Developement of Polarized Solid Target for Nuclear Physics Experiment

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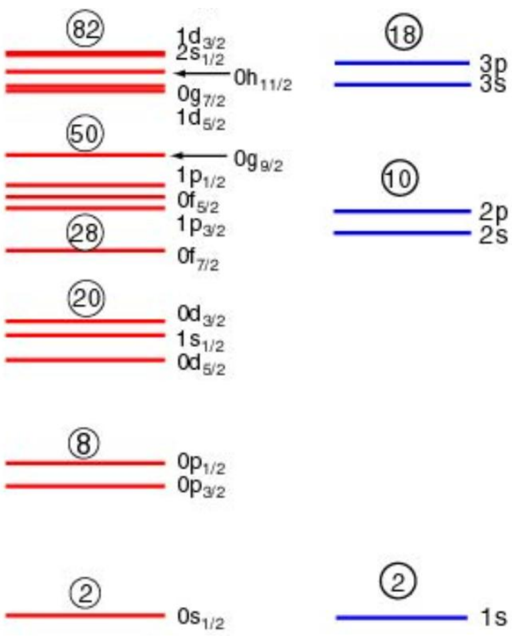
RIKEN Nishina Center

22-26 Sep. 2025

SPIN2025 @ Qingdao, China

Spin in Nuclei

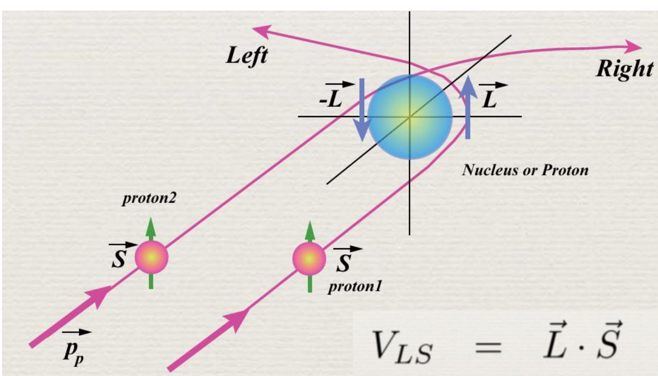


Nuclei Electron

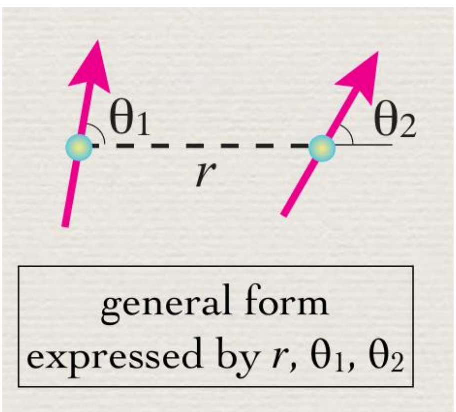
- Spin strongly influences nuclear shell structure
- Magic numbers: Electron (2, 10, 18, 36, 54...)
  stable Nuclei (2, 8, 20, 28, 50...)
  unstable Nuclei (6, 16, 32, 34...)

- **Spin-dependent (non-central) forces**

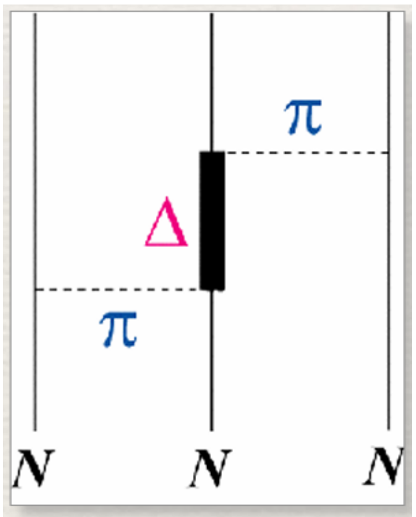
Spin-Orbit Force



Tensor Force

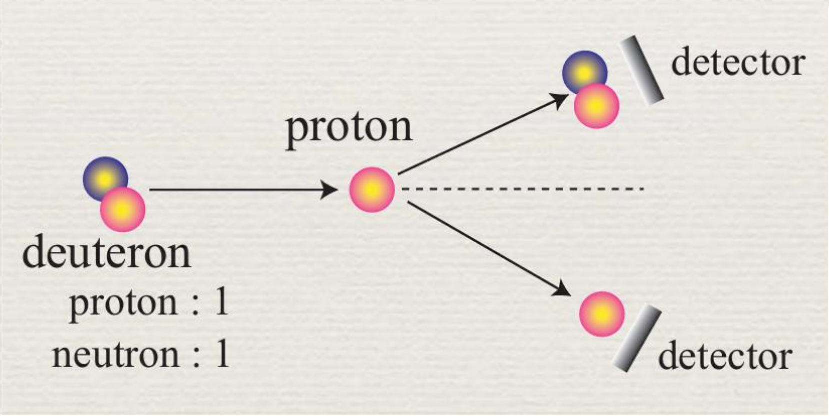


Three-nucleon Force

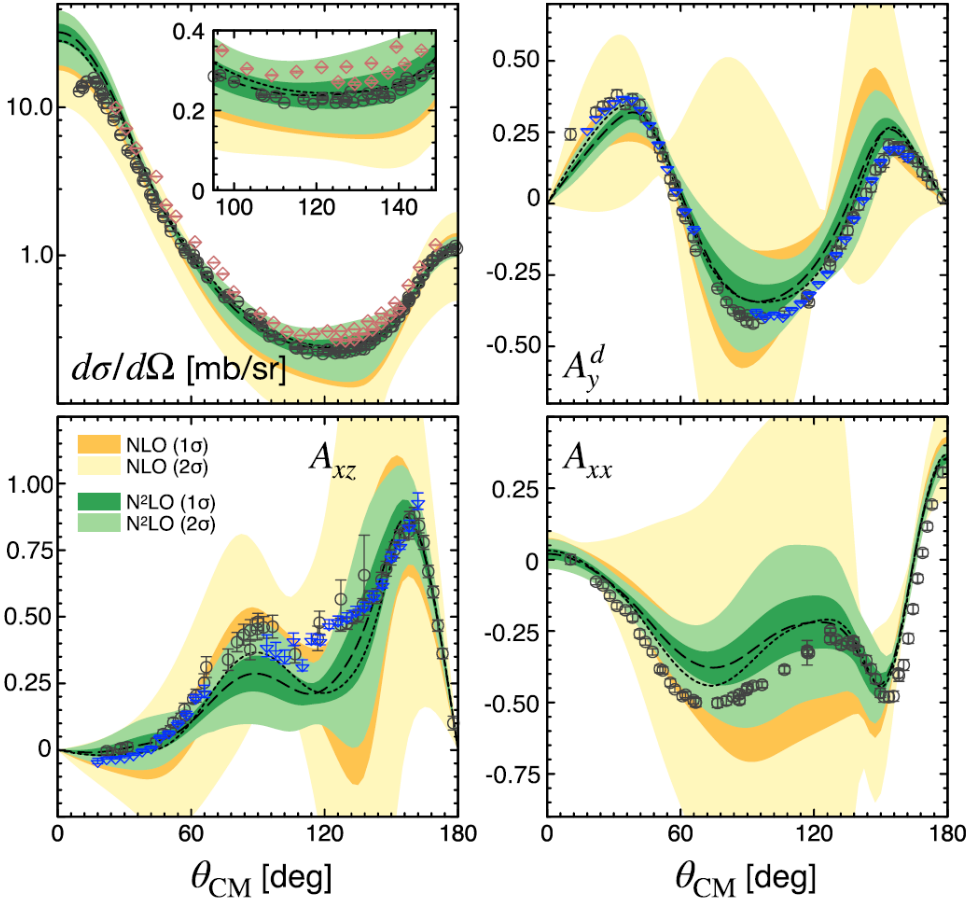


Study of Three-Nucleon Force using *dp* Elastic Scattering

dp elastic scattering @100 MeV/u



χEFT predictions
dp elastic scattering @135 MeV/u



[S. Endo, EPJA 2025]

Measurement of <u>all the spin observables</u>

- Differential cross section ($\frac{d\sigma}{d\Omega}$)

  unpol. beam × unpol. target

- Vector analyzing power ($A_{ij,}$ i,j =x, y, z)

  pol. beam × unpol. target

- Spin correlation coefficient ($C_{ij,\,k,}$ i,j,k =x, y, z)

  pol. beam × **pol. target**

Influence of the Target Magnetic Field on Particle Trajectories

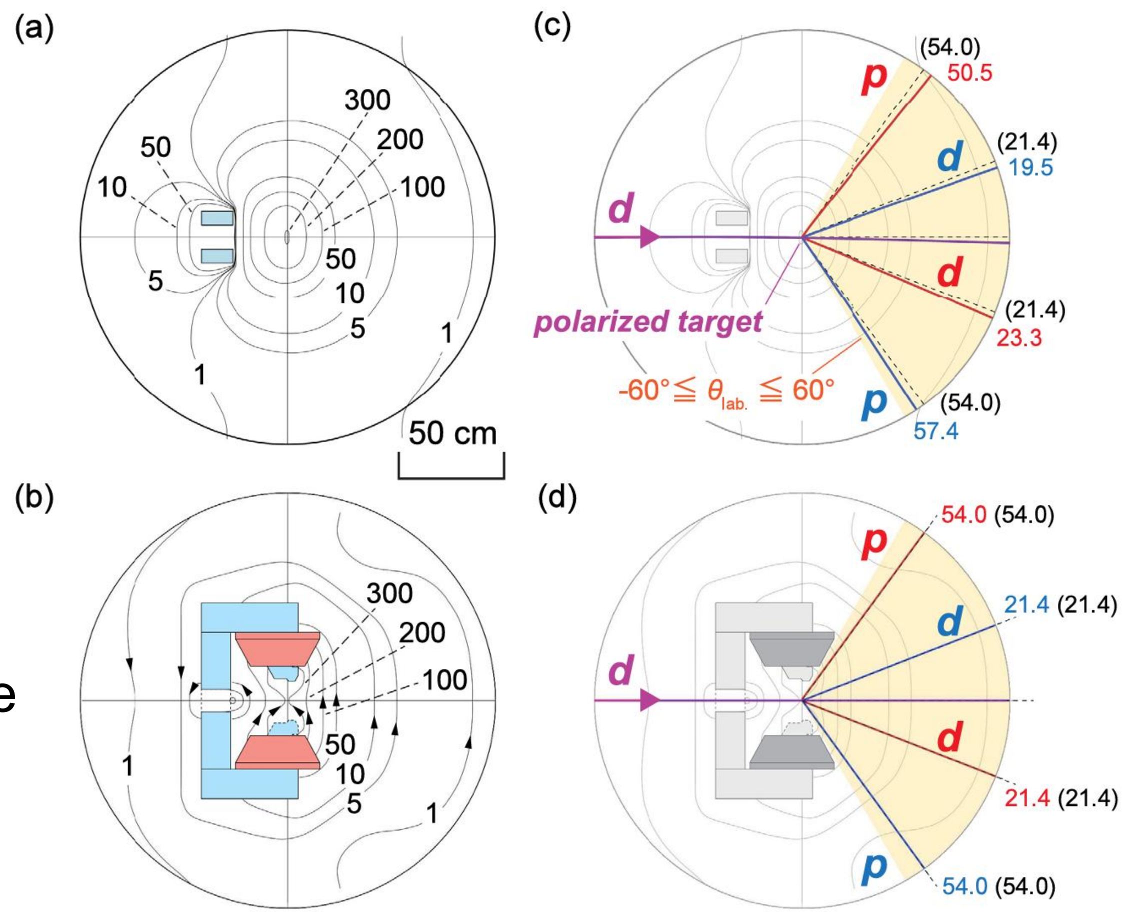
Requirements for the polarized target are to be operated **with a low magnetic field (0.1 T order)** which does not significantly affect the trajectories of the incident and scattered particles.

magnetic field distribution [mT]

Trajectories of incident ***d*** beam (100 MeV/u), scattered ***d*** and recoiled ***p*** ($\theta_{\mathrm{c.m.}}$ = 69.6°)

top

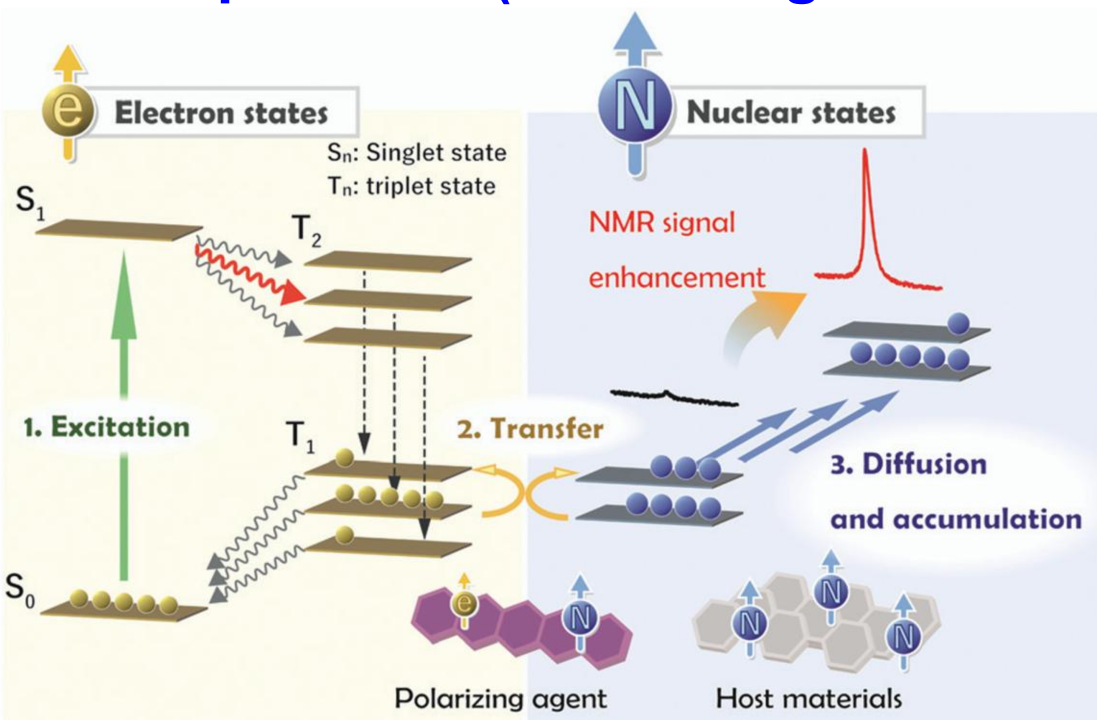
side



Solid line：0.3 T Dotted line：0 T

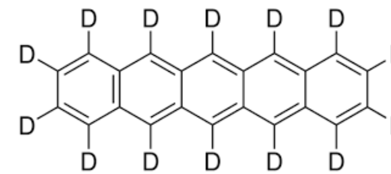
[A. Watanabe, NIMA 2025]

Triplet-DNP (DNP using Photoexcited Triplet Electron)



[K. Nishimura, Chem. Comm. 2020]

Polarizing agent

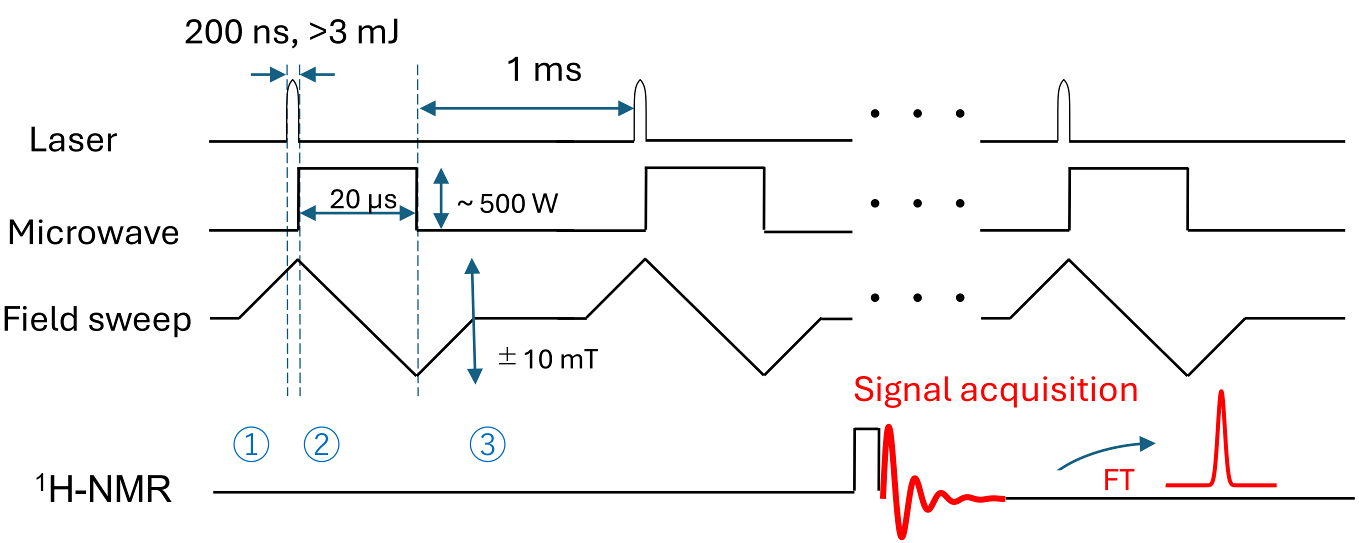


Pentacene-d_{14}

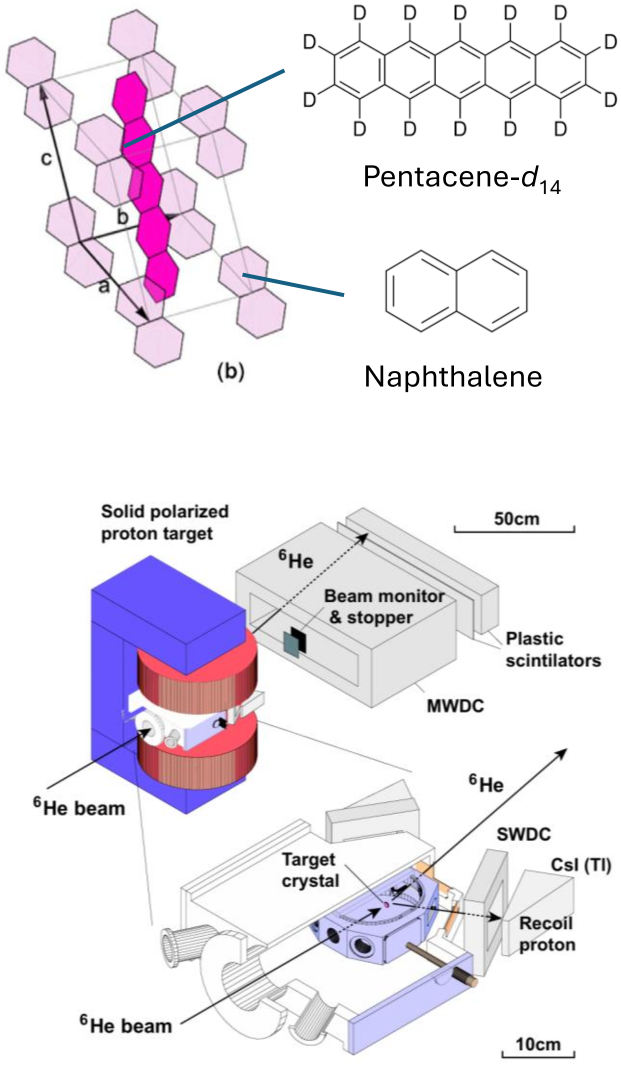
P(e) > 70% (independent of B_0 and T)

Lifetime 20-100 μs

Triplet-DNP sequence

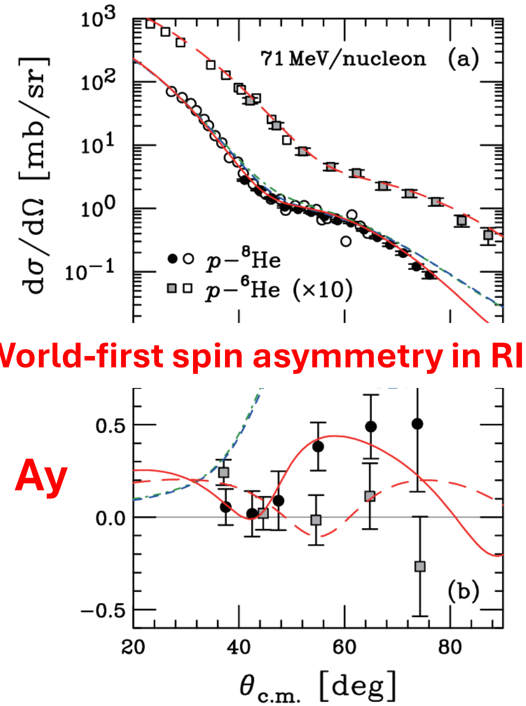


1^{st} gen. Polarized Proton Solid Target (~2023)

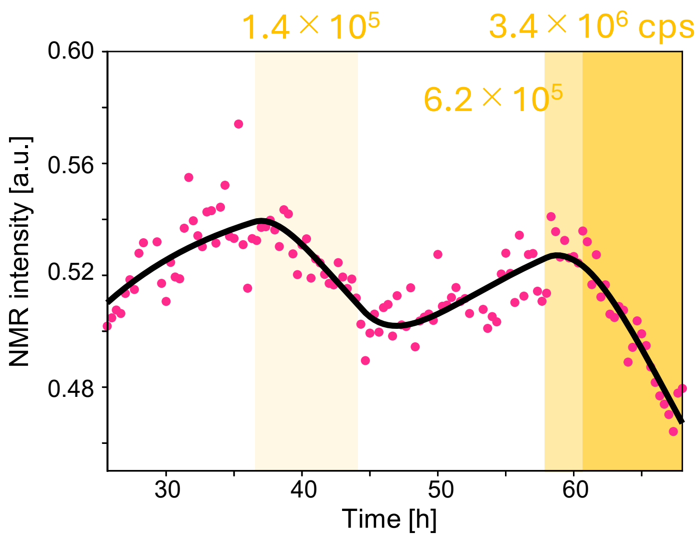


[T. Uesaka, PRC 2010]
[S. Sakaguchi, PRC 2011]

$\vec{p} - {}^{6,8}$He



$\vec{p} - p$



[A. Watanabe, NIMA 2025]

Target material: naphthalene crystal (0.003 mol% pentacene-d_{14})

Experimental: 0.1-0.3 T and 100 K

P(^{1}H): 15-30%

beam intensity: < 10^6 cps

The accelerator potential is not fully used.

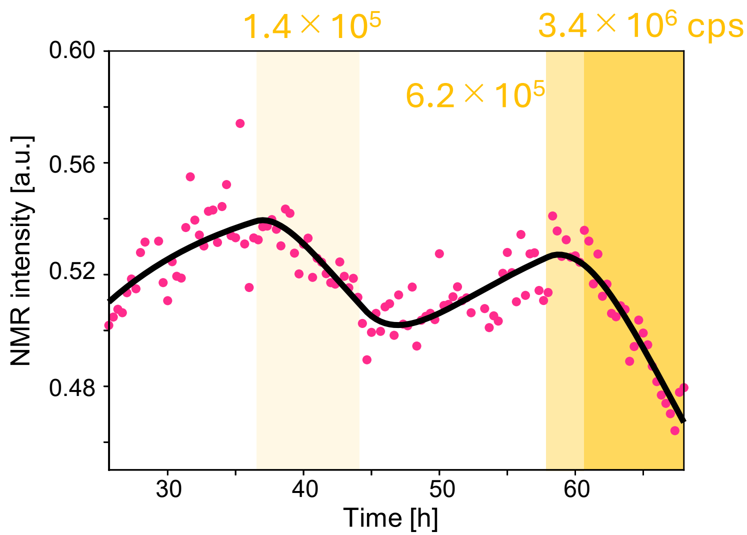
- **Pol. proton solid target operating at low-magnetic field**
  Nuclear physics experiments (*e.g.* three nucleon force)
  DNP using photoexcited triplet electrons (Triplet-DNP)

- **Radiation-tolerant polarized solid target**
  (*arXiv:2508.06549*.)

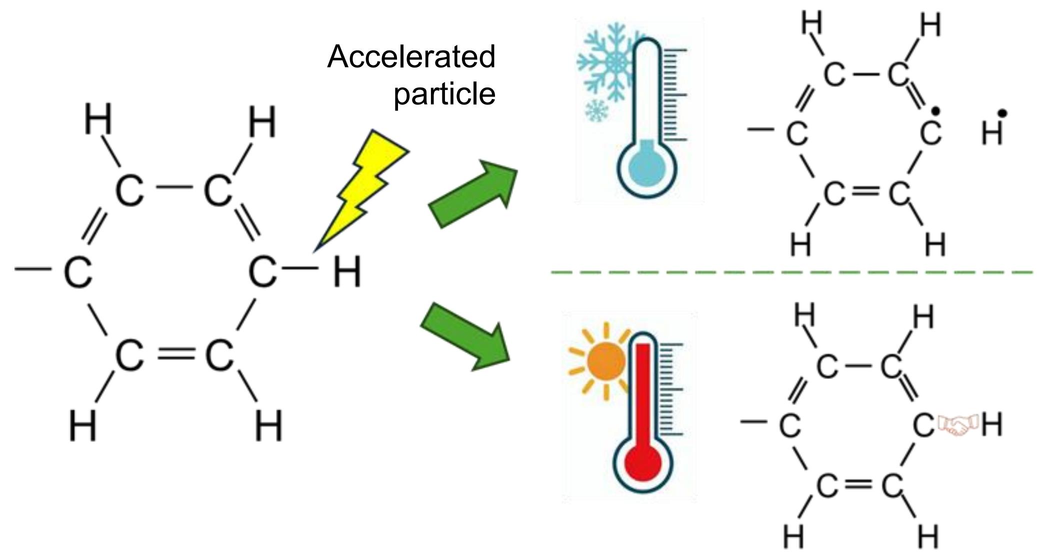
- **^{1}H pol. over 60 % at room temperature and in 0.65 T**
  (*arXiv:2507.15217*.)

Radiation Damage —Cause and Our approach

$\vec{p} - p$



A. Watanabe, NIMA 2025

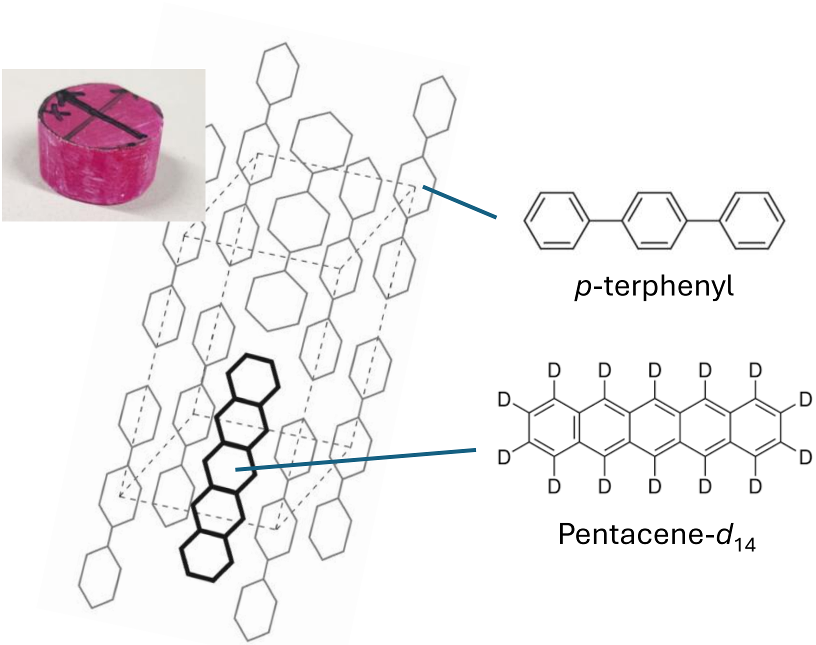


The high-energy beam induces chemical bond breaking of the target material, producing unwanted radicals that accelerate depolarization.

< 200 K: act as a relaxation source
> 200 K: spontaneous recombination (annealing effect)

<u>radiation damage can be ***effectively*** canceled if the repairing rate exceeds the damage.</u>

2^{nd} gen. Pol. Target Operating at Room Temperature



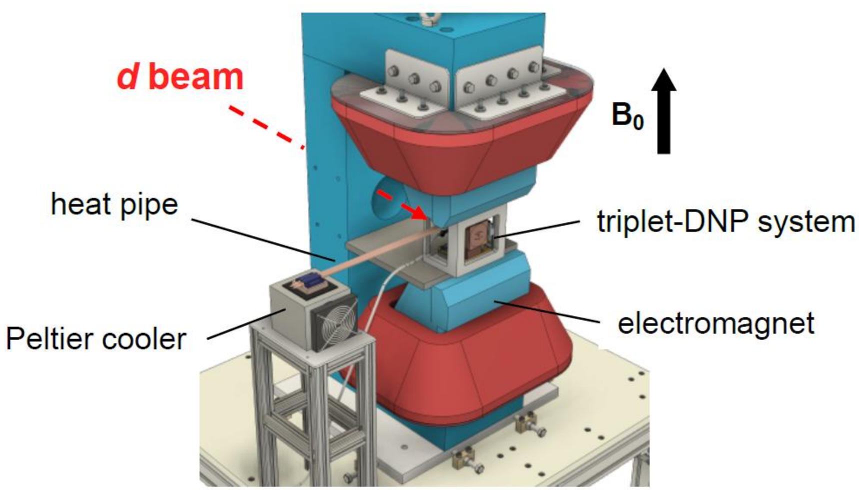
Target material: *p*-terphenyl crystal

(0.003 mol% pentacene-d_{14})

size: Φ10 × 2 mm

Experimental: 0.4 T and 293 K

(e: 10.2 GHz, ^{1}H 15 MHz)



Electromagnet: gap 145 mm

Laser wavelength: 556 nm

pulse width: ~ 600 ns

ave. power: 4 W (4 mJ/pulse, 1 kHz)

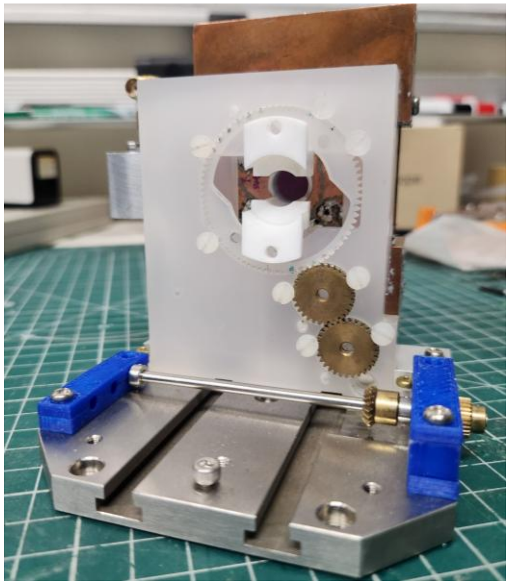
Microwave: Cavity TE_{011} mode

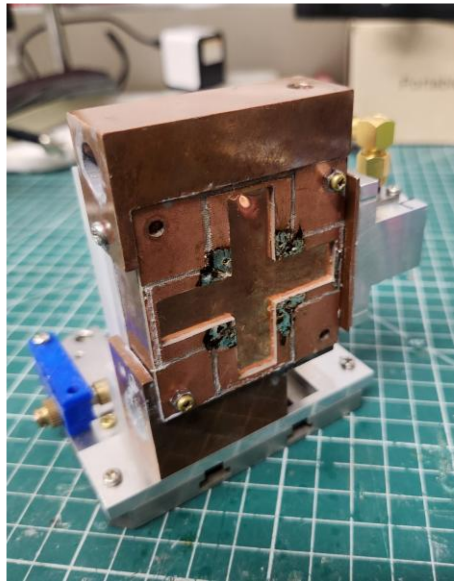
Amp: 2 kW, 20 μs (duty 2%)

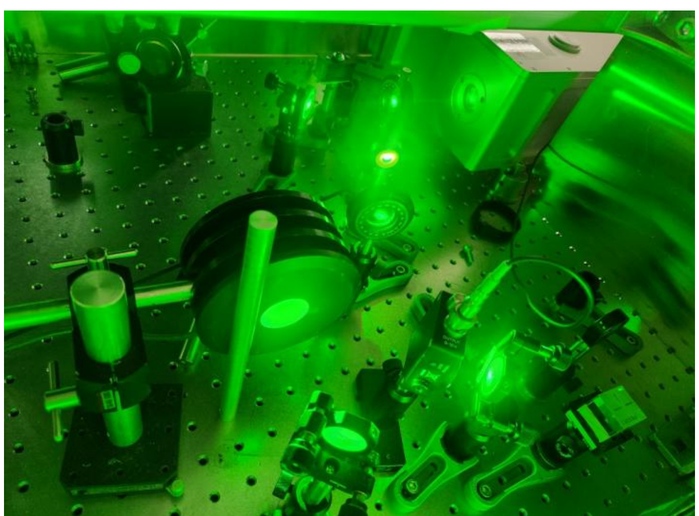
microwave cavity is cooled using a Peltier device

[K. Tateishi, arXiv 2025]

Room-Temperature Pol. Target System







Radiation-Tolerant Pol. Proton Solid Target

dp elastic scattering @RIBF, RIKEN

Energy: 135 MeV/u

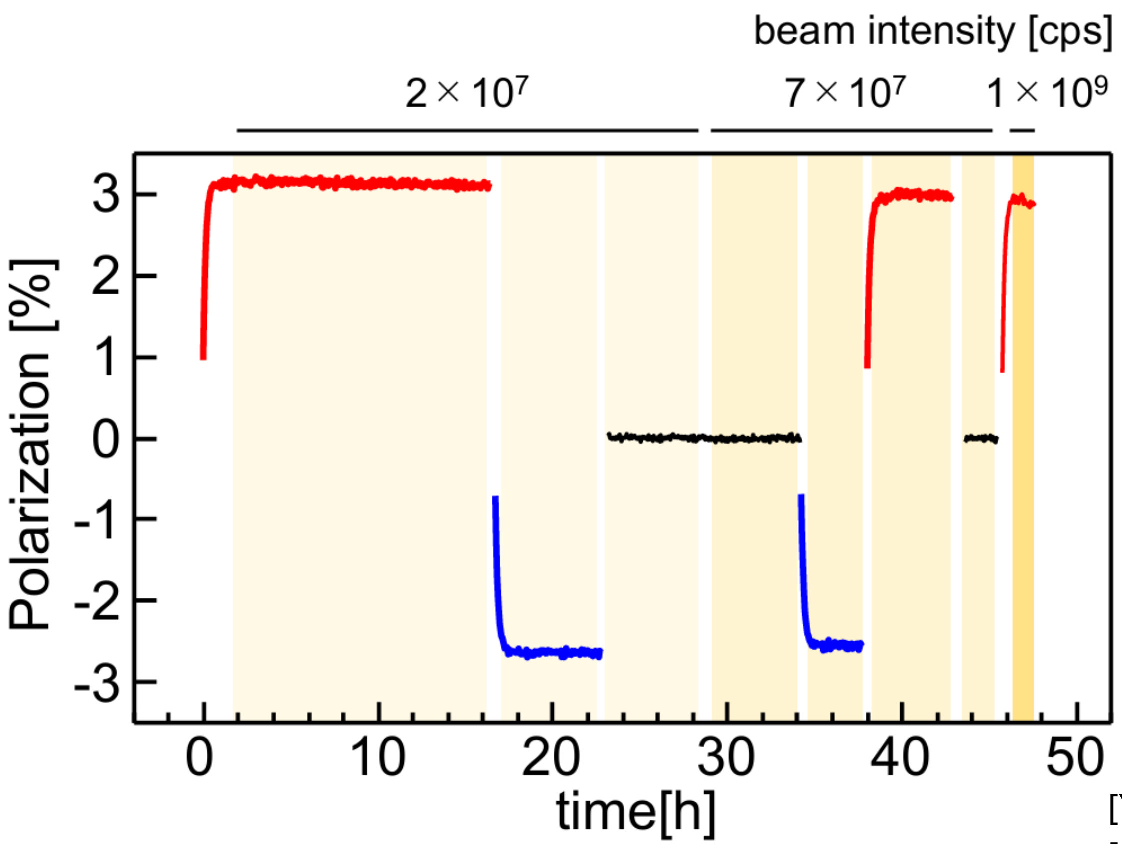
Intensity: 10^7-10^9 cps

Observable: $\frac{d\sigma}{d\Omega}$, A_y

Target material: *p*-terphenyl crystal
(0.03 mol% pentacene-d_{14})

Experimental: 0.4 T and 293 K

Proton pol. : 3.0% $\pm$ 0.2%(stat.) $\pm$ 0.1%(sys.)
(determined from scattering asymmetry)



[Y. Saito, Ph.D Thesis 2024]
[K. Tateishi, arXiv 2025]

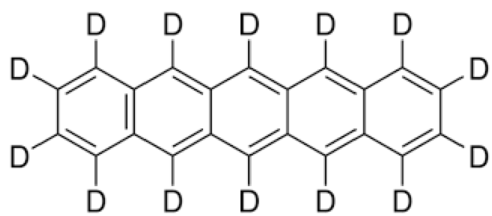
- **Pol. proton solid target operating at low-magnetic field**
  Nuclear physics experiments (*e.g.* three nucleon force)
  DNP using photoexcited triplet electrons (Triplet-DNP)

- **Radiation-tolerant polarized solid target**
  Room temperature operation (annealing effect)
  p-terphenyl crystal (pentacene-d_{14})

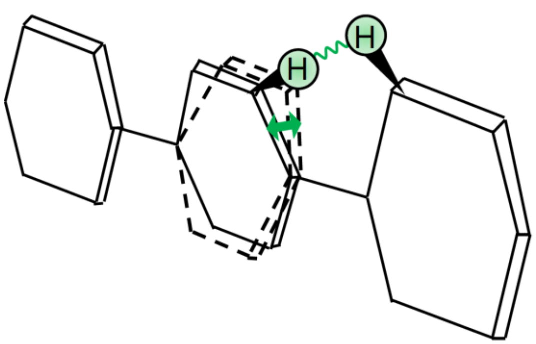
- **^{1}H pol. over 60 % at room temperature and in 0.65 T**
  (*arXiv:2507.15217*.)

Target Materials for Room Temperature Operation

- Air-stable
- Pentacene capacity
- **Long T_1** (strongly coupled with molecular vibrations)

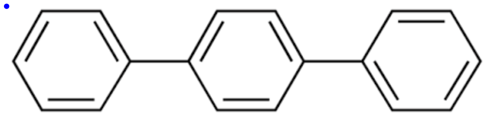


pol. agent（pentacene-d_{14}）

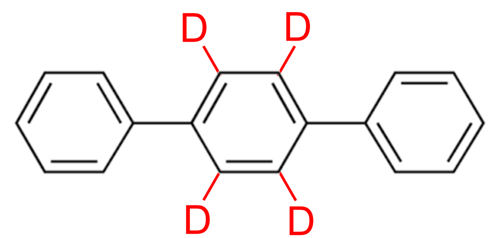


Pedulum motion of *p*-terphenyl

2nd gen.



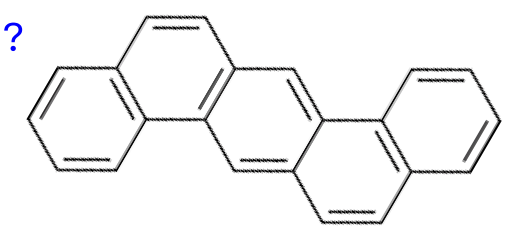
p-terphenyl (T_1: 11 min)



p-terphenyl-d_4 (T_1: 37 min)

[K. Tateishi PNAS 2014]

3rd gen.?

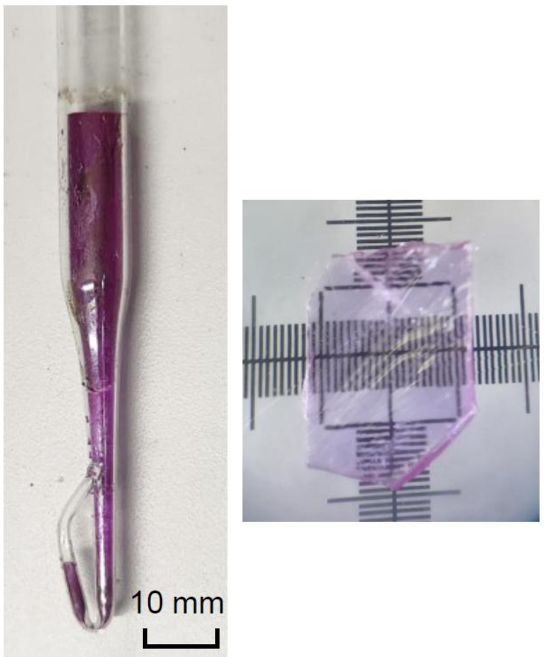


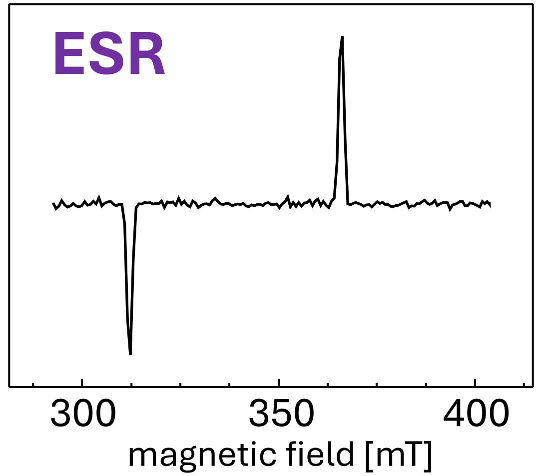
dibenz[*a*,*h*]anthracene

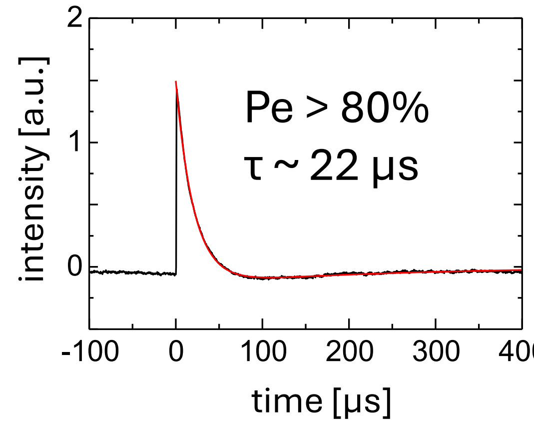
[K. Tateishi, arXiv 2025]

Fabrication and Evaluations:
single crystal of dibenz[a,h]anthracene doped with pentacene-d_{14}

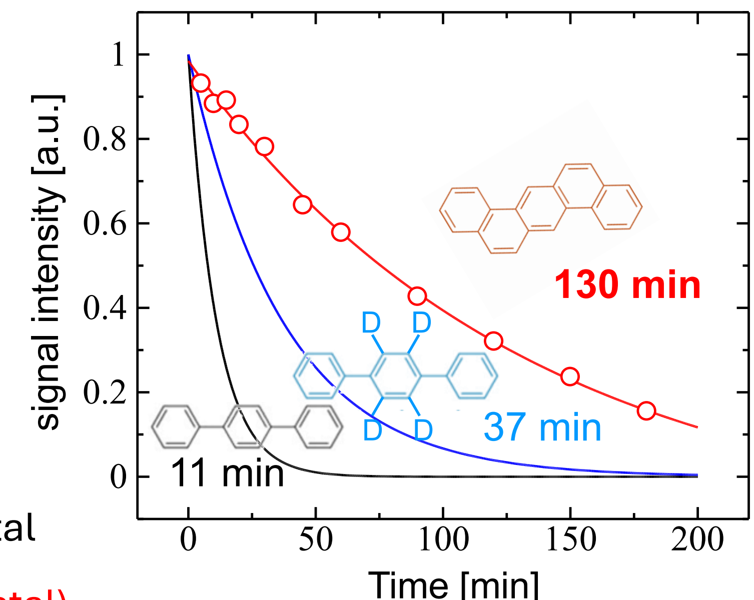
Crystal growth (Bridgman method)





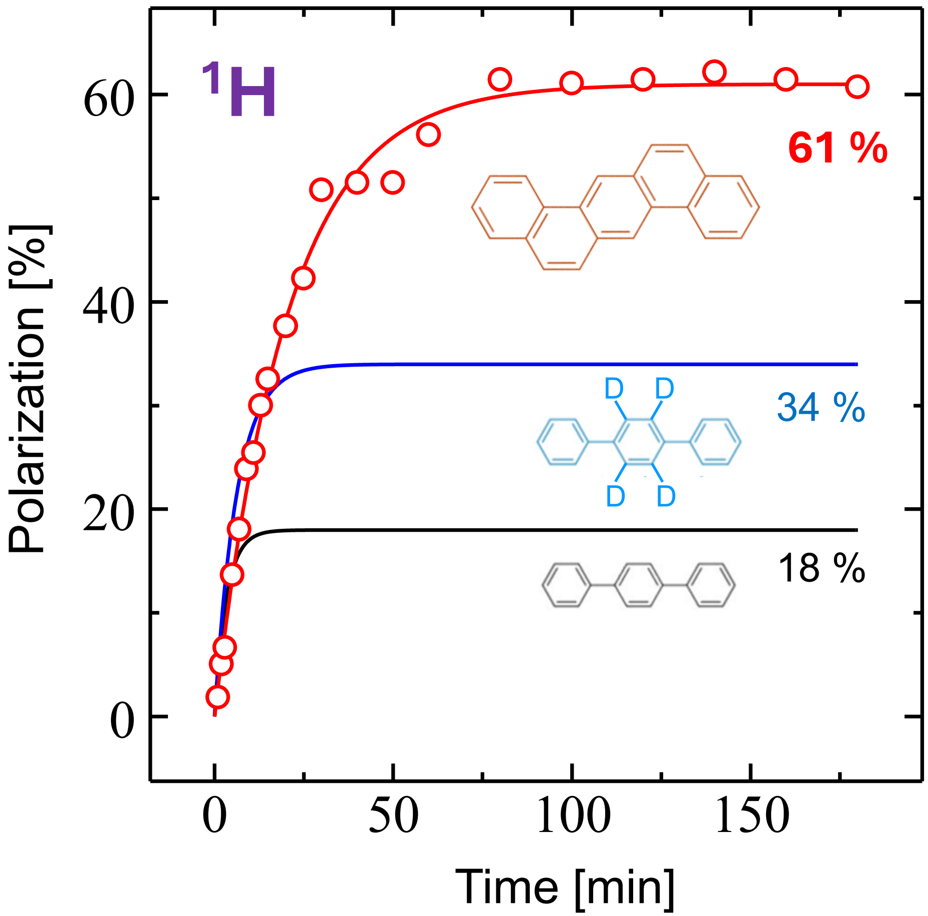


T_1 of ^1H @ RT



- ✓ Air-stable : melting point ~270 ℃
- ✓ Pentacene capacity: comparable with p-terphenyl crystal
- ✓ **Long T_1** : > 2 hour (10 times longer than p-terphenyl crystal)

Room Temperature ^{1}H Polarization



- single crystal of dibenz[a,h]anthracene doped with pentacene-d_{14}
  - Size: ~1 mg
- Experimental: 0.65 T, 293 K (e: 17.5 GHz, ^{1}H 28 MHz)
- Triplet-DNP: 1 kHz
  - Laser: 556 nm, 1 mJ/pulse
  - Microwave: ~200 W (peak)
  - Sweep: ±10 mT

[K. Tateishi, PNAS 2014]
[K. Tateishi, arXiv 2025]

Record-high nuclear polarization in solid & at room temperature

Polarization slightly decreases in the target magnetic field (0.4 T)?

Fabrication of large crystal is essential for implementing the target system

Summary

- **Pol. proton solid target operating at low-magnetic field**
  Nuclear physics experiments (*e.g.* three nucleon force)
  DNP using photoexcited triplet electrons (Triplet-DNP)

- **Radiation-tolerant polarized solid target**
  Room temperature operation (annealing effect)
  p-terphenyl crystal (pentacene-d_{14})

- **^{1}H pol. over 60 % at room temperature and in 0.65 T**
  dibenz[a,h]anthracene crystal (pentacene-d_{14})
  long T_1 (> 2 hour)

Acknowledgements

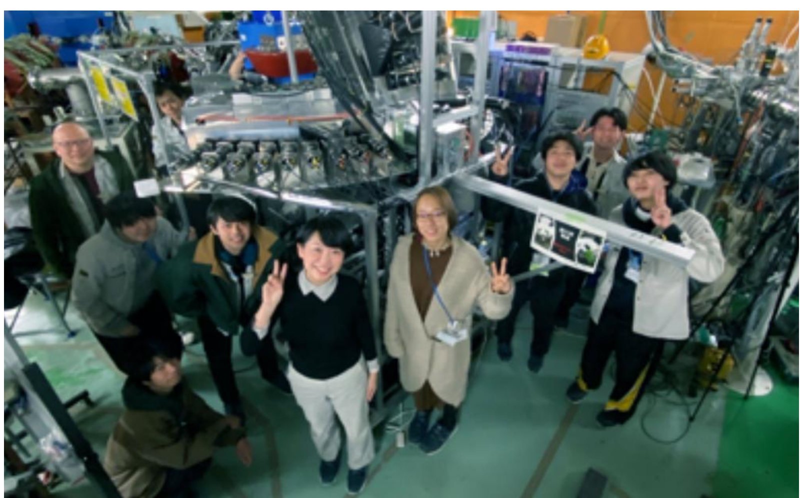
RIKEN
T. Uesaka
D. Miura
S. Otsuka

N. Sakamoto
H. Sakai

Tohoku U.
Science Tokyo
Kyoto U.
K. Sekiguchi
A. Watanabe
Y. Saito
K. Yoshida
Y. Maruta
T. Matsui
K. Suzuki
D. Takahashi
H. Sugahara
S. Takahashi

Kyusyu U.
T. Wakasa
H. Nishibata
K. Aradono
T. Kajihara
K. Hirasawa
Y. Nagao

Kwansei Gakuin U.
T. Hamura
Tohoku U.
S. Kurosawa
A. Yamaji
QST
E. Takada
T. Wakui
Miyazaki U.
Y. Maeda



Thank you for your attention.