2024/9/25

The 23rd International Conference on Few-Body Problems in Physics

Plan of spin correlation coefficient measurements of deuteron-proton scattering at intermediate energies

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- **Tohoku Univ. :** T. Matsui
- **RIKEN :** K. Tateishi, N. Sakamoto, H. Sakai , T. Uesaka
- **Kyushu Univ. :** T. Wakasa, K. Nishibata, K. Aradono, K. Hirasawa, Y. Nagao, S. Sakaguchi
- **Miyazaki Univ.:** Y. Maeda
- **Saitama Univ. :** S. Otsuka

TOMOE

Contents

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1. Three-Nucleon Force and deuteron-proton elastic scattering

Two-Nucleon Force (*NN*) and Three-Nucleon Force (3*N*F)

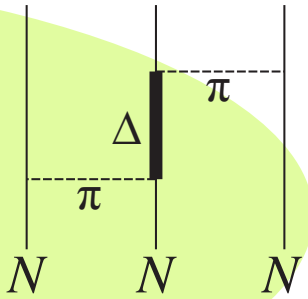
Realistic *NN* potentials : Argonne v_{18} (AV18), CD Bonn (CDB), Nijmegen I, II

- reproduce 4000 high-precision *NN* scattering data with accuracy of χ^2/data∼1
- excellent descriptions of deuterons ($A = 2$)

fail to describe properties of $A \geqq 3$ nucleon systems
eg. binding energies, nuclear matters

Three-Nucleon Force (3*N*F)

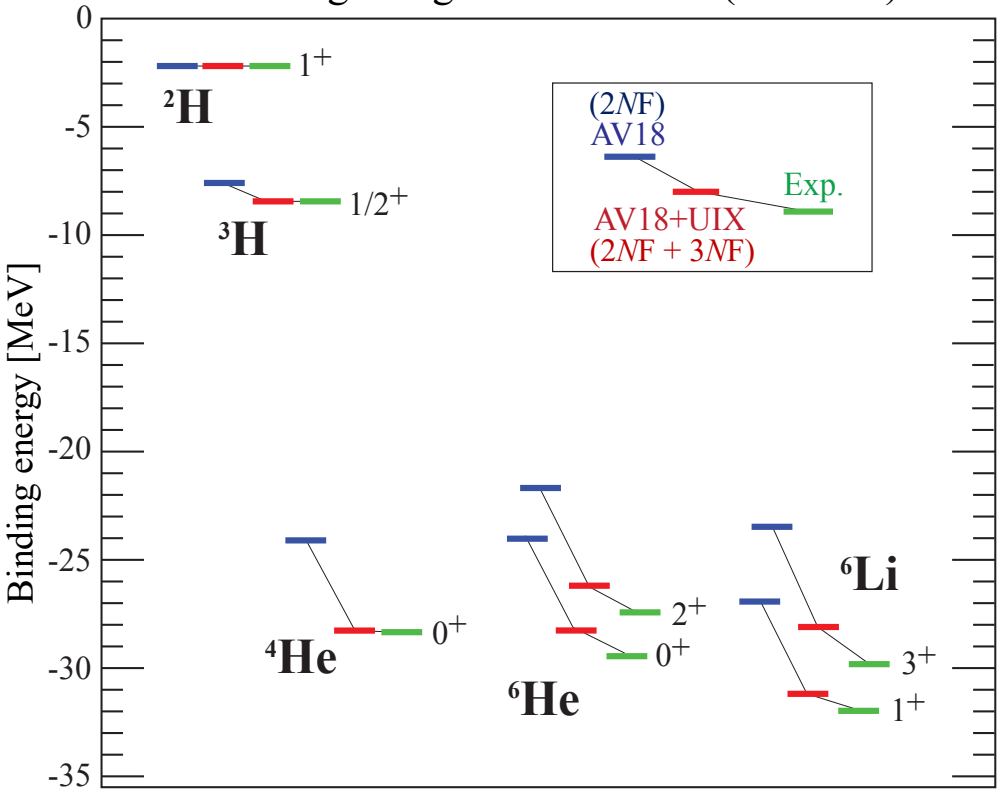
- Typical 3*N*F : Fujita-Miyazawa (2π-exchange) type



- Development of Urbana IX (UIX), Tucson-Melbourne (TM)
  → potentials based on 2π-exchange type 3*N*F

good descriptions of $A \geqq 3$ nuclear binding eneriges

Binding energies of nucleons (A = 2 - 6)



S. C. Pieper et al., Phys. Rev. C **64**, 014001 (2001).

1. Three-Nucleon Force and deuteron-proton elastic scattering

Study of 3*N*Fs via few-nucleon scattering experiments

- momentum, spin, isospin dependence of the 3*N*Fs

  Direct comparison between…

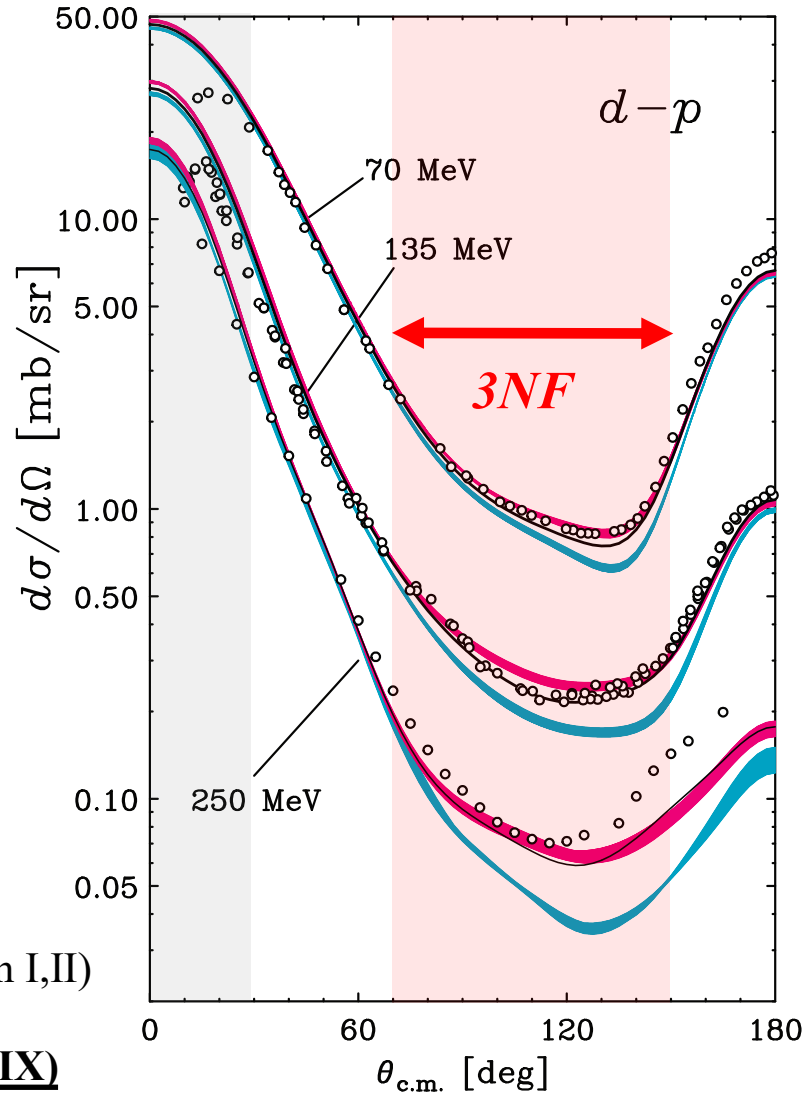
  - **high-precision data** in few-nucleon scattering (differential cross sections, spin observables)
  - **theoretical predictions** based on rigorous numerical calculations

- *d*-*p* elastic scattering (*E*/*A* 70–300 MeV)

  Differential cross section
  →<u>3*N*F effect observed at cross section minimum</u>

_d-p_ elastic scattering :
effective probe for investigation of the 3*N*Fs

❖ Differential cross section



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

1. Three-Nucleon Force and deuteron-proton elastic scattering

Chiral Effective Field Theory and Three-Nucleon Force

Chiral Effective Field Theory (χEFT)

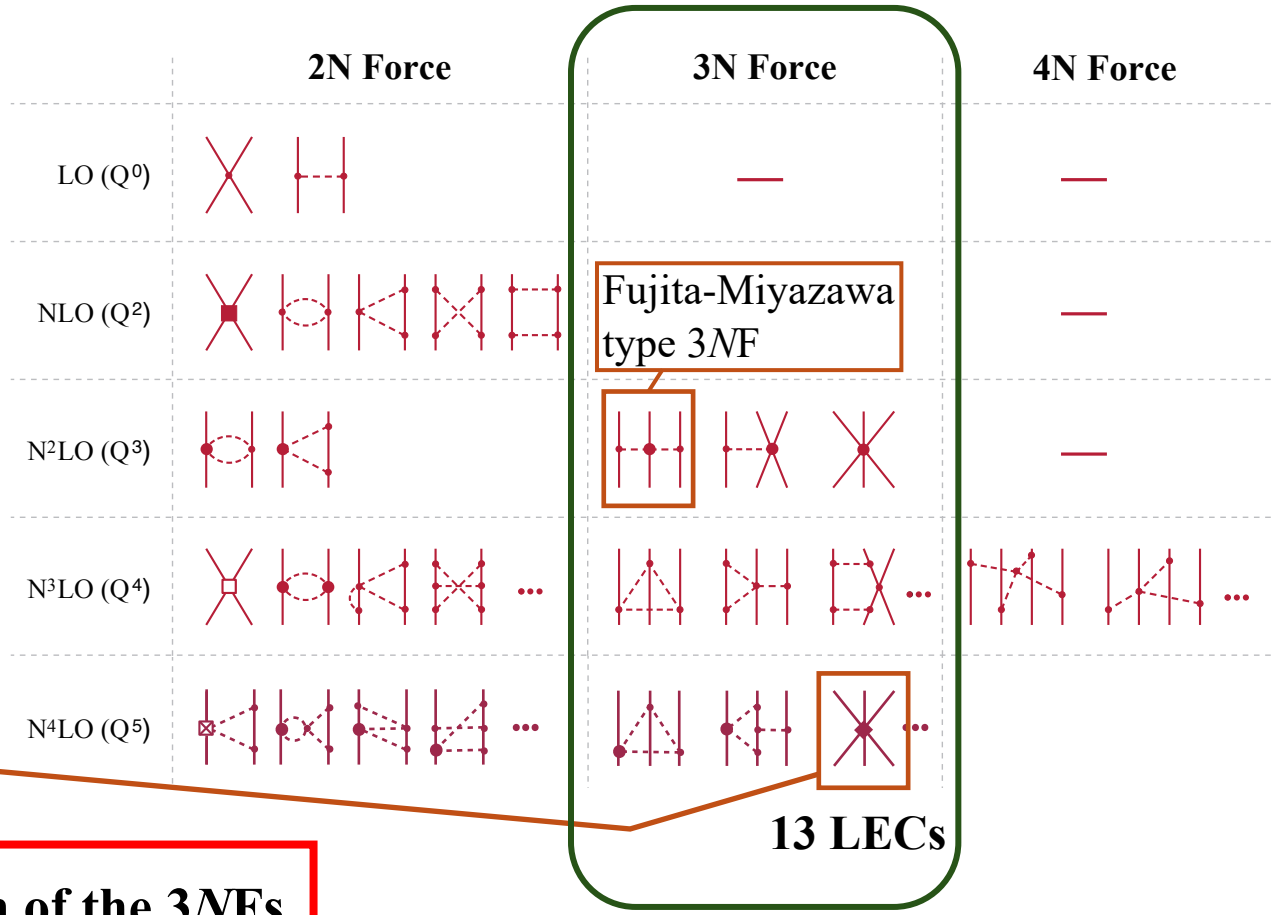
- Newly progressing theory based on low energy QCD

χEFT's 2*N* : achieved to level of high precision (N^{4}LO)

P. Reinert, H. Krebs, and E. Epelbaum, Eur. Phys. J. A **54**, 86 (2018).

χEFT's 3*N* : aim to develop an accurate potential at N^{4}LO

→**low energy constants (LECs)** must be fixed from experimental data



E. Epelbaum, arXiv:1908.09349 (2019).

11/13 LECs can be probed in *Nd* scattering

***d-p* elastic scattering : good probe for investigation of the 3*N*Fs**

→ determination of 11 LECs in N^{4}LO's 3*N*F sector

→ New Experiment necessary!

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2. Measurement of Spin Correlation Coefficients in $\vec{d}$-$\vec{p}$ elastic scattering

- ❖ Polarized Proton Target
- ❖ KuJyaku Detector System
- ❖ Polarized Deuteron Beam

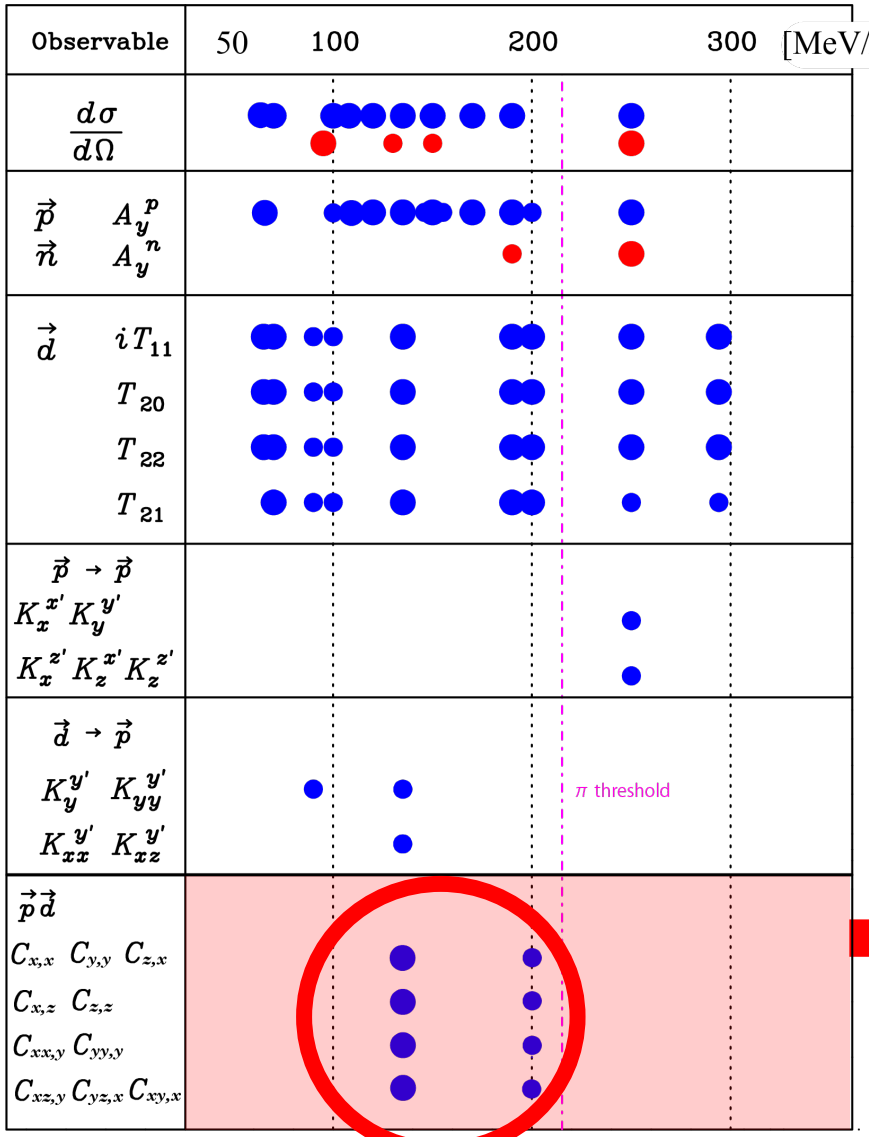
3. Experiment with the new systems in January 2024
   (d-$\vec{p}$ elastic scattering @ 135 MeV/Nucleon)

4. proton-^{3}He (p-^{3}He) elastic scattering experiments

5. Summary

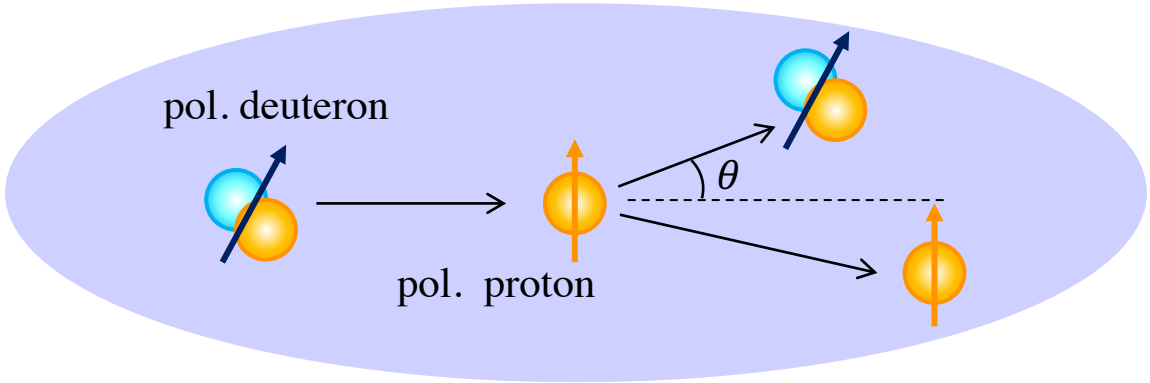
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering
New d-p experiment for the determination of the 3NF

pd and *nd* elastic scattering at 65-300 MeV/nucleon



Measurement of spin correlation coefficients in d-p elastic scattering @ RIKEN

➢ for the determination of LECs in N4LO 3NFs



Polarization of both beam and target necessary!

- ❖ **Polarized deuteron beam ($\vec{d}$)** : polarized ion source @ RIKEN
- ❖ **Polarized proton target ($\vec{p}$)** : newly developed based on triplet-DNP
- ❖ **New detector system (KuJyaku)** developed for measurement of *L, R, U, D* at wide angular (θ) range

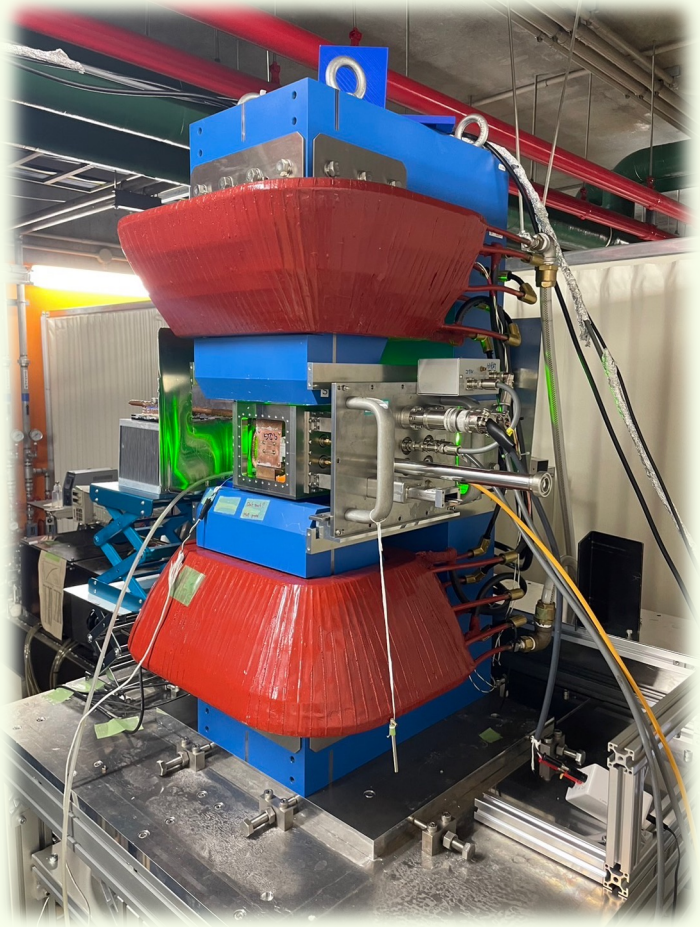
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

Polarized Proton Target ($\vec{p}$)

→based on the **Triplet-Dynamic Nuclear Polarization (triplet-DNP) Method**

Past achievements : Proton polarization of 34% @ 0.4 T and ~300K

K. Tateishi *et al.*, www.pnas.org/cgi/doi/10.1073/pnas.1315778111



necessary conditions for $\vec{d}$ - $\vec{p}$ elastic scattering experiment

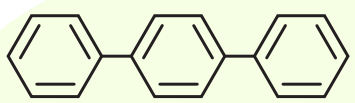
- **measurement at wide angular range (θ_{lab} : ±60°)**
- **detection of scattered particles with relatively low energy (60-200 MeV)**
  → static field under ~1 T
- **polarization around 10 %**

2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

Polarized Proton Target ($\vec{p}$)

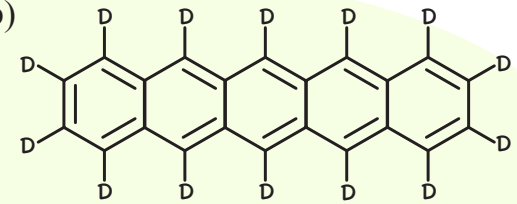
Target : **pentacene doped *p*-terphenyl single crystal**

(a)



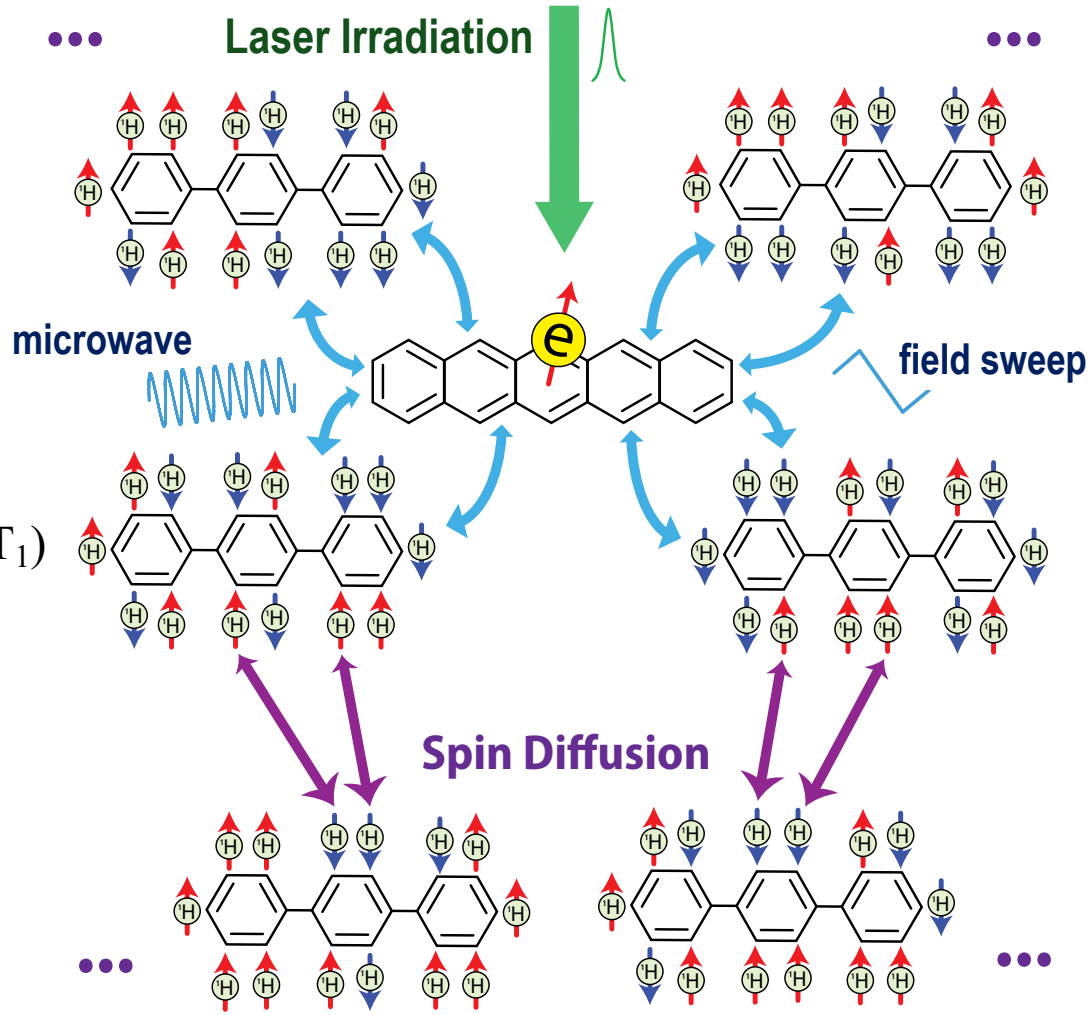
p-terphenyl

(b)



deuterated pentacene
(0.005 %/mol)

Size : φ10×2.5 mm^3



① Optical excitation of electrons in pentacene and decay to triplet state (T_1)
→ **Electron polarization** of ~ **85%**

② **Polarization transfer** from electrons to protons
: integrated solid effect (ISE) = Microwave irradiation + field sweep

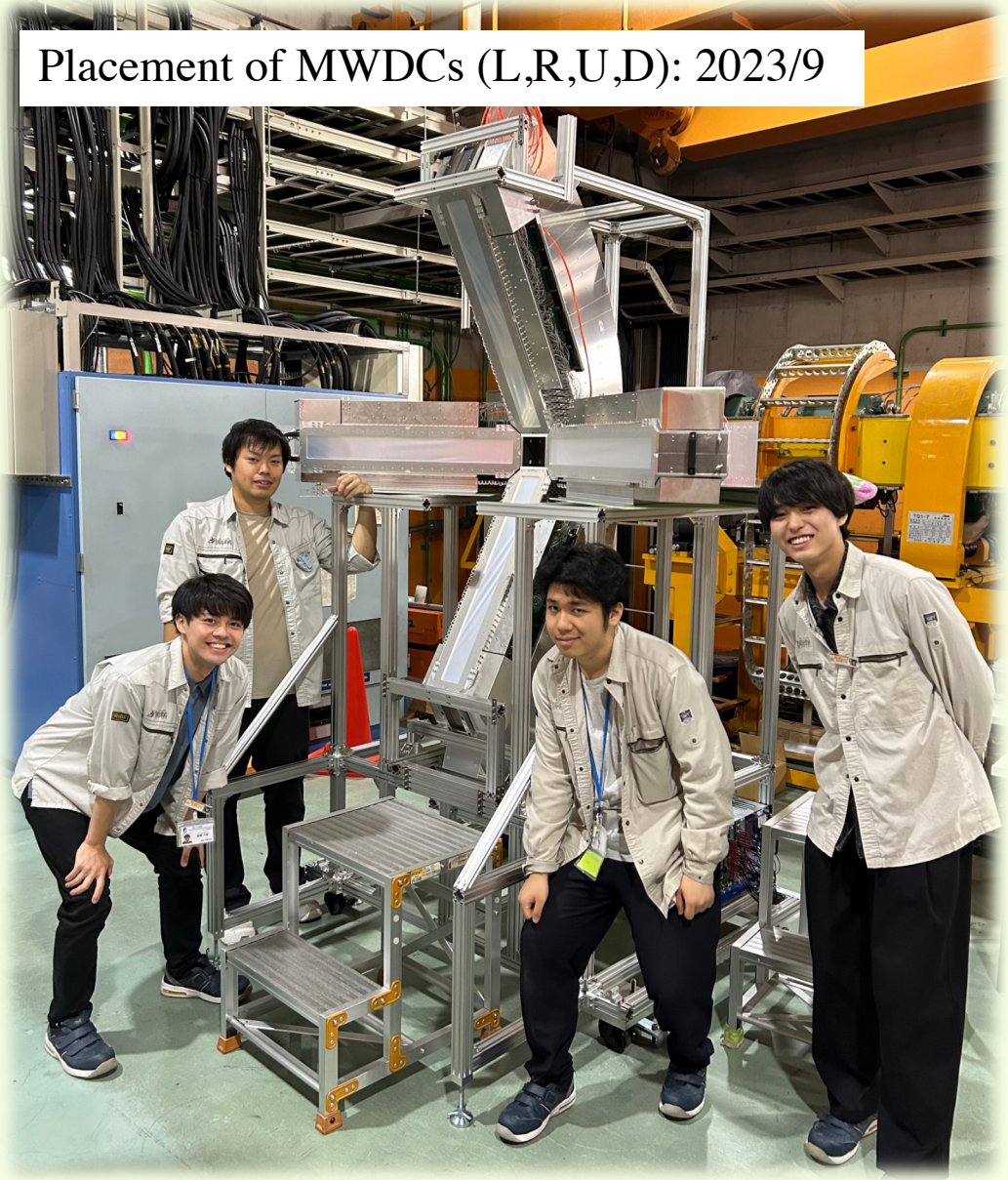
③ Proton polarization localized around pentacene after ISE
→ spontaneously diffused and averaged out = **Spin diffusion**

Aim : proton polarization of around 10%

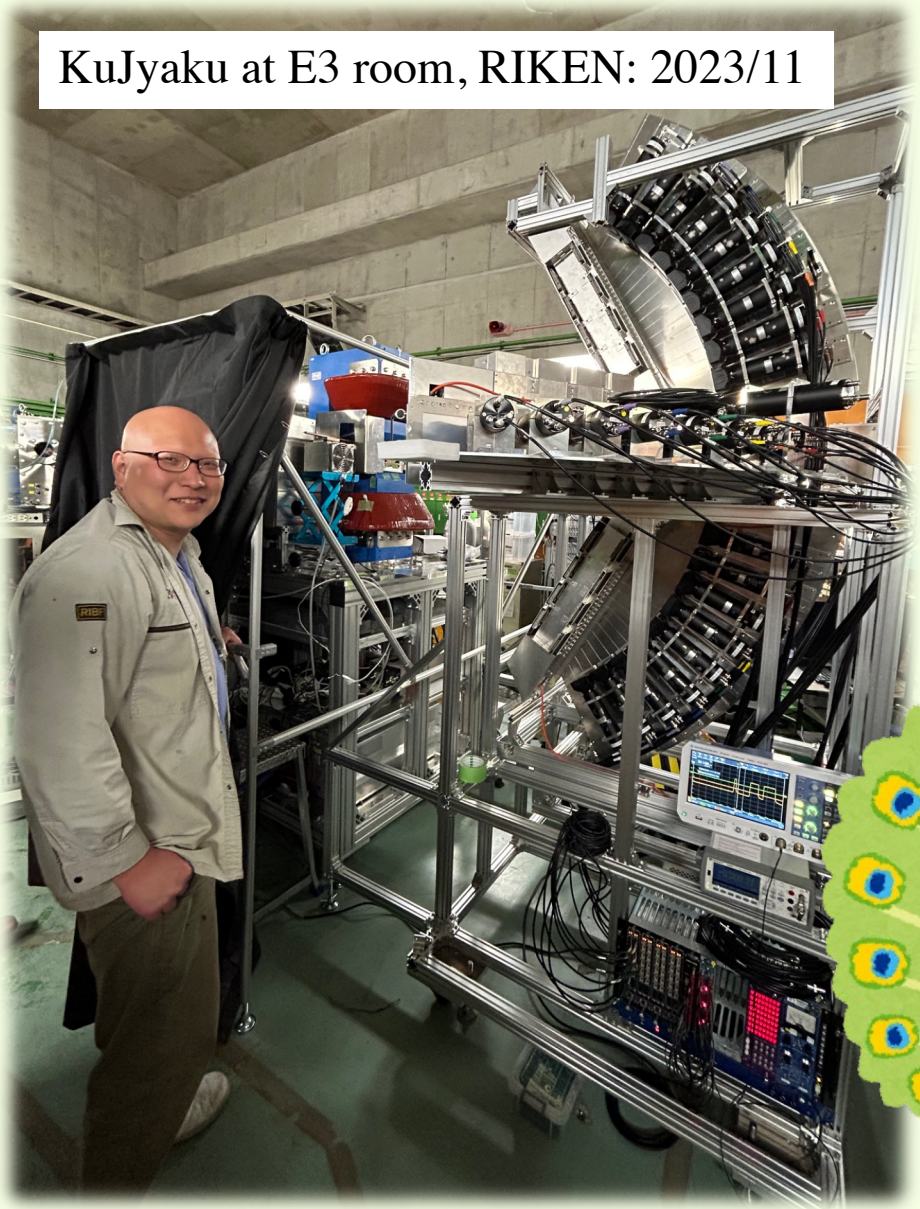
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

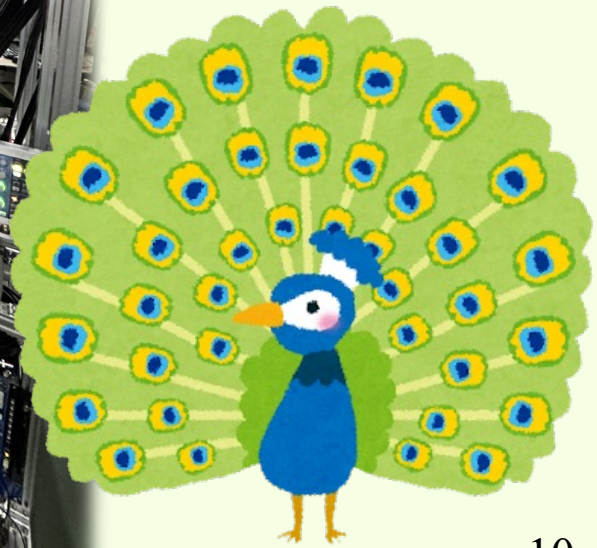
KuJyaku Detector System

Placement of MWDCs (L,R,U,D): 2023/9



KuJyaku at E3 room, RIKEN: 2023/11

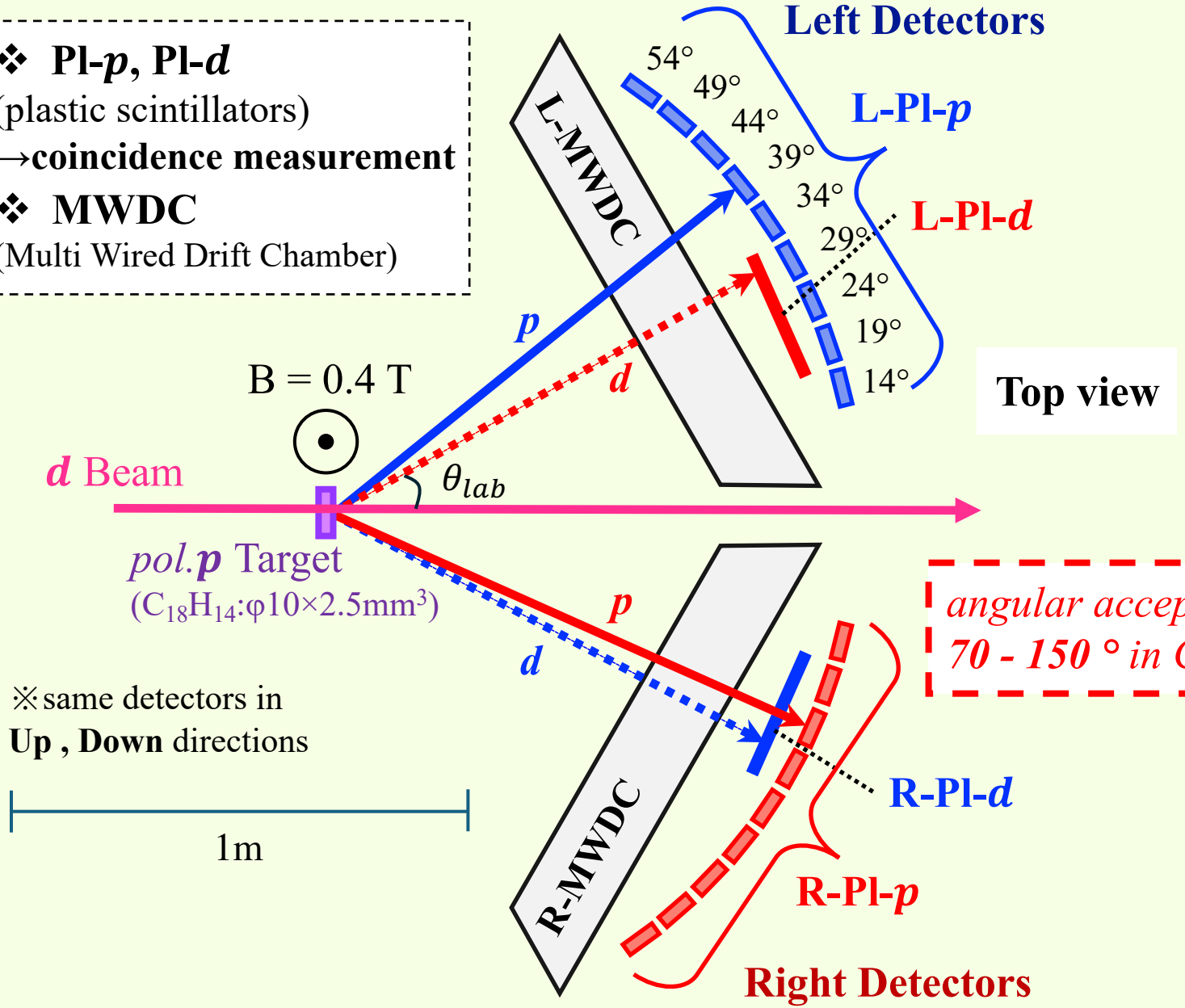




2. KuJyaku Detector System

❖ **Pl-*p*, Pl-*d***
(plastic scintillators)
→**coincidence measurement**

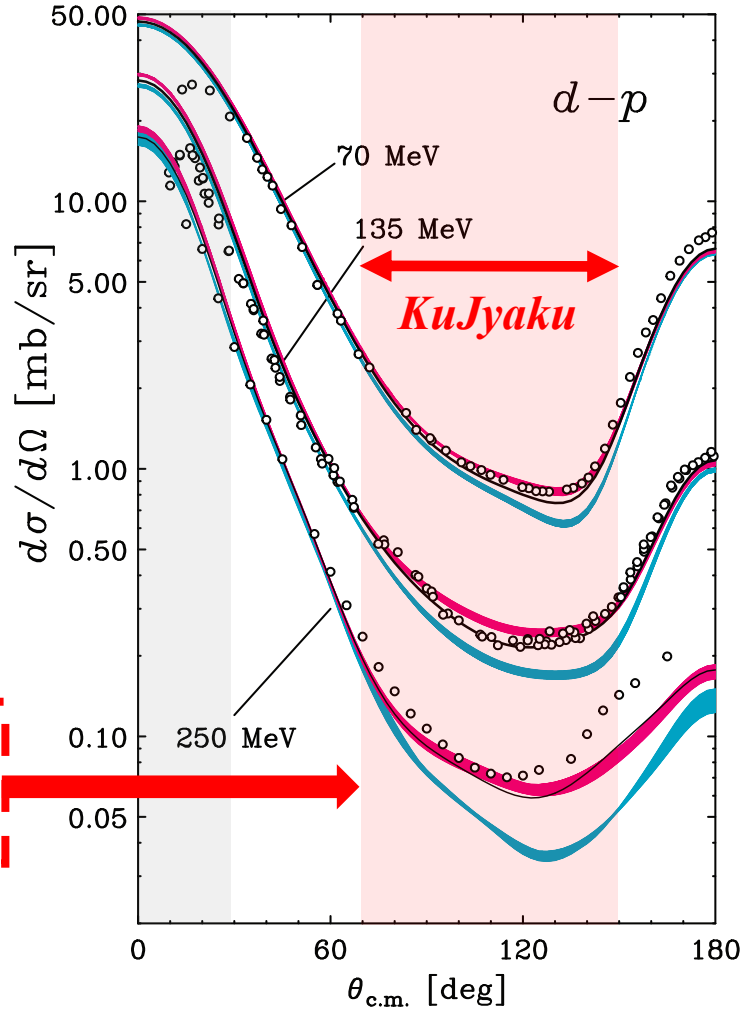
❖ **MWDC**
(Multi Wired Drift Chamber)



Top view

angular acceptance of
70 - 150 ° in CM

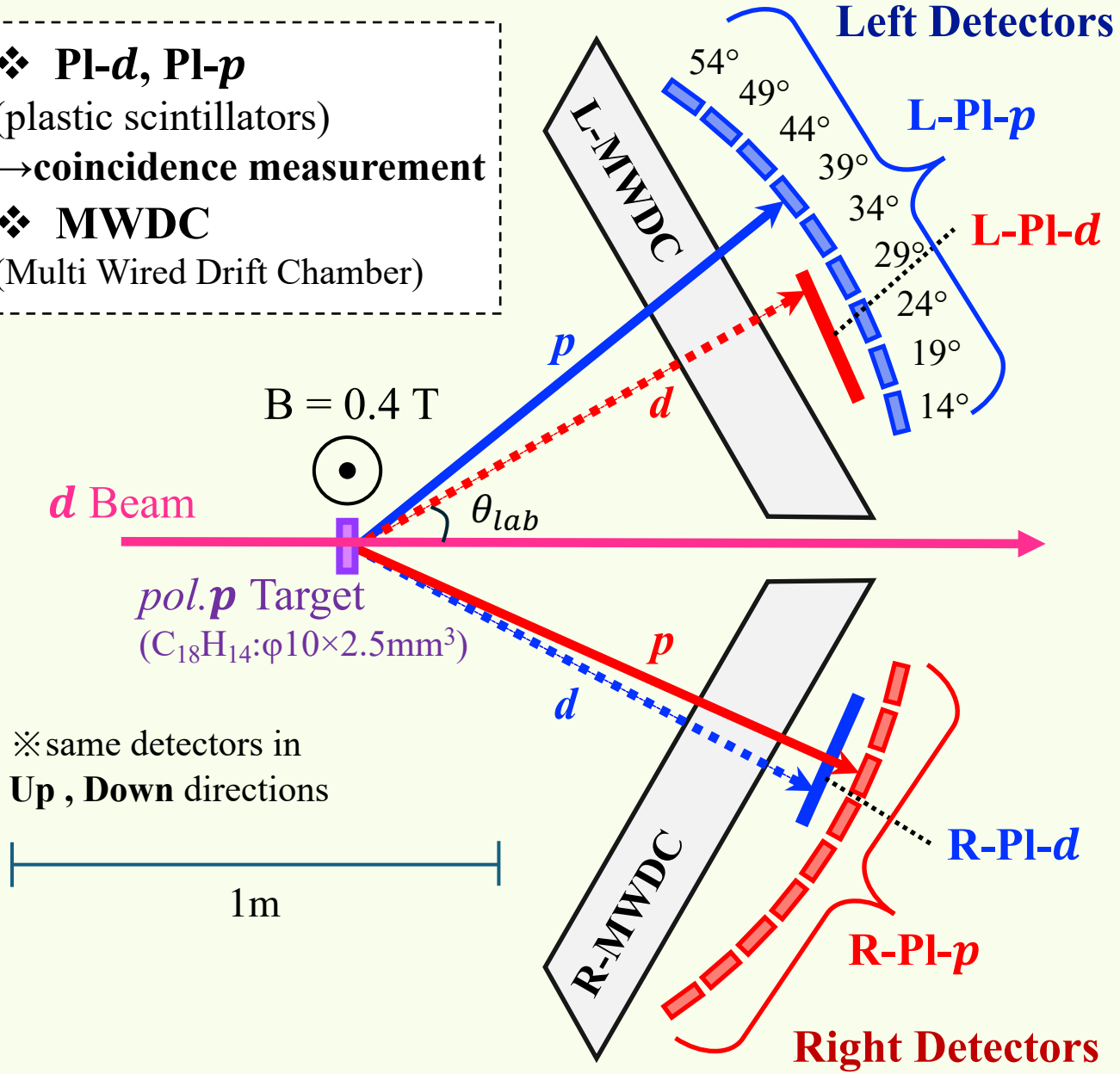
❖ Differential cross section



2*N*F (CDB, AV18, Nijm I,II)
2*N*F + **3*N*F (TM)**
AV18 + **3*N*F (Urbana IX)**
○ data
- K. Sekiguchi *et al.*, PRC **65**, 034003 (2002).

2. KuJyaku Detector System

❖ **Pl-*d*, Pl-*p***
(plastic scintillators)
→**coincidence measurement**
❖ **MWDC**
(Multi Wired Drift Chamber)



❖ trajectories of ***d*** and ***p***
→ *bent* at target (0.4T)

●simulation via:
・TOSCA (OPERA-3d)
・GEANT4

●**MWDC**:
→for tracking trajectories of ***d*** and ***p***

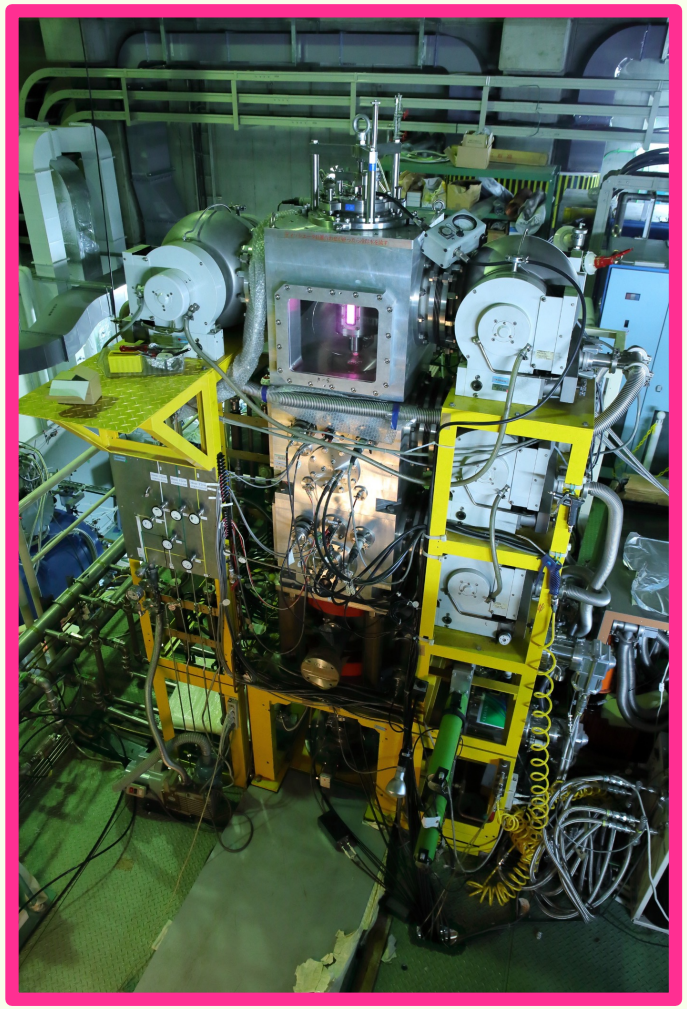
→ consistency between simulation and measured trajectory

→ *analysis ongoing*

2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

Polarized deuteron beam ($\vec{d}$) : Polarized ion source

Polarized ion source



3 m

~2012
- **polarization : 60-80% of theoretically maximum values**

2023/7~
- *water leakage from cooling pipe inside vacuum chamber*
  → repairing / maintenance

2024/9/14 → beam test to check the deuteron polarization !
- **polarization : 50-80%** (preliminary)

Ready for the Spin Correlation Coefficients Measurement

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(d-$\vec{p}$ elastic scattering @ 135 MeV/Nucleon)

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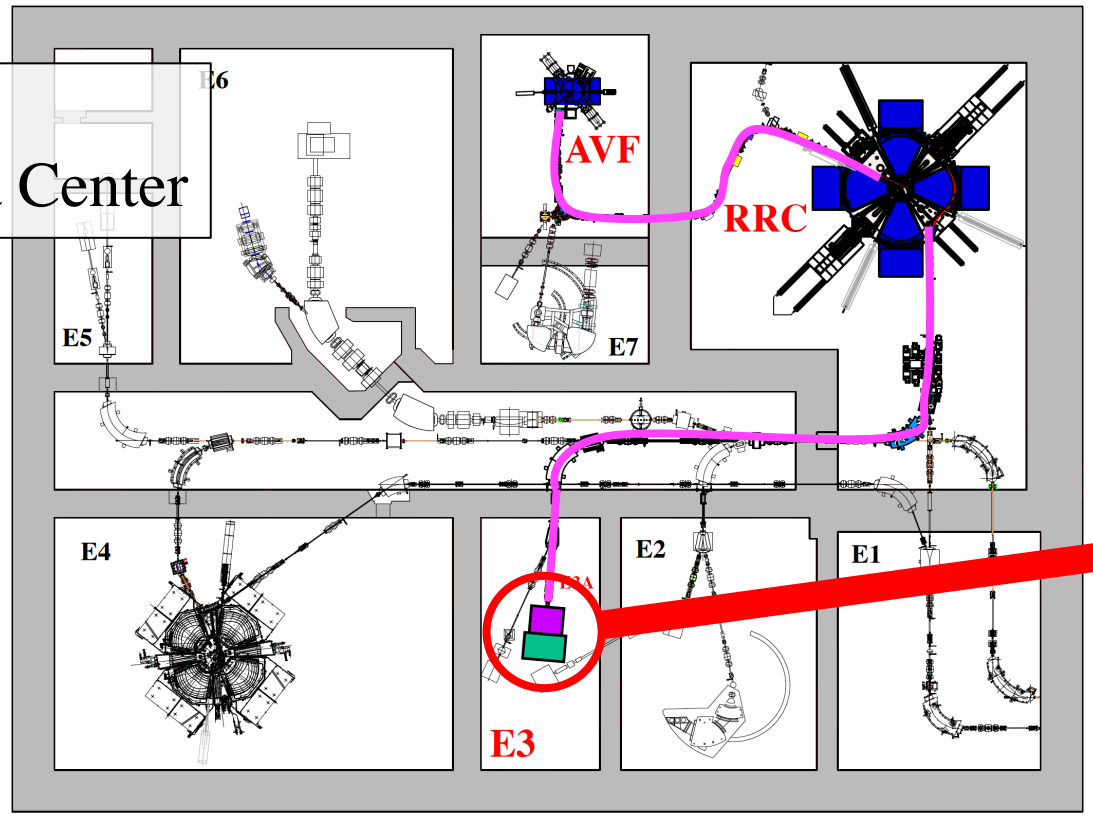
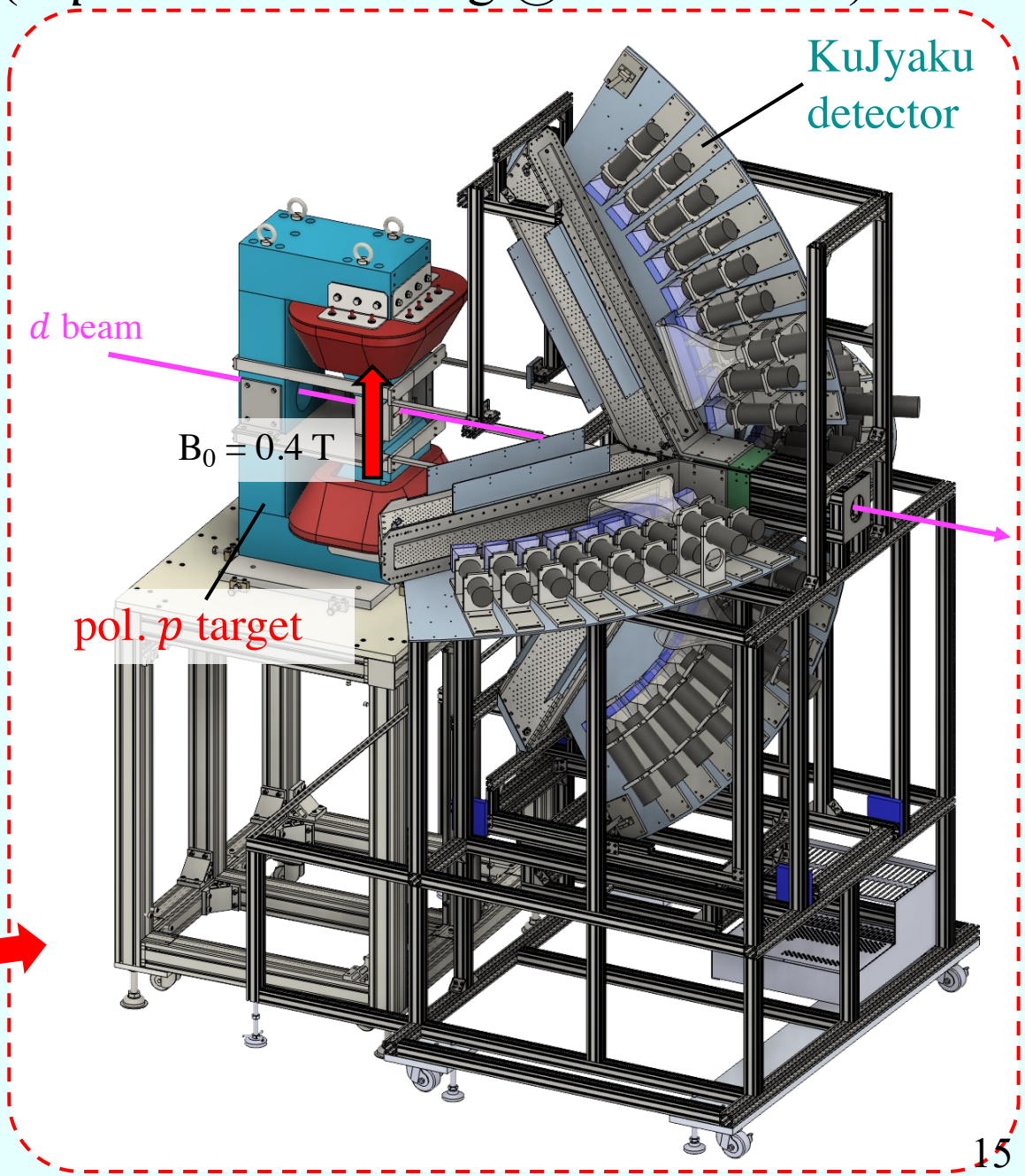
3. Experiment with the new systems in January 2024 (d-$\vec{p}$ elastic scattering @ 135 MeV/N)

➢ First beam test on target/detector systems using d beam

Observables	$d\sigma/d\Omega$, A_y , target polarization
Machine time	1/8 9:00 - 1/10 9:00
beam	135 MeV/Nucleon unpolarized d beam
target	pol. p target ($C_{14}H_{18}$ crystal : ϕ10, 2.5 mm)
detector	KuJyaku system (plastic scintillators, MWDCs)

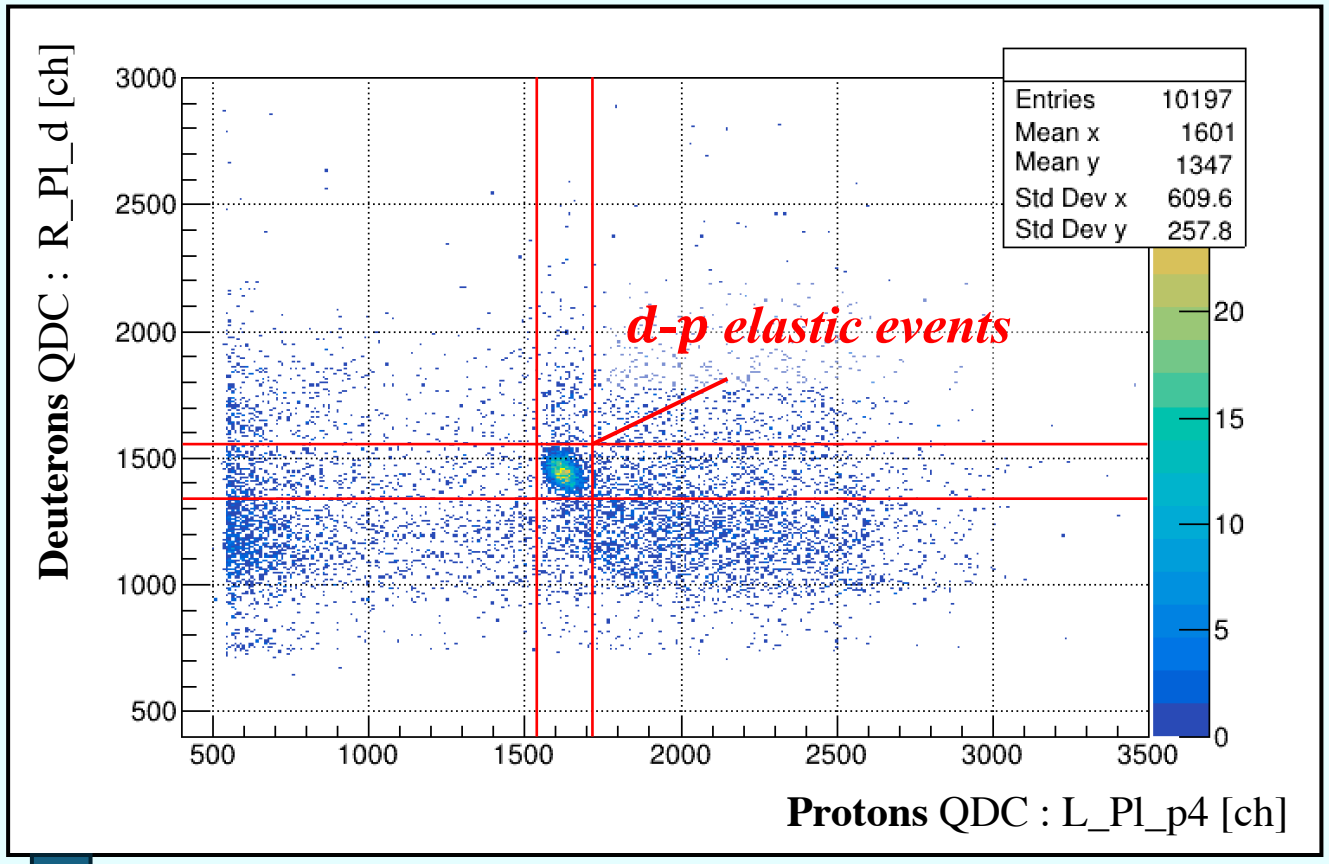
RIKEN
Nishina Center

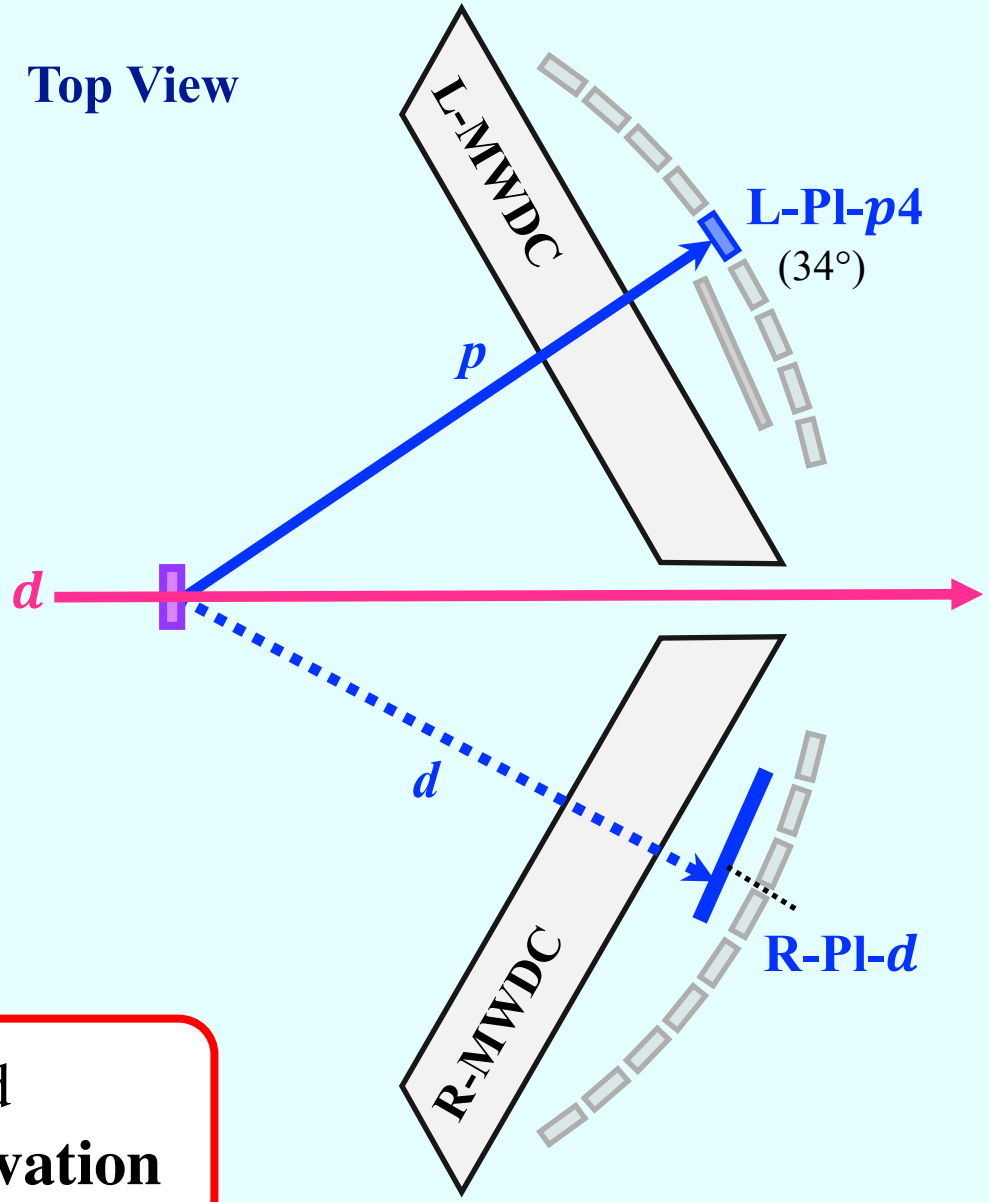




3. Experiment with the new systems in January 2024 (d-$\vec{p}$ elastic scattering @ 135 MeV/N)

Event Selection

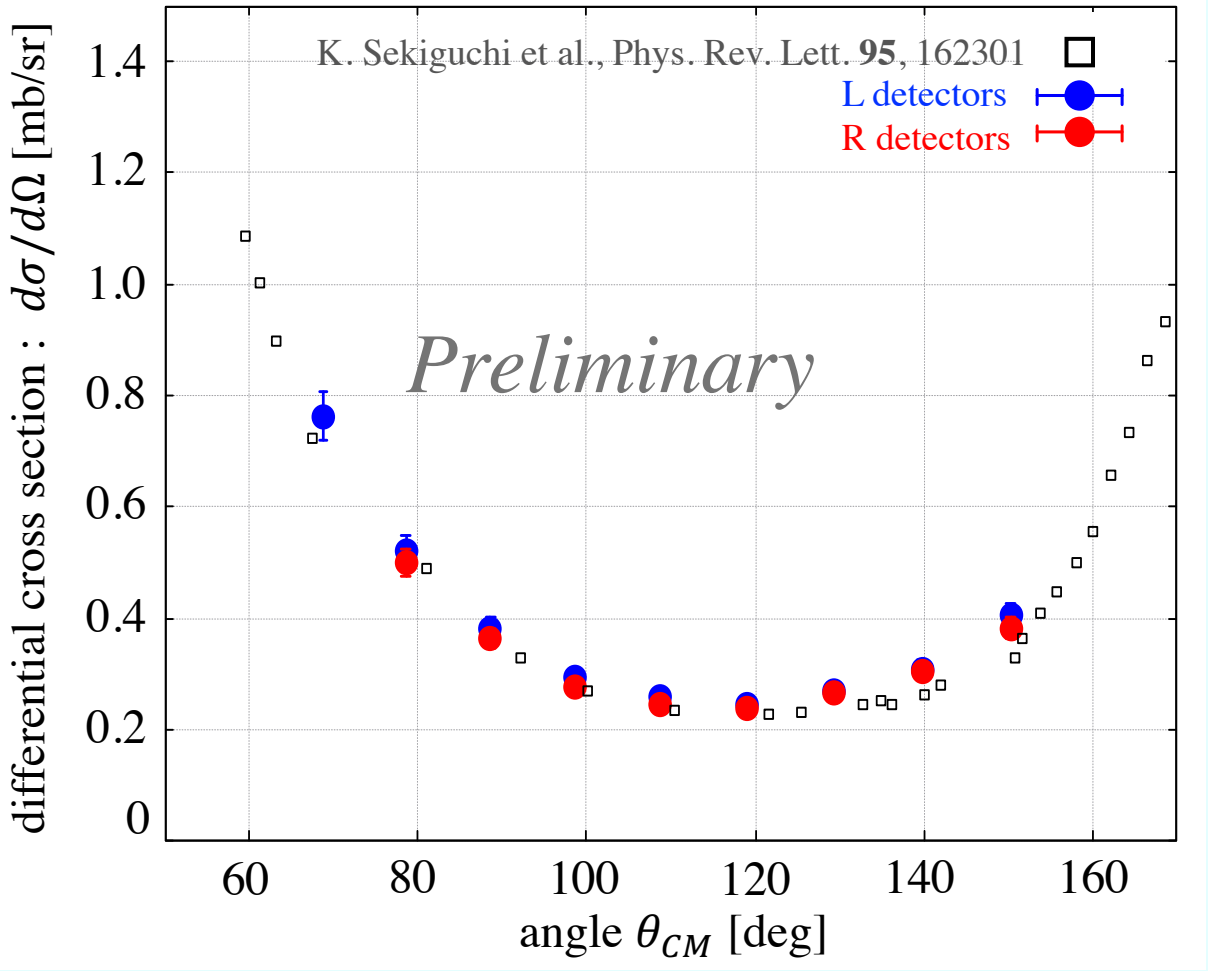




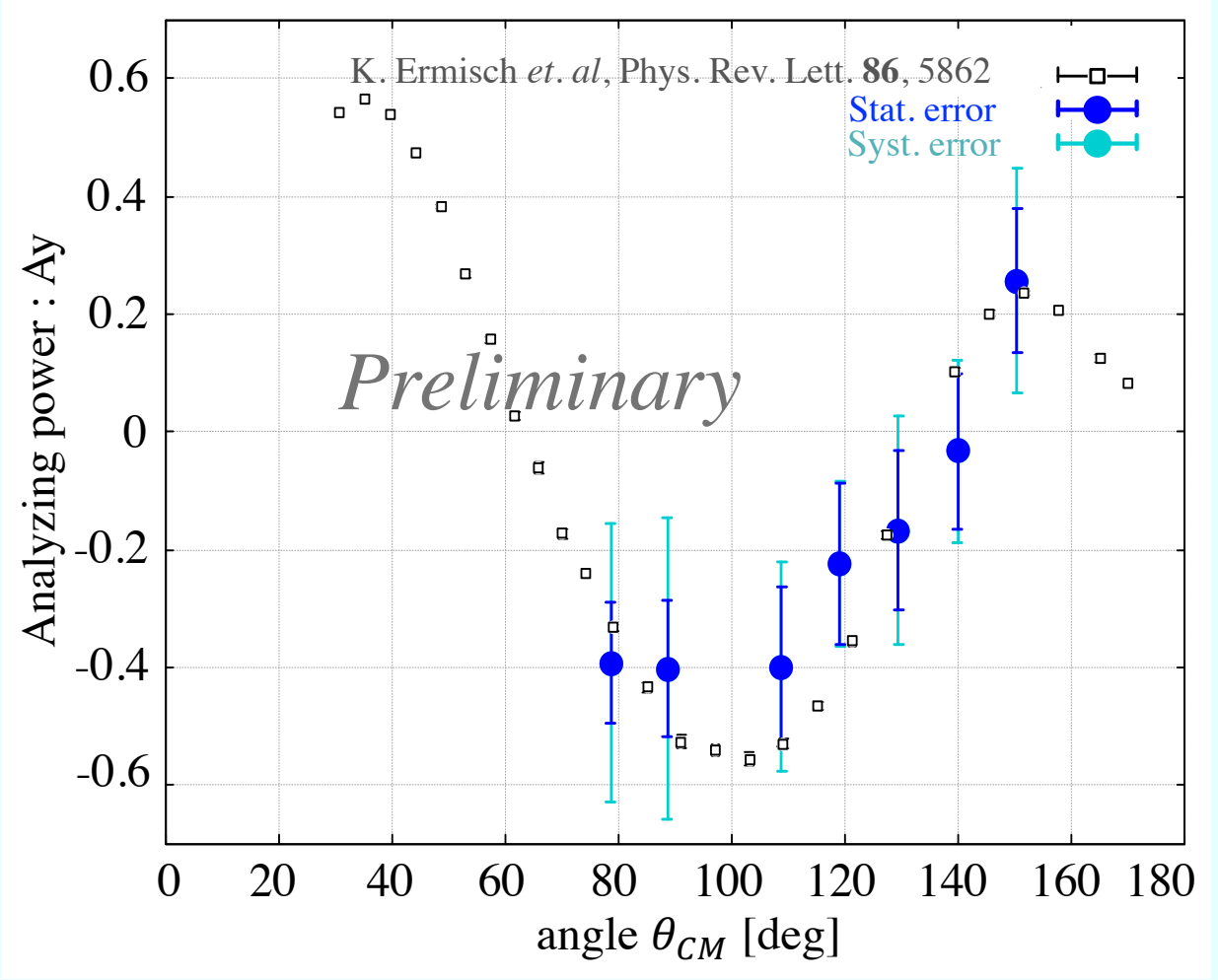
d-p elastic events *successfully* observed
→**yield used for dσ/dΩ and Ay derivation**

3. Experiment with the new systems in January 2024 (d-$\vec{p}$ elastic scattering @ 135 MeV/N)

Preliminary Results



※error bars: systematic error
(static error within circles)



※large error due to *low polarization of proton target (~2-3%)*
→improvements necessary!

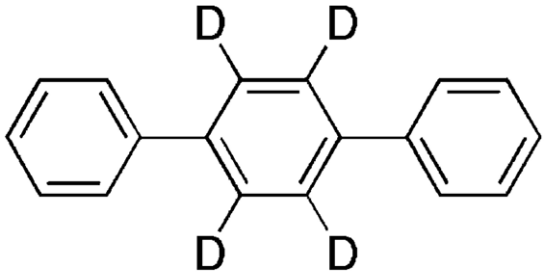
Future plans for the Measurement of Spin Correlation Coefficients in $\vec{d}$-$\vec{p}$ elastic scattering

❖ *Necessity of improvements in target polarization*

✓ new material for target crystal : ***p*-terphenyl-d_4**

→ under development

→ polarization expected to rise to ~10%



❖**Measurement of Spin Correlation Coefficients in $\vec{d}$-$\vec{p}$ elastic scattering**

✓ Next : $\vec{d} + \vec{p}$ @ 100 & 135 MeV/Nucleon → $C_{y,y}$, $C_{x,x}$, $C_{yy,y}$

✓ Future : $\vec{d} + \vec{p}$ @ 100 & 135 MeV/Nucleon → $C_{z,x}$, $C_{xx,y}$, $C_{xy,x}$, $C_{yz,x}$, $C_{xz,y}$

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4. proton-^{3}He (p-^{3}He) scattering experiments

Isospin Dependence of 3*N*Fs

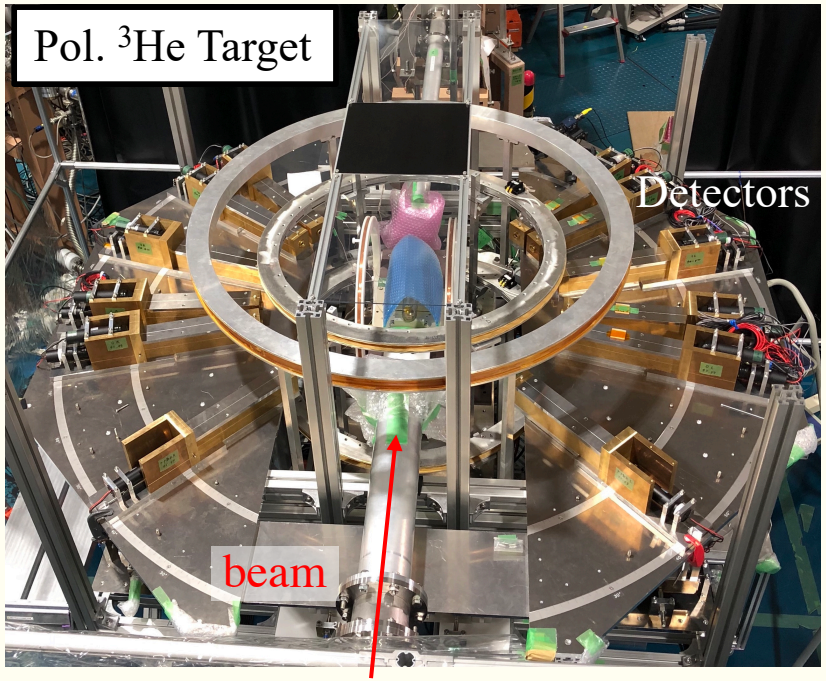
- $d + p$: isospin channel limited to $\boldsymbol{T = 1/2}$
- **$T = 3/2$ channel** of 3*N*Fs : Important roles for exploring **neutron-rich nuclei & pure neutron matter**

Proton-^{3}He elastic Scattering @ 65-100 MeV for investigation of $T = 3/2$ channel in 3*N*Fs

Our Experiments

Incident Energy	65 MeV	70 MeV	65 MeV	100 MeV
Beams	pol. p	p	pol. p	pol. p
Observables	$d\sigma/d\Omega$, A_y^p	A_y^{3He}	A_y^p, A_y^{3He}, $C_{y,y}$	A_y^p, A_y^{3He}, $C_{y,y}$
Measured Angles ($\theta_{c.m.}$)	27°–170°	46°–141°	46°–133°	47°–149°
Facilities	RCNP, Osaka Univ.	CYRIC, Tohoku Univ.	RCNP, Osaka Univ.	RCNP, Osaka Univ.
Exp. Course	WS course	41 course	ENN course	ENN course

- **pol. ^{3}He gas target** : Alkali-Hybrid SEOP type
  → polarization : **30-40%** as of 2018



4. proton-^{3}He (p-^{3}He) scattering experiments

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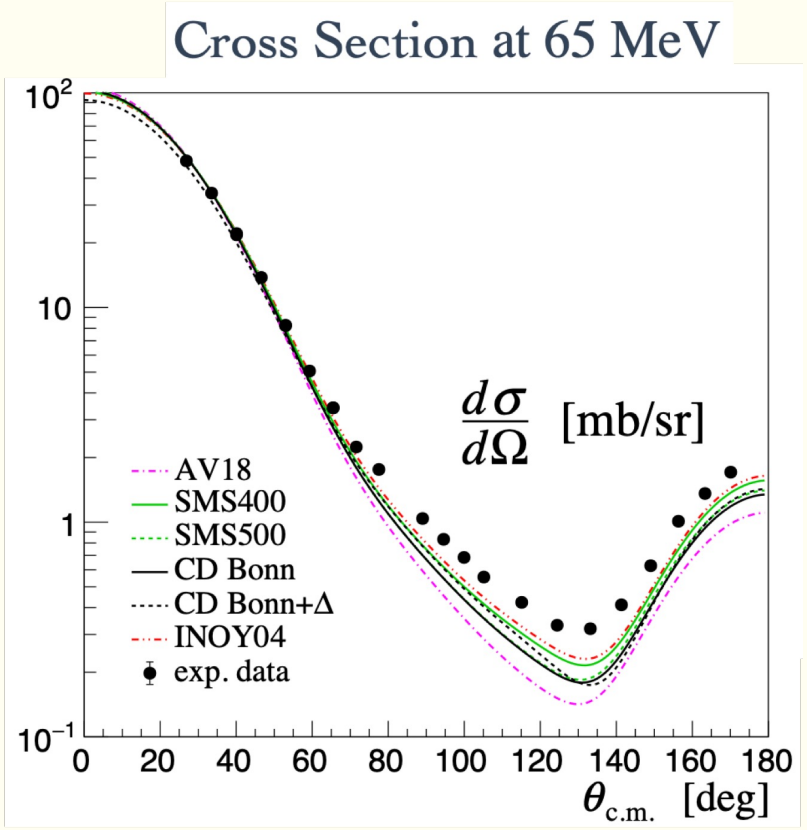
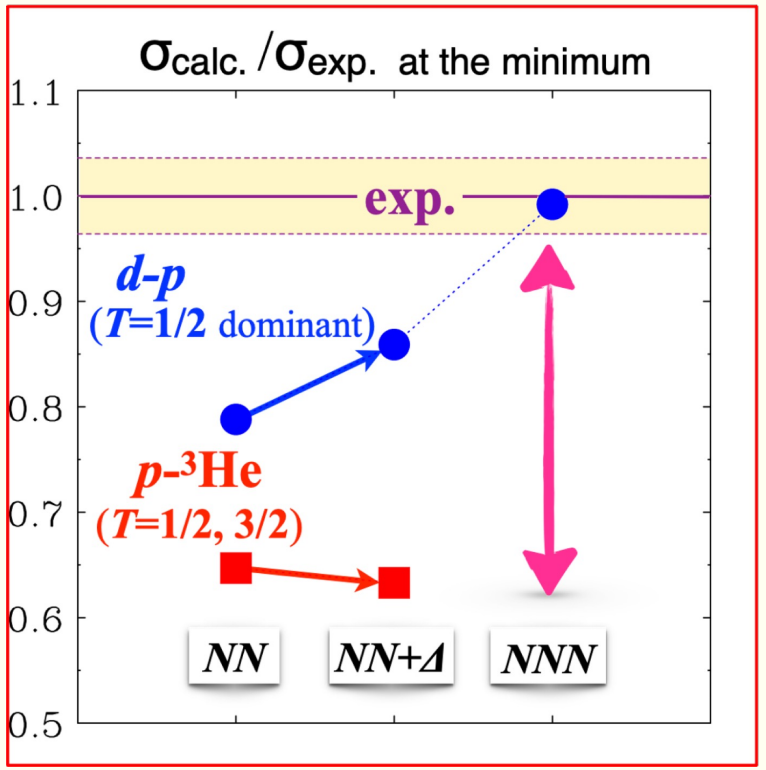
- $d + p$: isospin channel limited to $\boldsymbol{T = 1/2}$
- **$T = 3/2$ channel** of 3*N*Fs : Important roles for exploring **neutron-rich nuclei & pure neutron matter**

Proton-^{3}He elastic Scattering @ 65-100 MeV for investigation of $T = 3/2$ channel in 3*N*Fs





A.Watanabe *et al.*, Phys. Rev. C 103, 044001 (2021)

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   (d-$\vec{p}$ elastic scattering @ 135 MeV/Nucleon)

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5. Summary

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5. Summary

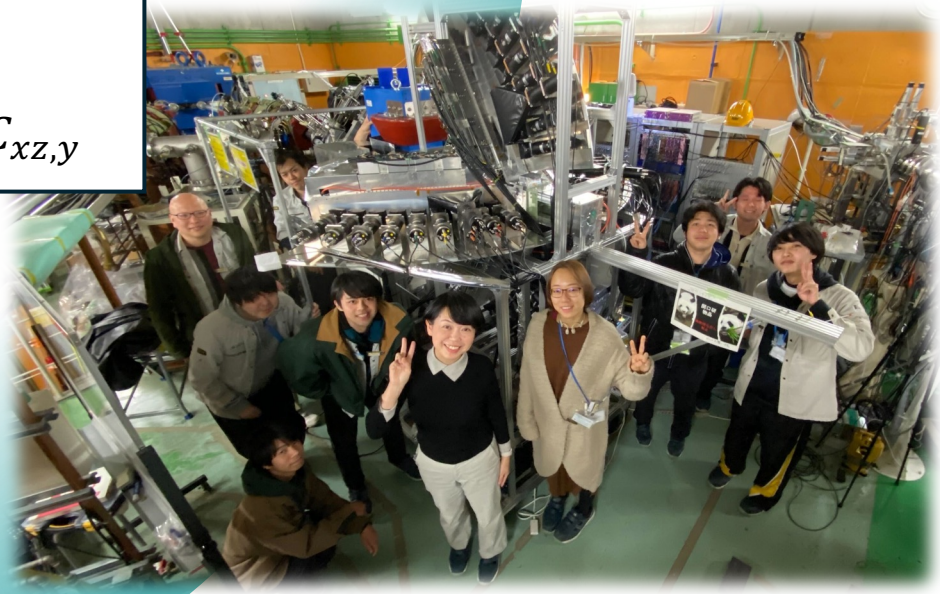
TOMOE

- Measurement of spin correlation coefficients in $\vec{d}$-$\vec{p}$ **elastic scattering** to determine 11 LECs in N^{4}LO of the 3*N*F sector in Chiral EFT
  - ❖ Polarized Deuteron Beam ❖ Polarized Proton Target ❖ KuJyaku Detector System
- Experiment with the new systems in January 2024 (d-$\vec{p}$ elastic scattering @ 135 MeV/Nucleon, RIKEN)
  - ✓ First beam test on the target and detector systems via deuteron beam
  - ✓ Analysis on the differential cross sections / Analyzing Powers → ongoing
  - ✓ New material for target crystal : ***p*-terphenyl-d_4**

❖ **Plan for Measurement of Spin Correlation Coefficients**

- ✓ Next : $\vec{d} + \vec{p}$ @ 100 & 135 MeV/Nucleon → $C_{y,y}$, $C_{x,x}$, $C_{yy,y}$
- ✓ Future : $\vec{d} + \vec{p}$ @ 100 & 135 MeV/Nucleon → $C_{z,x}$, $C_{xx,y}$, $C_{xy,x}$, $C_{yz,x}$, $C_{xz,y}$

- ***p*-^{3}He elastic scattering**
  →for investigation of $T = 3/2$ channel in 3*N*Fs



Thank you for your attention.

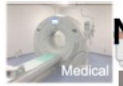
Back ups

Japan Science and Technology Agency

TOMOE

Term Oct. 2023-Mar.2029

JST ERATO Three-Nucleon Force Project (PI : Kimiko Sekiguchi)

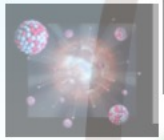


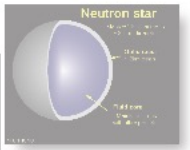
Nuclear Medecine

RI production

Engineering

Nuclear fusion & fission Nucleosynthesis Neutron star

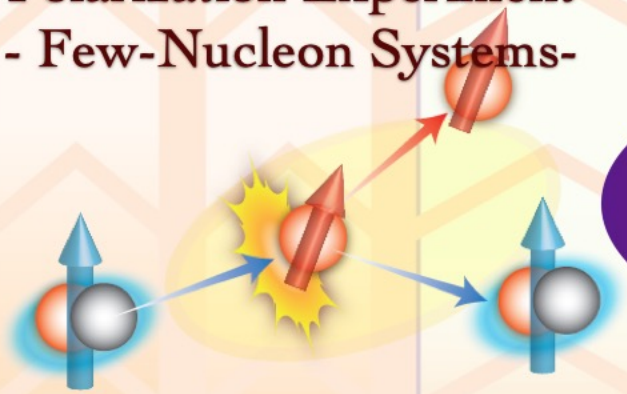




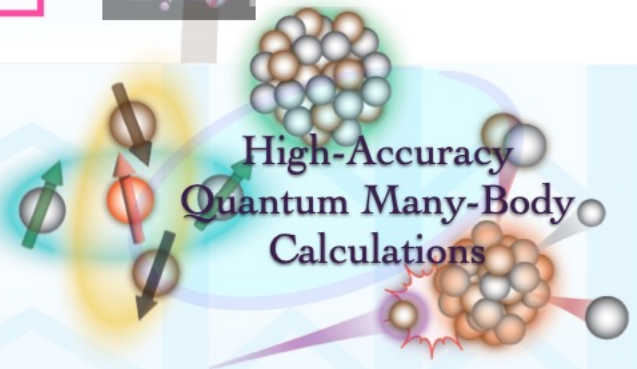
Applied Science

Evolution of Nuclear Data

Polarization Experiment
- Few-Nucleon Systems-



High-Accuracy Quantum Many-Body Calculations



High Precision NN+NNN Force

Nuclear Forces from Chiral Effective Field Theory

Ultra Cold Atom Experiment

Fundamental Science

Descriptions of Nuclei from First Principles

Establishment of Quantum Many-Body Simulation Tool of Nuclear Phenomena with High-predictive Power

2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$ - $\vec{p}$ elastic scattering

→ polarization of **beam** and **target** necessary

❖ **Polarized deuteron beam ($\vec{d}$)** : polarized ion source @ RIKEN RIBF

H. Okamura *et al.*, AIP Conf. Proc. **293**, 84 (1994).

❖ **Polarized proton target ($\vec{p}$)** : newly developed based on triplet-DNP method (2021~)

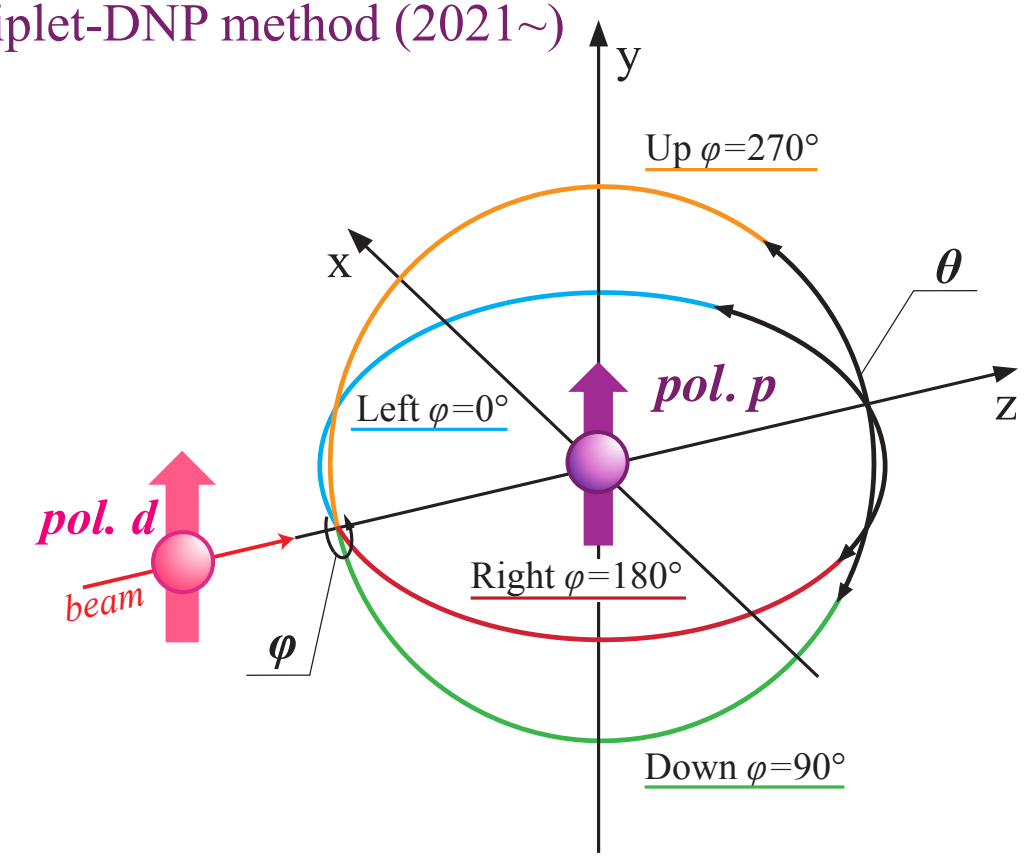
Polarized cross sections of Left, Right, Up, Down directions

$$L(\theta) = L_0(\theta)\left\{1 + \frac{3}{2}p_y\left(A_y^d(\theta) + p_y^T C_{y,y}(\theta)\right) + p_y^T A_y^p(\theta) + \frac{1}{2}p_{yy}\left(A_{yy}^d(\theta) + p_y^T C_{yy,y}(\theta)\right)\right\},$$

$$R(\theta) = R_0(\theta)\left\{1 + \frac{3}{2}p_y\left(-A_y^d(\theta) + p_y^T C_{y,y}(\theta)\right) - p_y^T A_y^p(\theta) + \frac{1}{2}p_{yy}\left(A_{yy}^d(\theta) - p_y^T C_{yy,y}(\theta)\right)\right\},$$

$$U(\theta) = U_0(\theta)\left\{1 + \frac{3}{2}p_y p_y^T C_{x,x}(\theta) + \frac{1}{2}p_{yy}A_{xx}^d(\theta)\right\},$$

$$D(\theta) = D_0(\theta)\left\{1 + \frac{3}{2}p_y p_y^T C_{x,x}(\theta) + \frac{1}{2}p_{yy}A_{xx}^d(\theta)\right\}.$$



❖ **New detector system (KuJyaku)** developed for Measurement of *L, R, U, D* at wide angular (θ) range

2. Detector System for $\vec{d} - \vec{p}$ scattering experiment

derivation of $C_{i,j}$
→measurement of
pol. cross sections

Coincidence measurement of $\vec{d}$ and $\vec{p}$
※for reduction of background events
from target crystal ($C_{10}H_8$)

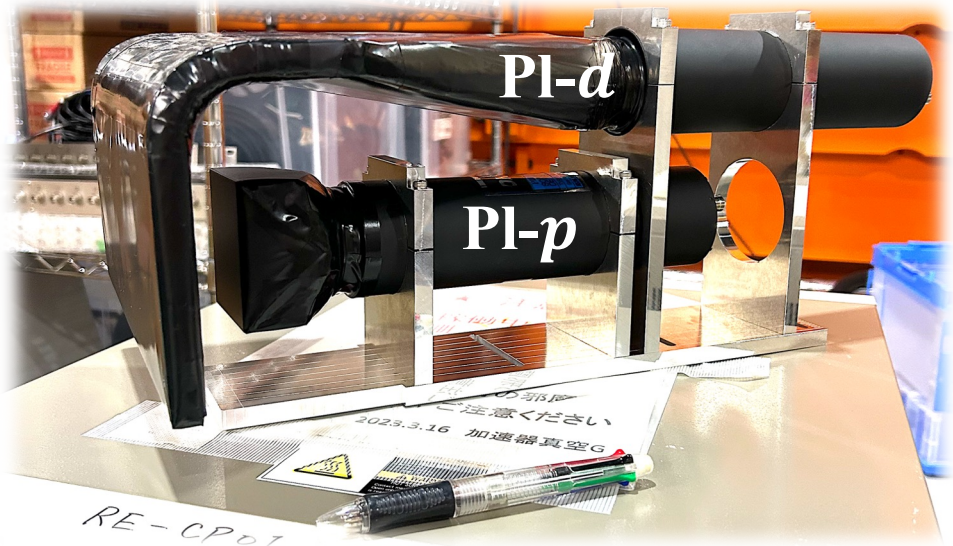
Pl-*p* (plastic scintillators):→recoil **protons**

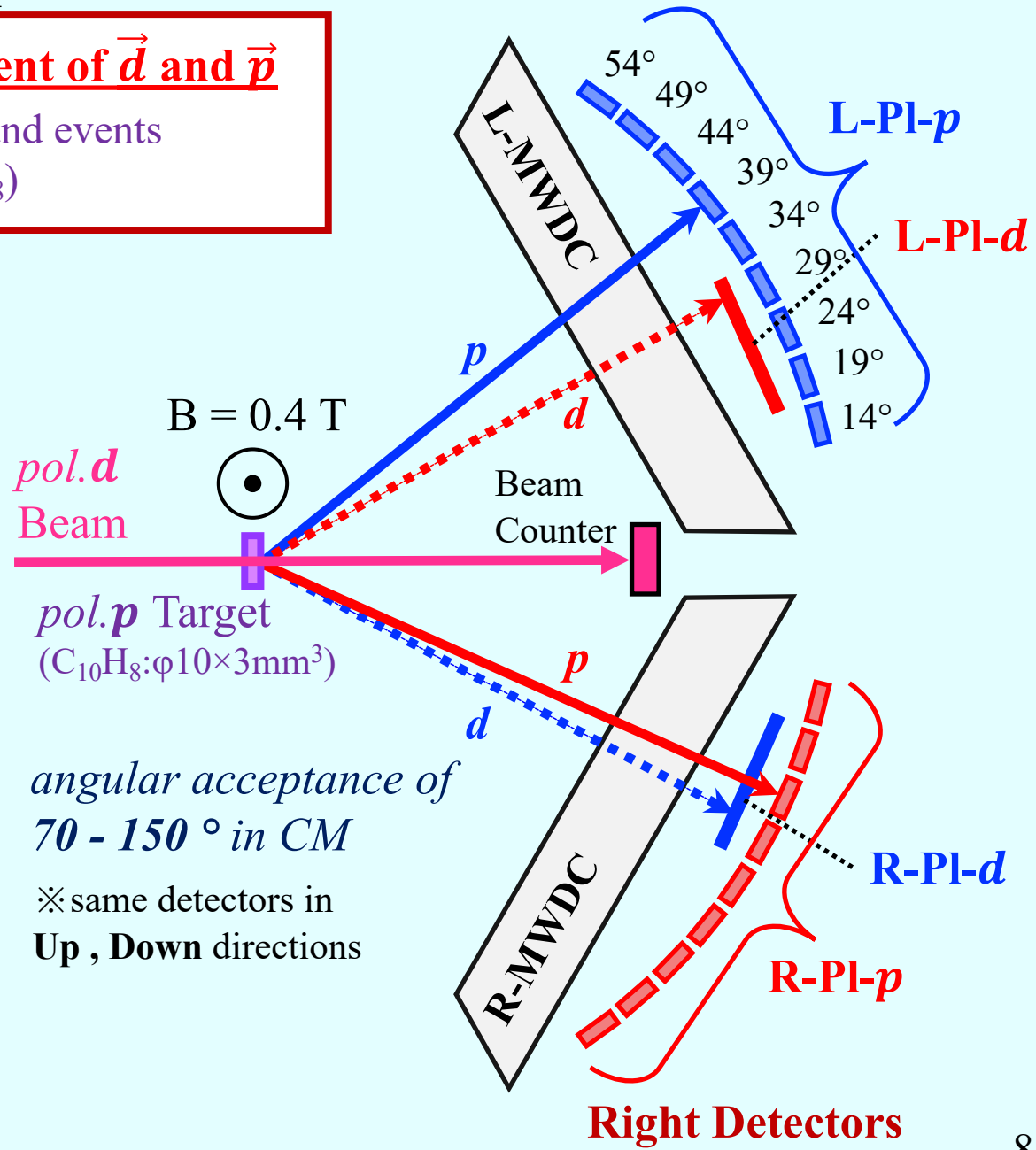
Size	$70mm^L \times 70mm^H \times 25mm^t$
PMT	H7195

$\Delta\Omega$: ±2[deg]
(3.8×10^{-3} [sr])

Pl-*d* (plastic scintillators):→scattered **deuterons**

Size	$250mm^L \times 70mm^H \times 10mm^t$
PMT	H7195





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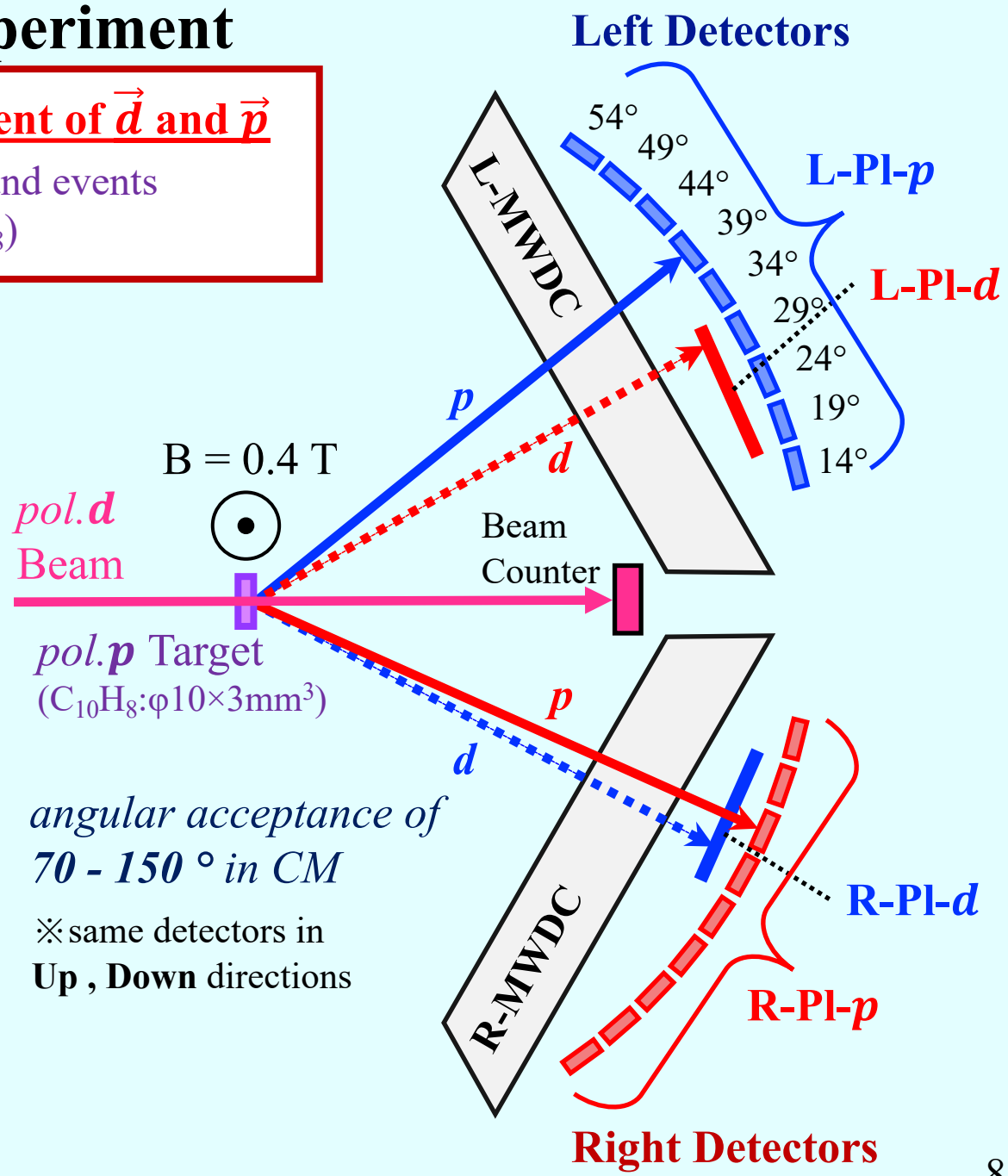
MWDC (Multi Wired Drift Chamber):
→for tracking trajectories of ***d*** and ***p*** *bent* at target (0.3T)

Wire configuration	X(31)-X'(32)-X(33)-X'(32)
Cell shape	Hexagonal
Active area	$878mm^L \times 70mm^H$
Sense wire spacing	24mm (X-X' : 12mm)
Sense wires	30μm φ Au-plated W wire
Cathode / Shield wires	100μm φ Au-plated Be-Cu wire
Gas	Ar(50%) + C_2H_6(50%)



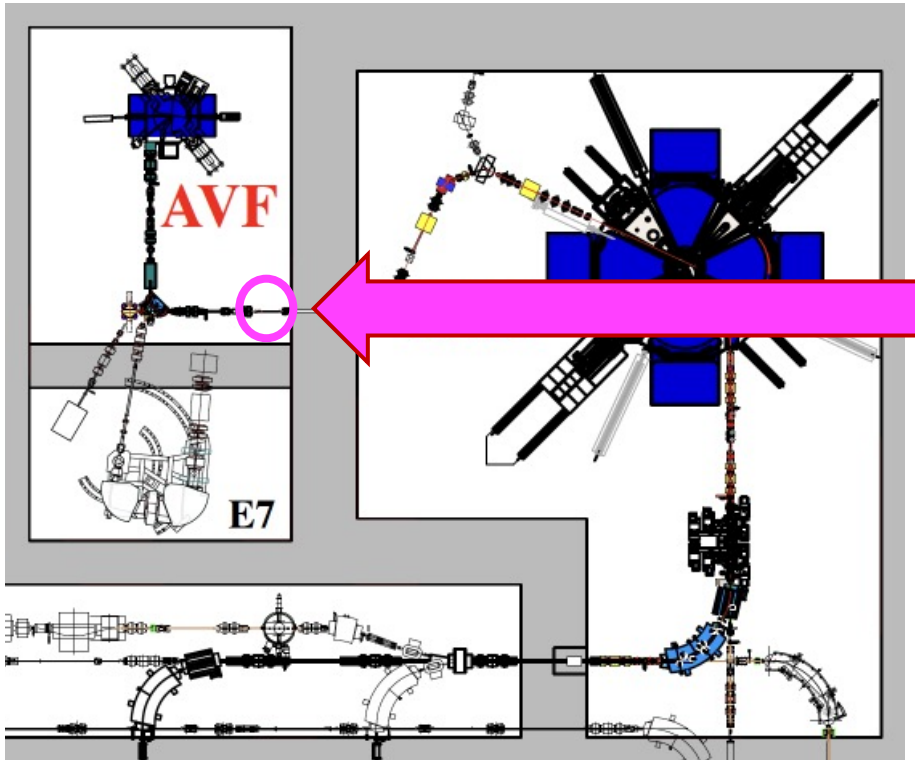
Deuteron polarization beam test (2024/9/14) @ RIKEN

Observables	d polarization
Machine time	9/14 0:00 - 9/15 0:00
beam	7 MeV/Nucleon polarized d beam
target	^{12}C target (0.5 mg/cm^2)
detector	ΔE-E detectors

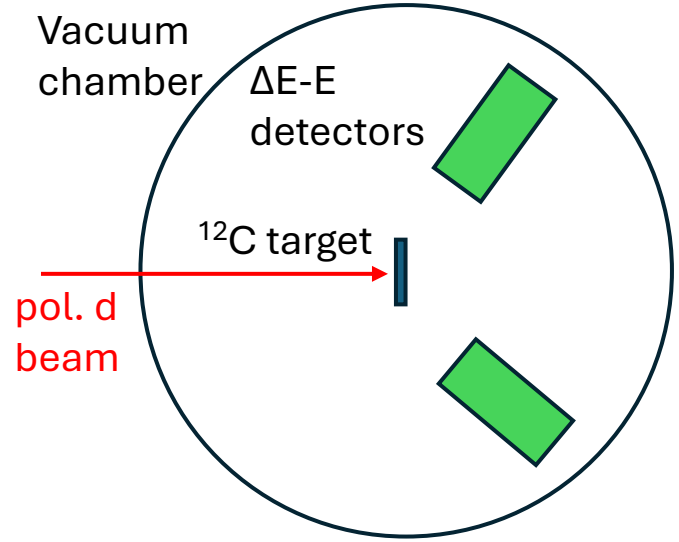
polarization : 50-80% (preliminary)

Ready for the Spin Correlation Coefficients Measurement

RIKEN Nishina Center



$^{12}C(d,p)^{13}C_{gnd}$ reaction

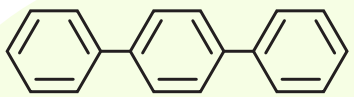


→derivation of deuteron polarization from measurement of yield asymmetry

Laser spot size on target

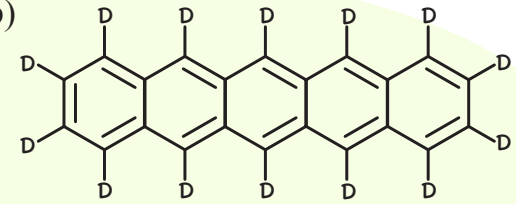
Target : **pentacene doped *p*-terphenyl single crystal**

(a)



p-terphenyl

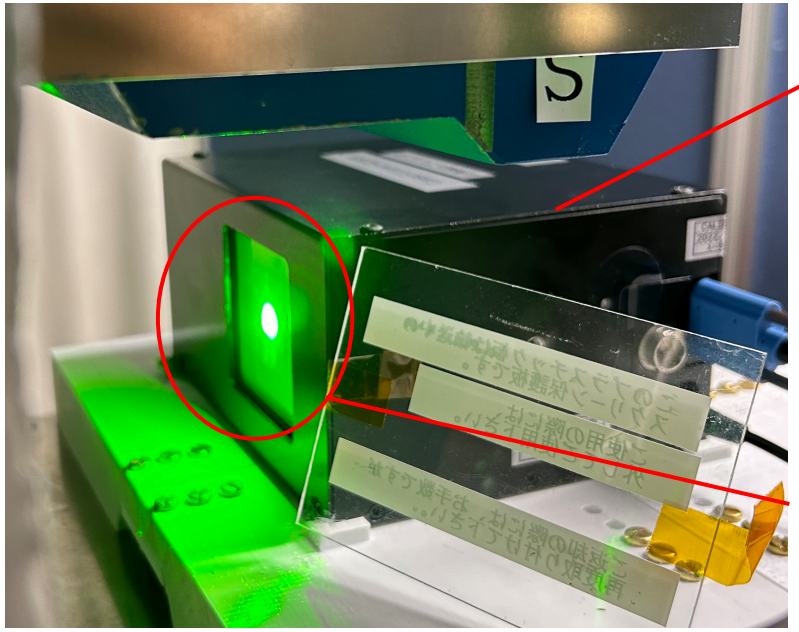
(b)



deuterated pentacene
(0.005 %/mol)

Want laser to cover
the full $\varphi 10 \times 2.5$ mm^3 range

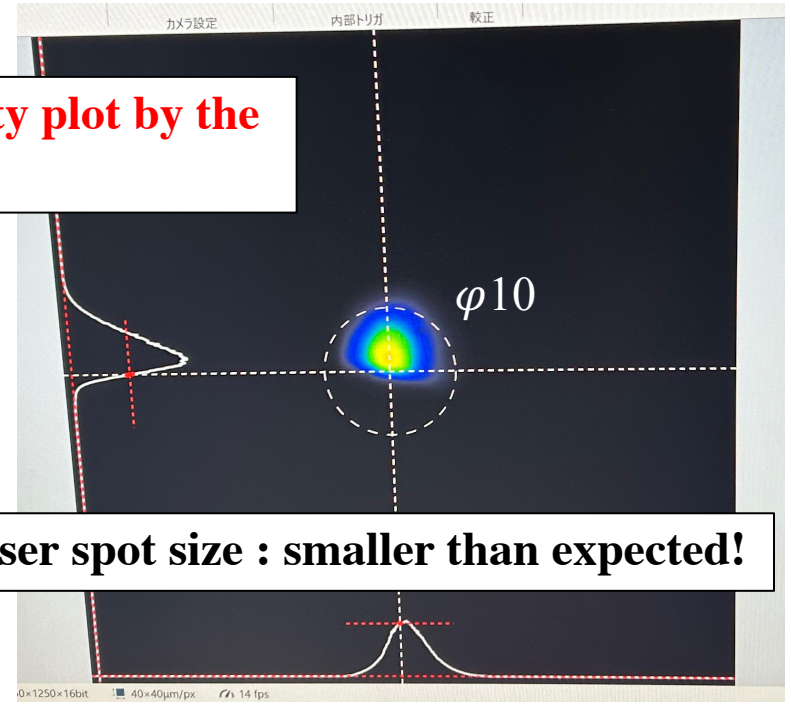
Size : $\varphi 10 \times 2.5$ mm^3



Beam profiler

To the eye,
Laser spot looks like φ10

Laser intensity plot by the laser profiler



Laser spot size : smaller than expected!

Motivation : **The Spin Correlation Coefficients $C_{i,j}$**

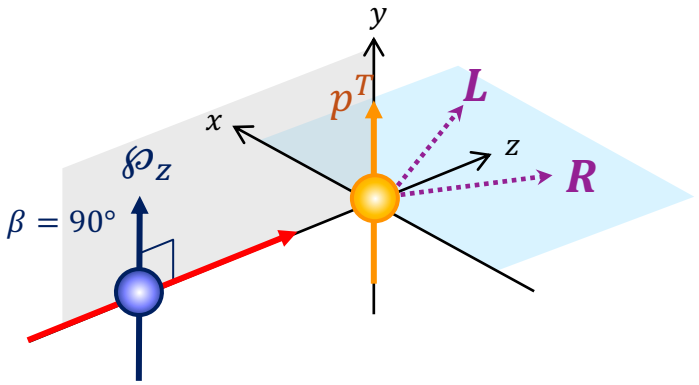
Form of spin 1 – spin ½ correlation experiments

$$\frac{I(\theta,\phi)}{I_0(\theta)} = 1 + \frac{3}{2}\wp_z\left[sin\beta cos\phi A_y + p^T\{-sin\beta sin\phi sin(\phi+\phi')C_{x,x} + sin\beta cos\phi cos(\phi+\phi')C_{y,y} + cos\beta sin(\phi+\phi')C_{z,x}\} + p_z^T\{-sin\beta sin\phi C_{x,z} + cos\beta C_{z,z}\}\right]$$
$$+\wp_{zz}\left\{\left[\frac{1}{6}\{(-cos^2\phi + (3sin^2\beta-1)sin^2\phi)A_{xx} + (-sin^2\phi + (3sin^2\beta-1)cos^2\phi)A_{yy} + (3cos^2\beta-1)A_{zz}\} - sin\beta cos\beta sin\phi A_{xz}\right]\right.$$
$$+p^T\left[\frac{1}{6}sin(\phi+\phi')\{(-cos^2\phi + (3sin^2\beta-1)sin^2\phi)C_{xx,y} + (-sin^2\phi + (3sin^2\beta-1)cos^2\phi)C_{yy,y} + (3cos^2\beta-1)C_{zz,y}\right.$$
$$\left.+\{-sin^2\beta sin2\phi sin(\phi+\phi')C_{xy,x} + 2sin\beta cos\beta cos\phi sin(\phi+\phi')C_{yz,x} - 2sin\beta cos\beta sin\phi cos(\phi+\phi')C_{xz,y}\right]$$
$$\left.+ p_z^T\left[-sin^2\beta sin2\phi C_{xy,z} + 2sin\beta cos\beta cos\phi C_{yz,z}\right]\right\} + p^T cos(\phi+\phi')A_y^T$$

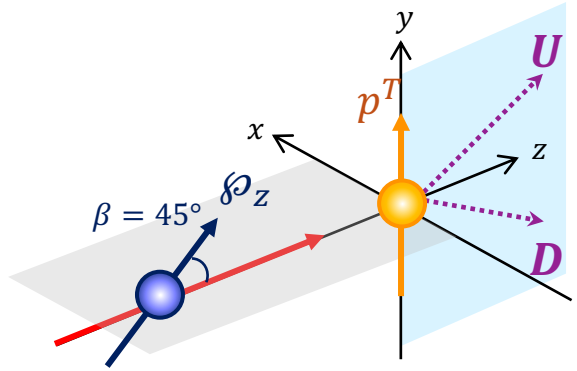
Total $C_{i,j}$ s : 12 (***8 will be measured***)

→ ***polarized beam & target*** neccesary

$$C_{y,y} = \frac{1}{6\wp_z p^T}\left(\frac{L^{u^T} + R^{u^T}}{I_0^{u^T}} - \frac{L^{d^T} + R^{d^T}}{I_0^{d^T}}\right)$$



$$C_{yz,x} = \frac{1}{2\wp_{zz} p^T}\left(\frac{U^{u^T} + D^{u^T}}{I_0^{u^T}} - \frac{U^{d^T} + D^{d^T}}{I_0^{u^T}}\right)$$



→ ***Yield unsymmetry (L&R, U&D)*** must be measured