Spin-orbit Splitting in Oxygen Isotopes Studied via $(\vec{p}, 2p)$ Reaction

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- Introduction
  - Spin-orbit coupling
  - Why oxygen?
  - Exclusive measurement of the (*p*,2*p*) reaction as a spectroscopic tool
- Experiments
  - E349 exp.: ^{16,18}O(p,2p)
  - SHARAQ04 exp.: ^{14,22,24}O(p,2p) *(analysis WIP)*
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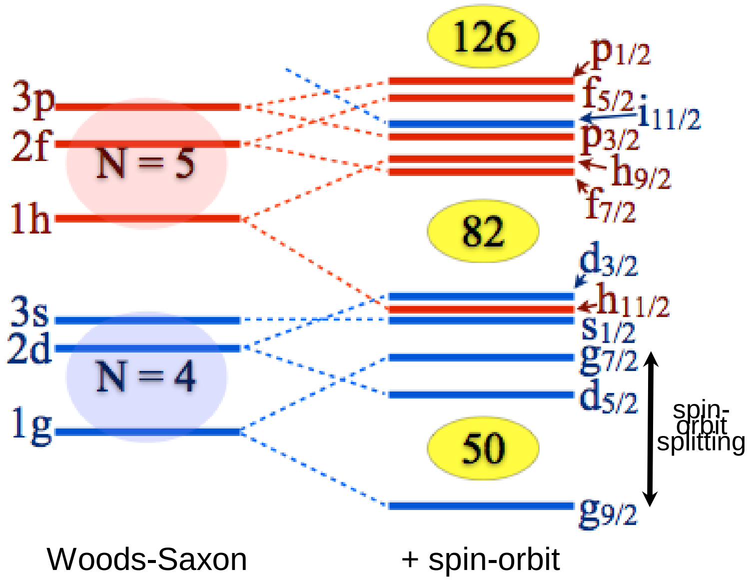
Spin-orbit coupling in nuclei

- Strong spin-orbit coupling …
  - is unique to nuclear system
  - explains magic numbers of nuclei



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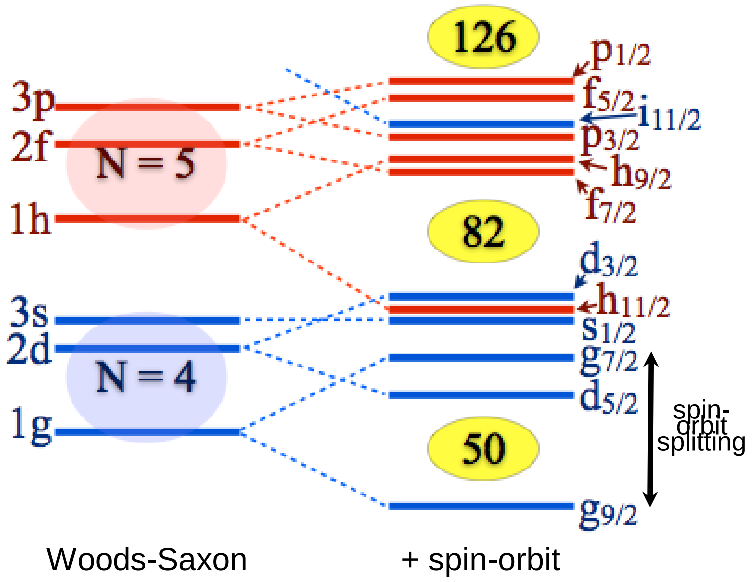
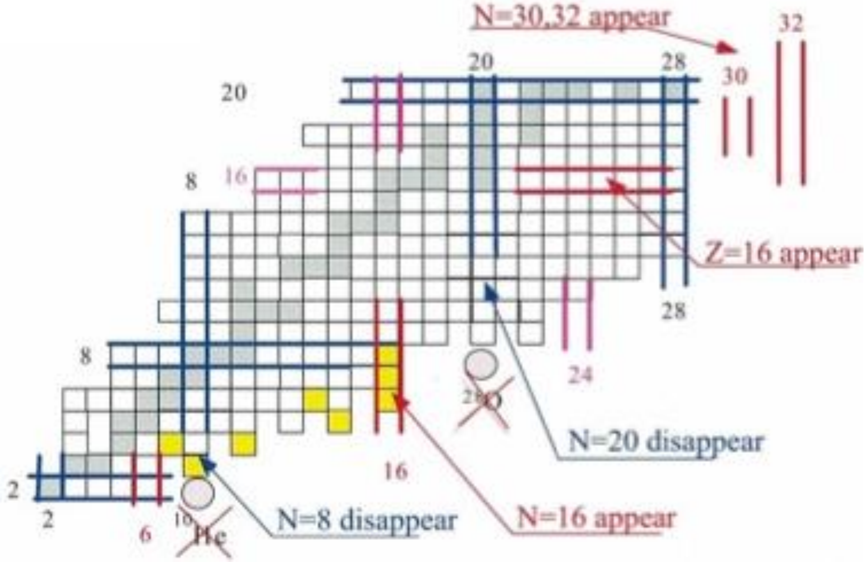


- (Dis)appearance of magic numbers in unstable region

  A. Ozawa *et al.* Phys. Rev. Lett., **84**, 5493 (2000).

- Spin-orbit interaction makes dissolution of clusters (Cluster-shell competition)

  H. Masui and N. Itagaki

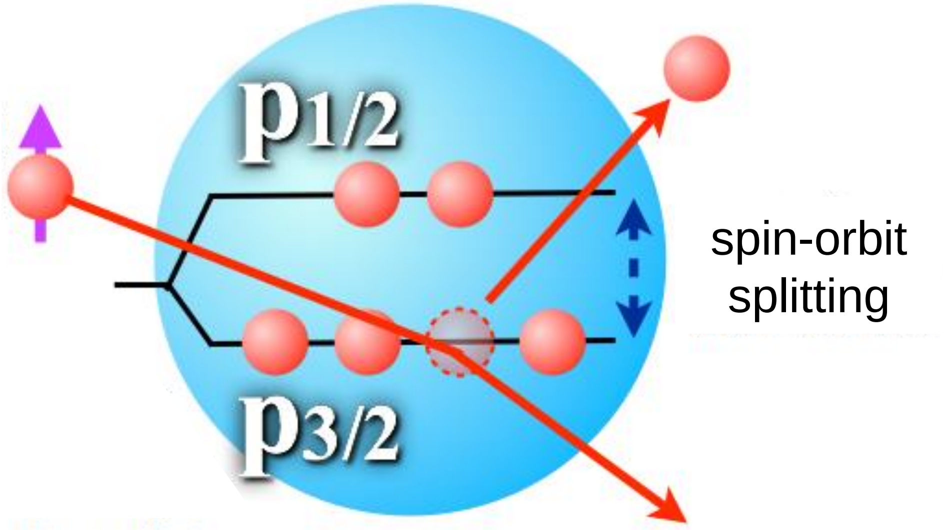


The change of the spin-orbit coupling is a key to the understanding of the evolution of nuclear structure.

Goal of this study

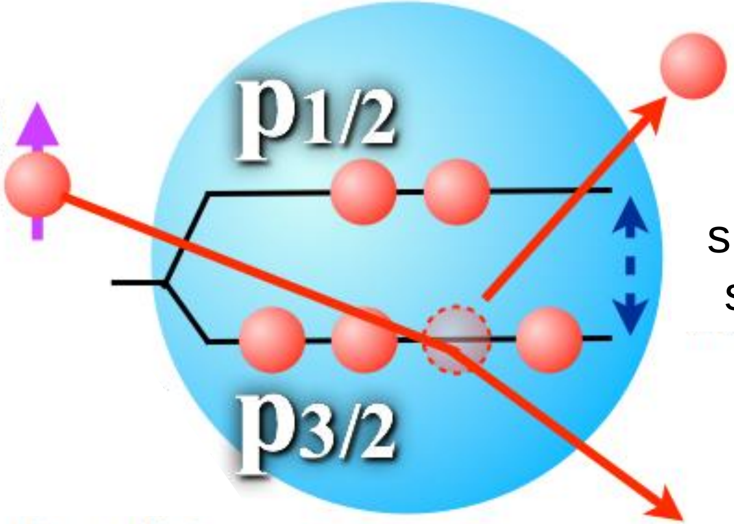
- Experimentally, spin-orbit splitting is the most direct measure that we can determine.
- However, experimental data are scarce … especially for unstable isotopes

Goal of This study:
Determine 1p proton spin-orbit splittings in oxygen isotopes
as a function of neutron number



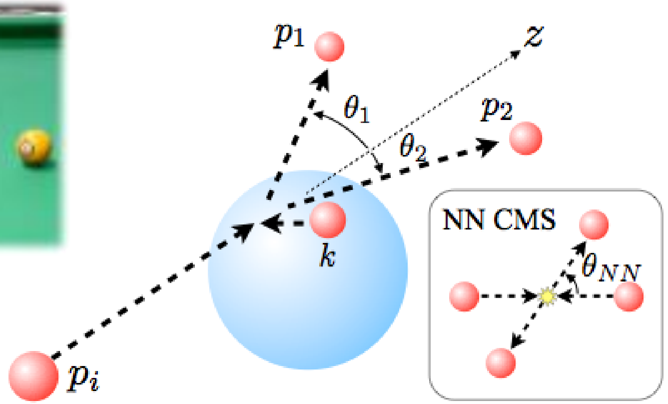
Why Oxygen?

- ✓ Proton magicity ($Z = 8$)
  - Shell model (single-particle orbit) picture goes well
- ✓ Moderate number of nucleons in the reach of *ab initio* calculations
- ✓ Isotopes from drip-line to drip-line are available at RIBF
  - Systematic study in wide range of isospin is capable

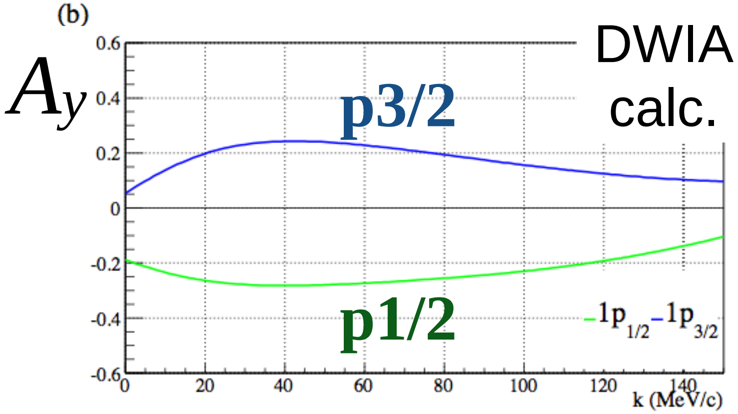


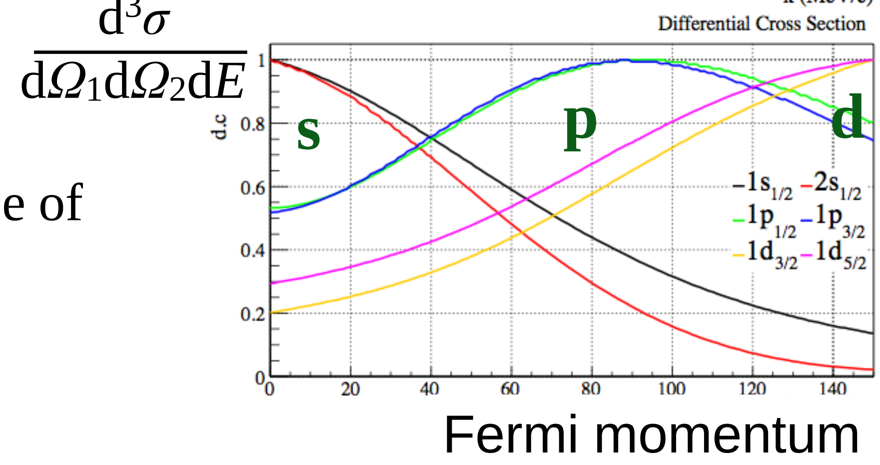
spin-orbit
splitting

Method: Exclusive measurement of the ($\vec{p}$,2p) reaction



- Impulse picture > 200 MeV
  - Selectivity populates single-hole states
  - kinematics is not restricted by momentum matching
  - Proton momentum in nucleus can be determined from momenta of two scattered protons
- Spin-parity can be determined by momentum dependence of differential cross section (→L) and analyzing power A_y (→J)
  - The best energy region is 200-300 MeV because of the large spin correlation coefficient C_{yy} of NN scattering





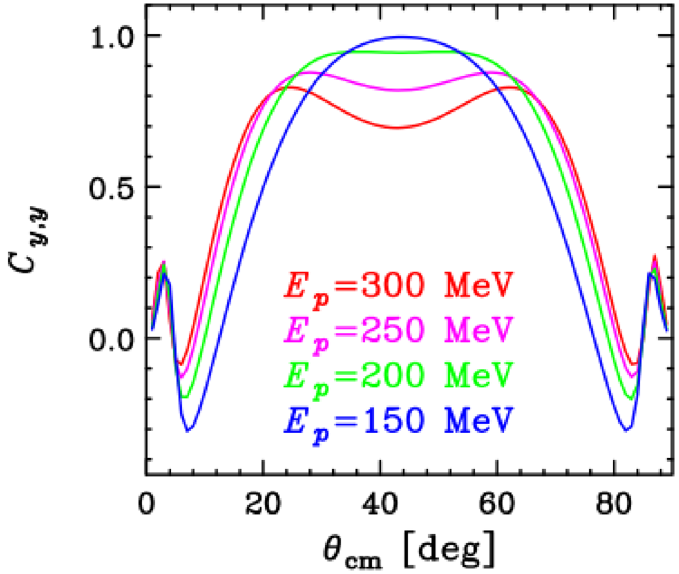
Spin asymmetry of ($\vec{p}$,2p)

Large spin-correlation coefficient Cyy

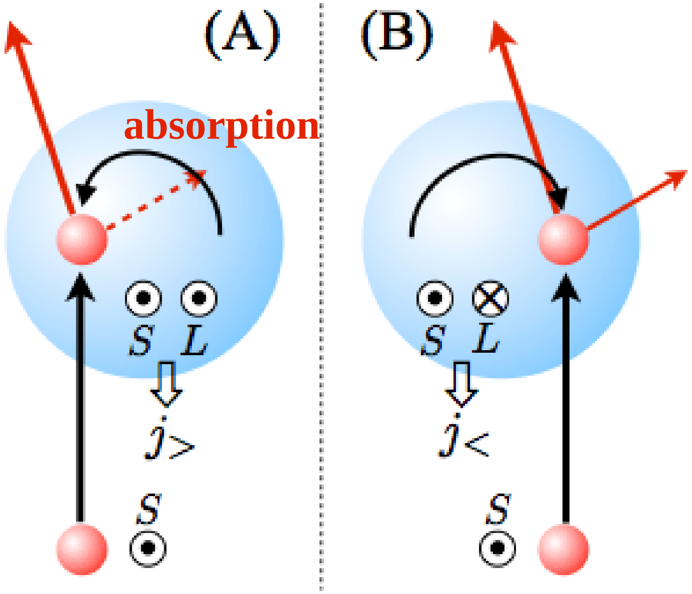
Proton absorption in nuclei

Large spin asymmetry

Model-independent spin-parity assignment!



C_{yy} for pp scattering



($\vec{p}$,2p) is an effective probe for the study of spin-parity of single particle orbit

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E349 Collaboration

CNS, U. Tokyo	S. Kawase, S. Ota, H. Tokieda, K. Kisamori, M. Takaki, Y. Kikuchi
RIKEN Nishina Center	*T. Uesaka*, M. Dozono
Toho U.	T. Kawahara
RCNP, Osaka U.	A. Tamii, T. Suzuki
Kyoto U.	T. Kawabata, N. Yokota, Y. Nozawa
Kyushu U.	T. Noro, T. Wakasa, M. Okamoto
U. Miyazaki	Y. Maeda, T. Saito, H. Miyasako

E349 Experiment: $^{16,18}O(p,2p)$

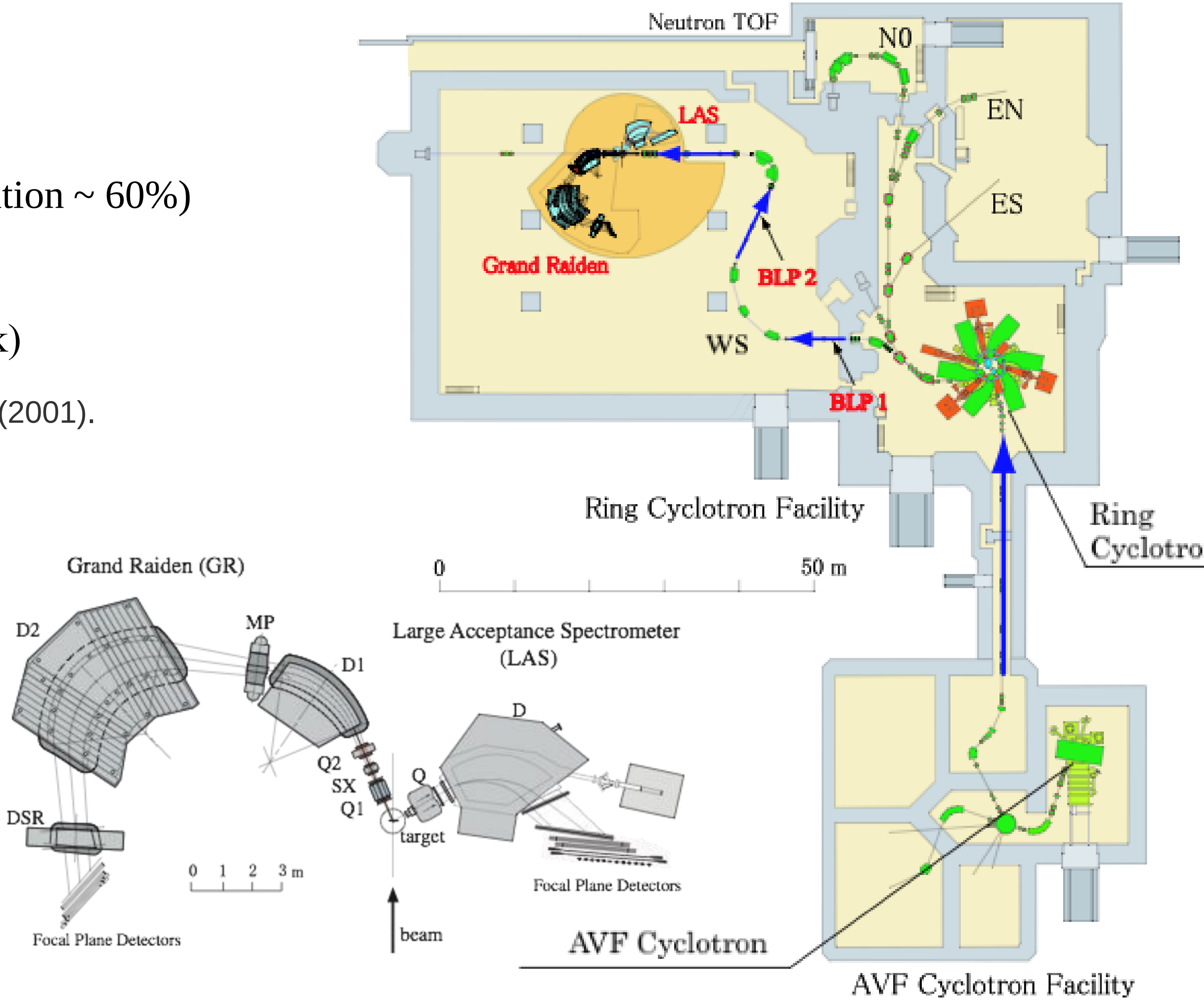
@RCNP, Osaka U.

$^{18}O(p,2p)$ in **normal** kinematics

Polarized proton beam (Polarization ~ 60%)
@ 200 MeV, 200 nA

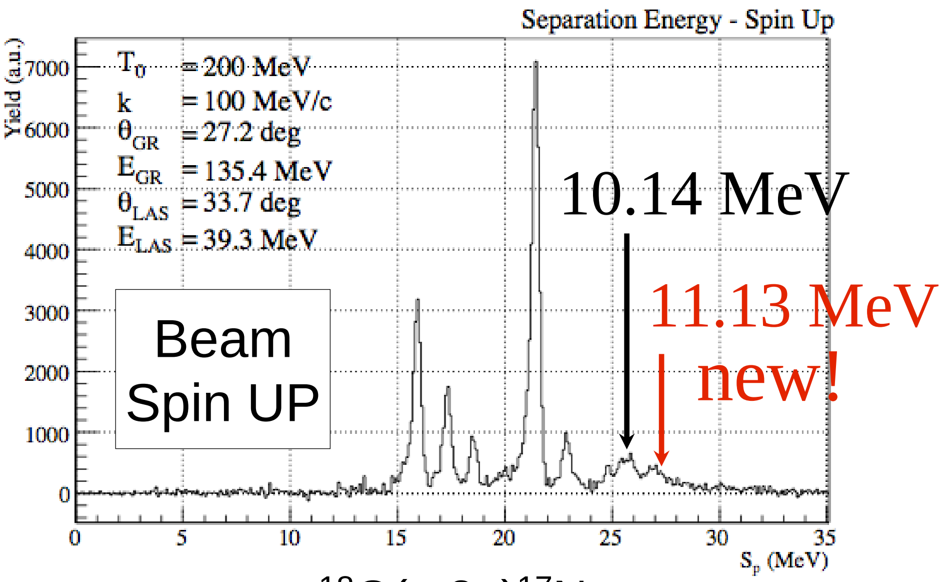
$H_2{}^{18}O$ ice target (~ 200 μm thick)

T. Kawabata *et al.*, NIM A **459**, 171 (2001).

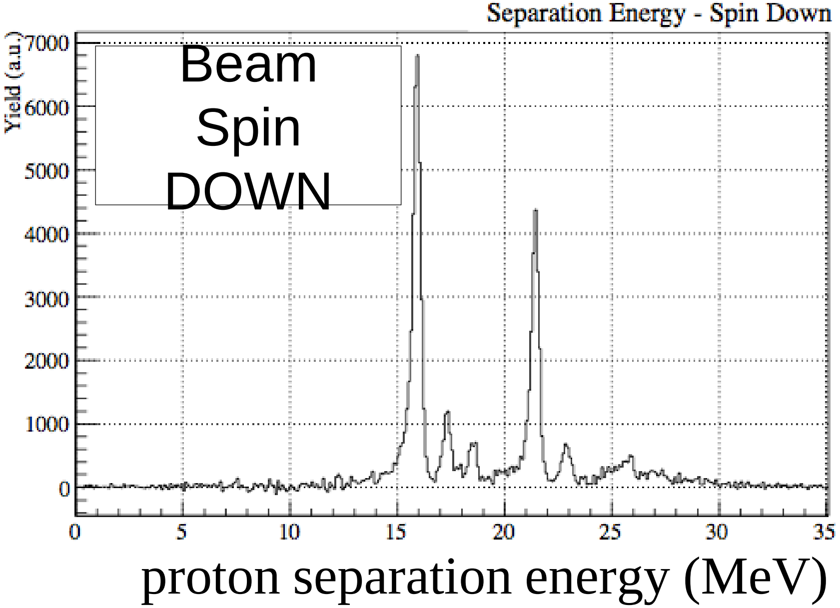


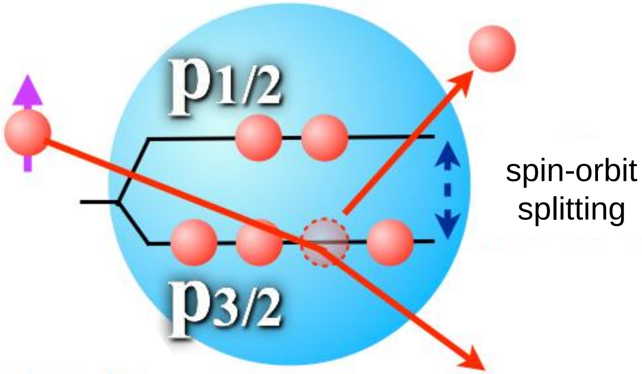
Separation Energy Spectra

- Each peak corresponds to a 1-hole state of ^{17}N =
- A new state was observed at ~ 11 MeV
- Energy resolution ~ 300keV
  (Main source = multiple scat. in the ice target)
- Spin asymmetry is clearly opposite for 2 large peaks.

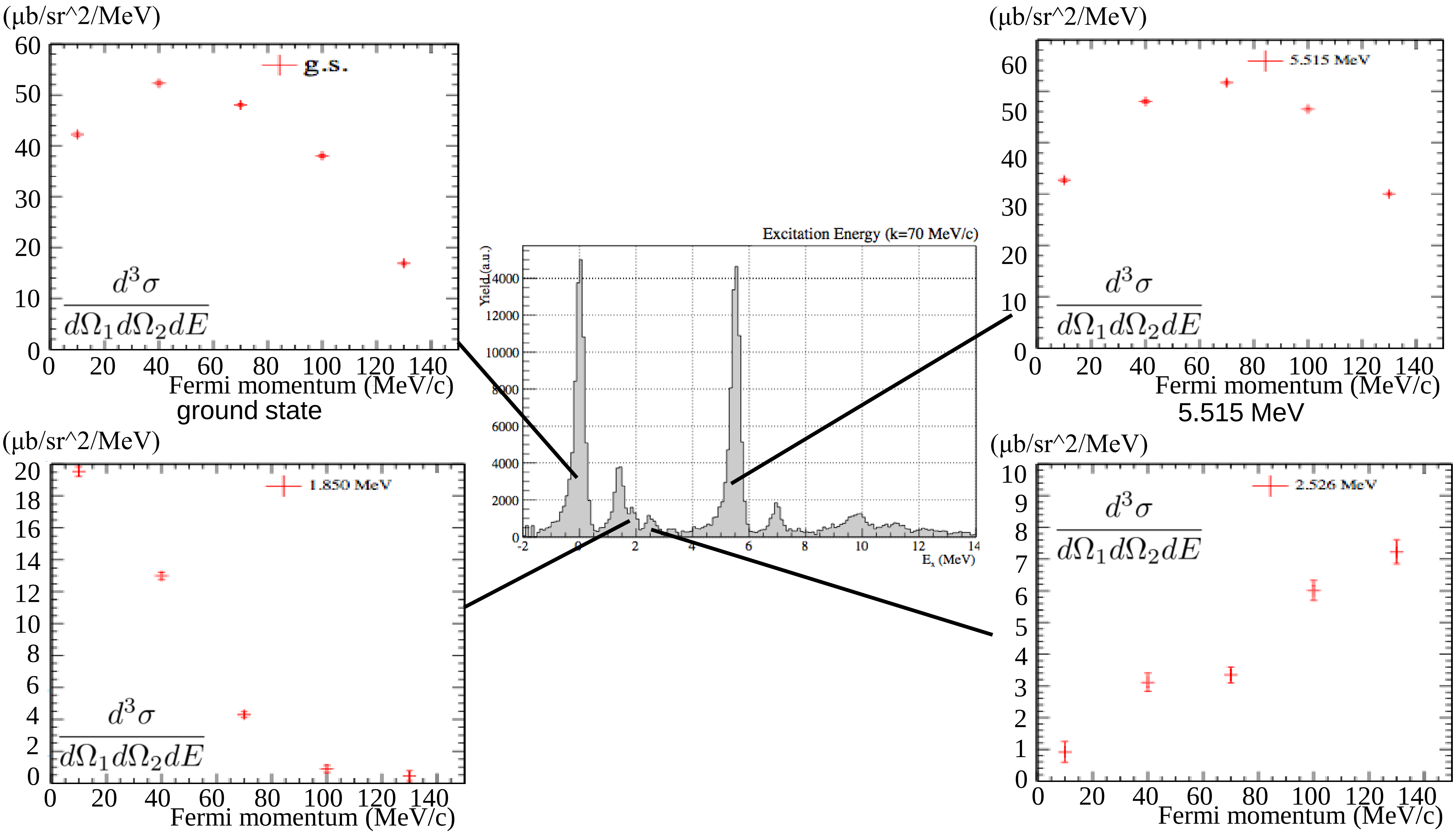


^{18}O(p,2p)^{17}N





Comparison w/ DWIA: Differential Cross Section



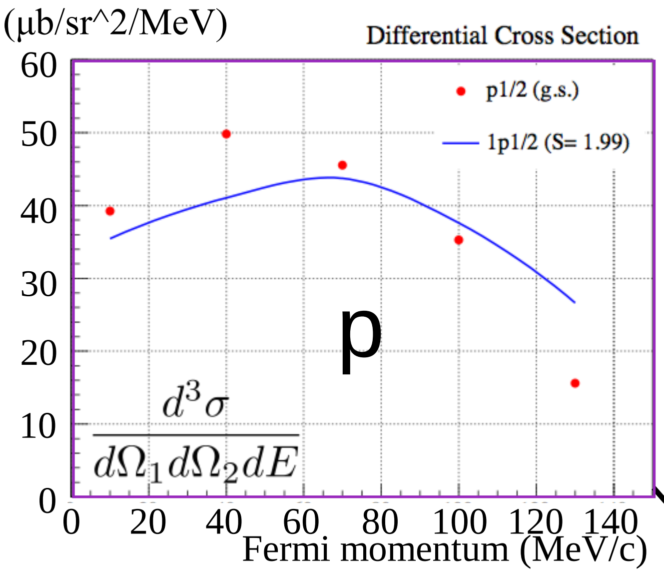
ground state

5.515 MeV

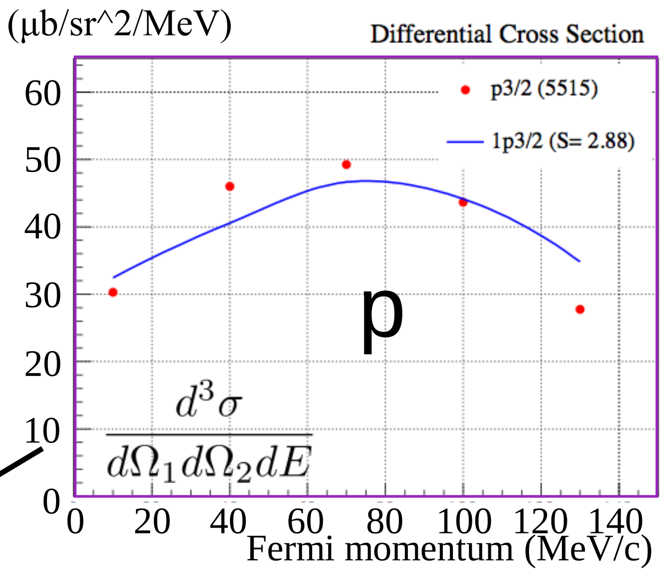
1.850 MeV

2.526 MeV

Comparison w/ DWIA: Differential Cross Section



ground state



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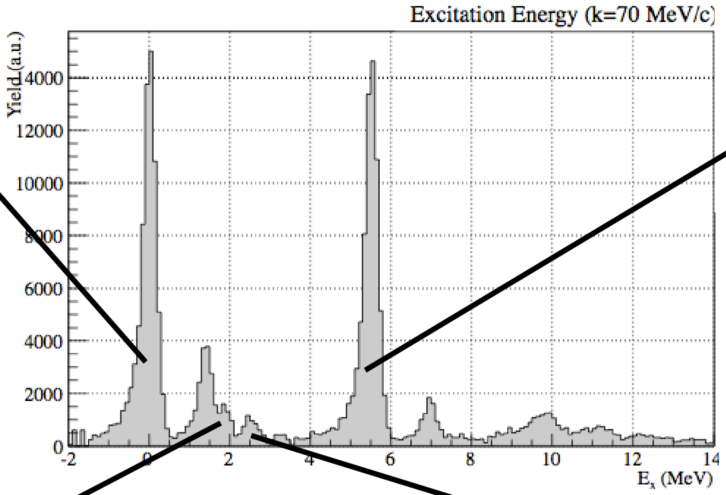
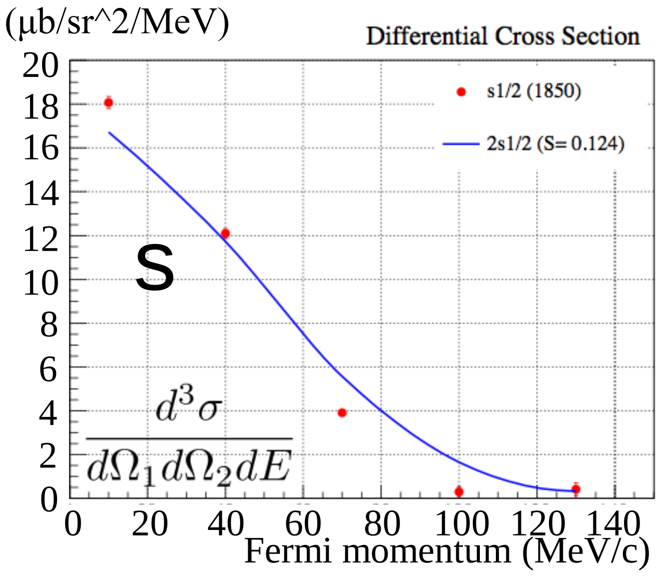
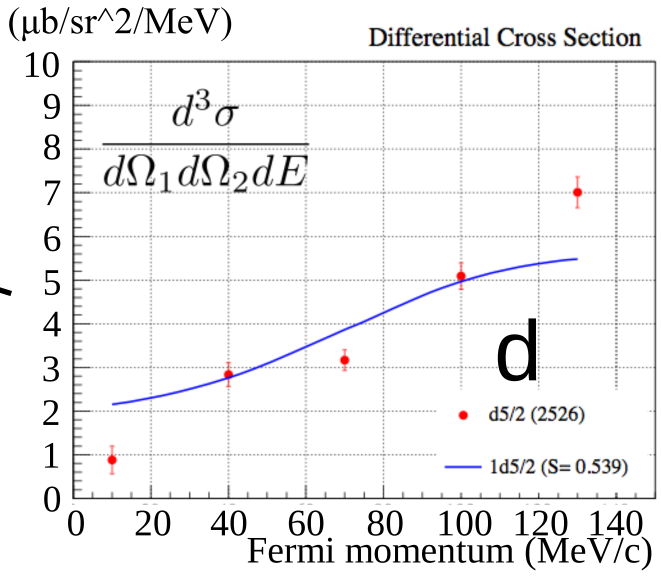




1.850 MeV

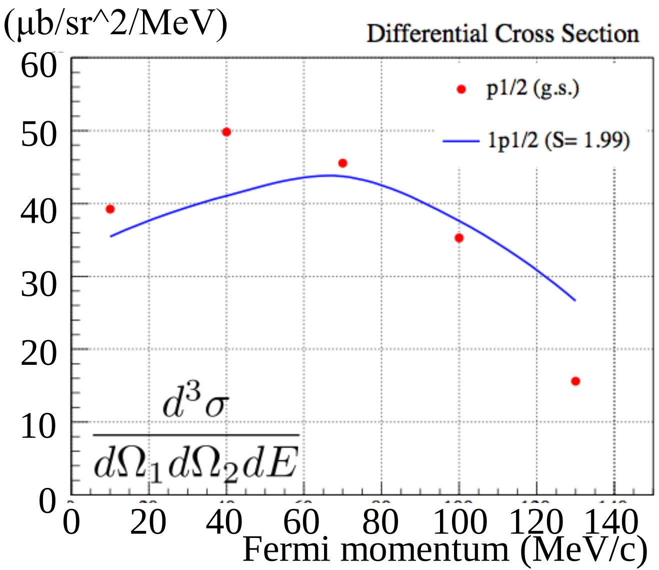
the calculation reproduces the dependence very well!



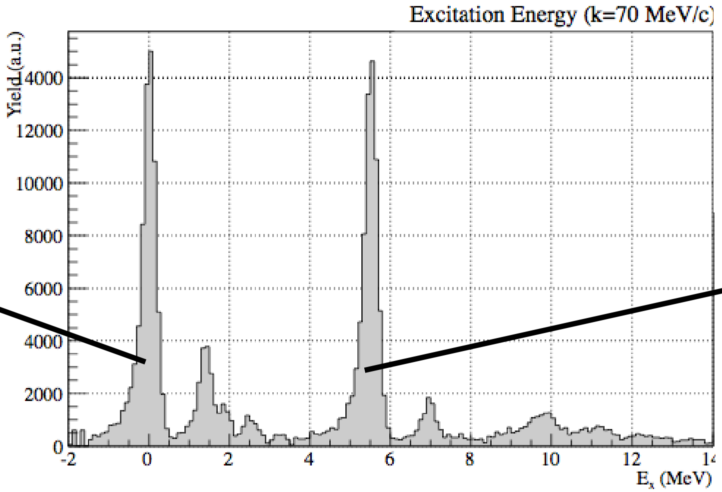
2.526 MeV

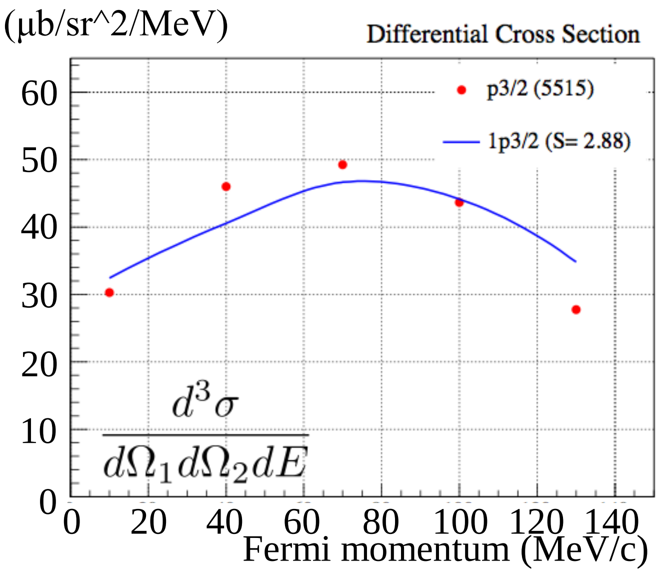
Intuitive ID of s, p, d!

Comparison w/ DWIA: Analyzing Power

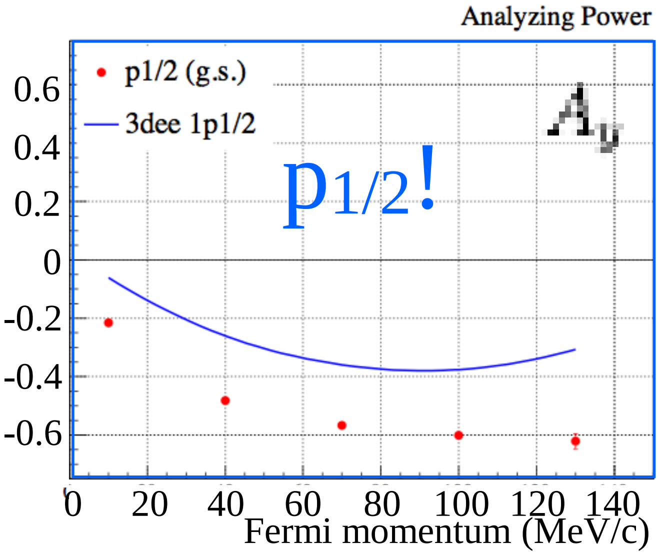


ground state





5.515 MeV

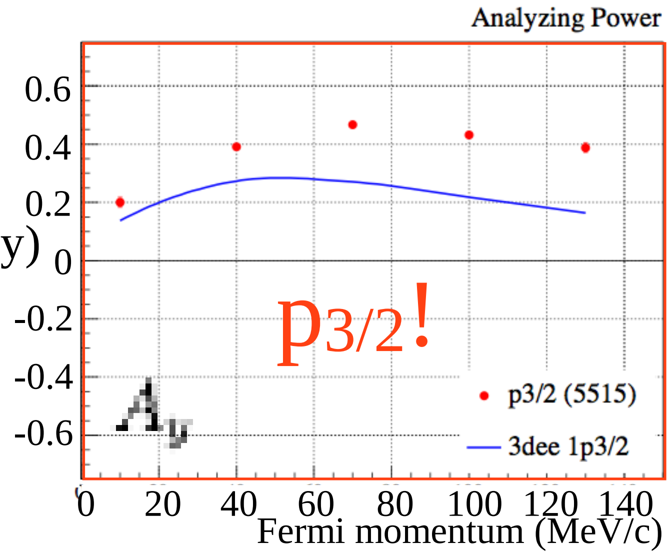


$p_{1/2}$!

A_y: analyzing power (spin asymmetry)

A_y has J-sensitivity!

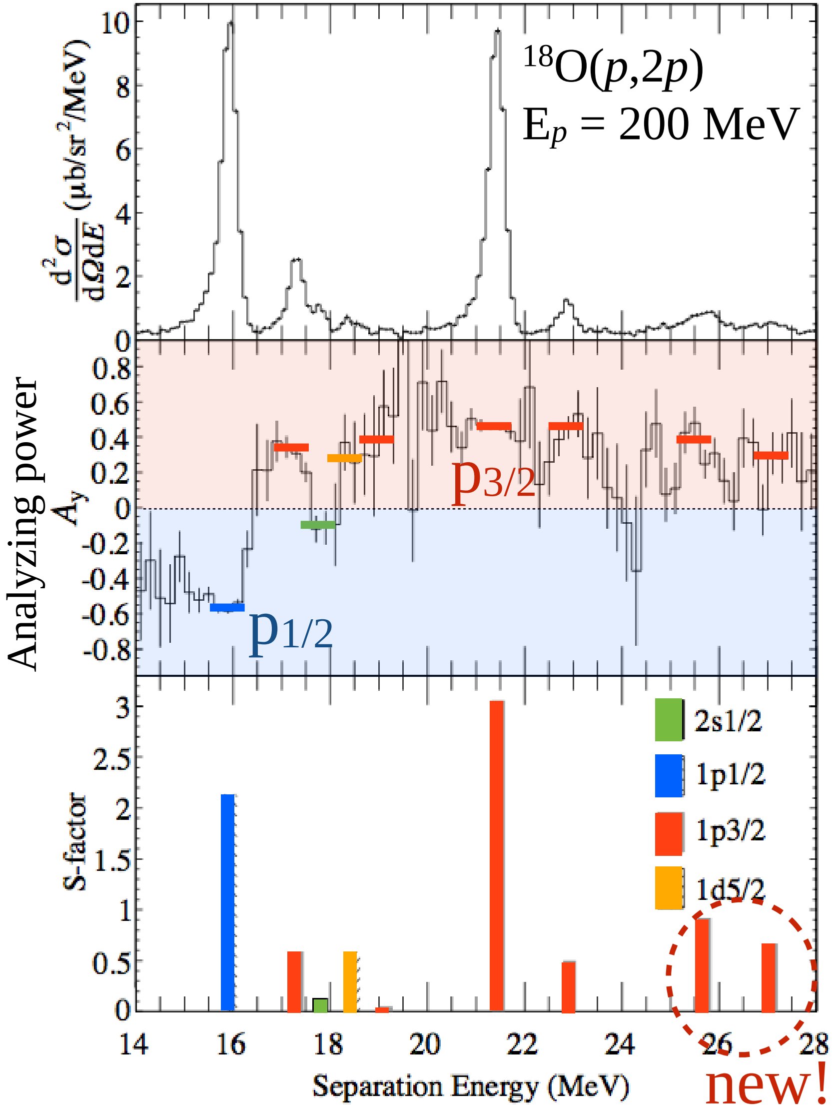
$A_y < 0$: $p_{1/2}$
$A_y > 0$: $p_{3/2}$



$p_{3/2}$!

Result for ^{18}O($\vec{p}$,2p)

S.K. *et al.*

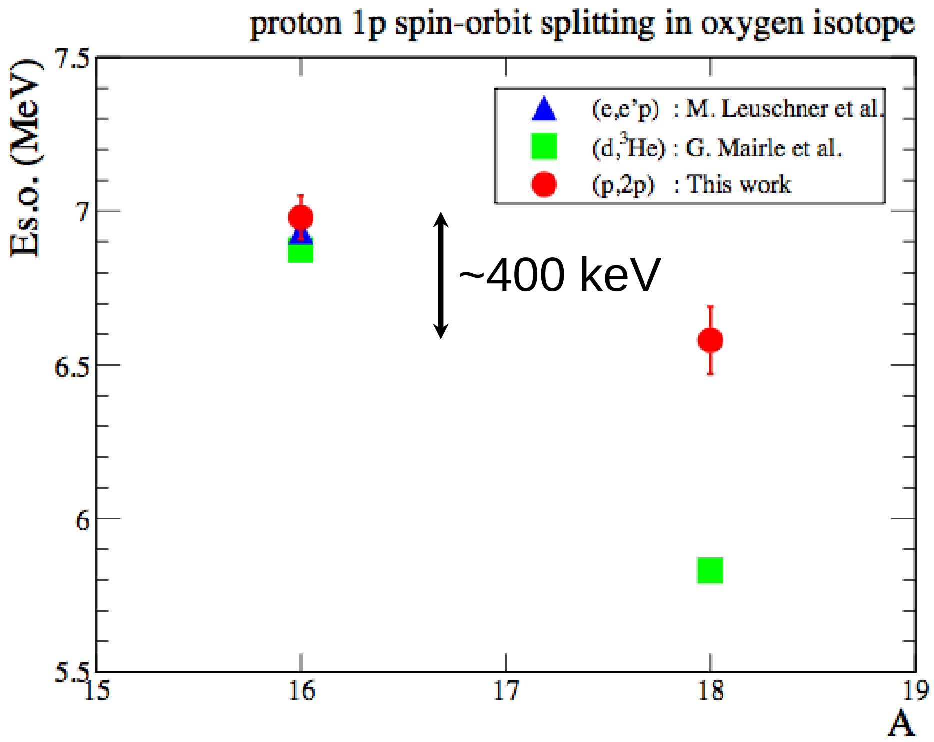


spin-orbit splitting = ESPE(p3/2) - ESPE(p1/2)

= **6.58(11) MeV**

Effective Single particle energy(ESPE):
spectroscopic-factor-weighted mean of excitation energies

Spin-orbit splitting: ^{18}O vs ^{16}O



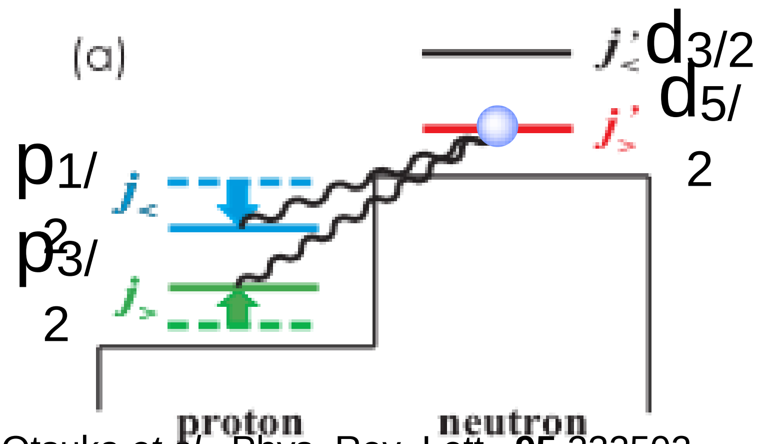
Spin-orbit splitting of ^{18}O is narrower than that of ^{16}O by ~400 keV !!

NN Tensor force narrows spin-orbit splitting?

1p LS splitting reduces by 540 keV per a neutron in $d_{5/2}$ orbit

T. Suzuki, private communication

→ One out of two neutrons in sd shell of ^{18}O is in $d_{5/2}$ orbit



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

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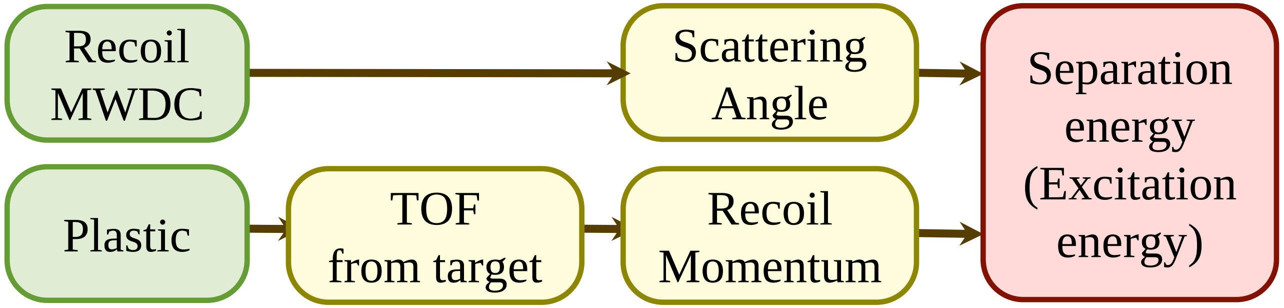
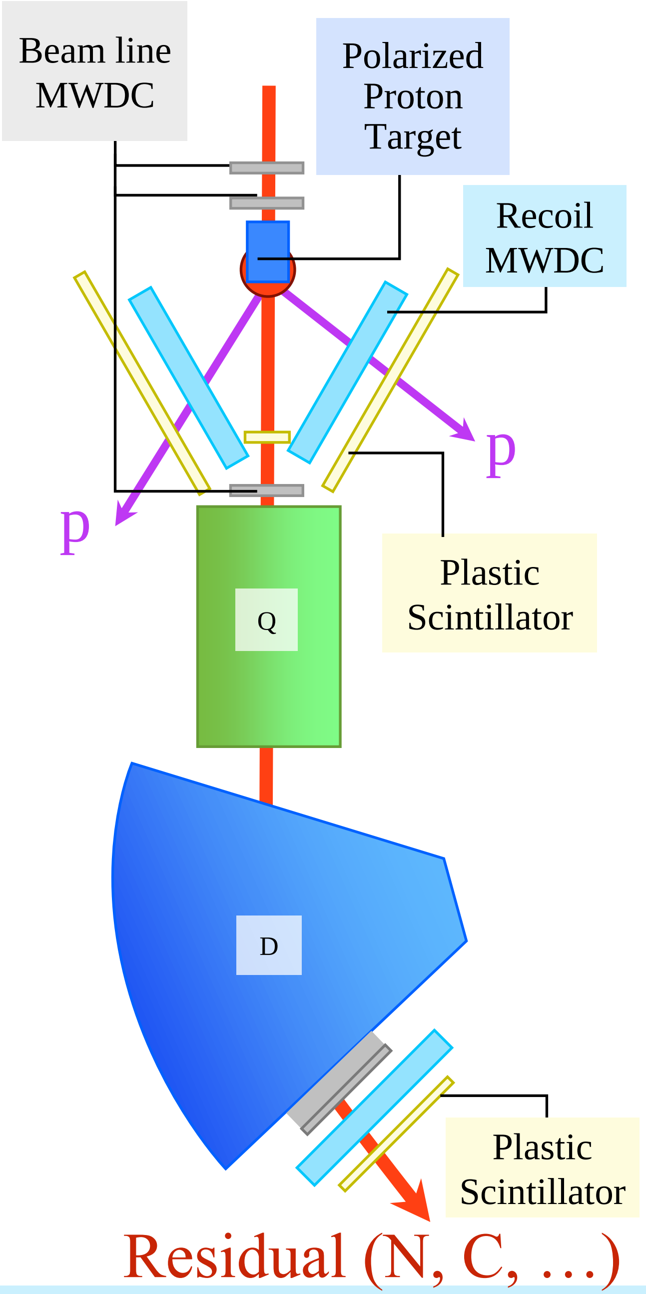
SHARAQ04 Collaboration

CNS, U Tokyo	S. Kawase, T.L. Tang, S. Shimoura, K. Yako, S. Ota, S. Michimasa, H. Tokieda, H. Miya, K. Kisamori, M. Takaki, Y. Kubota, C.S. Lee, R. Yokoyama, T. Fujii, M. Kobayashi
RIKEN Nishina Center	T. Uesaka, M. Sasano, J. Zenihiro, H. Matsubara, M. Dozono, H. Sakai, T. Kubo, K. Yoshida, N. Inabe, Y. Yanagisawa, H. Takeda, K. Kusaka, N. Fukuda, D. Kameda, H. Suzuki
Toho U.	T. Kawahara
Tohoku U.	T. Wakui
Kyushu U.	T. Noro, T. Wakasa, S. Sakaguchi, J. Yasuda, T. Fukunaga
U. Miyazaki	Y. Maeda
Kyungpook Nat'l U., Korea	W. Kim, S.H. Hwang, S.S. Stepanyan
IPN Orsay, France	D. Beaumel
CEA Saclay, France	A. Obertelli
ORNL, USA	A. Galindo-Uribarri
ICN-UNAM, Mexico	E. Padilla-Rodal

SHARAQ04 experiment: $^{14,22,24}\mathrm{O}(\vec{p},2p)$

Facility	RIKEN RIBF
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

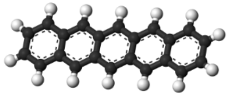

Recoil MWDC
Scattering Angle
Plastic
TOF from target
Recoil Momentum
Separation energy (Excitation energy)



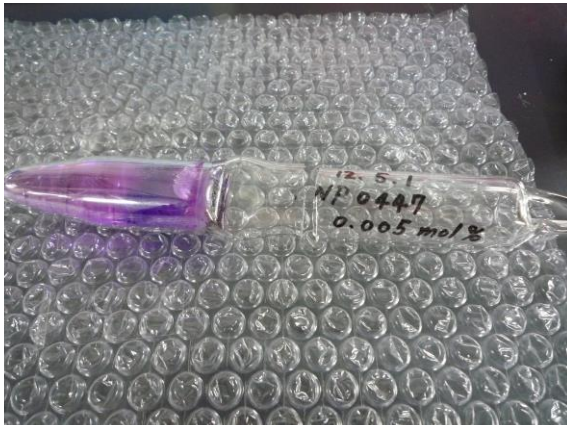
The first (*p*,2*p*) reaction measurement with polarized target!

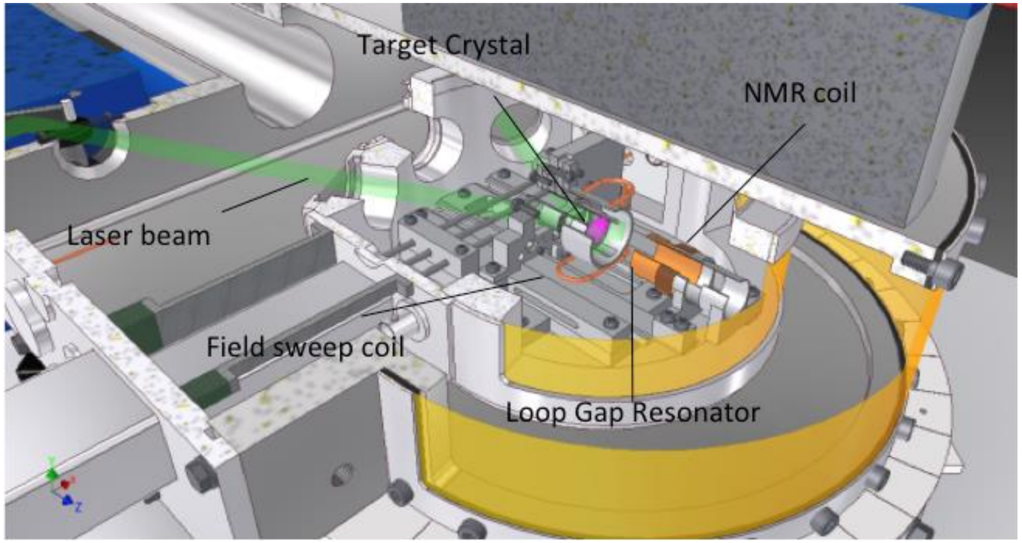
Polarized proton target

- Material: Naphthalene + Pentacene (0.005 mol%)

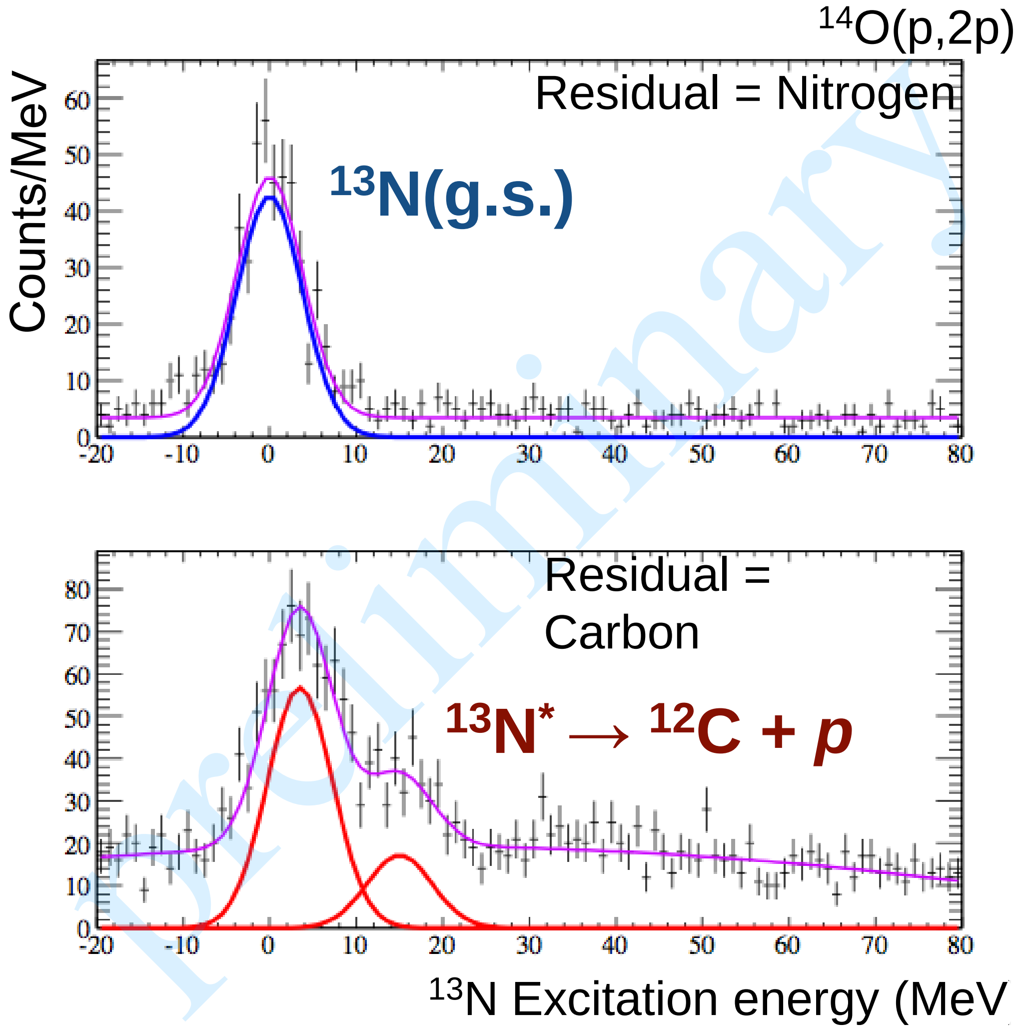


- Polarization method:
  Triplet Dynamic Nuclear Polarization (DNP)
  - Low magnetic field ~ 60 mT
  - High temperature ~ LN_2
- Polarization: 31(7)%
  (calibrated with pp elastic scattering)



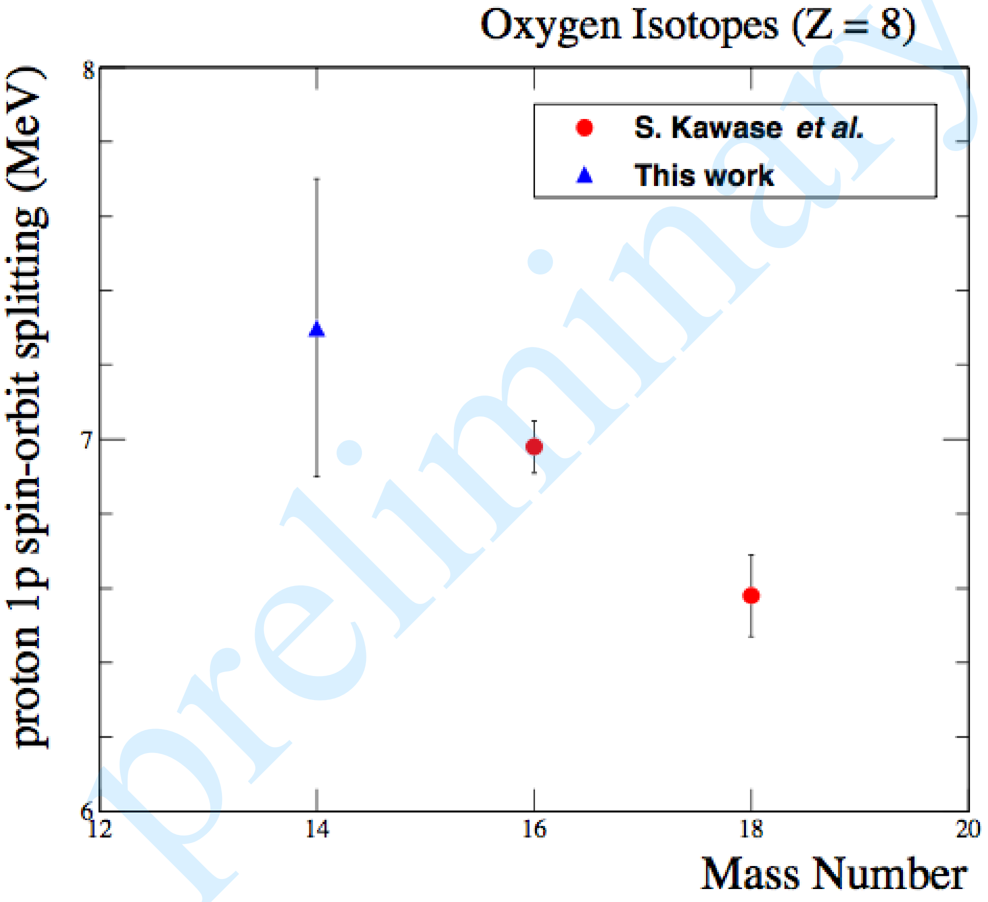


Preliminary result for ^{14}O(p,2p)

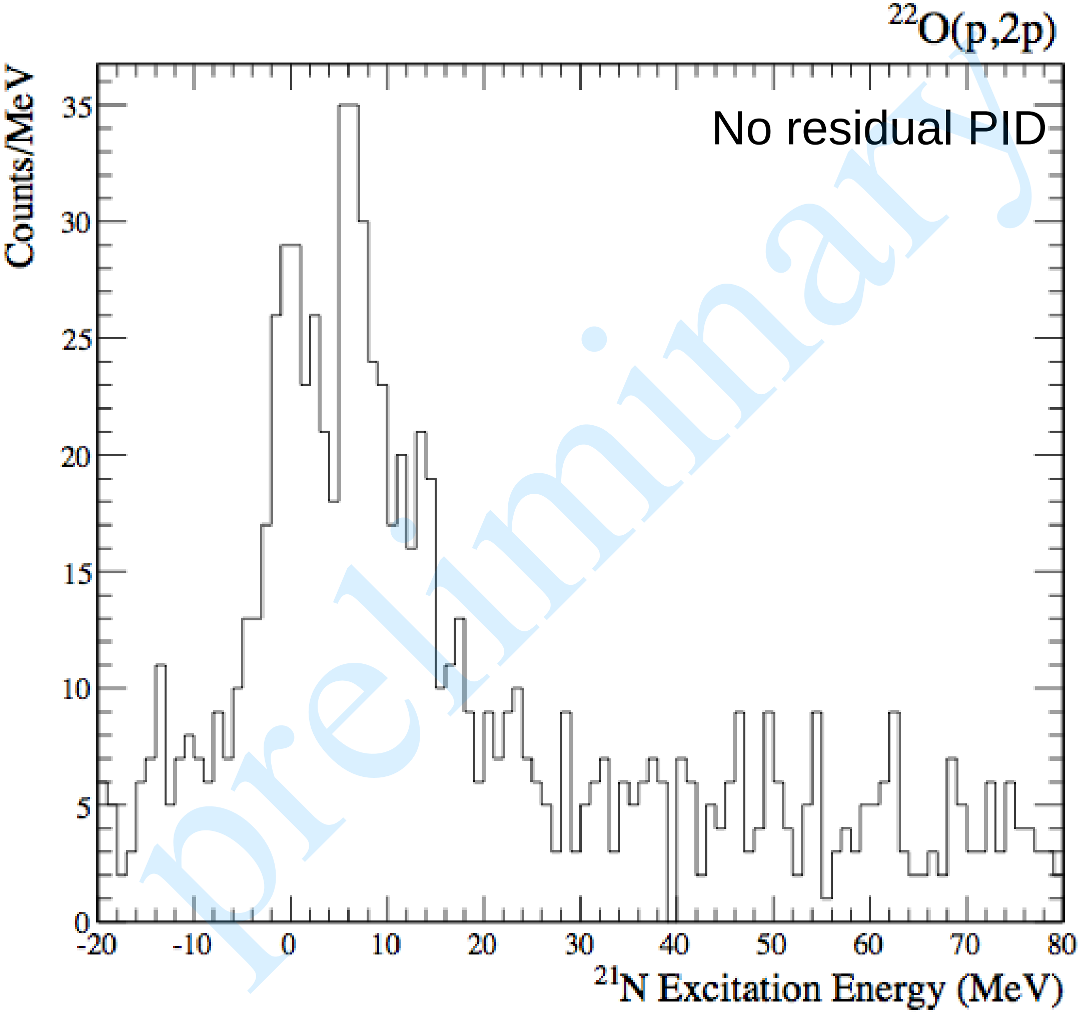


state	counts	σ_{exp} (μb)
g.s.	404(22)	229(12)
3.5 MeV	538(30)	305(17)
15 MeV	162(24)	92(14)

Polarization analysis has not been done yet.



^{22}O(p,2p) spectrum



Polarization analysis has not been done yet.

multipole decomposition analysis (MDA)
will be done in near future.

Summary & Outlook

- Goal: determine the proton spin-orbit splitting in oxygen isotopes
- The exclusive measurement of the $(\vec{p},2p)$ reaction is a powerful tool for the study of single-particle orbit and spin-orbit splitting in nuclei
- 1p proton spin-orbit splitting of ^{18}O was determined to be 6.58(11) MeV through an $^{18}\mathrm{O}(\vec{p},2p)$ reaction measurement.
  - Effectiveness of the method was clearly demonstrated
- An $^{14,22,24}\mathrm{O}(\vec{p},2p)$ reaction measurement was carried out at RIKEN RIBF
  - We obtained 7.3(4) MeV of 1p proton spin-orbit splitting in ^{14}O
  - Analysis on polarization observables will be done in near future

Backup slides

Polarized Target:

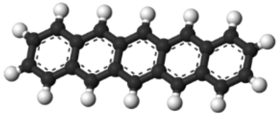
Operation under low magnetic field (65 mT) and high temperature (-160 °C) are the advantage of the polarized target.

1. Low magnetic field does not trap low energy protons.
2. High temperature is easier to operate.

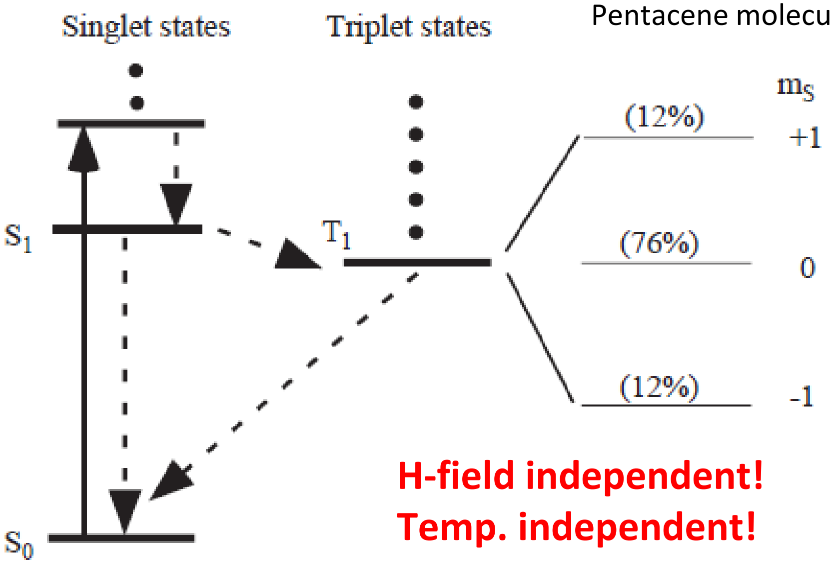
The proton polarization is based on the hyperfine coupling between electron(s) and proton(s). The steps are:

1. Excited the electrons to polarized triplet state by Laser.
2. Apply a microwave to matching the proton precession frequency with that of electron (Dynamic Nuclear Polarization).
3. Spin polarization diffused, stored and accumulated.

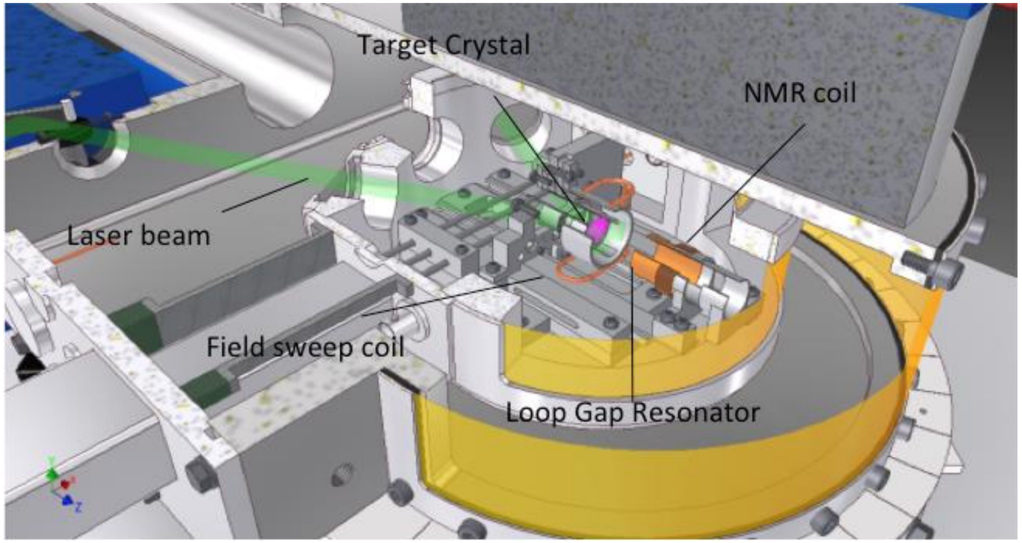
Pentacene Energy Levels



Pentacene molecule



H-field independent!
Temp. independent!



Magnitude of Polarization

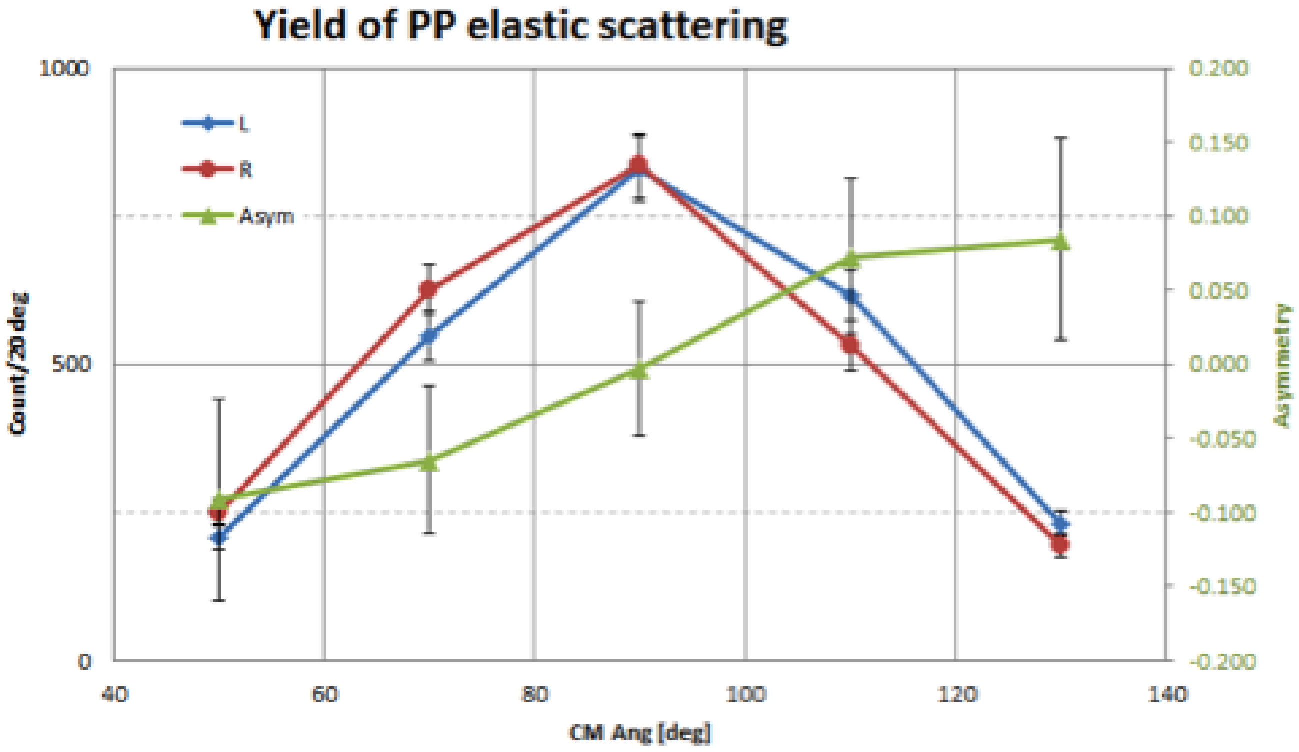
- Spin-up and spin-down measurement

$$Y_L = \sqrt{Y_L^{\uparrow} Y_R^{\downarrow}}, \qquad Y_R = \sqrt{Y_R^{\uparrow} Y_L^{\downarrow}}$$

- Asymmetry:

$$asym = A_y P = \frac{Y_L - Y_R}{Y_L + Y_R}$$

- Magnitude:
  - 30.5% ± 7.3%.



Comparison with DWIA calculation

- DWIA: Distorted-Wave Impulse Approximation
- Computer code: THREEDEE

  N. S. Chant *et al.*, Phys. Rev. C **15**, 57 (1977).
- Single particle wave function: Schrödinger eq. w/ Woods-Saxon pot.
- Optical potential: Energy-dependent atomic-mass-dependent global Dirac phenomenology

  E. D. Cooper *et al.*, Phys. Rev. C **47**, 297 (1993).
- NN scattering amplitude: phase shift analysis by Arndt

  R. A. Arndt *et al.*, Phys. Rev. D **35**, 128 (1987).

Spectroscopic factor

$$C^2S := \frac{\sigma_{\mathrm{exp}}}{\sigma_{\mathrm{DWIA}}}$$

- σ_{DWIA} was calculated by using DWIA calculation code THREEDEE

N. S. Chant *et al.*, Phys. Rev. C **15**, 57 (1977).

- optical potential: Energy-dependent atomic-mass dependent global Dirac potential

E. D. Cooper *et al.*, Phys. Rev. C **47**, 297 (1993).

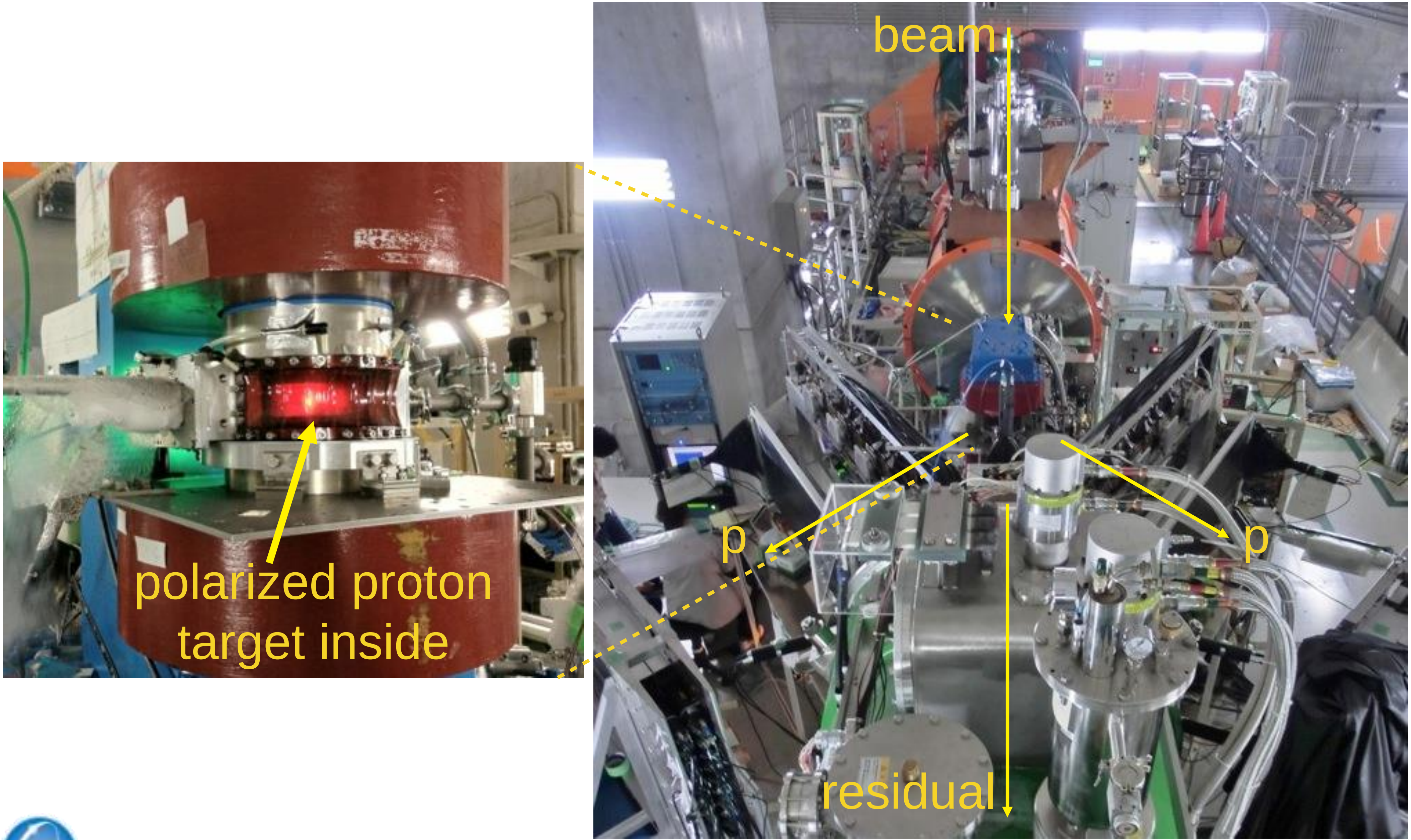
- NN scattering amplitude by Arndt

R. A. Arndt *et al.*, Phys. Rev. D **35**, 128 (1987).

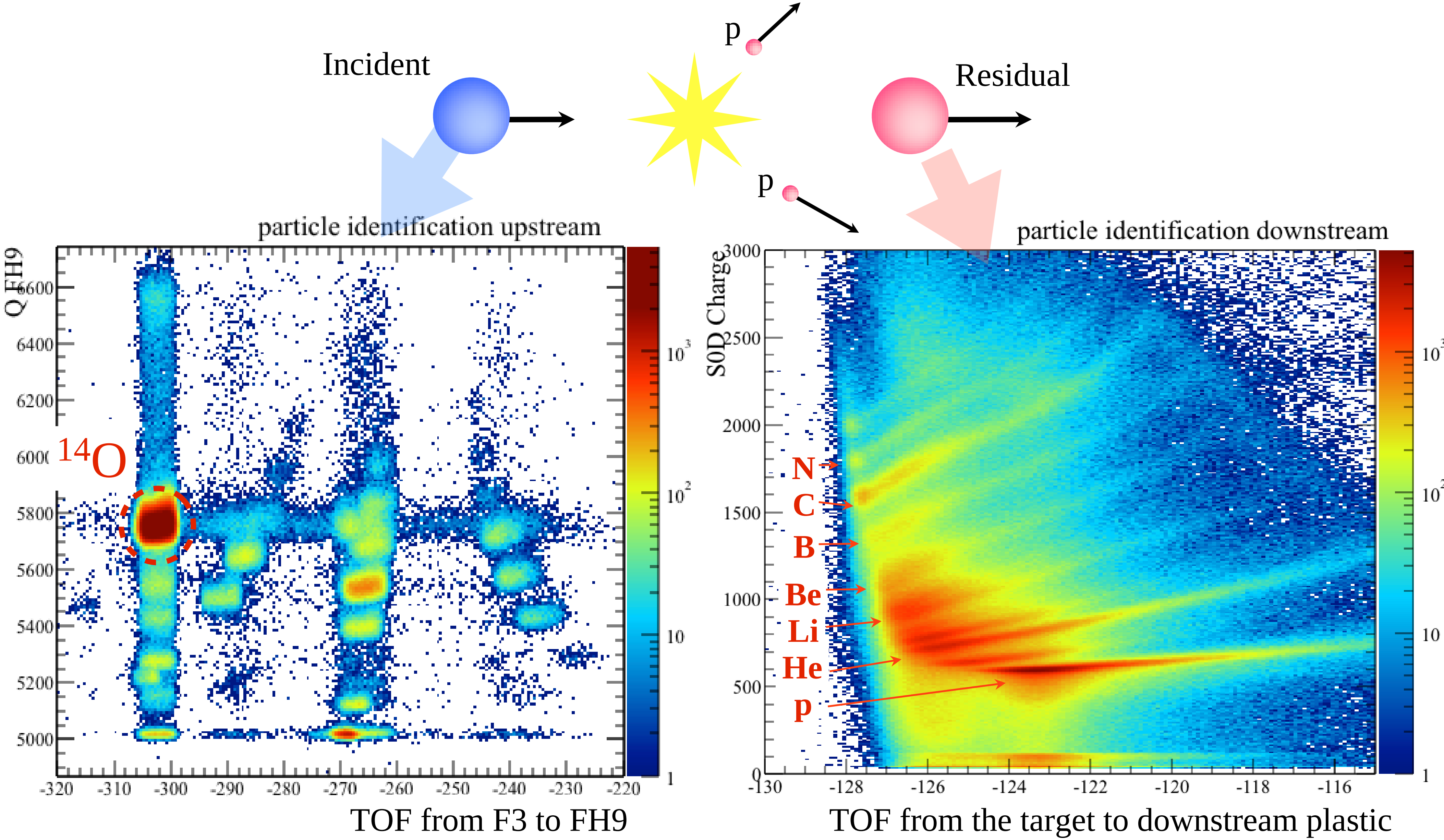
state	σ_{exp} (μb)	σ_{DWIA} (μb)	C^2S	C^2S / Shell Limit	
g.s. (1/2-)	229(12)	166	1.38(7)	0.69(4)	
3.5 MeV (3/2-)	305(17)	161	1.89(11)	0.47(3)	0.71(4)
15 MeV (3/2-)	92(14)	97.8	0.94(14)	0.24(4)	

The sum of C^2S is slightly smaller than expected from the quenching effect of (p,2p)

Picture of SHARAQ04 Setup



Reaction Identification



Reference: ^{14}C(*p*,*d*) spectrum

- strength is concentrated to 3 states:
  - g.s. (1/2-)
  - 3.5 MeV(3/2-)
  - 15 MeV (3/2-): IAS of ^{13}B

M.Yasue et al., Nucl.Phys. A509, 141 (1990)

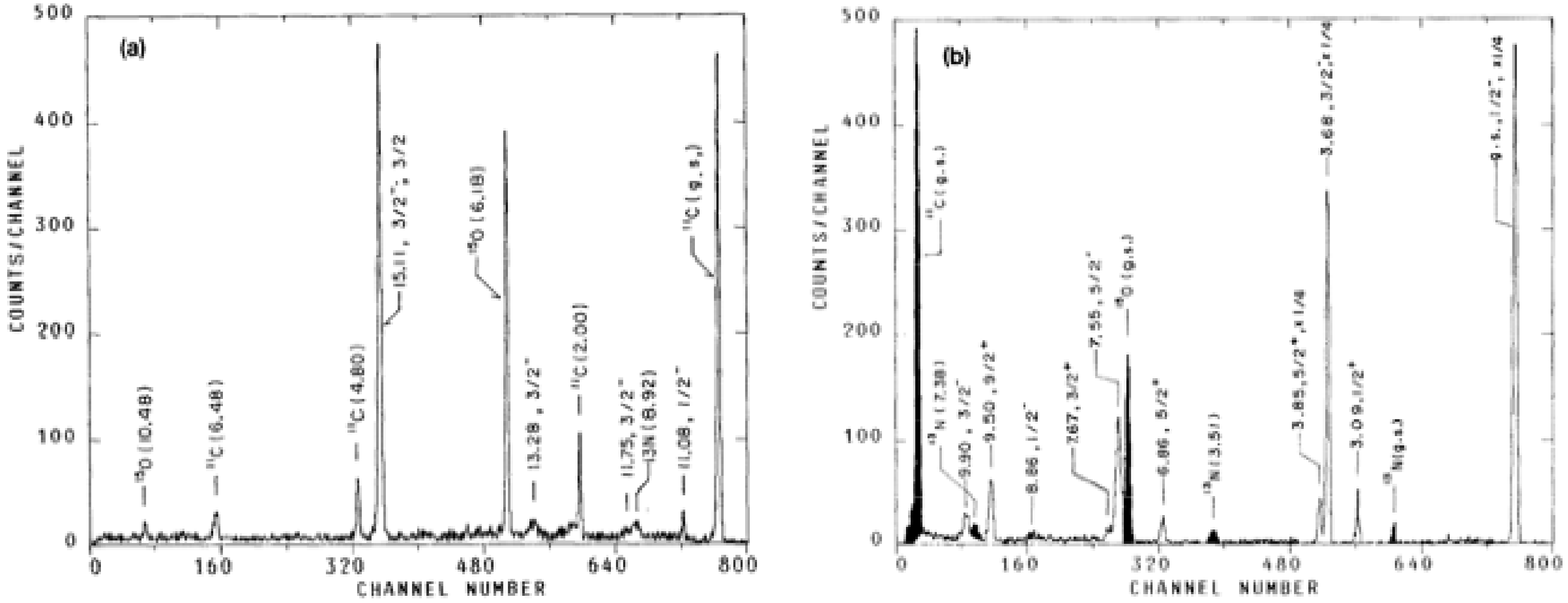
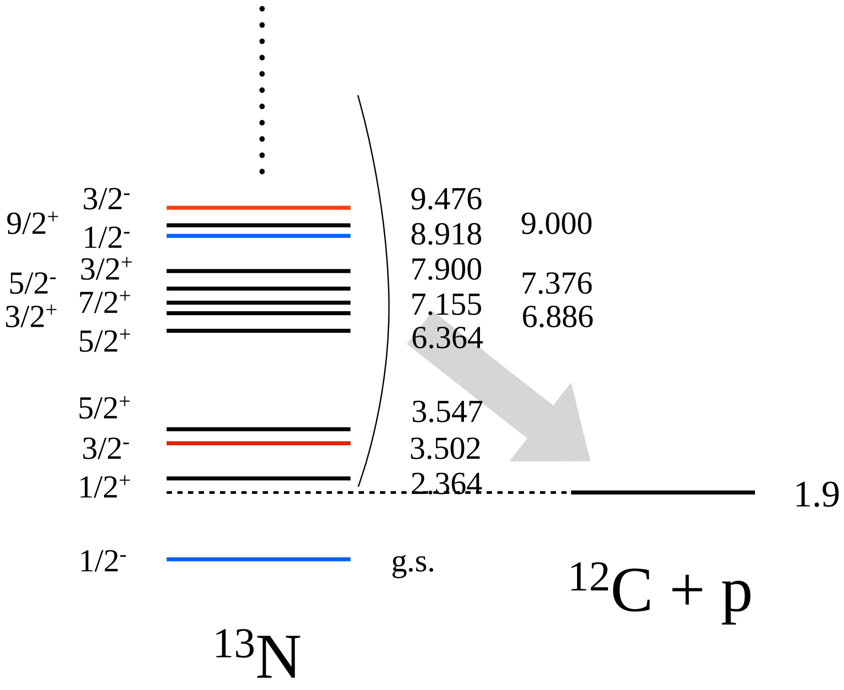


Fig. 1. Sample momentum spectra for the ^{14}C(p, d)^{13}C reaction obtained (a) at $E_p = 35.0$ MeV and $\theta_{lab} = 30°$ for $E_x = 0$-10 MeV, and (b) at $E_p = 40.1$ MeV and $\theta_{lab} = 10°$ for $E_x = 11$-18 MeV. (c) is same as (a) but counts are summed over 8 channels for $E_x = 6$-11 MeV (see next page).

$(\vec{p},2p)$ in inverse kinematics

- Less beam intensity
  - compensated with larger acceptance for recoil protons
- Identifiability of residual nucleus
- Require polarized proton target for spin observable

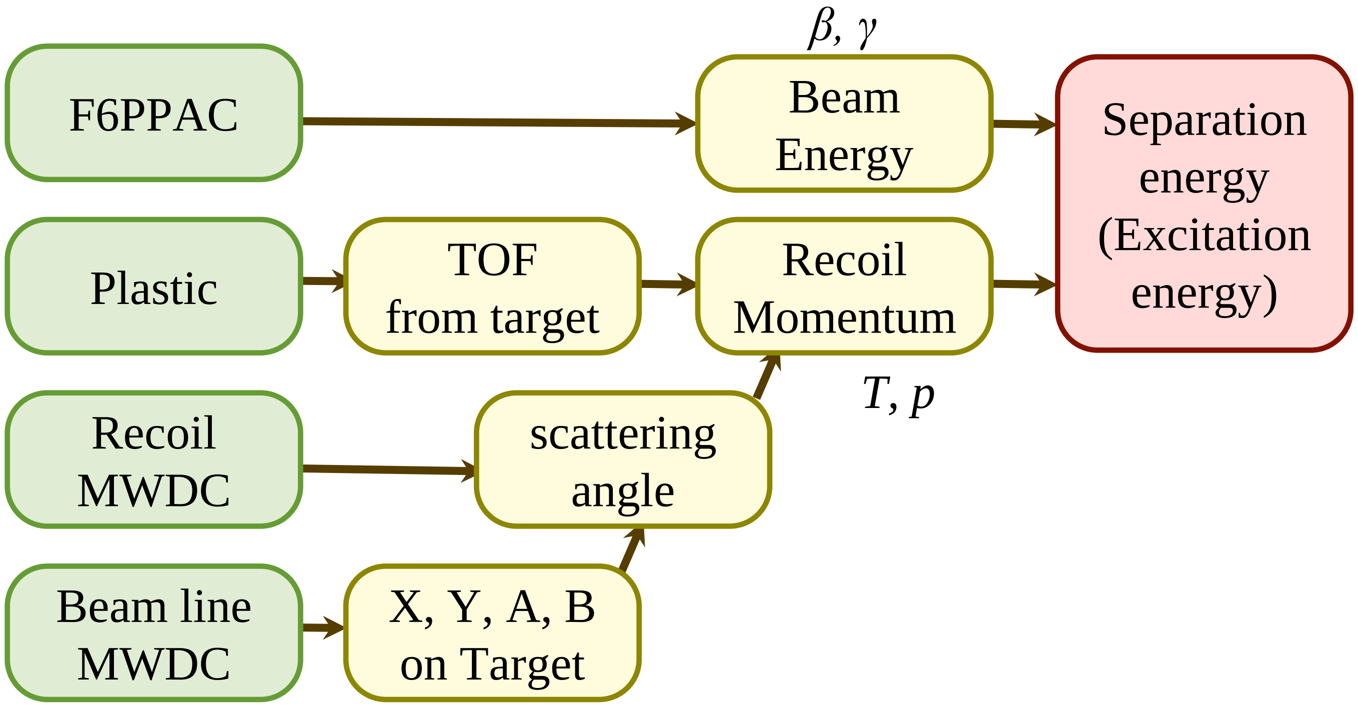


Absence of suitable polarized proton target ············→ Data are scarce...

Observables

- Proton separation energy

$$S_p = -m_p(\gamma - 1) - \gamma(T_1 + T_2) + \beta\gamma(p_{1\parallel} + p_{2\parallel}) - \frac{q^2}{2m_r}$$



β, γ

F6PPAC

Beam Energy

Separation energy (Excitation energy)

Plastic

TOF from target

Recoil Momentum

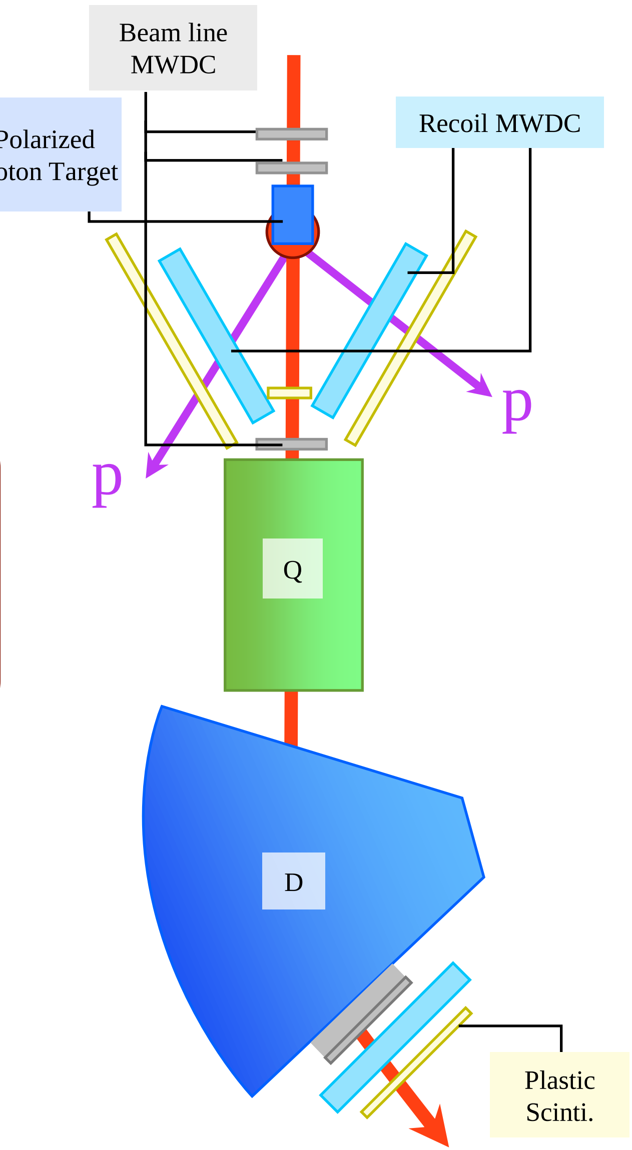
T, p

Recoil MWDC

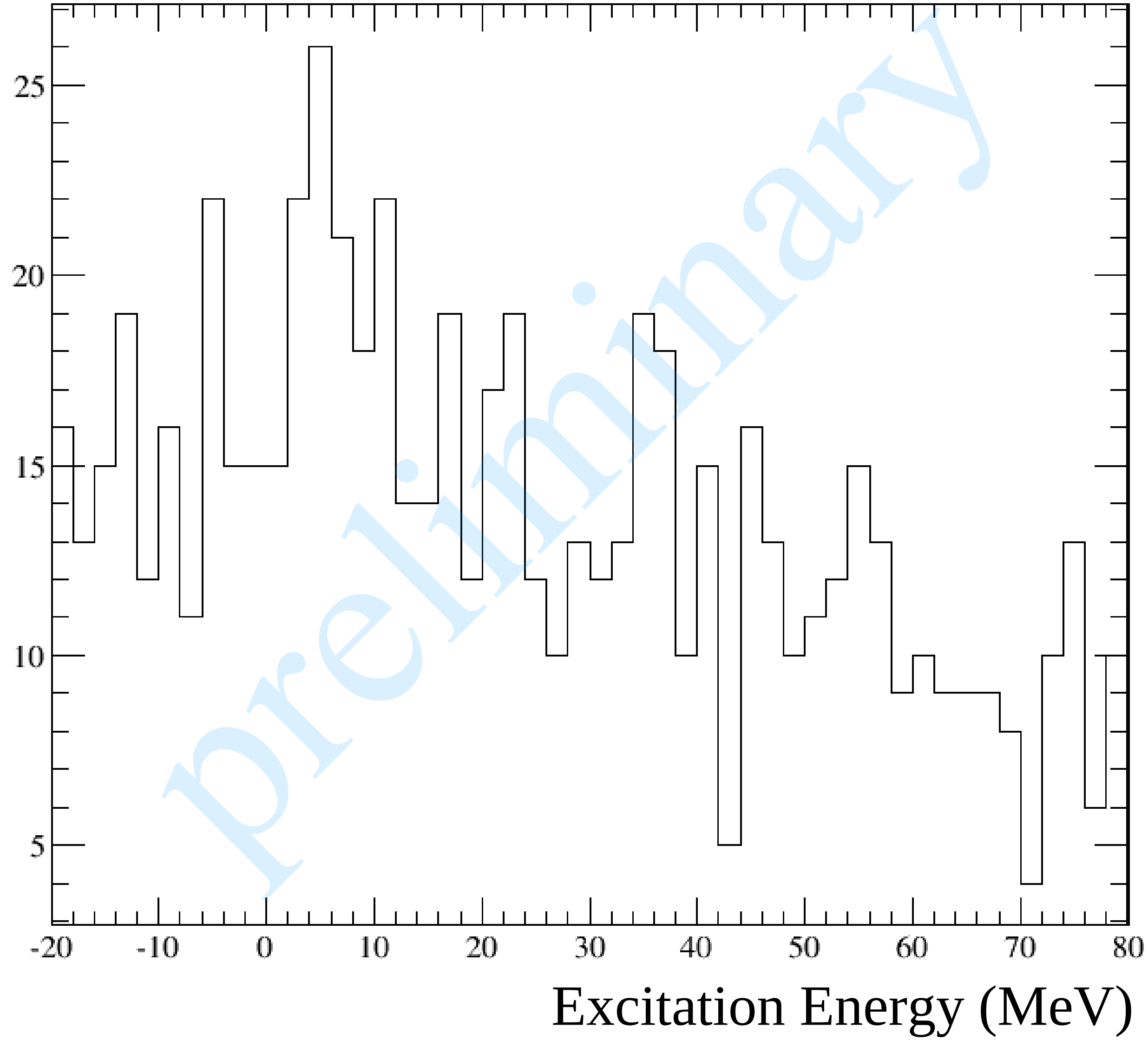
scattering angle

Beam line MWDC

X, Y, A, B on Target

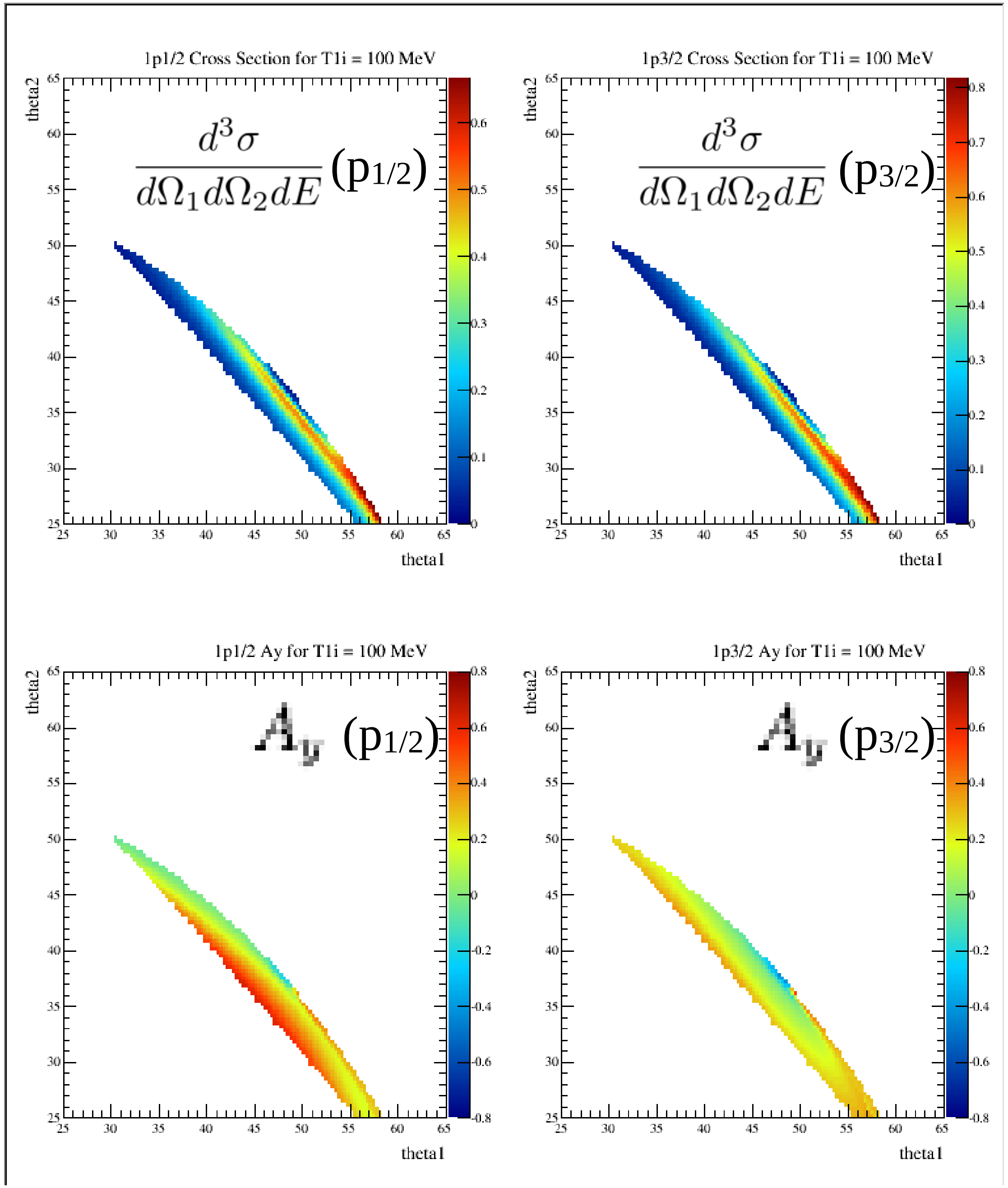


Spectra for $^{24}O(p,2p)N$

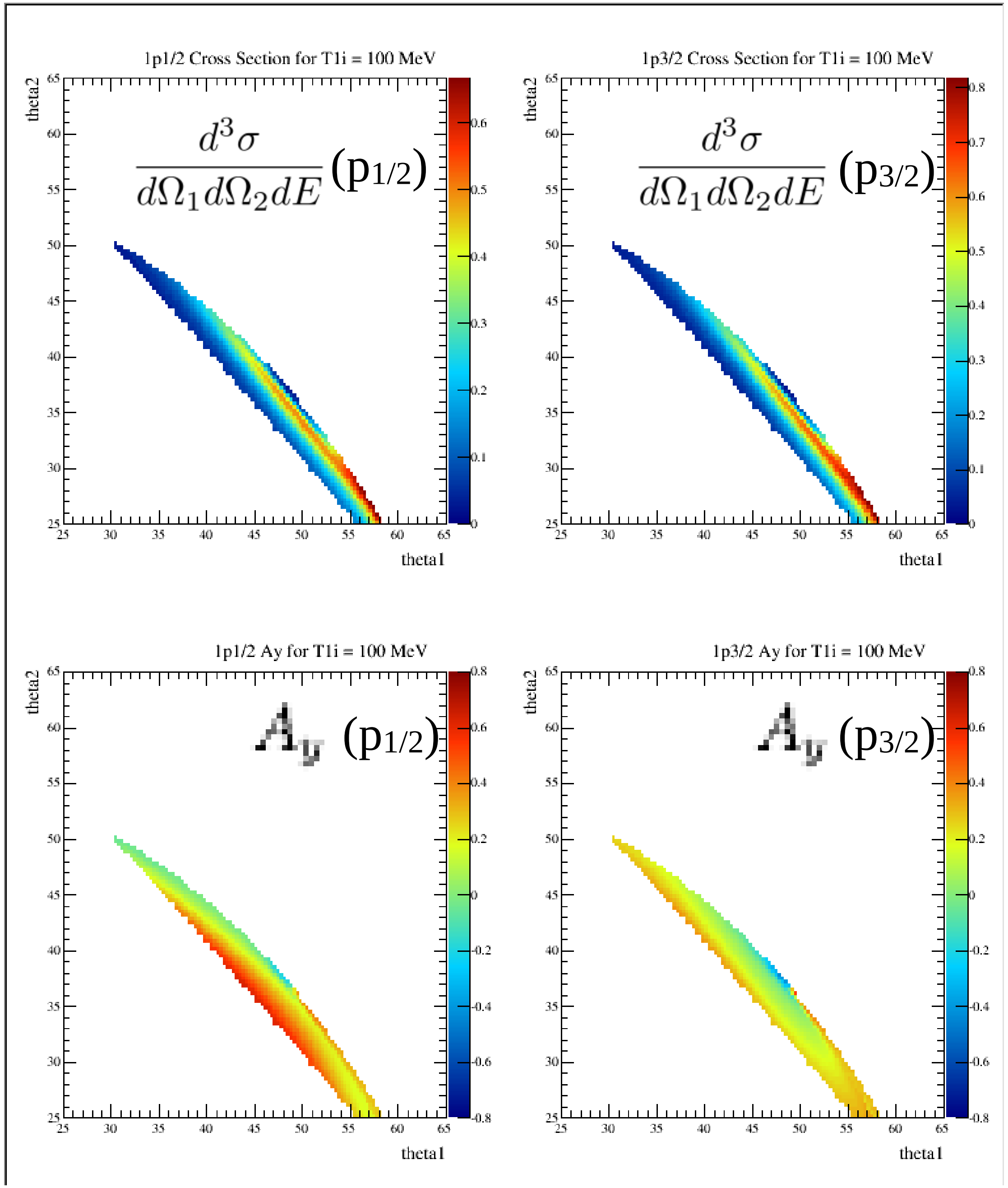


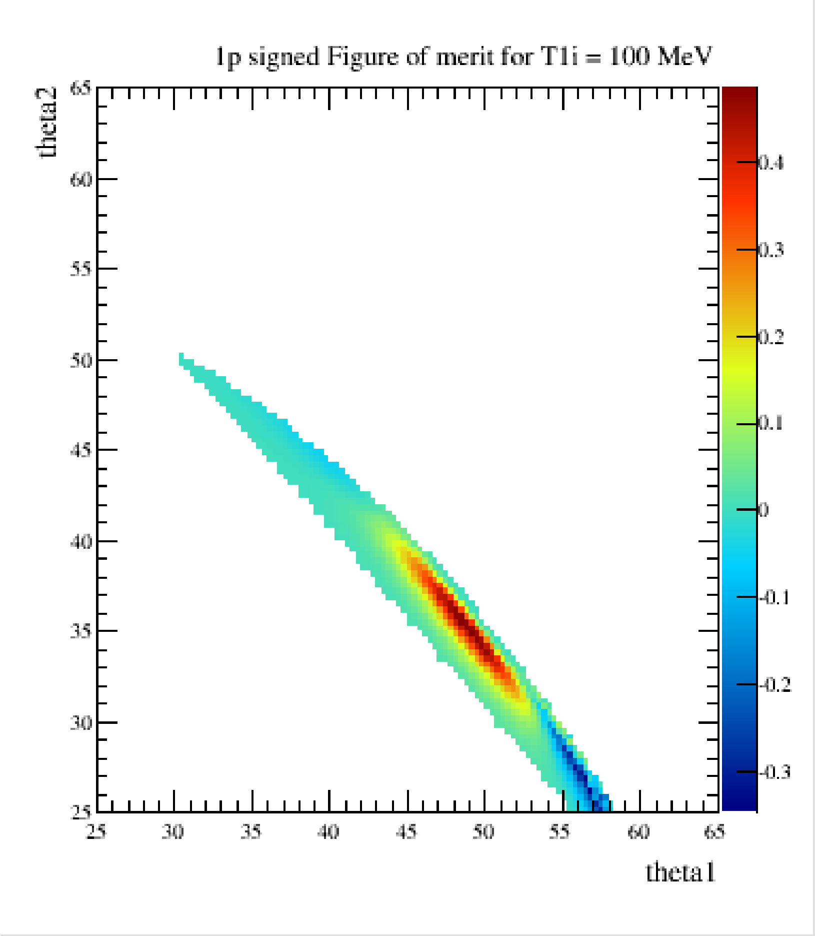
DWIA calculation for ^{14}O(p,2p)

- ^{14}O(p,2p)
- $T_1 = 100$ MeV



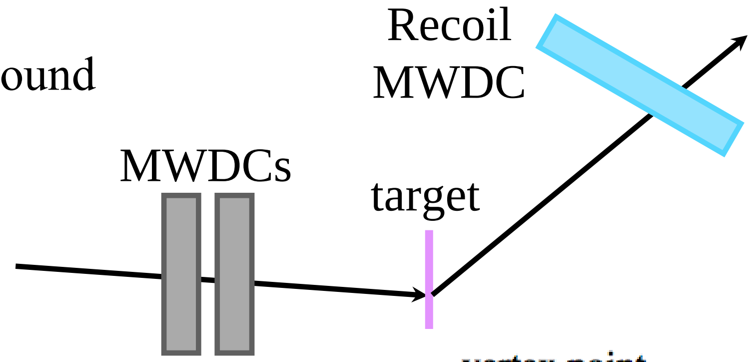
DWIA calculation for ^{14}O(p,2p)





Reaction Position

- more material in target holder → larger luminosity and background
- beam position was lower than center of the target



Recoil MWDC

MWDCs

target