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Spin-orbit Splitting in Oxygen Isotopes

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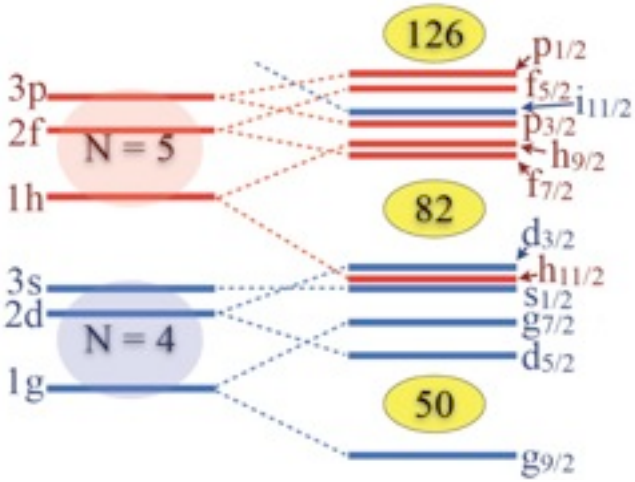
for E349 & SHARAQ04 Collaborations

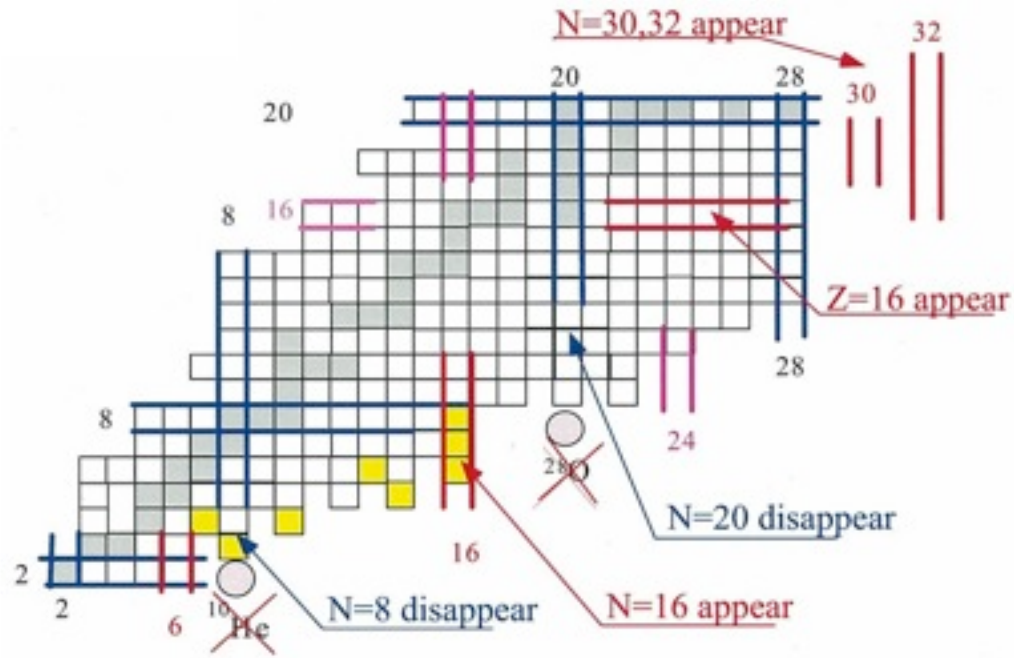
Magicity and spin-orbit coupling

Magic number : Appearance of closed shells 2, 8, 20, 28, 50, 82, 126 . . . .

The most established "regularity" in (stable) nuclei.



+Spin-orbit coupling

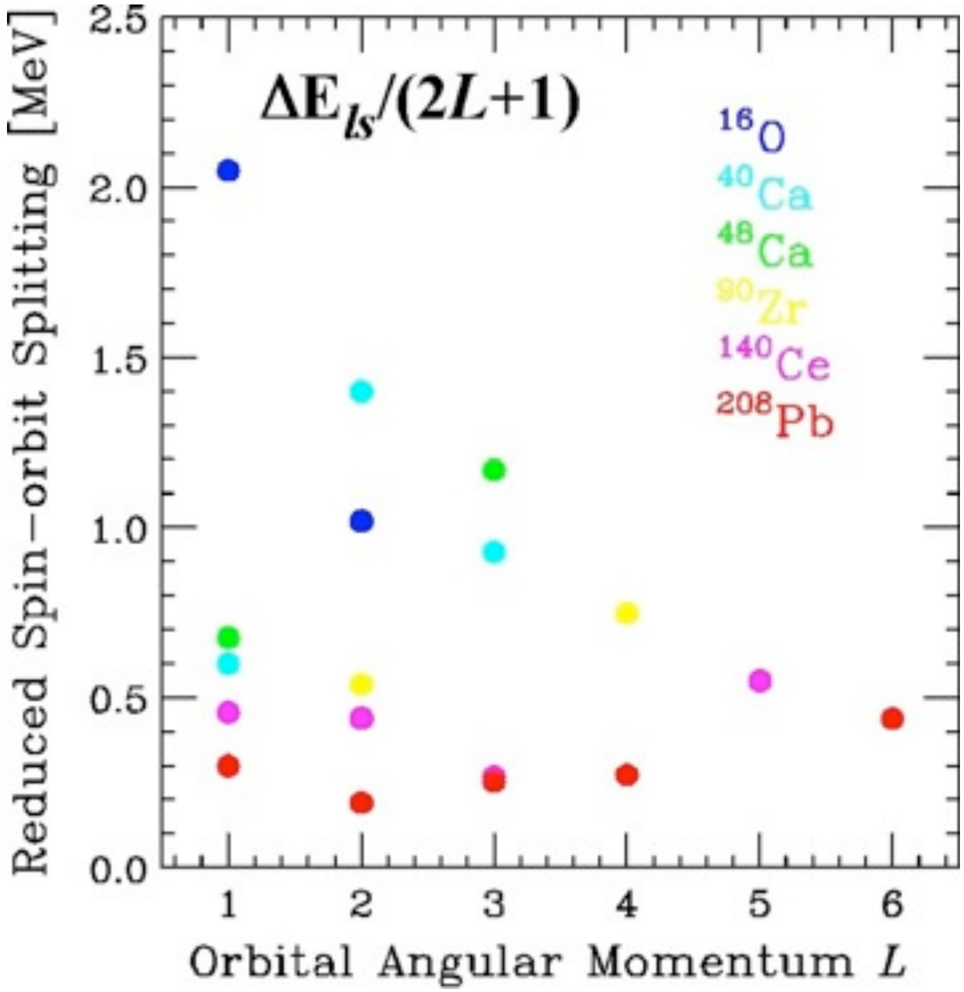


Spin-orbit coupling should be revisited.

A simple "spin-orbit potential" picture doesn't work . . . .

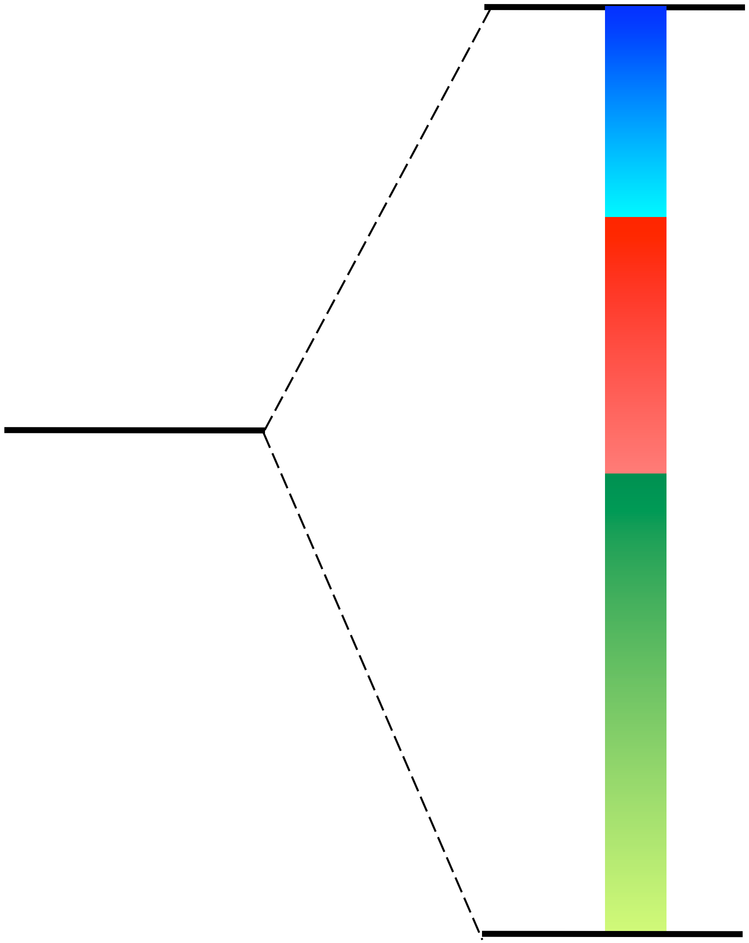
$$U_{\rm LS} = V_{\rm LS}(r)\vec{L}\cdot\vec{S}$$

$$\Delta E_{\rm LS} \propto (2L+1)\langle V_{\rm LS}(r)\rangle$$

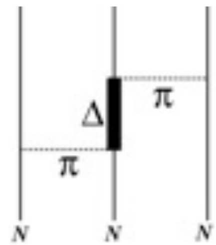


Microscopic origins of spin-orbit coupling in ^{16}O, ^{40}Ca

Scheerbaum, Nucl. Phys. A 257 (1976) 77.
Ando and Bando, Prog. Theor. Phys. 66 (1981) 227.
Pieper and Pandharipande, Phys. Rev. Lett. 70 (1993) 2541.



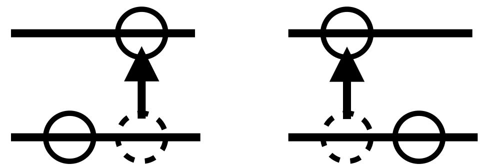
3N force



“Spin-orbit coupling in heavy nuclei”
Fujita and Miyazawa, PTP 17 (1957) 366.

Tensor force

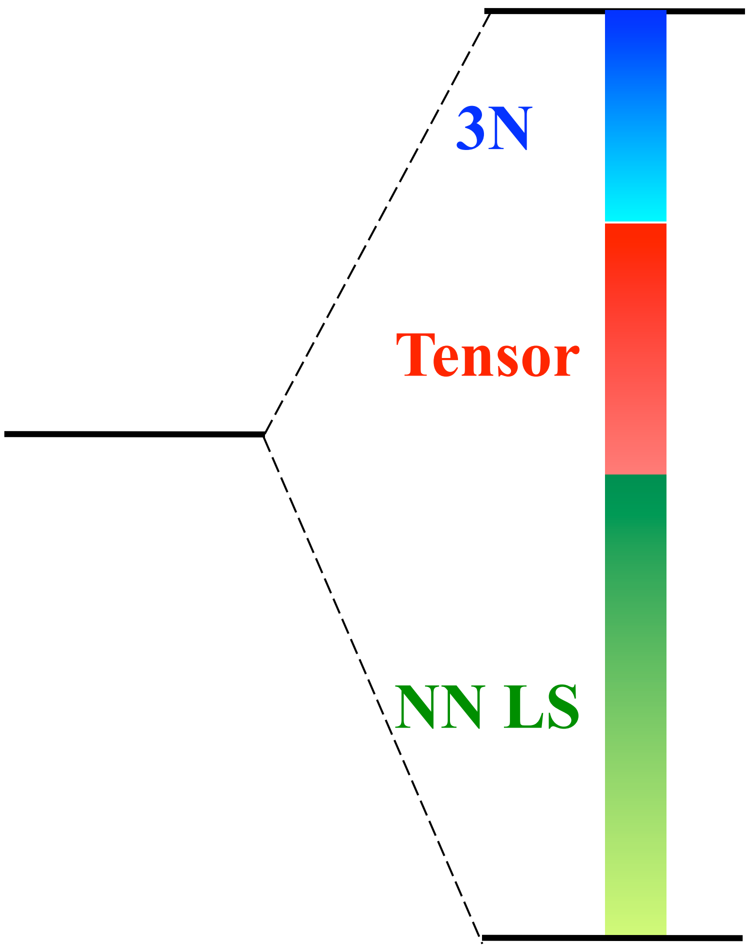
Wigner & Feingold, PR 79 (1950) 221.
Arima & Terasawa, PTP 23 (1960) 87.

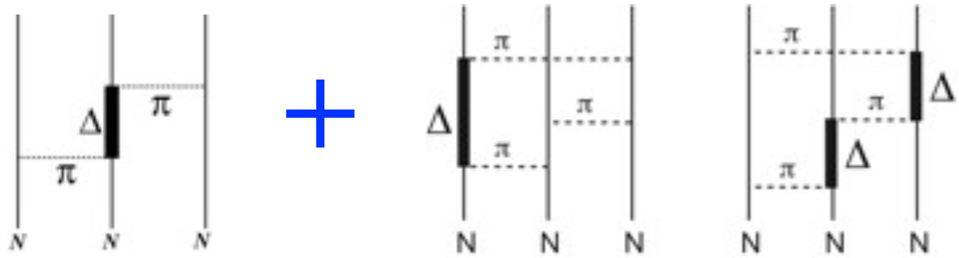


NN LS interaction

σ and ω exchange
isoscaler in nature

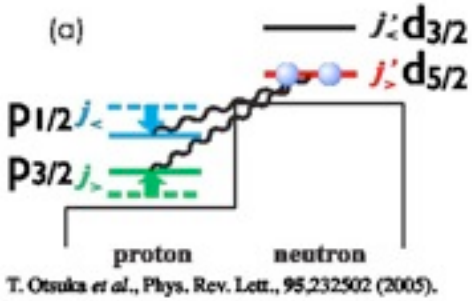
Spin-orbit coupling in unstable nuclei



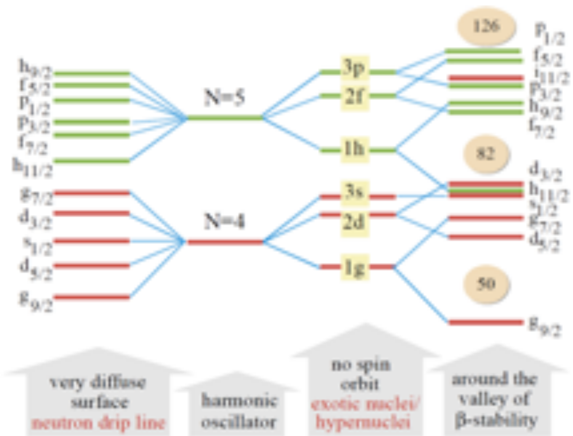


Correlation: 2p2h → Myo-san's talk

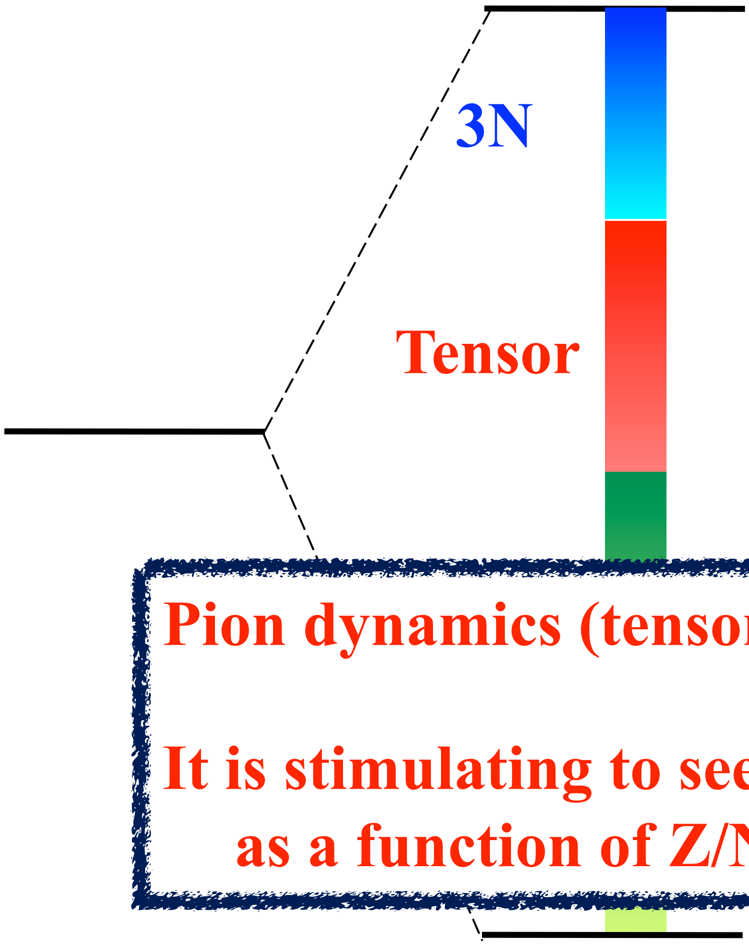
First-order tensor effect by Otsuka

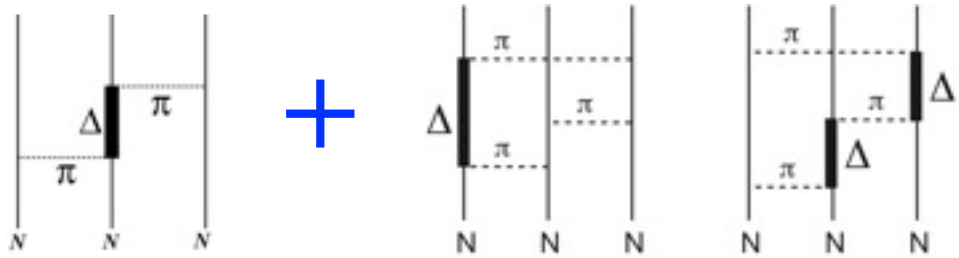


Mean-field effects



Spin-orbit coupling in unstable nuclei





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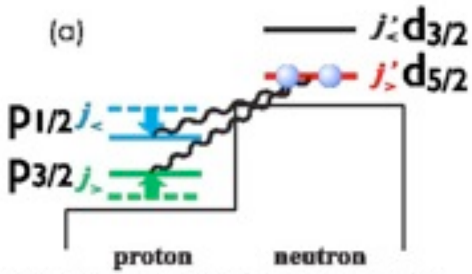
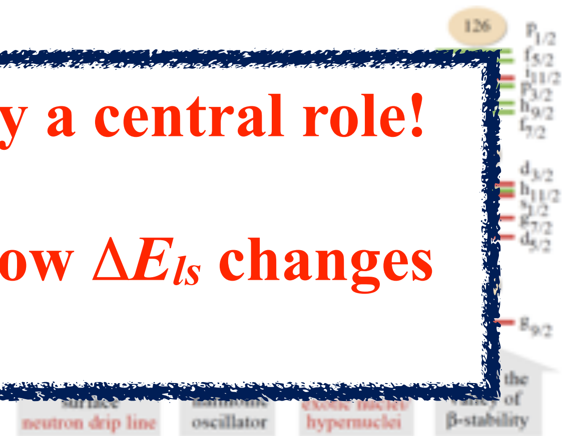


T. Otsuka et al., Phys. Rev. Lett., 95,232502 (2005).



Pion dynamics (tensor + 3N) should play a central role!

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

Oxygen Isotopes

Z=8: proton magicity

^{16}O: most intensively studied nucleus

Ando and Bando, PTP **66** (1981) 227.

Pieper and Pandharipande, PRL **70** (1993) 2541.

Within the reach of recent rigorous calculations with realistic NN(+3N) interactions.

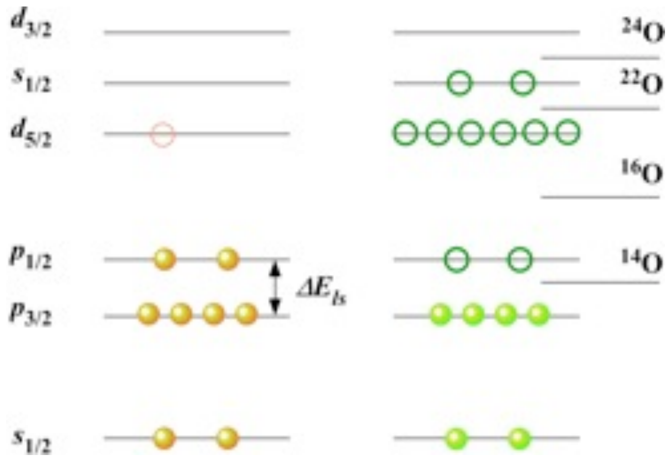
C. Barbieri, PLB **643**, 268 (2006).

G. Hagen *et al.*, PRC **80**, 021306(R) (2009).

S. Fujii et al. PRL **103**, 182501 (2009).

Table 1: Experimental values of the spin-orbit splittings in ^{16}O

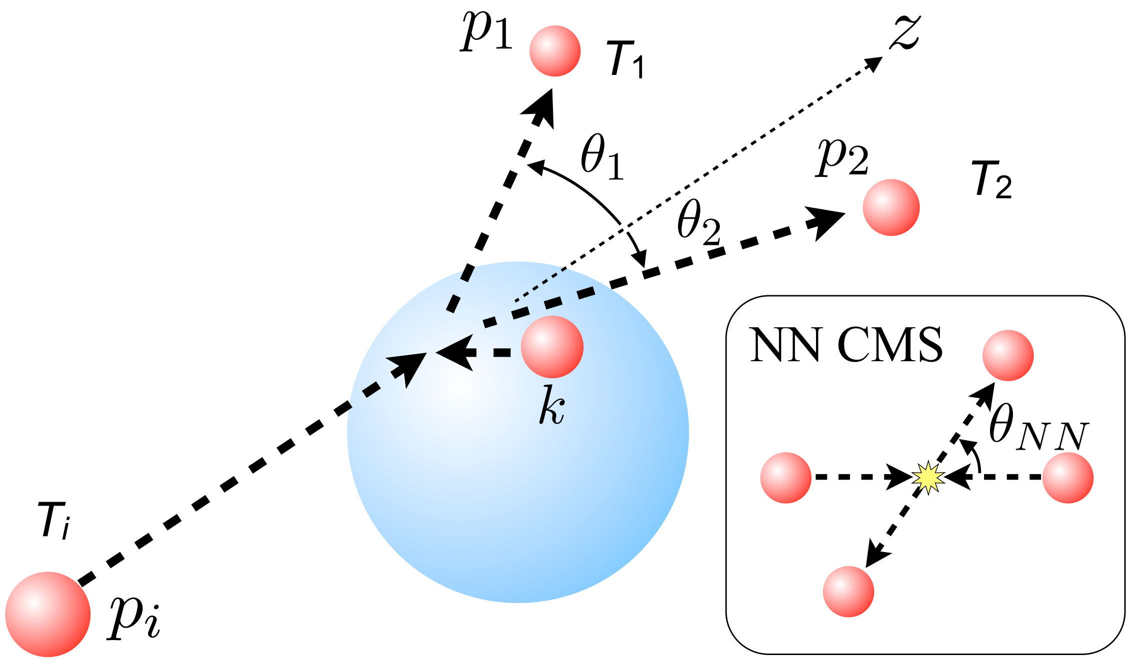
	Proton	Neutron
$\Delta E_{1p_{1/2}-1p_{3/2}}$	6.32 MeV	6.18 MeV
$\Delta E_{1d_{3/2}-1d_{5/2}}$	5.10 MeV	5.09 MeV



$^{14,22-24}$O : Future experiment at RIBF

^{18}O : Experiment at RCNP

(p,2p)/(p,pn) Knockout Reactions



A nucleon is knocked out without serious disturbance to the residual nucleus.

Scattering observables are directly connected to properties of the nucleon.

Spin asymmetry is a good signature of J (total angular momentum).

NN scattering in the nuclear medium

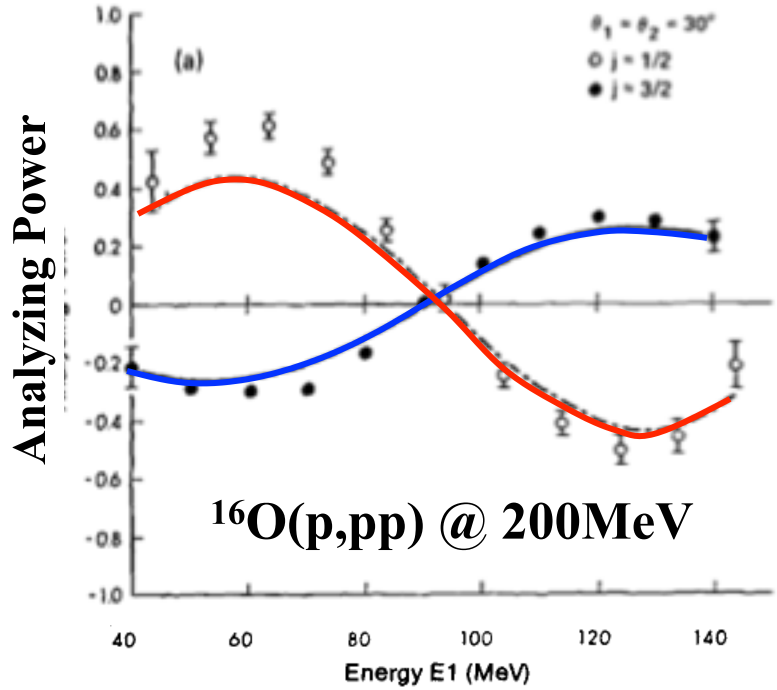
Reaction mechanism is reasonably simple.

$(\vec{p},pN)$ Reaction

- Good probe to single hole states at E≧100 MeV/nucleon.
  RIBF/FAIR/FRIB/RCNP energies
  ⇔ transfer reactions at lower energies (10－30 MeV/nucleon)

- Momentum dependence of dσ/dΩ
  ⇒ L and S-factor
- Analyzing power (A_y)
  ⇒ J

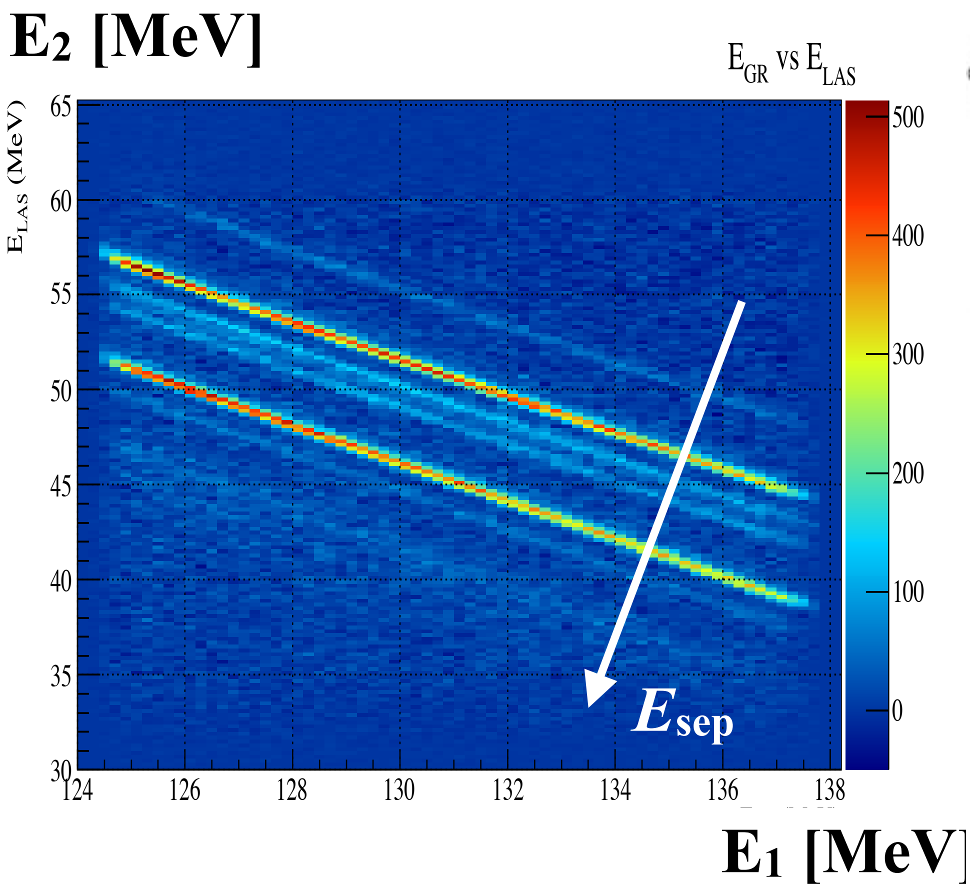
Proposed by Maris & Jacob
Demonstrated at TRIUMF
by Kinching
Sophisticated at RCNP
by Noro



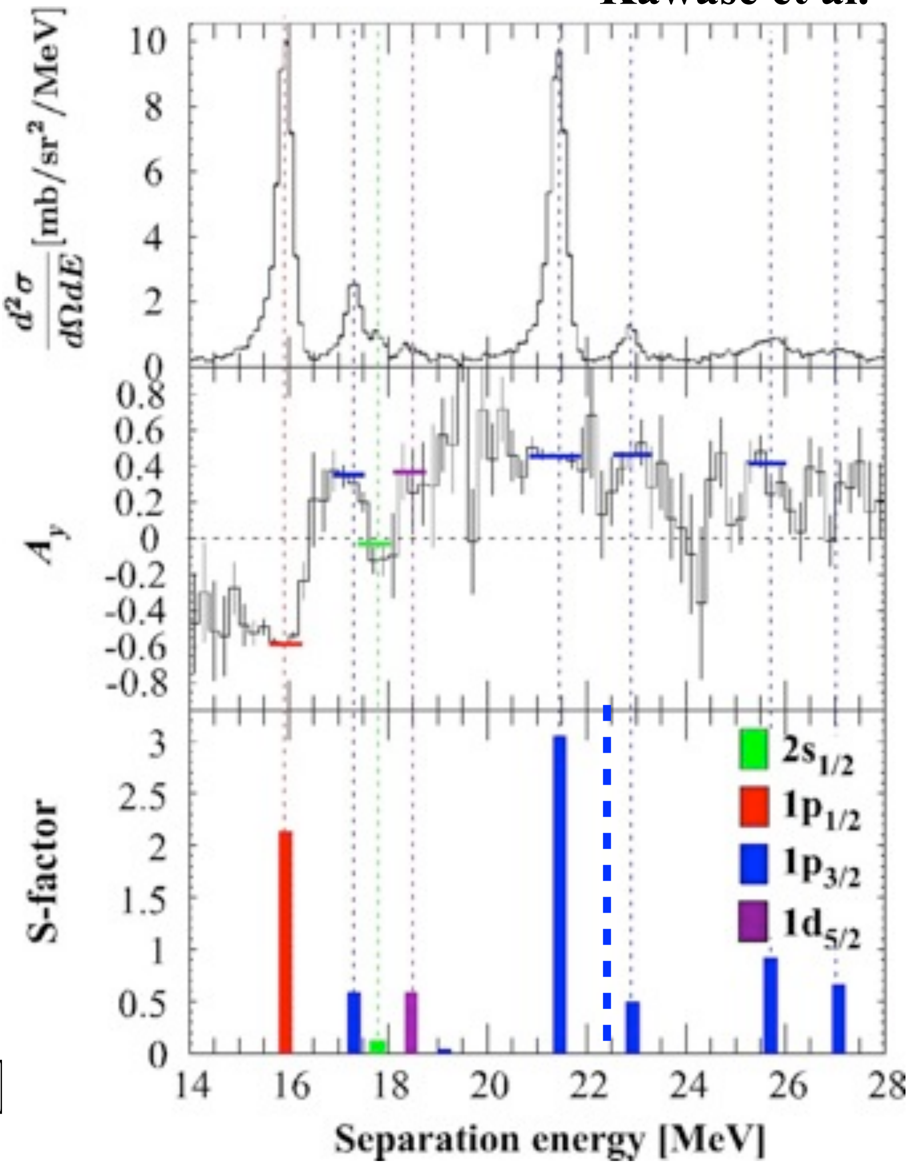
P. Kinching et al.,
NPA 340 (1980) 423.

^{18}O(p,2p) experiment @RCNP

^{18}O(p,2p) @ 200 MeV

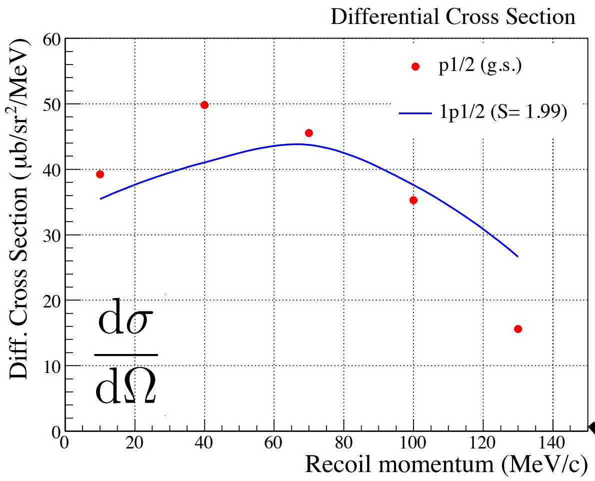


Kawase et al.

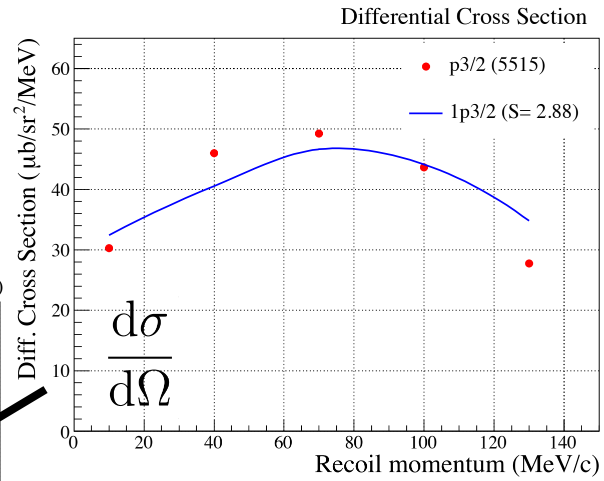


Momentum distributions

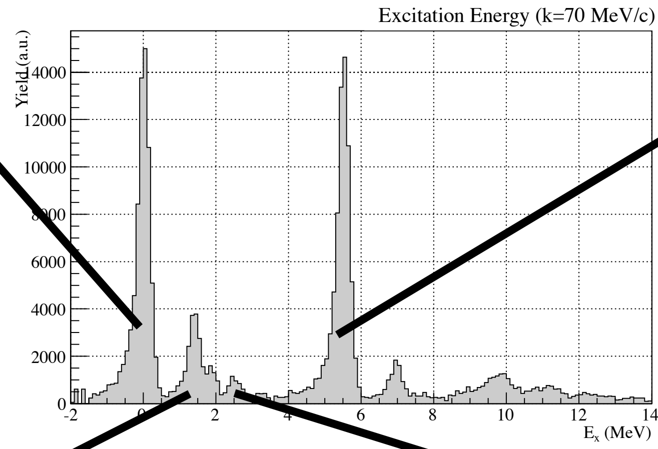
Kawase et al.

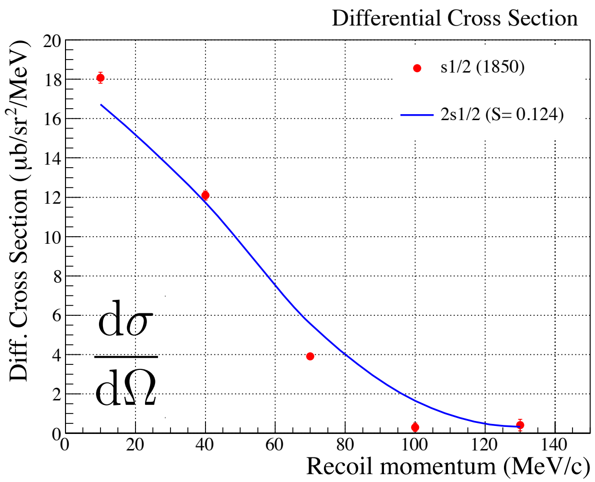


gnd. 1p1/2

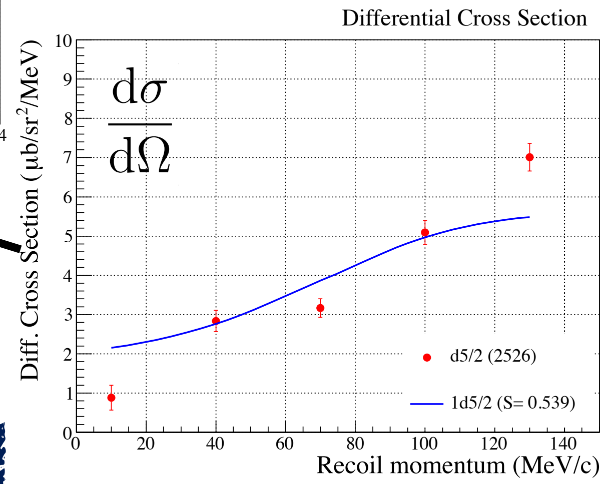


5.515 MeV 1p3/2





1.850 MeV 2s1/2

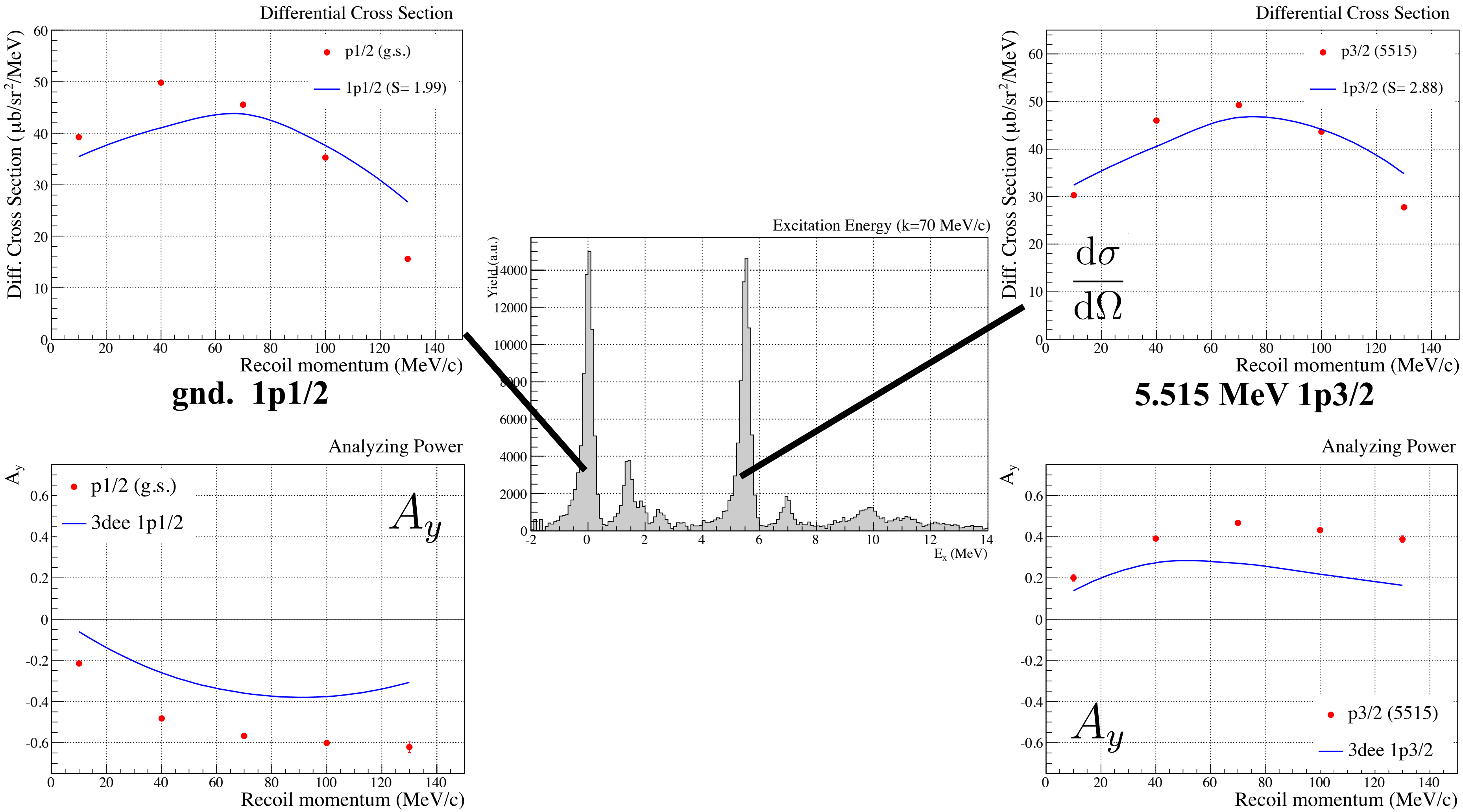


2.526 MeV 1d5/2

We can not differentiate $p_{1/2}$ and $p_{3/2}$ states. . . .

Analyzing Power!

Kawase et al.



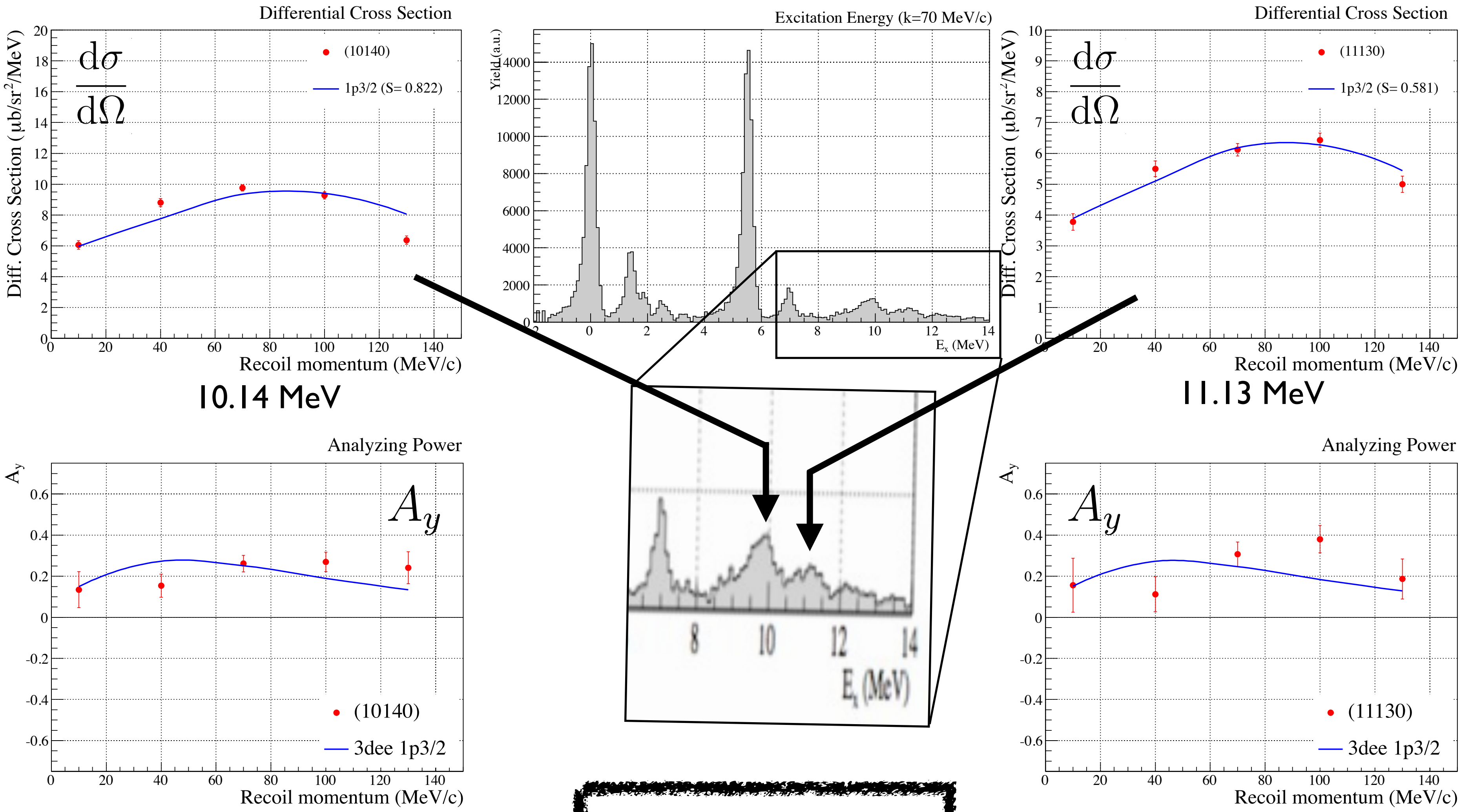
$A_y < 0$: $p_{1/2}$

J^π dependence of A_y is robust.

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

Application of the method to continuum

Kawase et al.



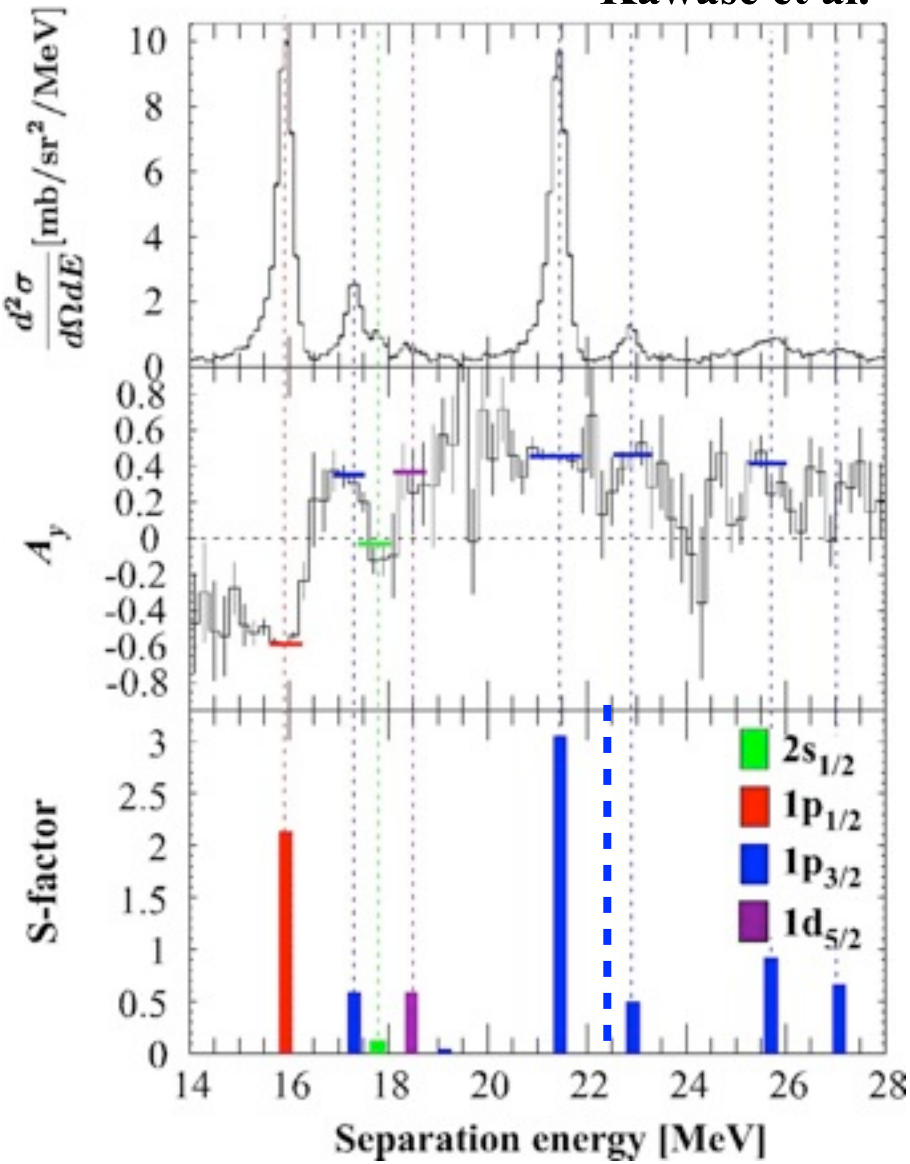
Both of the states are $p_{3/2}$-hole states.

^{18}O(*p*,2*p*) experiment @RCNP

Kawase et al.

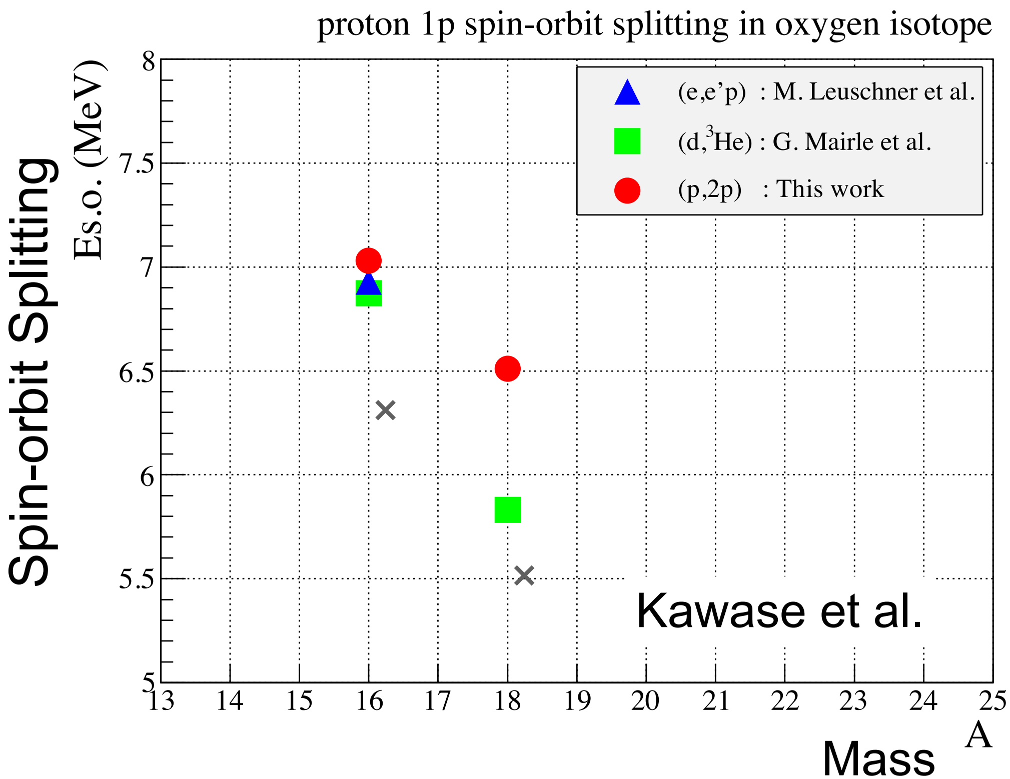
1) Fragmented strengths ($p_{3/2}$) can not be neglected.
2) Spin-asymmetry (A_y) plays an important role in determining *J*.

$$E_{1p3/2} = \sum_{1p3/2\ \text{states}} w_i E_i$$

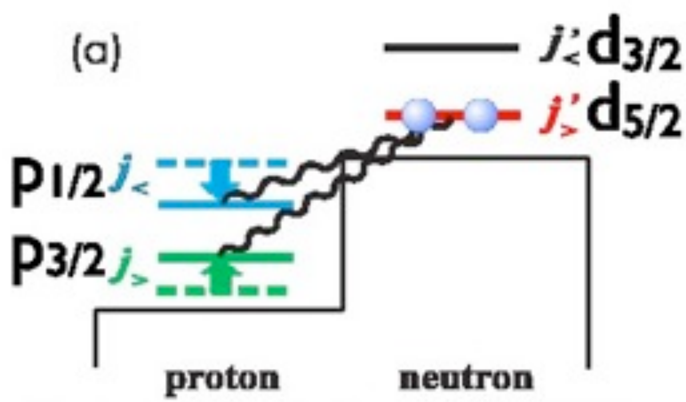


ΔE_{LS}(1p;^{18}O) = 6.5 ± 0.1 MeV

Spin-orbit splitting in ^{18}O



Tensor force effect!



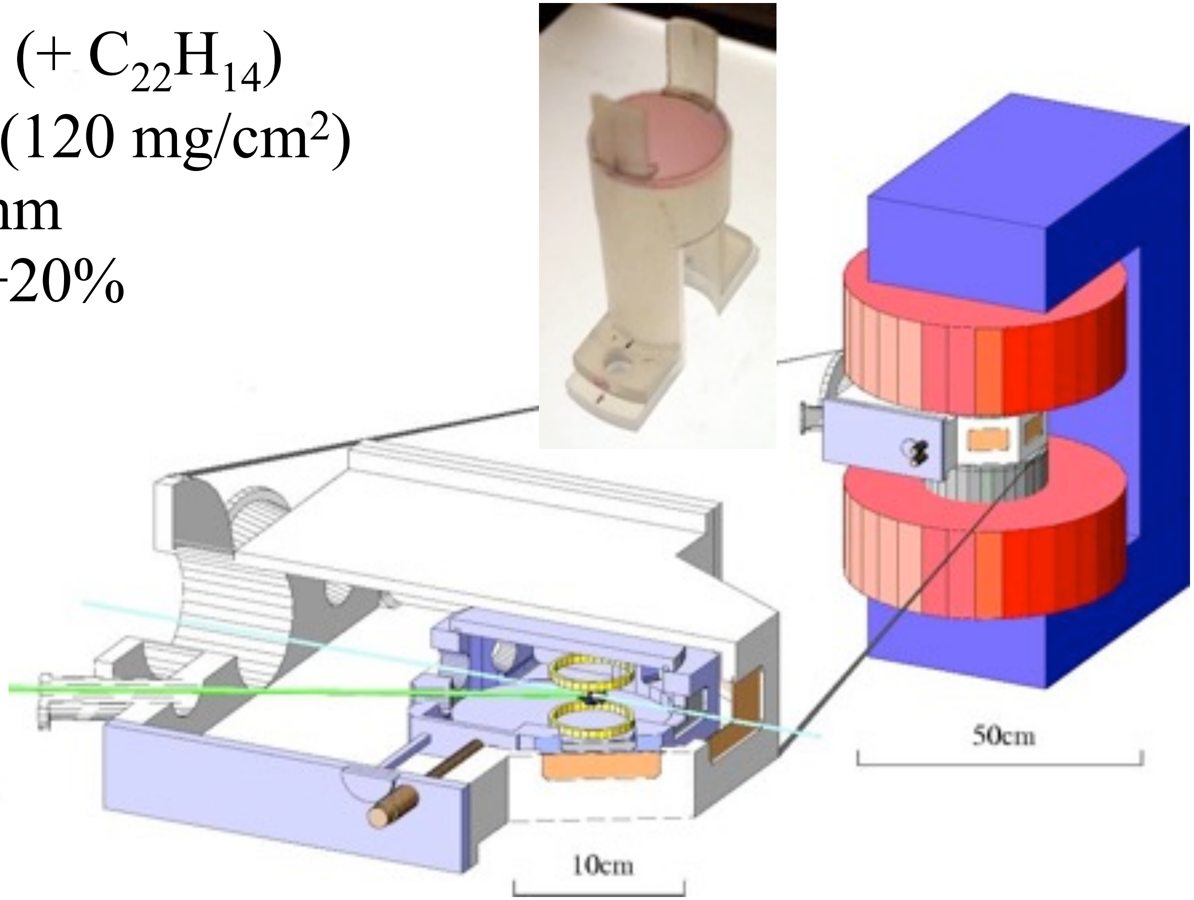
T. Otsuka *et al.*, Phys. Rev. Lett., 95,232502 (2005).

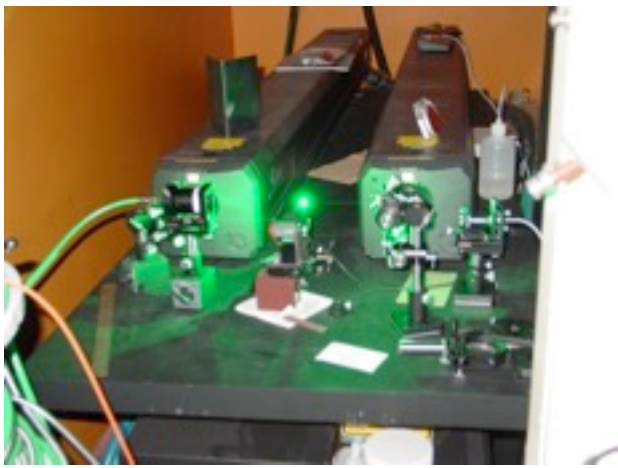
Spin-orbit splitting in ^{18}O is smaller than that in ^{16}O.
We can extend this work to ^{24}O / ^{14}O at RIBF!

Solid Polarized Proton Target at CNS-RIKEN

Polarized Proton Target applicable to RI beam exp.

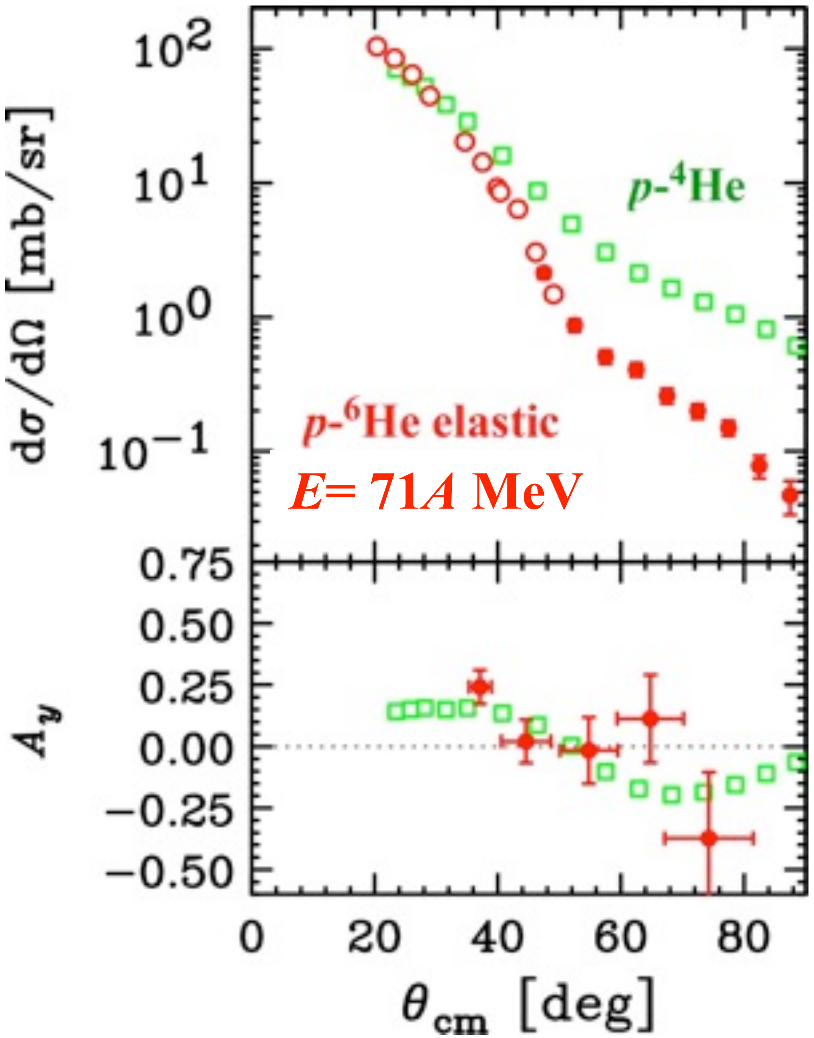
Material: $C_{10}H_8$ (+ $C_{22}H_{14}$)
Thickness: 1 mm (120 mg/cm^2)
Size: φ14 mm
Polarization: P=15−20%
Temperature: 100 K
Mag. field: 0.1 T

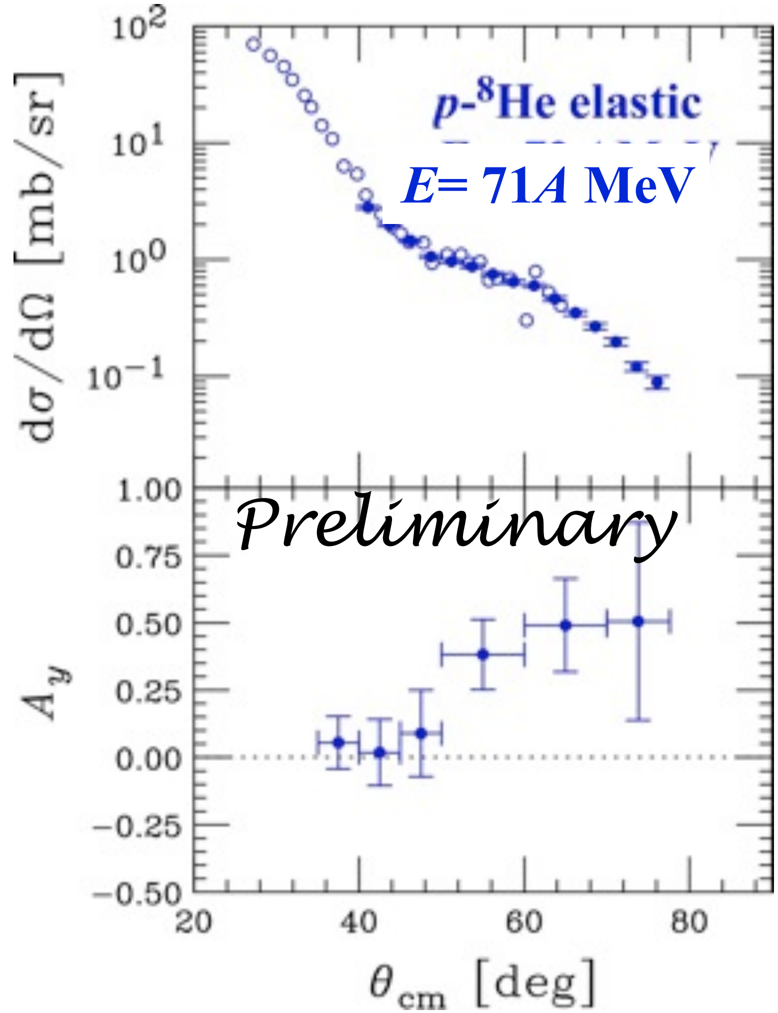




T. Wakui et al., NIM A 550 (2005) 521.
T. Uesaka et al., NIM A 526 (2004) 186.
M. Hatano et al., EPJ A 25 (2005) 255.

Proton Elastic Scattering of ^{6,8}He

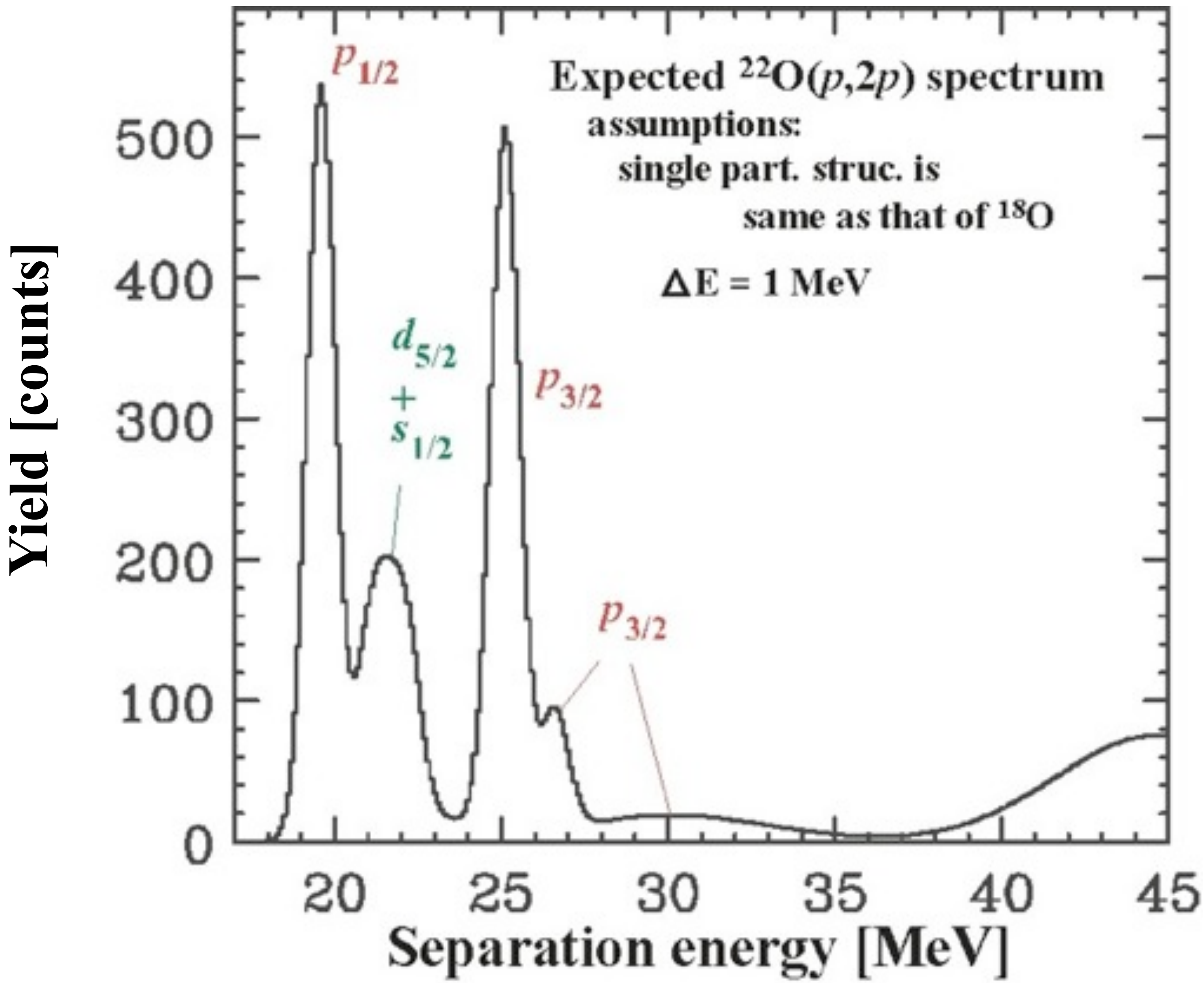




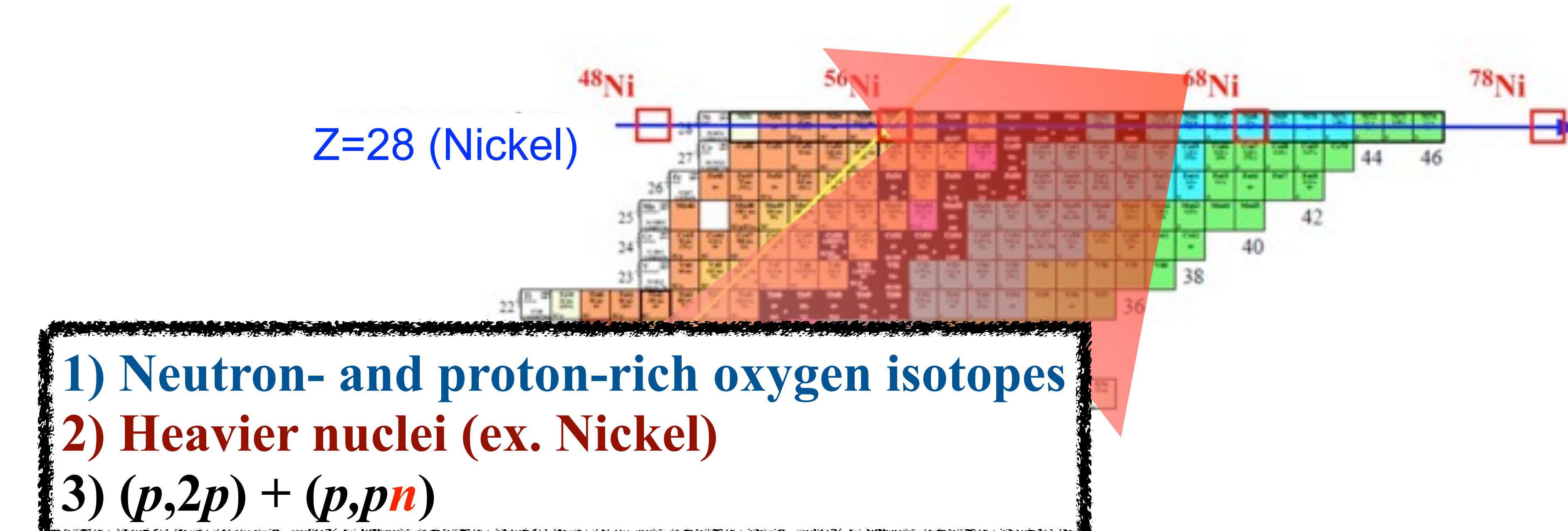
TU, S. Sakaguchi et al., PRC **82** (2010) 021602.
S Sakaguchi, TU et al., PRC **84** (2011) 024604.

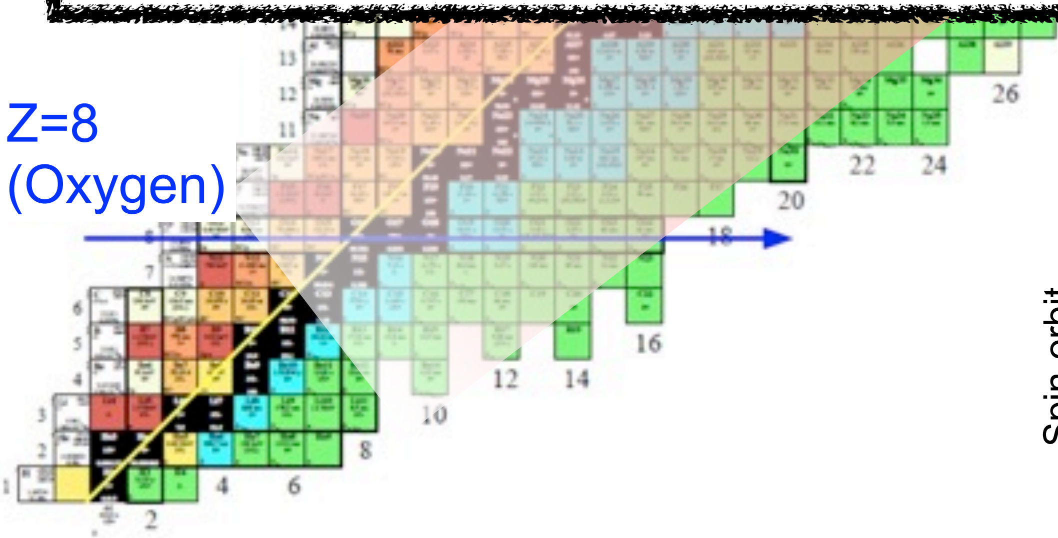
S. Sakaguchi, PhD thesis.

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

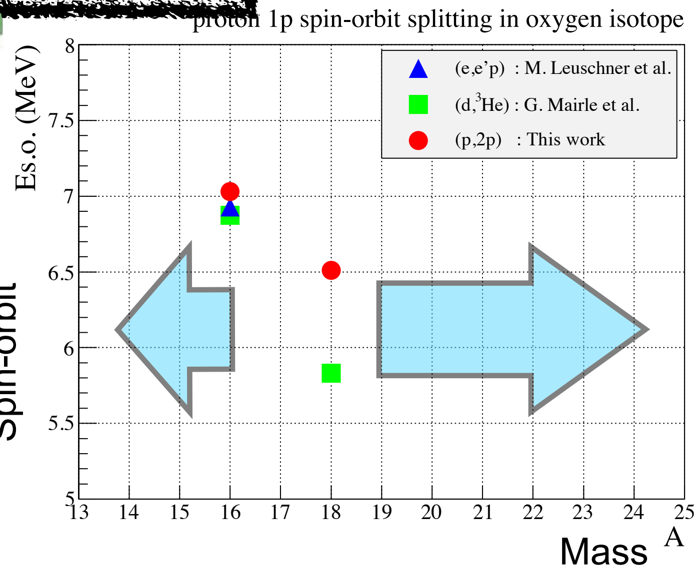


Perspective at RIBF





1) Neutron- and proton-rich oxygen isotopes
2) Heavier nuclei (ex. Nickel)
3) (*p*,2*p*) + (*p*,*pn*)



Summary

Spin-orbit coupling in nuclei should be revisited.
  Tensor and 3N interactions play central roles.

Experiments to determine ΔE_{LS} in oxygen isotopes are ongoing:
a direct measure of the spin-orbit coupling

$^{18}O(p,2p)$ @RCNP

$\Delta E_{LS}(1p, ^{18}O) = 6.5$ MeV $<$ 7 MeV in ^{16}O

- One should pay attention to fragmented strengths.
- Spin-asymmetry is useful for unambiguous J^{π} determination

$^{14,22-24}O(p,2p)$ @RIBF in near future
Polarized proton target can be used for the spin-asymmetry measurement