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TOHOKU UNIVERSITY

Development of a polarized proton target for spin-correlation coefficient measurements

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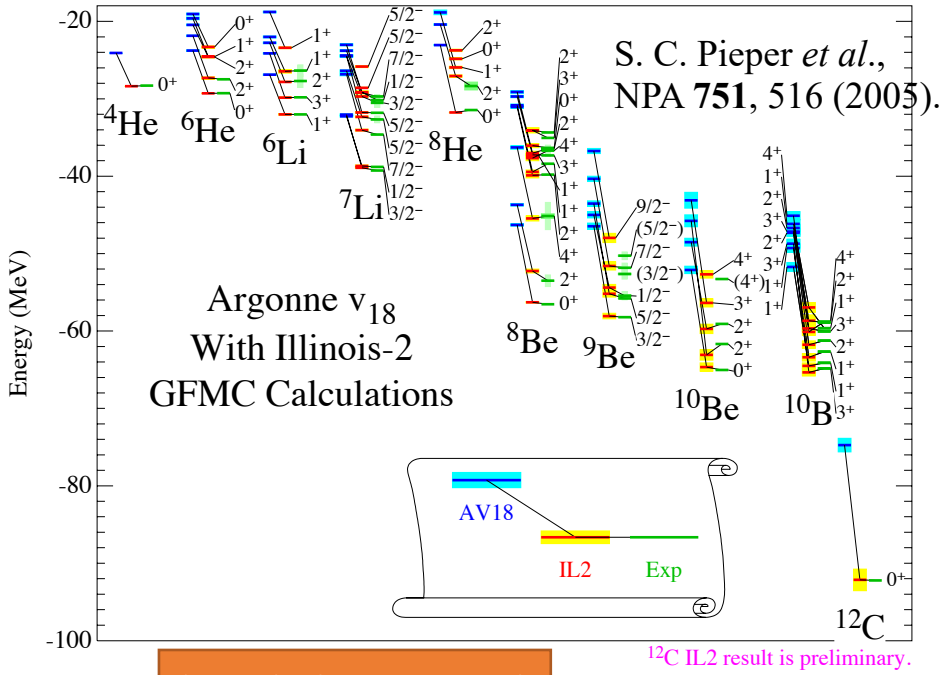
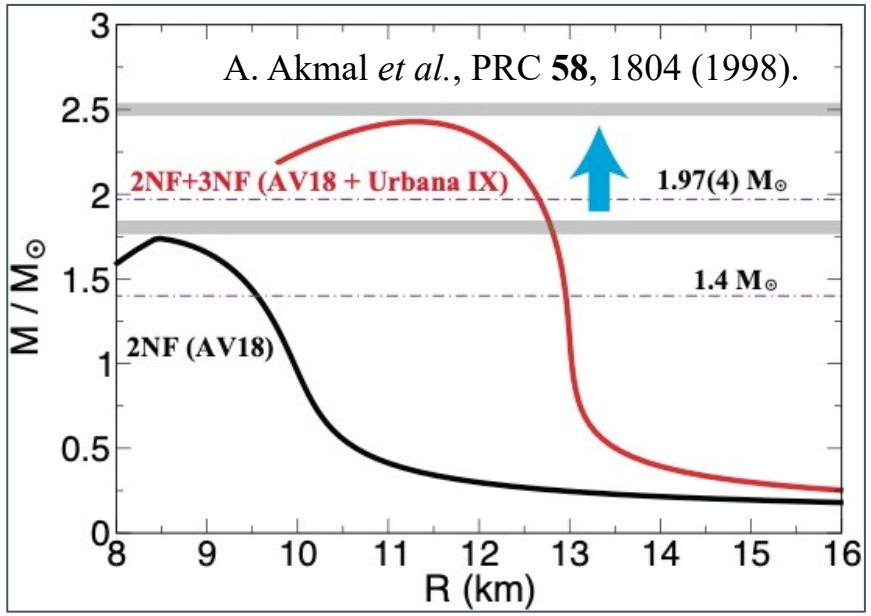
Three-Nucleon Forces (3NFs)

- Binding energies of light mass nuclei ($A \geq 3$)
- Scattering observables of few-nucleon scattering
- Properties of nuclear matter
  (e.g., saturation density, radius or mass of neutron star)

Necessity of
Three-Nucleon Forces (3NFs).



in Finite Nuclei



in Infinite Nuclei (Neutron Star)

Few-Nucleon Scattering

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

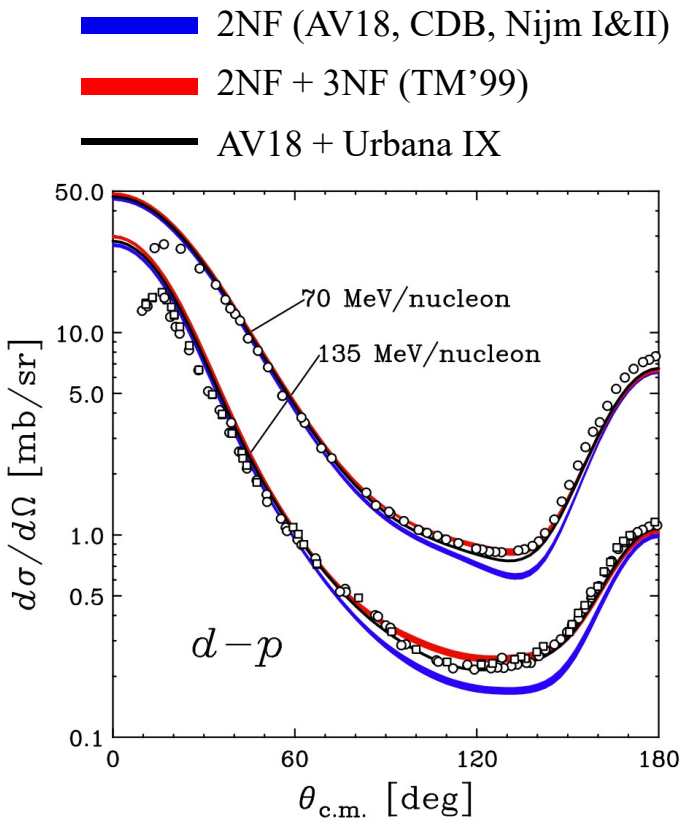
Direct Comparison

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

d + *p* Elastic Scattering at 70–250 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.

Solid basis to explore the 3NF properties



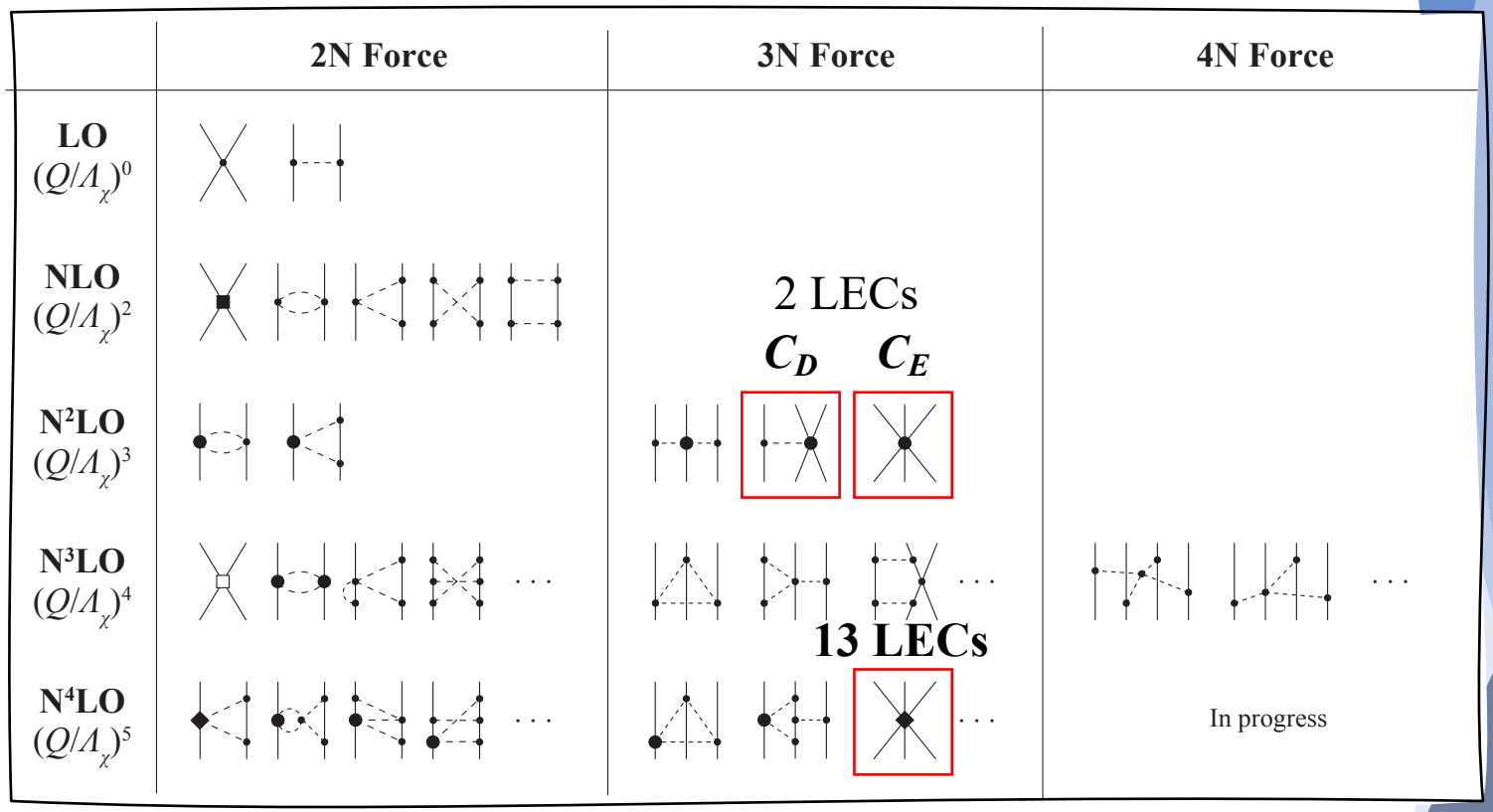
K. Sekiguchi *et al.*, PRC **65**, 034003 (2002).

Chiral EFT based Nuclear Potential

Chiral Effective Field Theory (EFT)

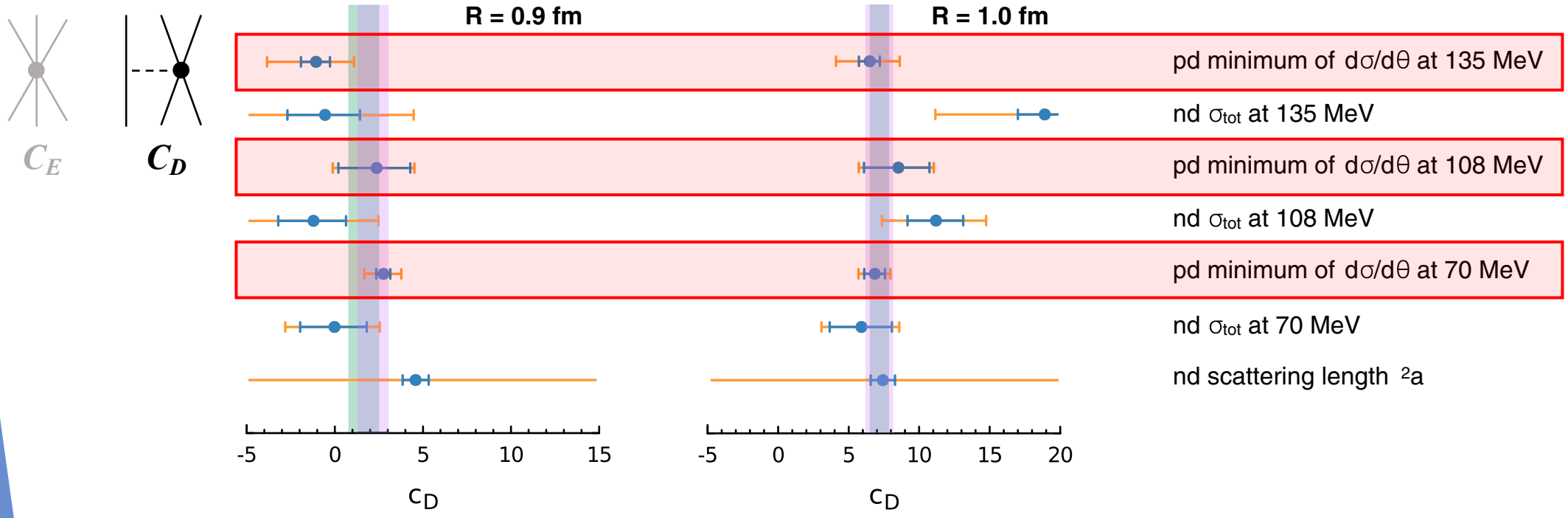
- ✓ Based on chiral symmetry of QCD.
- ✓ Lagrangian is organized by the power of Q/Λ_χ.

  $Q \sim m_\pi$ (140 MeV)
  Λ_χ : chiral symmetry breaking scale (~1 GeV)
- ✓ Consistent two-, three-, and many nucleon forces are derived on **the same footing**.
- ✓ 3NFs appear at N^{2}LO.
- ✓ Short range interactions involve Low Energy Constant (LEC).



Our Goal: ***Determining LECs from the 3N scattering and the 3NFs at N4LO***

Determination of LECs



Differential cross sections give **strong constraints** for LEC c_D !

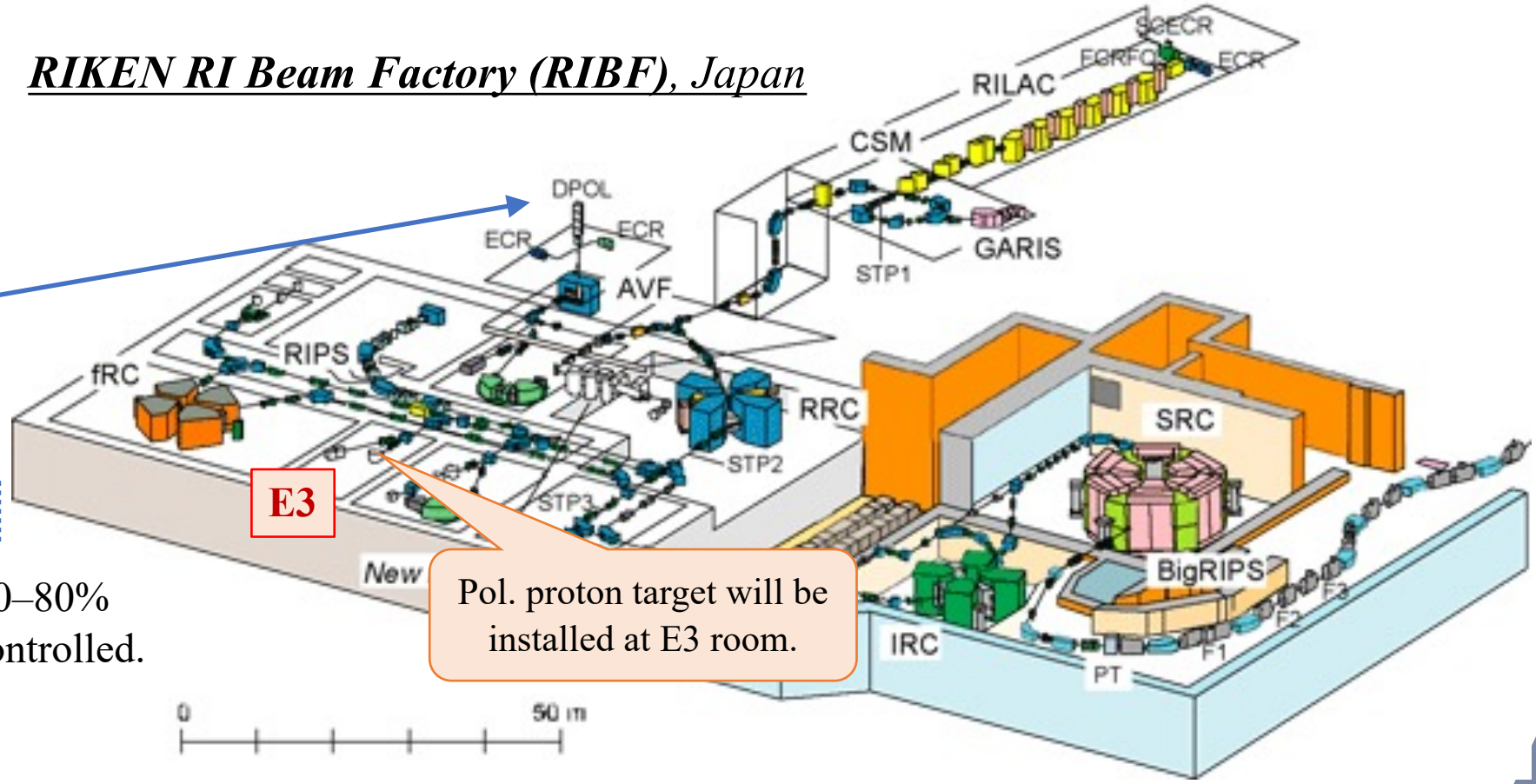
The rich date set of 3N scattering is highly demanded.

New Experiment: Measurement of Spin-Correlation Coefficients

pol. *d*-pol. *p* Elastic Scattering @100 MeV/u

***RIKEN RI Beam Factory (RIBF)*, Japan**

Polarized Ion Source



Pol. proton target will be installed at E3 room.

- ✓ High polarization: 60–80%
- ✓ Spin axis is freely controlled.

Spin-Correlation Coefficients $C_{i,j}$, $C_{ij,k}$

differential cross section with polarized beam and polarized target (spin 1 + ½)

$$\frac{I}{I_0} = 1 + \frac{3}{2}p_y A_y + p_y^T A_y^T + \frac{1}{3}(p_{xx} - p_{zz})A_{xx} + \frac{1}{3}(p_{yy} - p_{zz})A_{yy}$$
$$+ \frac{3}{2}p_x p_x^T C_{x,x} + \frac{3}{2}p_y p_y^T C_{y,y} + \frac{1}{3}(p_{yy} - p_{zz})p_y^T C_{yy,y}$$

※Spin axis of beam and target is aligned to the vertical (y) axis.

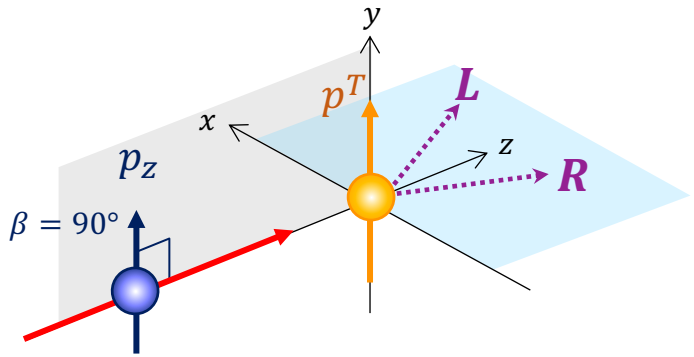
p_{ij} : Beam (d) polarization

p_k : Target (p) polarization

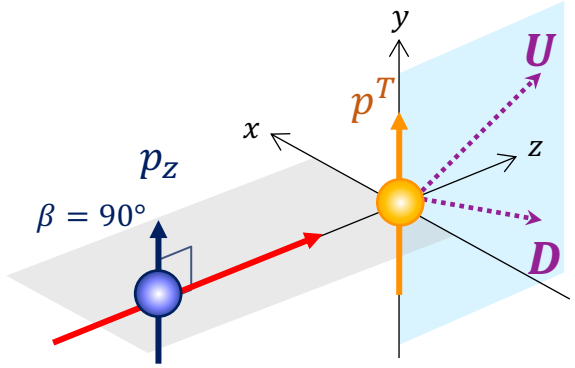
$A_{i,j}$, A_k : Analyzing power

$C_{i,j}$, $C_{ij,k}$: **Spin-correlation coefficient**

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



$$C_{x,x} = \frac{1}{6p_z p^T}\left(\frac{U^{u^T} + D^{u^T}}{I_0^{u^T}} - \frac{U^{d^T} + D^{d^T}}{I_0^{u^T}}\right)$$



We need to measure scattering asymmetry of L&R, U&D!

Polarized Proton Target

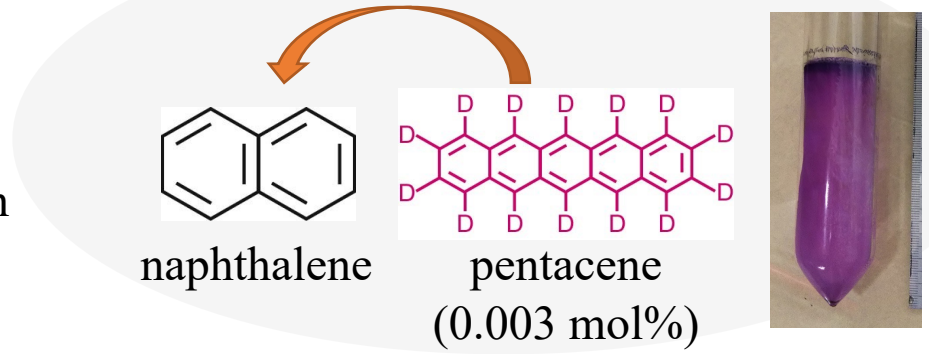
~for measurements of spin-correlation coefficients~

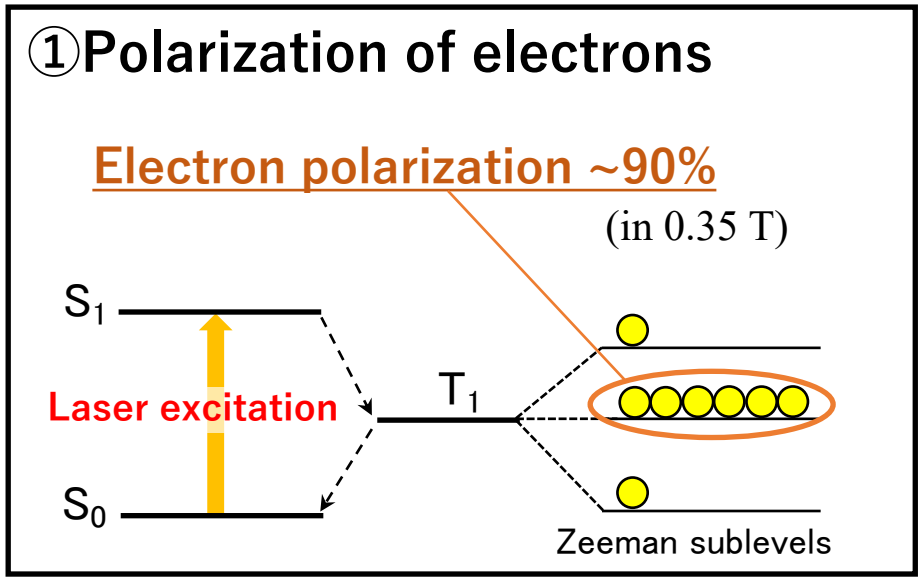
Polarization Method

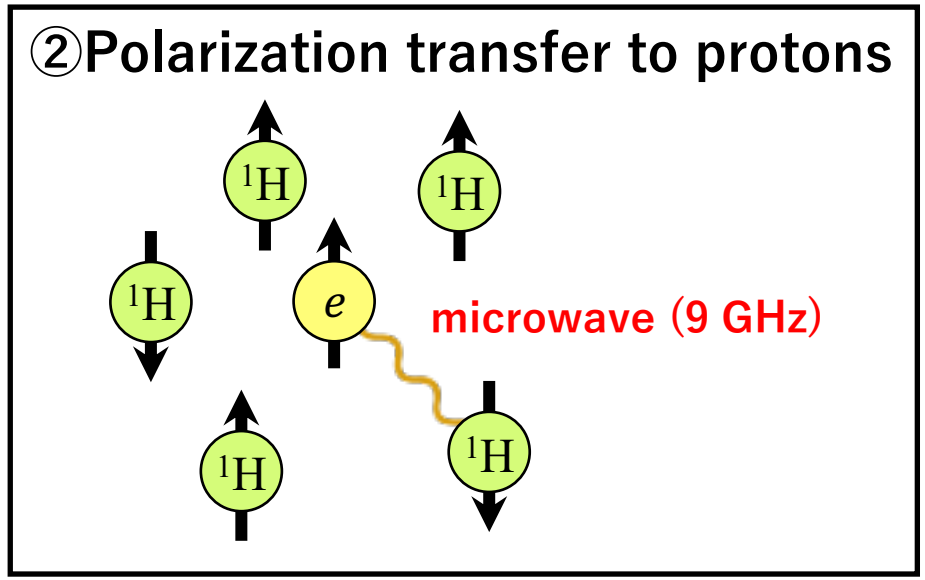
Triplet DNP (Dynamic Nuclear Polarization)

- ✓ Optical excitation of pentacene and decay to triplet state → electron polarization
- ✓ Polarization transfer to protons by microwave irradiation
- ✓ It is operated at a relatively lower magnetic field and a higher temperature (~100 K).

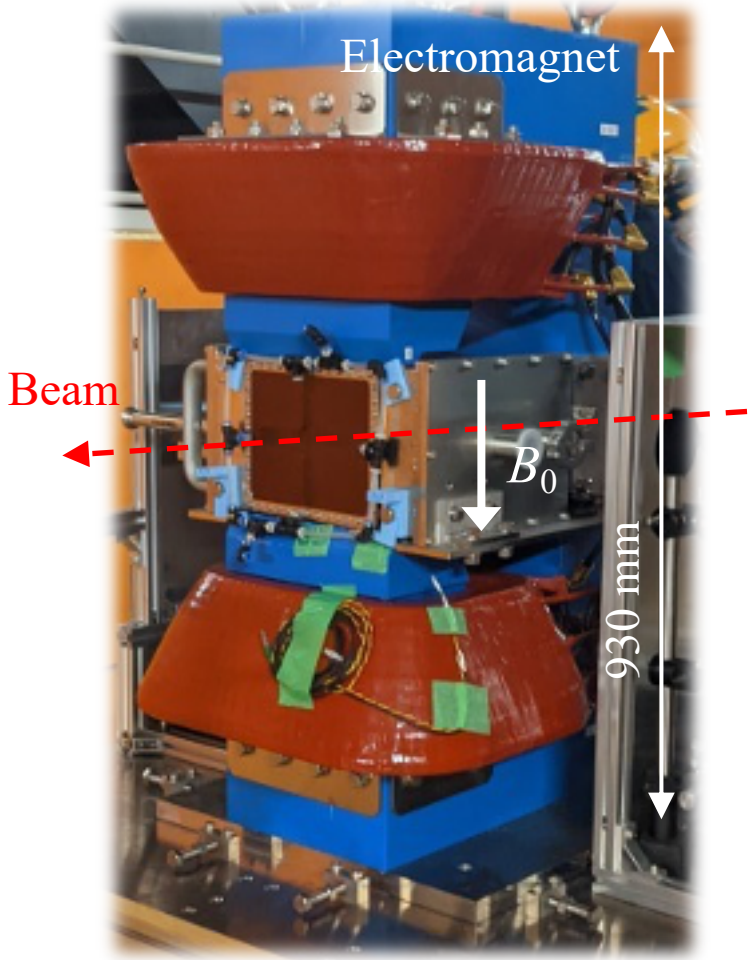
Target: **pentacene doped naphthalene crystal**
(size: φ10, 3 mm^t)

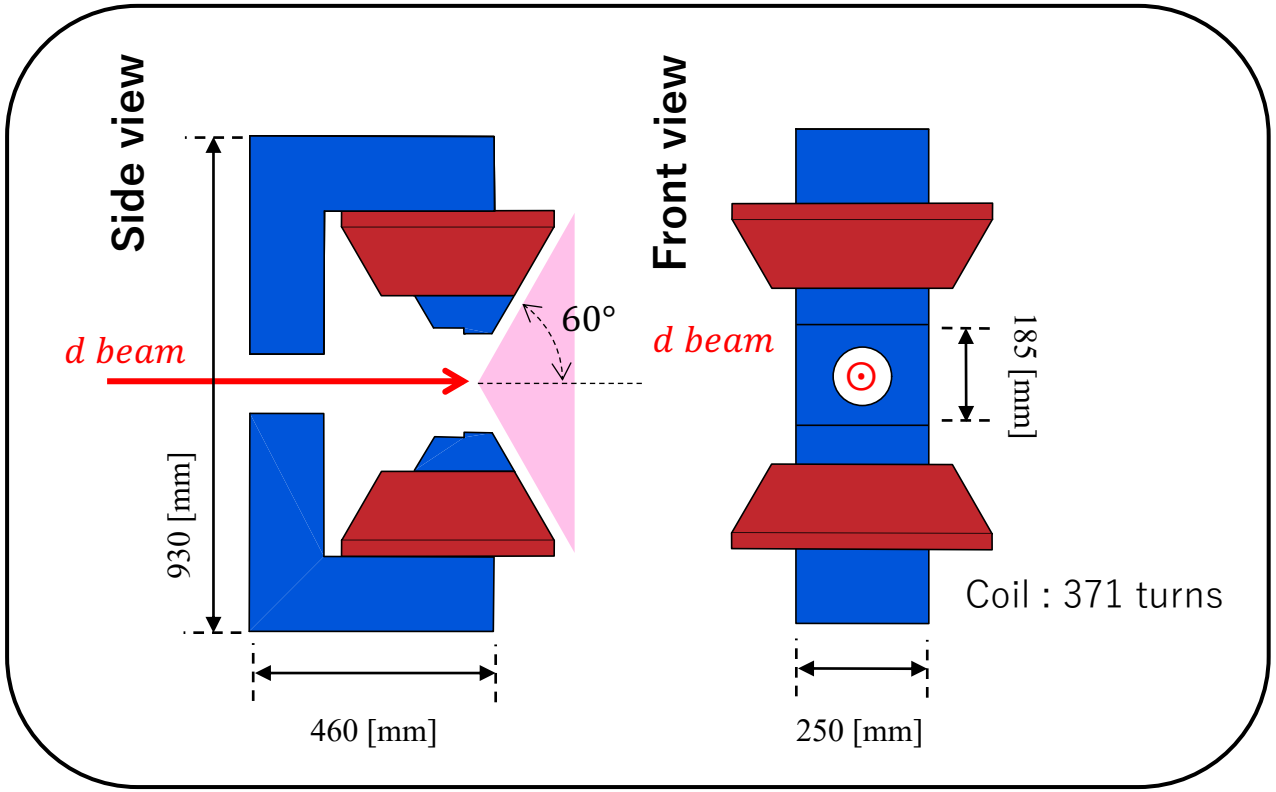






Polarized Proton Target System

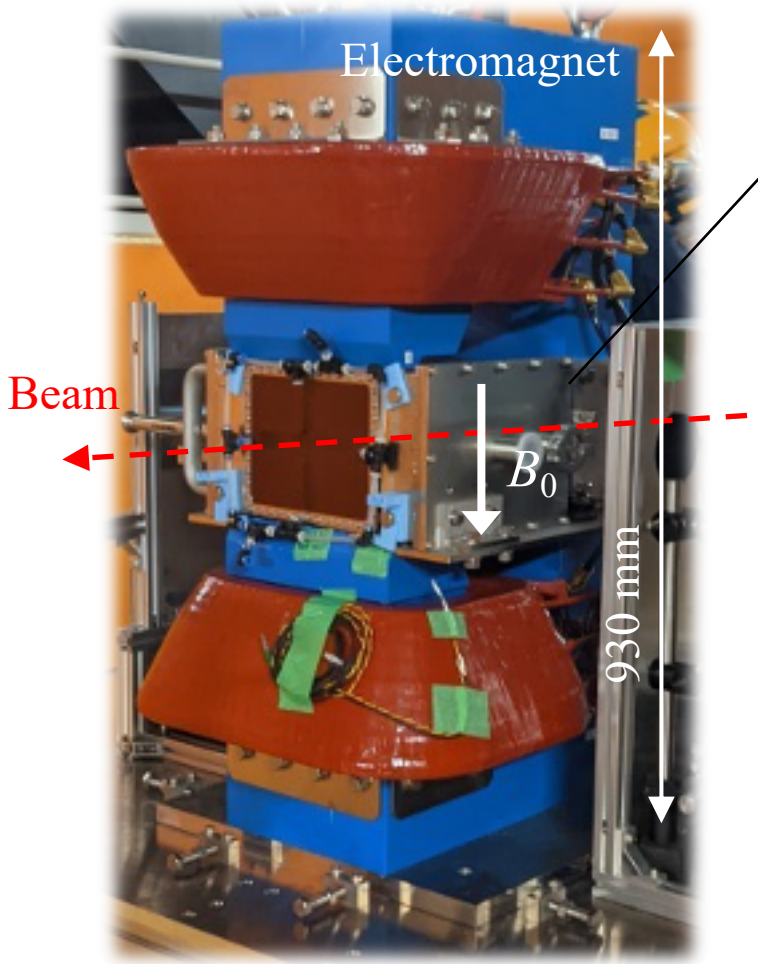


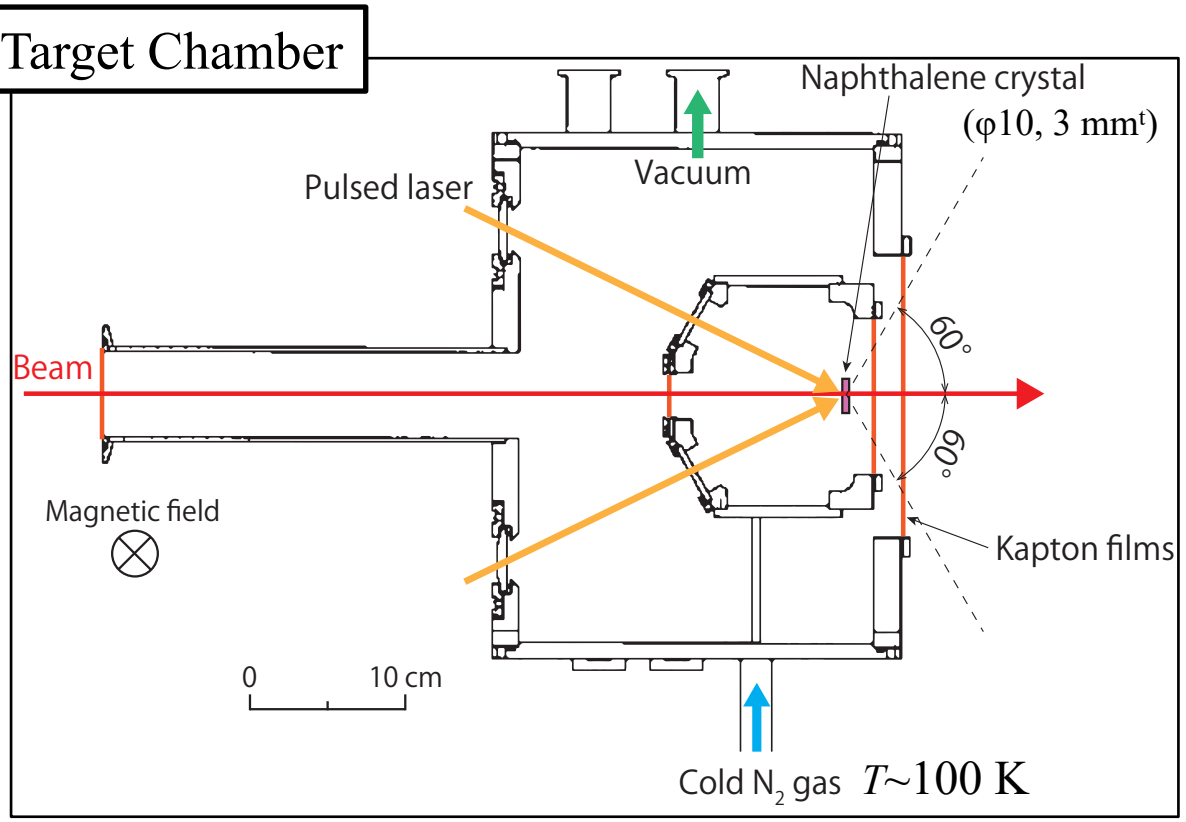


Within target range (ϕ10, 3mm):

- **Magnetic fied : ~0.3 T**
- **Field variation : ≤ 0.1%**

Polarized Proton Target System



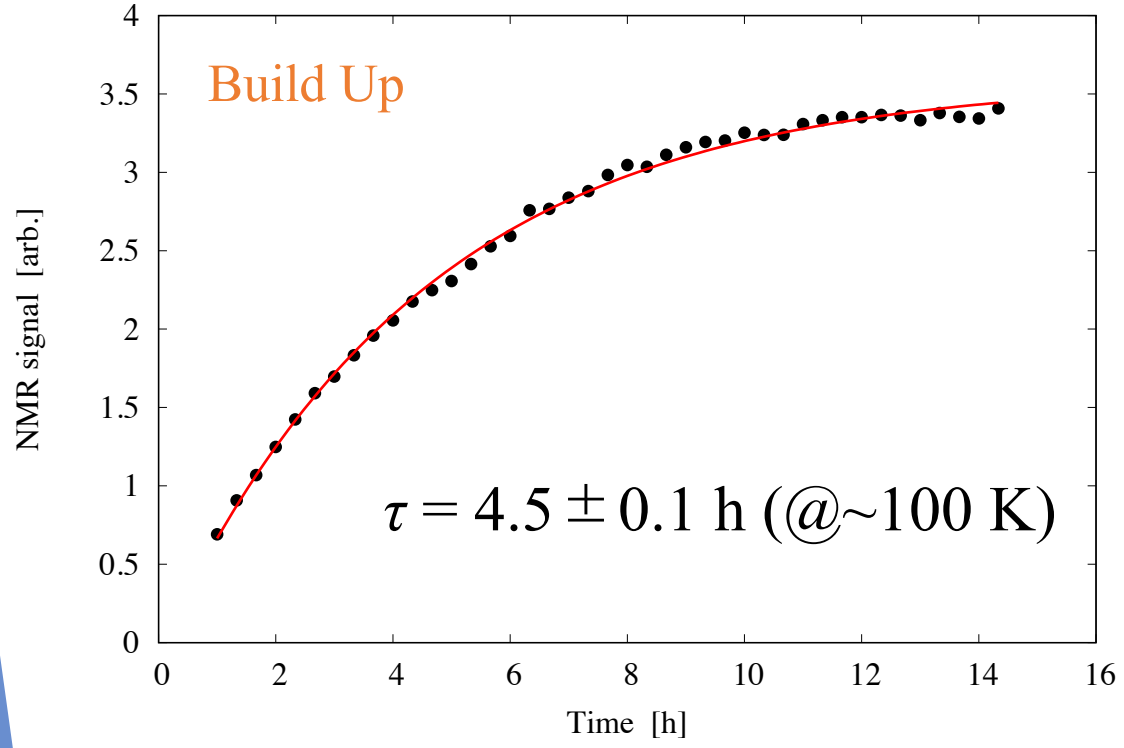


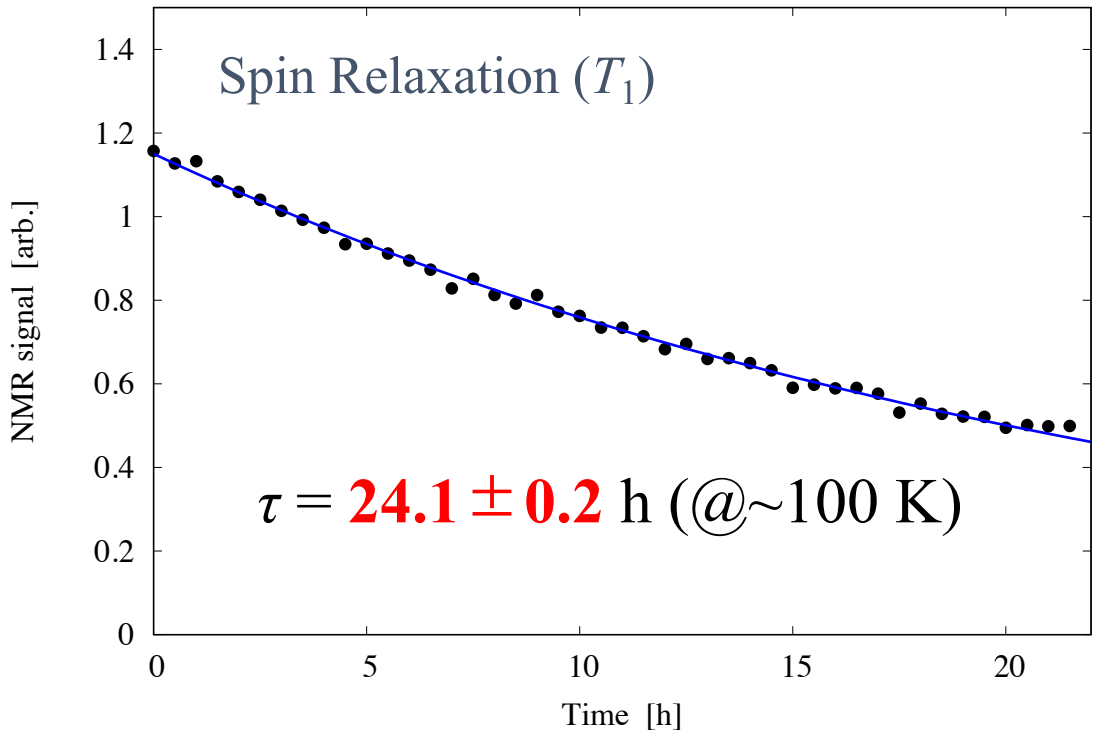
Pulsed Laser

wavelength：589 nm
pulse width：180 nsec
repetition rate：4.5 kHz
power：9 W

Target Performance

- We performed a performance test for the newly-developed polarized proton target system.
- Time evolution of polarization is monitored by NMR.





Polarization signal was confirmed, and spin-relaxation time more than 20 hours was achieved.

Summary and Outlook

Studying 3NFs via few-nucleon scattering at intermediate energies ($E/A \geq 65$ MeV).

- *dp* elastic scattering at RIKEN provided a solid basis for 3NF study.
- Systematic 2NF&3NF potential → **Chiral Effective Field Theory**

We plan to the measurement of spin-correlation coefficients (@100 MeV/u) for *dp* elastic scattering.

- Our Goal: determination of LECs in chiral EFT and 3NFs at N^4LO.

Polarized proton target was developed for the measurement of spin-correlation coefficients.

- The target system has a wide acceptance for horizontal and vertical planes.
- Polarization signal was confirmed, and spin-relaxation time was 24.1 h.

Future Plan

Beam test at CYRIC, Tohoku University

→ Evaluating the absolute polarization via *pp* scattering
Estimating the radiation damage due to charged particle beams

Collaborators

- Tohoku University

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- RIKEN Nishina Center

  H. Sakai, N. Sakamoto, K. Tateishi, T. Uesaka

- Kyushu University

  H. Nishibata, S. Sakaguchi, T. Wakasa

- Kyoto University

  M. Dozono

- University of Miyazaki

  Y. Maeda

- Ruhr-Universität Bochum

  E. Epelbaum

Thank you for your attention.