Studies of unstable nuclei with spin-polarized proton target

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CNS

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CYRIC
TOHOKU UNIVERSITY

Outline

- Direct reaction of spin-polarized light ions
- Solid polarized proton target for RI-beam
- Experimental programs undergoing
  - Proton elastic scattering from ^{6,8}He
  - (p,2p) knock-out reaction on oxygen isotopes
- Future applications
  - Proton resonant scattering
  - Polarizing neutrons and RIs

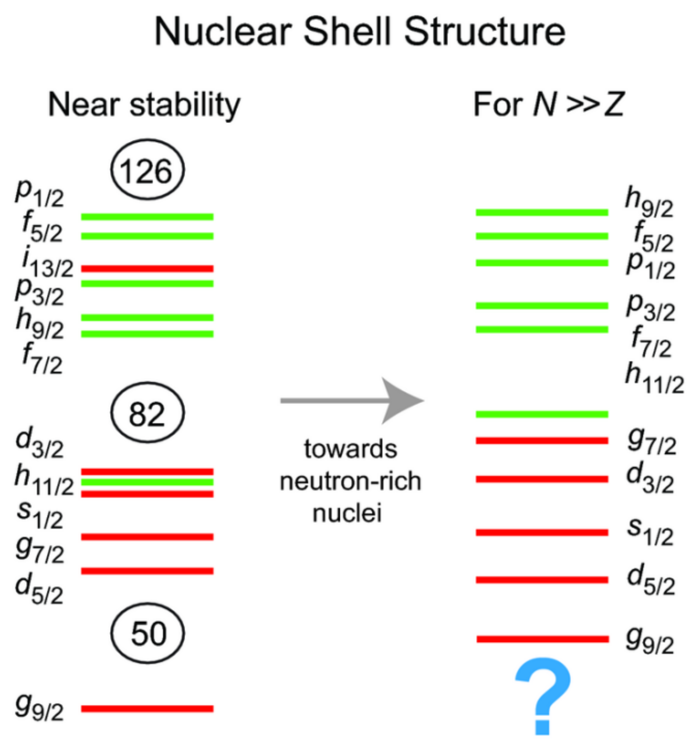
Spin-dependent interaction in unstable nuclei

- Spin-dependent interaction
  - Spin-orbit int., tensor int., 3NF
    ⇔ Magicity, binding energy, …

Spin-dependent int. in unstable nuclei attract increasing interest.

ex.) Change of shell structure

- Tensor interaction, 3NF
  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.



- Mean field near stability
- Strong spin-orbit term

- Mean field for N>>Z
- Reduced spin-orbit
- Diffuse density
- Tensor force

Polarization study of unstable nuclei

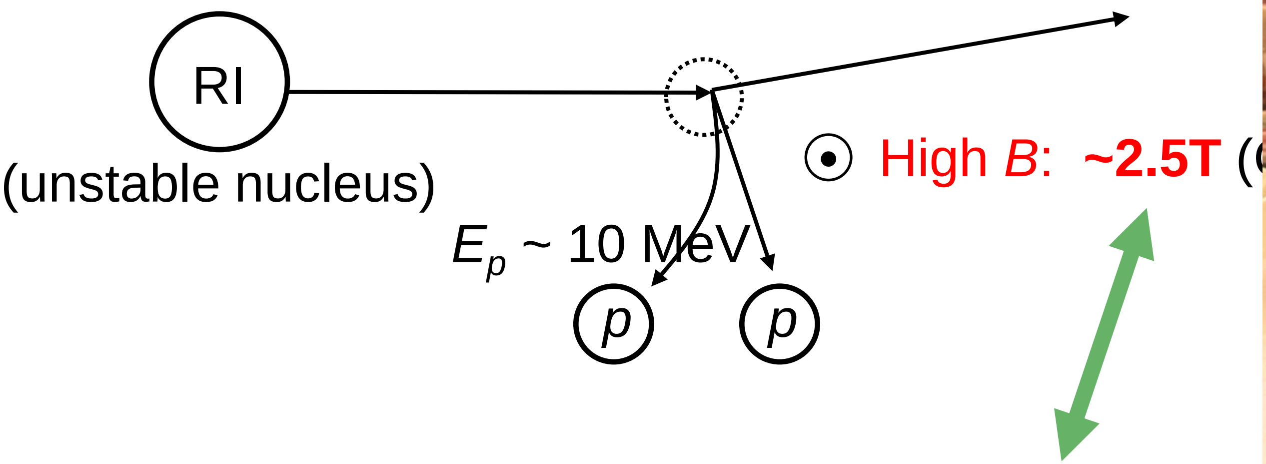
- **Direct reactions** induced by **polarized light ions**
  - Powerful probe for studying manifestation of spin-dependent interactions in nuclei
  - Reactions
    - $(\vec{p},p')$, $(\vec{p},n)$ — spin-isospin response
    - $(\vec{p},d)$, $(\vec{d},p)$, $(\vec{p},p\mathrm{N})$ — spin-parity of single particle/hole states
    - $(\vec{p},p)$, $(\vec{d},d)$ — 3-body force, spin-orbit interaction
  - Method

    Radioactive ion beam + polarized target ***(key element)***

Reaction of polarized light ion × Physics of unstable nuclei

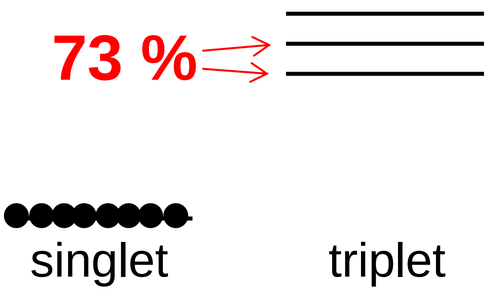
Polarized target for inverse kinematics

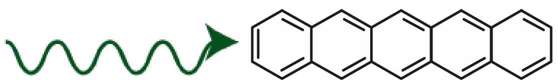
- Inverse kinematics



- **Solid pol. proton target at 0.1 T**
  - High electron polarization in photo-excited aromatic molecule

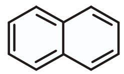
    A. Henstra et al. Phys. Lett. A 134 (1988) 134.
  - **Independent** of mag. field strength

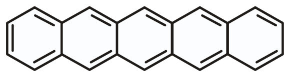


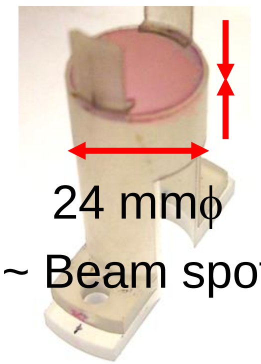


Solid polarized proton target @RIKEN

Target material:

Naphthalene 

+ pentacene 

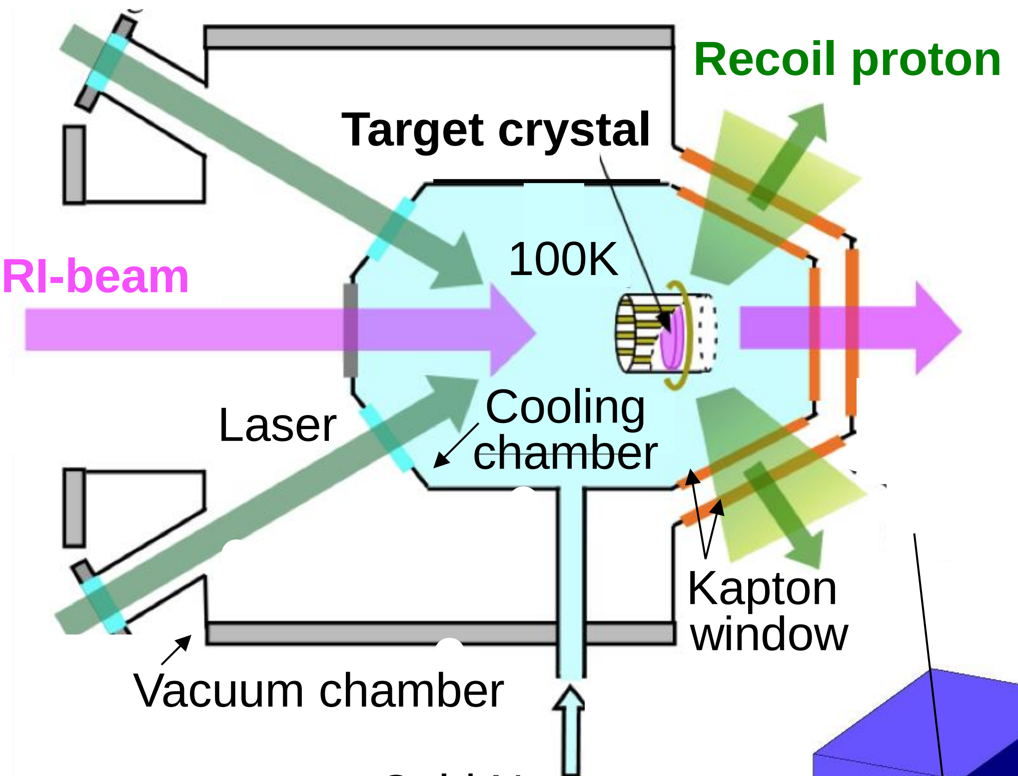


1 mm^t : 4 × 10^{21} protons/cm^2

24 mmϕ

~ Beam spot

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



Summary of target

Material: $C_{10}H_8$ **(solid)**

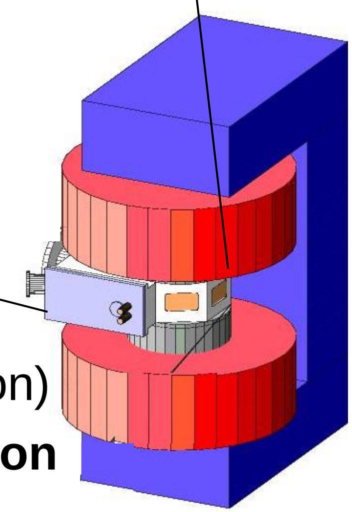
Size: **24 mmϕ, 1-3 mm^t**

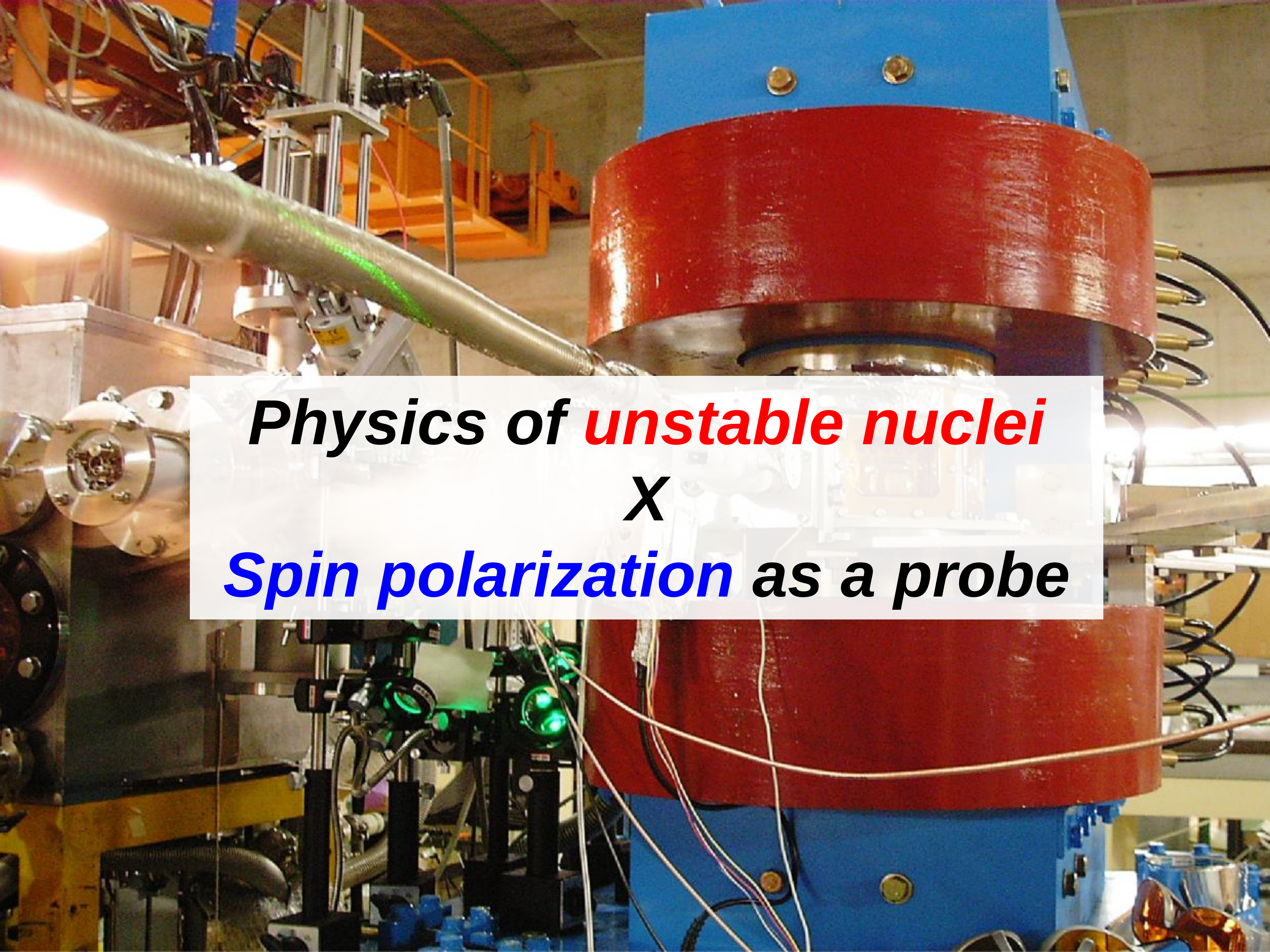
Proton polarization: ~ 20%

Mag. field of **0.1 T**

→ ρ ~ 10 m (20 MeV proton)

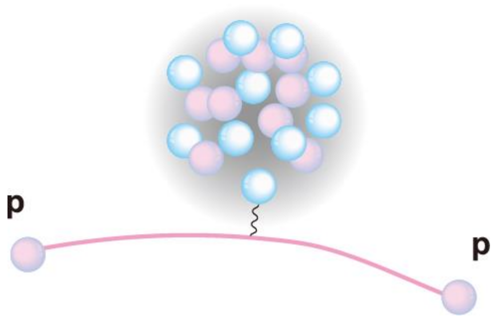
→ **Recoil particle detection**





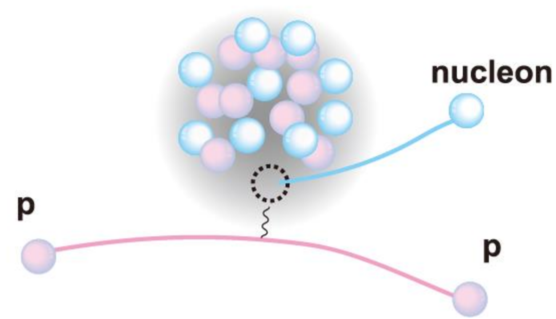
Physics of unstable nuclei
X
Spin polarization as a probe

(p,p) elastic



Spin-orbit part of optical potential

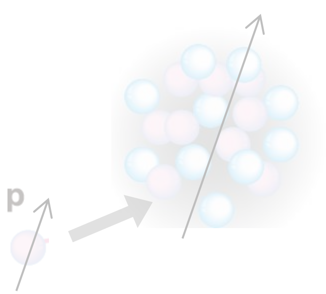
(p,pN) quasi-elastic



Spin-orbit splitting

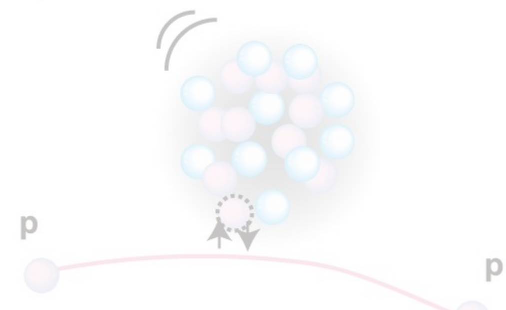
Plenty of physics opportunities!

Polarization transfer to RI



β-NMR, **Magnetic moment**

(p,p) resonance elastic



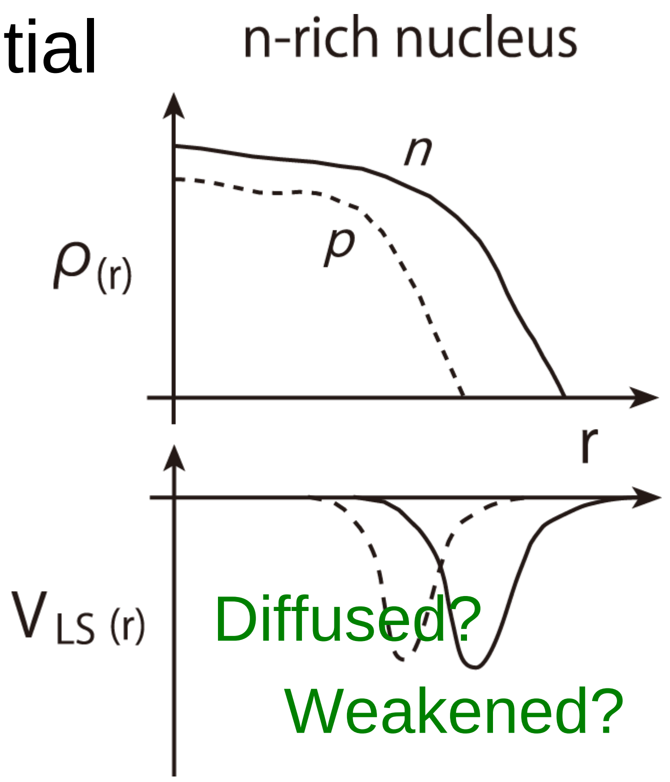
Nuclear **spectroscopy**

Spin-orbit coupling in *pA* scattering

- Spin-orbit term of optical potential
  - Proton feels spin-orbit force at nuclear surface

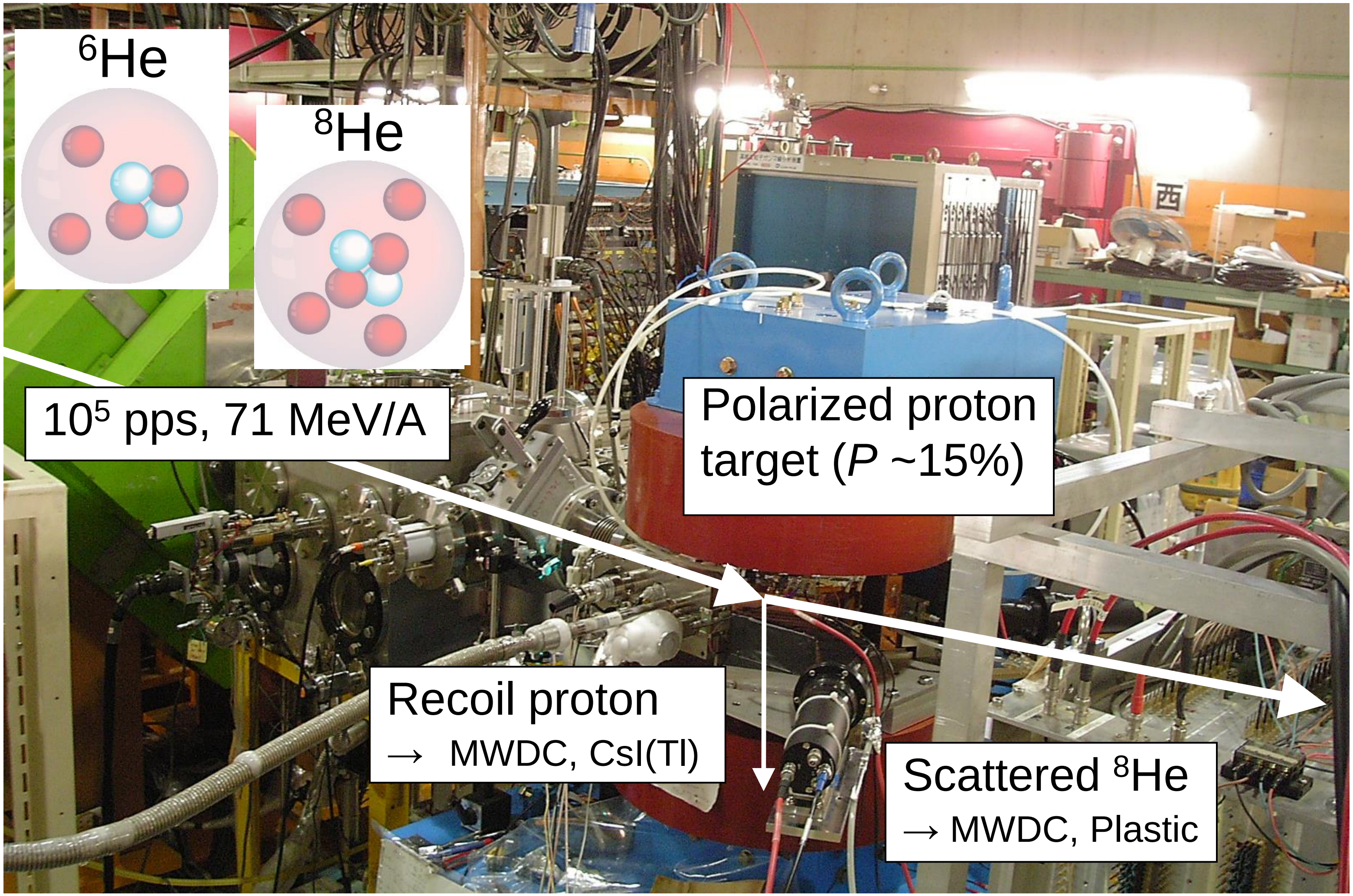
$$U_{so} = [1 + \alpha\rho(r)]^{-1} \frac{1}{r} \frac{d\rho}{dr}$$

  - Neutron-rich nuclei: extended neutron distribution (neutron halo/skin structure)



How does **extended neutron distribution** affect the **spin-orbit part of optical potential**?

p-^{6,8}He elastic scattering at 71MeV/A



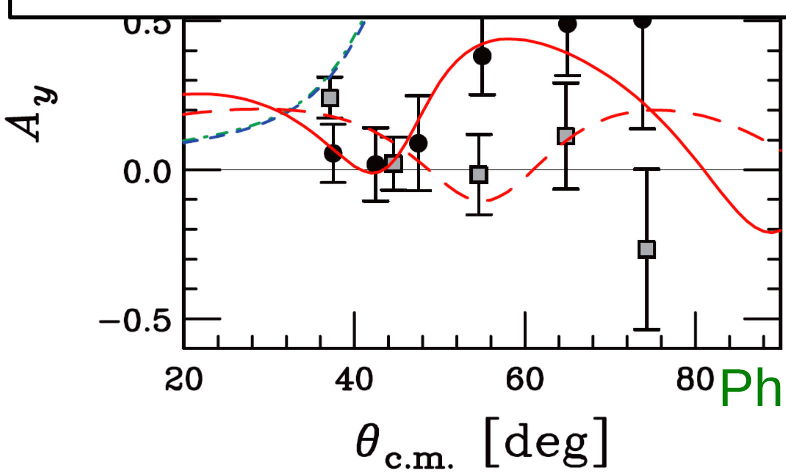
RIPS facility @RIKEN

Spin asymmetry for $\vec{p}$-^{6,8}He scattering

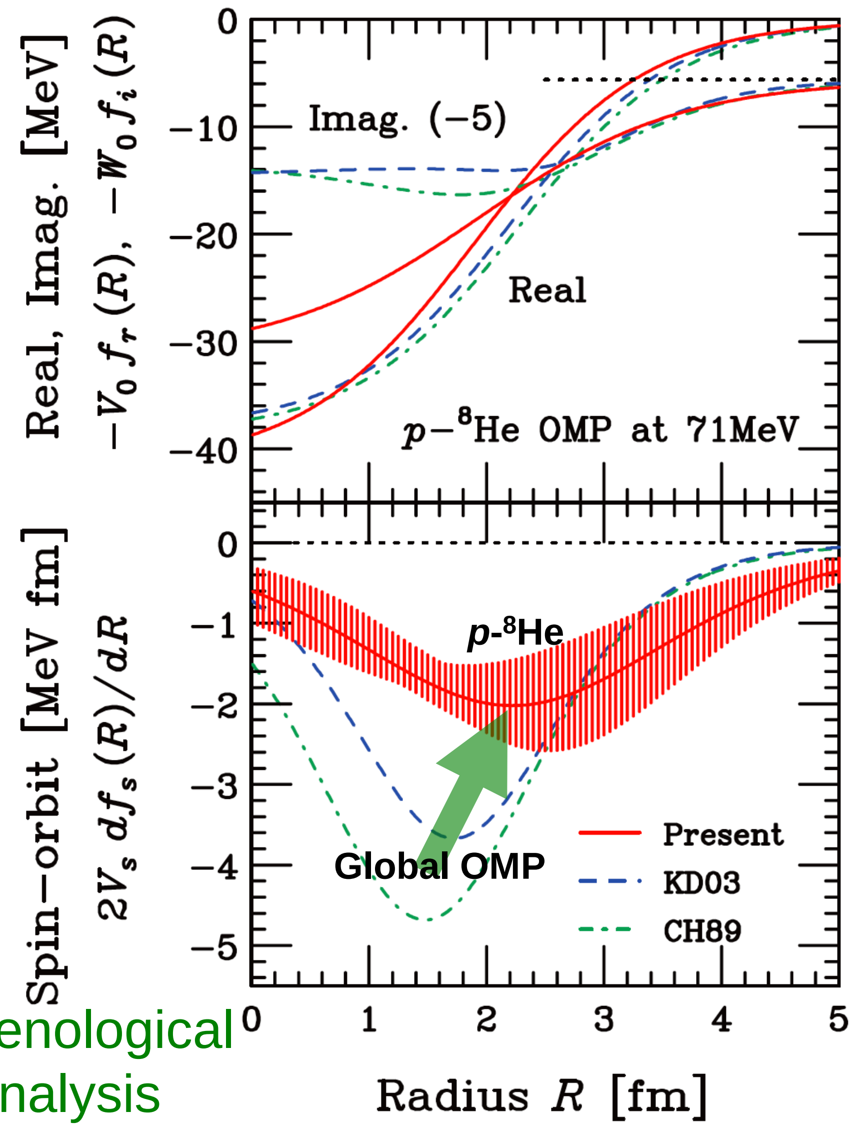
S.S. et al., Phys Rev C 84, 024604 (2011)
S.S. et al., Phys Rev C 87, 021601(R) (2013)

Spin-orbit potential in n-rich helium isotopes:
shallow and extended
⇔
Less steep and extended density distribution?

→ Measurement @200MeV

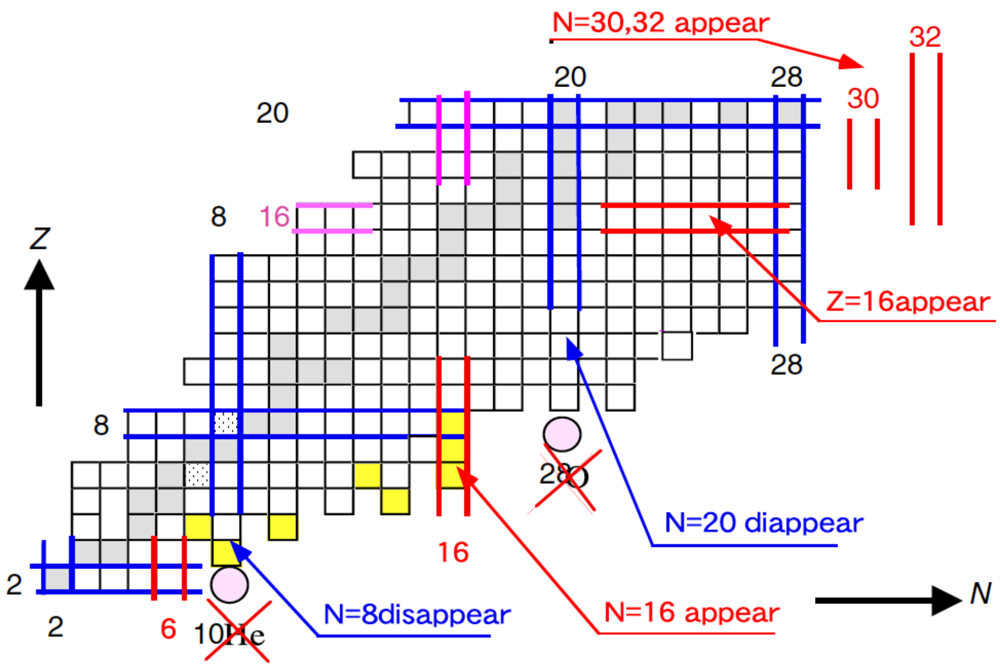


→ Phenomenological OM analysis

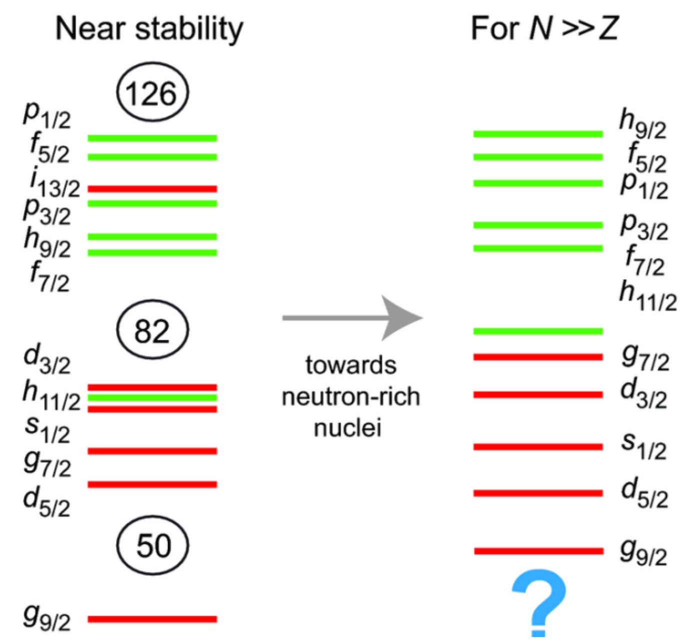


Change of shell structure in *n*-rich nuclei

I. Tanihata et al. / Progress in Particle and Nuclear Physics 68 (2013) 215–313



Nuclear Shell Structure



- Mean field near stability
- Strong spin-orbit term

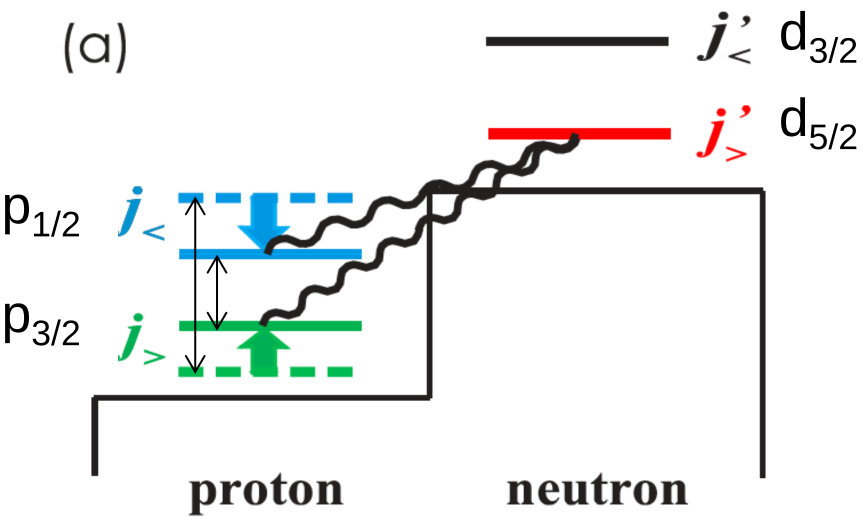
- Mean field for N>>Z
- Reduced spin-orbit
- Diffuse density
- Tensor force

Magic numbers newly appear or disappear (change of shell structure)

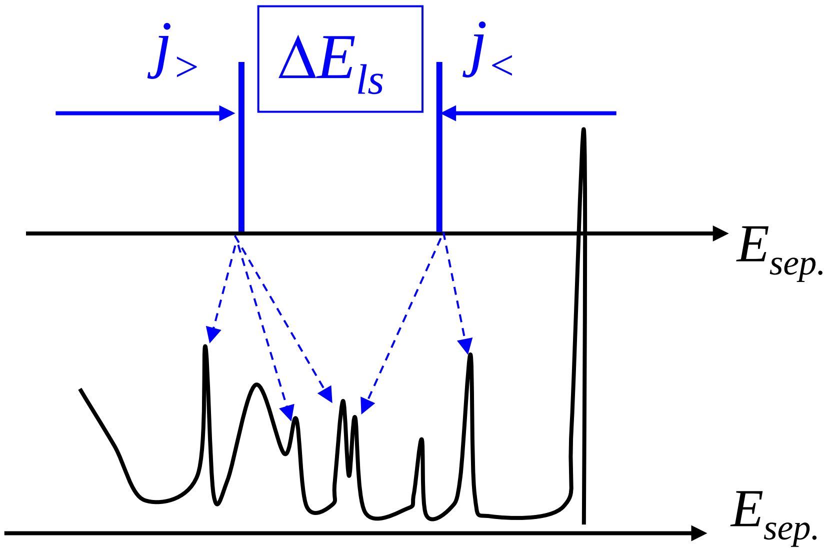
Reduction of spin-orbit splitting ($E_{j=l-1/2} - E_{j=l+1/2}$)

($\vec{p}$,2p) reaction as spectroscopic tool

- Determination of spin-orbit splitting
  - Single-particle states are fragmented
  - ($\vec{p}$,2p) reaction → distribution of $j_>$ and $j_<$ strengths



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

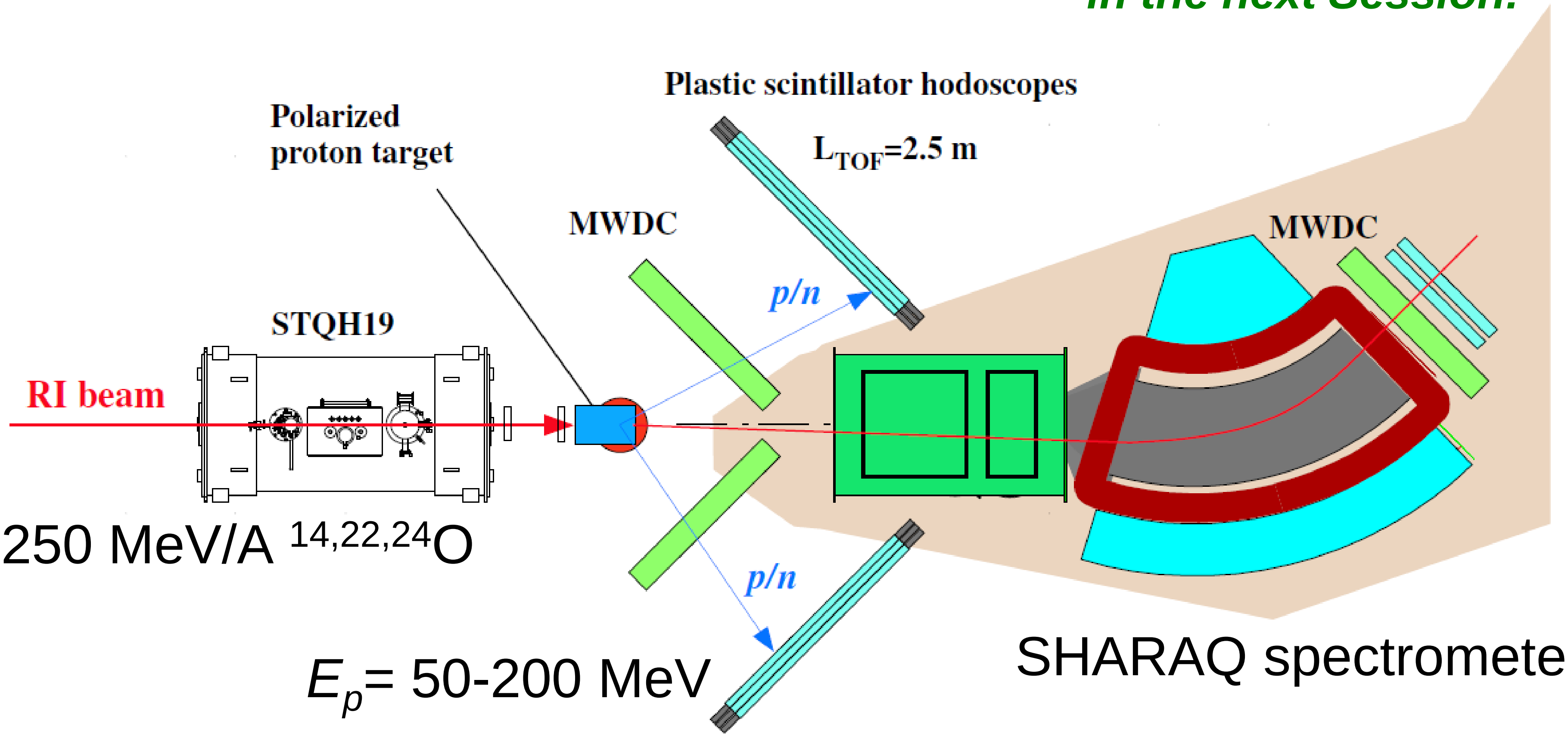


Change of spin-orbit splitting explored with ($\vec{p}$,2p)

($\vec{p}$,2p) knock-out reaction on $^{14,\ 22,\ 24}$O

- Experiment @SHARAQ, RIBF

Talk by S. Kawase in the next Session!



~250 MeV/A ^{14,22,24}O

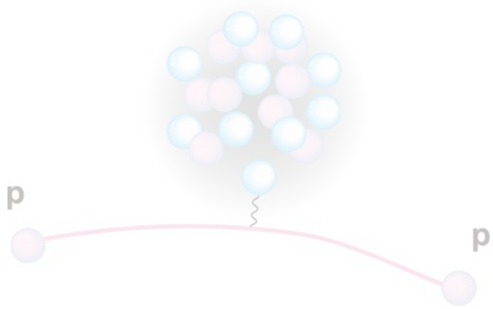
E_p= 50-200 MeV

SHARAQ spectrometer

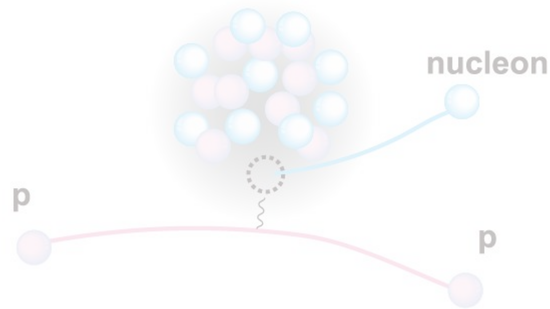
Data analysis now going on

T. Uesaka, S. Kawase, L. Tang et al., Experiment carried out in 2012

(p,p) elastic



(p,pN) quasi-elastic

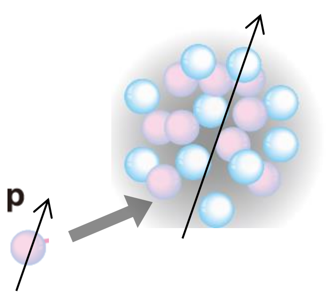


Spin-orbit part of optical potential

Spin-orbit splitting

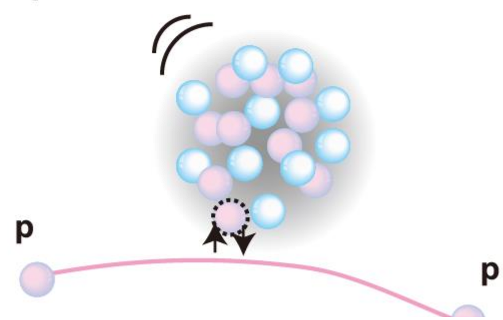
Plenty of physics opportunities!

Polarization transfer to RI



β-NMR, **Magnetic moment**

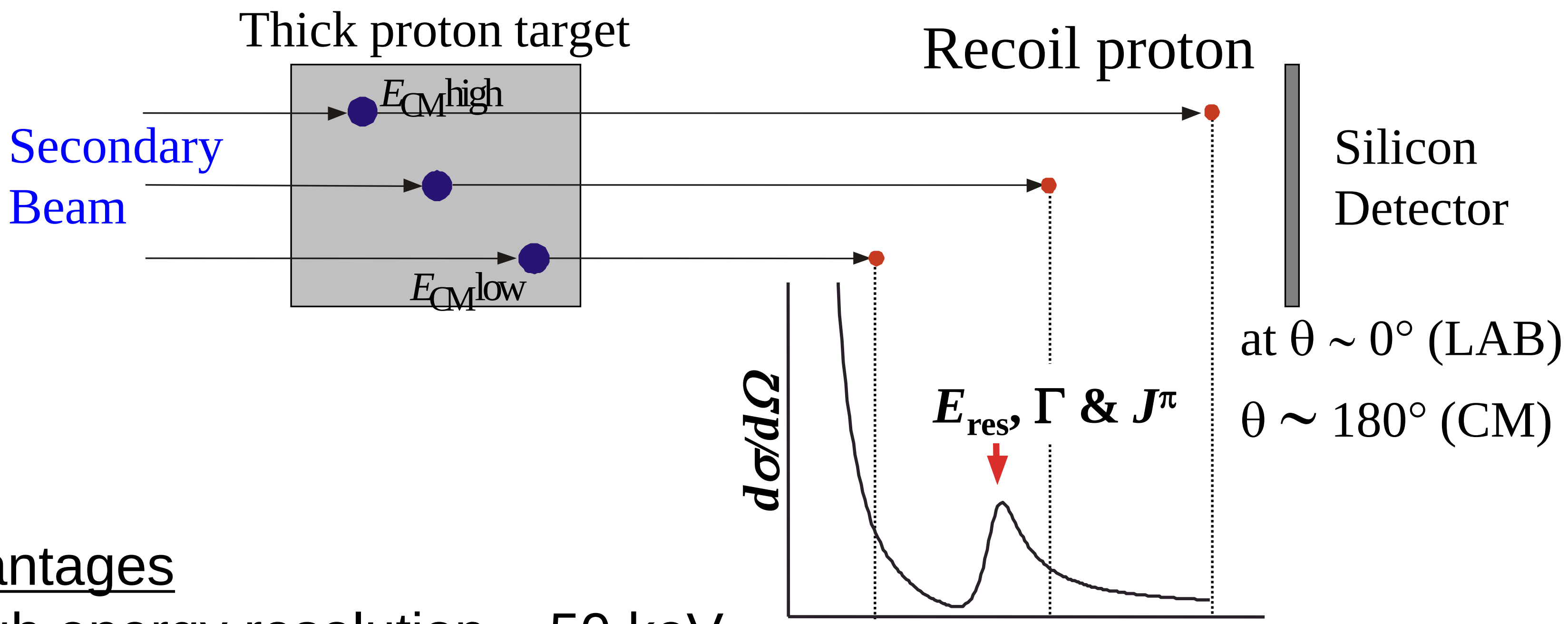
(p,p) resonance elastic



Nuclear **spectroscopy**

Proton resonant scattering on RI

- Thick-target method in inverse kinematics
  - Excitation function scanned with single incident energy



Advantages

High energy resolution ~ 50 keV
Large cross section ~ 500 mb/sr
Relatively thicker target

$$E_{CM} = \frac{1}{4\cos^2\theta_p}\frac{A+1}{A}E_p$$

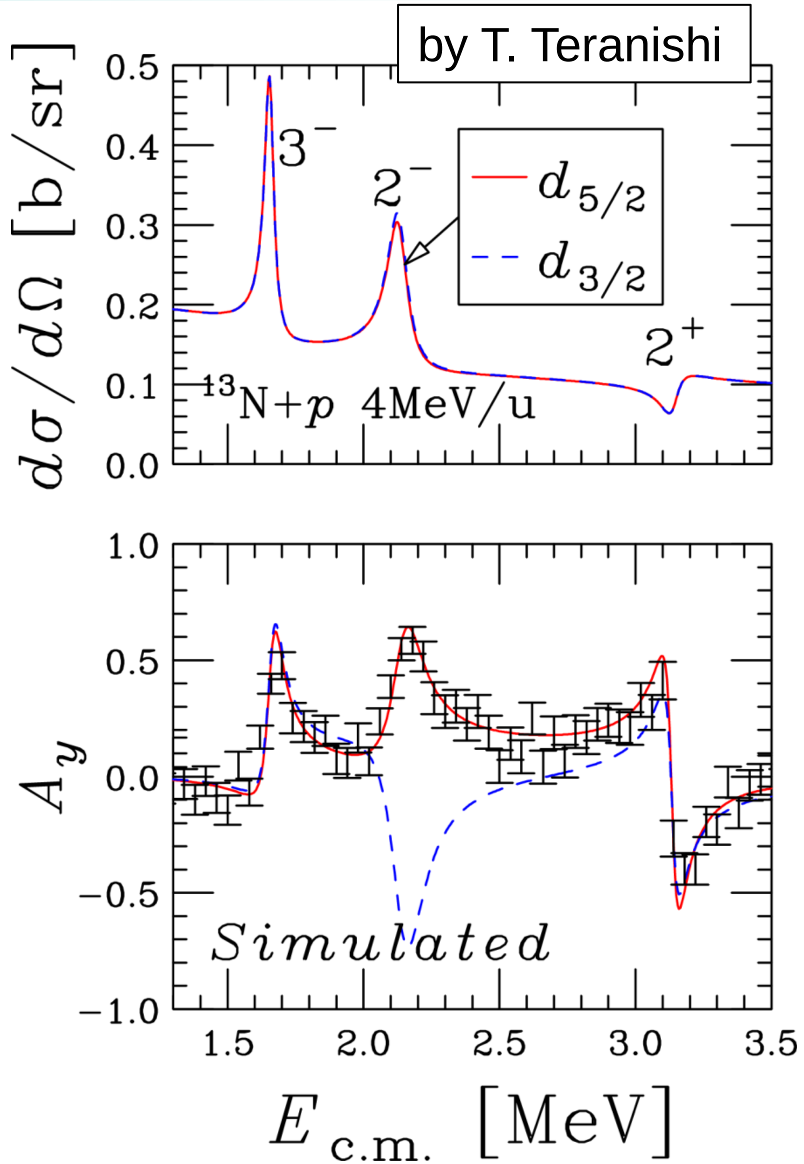
↑ 0.25~0.3

Powerful tool for particle unbound states

Role of spin polarization

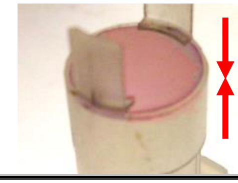
- Spin asymmetry
  - Determination of *j*
    - Projectile w/ non-zero spin
    - Sensitive to configuration mixing
  - Information for extremely wide resonances
- Feasibility demonstration
  - $^{13}N+\vec{p}$ scattering
  - Monte-Carlo simulation

    P_p = 20%, 10 mg/cm^2, 10^5 pps, 3 days, pure $d_{5/2}$

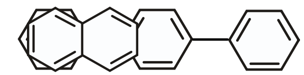


Toward low-*E* exp. with polarized protons

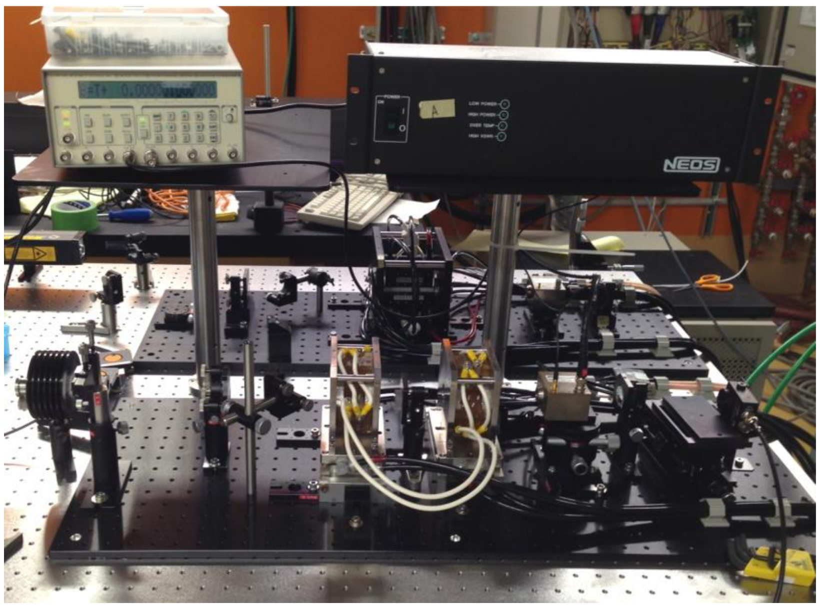
- New requirements for target



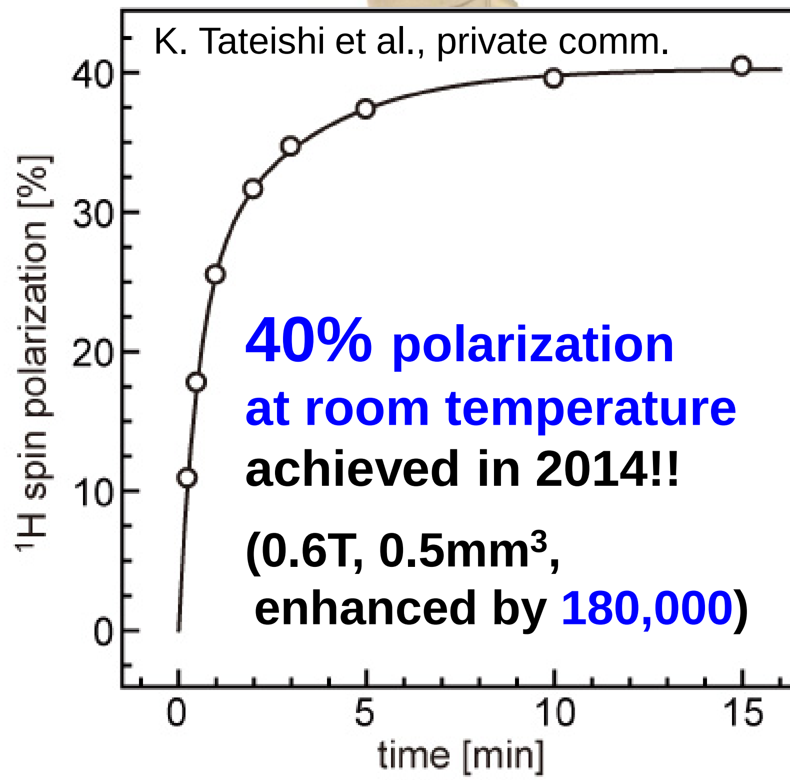
0.1mm^t (10 mg/cm^2) 1mm^t (1 mg/cm^2)

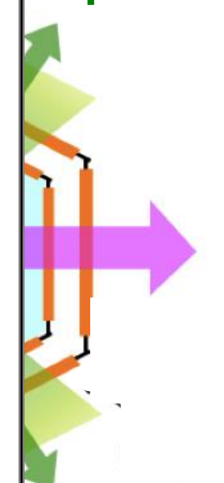


New laser w/ optimum λ (590nm)



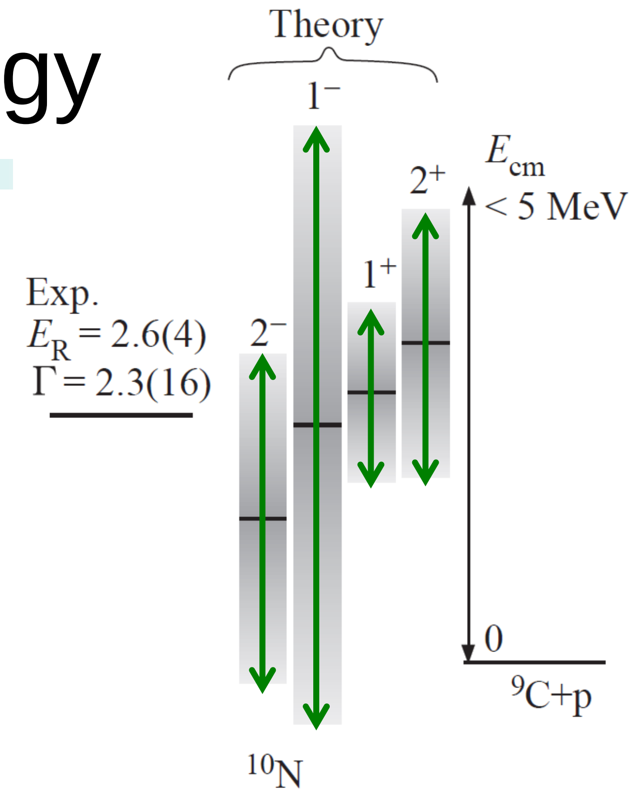
K. Tateishi et al., to be submitted to JMR.





Challenge: High proton polarization at room temperature

First experiment at low energy



Resonant elastic scattering

$$^{9}\mathrm{C} + \vec{p} \rightarrow {}^{10}\mathrm{N} \rightarrow {}^{9}\mathrm{C} + p$$

with a low-energy ^{9}C beam at 5.6 MeV/u

and a spin-polarized proton target.

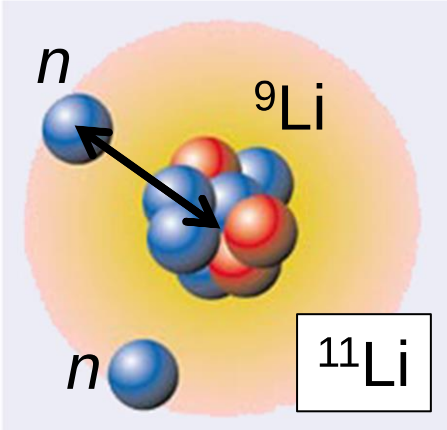
$d\sigma/d\Omega$ and analyzing power

→ **Search for extremely broad ^{10}N resonances**

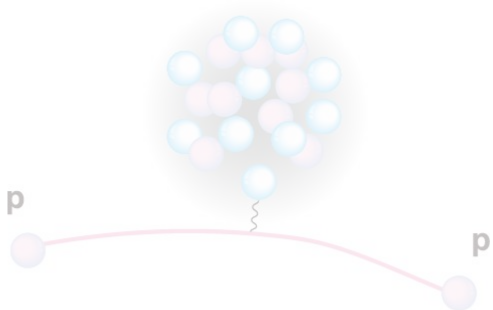
^{10}N (=^{9}C+p) ← mirror → ^{10}Li (=^{9}Li+n)

^{10}Li: subsystem of **borromean nucleus** ^{11}Li

→ **Understanding of ^{9}Li+n potential**

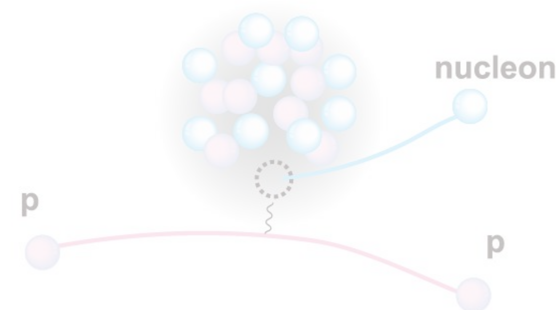


(p,p) elastic



Spin-orbit part of optical potential

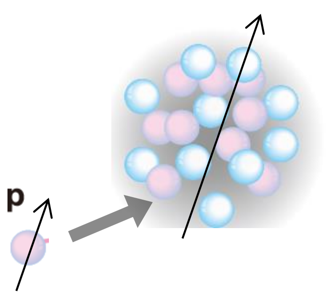
(p,pN) quasi-elastic



Spin-orbit splitting

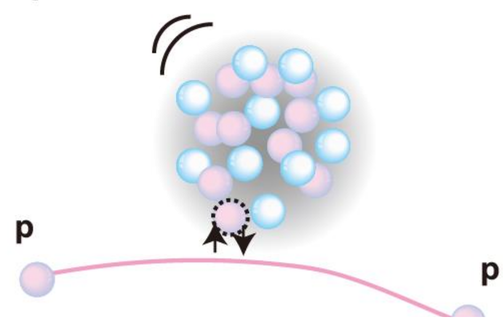
Plenty of physics opportunities!

Polarization transfer to RI



β-NMR, **Magnetic moment**

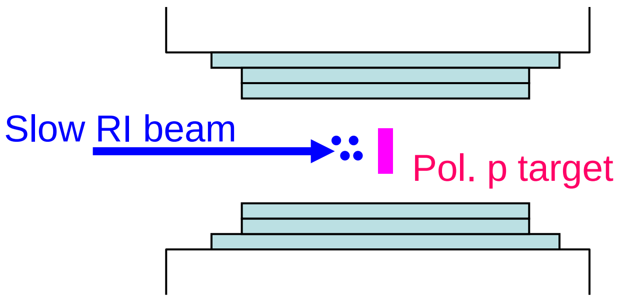
(p,p) resonance elastic

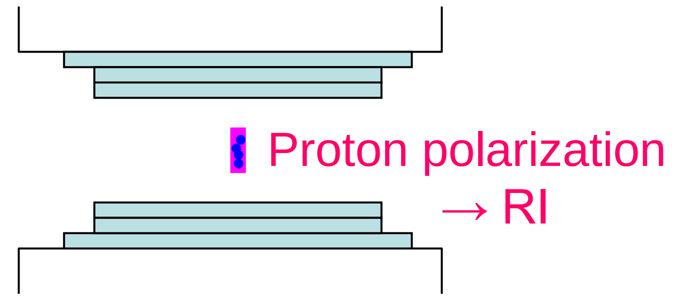


Nuclear **spectroscopy**

Measurement of magnetic moment

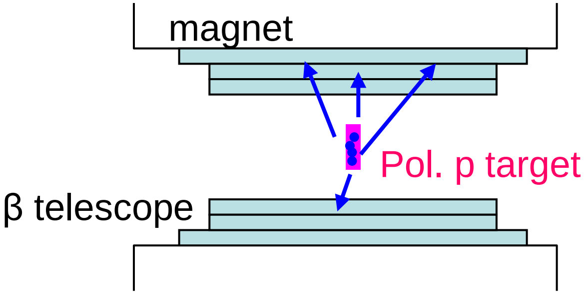
- Polarization transfer to stopped RI





  - "Cross-polarization technique" enables pol. transfer: Electron → Proton → RI (stable ^{13}C has been tested)

- Measurement of magnetic moment by β-NMR

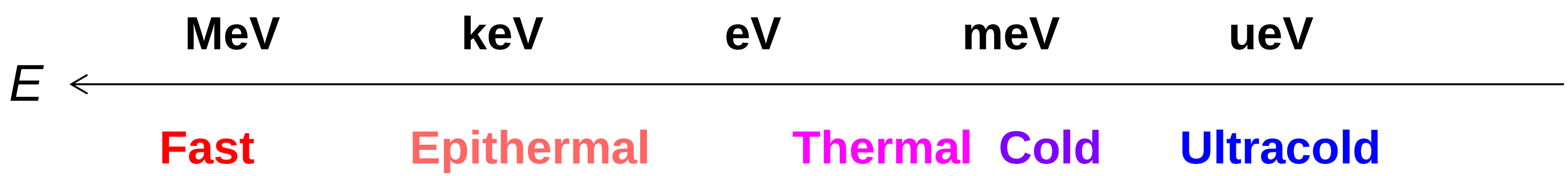


$$W(\theta) = 1 + AP\cos\theta$$

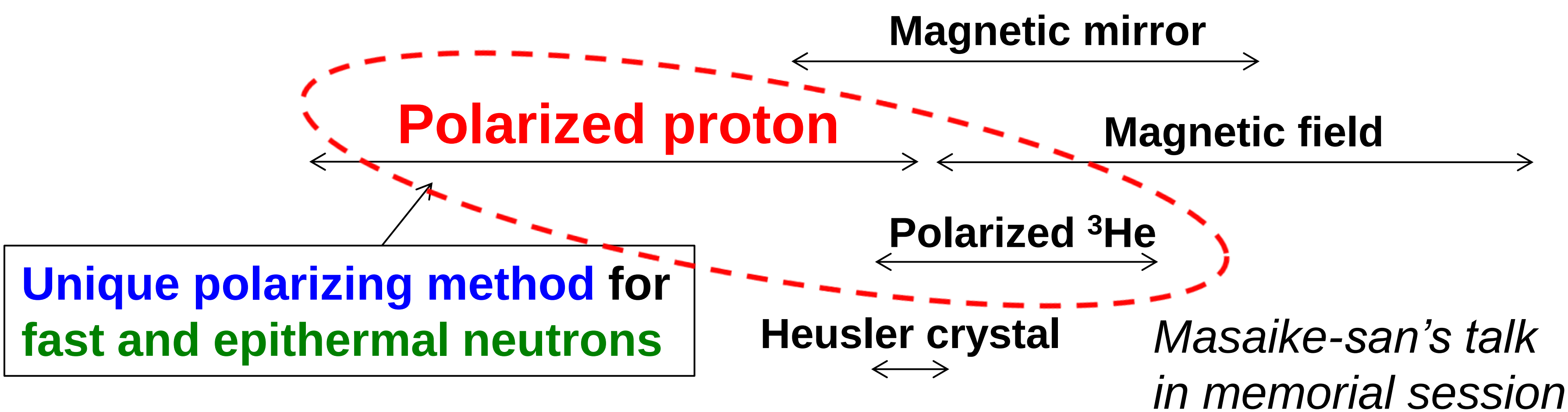
A : asymmetry factor
P : spin polarization

Polarizing neutrons

- Neutron energy region

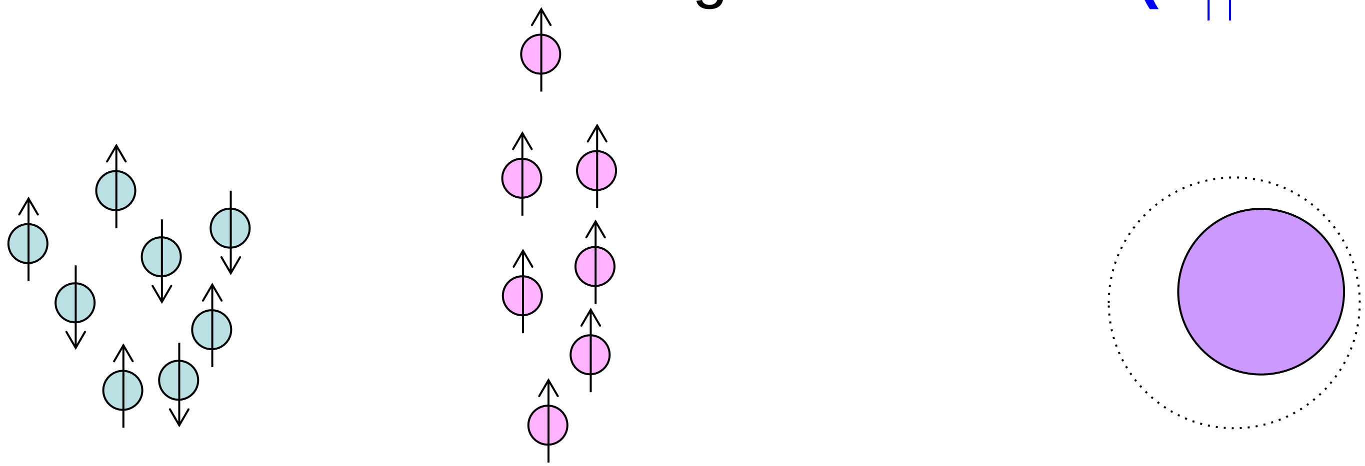


- Polarizing method



Spin filter for neutrons

- Spin filter
  - Difference between scattering cross section **($\sigma_{\uparrow\uparrow} \ll \sigma_{\uparrow\downarrow}$)**



- Test of fundamental symmetry
  - *P*-violation is enhanced in p-wave resonance
  - Time-reversal invariance can also be tested!

Prof. H. Shimizu @Nagoya

$$\Delta\sigma_{\mathrm{T}} = \kappa \frac{g_{\mathrm{CP}}}{g_{\mathrm{P}}} \Delta\sigma_{\mathrm{P}}$$

10^{-2}

10^{-3}

present EDM upper bound

Gudkov, Phys. Rep. 212 (1992) 77

Summary and perspective

- **Solid polarized proton target** (B~0.1T) has been constructed at RIKEN/CNS for **RI-beam exp**.

- Experimental programs with RI beams ongoing:
  - **Elastic scattering** to investigate **spin-orbit interaction**
  - $(\vec{p},2p)$ **knock-out reaction** to determine **spin-orbit splitting**

- Future applications planned:
  - **Resonant scattering**
  - $(\vec{p},d)$ **transfer reaction**

  (both: for **nuclear spectroscopy**)
  - Polarizing **neutrons** and **stopped RIs**

Collaborators

Kyushu Univ.

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W. Kim S. Stepanyan
V. Kavtanyuk J.A. Tan

IPN Orsay

D. Beaumel D. Suzuki

Univ. of Tsukuba

S. Kimura

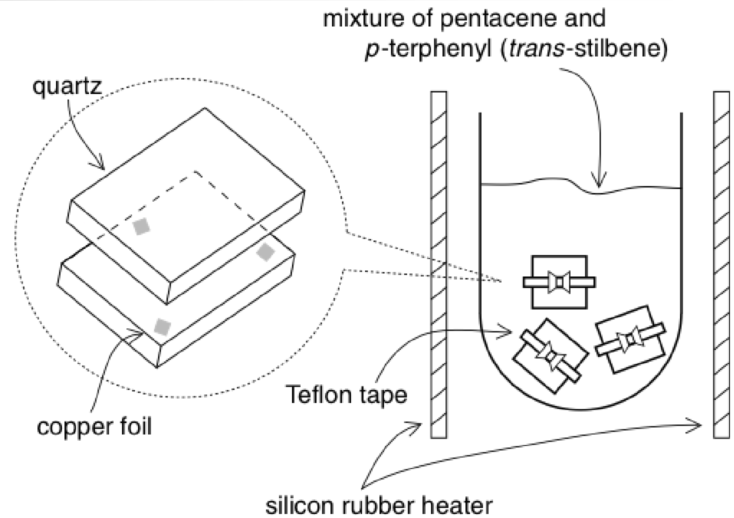
JAEA

S. Hwang

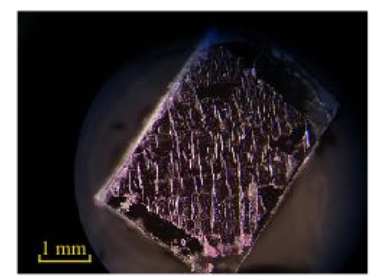
Back up

Fabrication of thin target (1/2)

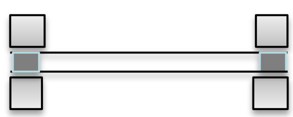
K. Tateishi, J. Phys. Soc. Jpn. 82 (2013) 084005



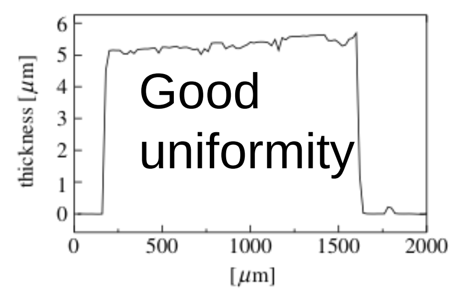
- Cell method
  - Grow single crystal between two glass plates
  - Crystal thickness can be adjusted from 1 to 100 um



- Film method (under development)
  - Use Kapton films instead of glass



⇒ Used as a backing for a thin crystal



Fabrication of thin target (2/2)

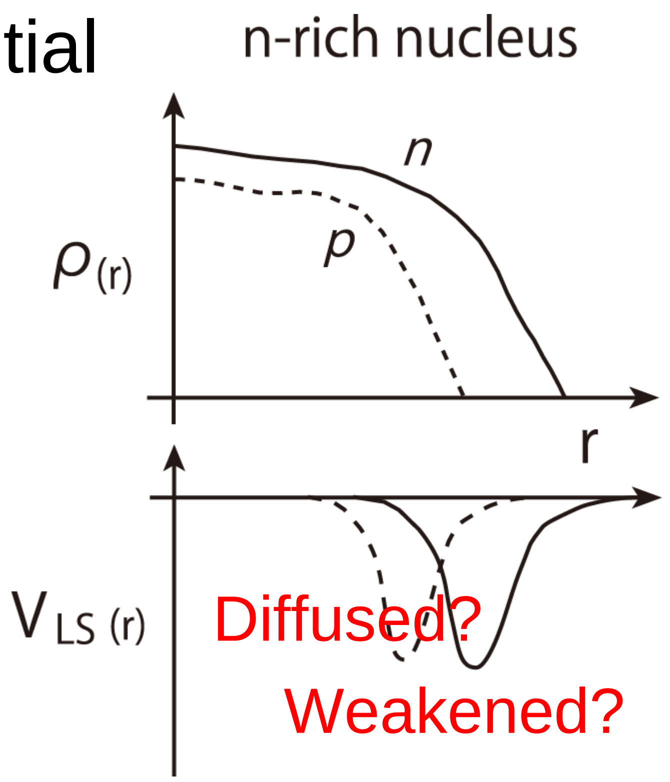
- Sublimation method
  - Proof-of-principle test succeeded two days ago!
  - Heat up one side of crystal in vacuum, let the crystal sublimate
  - Thickness is controllable. Uniformity is to be checked
- Just by polishing
  - Too fragile?

Spin-orbit coupling in *pA* scattering

- Spin-orbit term of optical potential
  - Proton feels spin-orbit force at nuclear surface

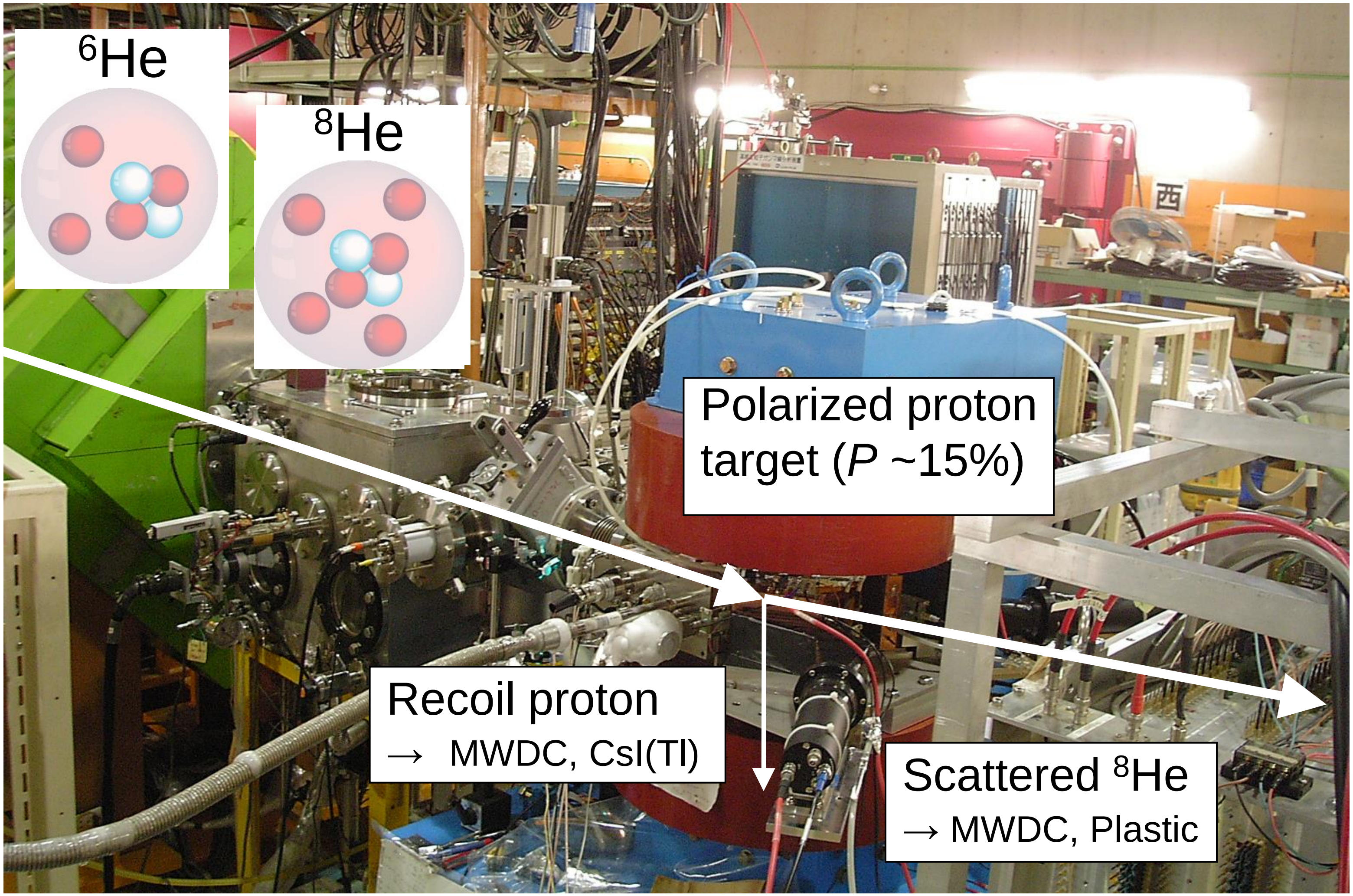
$$U_{so}=[1+\alpha\rho(r)]^{-1}\frac{1}{r}\frac{d\rho}{dr}$$

  - Nuclei with extended neutron distribution



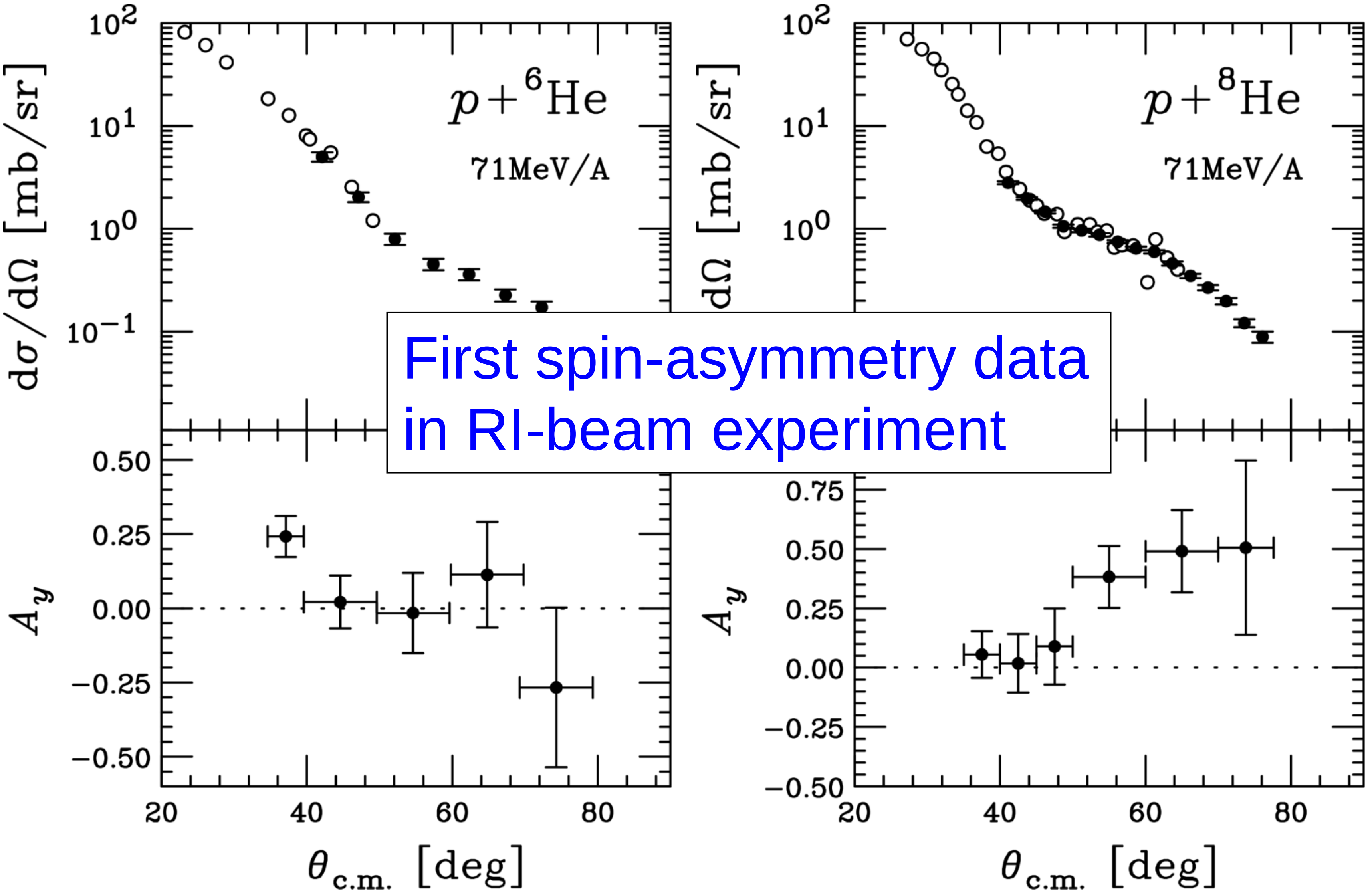
How does **extended neutron distribution** affect the **spin-orbit potential**?

p-^{6,8}He elastic scattering at 71MeV/A



RIPS facility @RIKEN

Experimental data

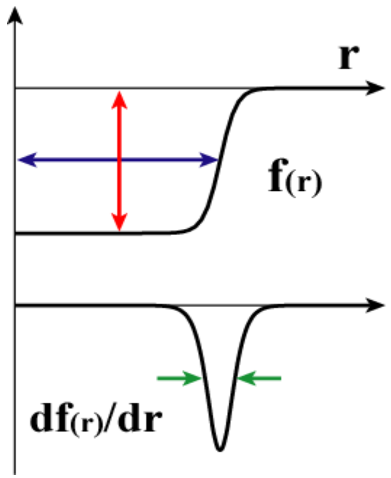


First spin-asymmetry data in RI-beam experiment

Optical potential is assumed

- Phenomenological potential
  - Parameter: Depth, Radius, Diffuseness

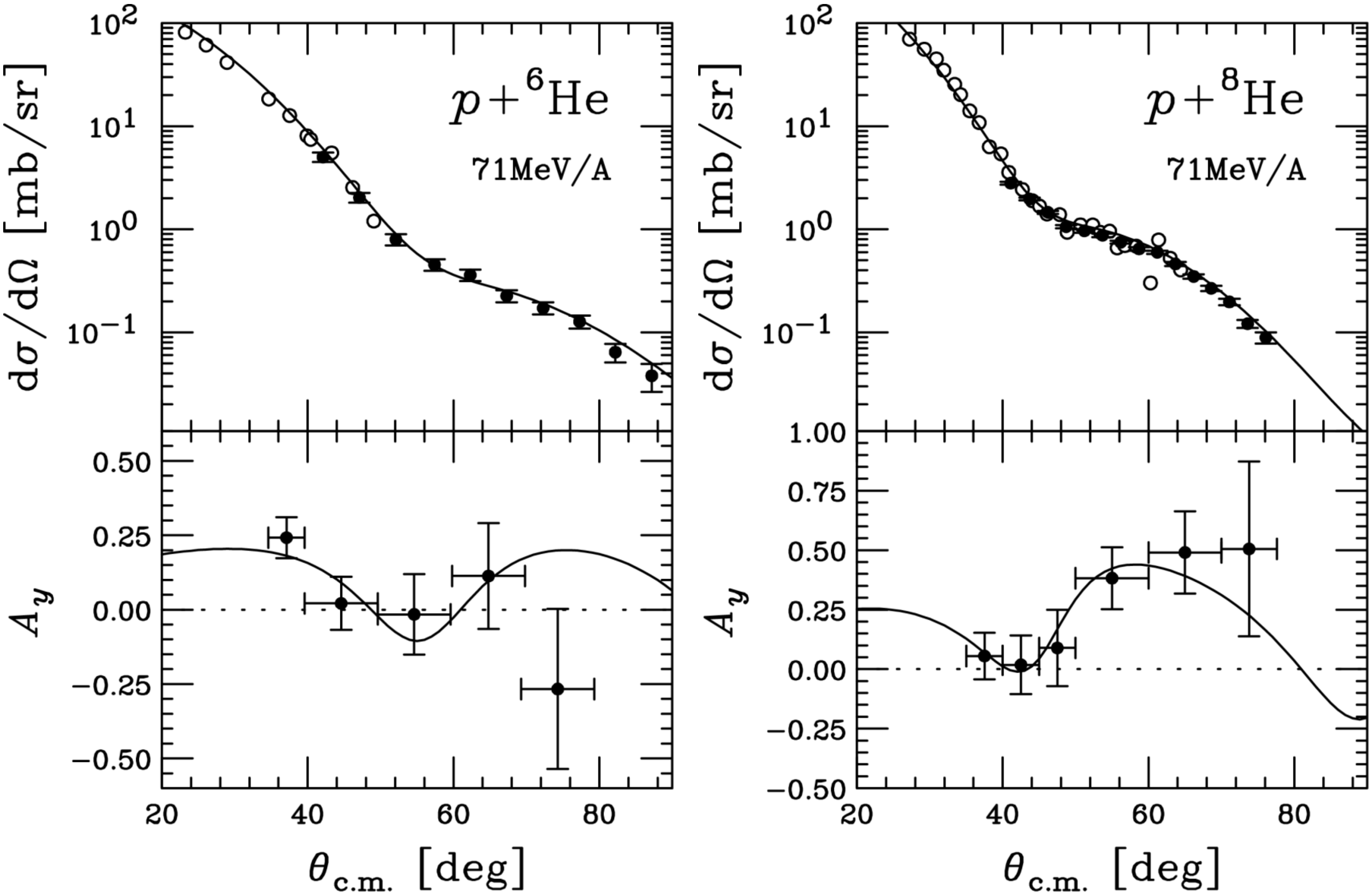
$$f(r; r_0, a_0) = \left[1 + \exp\left(\frac{r - r_0 A^{1/3}}{a_0}\right)\right]^{-1}$$



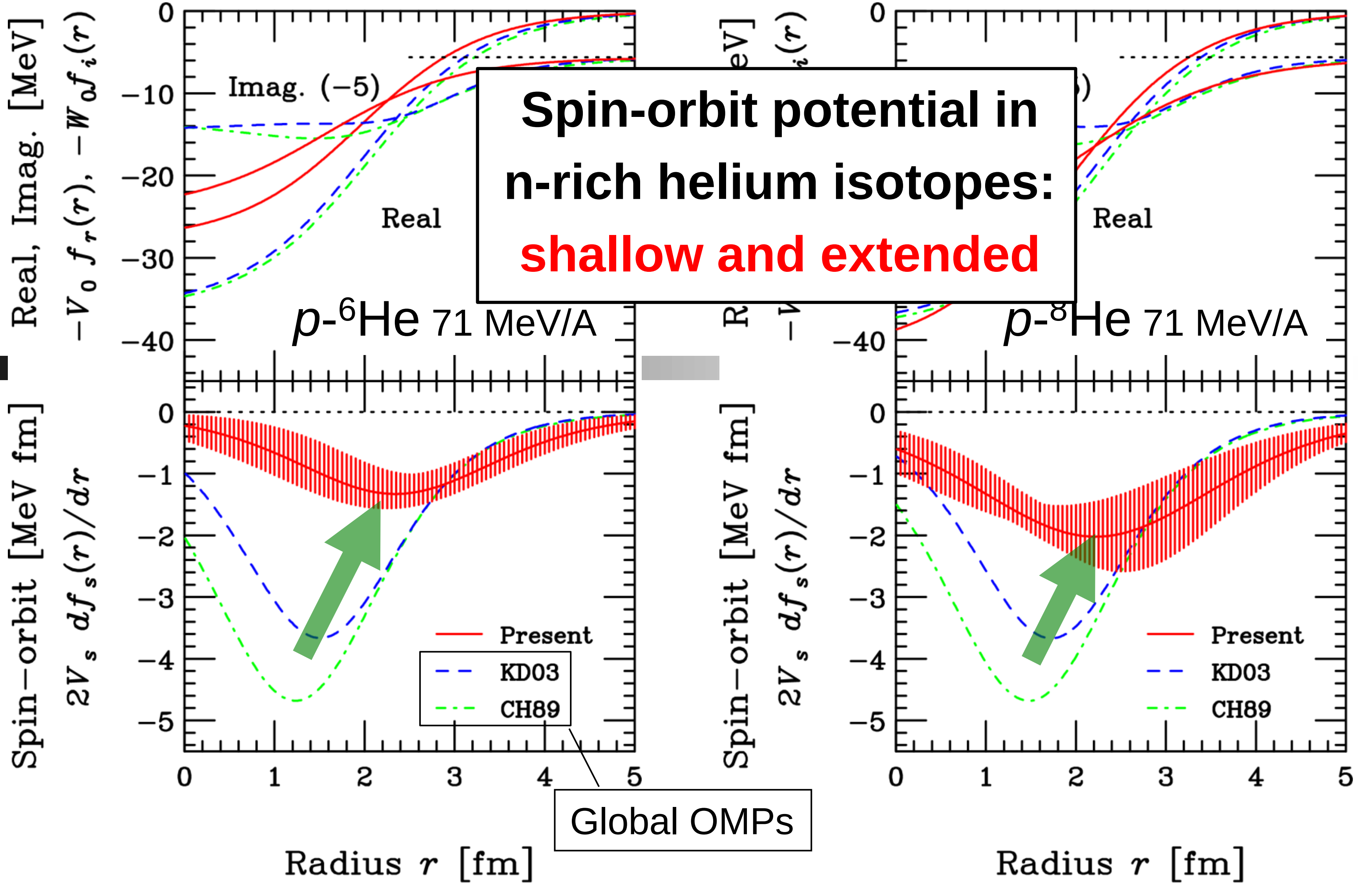
  - Central term : WS type, Spin-orbit term : Fermi type

$$\begin{aligned} U(r) &= V_{Coul}(r) + V_R f(r; r_R, a_R) + iW_{wv} f(r; r_{wv}, a_{wv}) \\ &\quad -4a_{ws} W_{ws} i \frac{d}{dr} f(r; r_{ws}, a_{ws}) \\ &\quad + V_{ls} \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r} \frac{d}{dr} f(r; r_{ls}, a_{ls}) (\overrightarrow{\sigma} \cdot \overrightarrow{L}) \end{aligned}$$

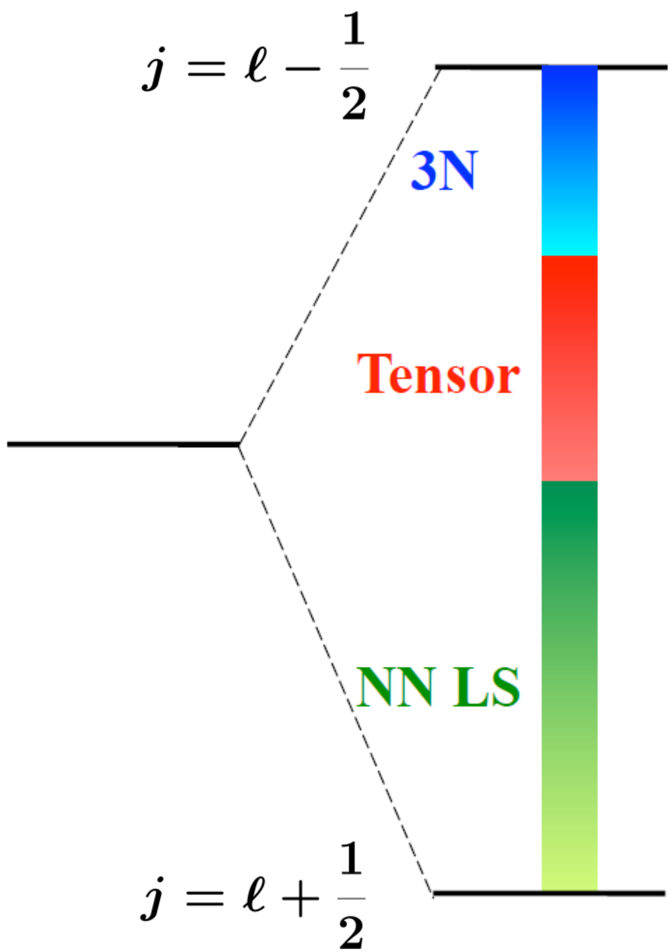
Fitted to data

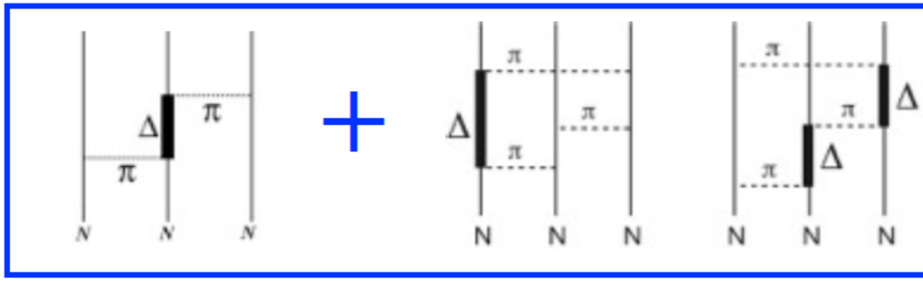


Obtained potentials. Strange behavior!

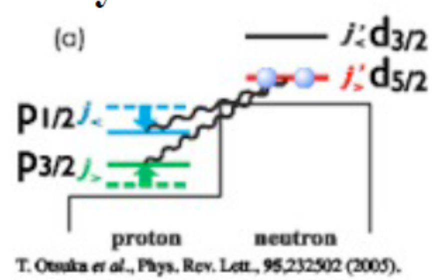


Closer look at spin-orbit splitting

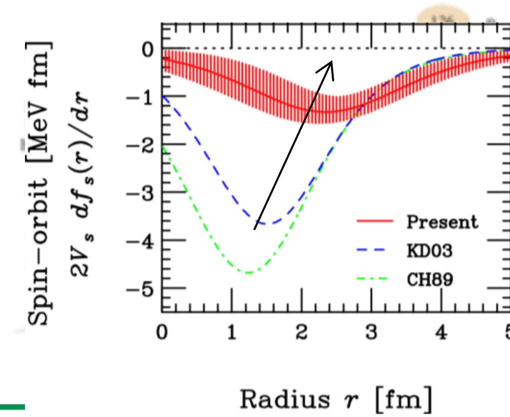




First-order tensor effect by Otsuka
2p2h+Pauli-blocking
→ Myo, Kato

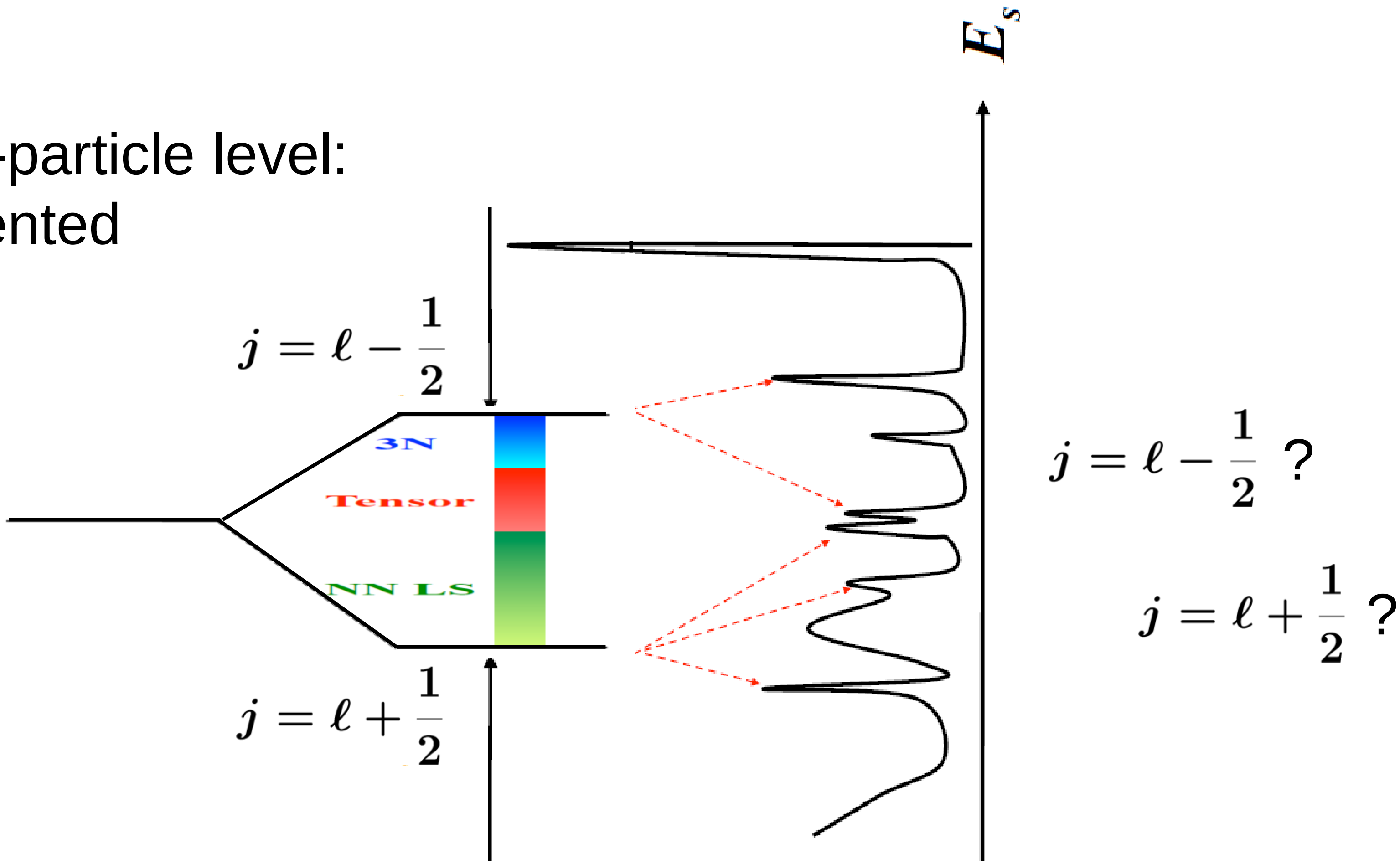


Mean-field effects



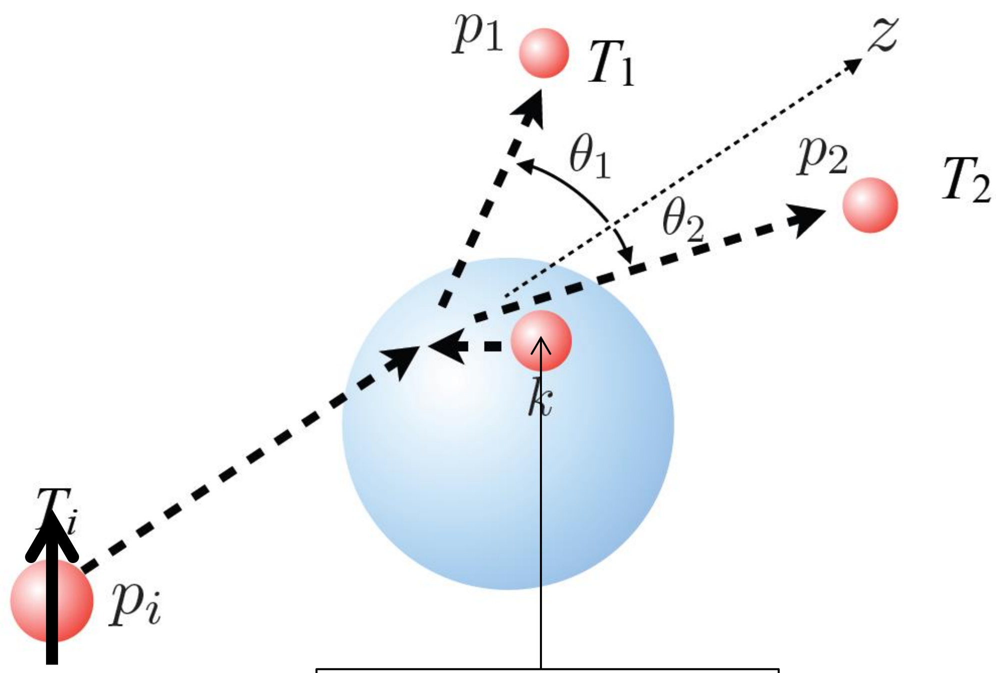
Determination of spin-orbit splitting

Single-particle level:
fragmented



Measure binding energy *E* and assign *L* and *J* state-by-state

J assignment by ($\vec{p}$,2p) reaction

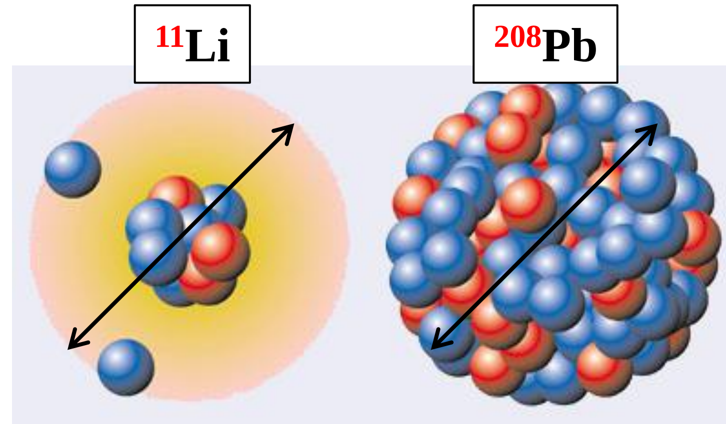


$j = \ell - \frac{1}{2}$?

$j = \ell + \frac{1}{2}$?

Experimental plan 1: $^{9}C+p$ (partially approved)

- **Why is ^{11}Li bound?**
  - ^{11}Li = borromean nucleus ($^{9}Li + n + n$: 3-body system)
  - Where is the ground state?
  - What is the spin-parity?
  - What is the n - ^{9}Li potential?
  - Spectroscopy of unbound ^{10}Li
  - Information of ^{10}N (IAS of ^{10}Li)
  - $^{9}C+p$ resonant scattering

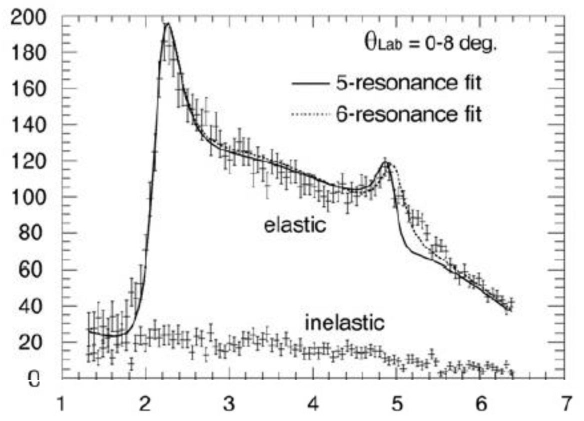


Borromean ring

Experimental plan 2: ^{7}Be+*p*

- Solar neutrino problem
  - Resonances in ^{8}B ⇔ Reaction rate of ^{7}Be(p,γ)^{8}B (key reaction in solar ^{8}B neutrino production)
  - Resonances of 2nd 1^{+} & 2nd 2^{+} Not found (probably due to extremely large width)
  - Polarization data will be useful for finding them!
  - **New spectroscopic method for nuclear astrophysics**

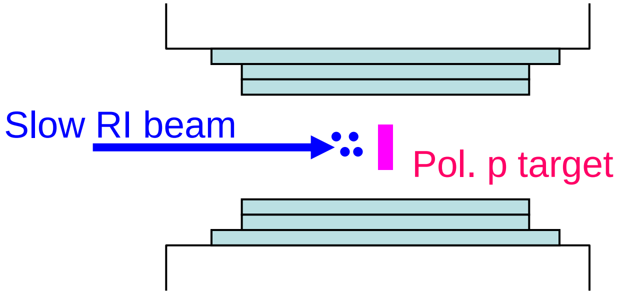
^{7}Be+*p* d.c.s.

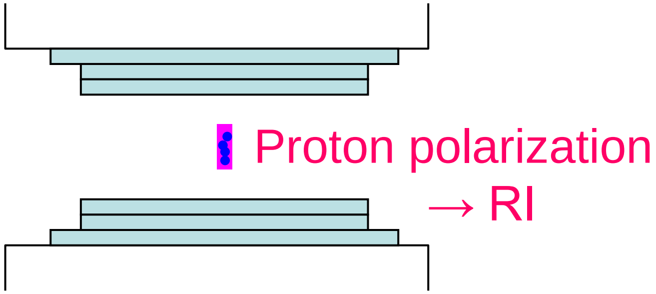


CRIB (CNS/RIKEN)
by H. Yamaguchi
PLB 672 (2009) 230.

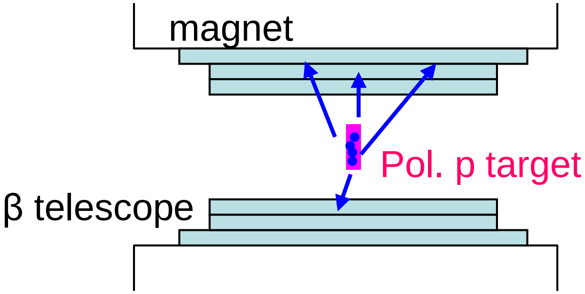
Measurement of magnetic moment

- Polarization transfer to stopped RI





- Measurement of magnetic moment by β-NMR
  - Angular distribution of β rays with respect to pol. axis

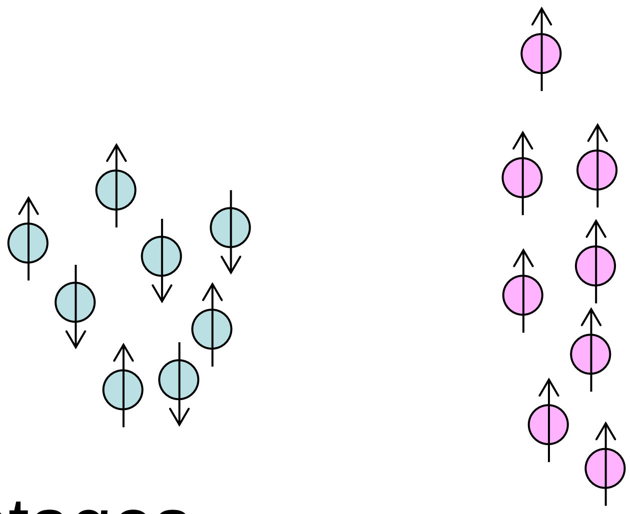


$$W(\theta) = 1 + AP\cos\theta$$

A : asymmetry factor
P : spin polarization

Production of slow neutron beam

- Neutron spin filter
  - Difference between scattering cross section **($\sigma_{\uparrow\uparrow} \ll \sigma_{\uparrow\downarrow}$)**



- Advantages
  - Any energy (cold, thermal, hot neutrons)

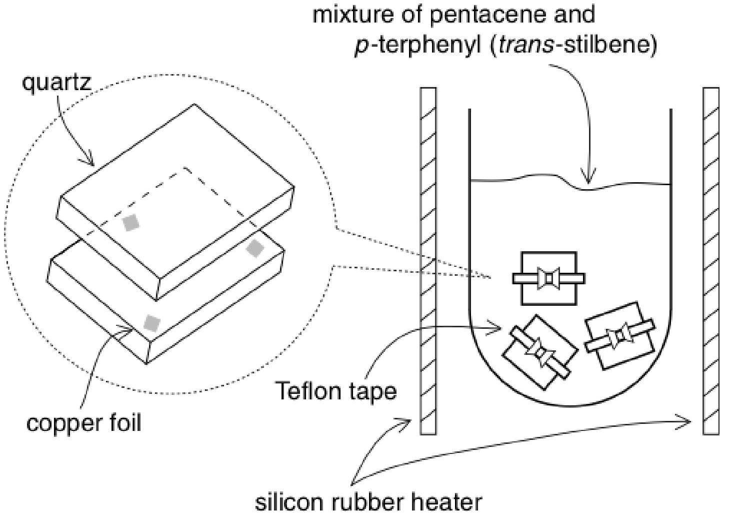
    ⇔ < 20meV (super mirror polarizer)
  - Low magnetic field of 0.3T, no complicated cryostat

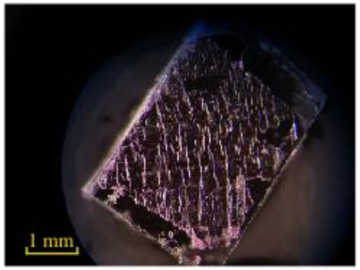
    ⇔ 2.5T, 0.5K (standard neutron filter)

Fabrication of thin target

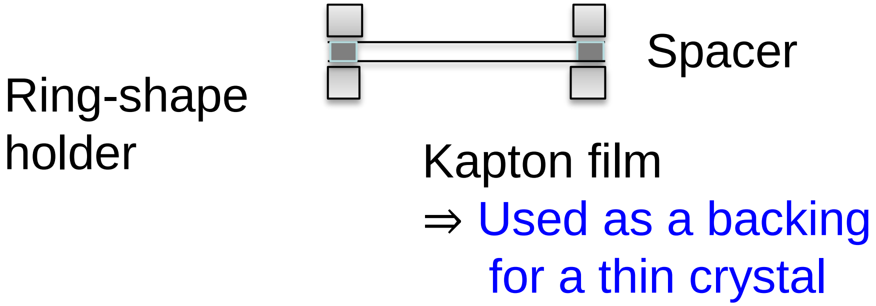
K. Tateishi, J. Phys. Soc. Jpn. 82 (2013) 084005

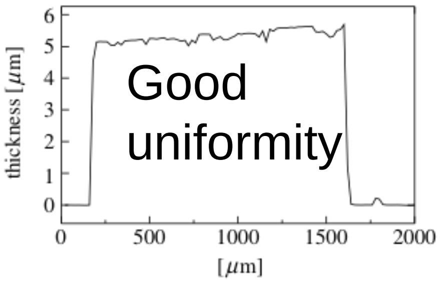
- Cell method
  - Grow single crystal between two glass plates
  - Crystal thickness can be adjusted from 1 to 100 um





- Film method (under development)
  - Use Kapton films instead of glass

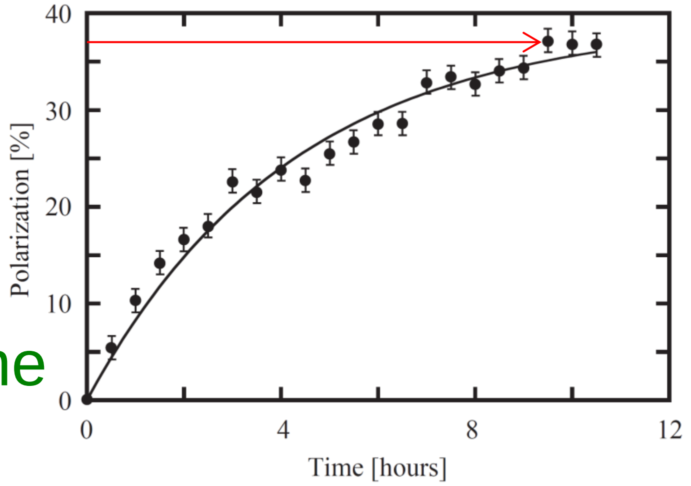




Enhancement of polarization

- Bottleneck of polarization
  - Small crystal: 37%

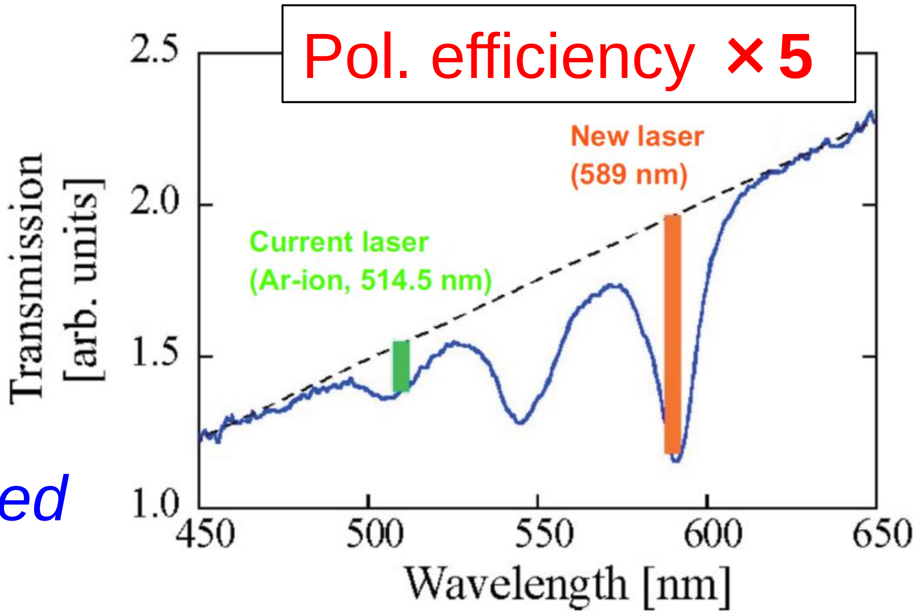
    ⇔ Large crystal: 13-20%
  - Shortage of laser power / volume
  - Mismatch of wavelength



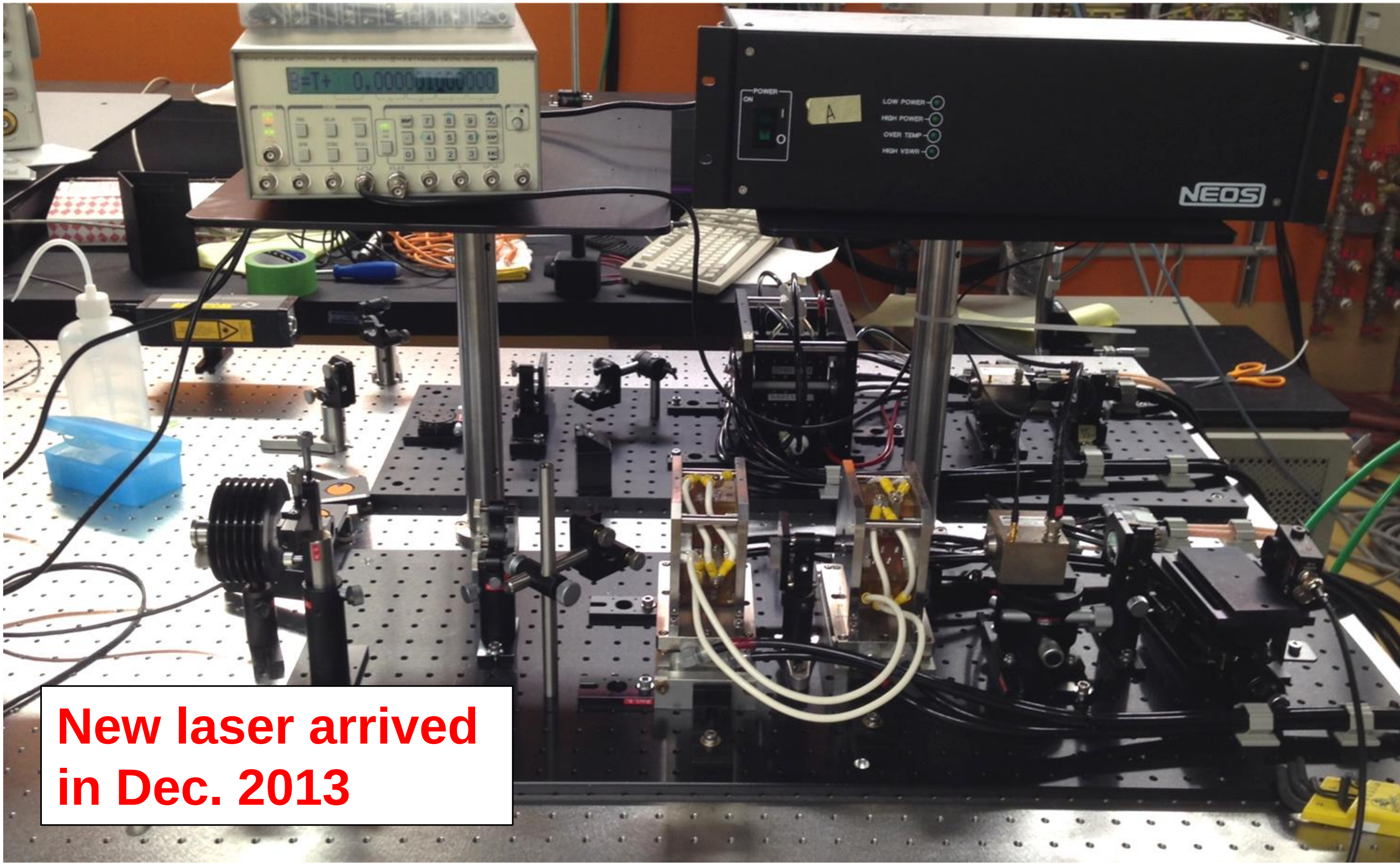
- New laser
  - Optimum λ: 589 nm
  - High power: 10 W

    (50 times higher)

Just arrived and being tested



Enhancement of polarization



New laser arrived in Dec. 2013

Expected polarization

- Estimation

$$P_p = \frac{A\,P_e}{A + G_{\mathrm{int}} + G_{\mathrm{para}} + G_{\mathrm{x}}}$$

Evaluated from current parameters. Laser power is assumed to be 12W.

P_e	Electron polarization	70 %
A	Build-up rate	0.19 min^{-1}
G_{int}	Relax. rate (intrinsic)	0.10 min^{-1}
G_{para}	Relax. rate (paramagnetic)	0.48 min^{-1}
G_{x}	Relax. rate (*e* dynamics)	0 – 0.28 min^{-1}
P_p	**Proton polarization**	**15 ± 2 %**

Applications of room-temp. polarization

- Hyper-sensitivity Magnetic Resonance Imaging
  - Use of proton polarization in thermal equilibrium

    P_p: ~ 5×10^{-4} % $\Leftrightarrow$ 14.1% (Present)
  - Polarization transfer to ^{13}C

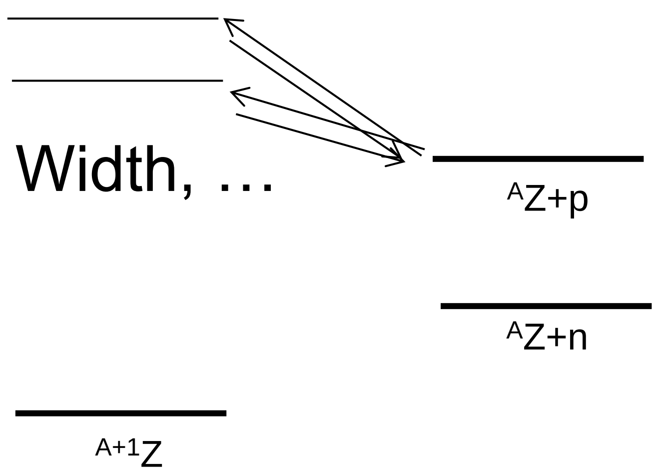
- Quantum computing
  - Long coherent time

- Structure analysis
  - Spin filter using $\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$
  - Polarized neutron beam

Study of resonance state of rare isotope

- Resonant proton scattering
  - Information of energy, width, J^{π} of resonance states
    - Excited states of proton-rich nuclei
    - g.s. of nuclei outside proton drip line
    - IAS of neutron-rich nuclei
  - $A_y \Rightarrow$ total angular momentum "j"

E, J$^{\pi}$, Width, …



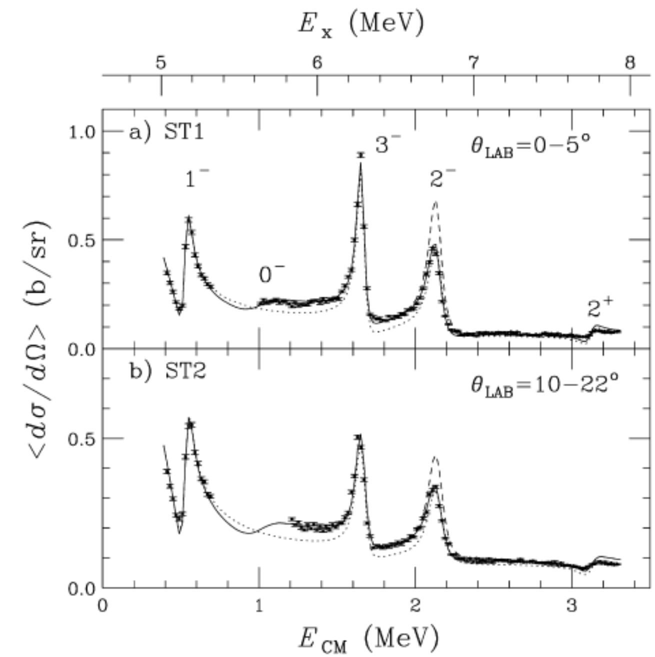
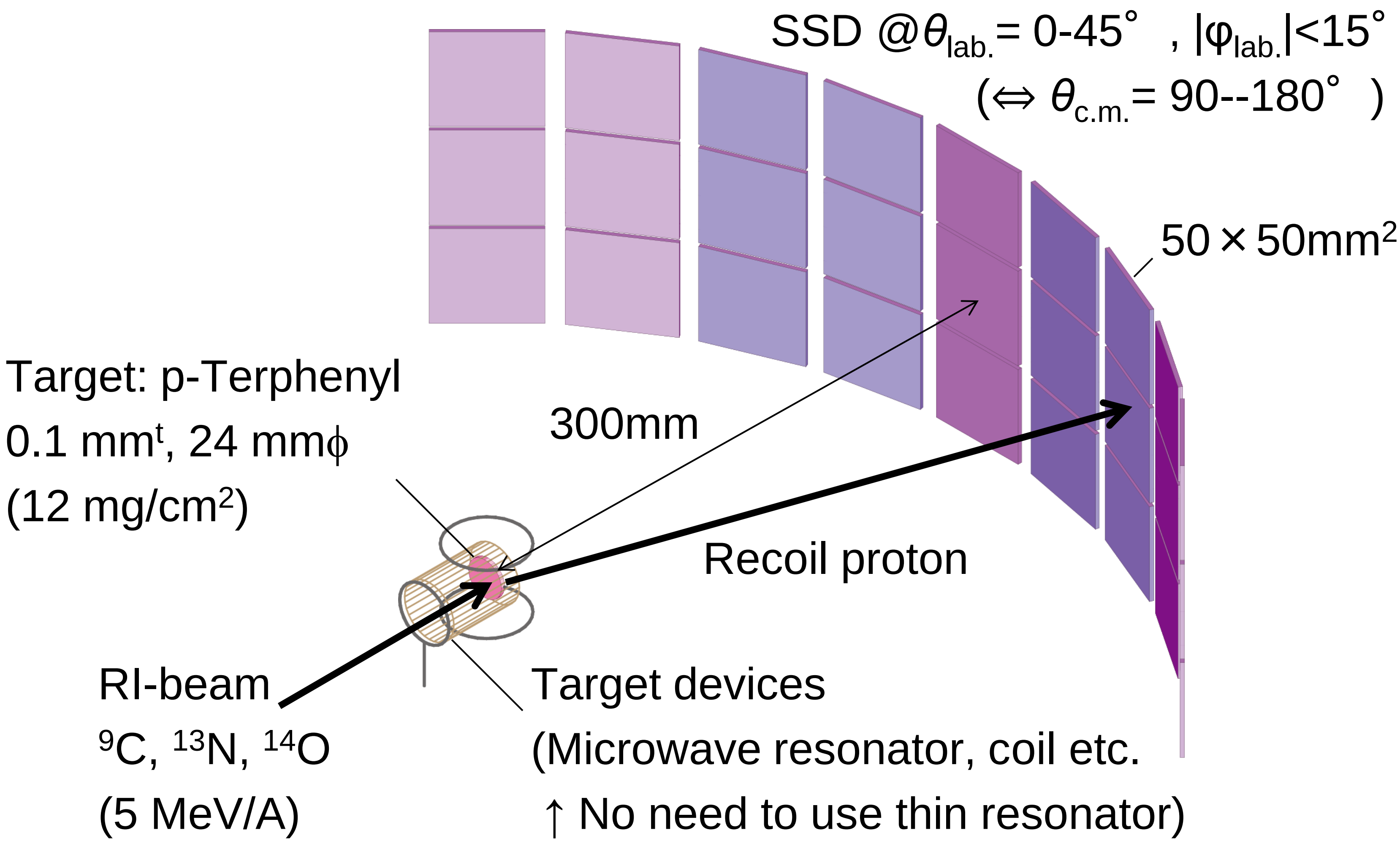


Fig. 3. Experimental excitation functions for the $^{13}N + p$ scattering measured by (a) ST1 and (b) ST2. The solid lines show the result of the fitting calculation. The dashed lines represent the result when J^{π} for the 6.8 MeV level is changed to 3^-. The dotted lines show the result without a contribution of the 0^- level at $E_x = 5.71$ MeV. The gaps at $E_{CM} \sim 0.8$ MeV are due to the detector dead layers.

T. Teranishi et al. ,
PLB 650 (2007) 129–134

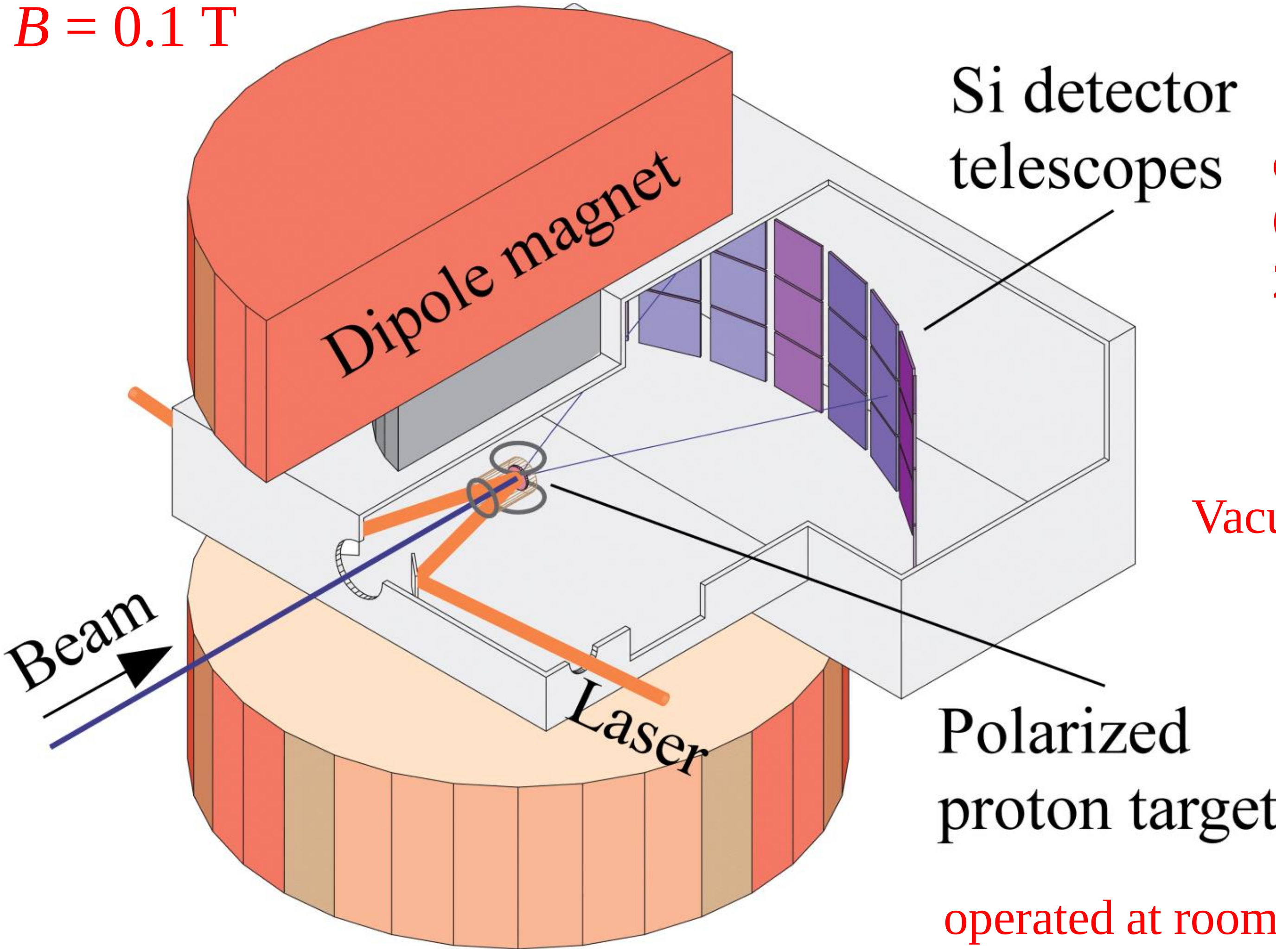
Solid polarized proton target @RIKEN

- Experimental setup in low-energy exp.



Experimental setup

B = 0.1 T



covering
$\theta_{lab} = -45^\circ$ -- $+45^\circ$
25 cm from the target

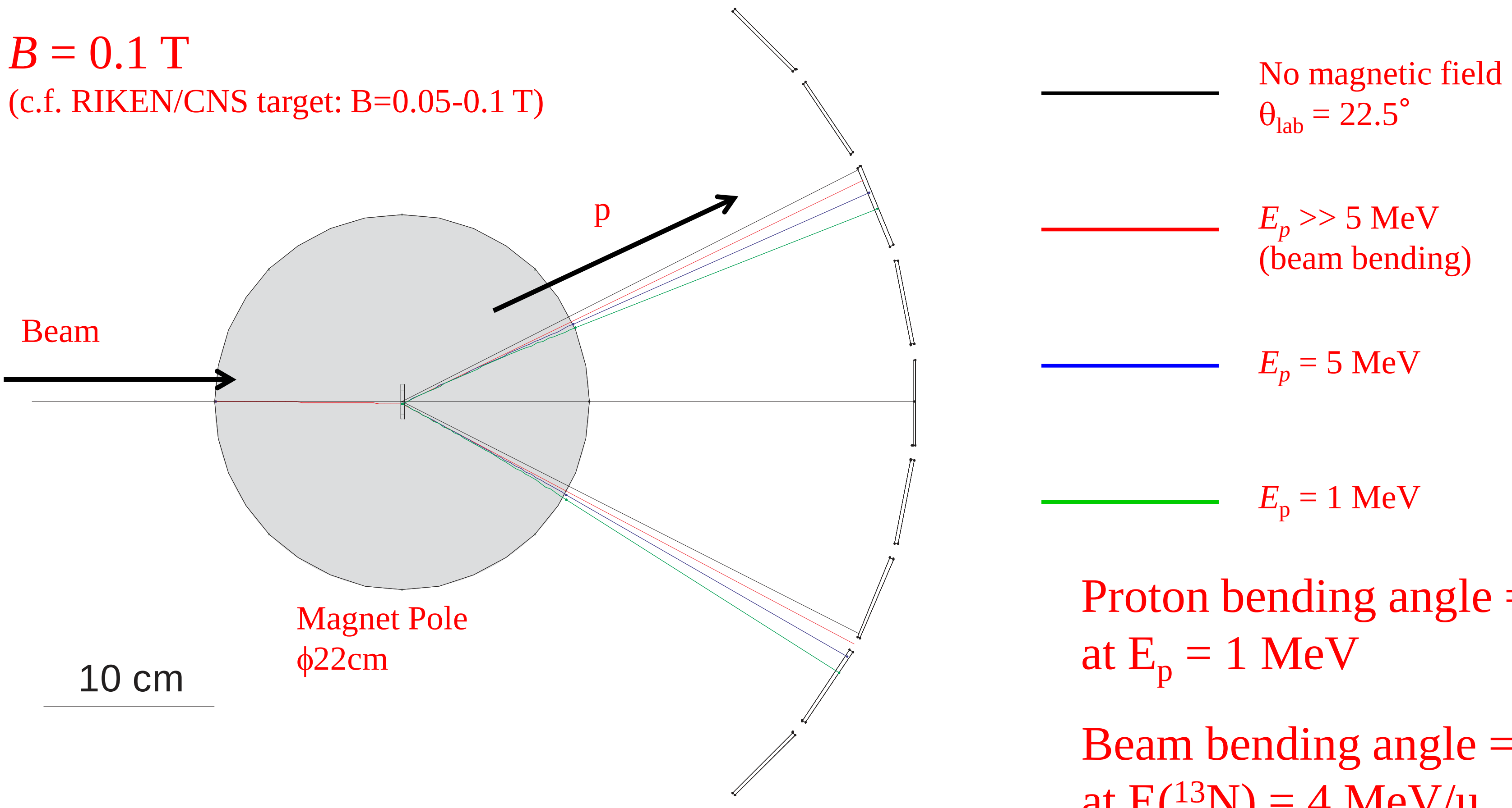
Vacuum chamber

ϕ25 mm
8 mg/cm^2

operated at room temperature

Laser: 10W, λ = 589 nm

Bending of particle trajectory in mag. field

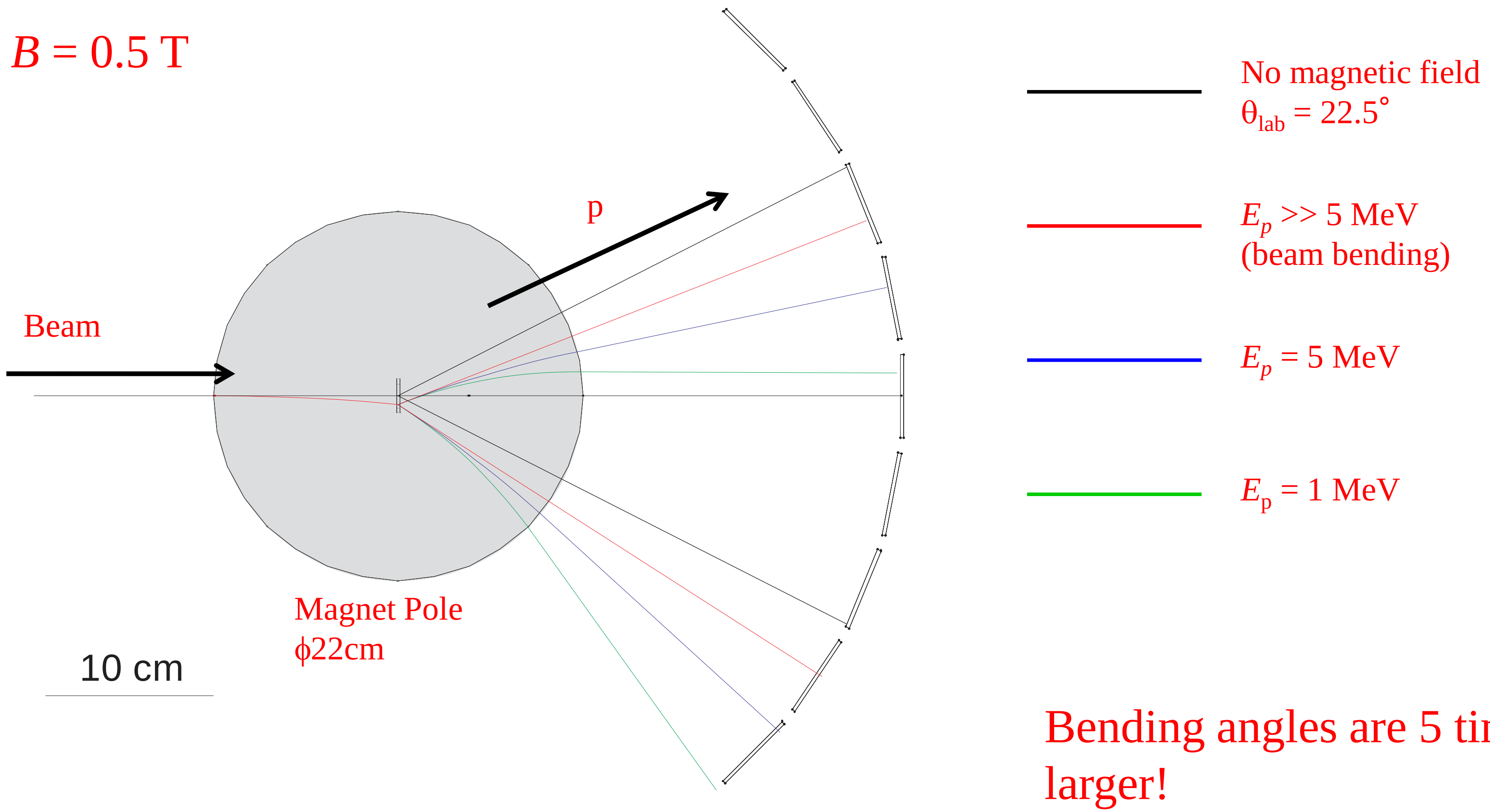


Proton bending angle = 4°
at E_p = 1 MeV

Beam bending angle = 1°
at $E(^{13}N)$ = 4 MeV/u

It is not difficult to make corrections for the trajectory bending in the data analysis.

B = 0.5 T case for comparison...



Bending angles are 5 times larger!

Detectors need to cover a large angular range for a single scattering angle.

Material thickness

- Energy loss of recoil proton and RI-beam
  - Typical energy: 1-10MeV (proton), ~7MeV/A (RI)
  - Range of recoil proton: 10-20 mg/cm^2