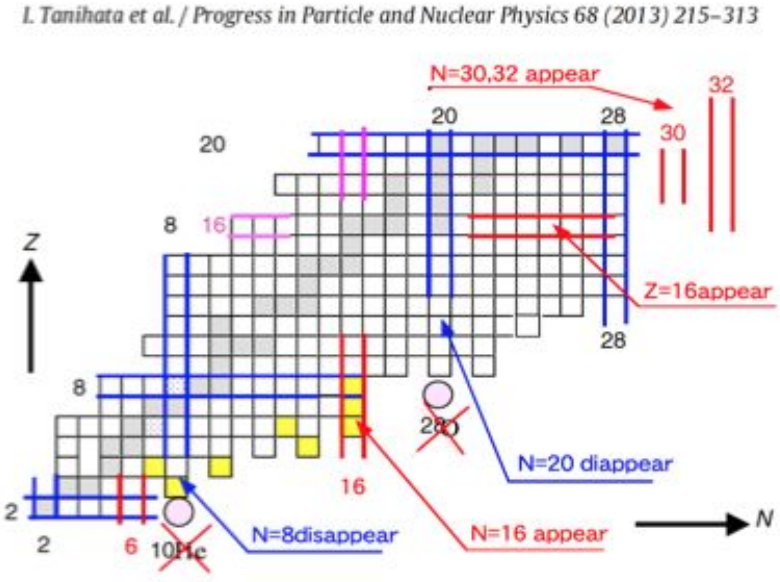

# Elastic scattering of neutron-rich $^{6}$He nuclei from polarized protons at 200 MeV/A

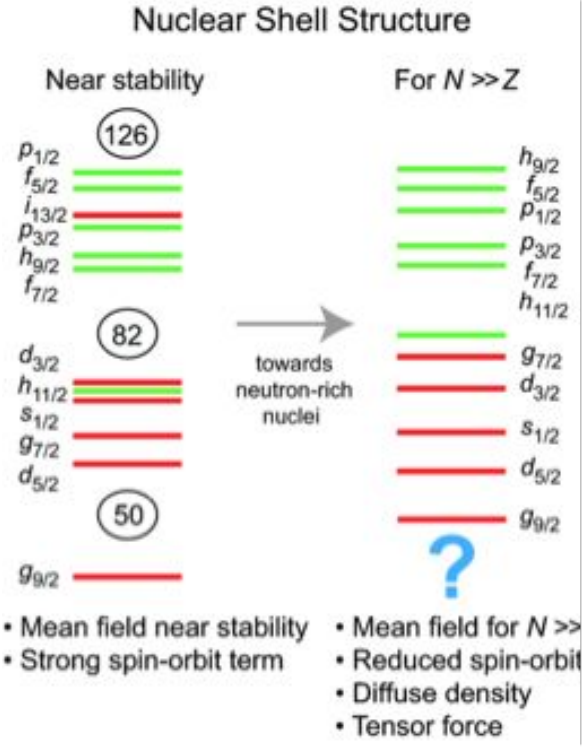
S. Chebotaryov

# Outline

- Role of spin-dependent interactions in unstable nuclei
  - How to experimentally study spin-dependent interactions
- Solid polarized proton target at RIKEN
  - Polarized targets: “brute force” DNP & triplet DNP techniques
  - Overview of the target system
  - Physics opportunities
  - Brief overview of carried out and planned experiments with polarized proton target
- p-$^{6}$He elastic scattering experiment
  - Motivation - spin-orbit coupling in unstable nuclei
  - Experimental setup
    - Target operation
  - Present results of data analysis: event selection & background extraction

# Role of spin-dependent interactions in unstable nuclei



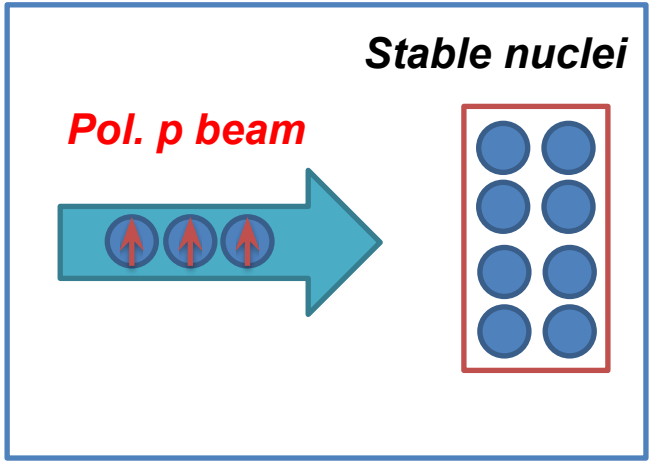




- Change in shell structure of unstable nuclei
  - Magic numbers newly appear or disappear
  - Reduction of spin orbit splitting ($E_{j=l-½} - E_{j=l+½}$)

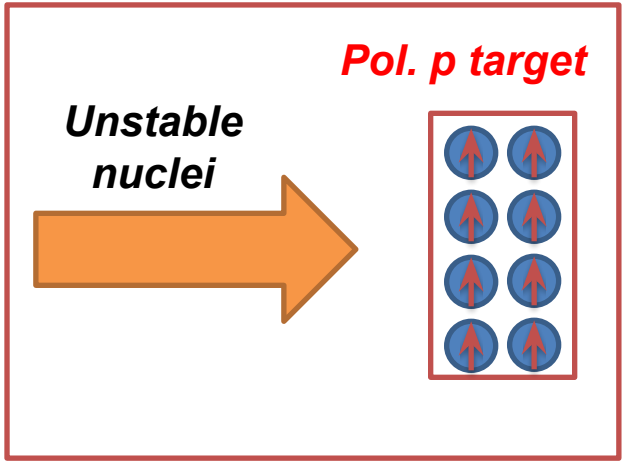
**Investigating role of spin-dependent interactions in unstable nuclei is essentially important**

# How to experimentally study spin-dependent interactions

RI-beam species are short lived ⇒ Must be supplied as a beam

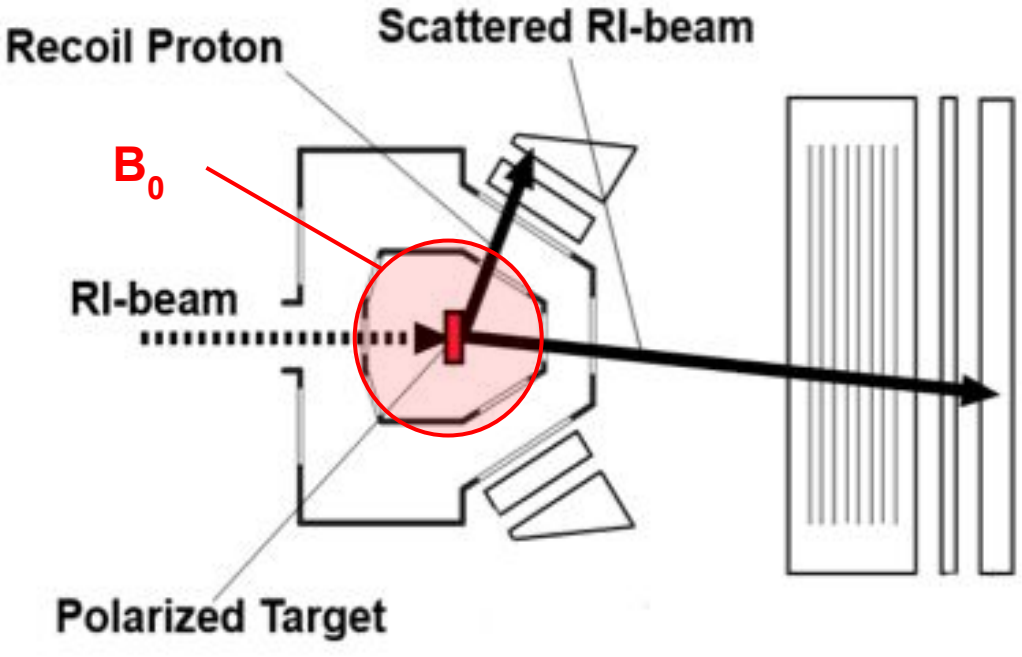



Experiments involving polarized protons with stable and unstable nuclei




**Polarized proton target is required**

# How to study spin-dependent interactions




Requirements of RI-beam experiments to the target:

**Avoid distortion of outgoing proton trajectories**

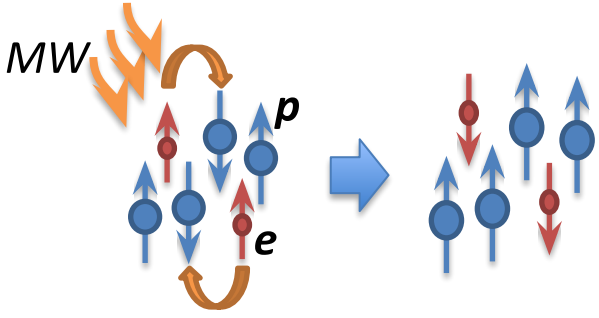
**($E_p$= 40 - 200 MeV)**

- Must work under low magnetic field
  - Angular resolution for recoil protons must be better than 1 deg.:

**$B_0$ < 0.15 T**

# Polarized proton targets using DNP technique

- Dynamic Nuclear Polarization
  - Electrons are firstly polarized
  - Electron polarization is transferred to protons system




- How to obtain high electron polarization
  - "Brute force" DNP

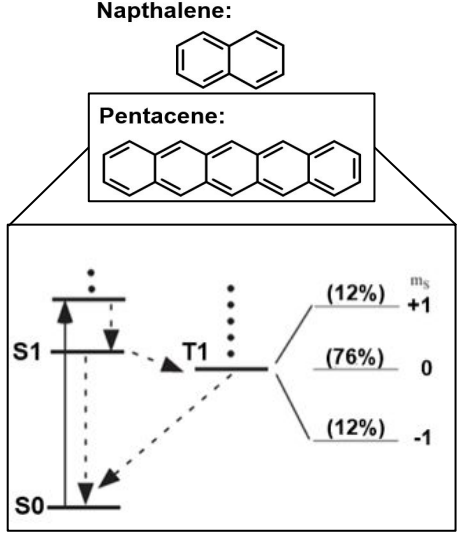
$B_0 > 1$ T
$T < 1$ K

(use electron thermal polarization)

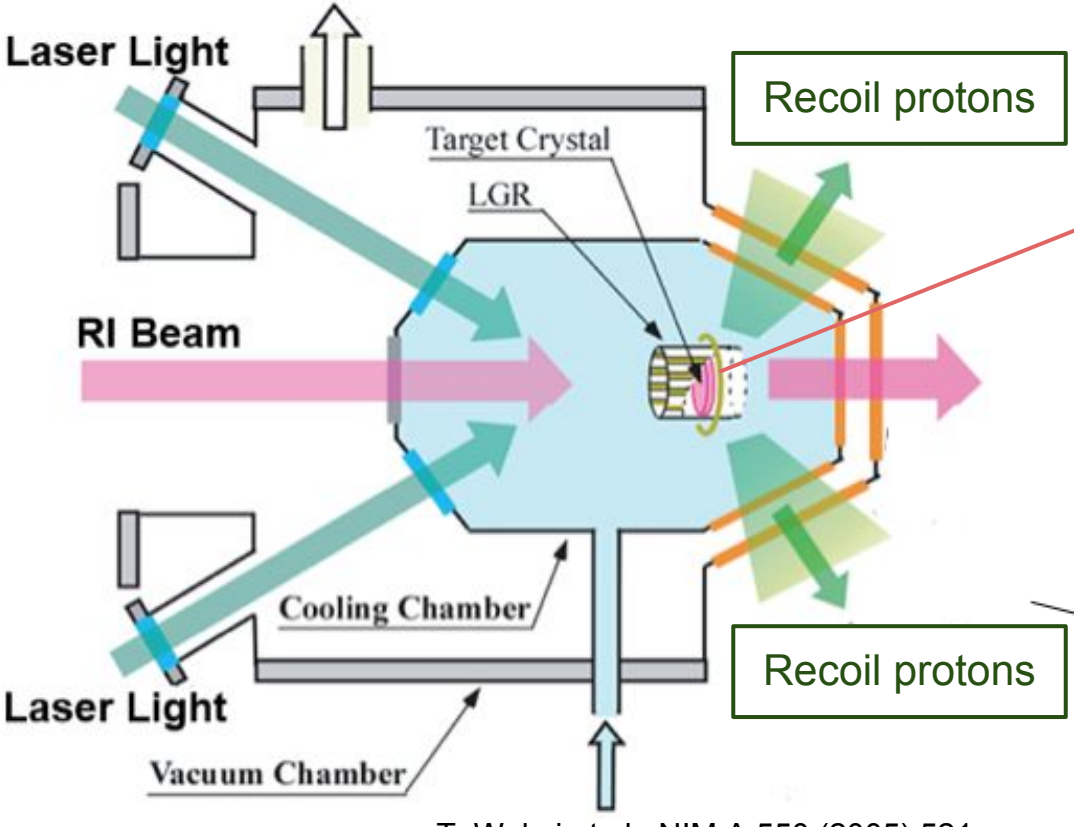
$$P = \tanh\left(\frac{\gamma \hbar B_0}{2kT}\right)$$

  - Triplet DNP
    - Electrons optically excited to triplet state
      - Spontaneous population difference of triplet sublevels
      - Weakly dependent on $B_0$

$B_0 \sim 0.1$ T
$T > 100$ K



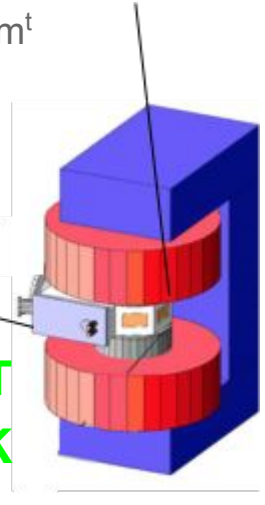
# Polarized proton target at RIKEN




Target material:

- Naphthalene ($C_{10}H_8$)
- 0.0004% pentacene

Size: 24 mm ∅, 1-3 $mm^t$



**Mag. field of 0.1 T**

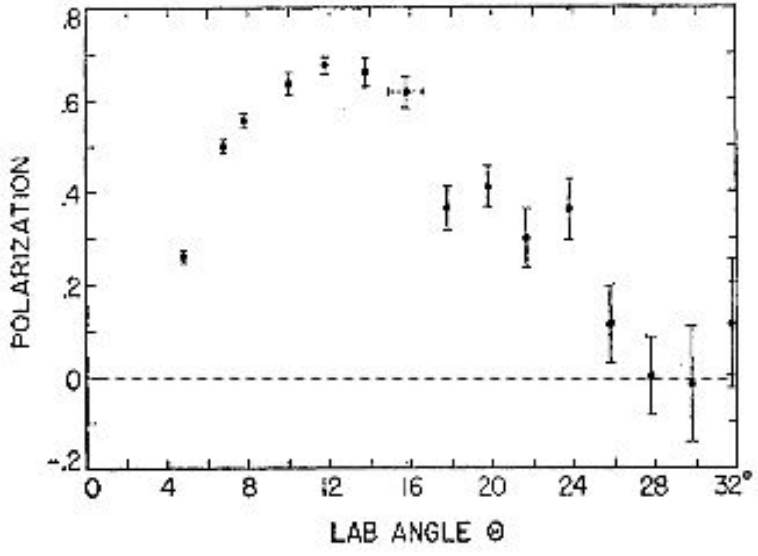
**Temp.: 100 K**

T. Wakui et al., NIM A 550 (2005) 521.
T. Uesaka et al., NIM A 526 (2004) 186.

# Physics opportunities:

## Spin-orbit coupling in proton-nucleus scattering

- Polarization phenomenon in elastic scattering
  - Large spin-asymmetry observed in p-$^4$He elastic scattering
    - O. Chamberlian et al., Phys. Rev. 102 (1956) 1659.
- Direct evidence of “strong” spin-orbit coupling in nuclei
  - E. Fermi, Nuovo Climento 10 (1954) 407.




**Extensive studies of spin-orbit potential ⇒**
**Almost constant depth/diffuseness for stable nuclei**

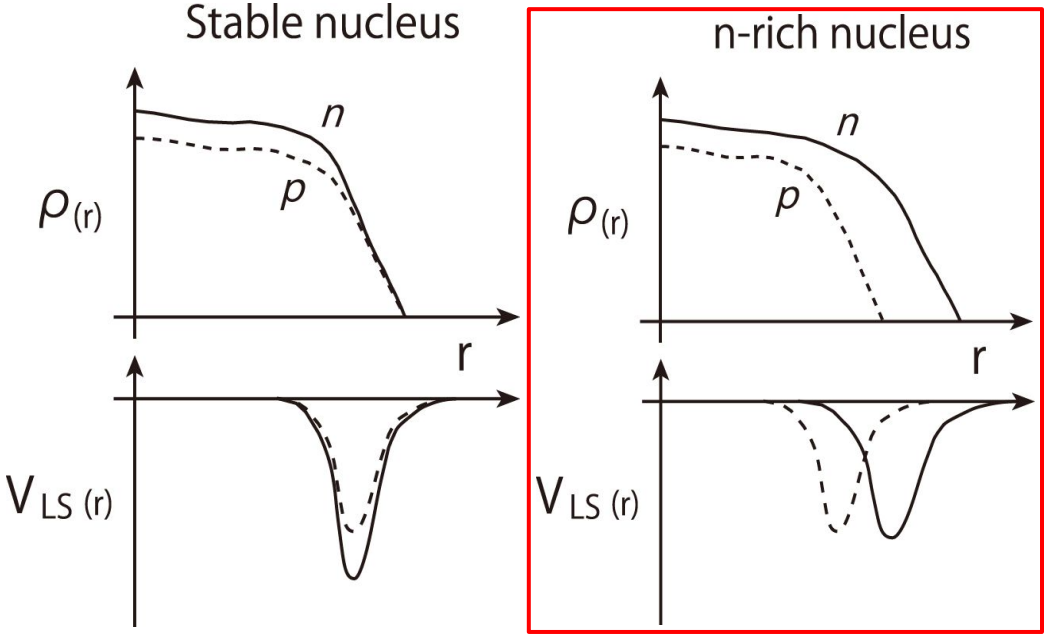
# Physics opportunities:

## Spin-orbit coupling in proton-nucleus scattering

Spin-orbit potential:

- Peaks at nuclear surface
- Almost constant for **stable nuclei**
- What is its shape for **unstable nuclei** with extended density distribution?
- Effects of the difference between proton and neutron density distributions?

$$U_{so} = [1 + \alpha\rho(r)]^{-1} \frac{1}{r} \frac{d\rho}{dr}$$

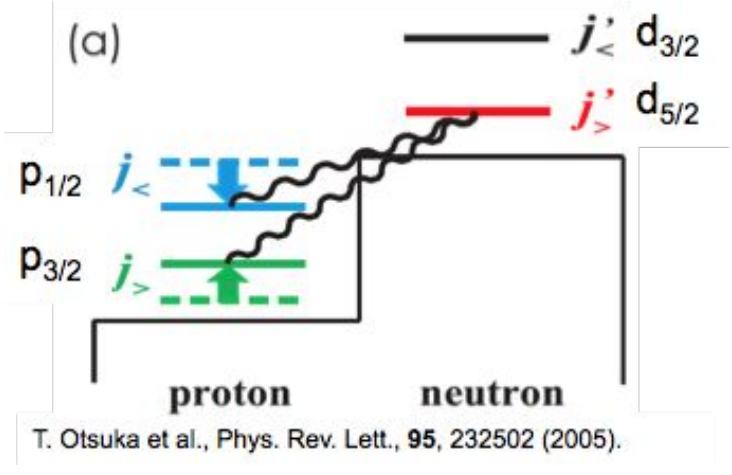



**Vector analyzing power in elastic scattering from unstable nuclei with extended neutron distribution**

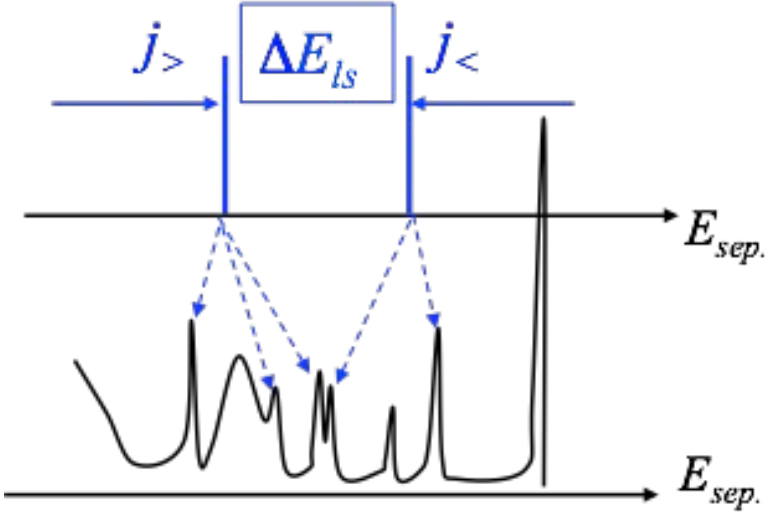
# Physics opportunities:

## Change in spin-orbit splitting

- Determination of spin-orbit splitting
  - Single-particle states are fragmented due to residual interaction
  - (*p*,2*p*) reaction
    - distribution of $j_>$ and $j_<$ strengths



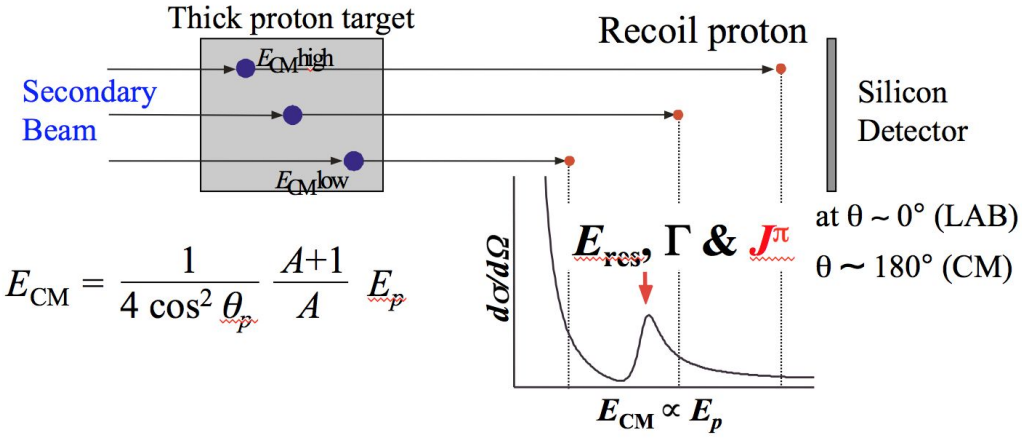

T. Otsuka et al., Phys. Rev. Lett., **95**, 232502 (2005).

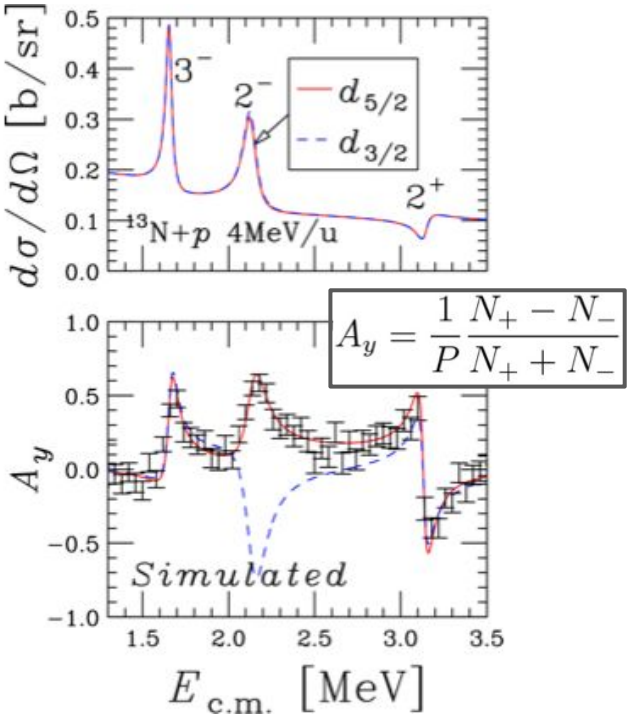



**Change of spin-orbit splitting** can be explored with (*p*,2*p*)

# Physics opportunities:

## Resonant scattering




Advantages:

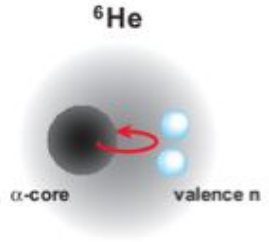
- Excitation function can be scanned with single $E_{beam}$
- High resolution of $E_{CM}$: 30 - 80 keV
- Large cross section: 10 - 100 mb/sr

**Powerful tool for resonance and particle unbound states**

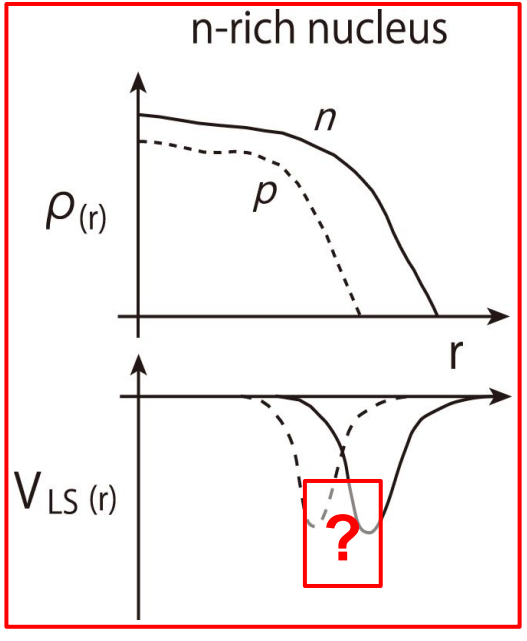
What can we add by polarization?

- **Clear assignment of *j***
  - Projectile with non-zero spin
  - Sensitive to configuration mixing
- **Disentangle overlapping broad resonances**

# p-$^{6}$He elastic scattering experiment

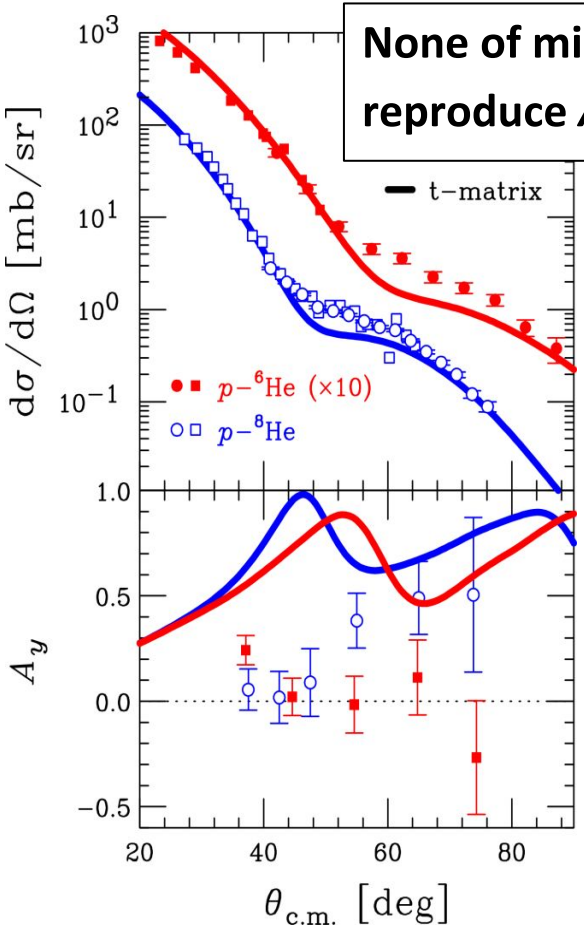



- Motivation
  - Explore change of spin-orbit coupling in p-A scattering
  - To clarify its relevance to halo structure of $^{6}$He
- Overview
  - SAMURAI, RIBF, RIKEN
  - Beam: 500 kpps $^{6}$He @ 200 A MeV
  - 5 days in June 2016
- Measurement
  - Measurement of vector analyzing power for p-6He
    - Angular region (CM): 35 - 59 deg.
    - q transfer: 2.0- 2.9 fm-1

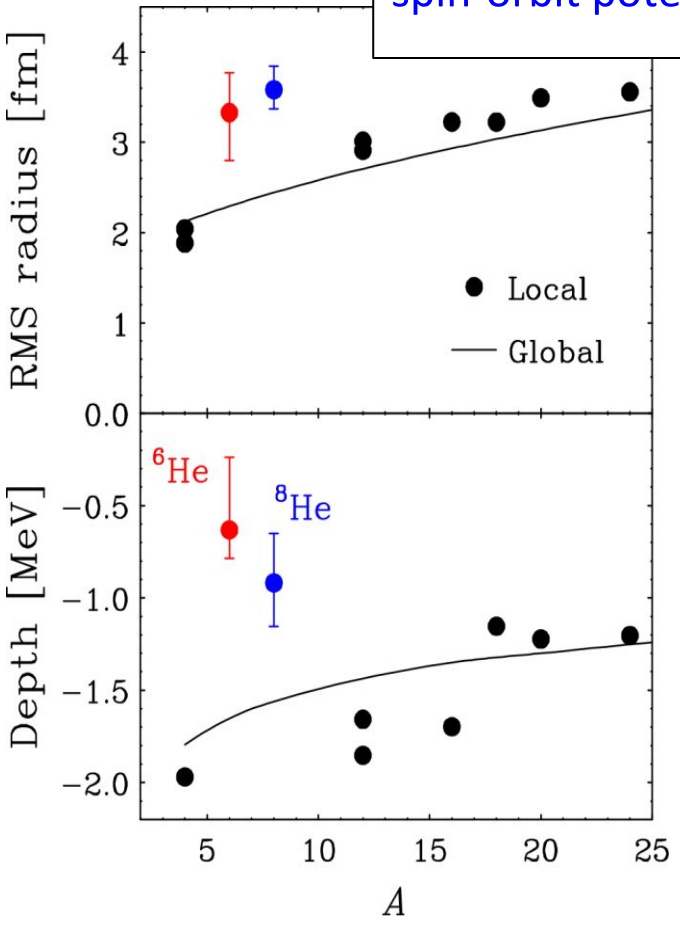


# First $A_Y$ data for p-$^{6,8}$He at 71 MeV/A

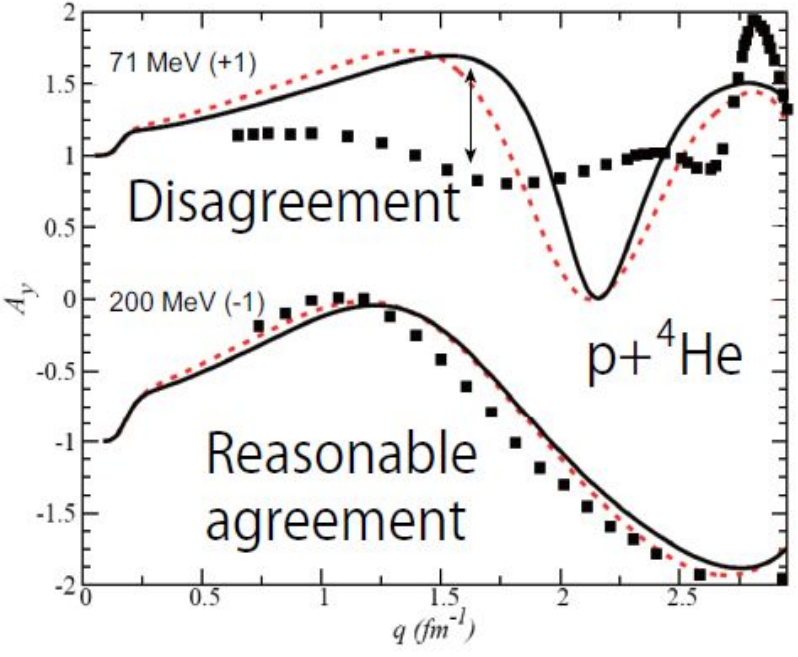
**None of microscopic models reproduce $A_y$ at 71 MeV**

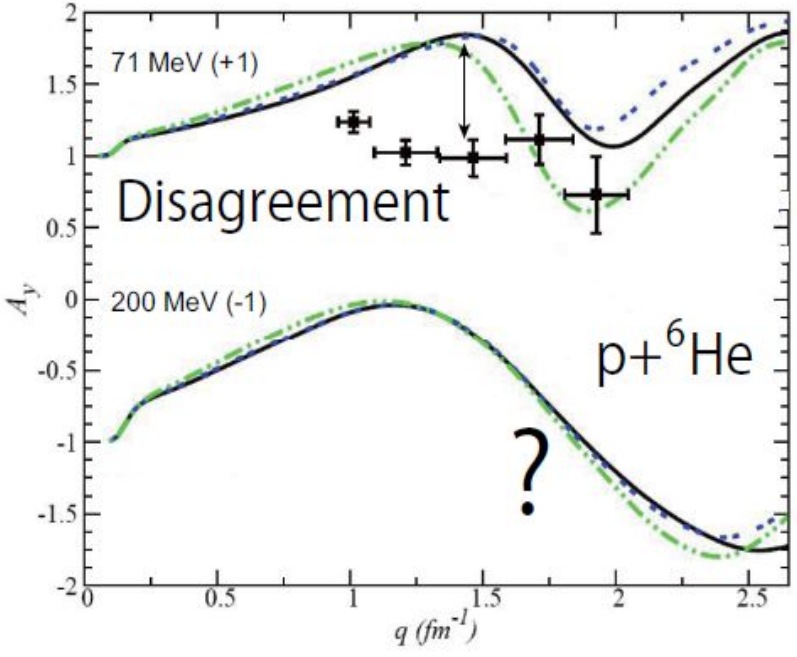



Diffuse shape of spin-orbit potential?



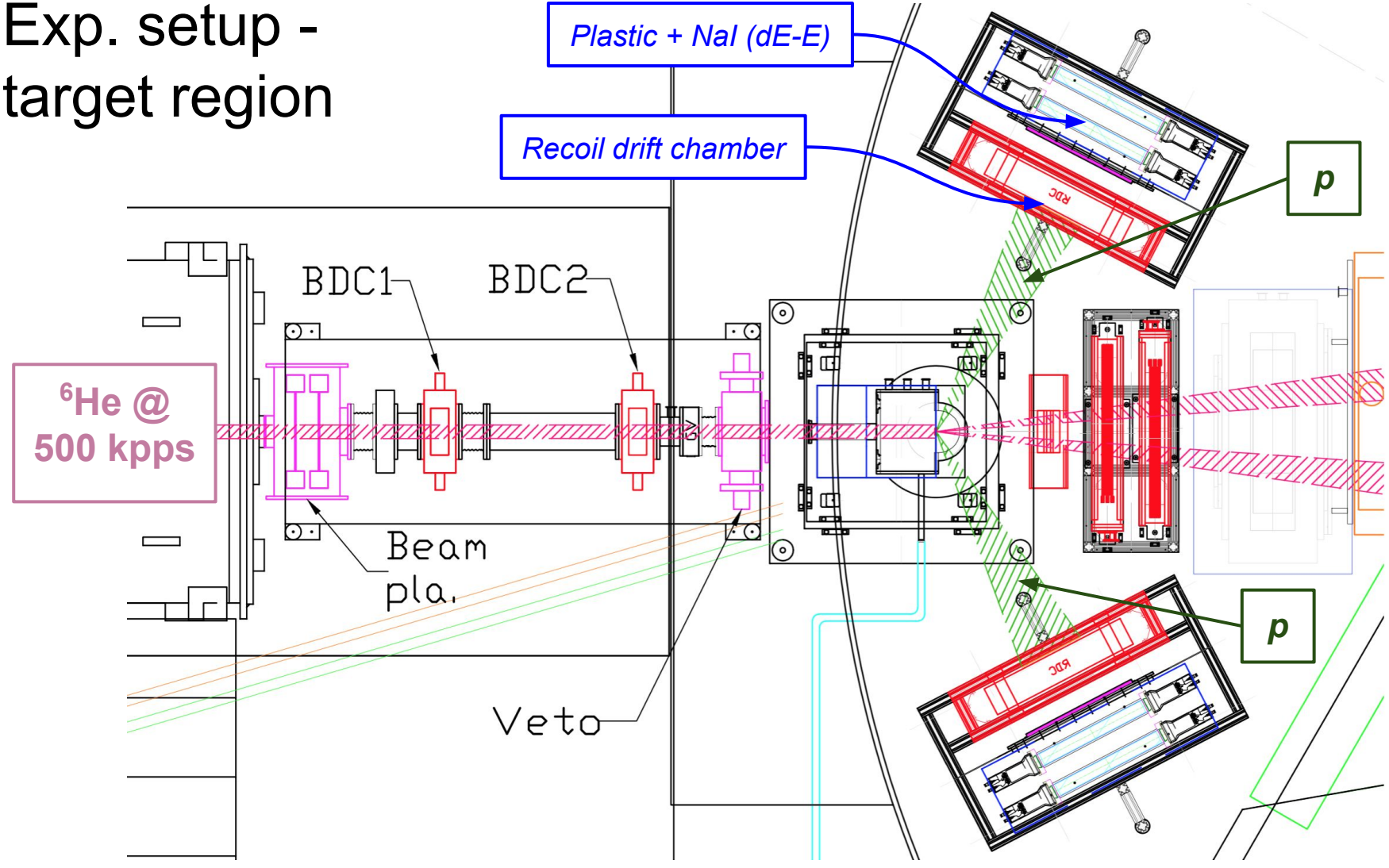
# Motivation for the new experiment at 200 MeV/A

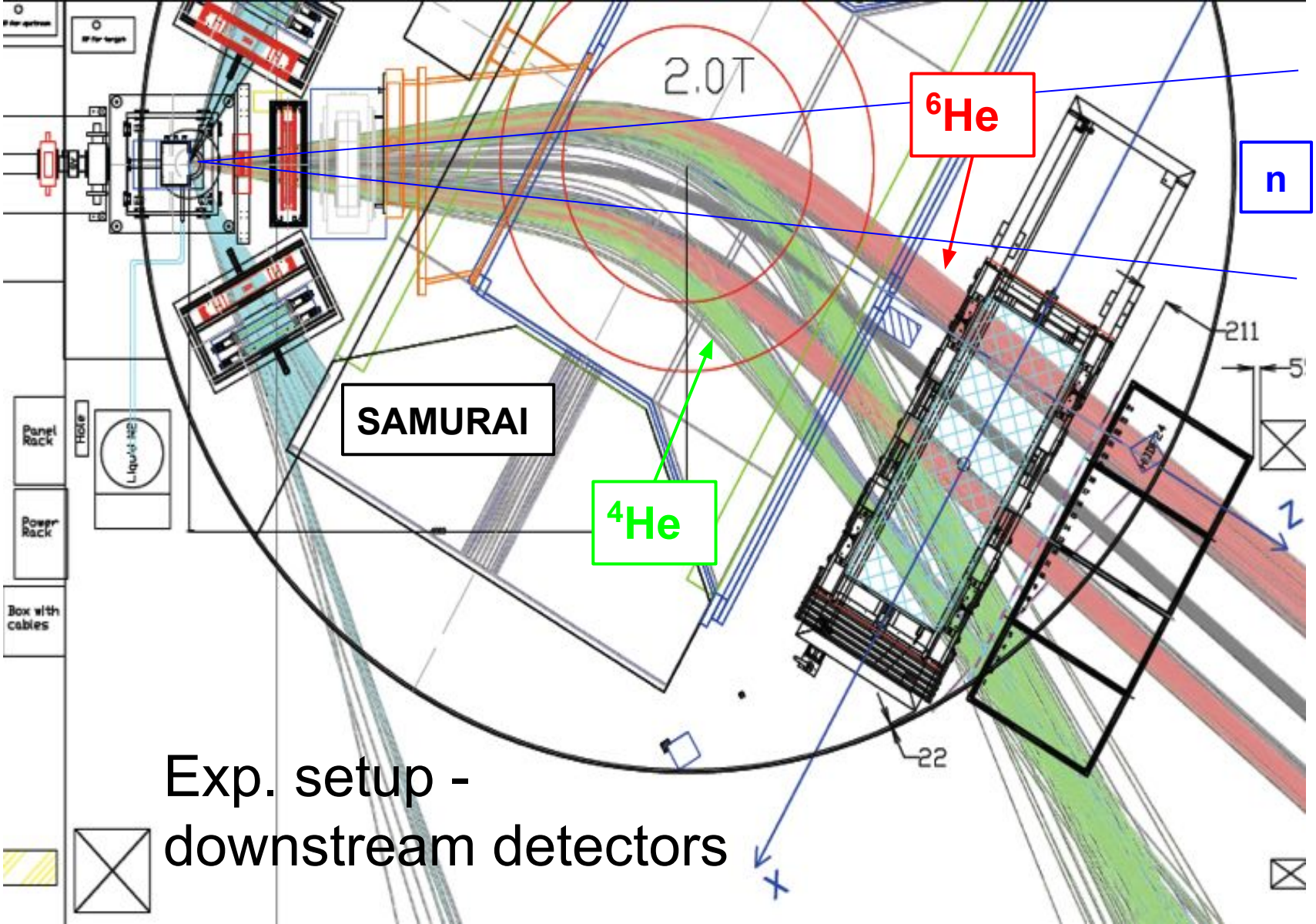



**To clarify the nature of spin-orbit coupling in *p*-$^6$He, $A_y$ data at 200 MeV would be valuable (simpler mechanism)**

# Exp. setup - target region



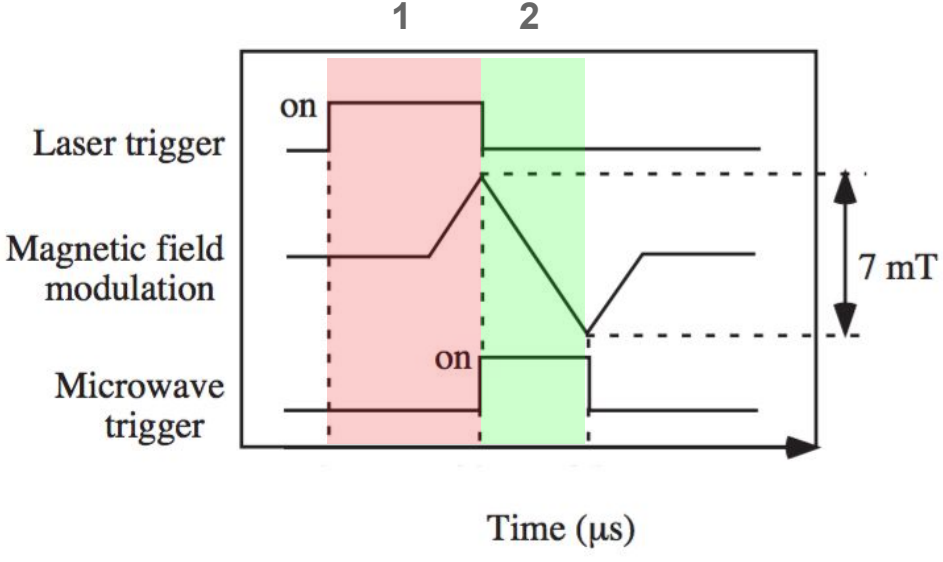



Exp. setup -
downstream detectors

# Polarized target operation

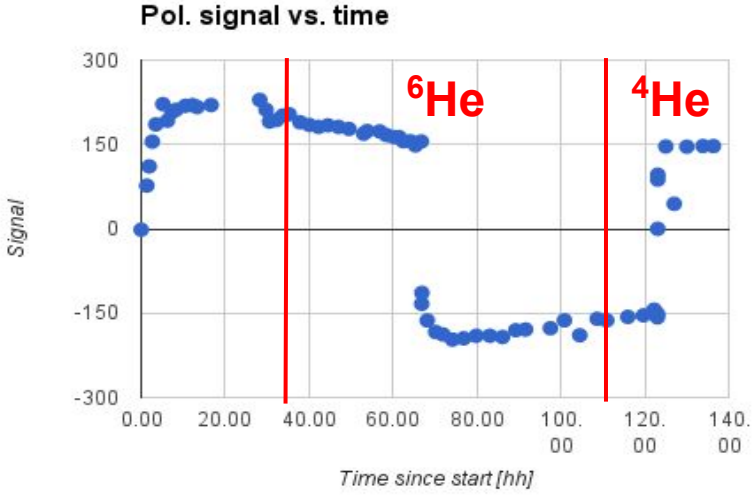
Dynamic Nuclear Polarization sequence:

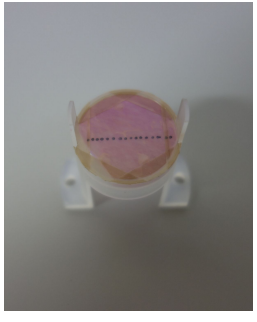
1. Laser pulse for pentacene excitation (1 us)
2. Transfer polarization from electron to proton systems (30 us)
   a. Microwave irradiation
   b. Field sweep (30 us)



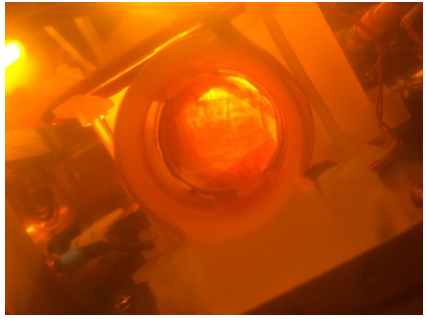
# Polarization measurement

- Polarization measurement
  - Pulse NMR method (arbitrary units)
    - Normalization with p-$^4$He $A_y$ will give absolute value
- Polarization trend
  - Polarization reversal to cancel disbalance of detection efficiency
  - Radiation damage observed

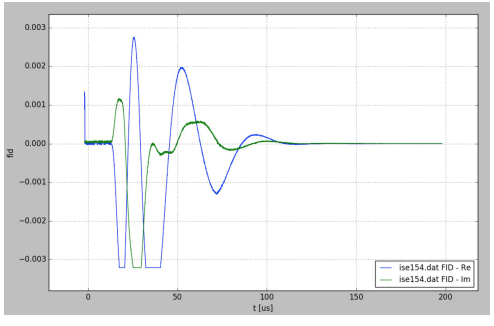


*Target crystal. ∅ 24 mm.*

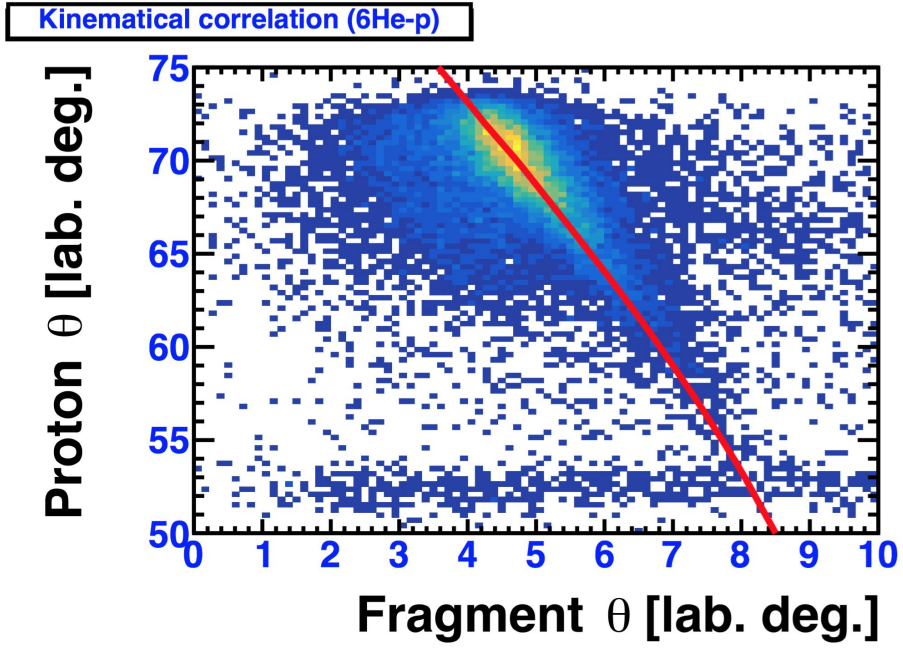


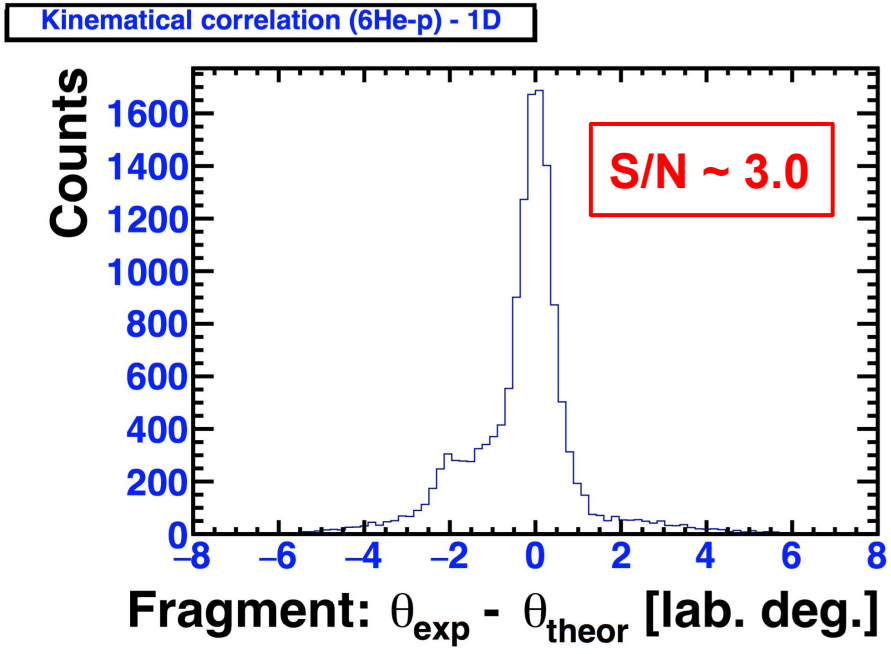
*Crystal installed in the target chamber.*



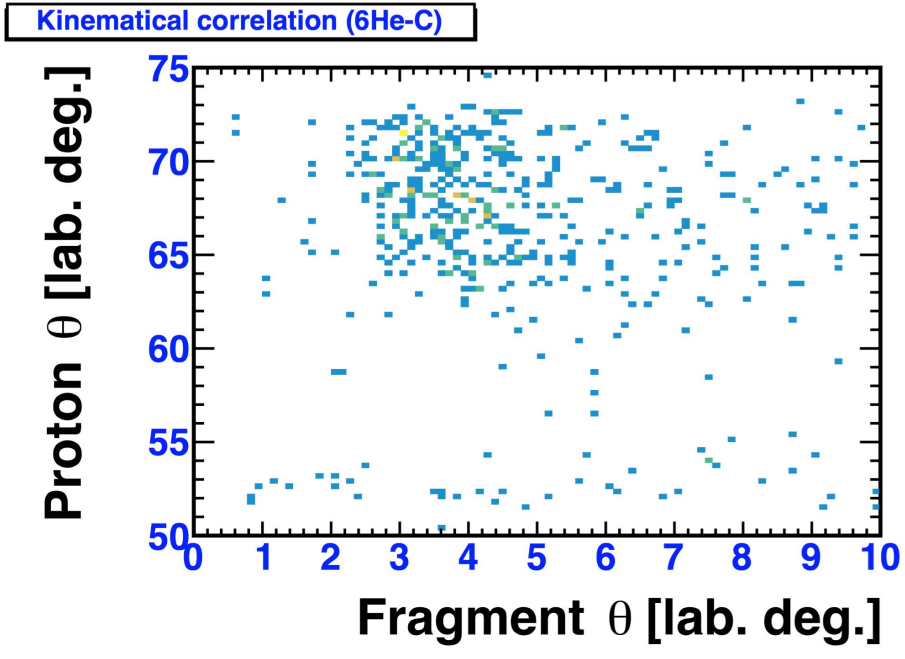

*A sample of NMR signal from polarized crystal.*

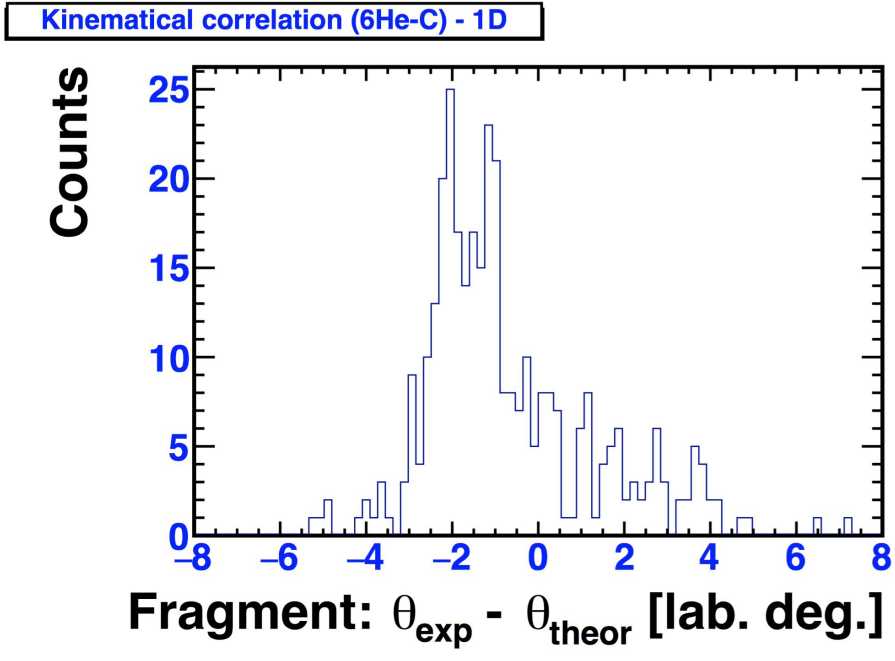
# p-$^{6}$He elastic scattering kinematical correlation



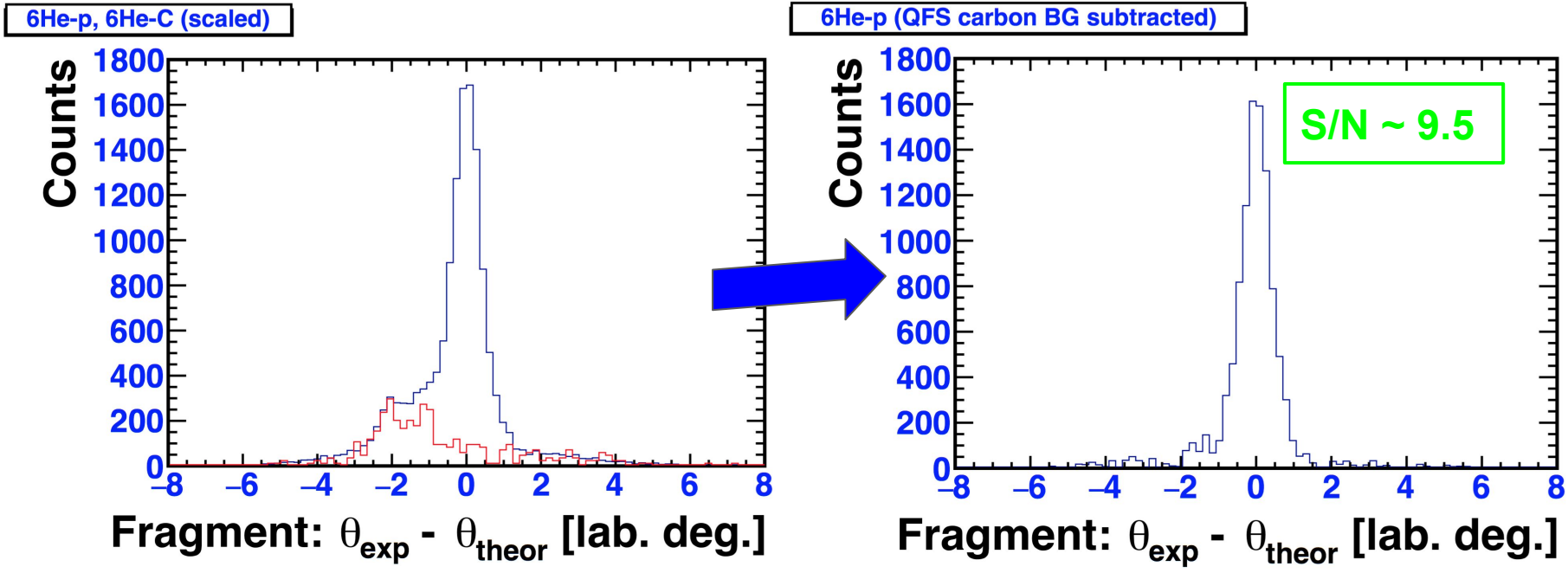



# Background from quasi-free scattering on $^{12}C$



# QFS background subtraction




**(p,$^{6}$He) elastic scattering - clear event selection**

**Data analysis is ongoing...**

# Summary

- **p-$^{6}$He elastic scattering measurement at 200 MeV/u was carried out**
  - Elastic scattering events were extracted with good S/N ratio
  - Background contribution from QFS on $^{12}$C was removed
- Next step
  - Obtain scattering asymmetry for p-$^{4}$He elastic scattering
    - Determine absolute polarization of the target
  - **Obtain $A_Y$ for p-$^{6}$He elastic scattering**
    - **Clarify relevance of the weakening of spin-orbit coupling to diffused density distribution of $^{6}$He by comparing experimental results to a microscopic model predictions**
- Polarized proton target
  - Valuable tool to explore spin-dependent interactions in experiments with RI-beams
  - Applications of polarized target to (p, 2p) reaction measurement & resonance scattering

# Collaborators list

| | |
|---|---|
| RIKEN, Nishina Center | **S. Chebotaryov**, N. Chiga, T. Isobe, Y. Kubota, E. Milman, T. Motobayashi, H. Otsu, V. Panin, H. Sakai, M. Sasano, H. Sato, Y. Shimizu, K. Tateishi, **T. Uesaka**, Z. Yang, K. Yoneda, J. Zenihiro |
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| TIT | A. Hirayama, Y. Kondo, T. Nakamura, T. Ozaki, A. Saito, Y. Togano, T. Tomai, H. Yamada, M. Yasuda |
| University of Hong Kong | S. Leblond, H. Lee, T. Lokotko |

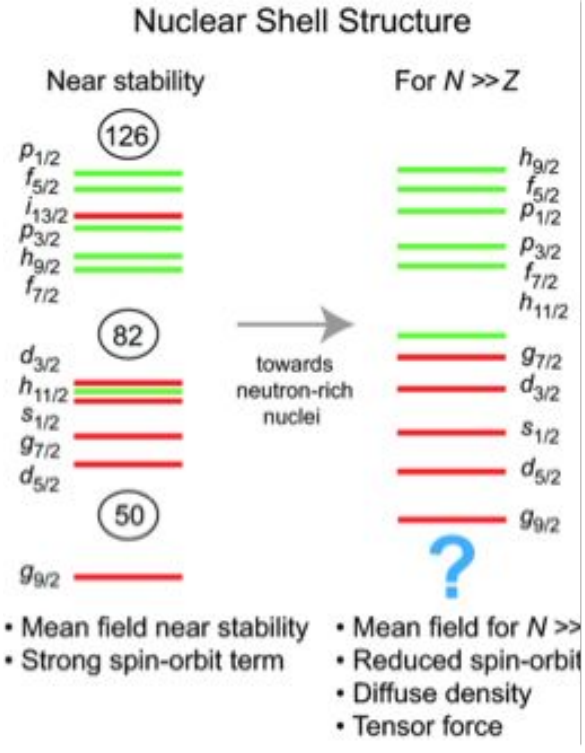
# Collaboration photo

# Backups

# Spin-dependent interactions in unstable nuclei

- Spin-dependent interaction
  - Magicity, binding energy, ...
  - Increasing interest in unstable nuclei

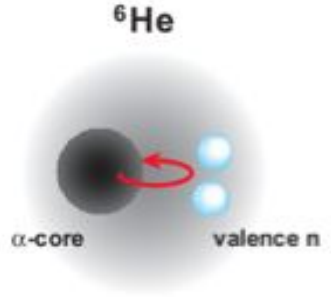
- Change of shell structure due to...
  - Tensor interaction, three nucleon force
    - T. Otsuka et al., Phys. Rev. Lett. 95 (2005) 232502.
    - T. Otsuka et al., Phys. Rev. Lett. 105 (2010) 032501.
  - Spin-orbit interaction
    - J. Dobaczewski et al., Phys. Rev. Lett. 72 (1994) 981.
    - G. A. Lalazissis et al., Phys. Lett. B 418 (1998) 7.
    - B. S. Pudliner et al., Phys. Rev. Lett. 76 (1996) 2416.




**Investigating role of spin-dependent interaction in unstable nuclei is essentially important**

# Spin-orbit coupling in proton-nucleus scattering

- Nuclei with extended neutron distribution
  - Different surfaces for protons and neutrons -> diffuse density distribution
  - Effects of the difference between proton and neutron density distributions are most prominent in nuclei with large neutron/proton ratios
  - How does extended neutron distribution affects spin-orbit coupling?



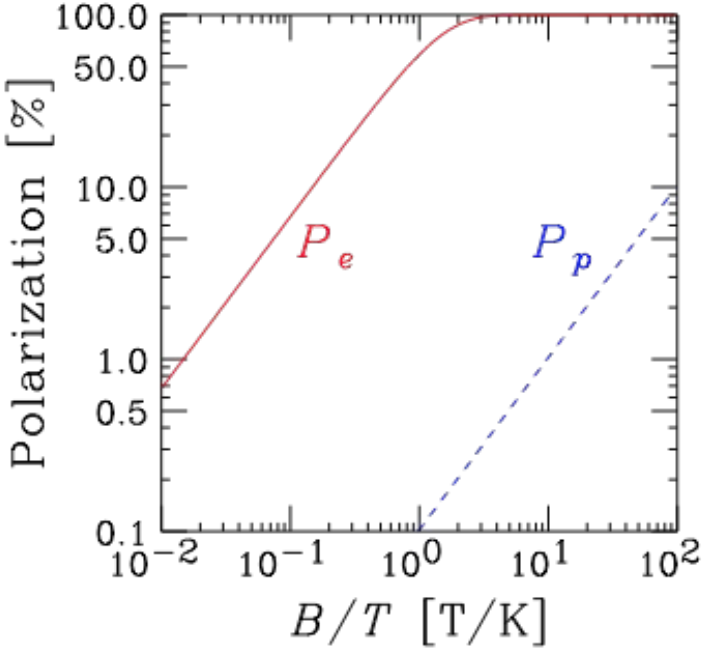

**Vector analyzing power in elastic scattering from unstable nuclei with extended neutron distribution**

# DNP to produce high proton polarization

- Use of electron polarization
  - Thermal polarization due to Boltzmann distribution
    - Electrons are more easily to polarize

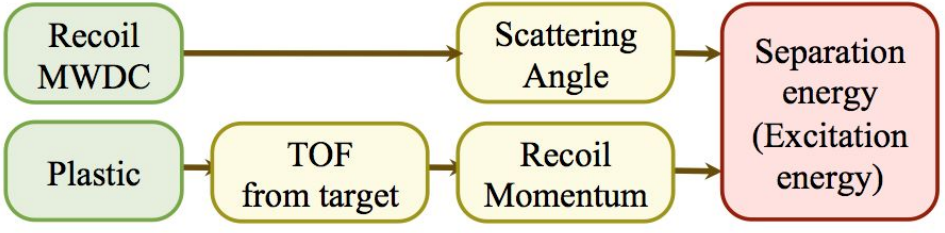
$$P = \tanh\left(\frac{\gamma \hbar B_0}{2kT}\right)$$

- Dynamic Nuclear Polarization
  - Electrons are firstly polarized
  - Electron polarization is transferred to protons system

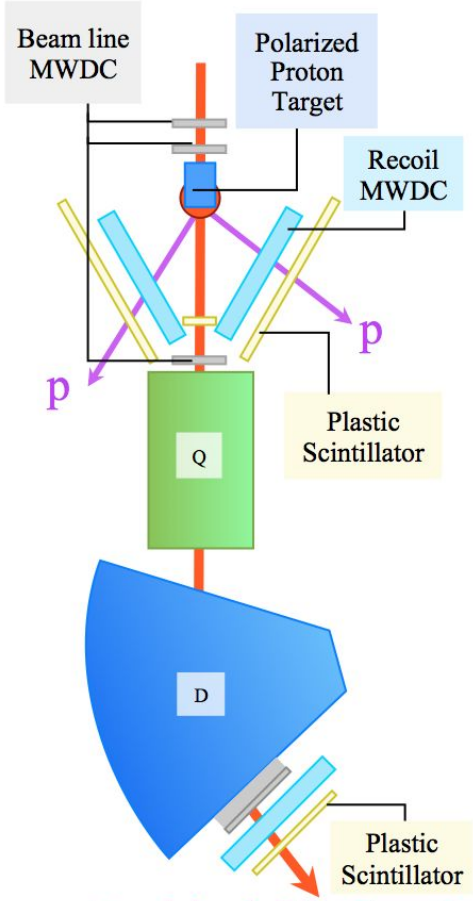


# Determination of spin-orbit splitting with (p,2p) reaction

| | |
|---|---|
| **Facility** | RIKEN RIBF SHARAQ spectrometer |
| **Reaction** | $(\vec{p},2p)$ in **inverse** kinematics |
| **Beam** | $^{14}O$, $^{22}O$, $^{24}O$ @ ~250 MeV/u |
| **Target** | **Polarized proton target** ~100 mg/cm$^2$ |

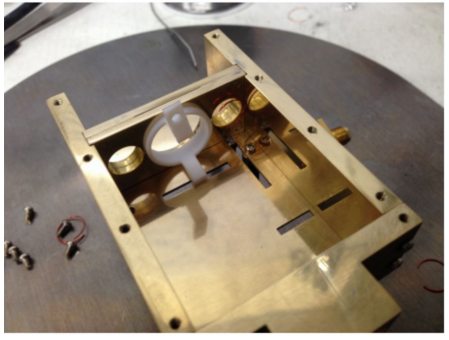


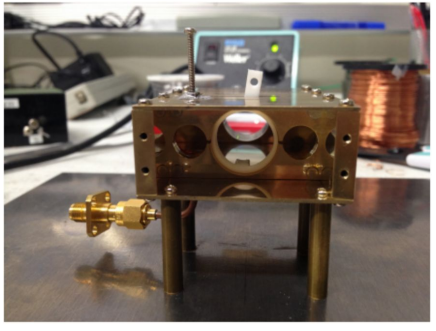

The first ($p$,2$p$) reaction measurement with polarized target!



# Target development for resonant scattering experiments

| | **High-E** | **Low-E** |
|---|---|---|
| Beam energy | > 100 MeV | ~ 5 MeV |
| Target thick. | ~ 3 mm | ~ 0.1 mm |
| Target env. | Cooling gas | Vacuum |
| Target material | Naphthalene | p-terphenyl |
| Temperature | 100 K | 300 K |





*Microwave resonator for new target system for B = 0.2 T.*

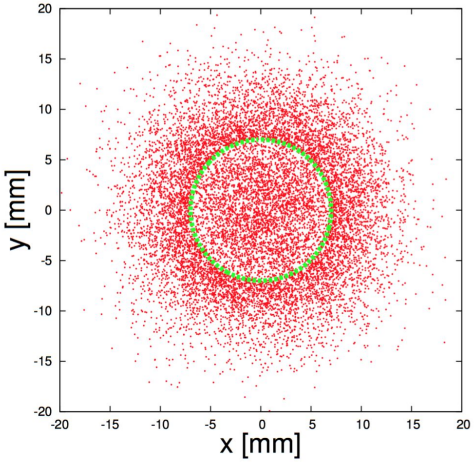
*Picture of a thin target crystal produced with sublimation method.*

# Upgrade: Target crystal enlargement

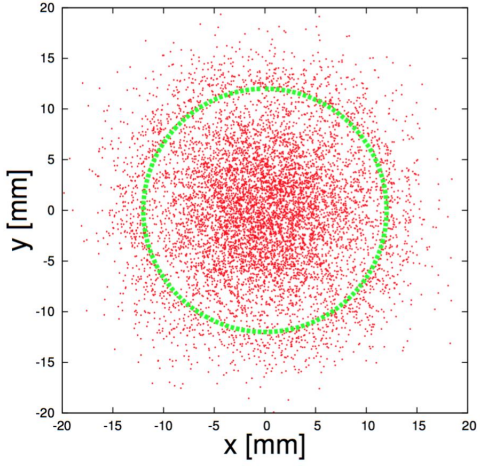
- Target size in previous experiments: 14 mm
  - High rate of noise events due to beam particles not hitting the target
  - Loss of statistics

**Target size was enlarged to 24 mm.**

**∅ 14 mm**




**∅ 24 mm**




**Enlarged target gives better S/N ratio and higher statistics**

# Upgrade: New laser

- Larger target size -> larger area
  - Shortage of laser power / volume
  - New target volume ~10 times larger

| | Old | New |
|---|---|---|
| Wavelength | 514 nm | **556 nm** |
| Power (pulsed mode) | ~1 W | **5 W** |

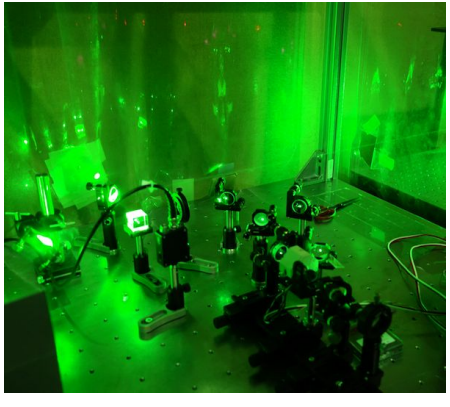
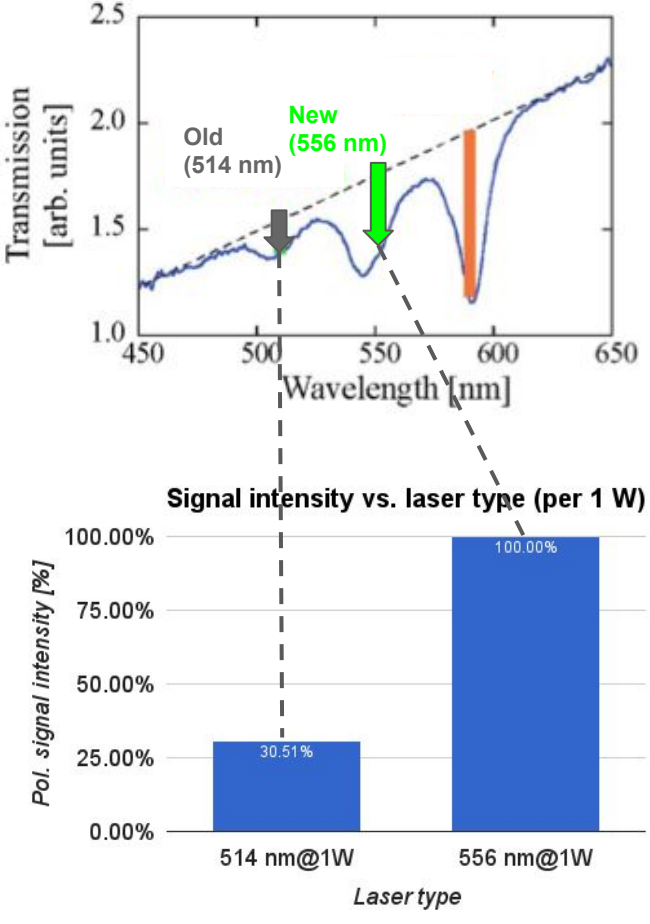
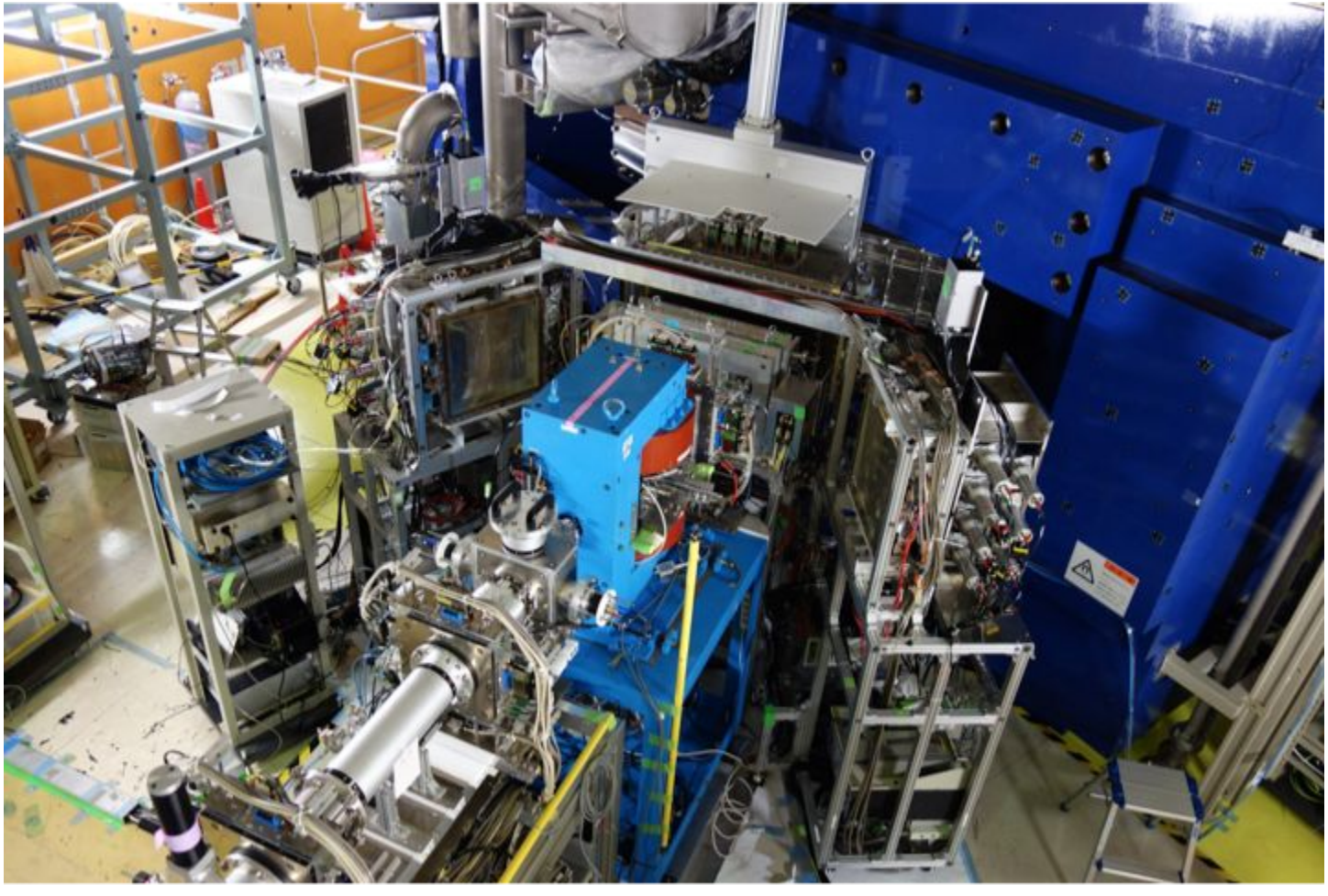


*Photo of optical system of the new laser*




**Higher intensity laser beam ⇒ higher polarization**

# Picture of experimental site

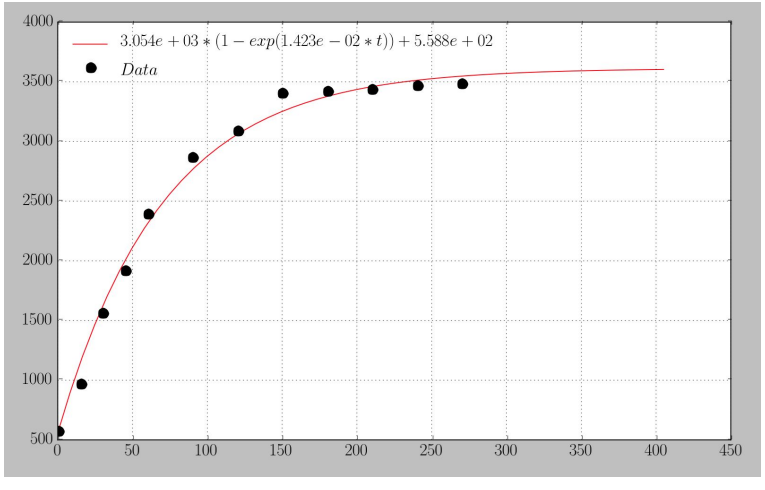


# Estimation of target absolute polarization

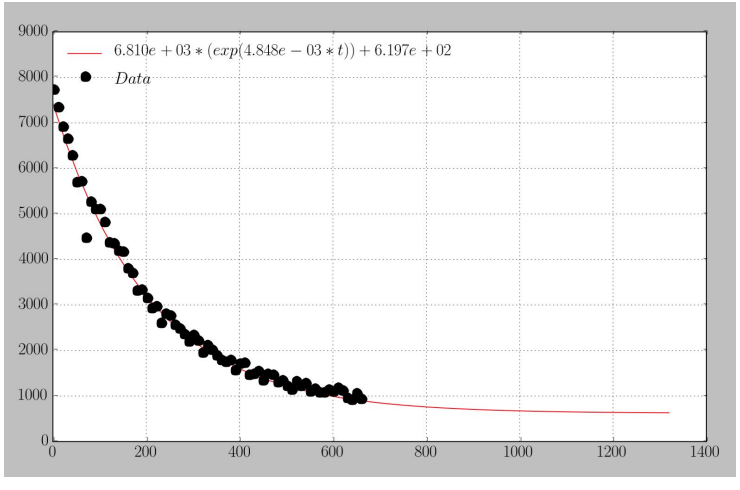
$$P_{proton} = P_{electron} \frac{A}{A + \Gamma} \cdot = 25 \pm 2\%$$

- *Average polarization*: 20% +/- 6%

Buildup time constant (**A**): 70.27 min




Relaxation time constant (**Γ**): 206.27 min



# Beam particles and scattered fragments tracking