QFS Workshop
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Spin polarization
in QFS experiments with RI beams

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Outline

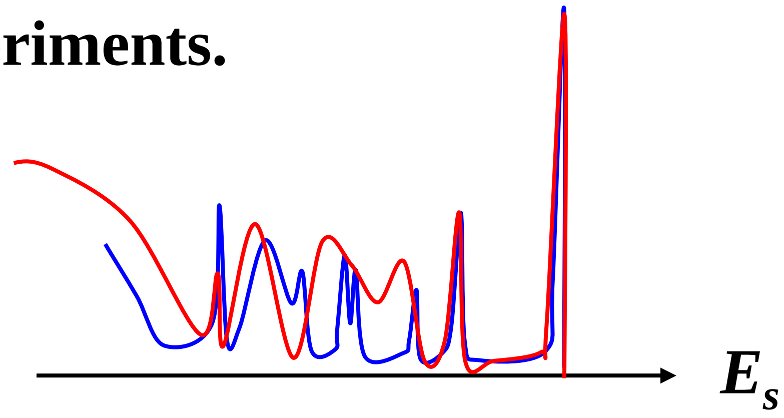
- **Why Polarization?**
  - **spin-parity assignment**
  - **determination of spin-orbit splitting**
    - **necessary or not necessary?**

- **CNS Polarized Proton Target for RI beam exp.**
  - **principle**
  - **appratus**
  - **target performance**
    - **can be used in RI beam induced QFS exp.?**

- **QFS experiments at RIBF**

Why Polarization?

In stable beam experiments, spin-parities of the hole states populated by (p,pN)/(e,eN) reactions are usually known prior to the experiments.



But, In (future) RI beam experiments, this is not the case.

experimental information is scarce

theoretical predictions are less reliable

In addition, even low-lying states are above the particle threshold in many cases.

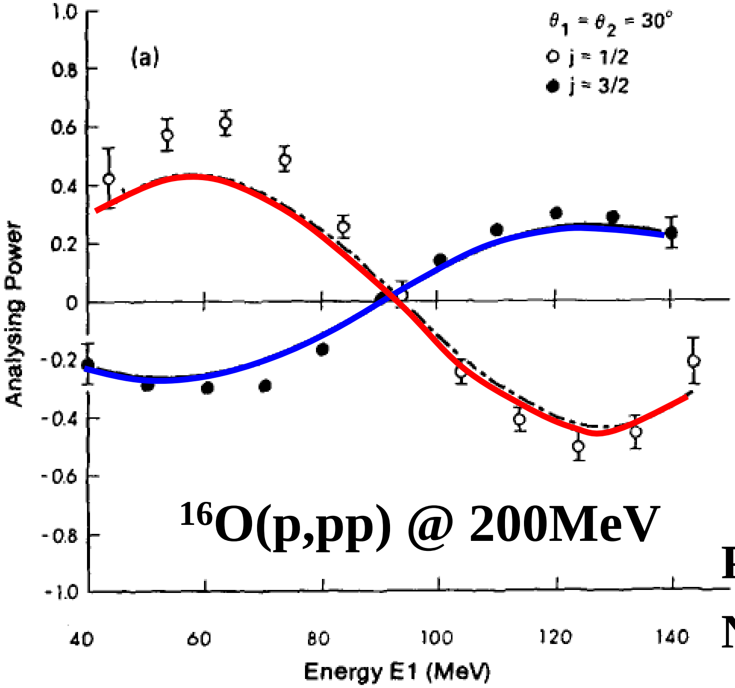
Why Polarization? (*cont.*)

An experimental method to determine spin-parties is required.

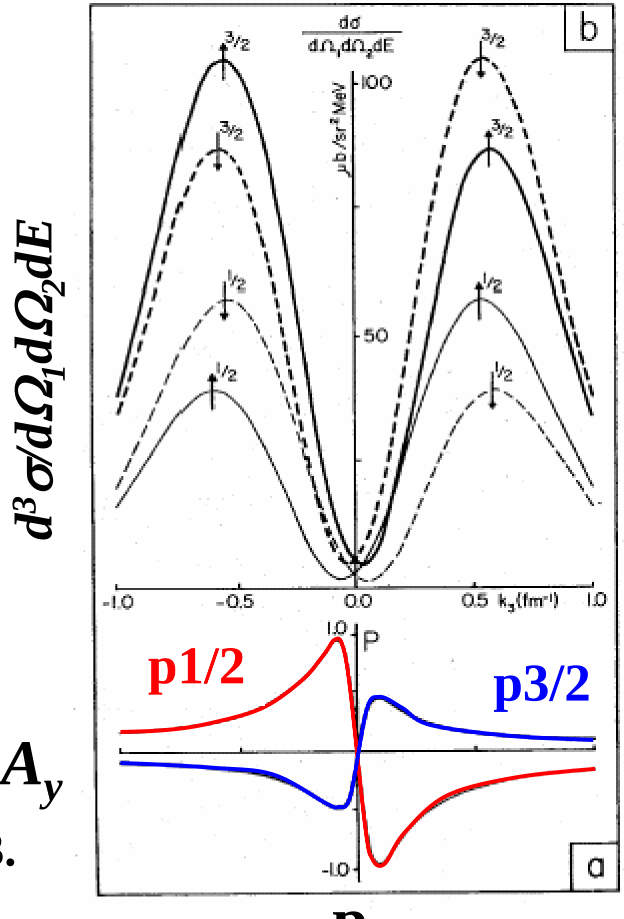
L, parity ← momentum dependences of cross section

J ← spin-asymmetry A_y

: Maris effect

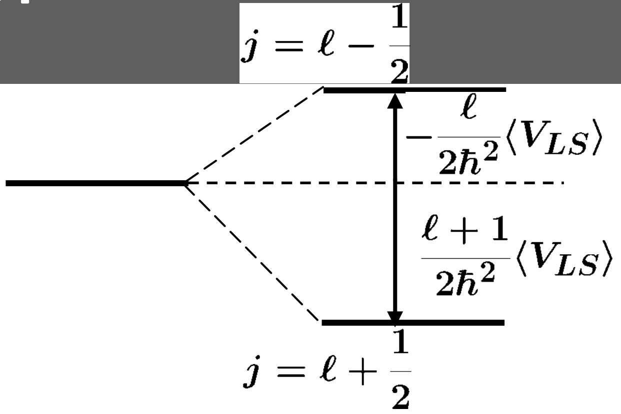


G. Jacob et al.,
PLB 45 (1973) 181.



P. Kinching et al.,
NPA 340 (1980) 423.

Spin-orbit coupling in nuclei



“Strong spin-orbit coupling” constitutes the basis of nuclear physics
→ conventional magic numbers

Spin-orbit splitting ($\Delta E_{ls} = E_{j>} - E_{j<}$) of single particle states can be a good measure of the spin-orbit coupling.

ΔE_{ls} (0*p* in ^{16}O) : ~ 6 MeV

Microscopic origins of the spin-orbit coupling

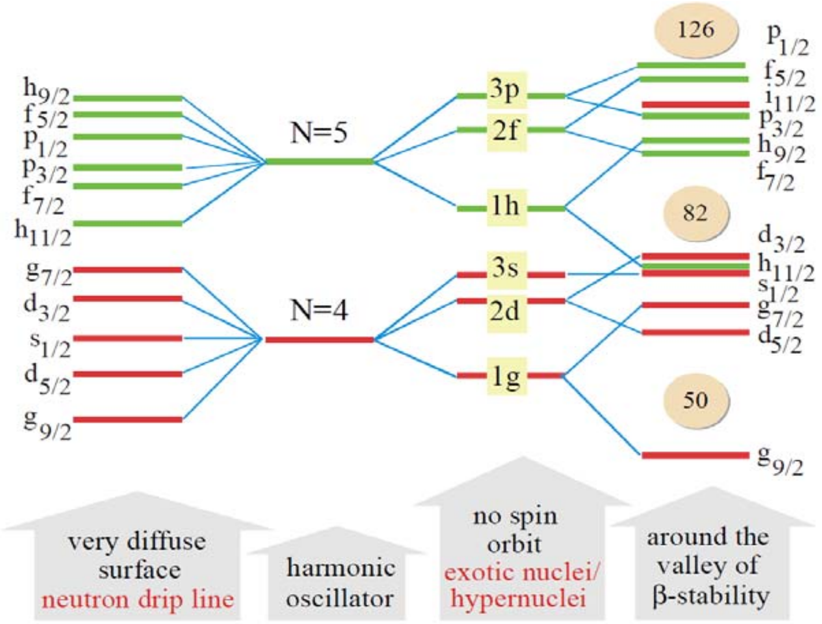
K.Ando and H. Bando, Prog. Theor. Phys. **66** (1981) 227.
S.C. Pieper and V.R. Pandharipande, Phys. Rev. Lett. **70** (1993) 2541.

^{16}O, ^{40}Ca cases,

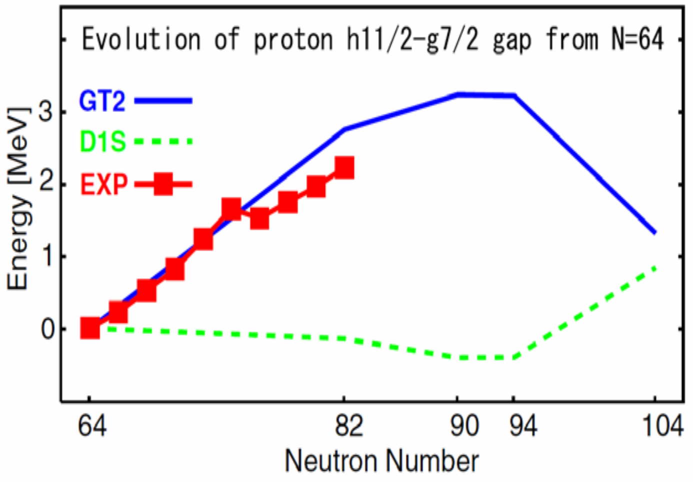
2N spin-orbit force	→	**~half of ΔE_{ls}**
2N tensor force	→	**~1/4 of ΔE_{ls}**
3N forces	→	**~1/4 of ΔE_{ls}**

Theoretical Predictions for n-/p-rich nuclei

Weakening of spin-orbit coupling Dobaczewski, Ring . . . .



Tensor force effects T. Otsuka



3N force B. Pudliner

^{15}N: ΔE_{ls} = 6.1 MeV

↓

^{7}n : ΔE_{ls} = 1.4 MeV

Spin-orbit splitting in n-/p-rich nuclei

How ΔE_{ls} changes as a function of Z/N?
a key to understand shell regularity
far from the stability line.

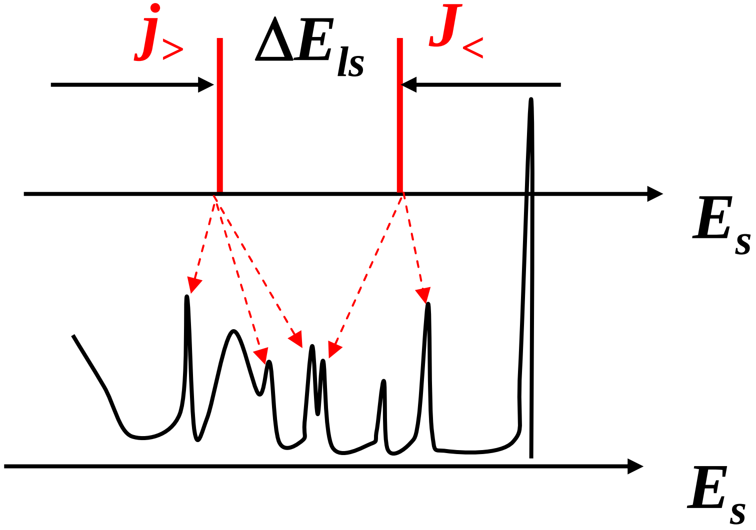
ex. J. Dobacewski et al., Phys. Rev. Lett. **72** (1994) 981.
M.M. Sharma et al., Phys. Rev. Lett. **72** (1994) 1431.
T. Otsuka et al., Phys. Rev. Lett. **97** (2006) 162501.
B.Pudliner et al. Phys. Rev. Lett. **76** (1995) 2416.
. . . .

⇔ **isospin-dependences of interactions**

NN spin-orbit	**weak isospin dependence**
NN tensor	**strong isospin dependence**
3N	**in *n*-rich region** **T=1/2 3NF → weaker** **T=3/2 3NF might be dominant**

It is stimulating to see experimentally
how ΔE_{ls} changes as a function of Z/N.

Experimental determination of ΔE_{ls}



Fragmented strength of $j_>$ and $j_<$

state-by-state assignment of J and L

multi-pole decomposition analysis for continuum states

We need a polarized target which can be used in radioactive isotope beam experiments.

Polarized proton targets in the market

recent review: St. Goertz et al., Prog. Part. Nucl. Phys. 49 (2002) 403.

Gas target

pure hydrogen gas
polarization ~ 70%
thickness ~ 10^{14} /cm^2
→ too thin for use in RI beam experiments

"Standard" solid target

C_4H_9OH, NH_3, LiH. . . . .
polarization > 50%
thermal polarization of electron

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \tanh\left(\frac{g\mu_N B}{2kT}\right)$$

→ high mag. field(and low temperature) are required
2.5 - 6.5 T (0.2 - 1.5K)
→ too high for use in QFS experiments

Operation at low magnetic field

Why necessary?

Separation energy resolution depends primarily on angular resolution of scattered and recoiled protons.

$\Delta\theta \sim 1$ mrad **$(B\rho)_p \sim 1 - 2$ Tm**

In the presence of magnetic field of 3 Tesla, the proton trajectory is bended by > 300 mrad before detection

Polarized target working at < 0.1 T is needed to achieve reasonable angular resolution of ~ 1 mrad (after correction)

How possible?

use of "spontaneous" polarization of electrons in photo-excited triplet states of aromatic molecules

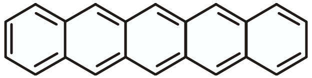
H.W. van Kesteren et al., PRL **55** (1985) 1642.
M. Iinuma et al., PRL **84** (2000) 171.
T. Wakui et al., NIM A **550** (2005) 521.

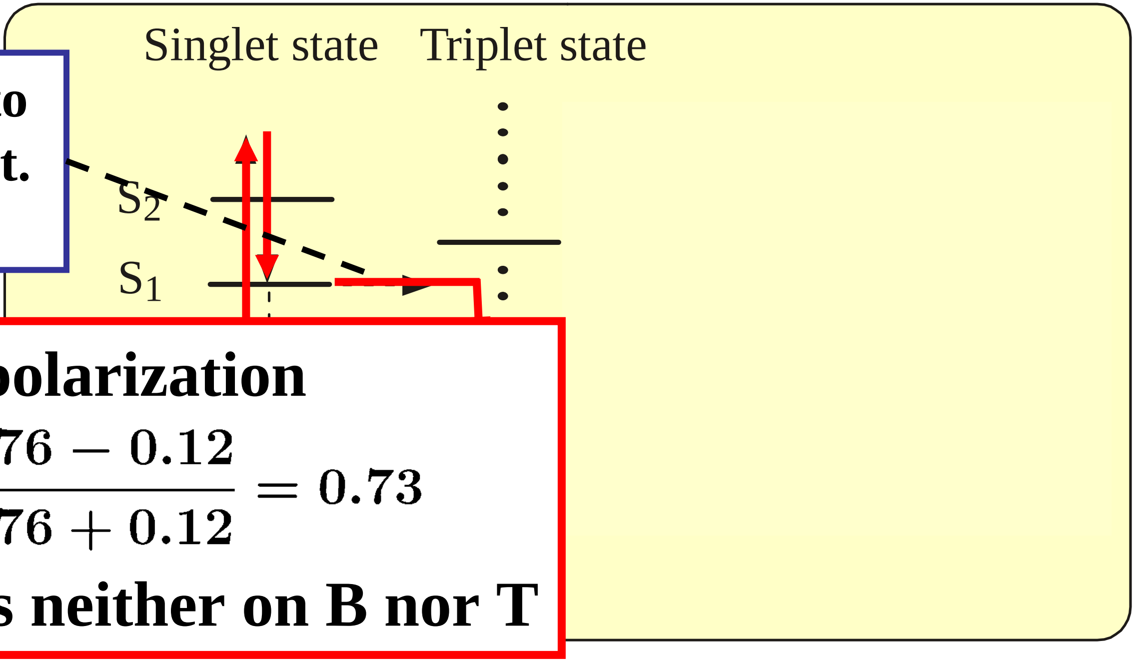
Proton Polarization at low mag. field

Idea: use of electron polarization (population difference) in photo-excited triplet state of aromatic molecule

H.W. van Kesteren et al., Phys. Rev. Lett. **55** (1985) 1642.
A. Henstra et al., Phys. Lett. A **134** (1988) 134.

Energy diagram of pentacene molecule





mixing due to spin-orbit int. in molecule

Electron polarization

$$P = \frac{0.76 - 0.12}{0.76 + 0.12} = 0.73$$

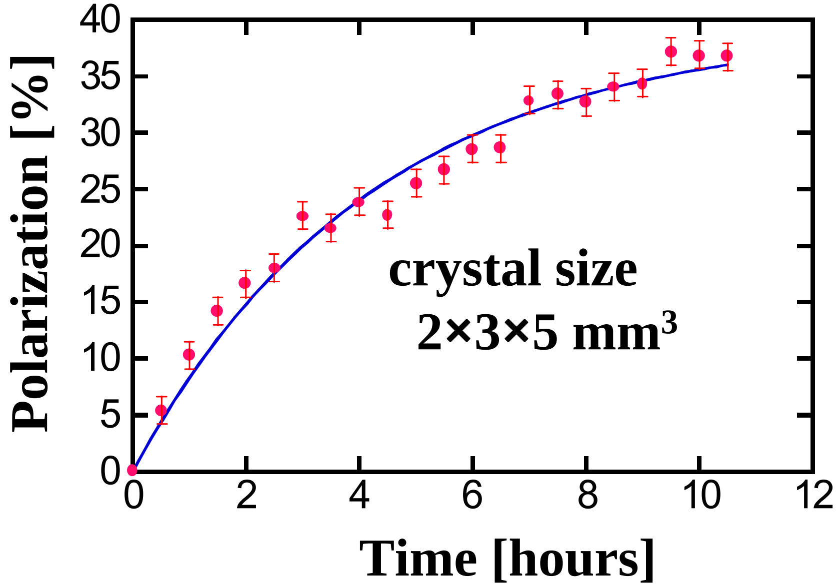
depends neither on B nor T

Test of Proton Polarization

Test with a small crystal

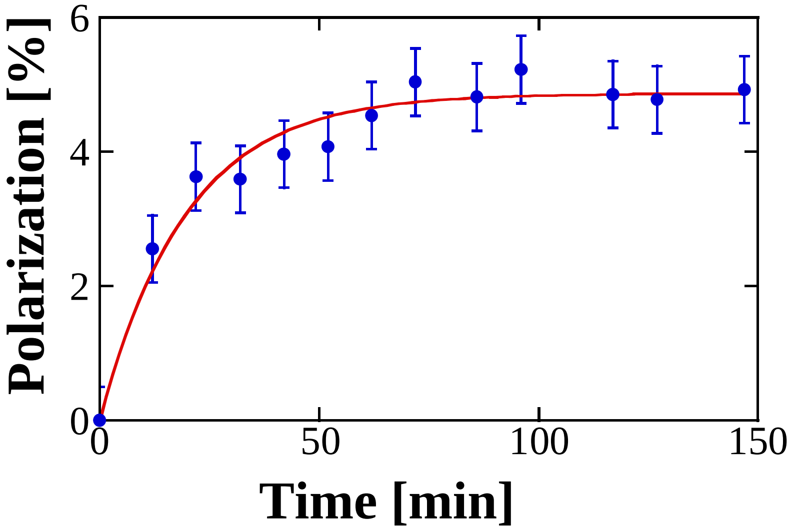
T. Wakui et al., NIM A 526 (2004) 182 & NIM A 550 (2005) 521.

Polarization in naphthalene at 0.3 T, 100K



crystal size $2\times3\times5\ \mathrm{mm}^3$

Polarization in p-terphenyl at 0.3T, room temperature



Proton polarization : 36.8± 4.3%
(39.3± 4.6%)

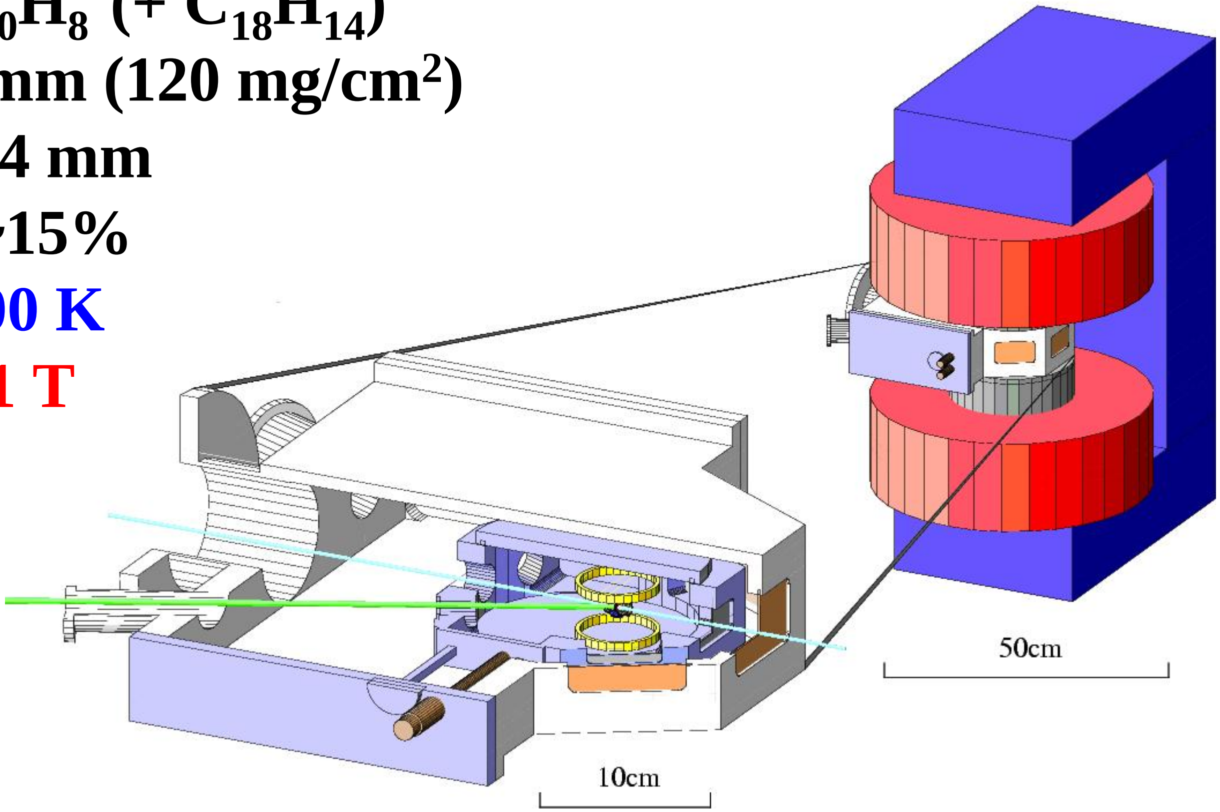
4.8±1.2%

enhancement factor > 5×10^4

Solid Polarized Proton Target at CNS

New Polarized Proton Target applicable to RI beam exp.

material: $C_{10}H_8$ (+ $C_{18}H_{14}$)
thickness: 1 mm (120 mg/cm^2)
size: ϕ14 mm
polarization: P~15%
temperature: 100 K
mag. field: 0.1 T



T. Wakui et al., NIM A 550 (2005) 521.
T. Uesaka et al., NIM A 526 (2004) 186.
M. Hatano et al., EPJ A 25 (2005) 255.

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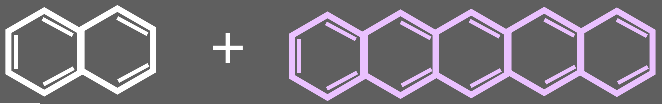
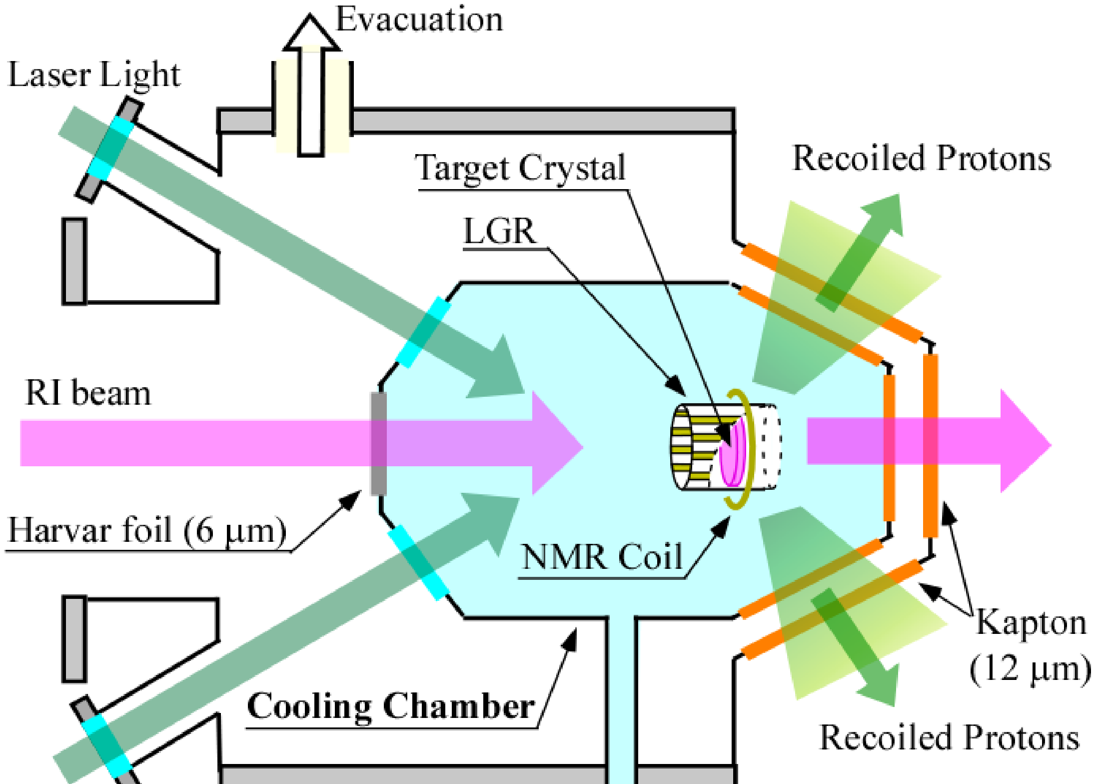
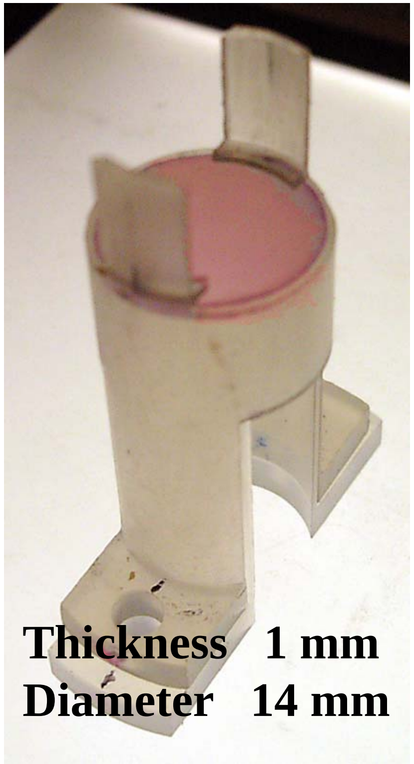
Around the Target



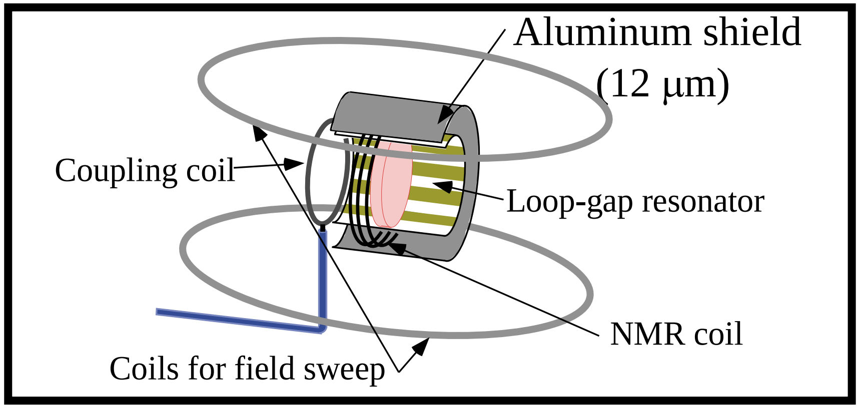


Cold N_2 Gas

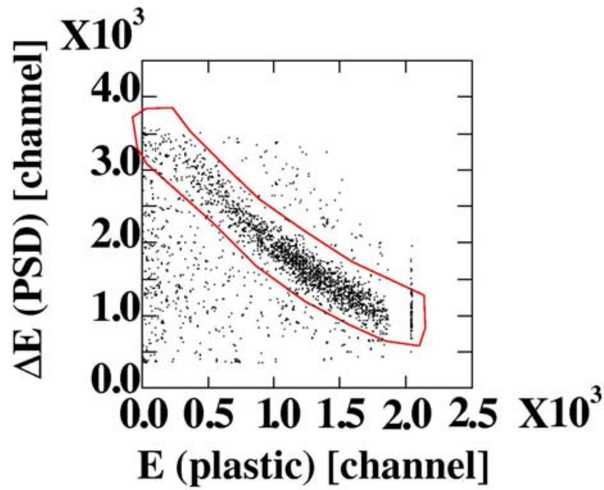
100 K



Thickness 1 mm
Diameter 14 mm



Recoil Proton Detection



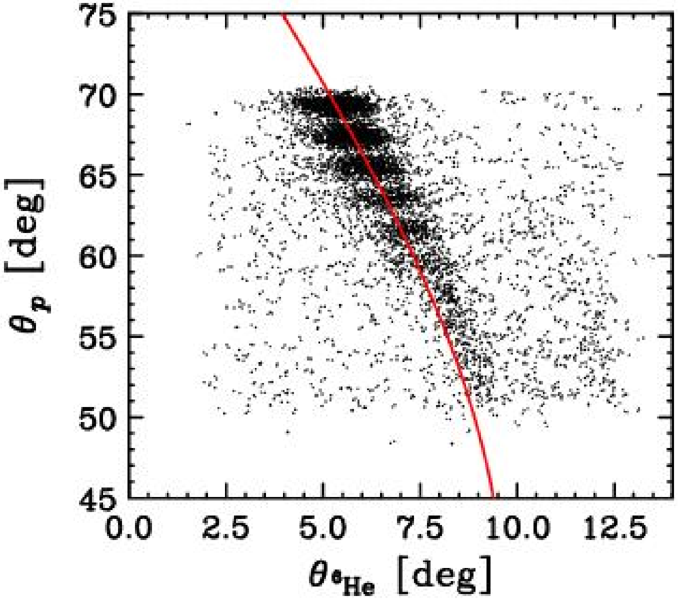
Energy of recoil protons

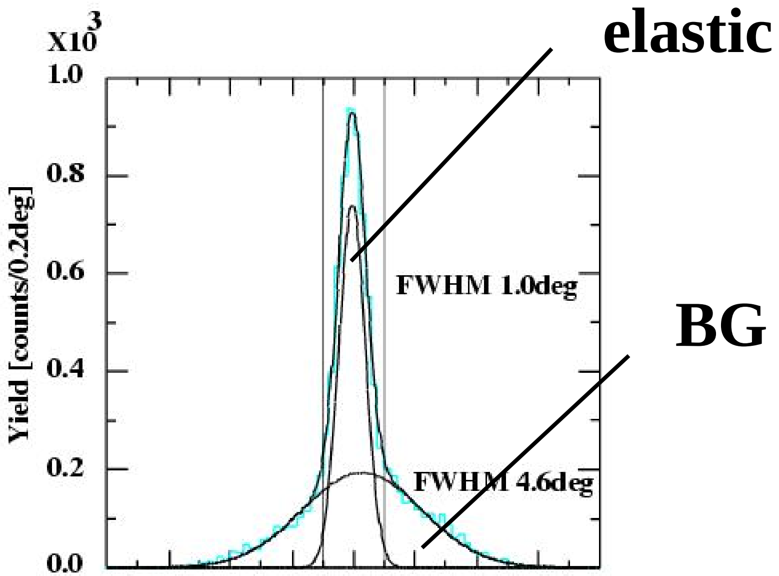
several - 100 MeV (depending on θ_p)

Background rejection

θ_p-θ_{6He} Correlation

ϕ_p-ϕ_{6He} Correlation





$$\Delta\phi = |\phi_{^6\mathrm{He}} - \phi_p|$$

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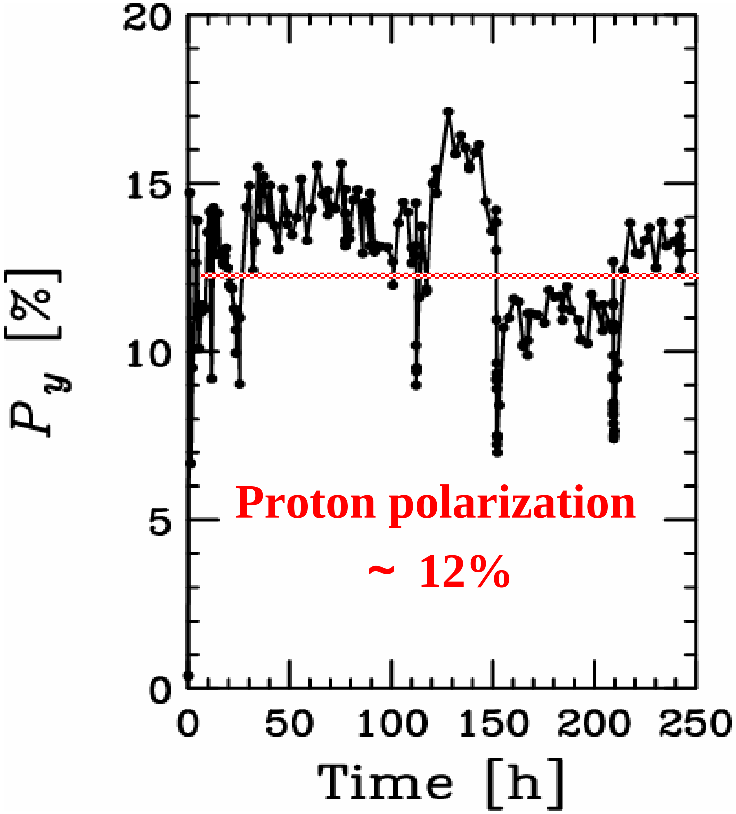
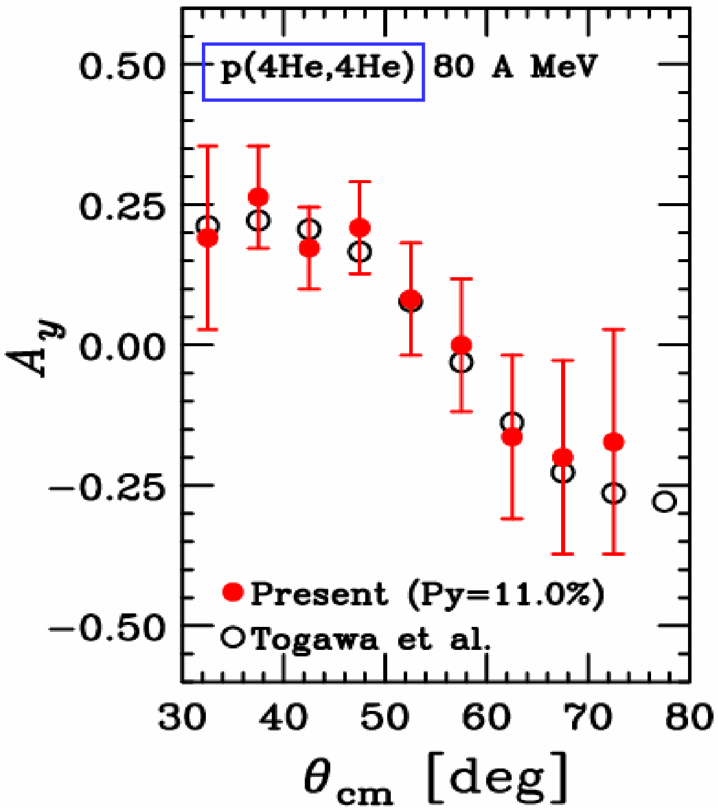
Proton Polarization



Proton polarization
~ 12%



12% target polarization was obtained.

→ << 37% for a small crystal: limited by the laser power.

A_y for *p*-^{4}He elastic scattering was reproduced.

p-^{6,8}He Elastic Scattering

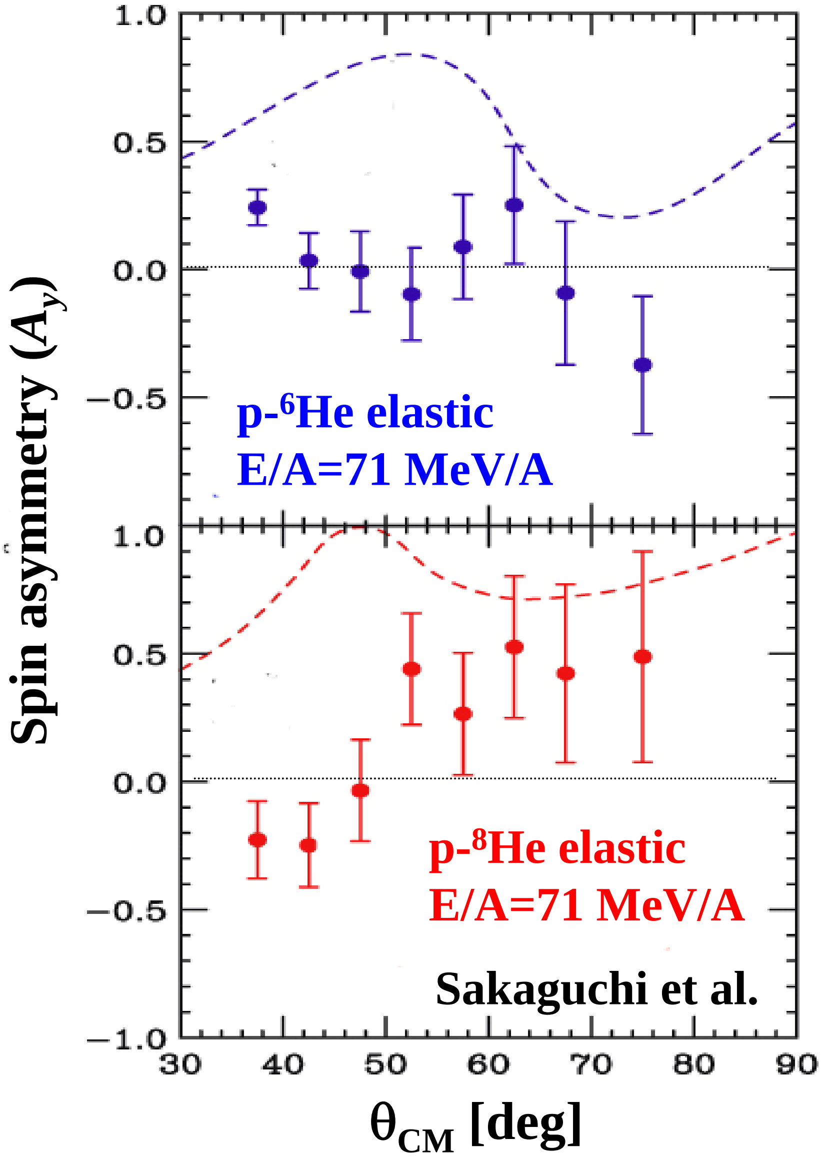
The polarized target has been successfully applied to RI-beam experiments at RIPS

spin-asymmetry in the p-^{6,8}He elastic scattering at 71 MeV/A.

Large discrepancies between data and microscopic theory (dashed lines)

S. P. Weppner et al.
Phys. Rev. C **61** (2000) 044601.

Angular distributions for p-^{6}He and p-^{8}He are different

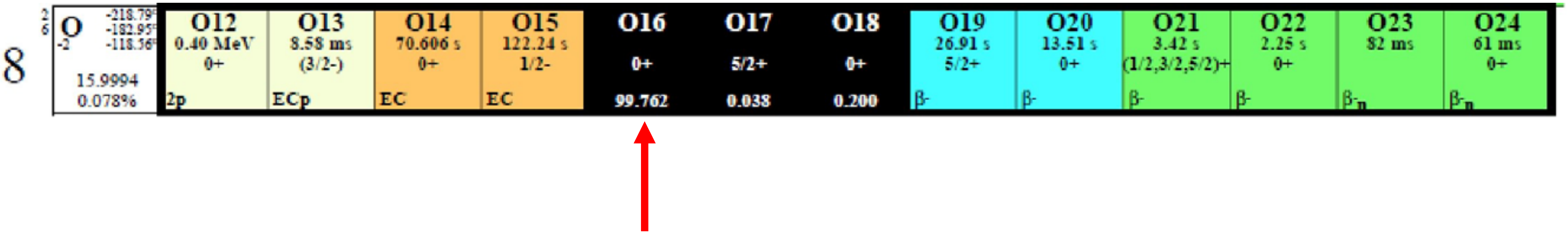


Sakaguchi et al.

Planned experiments at RIBF

Single hole state spectroscopy and

determination of ΔE_{ls} in neutron/proton-rich O isotopes



8	2 6 O -2 -218.79 -182.95 -118.56 15.9994 0.078%	O12	O13	O14	O15	O16	O17	O18	O19	O20	O21	O22	O23	O24
		0.40 MeV	8.58 ms	70.606 s	122.24 s				26.91 s	13.51 s	3.42 s	2.25 s	82 ms	61 ms
		0+	(3/2-)	0+	1/2-	0+	5/2+	0+	5/2+	0+	(1/2,3/2,5/2)+	0+		0+
		2p	ECp	EC	EC	99.762	0.038	0.200	β-	β-	β-	β-	β-$_n$	β-$_n$

ΔE_{ls}(1p,proton) ~ 6 MeV

→ **heavier elements in future**

$(\vec{p}$,pN) at RIBF

E/A = 200–300MeV:

best energy for the study

1) weak distortion for incoming and scattered proton

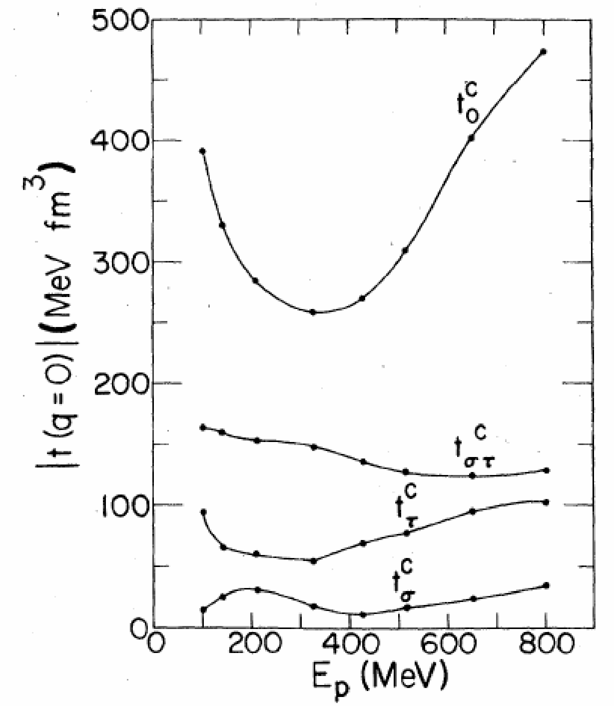
E_p=150 - 250MeV

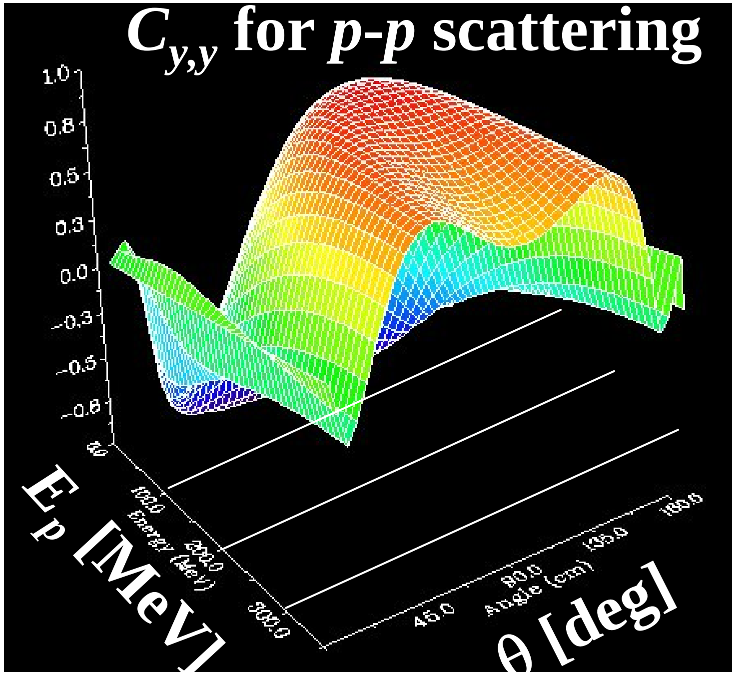
2) modest absorption for recoiled nucleon

E_N=50 - 100MeV

3) large spin-correlation parameter in N-N scattering

$C_{y,y}$ ~ 0.8





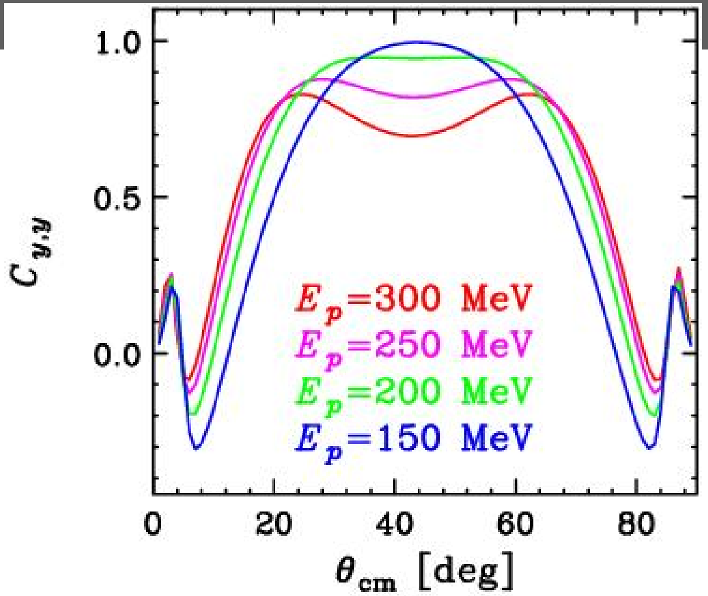
(possible) Experimental Setup

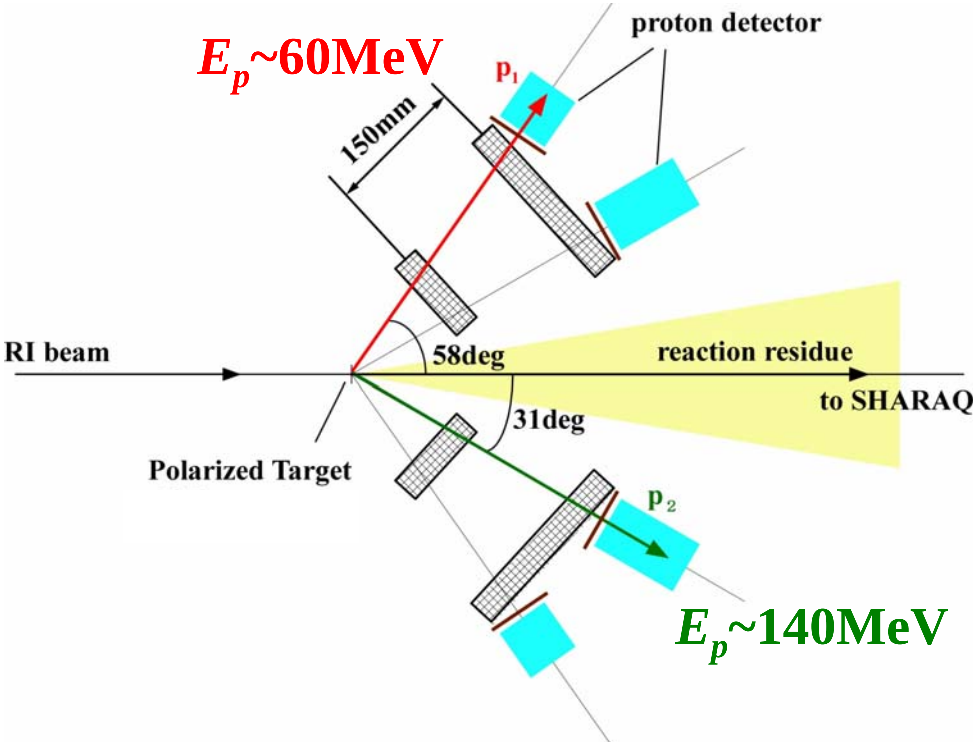
Large spin correlation coeff.

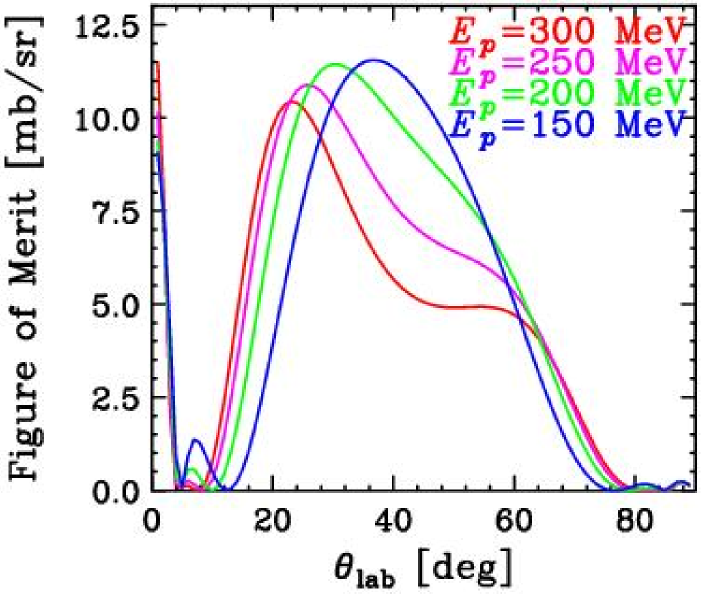
→ E_p=200 MeV

Large figure of merit ($d\sigma/d\Omega \times C_{y,y}^2$)

→ θ_{lab} ~ 30 deg







Feasibility

Target thickness should be optimized: statistics ⇔ resolution:

Target thickness:	**10^{21} /cm^2 (<u>0.25mm-thick target</u>)** **to be developed (1mm at present)**
Beam intensity:	**10^5 /sec**
Cross section	**0.1 mb** **(θ_{lab}=30–40deg, $\phi_{lab}<\pm30$deg)** **large solid angle: merit in inv. kinematics**
Polarization	**0.3 (to be developed. 0.15 at present)**

1-day measurement

→ $\Delta A_y/A_y \sim 0.05$ for a state with a unit spectroscopic factor

Resolution

ΔE_s depends on beam momentum(p_{beam}), energies (E_N) and scattering angles (θ_N) of scattered/recoiled nucleons.

$\Delta E_s \sim 5\ \mathrm{MeV}\times(\Delta p_{\mathrm{beam}}/p_{\mathrm{beam}})$

2 % resolution for $\Delta p_{\mathrm{beam}}/p_{\mathrm{beam}}$

$\Delta E_s \sim 10\ \mathrm{MeV}\times(\Delta E_N/E_N)$

a few % resolution for $\Delta E_N/E_N$

$\Delta E_s \sim 0.3\ \mathrm{MeV}\times\Delta\theta_{\mathrm{N}}$ [mrad]

$\Delta\theta_{\mathrm{N}} \sim 1.5$ mrad

← multiple scatt. in the target (0.25mm)

→ $\Delta E_s \sim 0.5$ MeV

Summary

- “Model independent” determination of ΔE_{ls} is made possible by spin-asymmetry measurements with polarized target.

- N/Z-dependences of spin-orbit splitting are of critical importance in understanding
  - shell regularity at far from the stability line
  - microscopic origins of SO coupling in nuclei

- Polarized proton solid target developed at CNS has brought into a practical use in RI beam experiments.

- (p,pN) measurements at RIBF will provide a unique opportunity to investigate SO coupling in n-/p-rich nuclei.