# Spectroscopy of Single-Particle States in Oxygen Isotopes via ($\vec{p}$, 2p) Reaction


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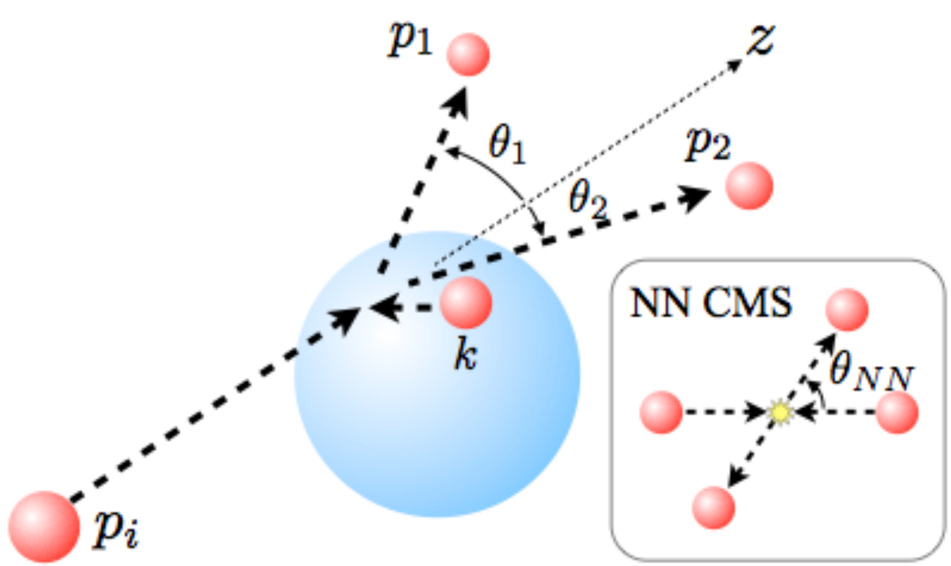
# ($\vec{p}$,2$p$) reaction as a spectroscopic tool

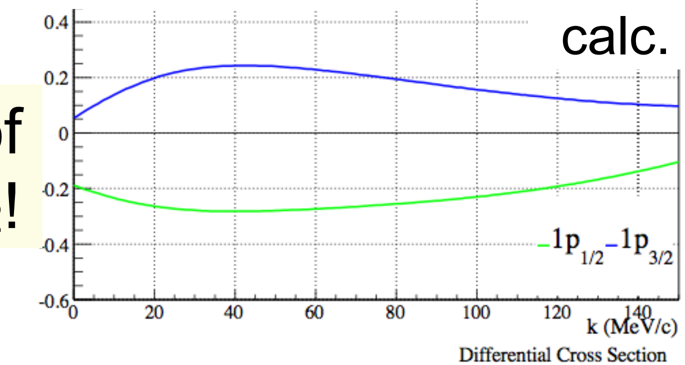
Simple reaction mechanism



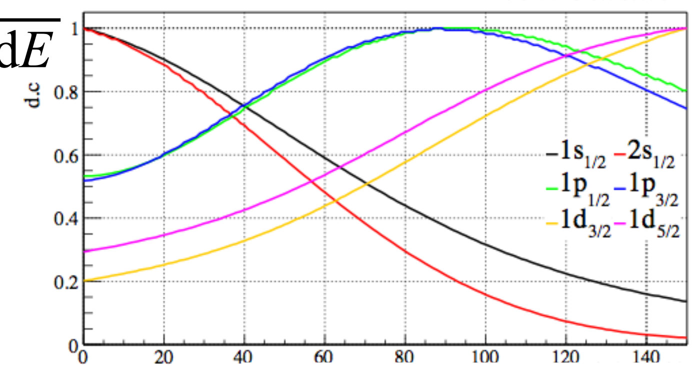

Spin-parity determinability

$A_y$(spin assymmetry) — DWIA calc.

easy ID of $p_{1/2}$ & $p_{3/2}$!




$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE}$$

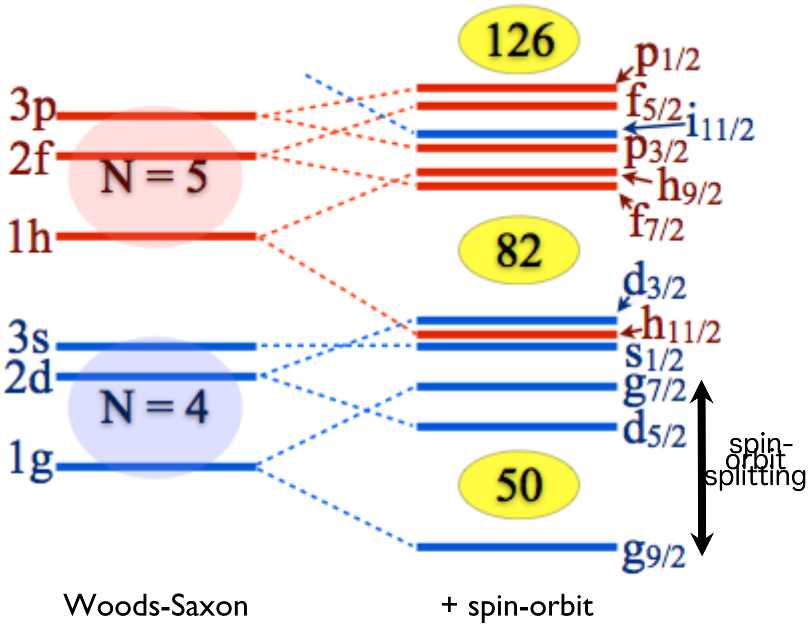


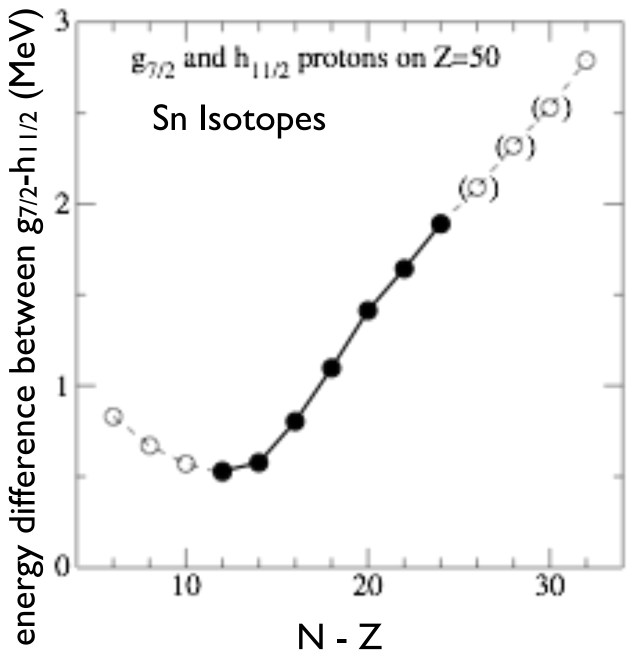

Fermi momentum

a powerful probe for the study of single particle/hole state

# Spin-orbit splitting

For the understanding of the nuclear structure,
it is necessary to know how the spin-orbit splitting changes with *Z*, *N*.



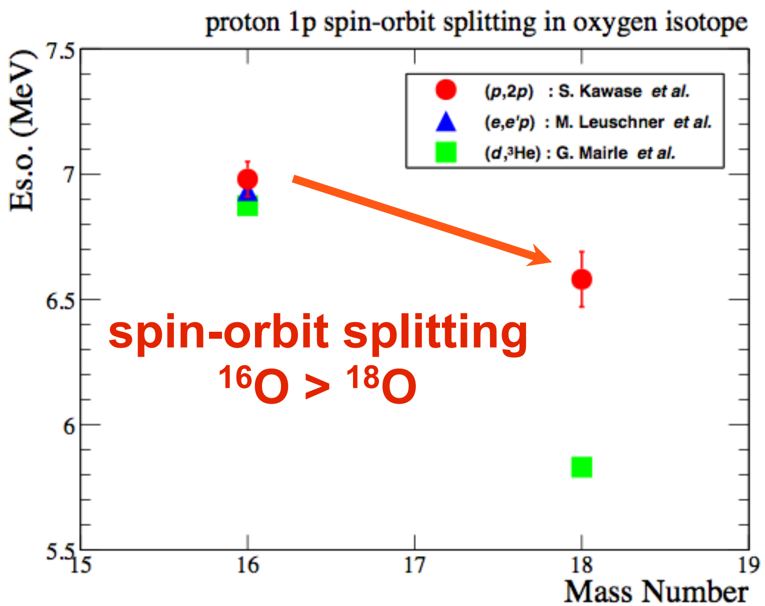

J. P. Schiffer *et al*. Phys. Rev. Lett., **92**, 162501 (2004).

Goal of this study:

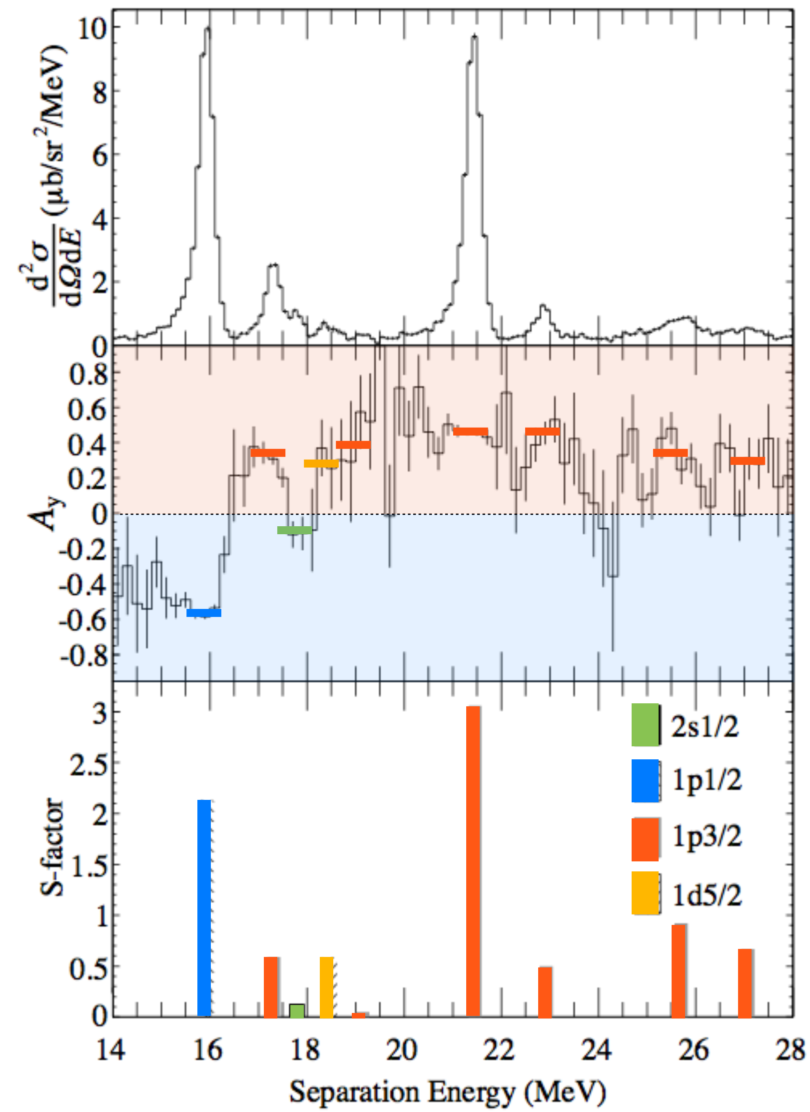
Determine 1p proton spin-orbit splittings
in oxygen isotopes
as a function of neutron number

# Previous experiment: $^{18}O(p,2p)$

| | |
|---|---|
| Facility | Ring Cyclotron, RCNP, Osaka U |
| Reaction | $(\vec{p},2p)$ in **normal** kinematics |
| Beam | **Polarized** proton @ 200 MeV/u |
| Target | $H_2{}^{18}O$ ice target ~20 mg/cm$^2$ |




S.K. *et al.*

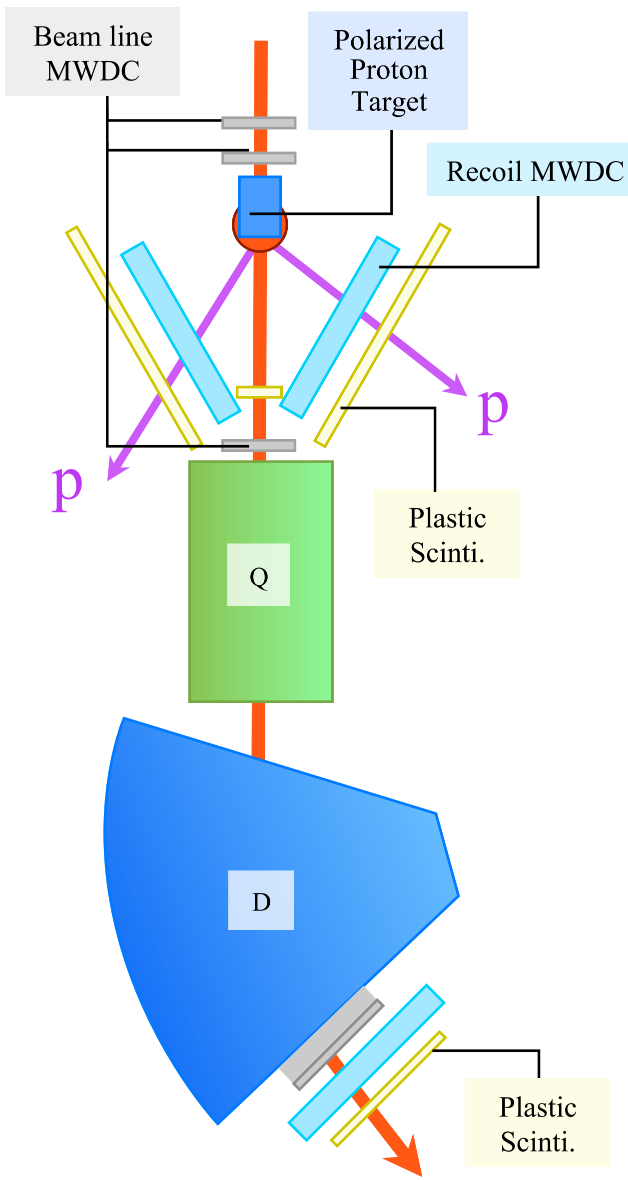



Effectiveness of $(\vec{p},2p)$ was clearly demonstrated

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

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

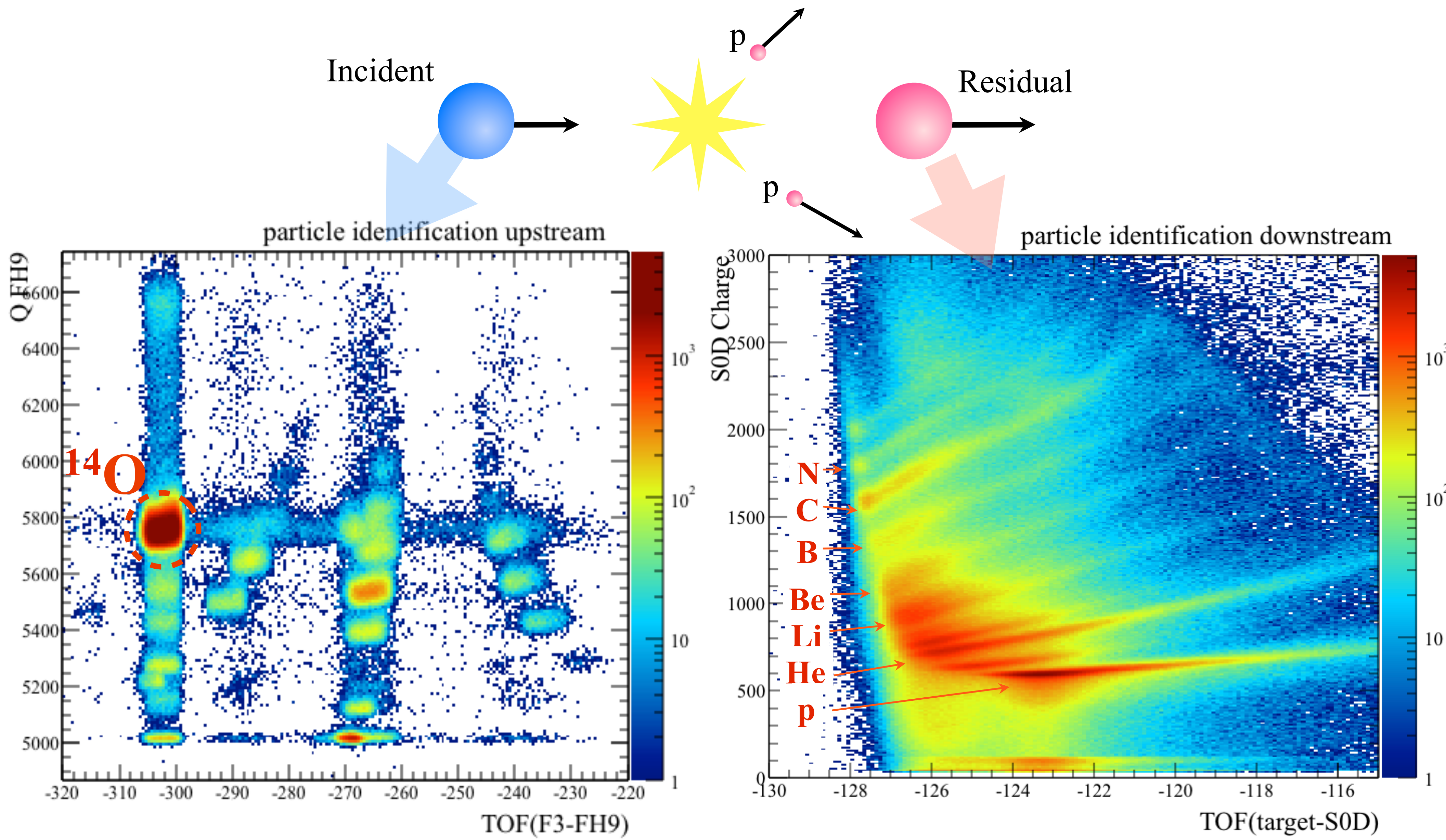
- Recoil MWDC → Scattering Angle → Separation energy (Excitation energy)
- Plastic → TOF from target → Recoil Momentum → Separation energy (Excitation energy)




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

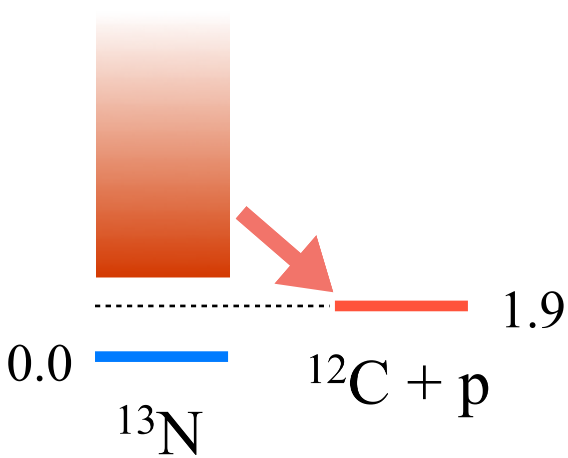
# SHARAQ04 Setup

# Reaction Identification for $^{14}O$ run



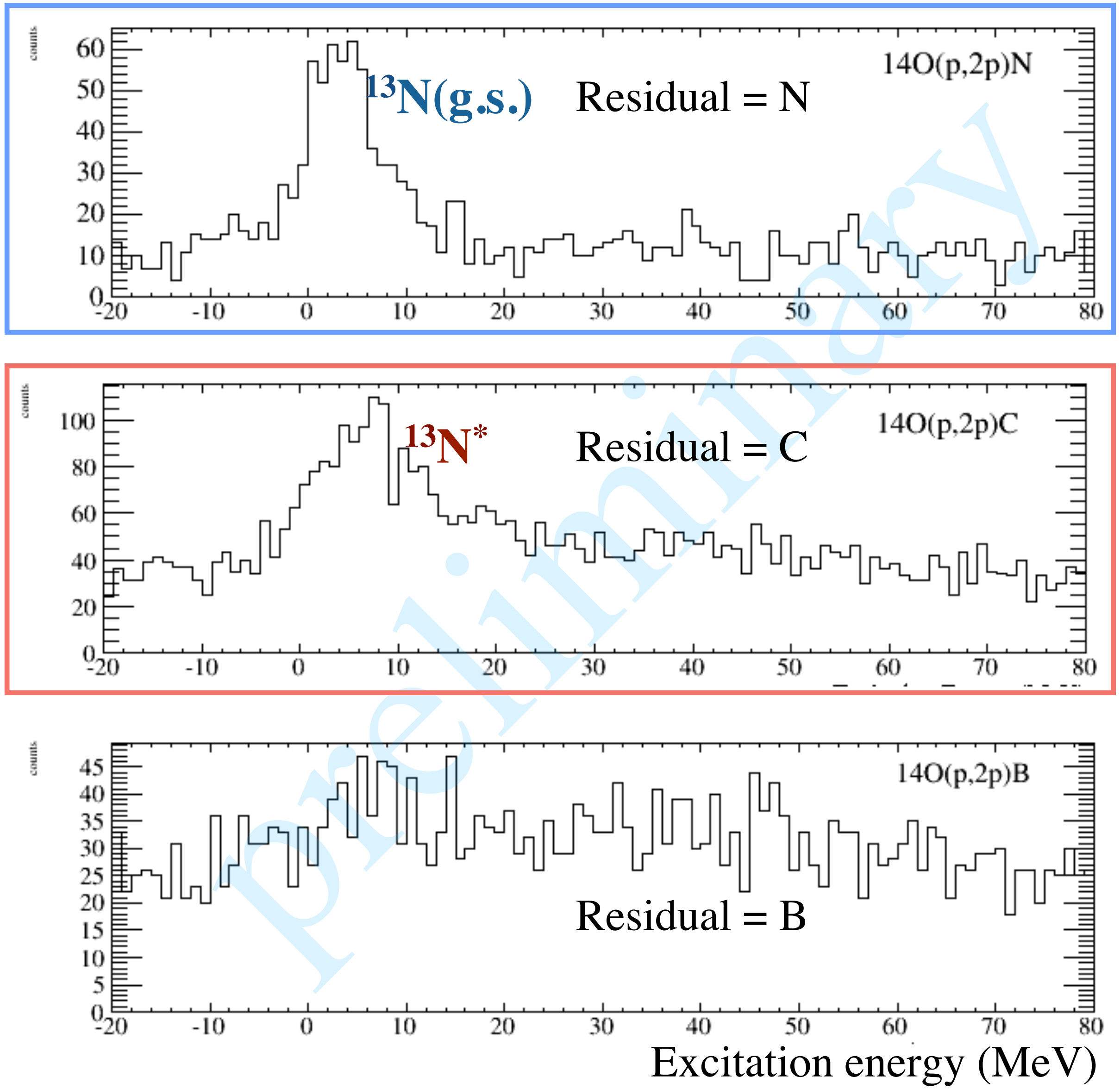
# $^{13}$N Excitation Energy Spectra

**Ground** and **excited** states can be distinguished by choosing residual nuclei.




Background is coming from…

- $^{14}$O($^{12}$C,2p) in the target
- surrounding materials



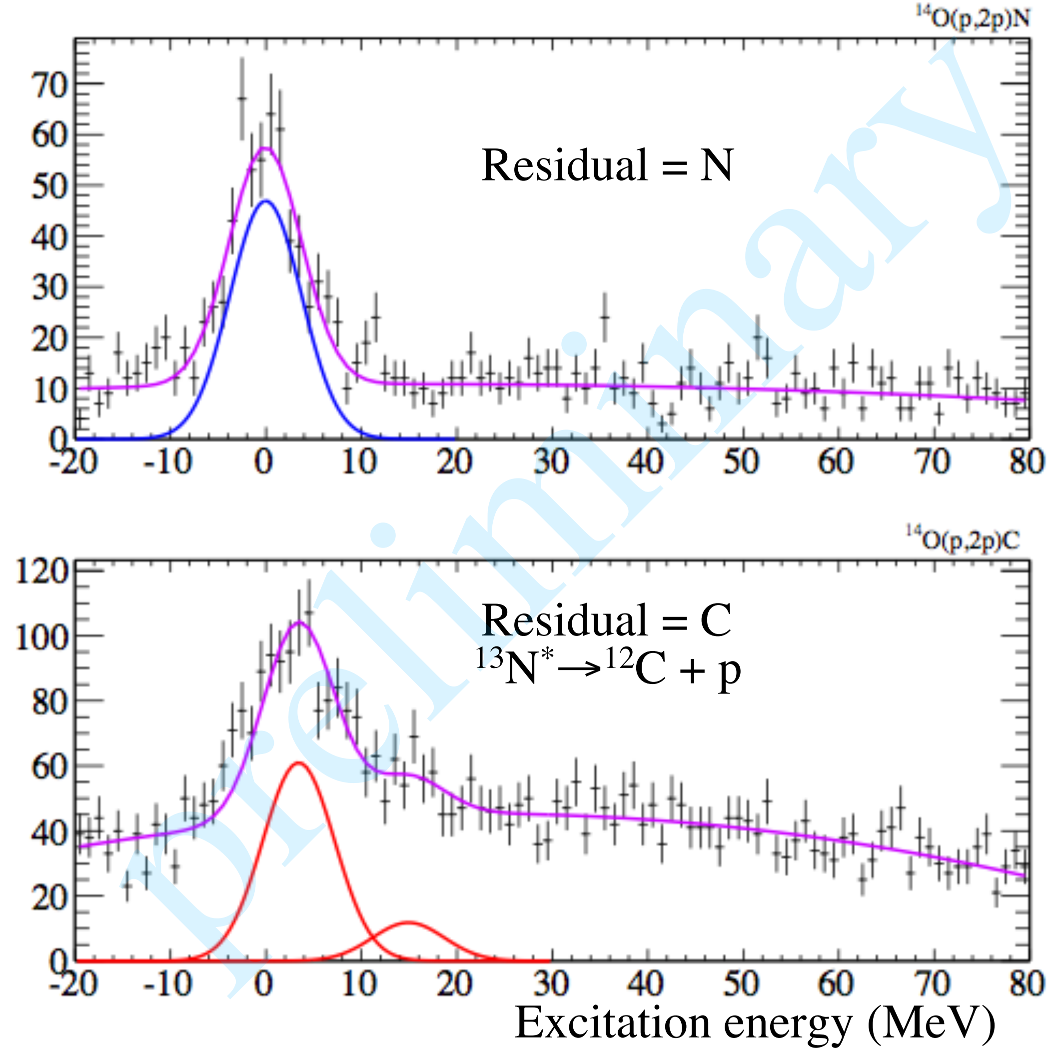
# Cross section

Assume …

- smooth background distribution
- the same peak width for every state
- excited states mainly consists of 3/2- components and includes 2 known states
  - 3.5 MeV (3/2-)
  - 15 MeV (3/2-) (IAS of $^{13}$O g.s.)

cf.) $^{14}$C(p,d)$^{13}$C: M.Yasue et al., Nucl.Phys. **A509**, 141 (1990)

| state | counts | $\sigma_{exp}$ |
|---|---|---|
| g.s. | 443(25) | 251(14) |
| 3.5 MeV | 576(38) | 326(22) |
| 15 MeV | 111(31) | 63(18) |




The strength of 15 MeV state is unignorable

# Spectroscopic factor

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

- $\sigma_{\mathrm{DWIA}}$ 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 | $\sigma_{\mathrm{exp}}$ (μb) | $\sigma_{\mathrm{DWIA}}$ (μb) | $C^2S$ | $C^2S$ / Shell Limit | |
|---|---|---|---|---|---|
| g.s. (1/2-) | 251(14) | 166 | 1.51(8) | 0.76(4) | |
| 3.5 MeV (3/2-) | 326(22) | 161 | 2.02(14) | 0.51(4) | 0.65(6) |
| 15 MeV (3/2-) | 63(18) | 97.1 | 0.65(19) | 0.14(5) | |

Consistent with quenching effect

# Spin-orbit splitting

Effective Single particle energy (ESPE)

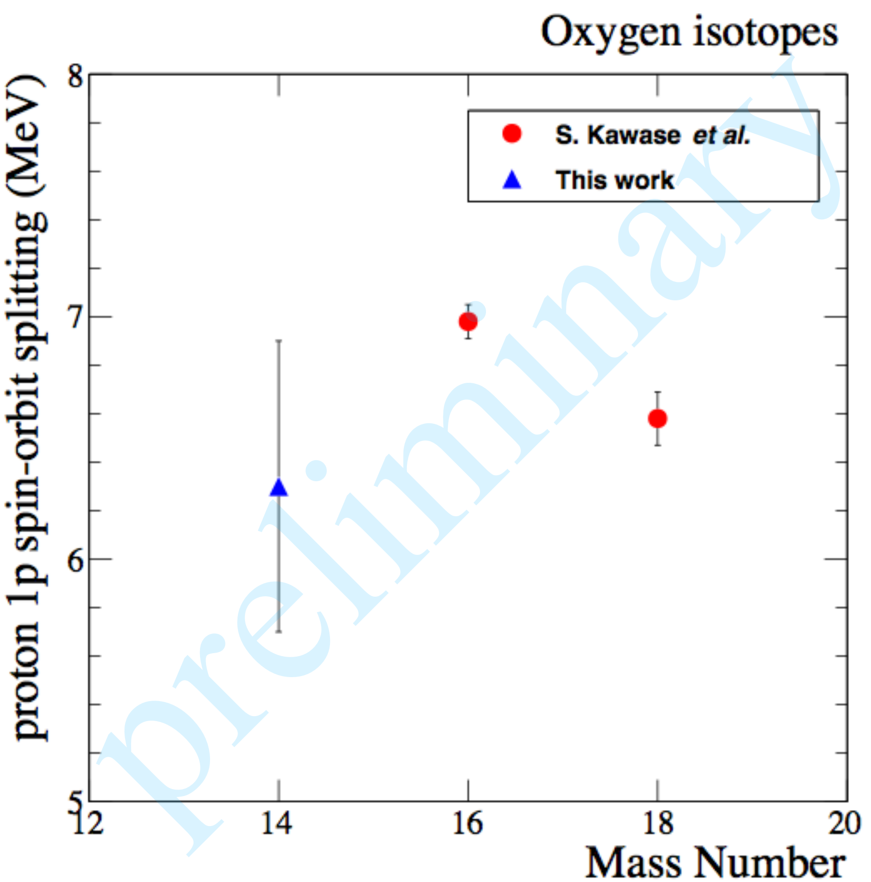
$\Rightarrow$ $C^2S$-weighted mean of excitation energy

spin-orbit splitting = ESPE($3/2^-$) - ESPE($1/2^-$)

= **6.3(6) MeV**

Untested Factors

- sd-shell mixture in $^{14}$O ground state
- background distribution
- optical potential in cross section calc.



# Summary & Outlook

- Goal: determine the proton 1p spin-orbit splitting in oxygen isotopes
- $(\vec{p},2p)$ reaction is a powerful tool to the study of single-particle orbit
- A $(\vec{p},2p)$ reaction experiment with $^{14,22,24}O$ have been carried out
  - Reasonable amount of spectroscopic factors for ground and excited states of $^{13}N$ were obtained
  - 1p proton spin-orbit splitting of $^{14}O$, 6.2(6) MeV was obtained

- Further analysis is needed …
  - Improvement of resolution
  - Momentum distribution analysis -> sd mixing ratio
  - Spin polarization observable -> spin assignment
  - Calculation with more realistic optical potential

# Collaborators

| | |
|---|---|
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Thank you for your attention!