2024/8/27

The 11th International Workshop on Chiral Dynamics

Few-Nucleon Scattering Experiments to Explore the Three-Nucleon Forces

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- **Kyushu Univ. :** T. Wakasa, K. Nishibata, K. Aradono, K. Hirasawa, Y. Nagao, S. Sakaguchi
- **Miyazaki Univ.:** Y. Maeda
- **Saitama Univ. :** S. Otsuka

TOMOE

Contents

TOMOE

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

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

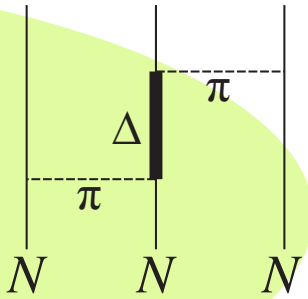
Realistic *NN* potentials : Argonne v_{18} (AV18), CD Bonn (CDB), Nijmegen I, II

- 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)

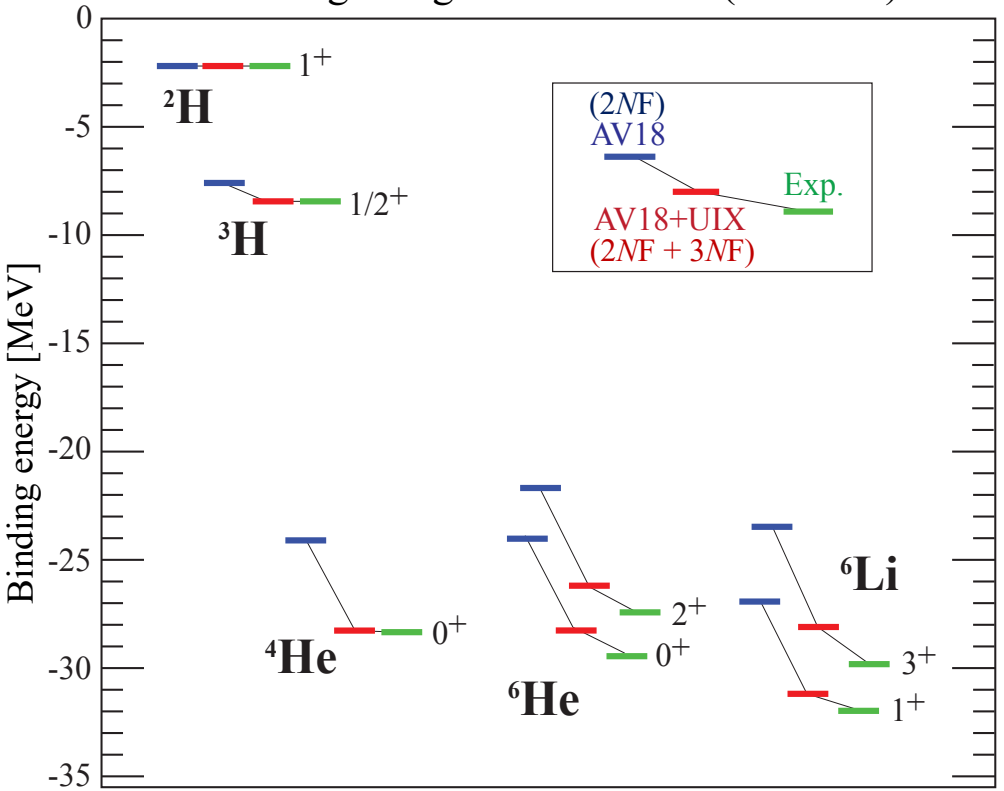
- Typical 3*N*F : Fujita-Miyazawa (2π-exchange) type



- 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…

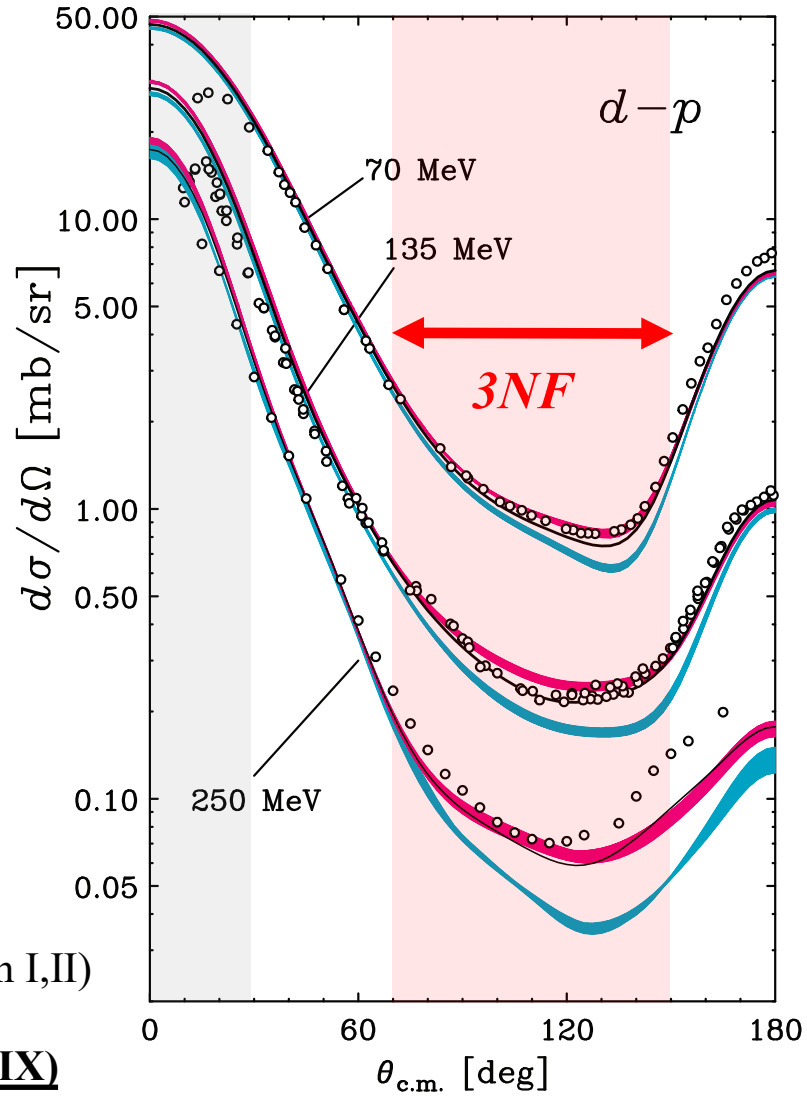
  - **high-precision data** in few-nucleon scattering (differential cross sections, spin observables)
  - **theoretical predictions** based on rigorous numerical calculations

- *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)

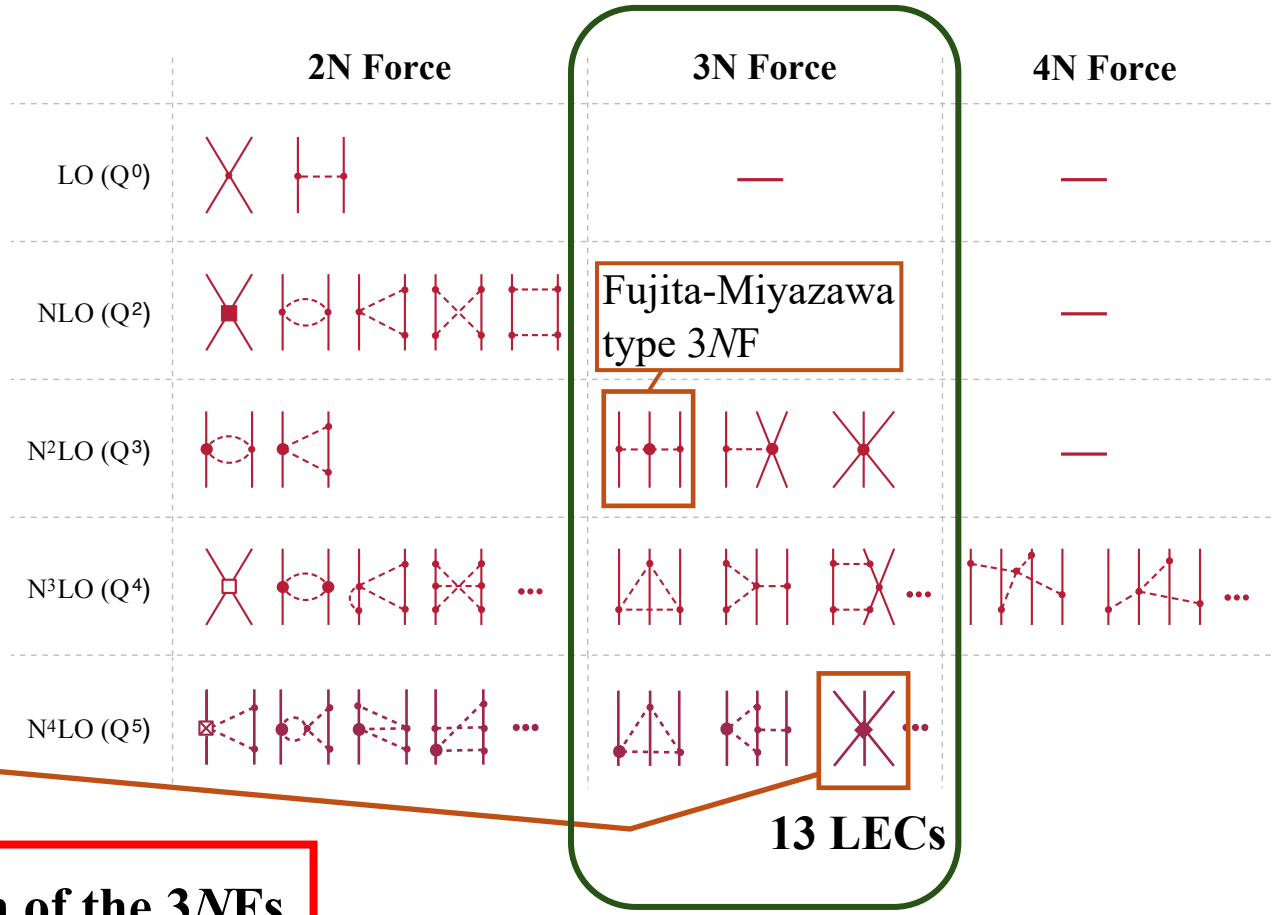
- Newly progressing theory based on low energy QCD

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!

Contents

1. Three-Nucleon Force and deuteron-proton (d-p) elastic scattering

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

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

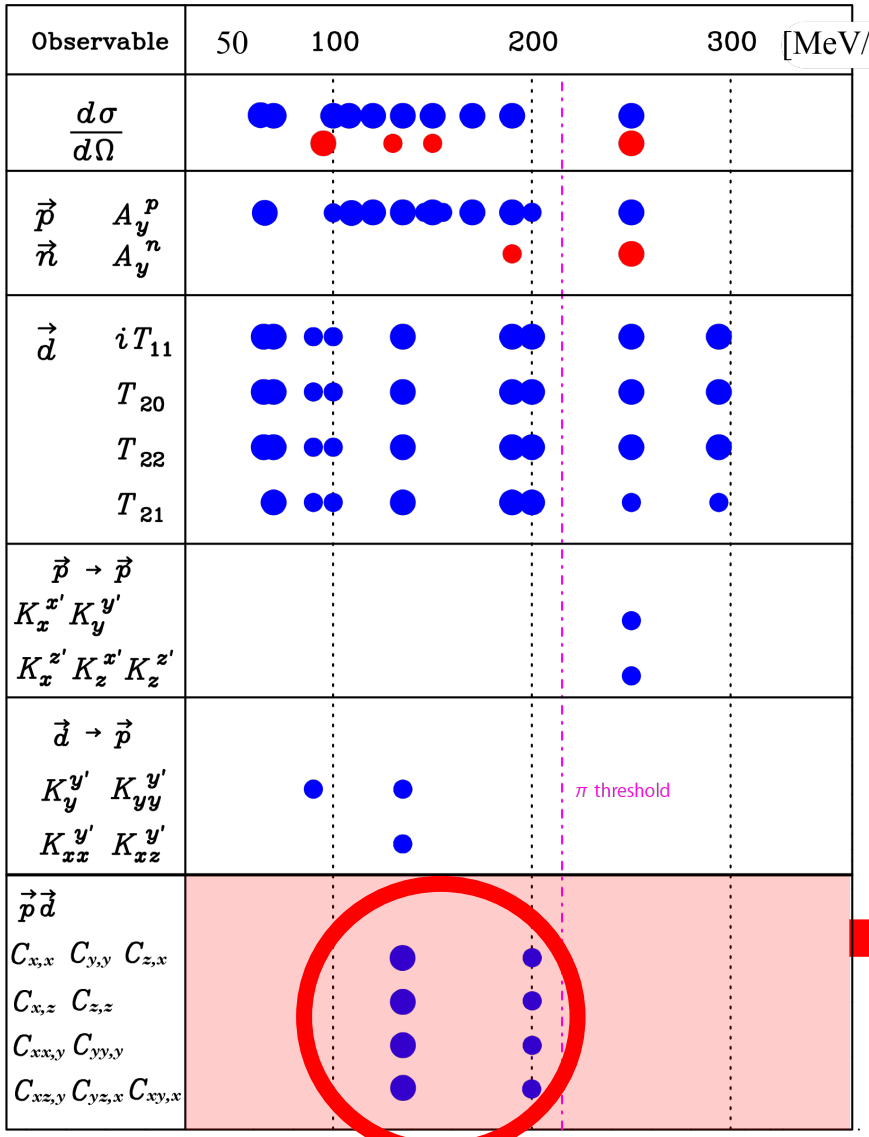
3. Experiment with the new systems in January 2024
   (d-$\vec{p}$ elastic scattering @ 135 MeV/Nucleon)

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

5. Summary

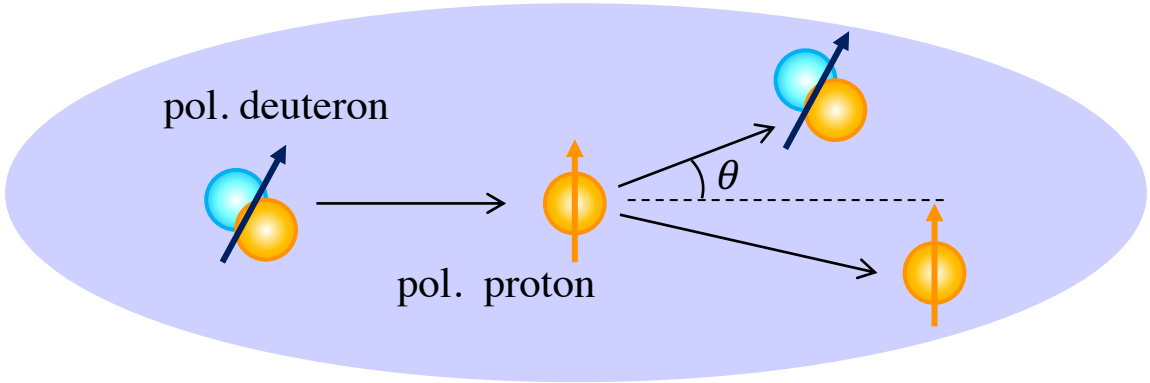
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering
New d-p experiment for the determination of the 3NF

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

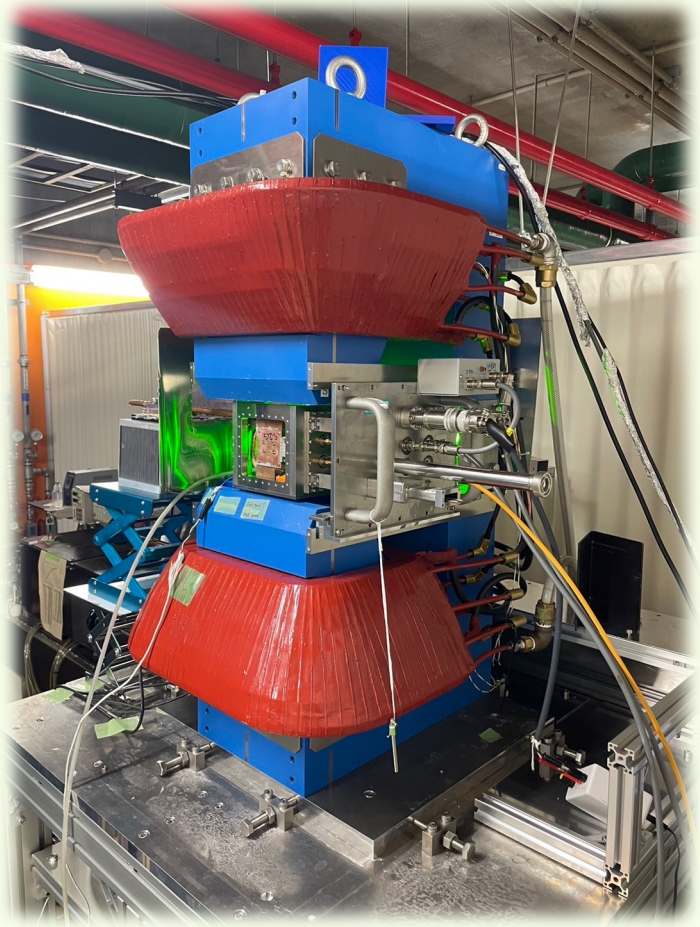
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

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

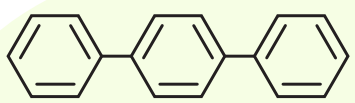
- **measurement in wide angular range (θ_{lab} : ±60°)**
- **detection of scattered particles with relatively low energy (60-200 MeV)**
  → static field under ~1 T
- **polarization around 10 %**

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

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

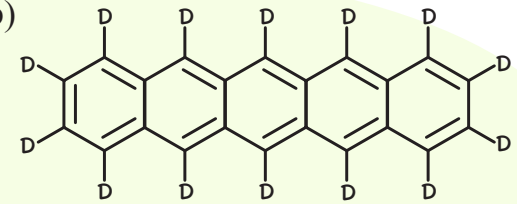
Target : **pentacene doped *p*-terphenyl single crystal**

(a)



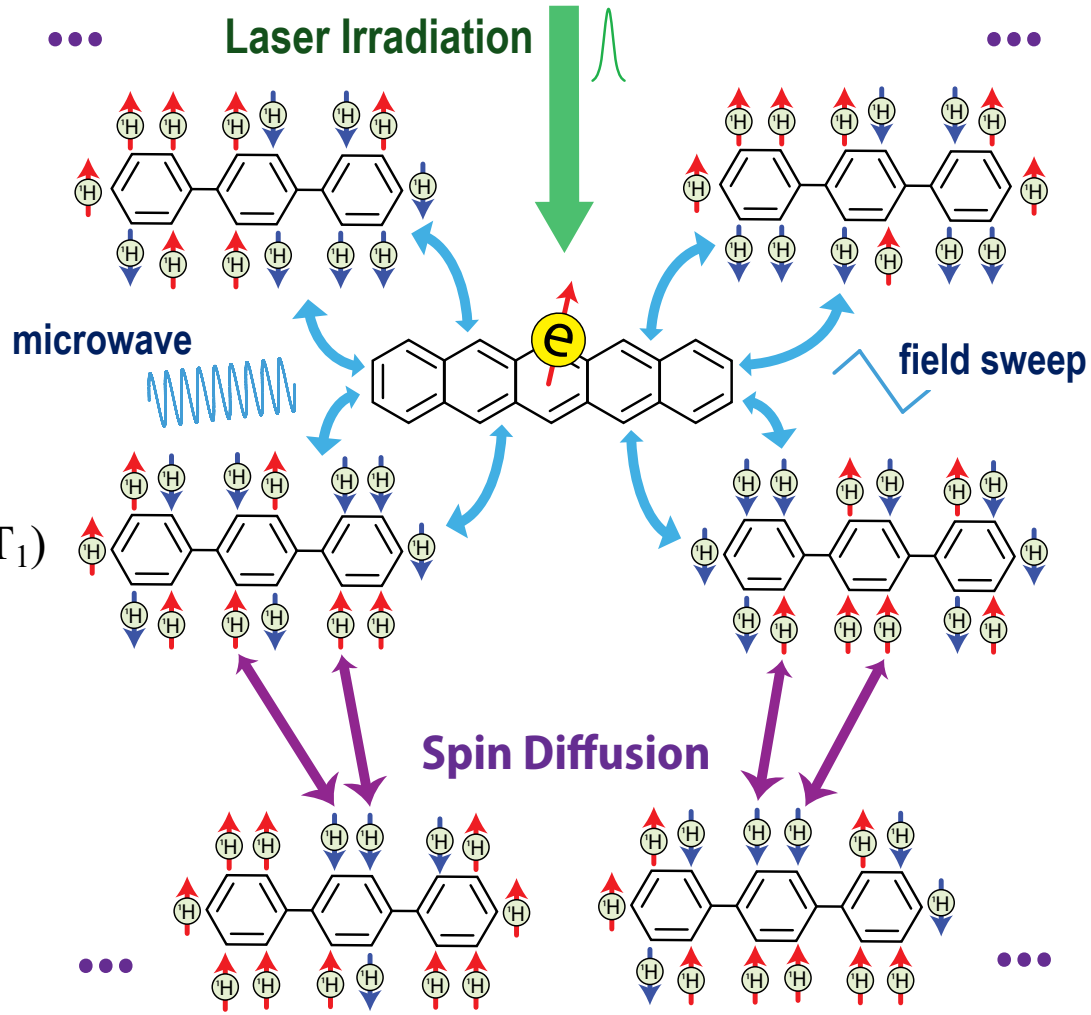
p-terphenyl

(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

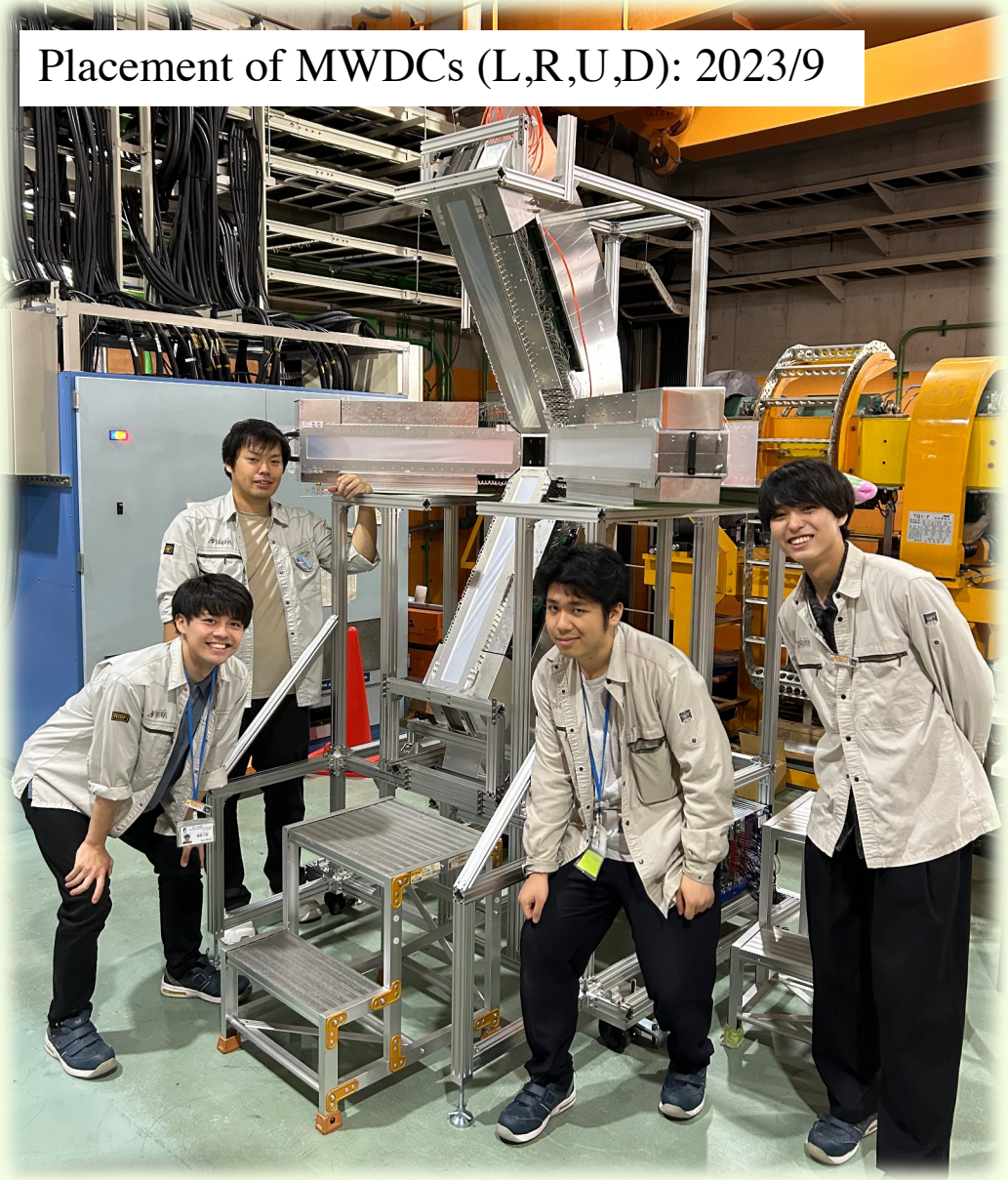
③ Proton polarization localized around pentacene after ISE
→ spontaneously diffused and averaged out = **Spin diffusion**

Aim : proton polarization of around 10%

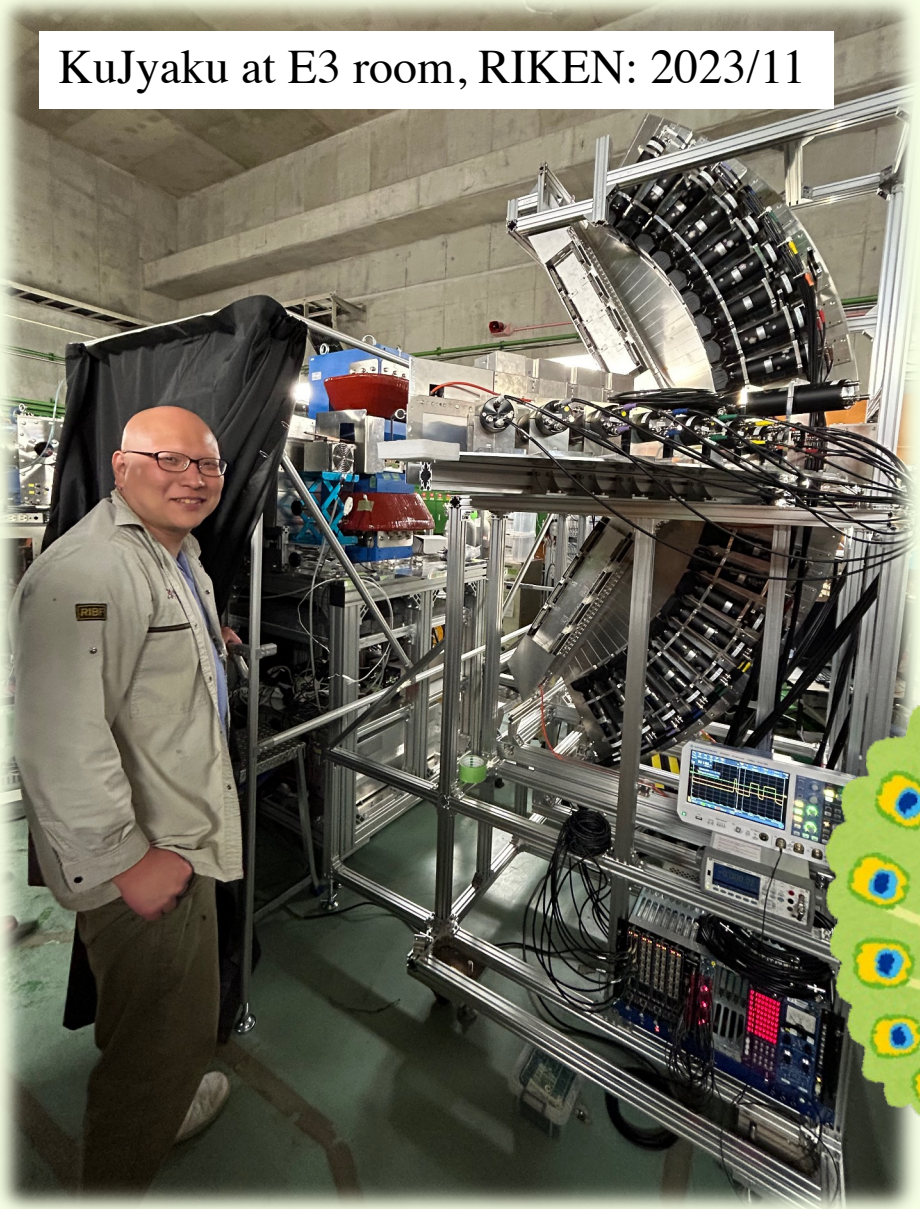
2. Measurement of Spin Correlation Coefficients ($C_{i,j}$) in $\vec{d}$-$\vec{p}$ elastic scattering

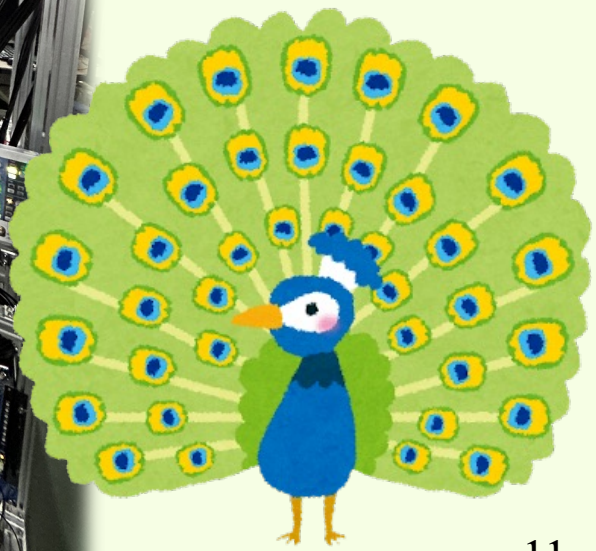
KuJyaku Detector System

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



KuJyaku at E3 room, RIKEN: 2023/11

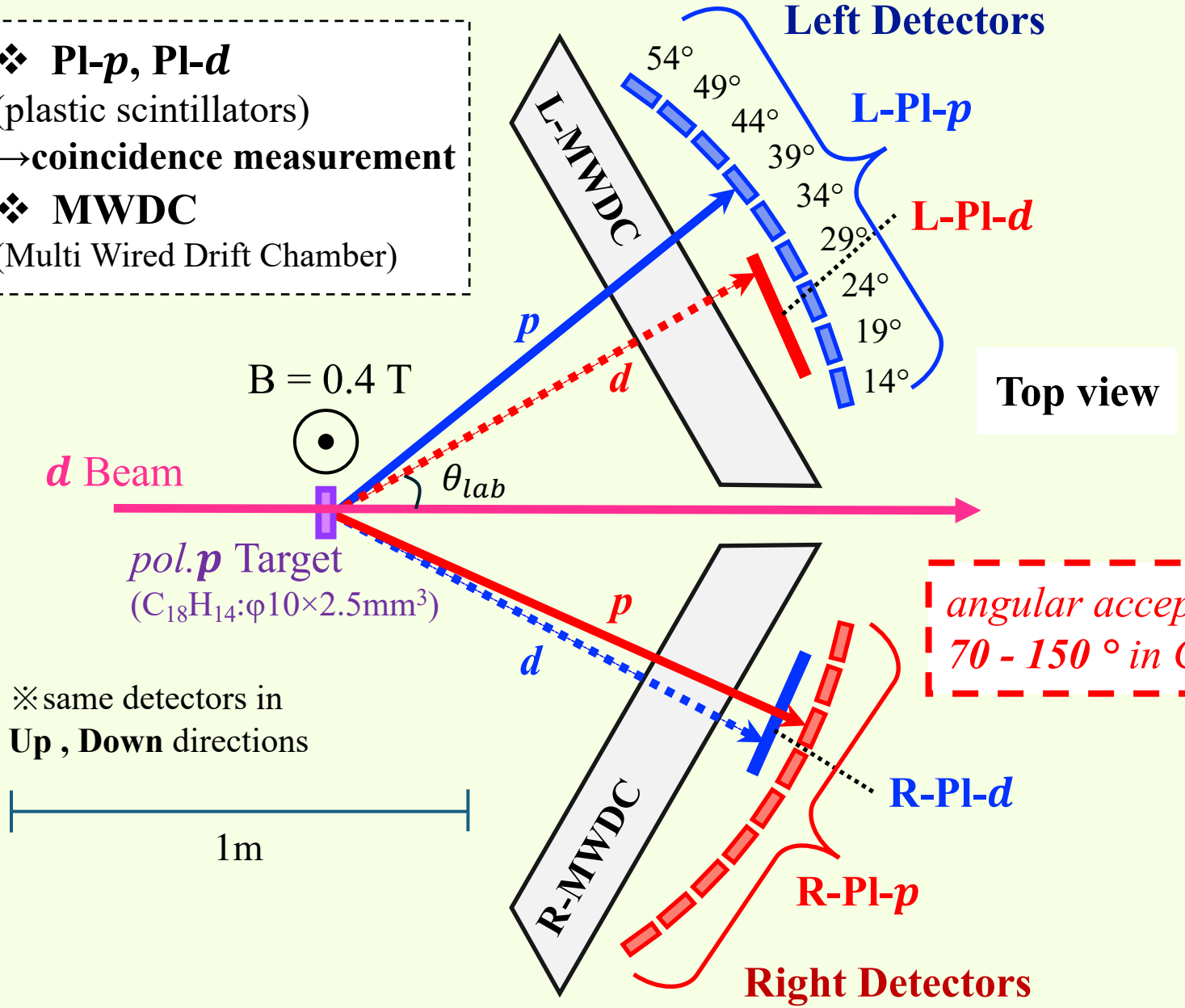




2. KuJyaku Detector System

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

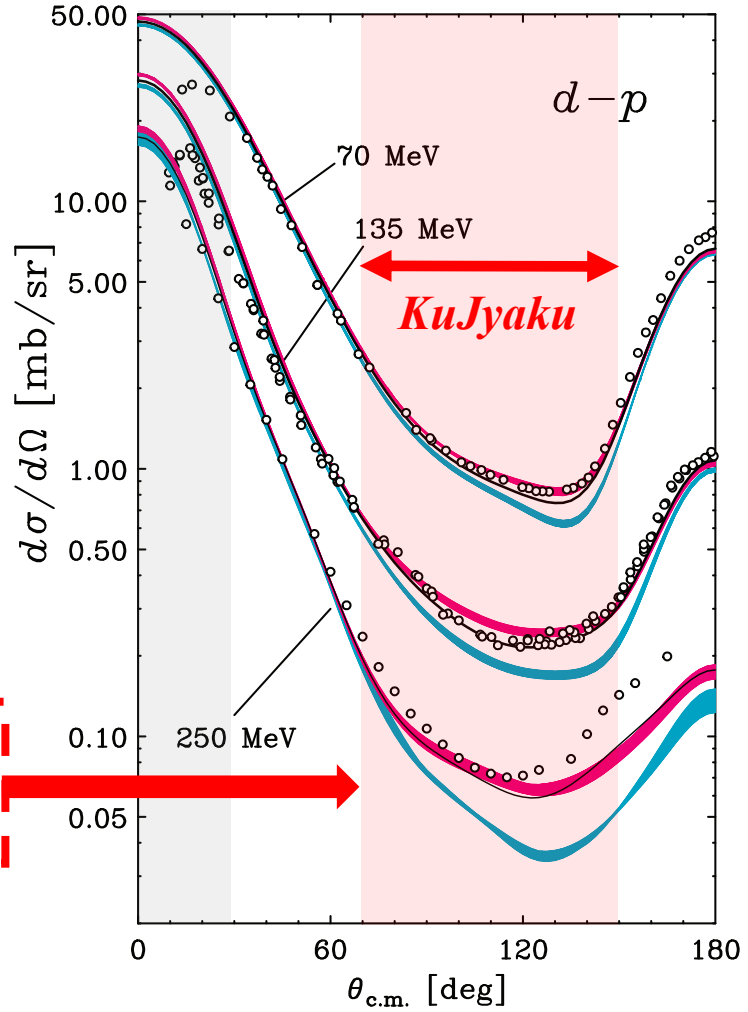
❖ **MWDC**
(Multi Wired Drift Chamber)



Top view

angular acceptance of
70 - 150 ° in CM

❖ Differential cross section

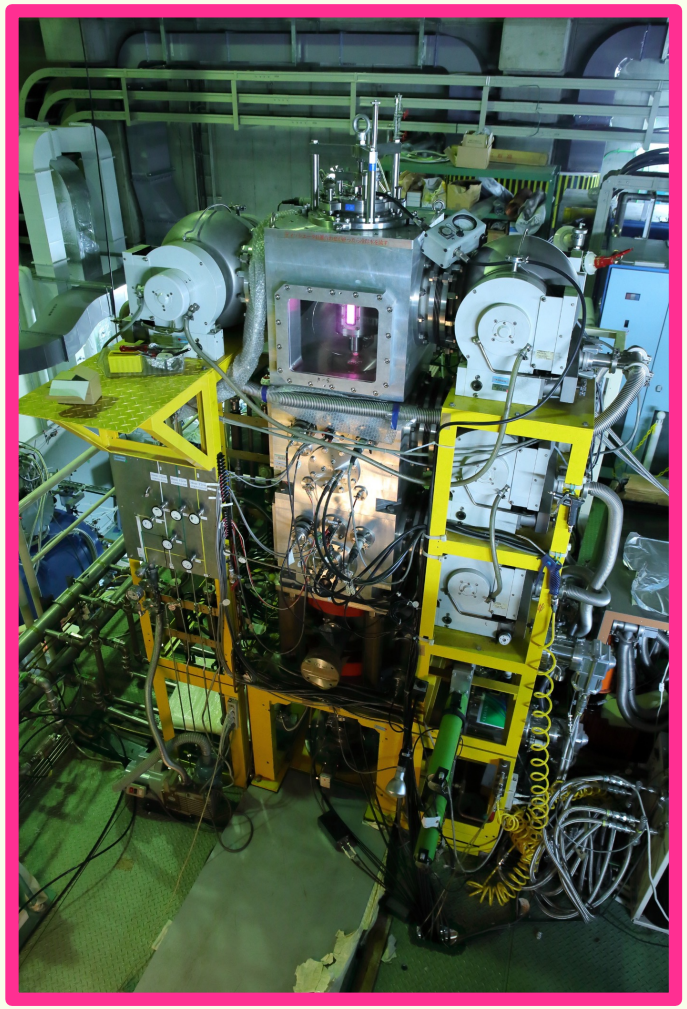


2NF (CDB, AV18, Nijm I,II)
2NF + **3NF (TM)**
AV18 + **3NF (Urbana IX)**
○ data
- K. Sekiguchi *et al.*, PRC **65**, 034003 (2002).

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

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

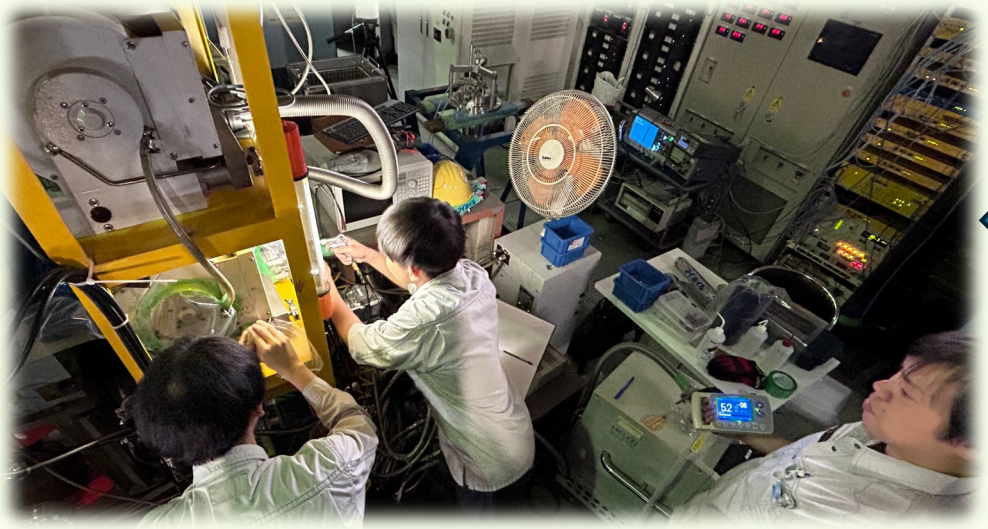
Polarized ion source



3 m

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

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



leak test of the fixed cooling pipe using He gas

2024/ 9 → deuteron polarization beam test !

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

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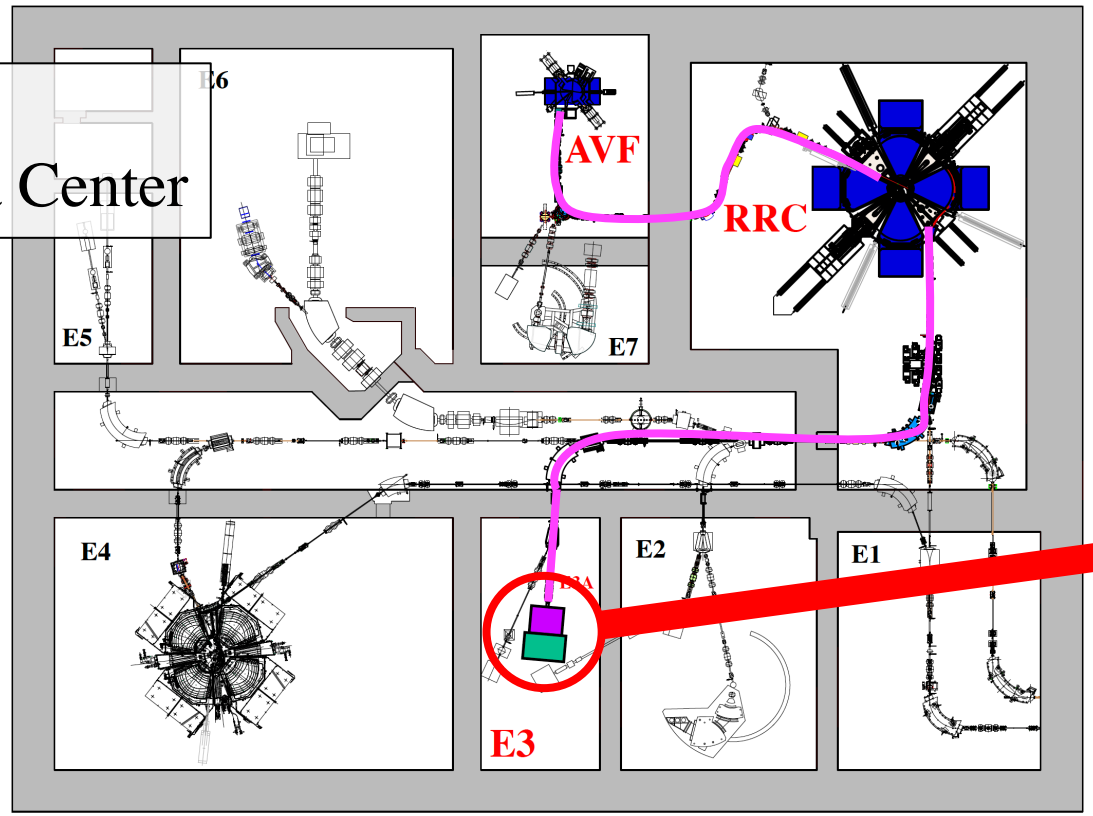
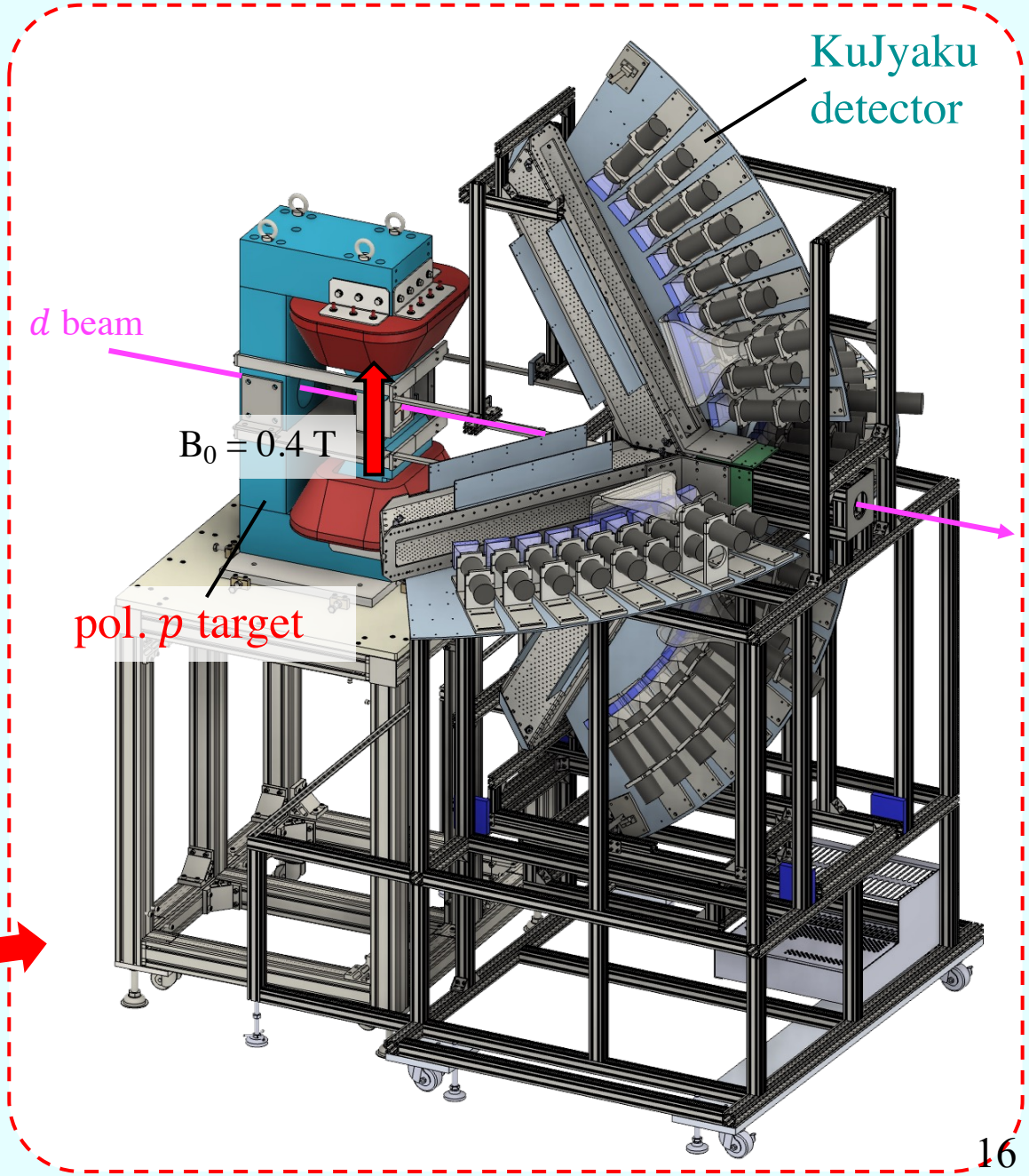
3. Experiment with the new systems in January 2024 (d - $\vec{p}$ elastic scattering @ 135 MeV/N)

➢ 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)

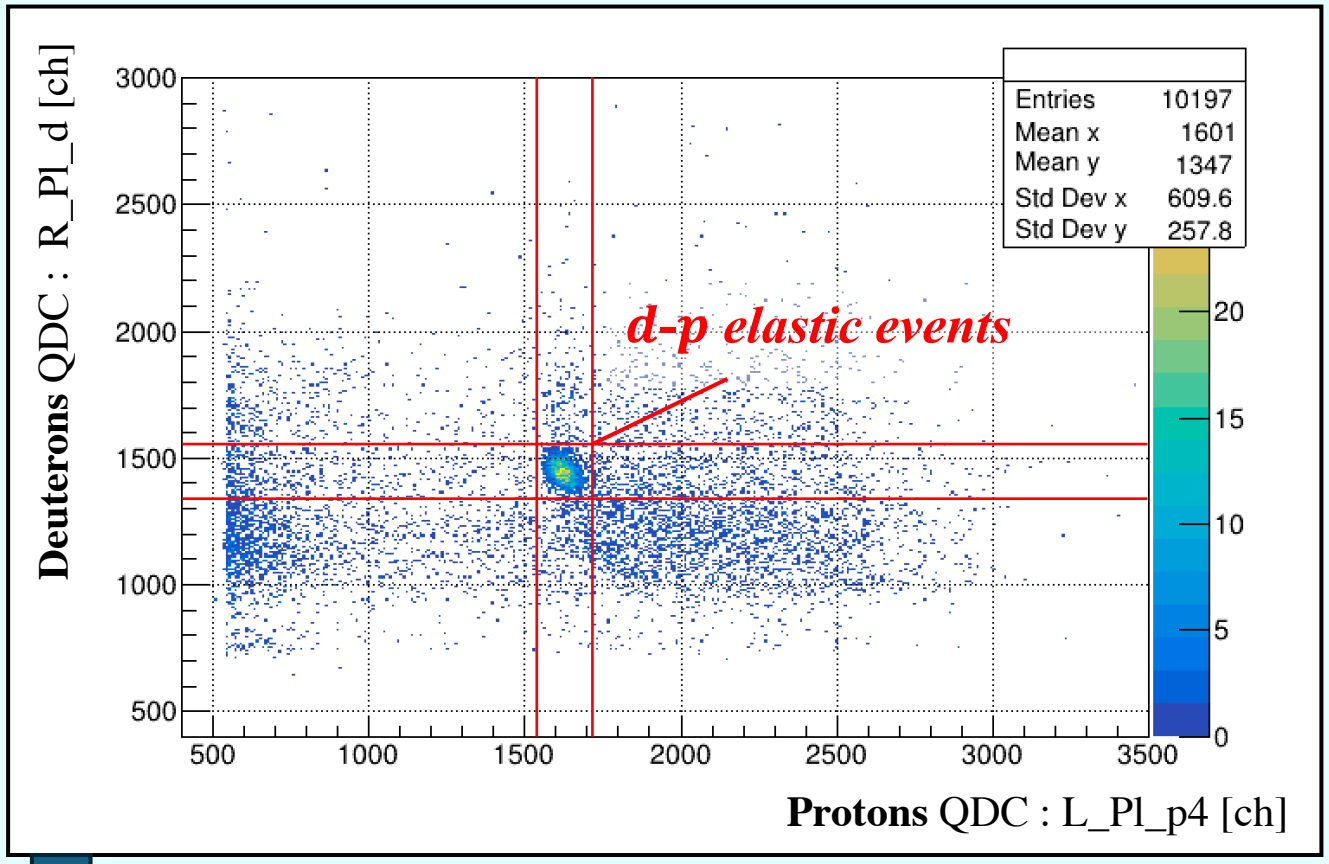
RIKEN
Nishina Center

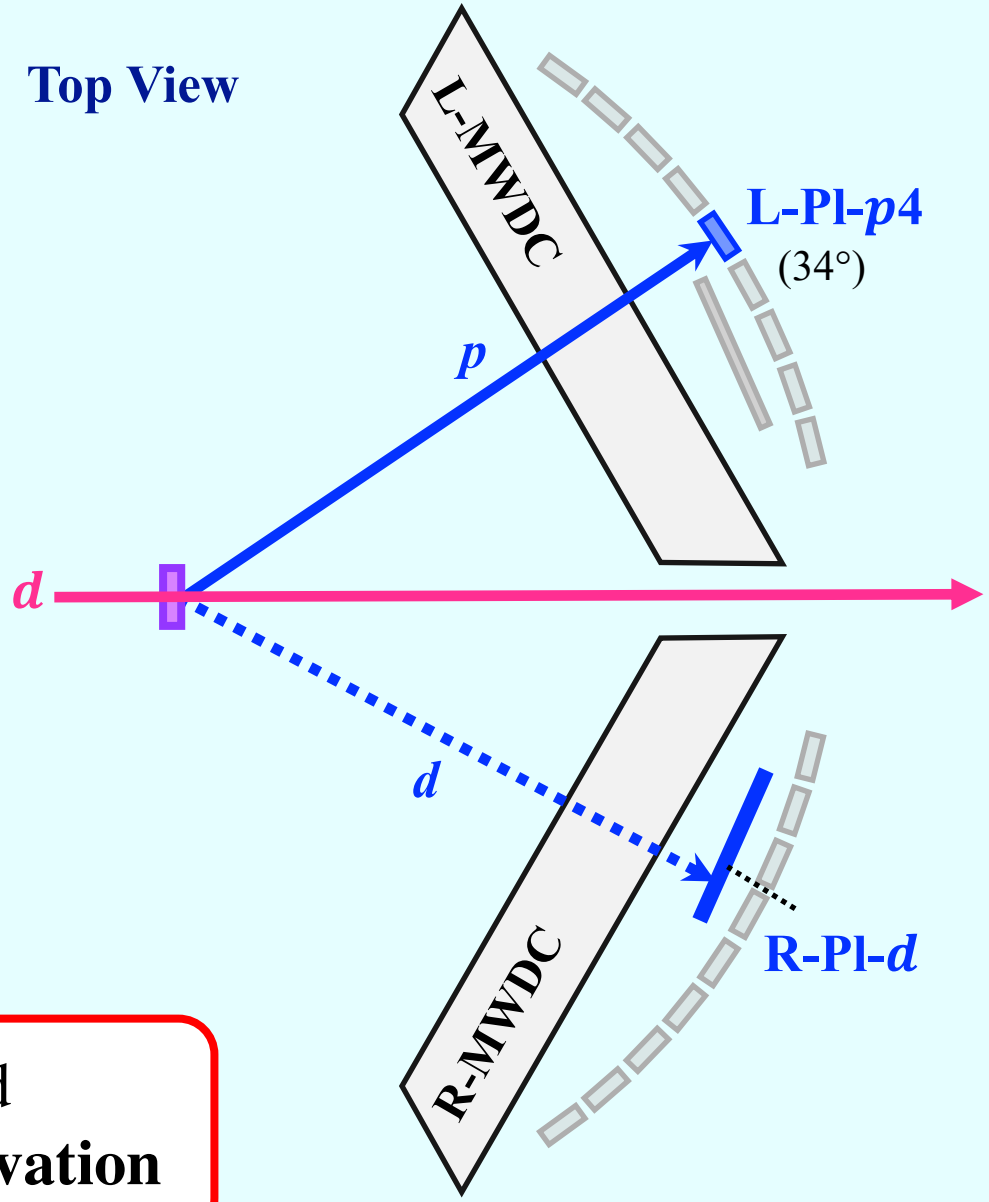




3. Experiment with the new systems in January 2024 (d - $\vec{p}$ elastic scattering @ 135 MeV/N)

Event Selection

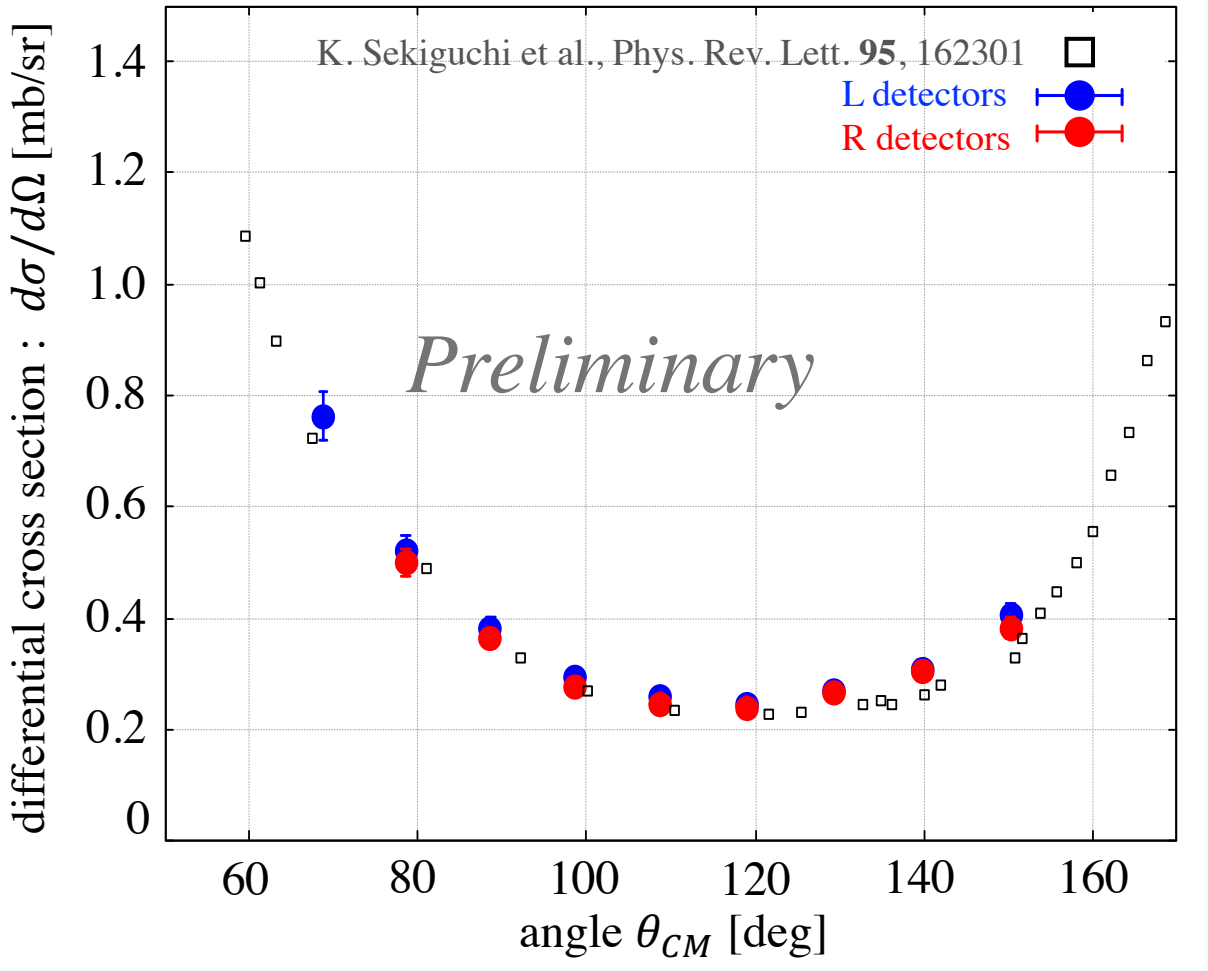




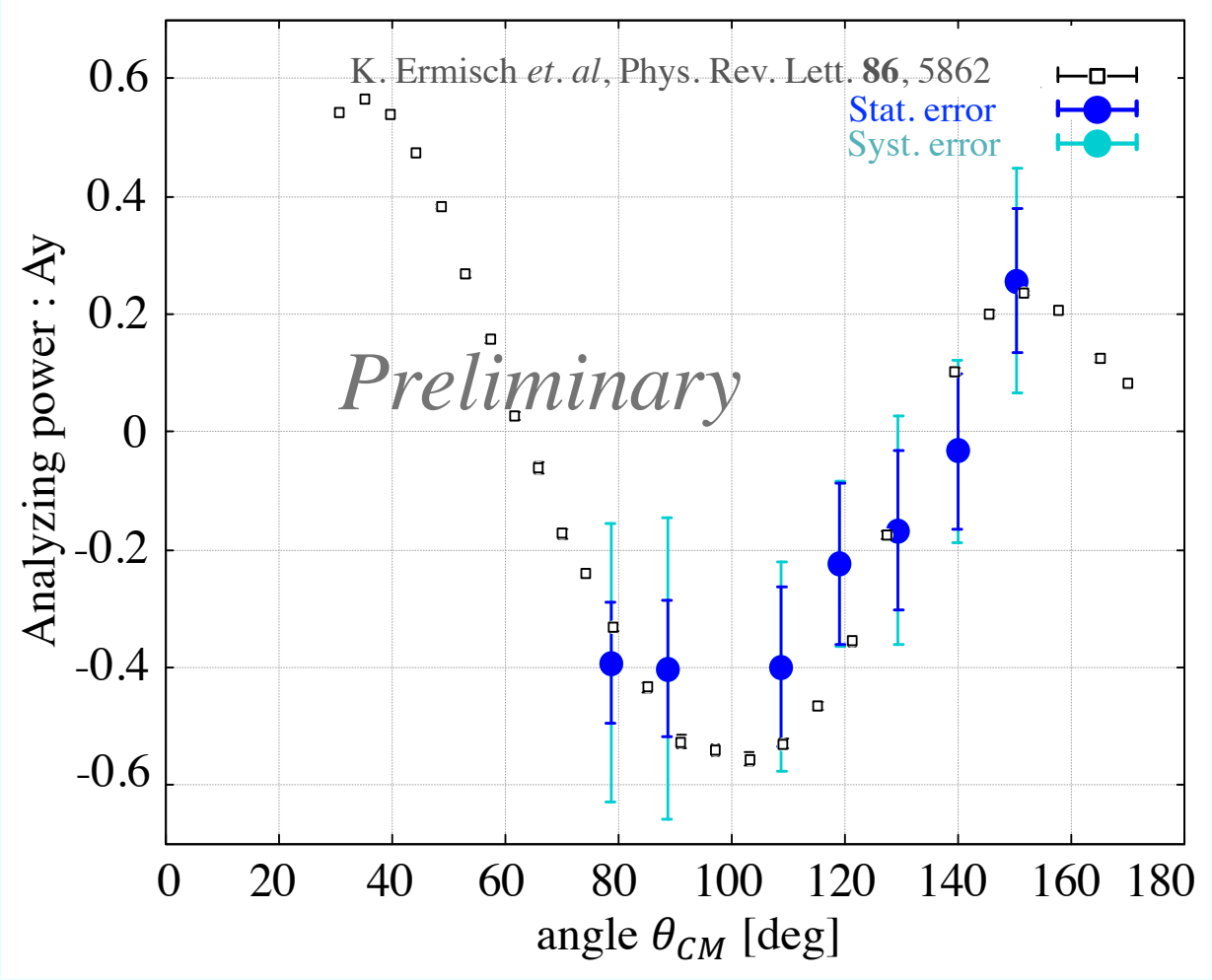
d-p elastic events *successfully* observed
→**yield used for dσ/dΩ and Ay derivation**

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!

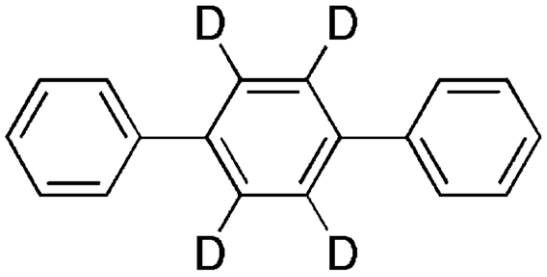
Future plans for the Measurement of Spin Correlation Coefficients in $\vec{d}$-$\vec{p}$ elastic scattering

❖ *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) elastic scattering experiments

5. Summary

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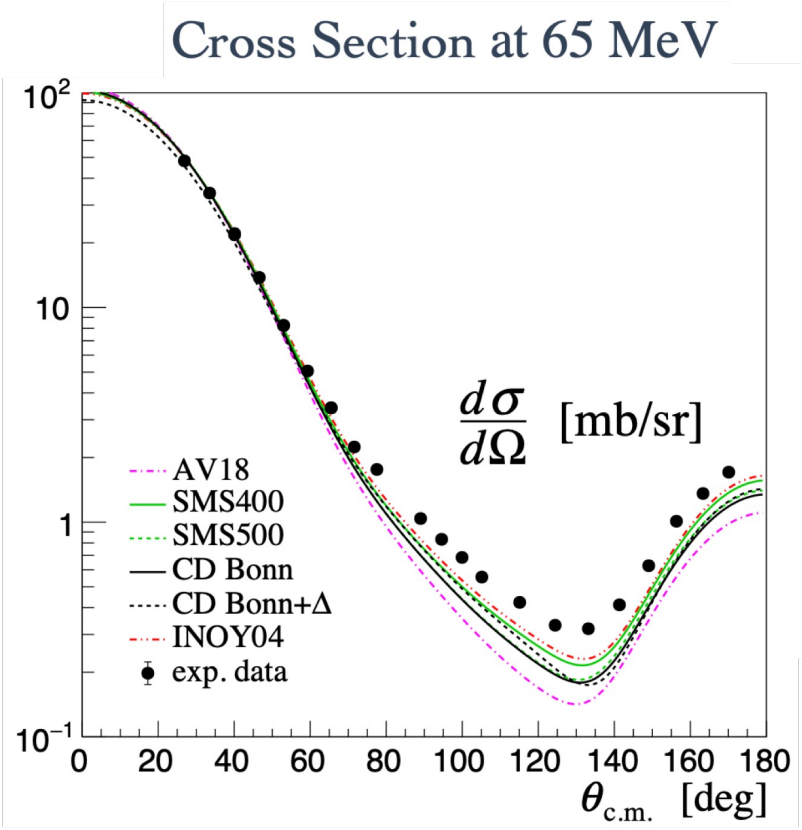
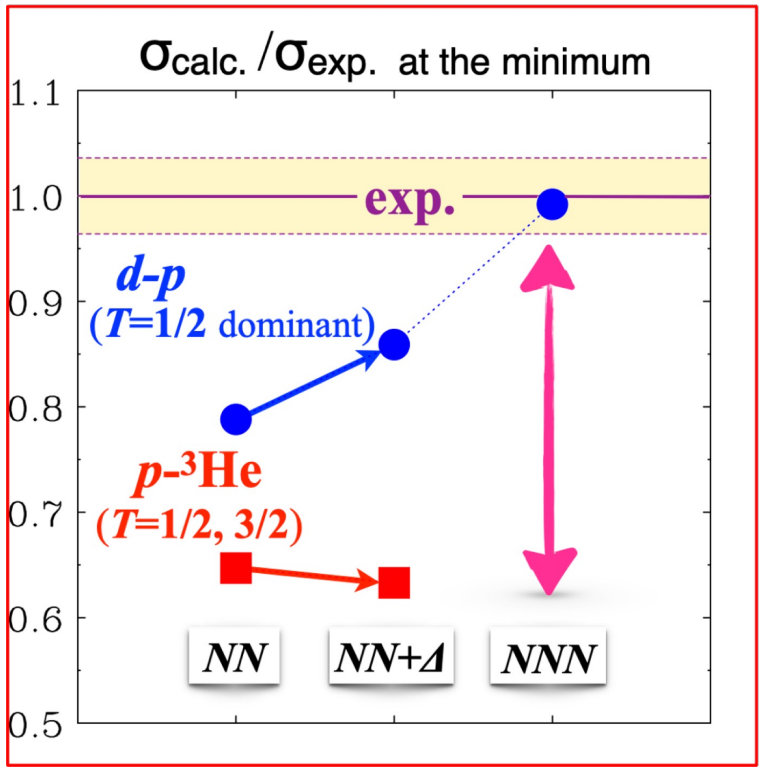
4. proton-^{3}He (p-^{3}He) scattering experiments

Isospin Dependence of 3*N*Fs

- $d + p$: isospin channel limited to $\boldsymbol{T = 1/2}$
- $\boldsymbol{T = 3/2}$ **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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Japan Science and Technology Agency

TOMOE

Term Oct. 2023-Mar.2029

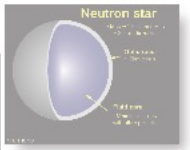
JST ERATO Three-Nucleon Force Project (PI : Kimiko Sekiguchi)

Nuclear Medecine

RI production

Engineering

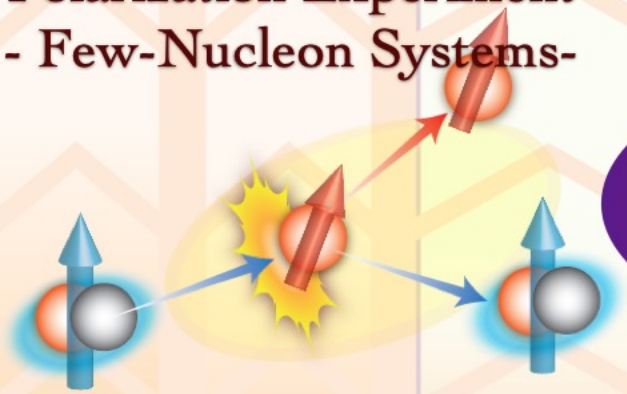
Nuclear fusion & fission Nucleosynthesis Neutron star



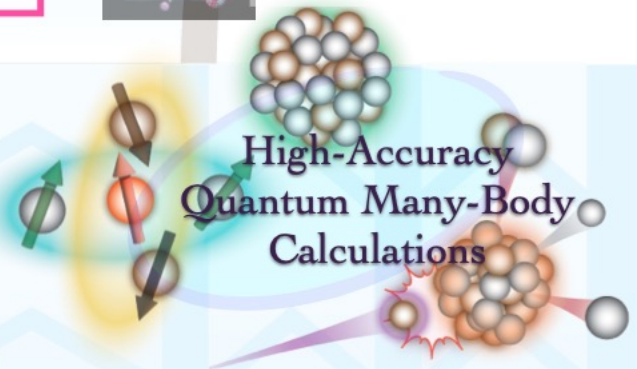
Applied Science

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

5. Summary

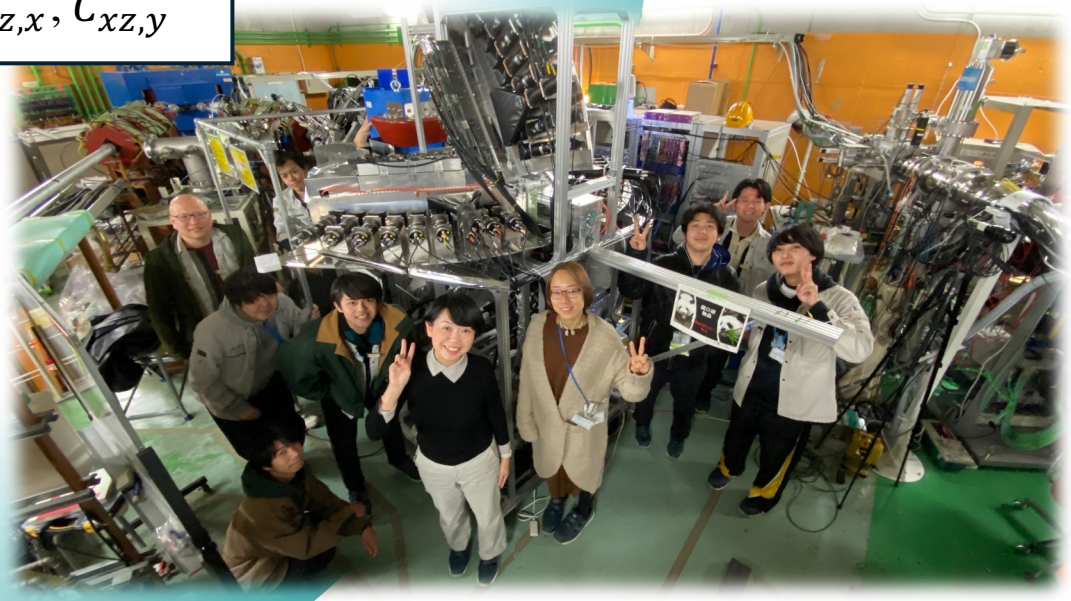
- Measurement of spin correlation coefficients in $\vec{d}$-$\vec{p}$ **elastic scattering** to determine 11 LECs in N^{4}LO of the 3*N*F sector in Chiral EFT

- 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

❖ **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.