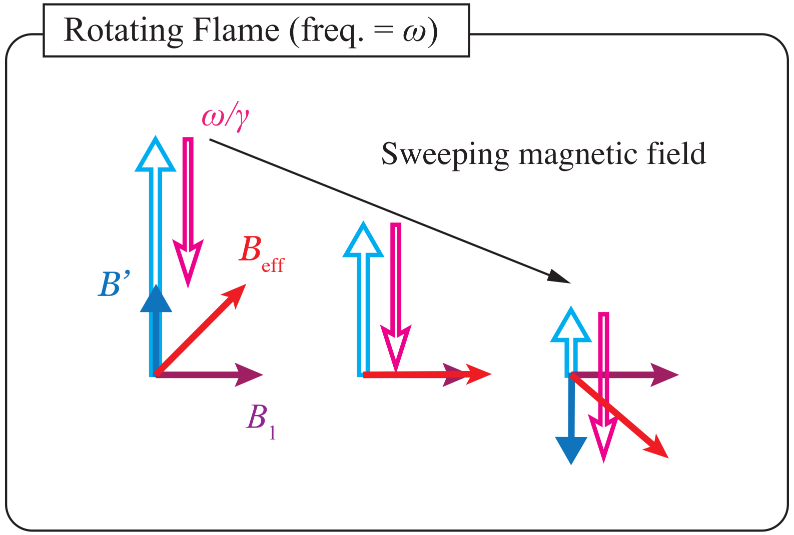
AFP-NMR (Adiabatic Fast Passage-NMR)

- RF + sweeping a static magnetic field

  → Flipping the ^{3}He nuclear spin without polarization loss.

- Detecting NMR signals by pick-up coils.





^{3}He Polarimetry : EPR

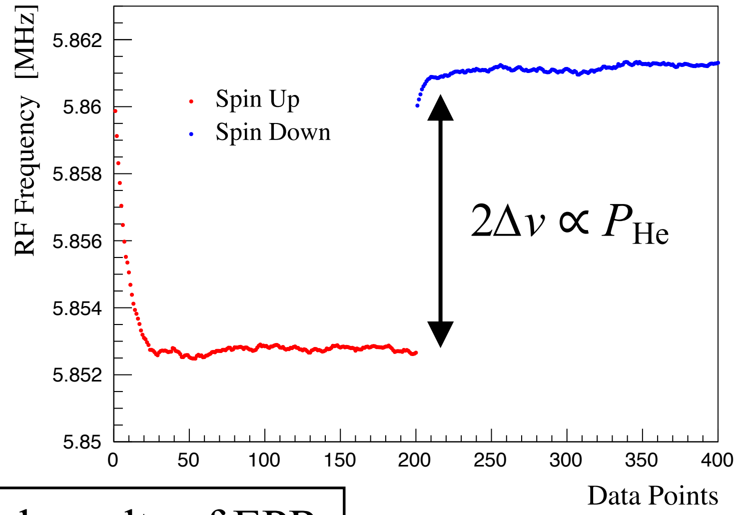
Electron Paramagnetic Resonance

- Rb, K @static magnetic field → Zeeman splitting
- EPR freq. shift of alkali metals is proportional to the ^{3}He polarization.

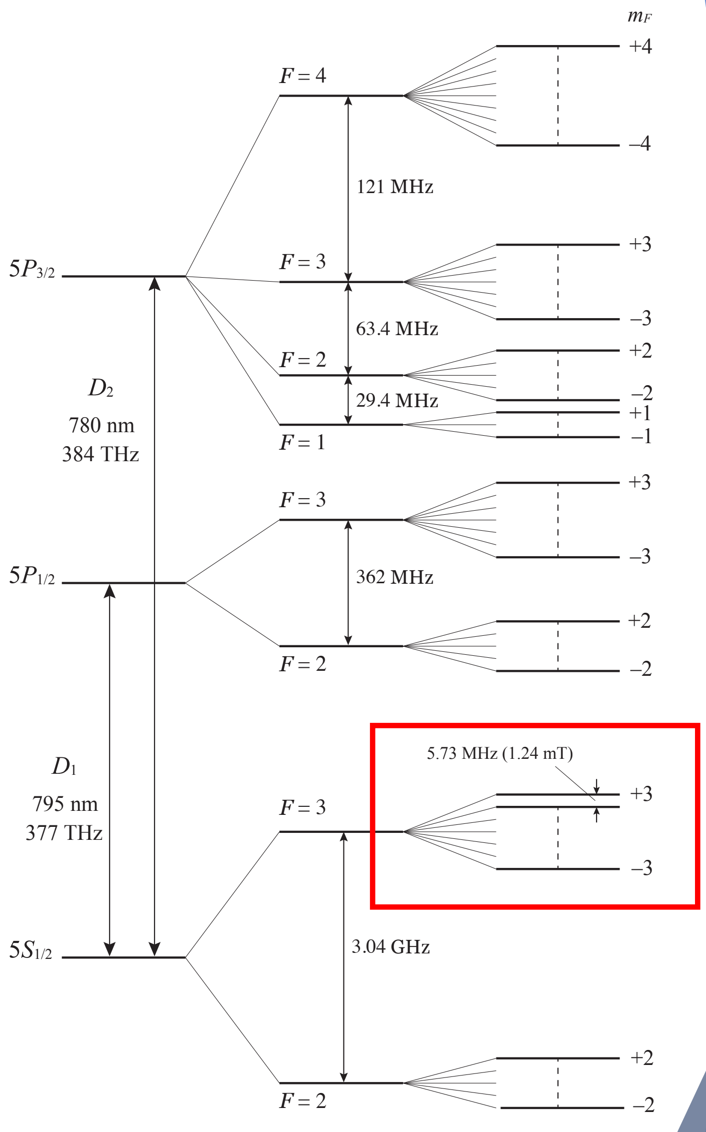
$$\Delta\nu(m_F = \pm F) = \frac{2\mu_0}{3}\frac{\mu_B g_e}{h(2I+1)}\left(1 \mp \frac{8I}{(2I+1)^2}\frac{\mu_B g_e B_0}{hA_{hfs}}\right)\kappa_0\mu_K[^3\text{He}]P_{^3\text{He}}$$

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

- Absolute ^{3}He polarization can be obtained with an uncertainty of ~5%.



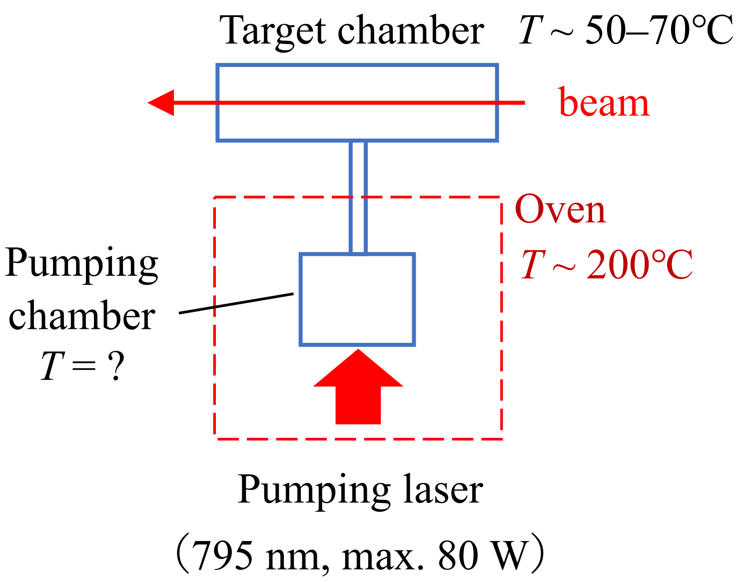
Typical results of EPR



Energy levels of ^{85}Rb

Estimation of Target Polarization

- EPR method gives us only the ^{3}He polarization in a pumping chamber.
- For scattering experiments, we need to know the ^{3}He polarization in a target chamber.
- However, …
  - Gas temperature inside the cell is uncertain (oven + pumping laser).
  - Polarization gradient between two-chambers.



For estimate the absolute ^{3}He polarization in a target chamber…

Direct Measurement *via* Neutron Transmission

- Utilizes the fact that neutron transmission for ^{3}He depends on the ^{3}He polarization.
- The measurement was performed at RANS, RIKEN.

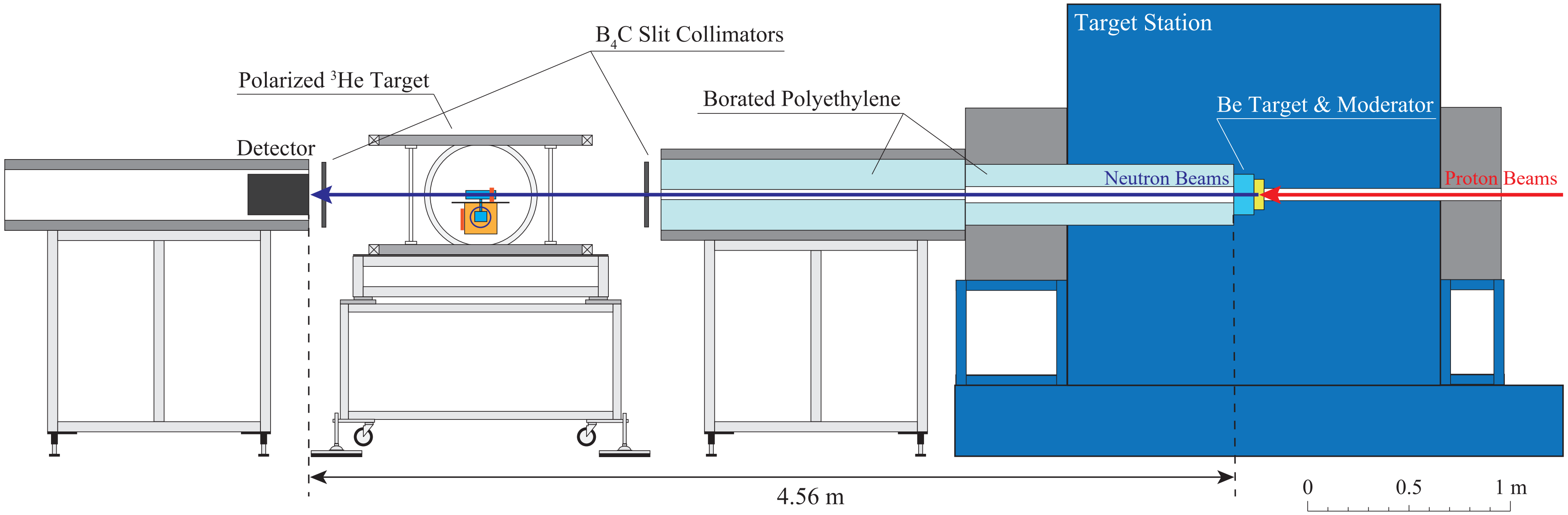
^{3}He Polarimetry : **Neutron Transmission** @RANS, RIKEN

- Neutron transmission T_n depends on the ^{3}He number density and **the ^{3}He polarization** P_{He}.
- The ^{3}He polarization can be directly obtained from the ratio of T_n and $T_{n,0}$.

$$P_{\mathrm{He}} = -\frac{1}{\ln(T_{n,0})}\cosh^{-1}\left(\frac{T_n}{T_{n,0}}\right)$$

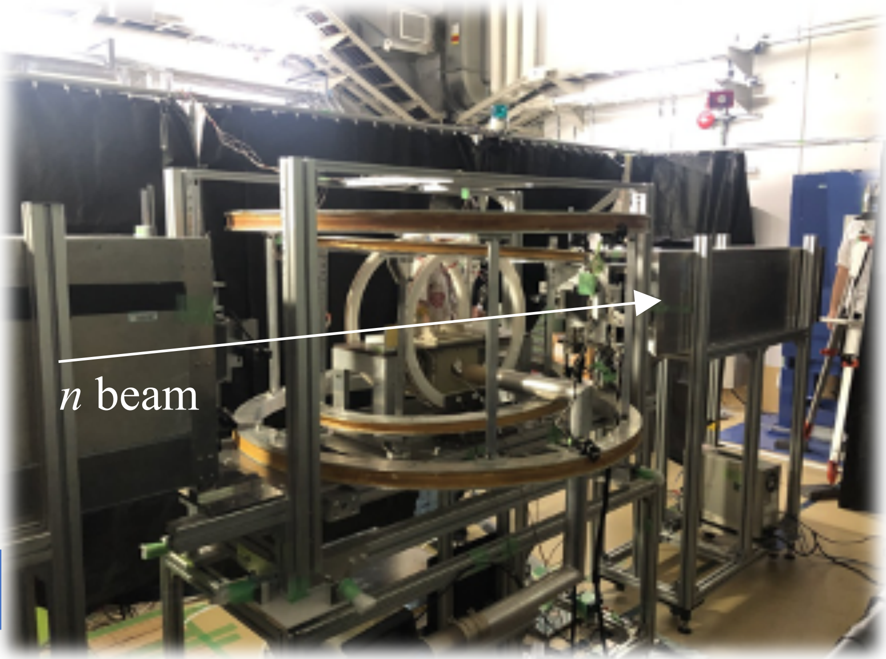
T_n : neutron transmission
$T_{n,0}$: neutron transmission @$P_{\mathrm{He}} = 0$

Exp. conditions	
Energy	7 MeV (proton) max. 5 MeV (neutron)
Current	20 µA (proton)
Beam pulse repetition	120 Hz
Pulse width	20 µsec



RANS (RIKEN Accelerator-driven compact Neutron Source)

Ref. Y. Ikeda *et al*., NIMA **833**, 61 (2016).



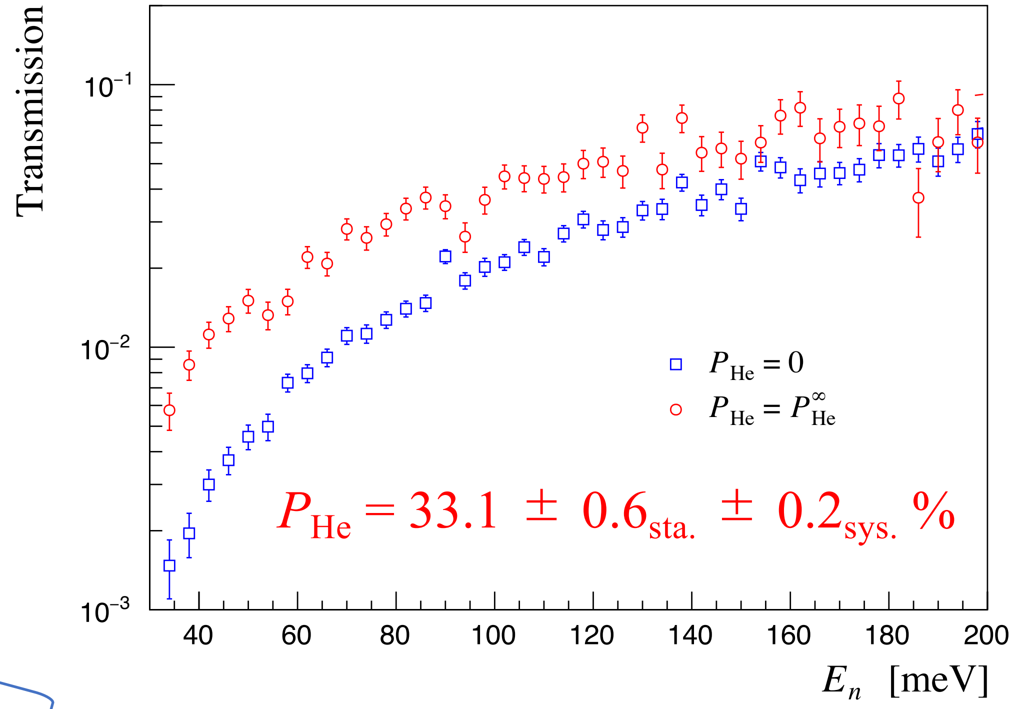
Pol. ^{3}He target @RANS

^{3}He Polarimetry : **Neutron Transmission** @RANS, RIKEN

Experimental Results

$$P_{\mathrm{He}} = -\frac{1}{\ln(T_{n,0})}\cosh^{-1}\left(\frac{T_n}{T_{n,0}}\right)$$

T_n : neutron transmission
$T_{n,0}$: neutron transmission @$P_{\mathrm{He}} = 0$



Neutron transmission vs. Neutron energy

uncertainty : **2%**

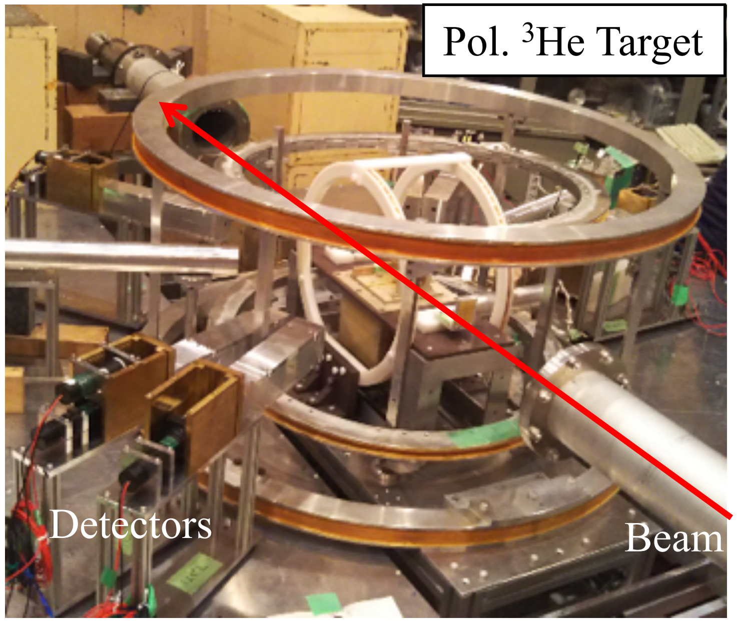
agree well with the result of EPR!

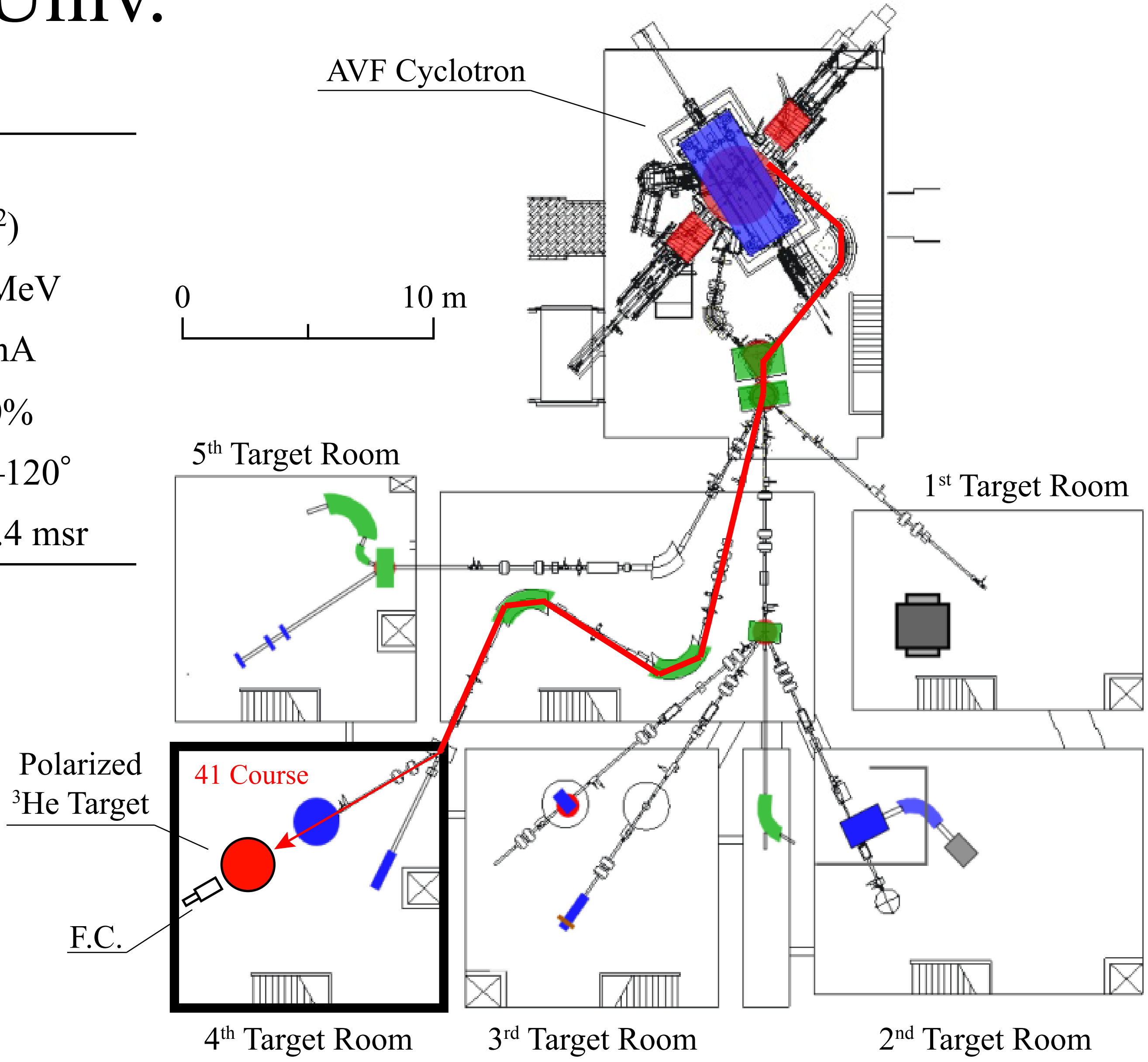
Measurements of p-^{3}He Scattering

~with the polarized ^{3}He target~

CYRIC @Tohoku Univ.

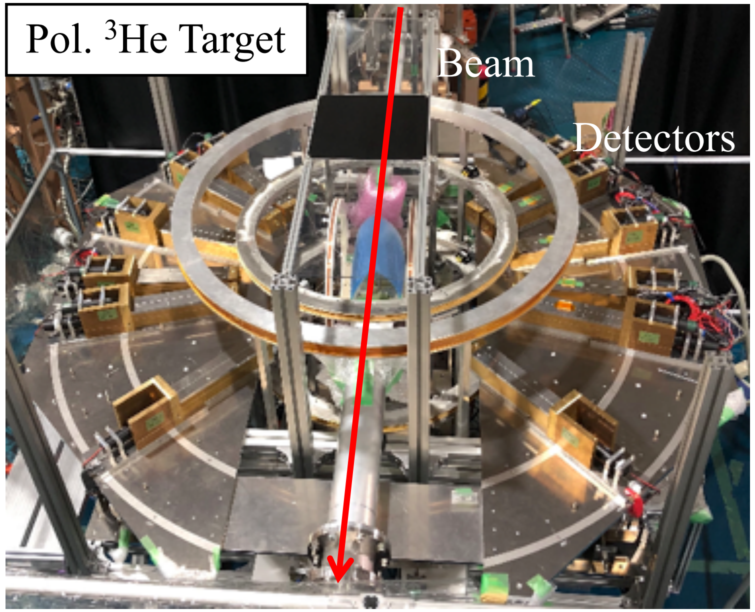
Beam	Proton	
Target	^{3}He gas (~2 mg/cm^2)	
Energy	70 MeV	50 MeV
Beam intensity	5–10 nA	3 nA
Target polarization	40% (max.)	50%
Measured angle (θ_{cm})	46° –141°	47° –120°
Solid angle	0.1–0.4 msr	0.1, 0.4 msr

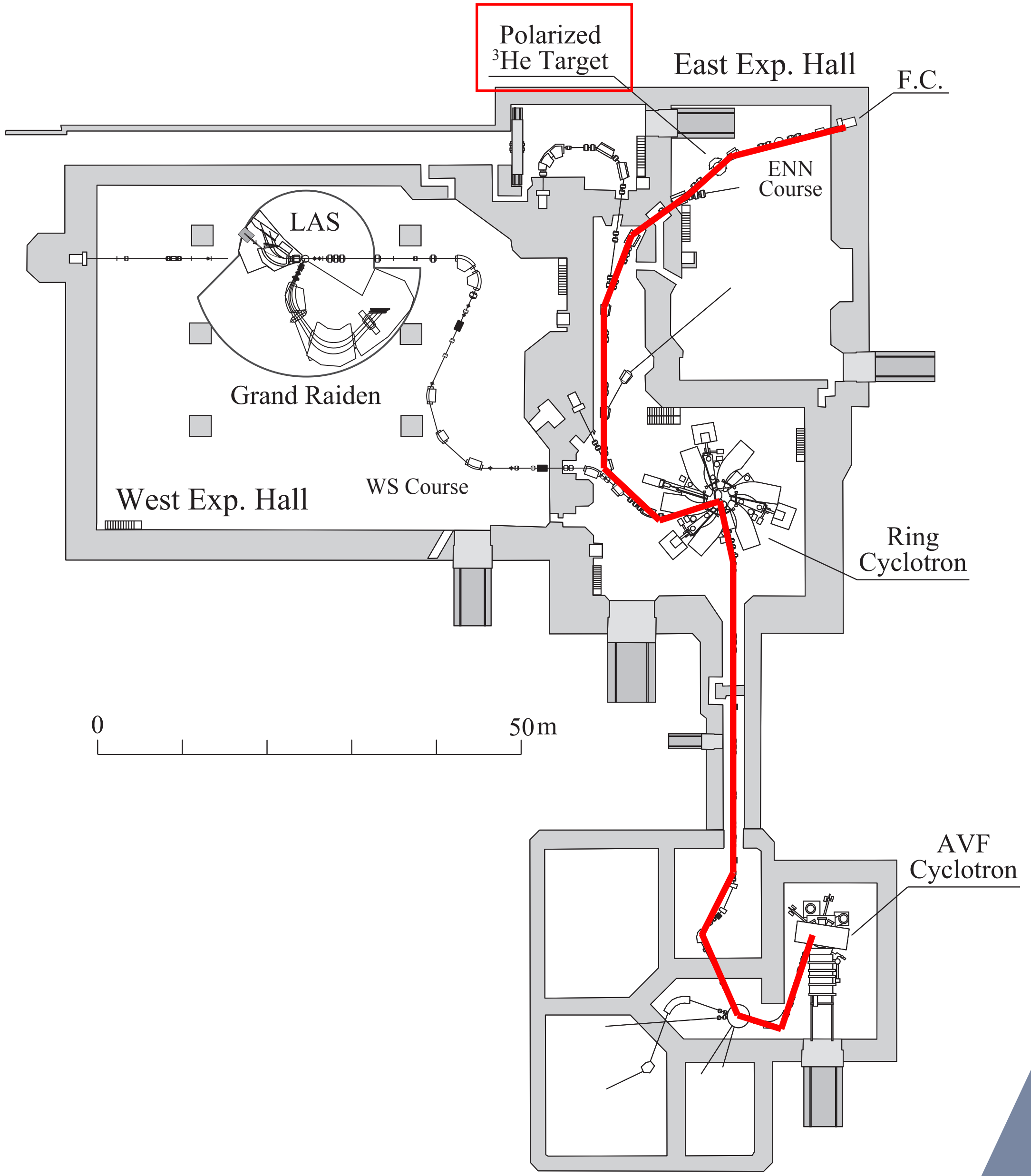




RCNP @Osaka Univ.

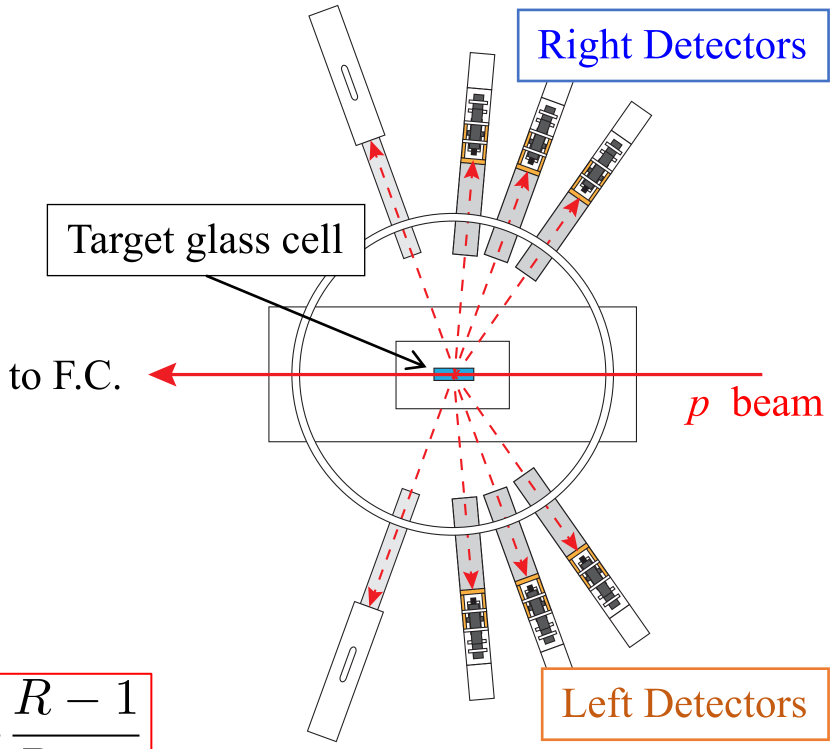
Beam	Proton	
Target	^{3}He gas (~2 mg/cm^2)	
Energy	65 MeV	100 MeV
Beam intensity	10 nA	30 nA
Target polarization	40%	40%
Measured angle (θ_{cm})	47, 89, 133°	47° –149°
Solid angle	0.1–0.4 msr	0.1–0.4 msr





Experimental Setup

- An experimental setup around the target was same at CYRIC and RCNP.
- *ΔE-E* detectors were placed at the left and right sides of the target.
  - *ΔE* det. : plastic scinti., 0.2 – 2.0 mm^t
  - *E* det. : NaI(Tl) scinti., 50 mm^t
- ^{3}He spin direction was reversed by AFP-NMR every 1 hour.



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + p_y A_y)$$

Left / Right

$$\Rightarrow \quad A_{0y} = \frac{1}{p_y}\frac{n_L^\uparrow - n_L^\downarrow}{n_L^\uparrow + n_L^\downarrow} = \frac{1}{p_y}\frac{n_R^\downarrow - n_R^\uparrow}{n_R^\uparrow + n_R^\downarrow} \quad \text{or}$$

$$A_{0y} = \frac{1}{p_y}\frac{R-1}{R+1}$$

$$R \equiv \sqrt{\frac{Y_L^\uparrow}{Y_L^\downarrow}\frac{Y_R^\downarrow}{Y_R^\uparrow}}$$

Cross asymmetry

p_y : Target polarization

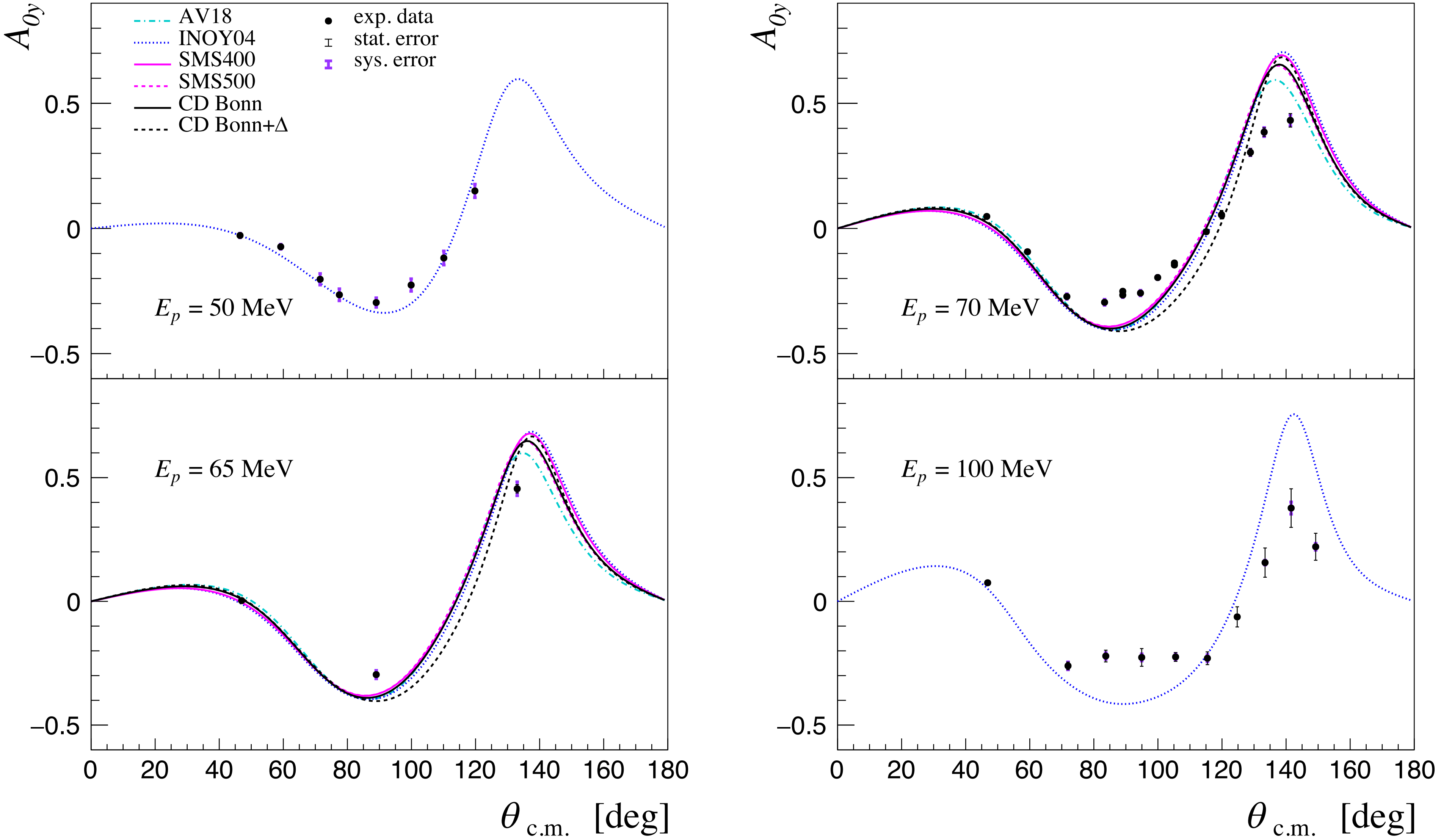
A_{0y} : ^{3}He analyzing power

$n^{\uparrow,\downarrow}$: Normalized yield at spin up (↑)/down (↓)

$Y^{\uparrow,\downarrow}$: Events at spin up (↑)/down (↓)

Experimental Results of A_{0y}

*Calculations : A. Deltuva, private communications



Summary and Outlook

Studying 3NFs via *p*-^{3}He scattering system at intermediate energies ($E/A \geq 65$ MeV).

- ✎ Approach to the $T = 3/2$ component of 3NFs.

The polarized ^{3}He target has been developed for the scattering experiments.

- ✎ Polarimetry : **AFP-NMR**, **EPR**, and **neutron transmission** using a neutron source at RIKEN.
- ✎ Typical ^{3}He polarization : **~50%** with uncertainties of **2–6%**

We obtained ^{3}He analyzing powers (50–100 MeV) and compared to the theoretical calculations.

- ✎ We confirmed <u>large discrepancies at around minimum and maximum angles.</u>
- ✎ The discrepancies are clearly arising from the intermediate energy.

Thank you for your attention.