Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics
Pisa (Italy), July 20th – 24th, 2015

Experimental methods and measured observables with Polarized Proton Targets: Understanding Spin-Orbit

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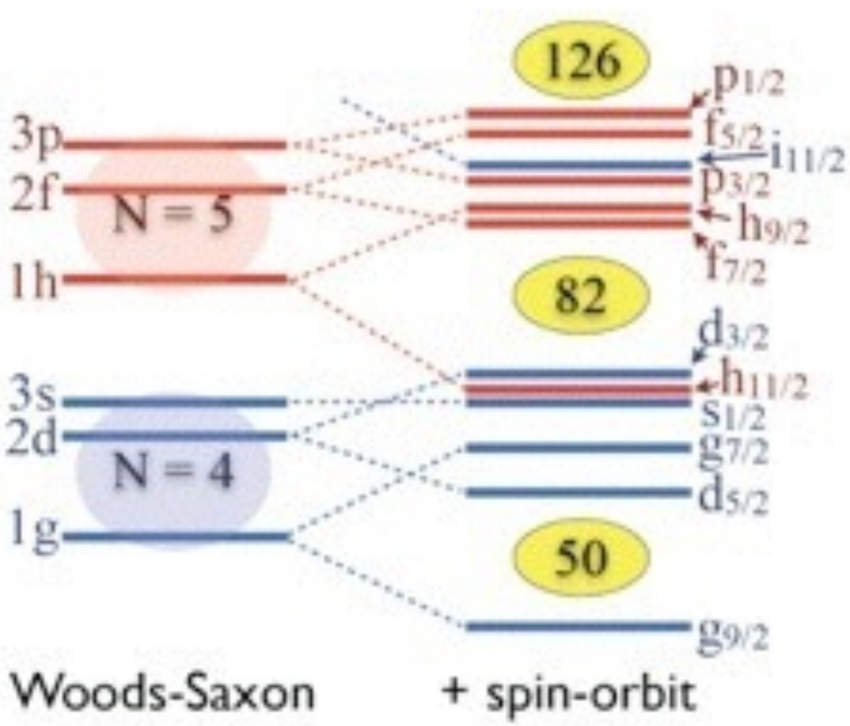
My First Message

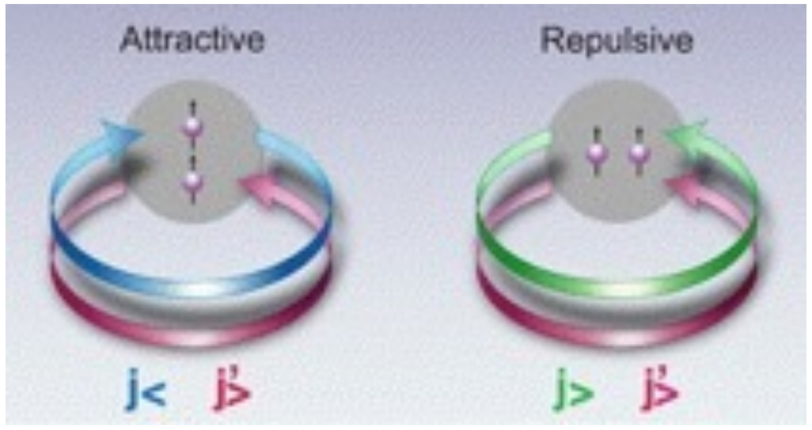
30-years research with radioactive isotope beams has revealed that "spin" plays more vital roles in exotic nuclei than expected!

Richness in nuclear structure is a manifestation of interplays among the spin-dependent interactions.

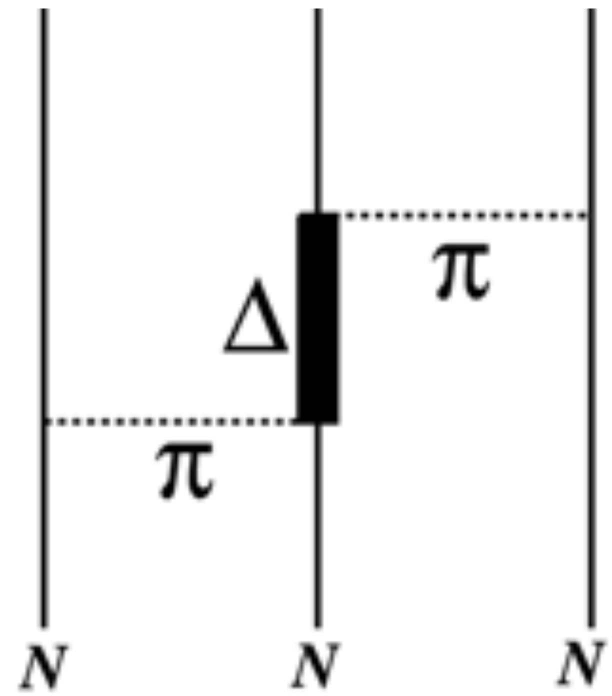
Spin-orbit force



Tensor force (pion exchange)



3N force



“The Secret” in the nuclear structure physics

What is the origin of spin-orbit coupling in nuclei?

(Why does a nuclear density saturate?)

How does the spin-orbit coupling change as a function of N/Z?

1st Half: Story of Nuclear Spin-Orbit Coupling

2nd Half: Experimental Approaches to SO Coupling in Exotic Nuclei

Outline of the 1st half

Why is nuclear shell structure so special?

Concept of "strong" spin-orbit coupling
introduced by Mayer and Jensen

Origins of the strong spin-orbit coupling

What we can expect in exotic nuclei

Shell structure

→ Sonia Bacca's lecture

Phenomena common to many-Fermion systems.

Shell structure in atoms:
Periodic table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1						1 H												2 He	**2**
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	**10**
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	**18**
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	**36**
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	**54**
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	**86**
7	87 Fr	88 Ra		104 Du	105 Jo	106 Rf	107 Bh	108 Ha	109 Mt										

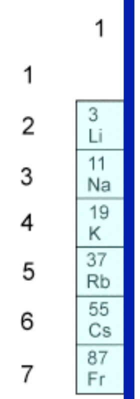
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Shell structure

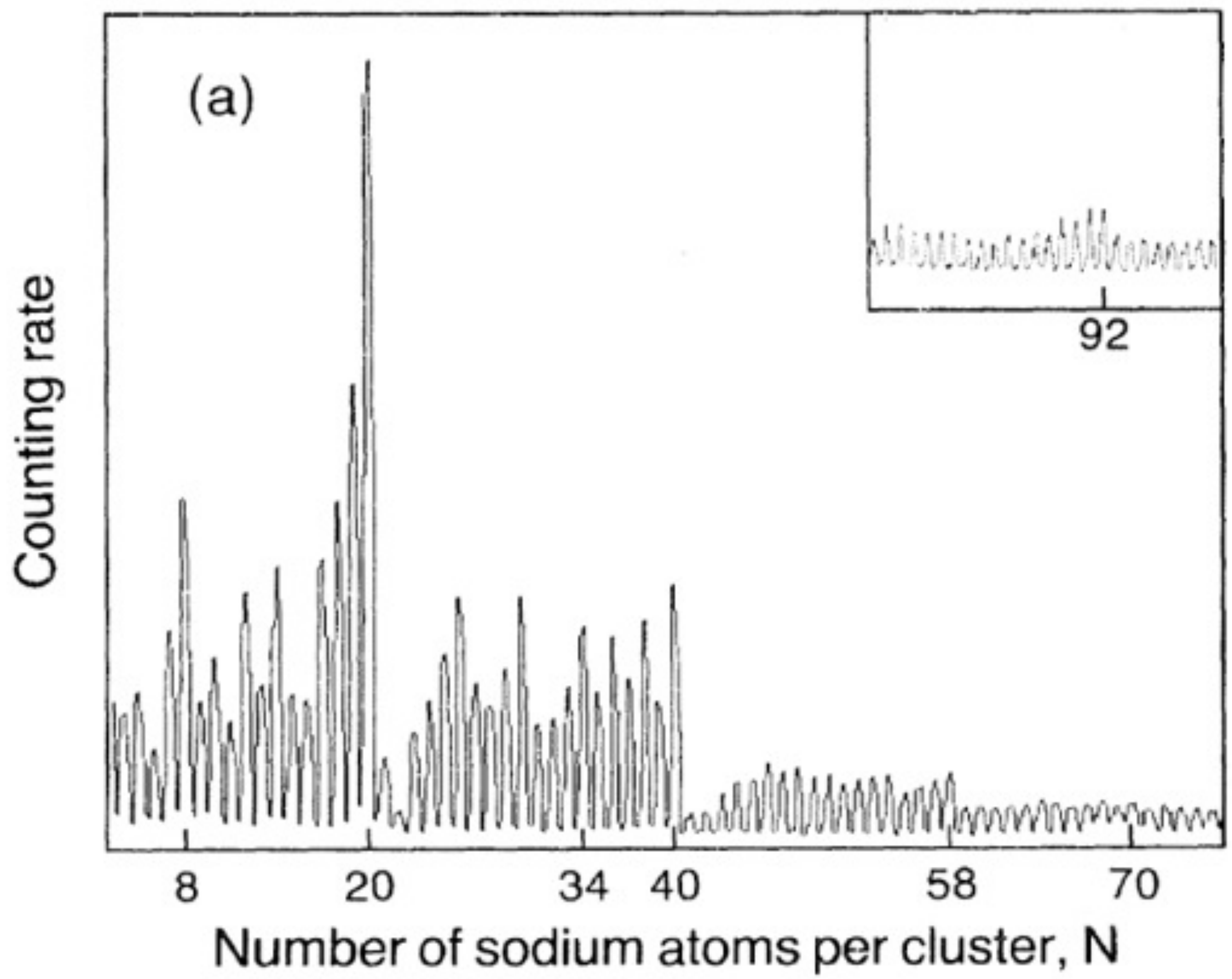
→ Sonia Bacca's lecture

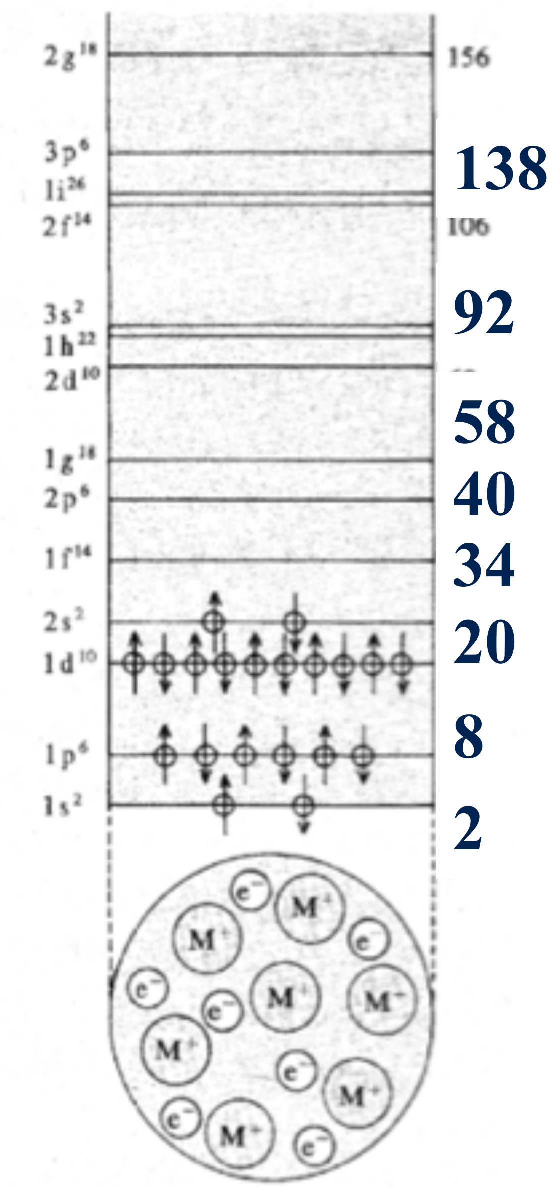
Phenomena common to many-Fermion systems.

Shell s



Shell structure in nano clusters





W.D.Knight et al., PRL 52 (1984) 2141.

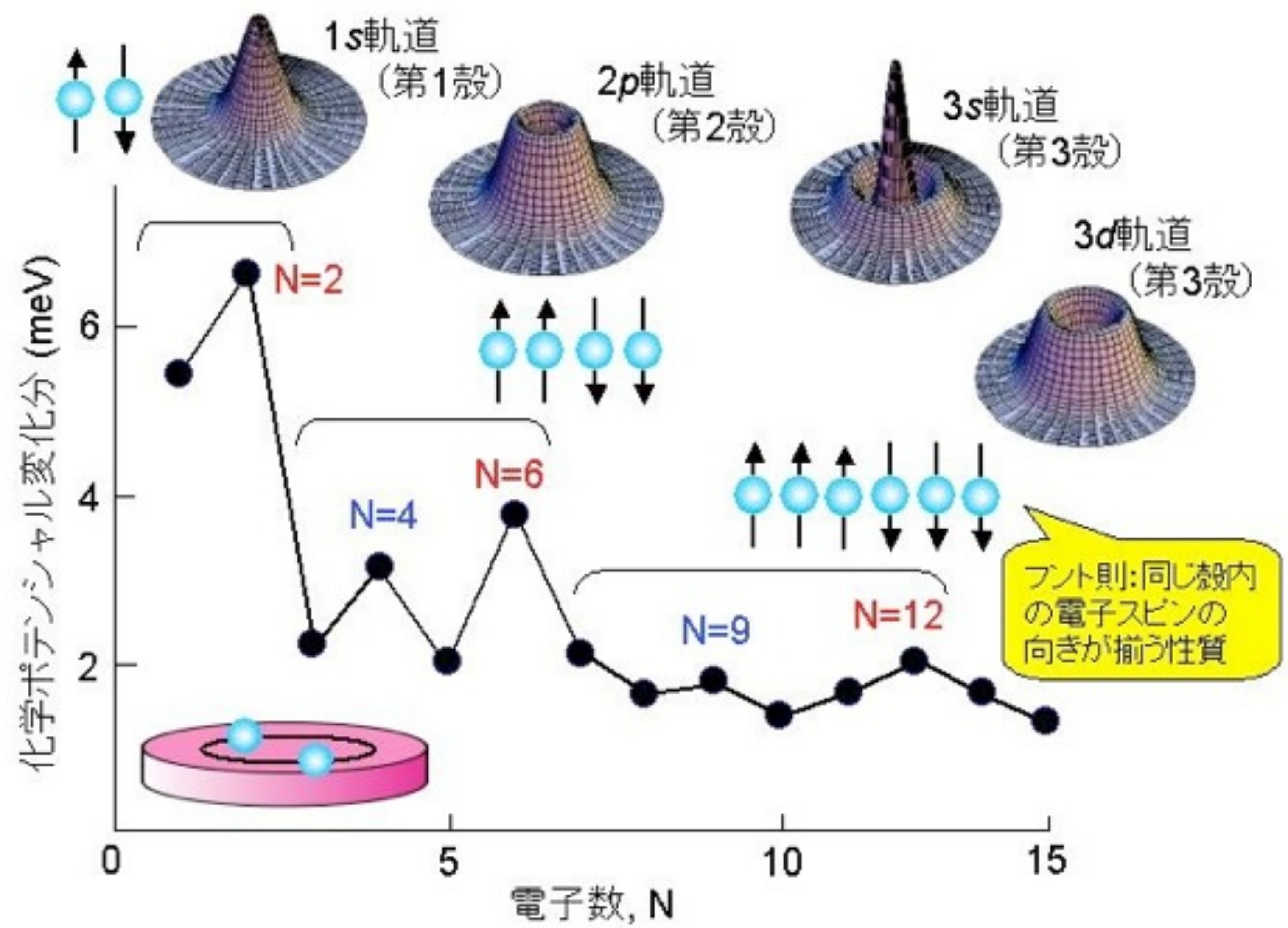
交久瀬、伊藤、
日本物理学会誌 53(7) (1998)

Shell structure

→ Sonia Bacca's lecture

Phenomena common to many-Fermion systems.

Shell structure in quantum dots (electrons in 2D)



S. Tarucha, http://www.nanonet.go.jp/japanese/.mailmag/2003/013a.html

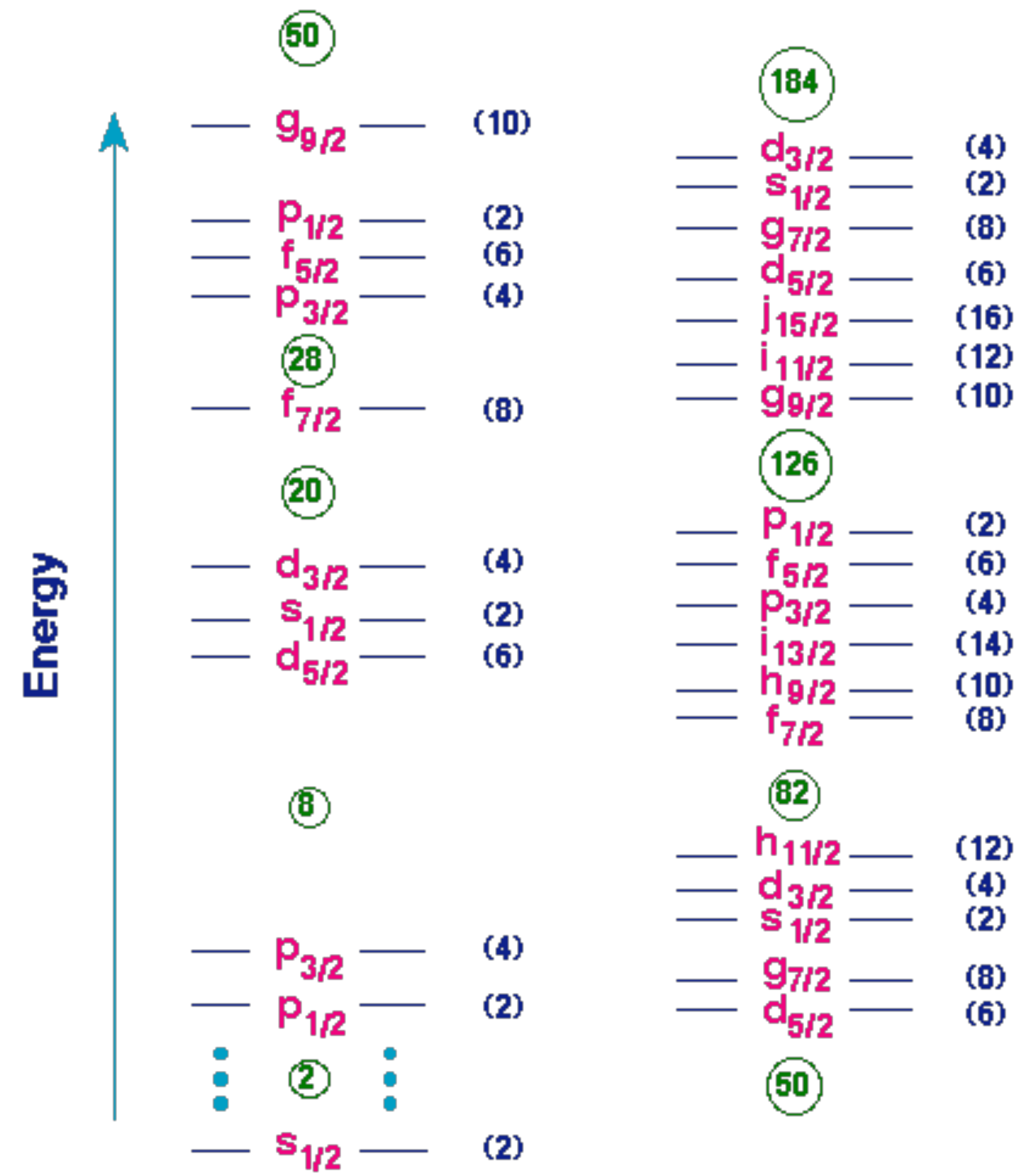
Shell structure

→ Sonia Bacca's lecture

Phenomena common to many-Fermion systems.

Shell structure in nuclei

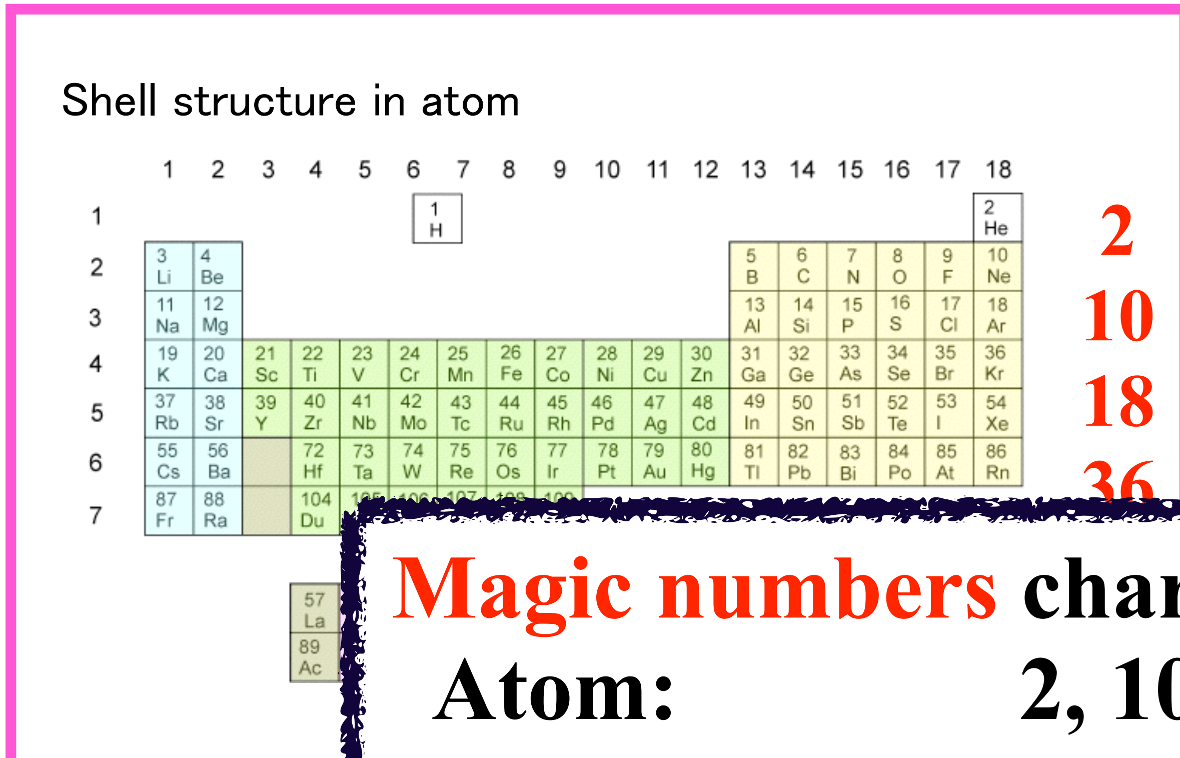
magic numbers
2, 8, 20, 28, 50, 82...

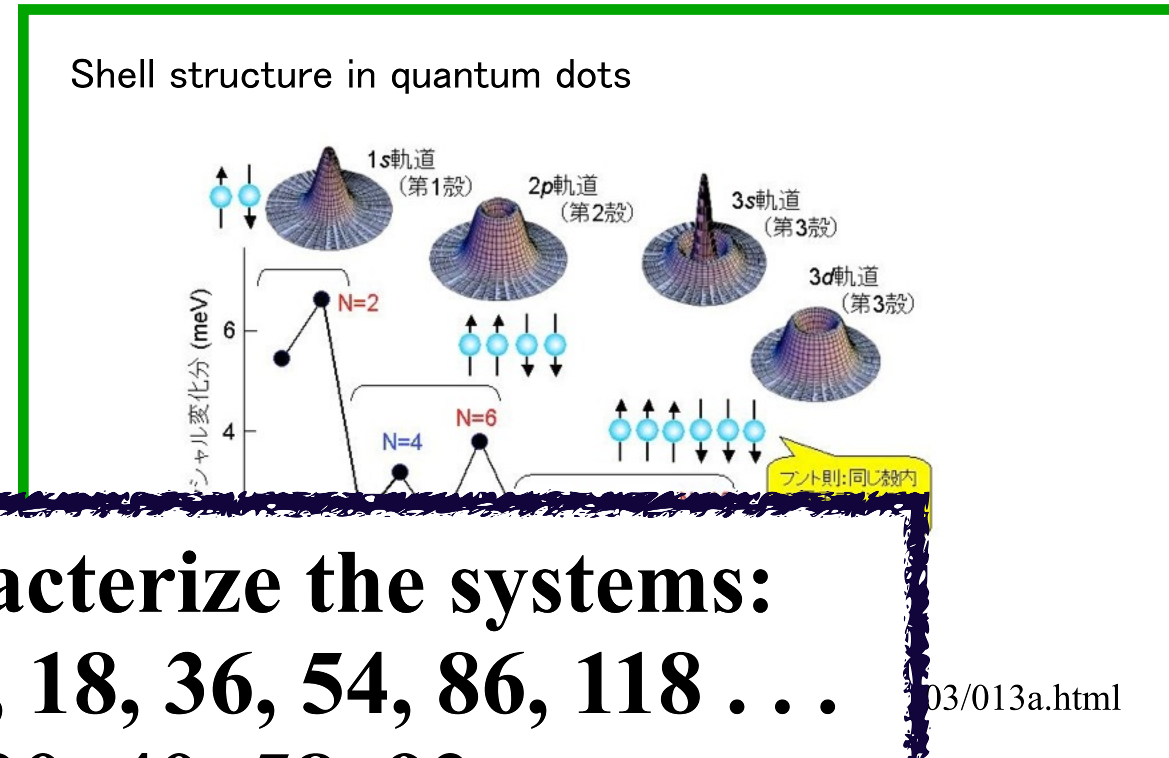


Shell structure

→ Sonia Bacca's lecture

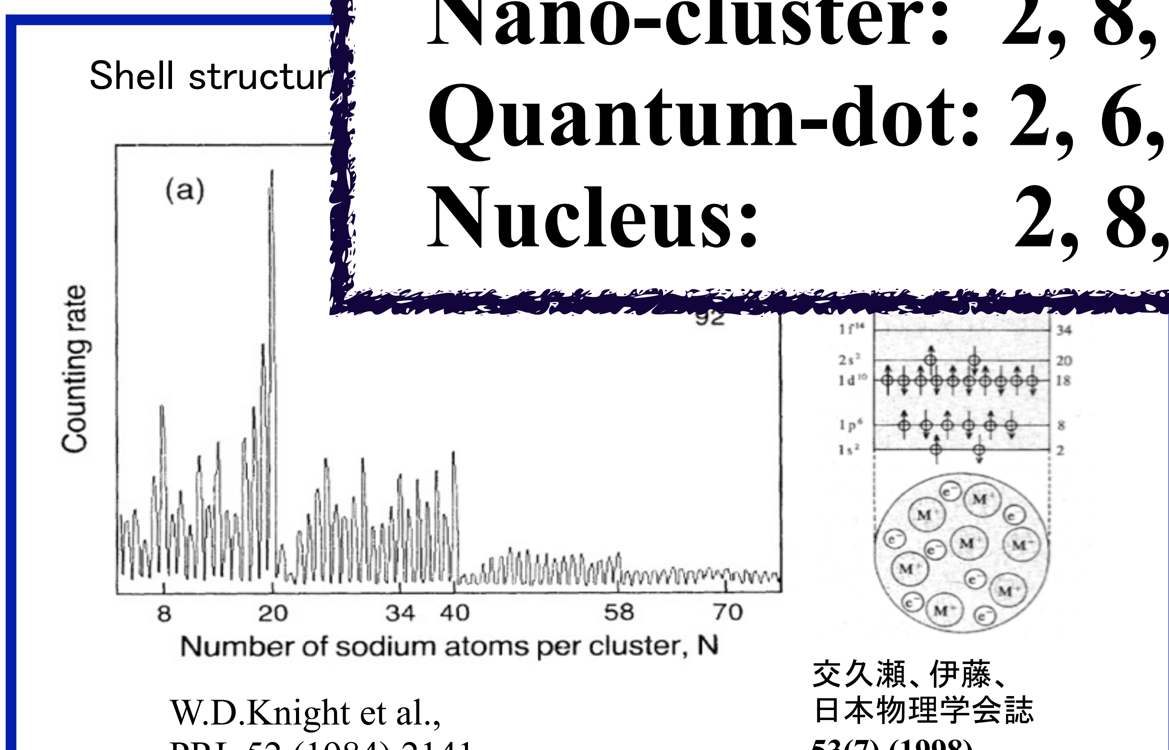
Phenomena common to many-Fermion systems.

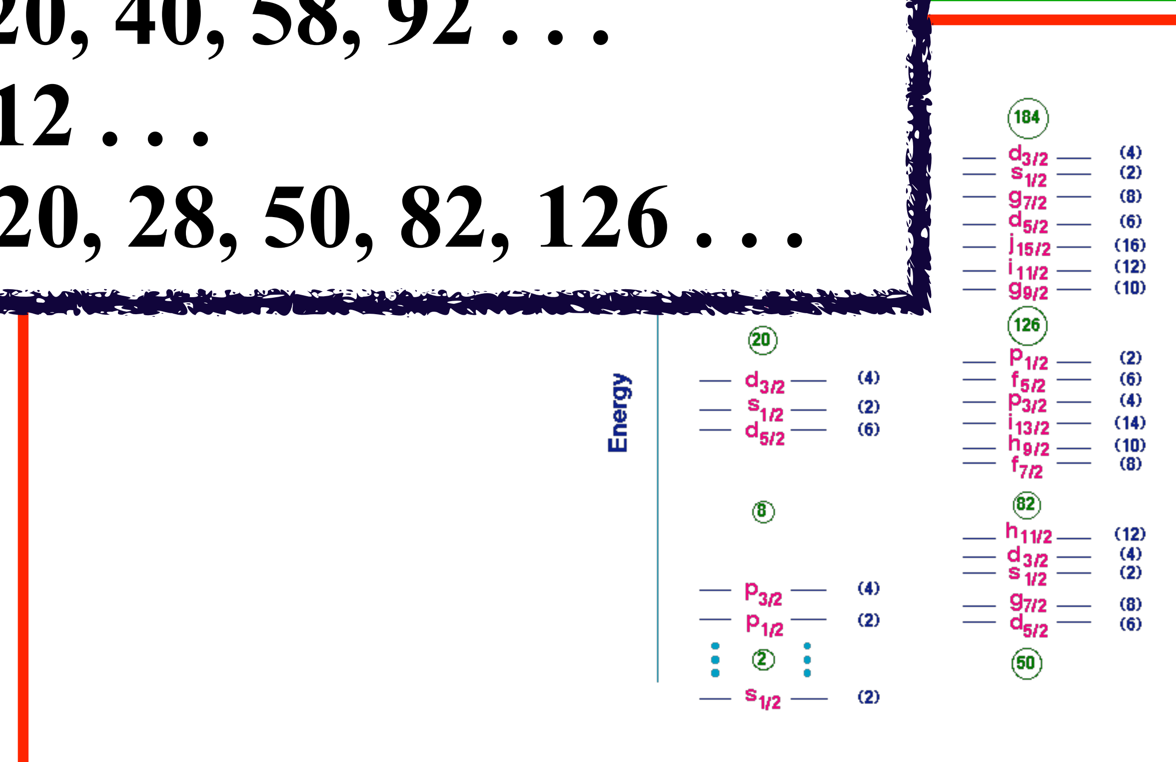




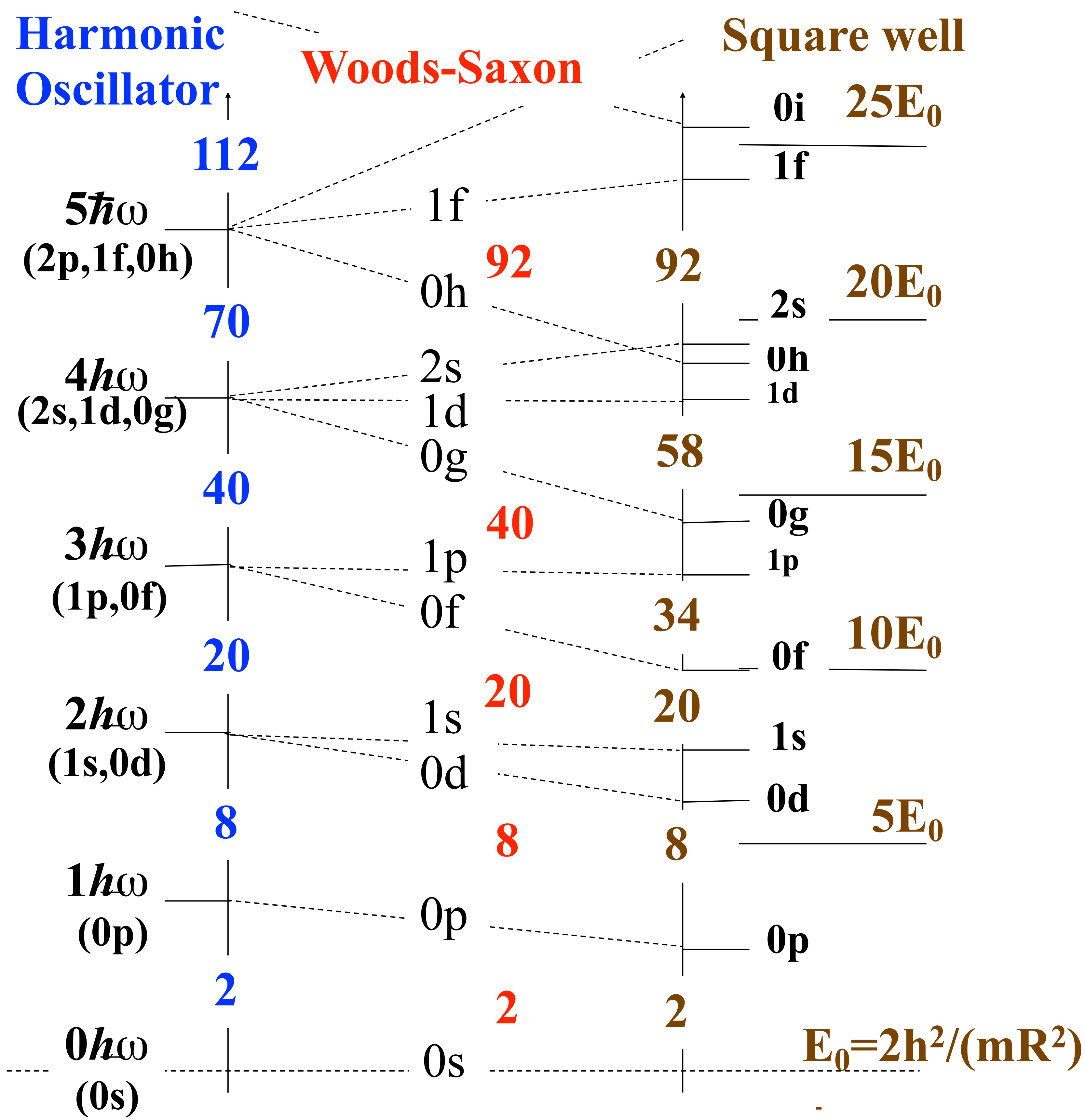
Magic numbers characterize the systems:

- **Atom:** 2, 10, 18, 36, 54, 86, 118 . . .
- **Nano-cluster:** 2, 8, 20, 40, 58, 92 . . .
- **Quantum-dot:** 2, 6, 12 . . .
- **Nucleus:** 2, 8, 20, 28, 50, 82, 126 . . .





Nuclear magic numbers were mysterious



Strange Potentials

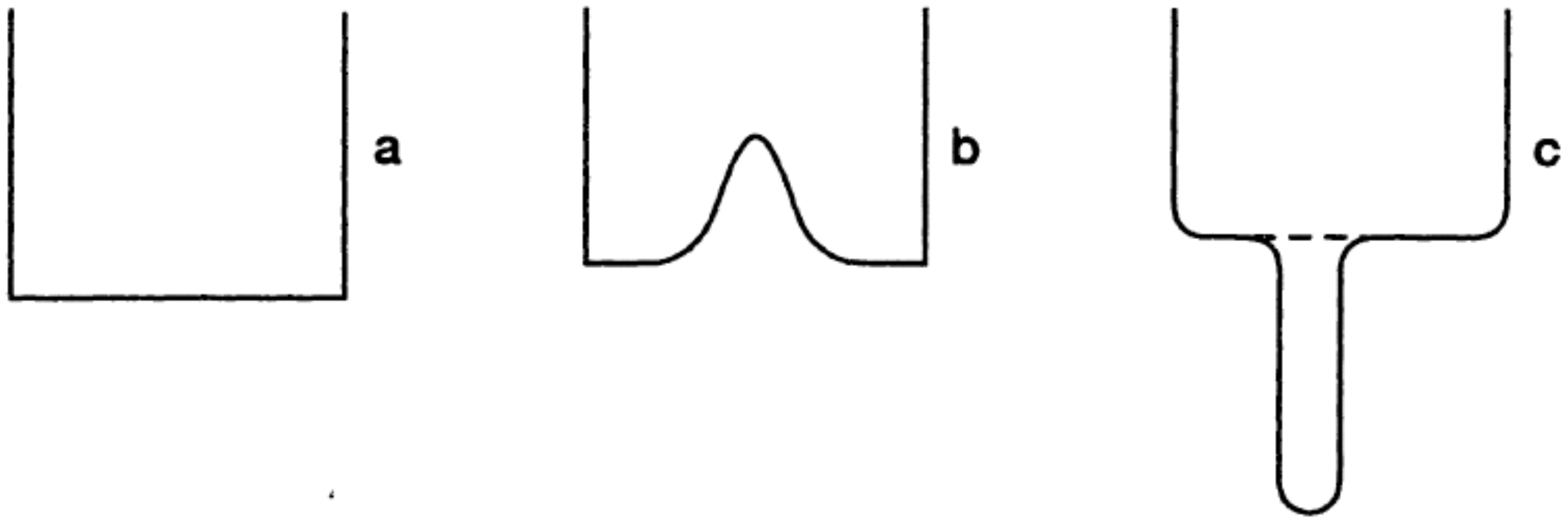
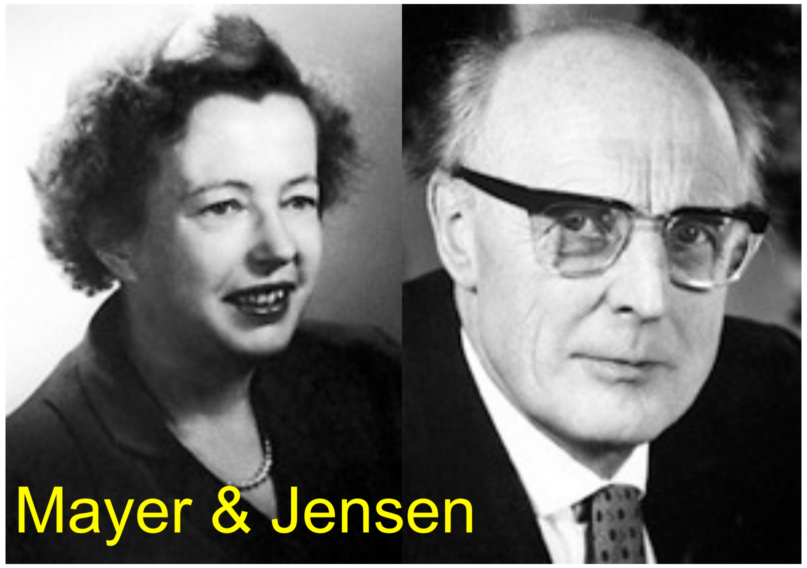
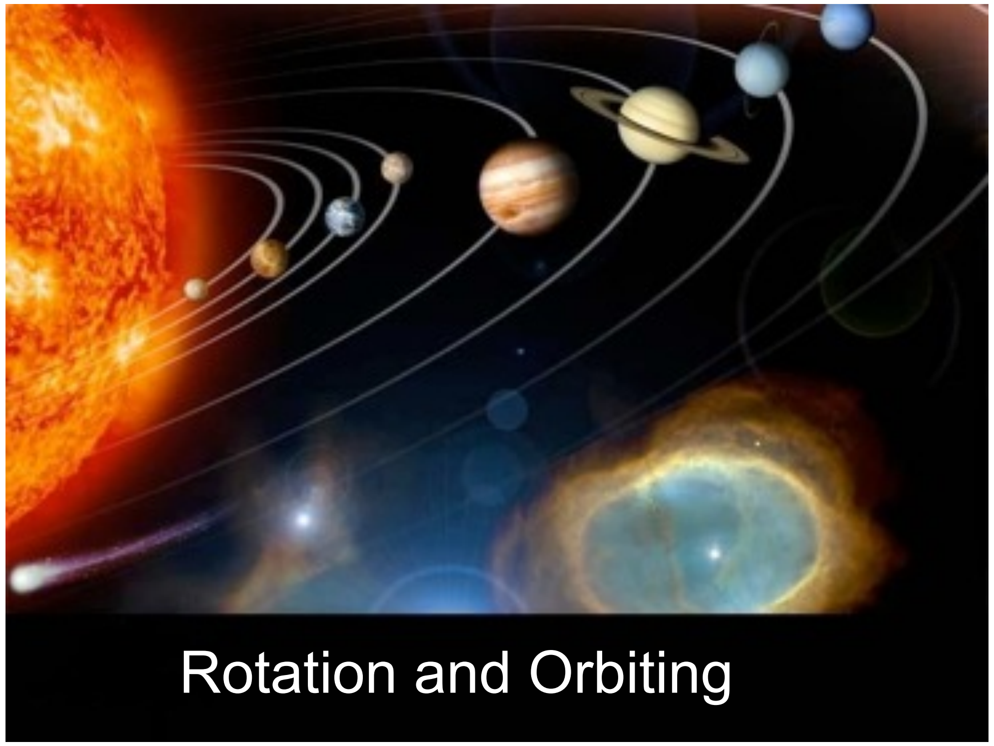


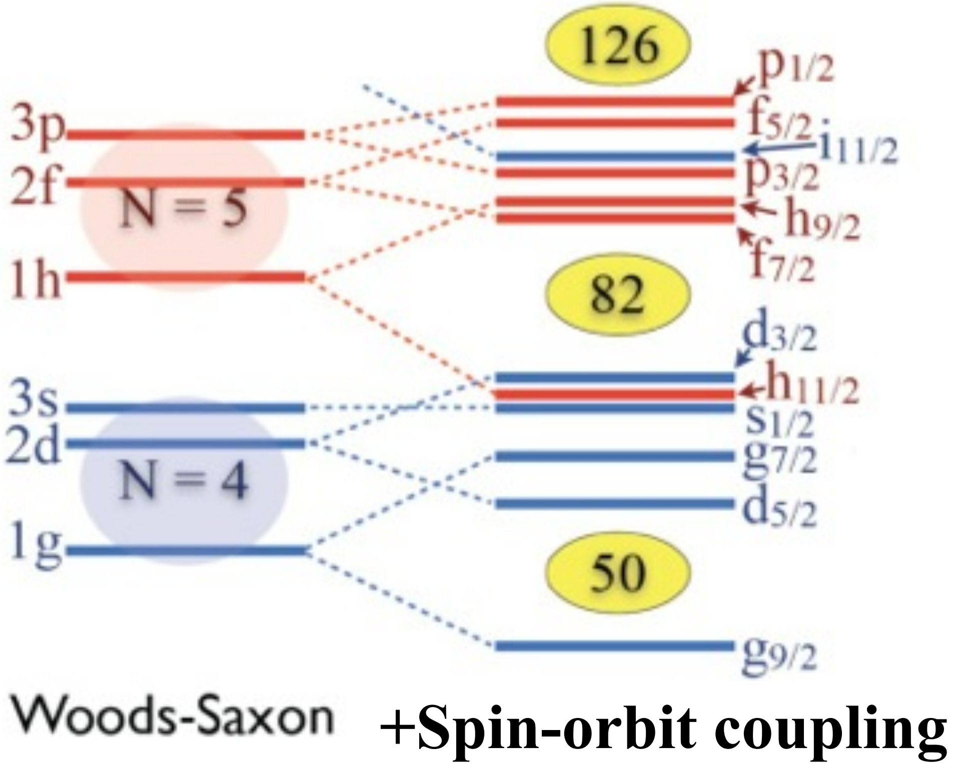
Figure 15.2. Three potentials considered by Elsasser [6].

All the efforts didn't succeed.

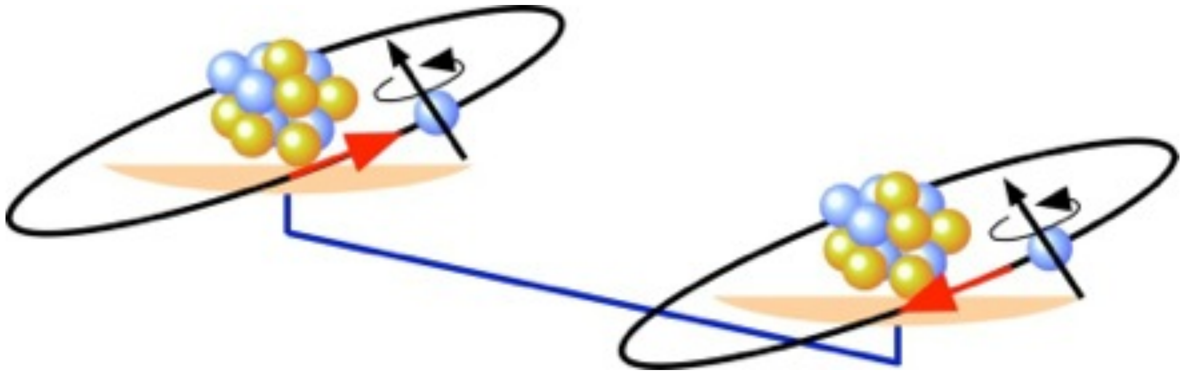
Magicity and spin-orbit coupling





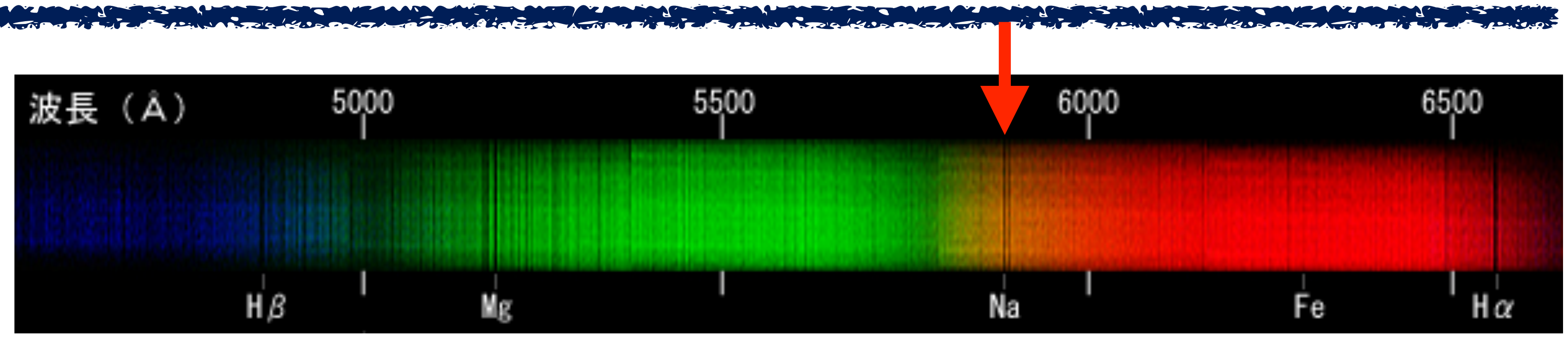


In nucleus, a state with parallel S & L has a smaller mass.



Discovery of Spin-Orbit Coupling

D-line: ^{23}Na



The line splits into two.

589.592 nm

588.995 nm

$\Delta E \sim 2$ meV

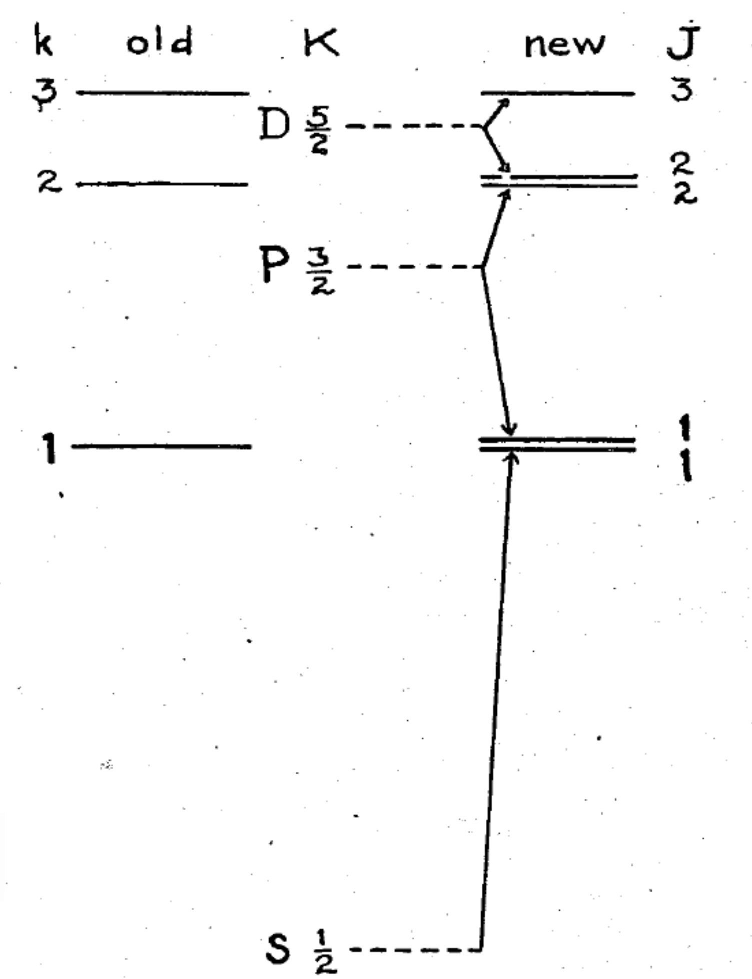


FIG. 1.

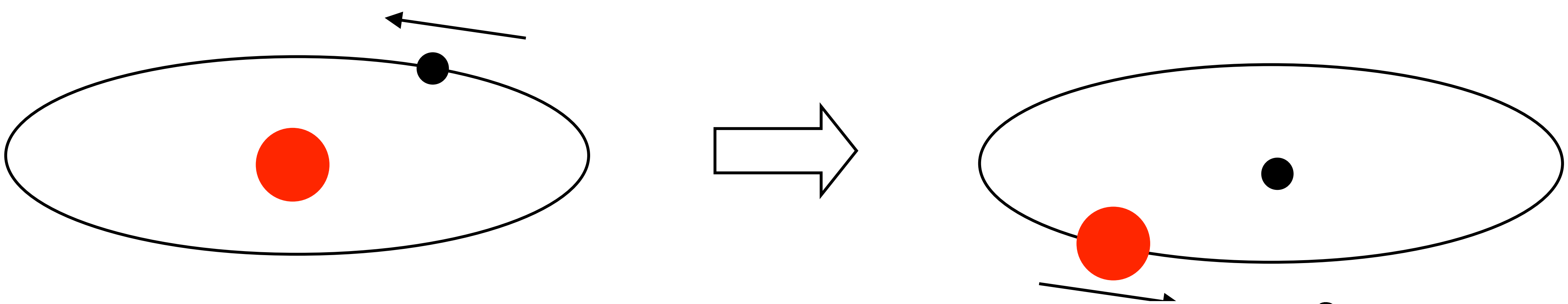
G.E. Uhlenbeck and S. Goudsmit, Nature 117 (1926) 264.

Spinning Electrons and the Structure of Spectra.

Spin-Orbit Coupling in Atoms

Magnetic term

Interaction between a magnetic field originating from orbital motion of electron(s) and an electron spin



$$V_{\mathrm{LS}} = \frac{e\hbar^2}{m_e^2 c^2}\frac{1}{r}\frac{dV}{dr}\vec{L}\cdot\vec{S}$$

In reality $$V_{\mathrm{LS}} = \frac{1}{\underline{2}}\frac{e\hbar^2}{m_e^2 c^2}\frac{1}{r}\frac{dV}{dr}\vec{L}\cdot\vec{S}$$

Thomas term

Relativistic effects taking place in a system under an accelerated motion

$$V_{\mathrm{LS}} = -\frac{e\hbar^2}{m_e^2 c^2}\frac{g}{2}\left(1-\frac{1}{g}\right)\frac{1}{r}\frac{dV}{dr}\vec{L}\cdot\vec{S}$$

Spin-Orbit Coupling in Atoms (*cont.*)

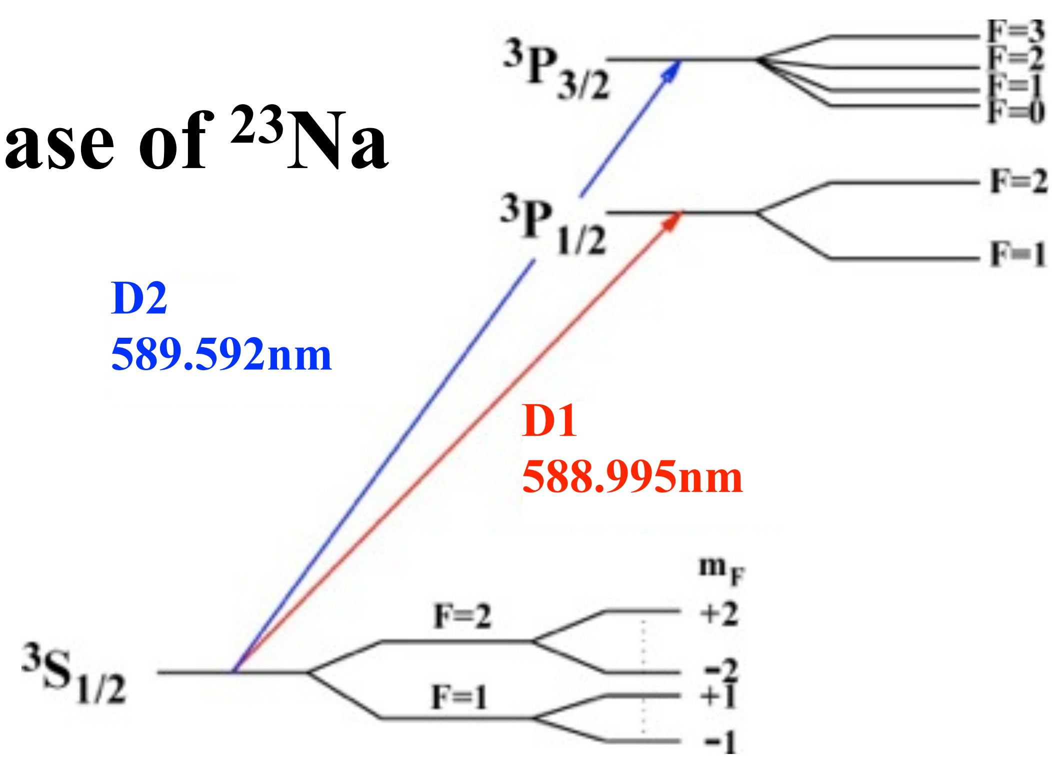
1) Repulsive

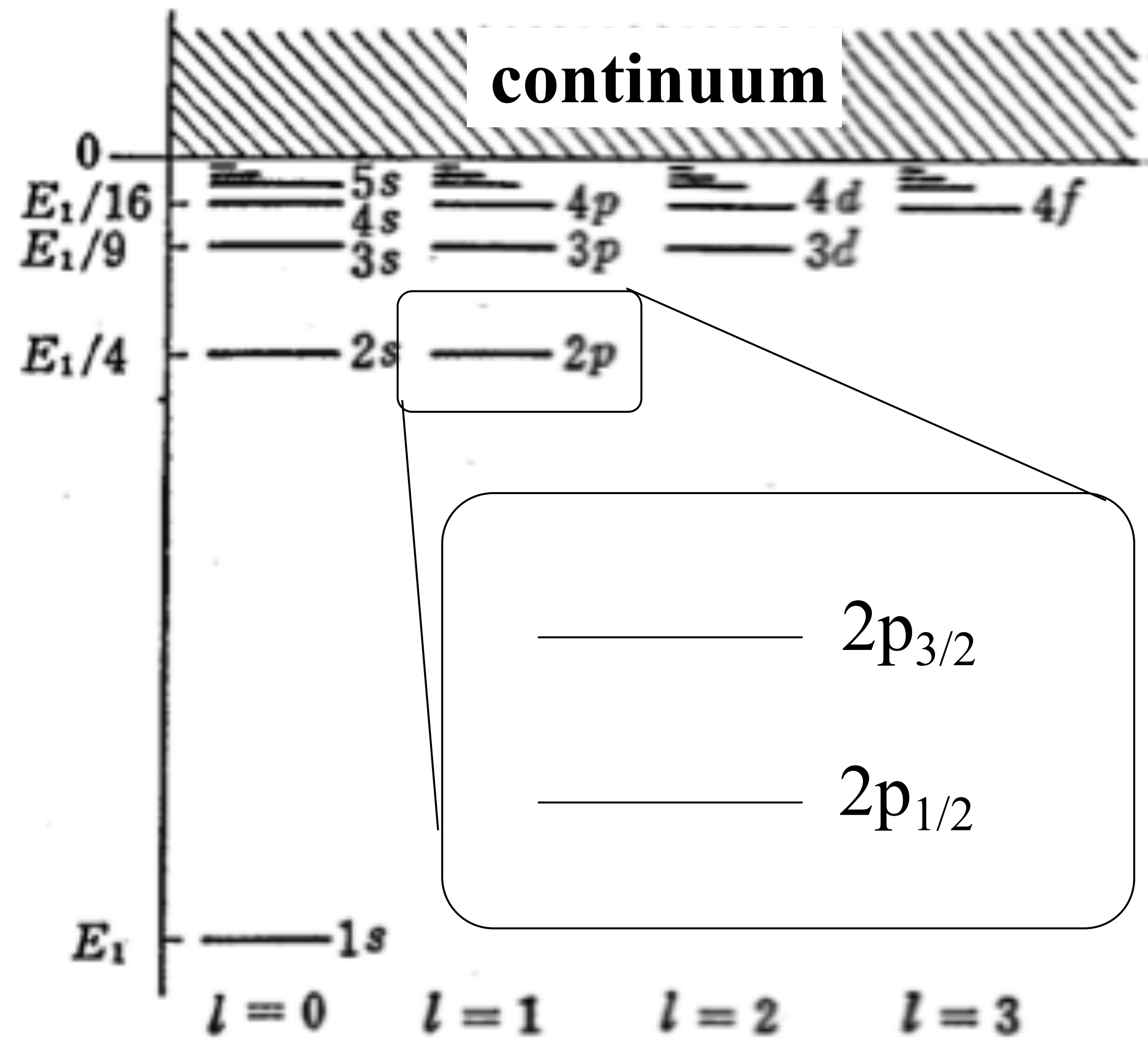
smaller *J* orbit (*J*=*L*-1/2) is more stable than *J*=*L*+1/2 orbit

2) Weak

→ "fine" structure

case of ^{23}Na



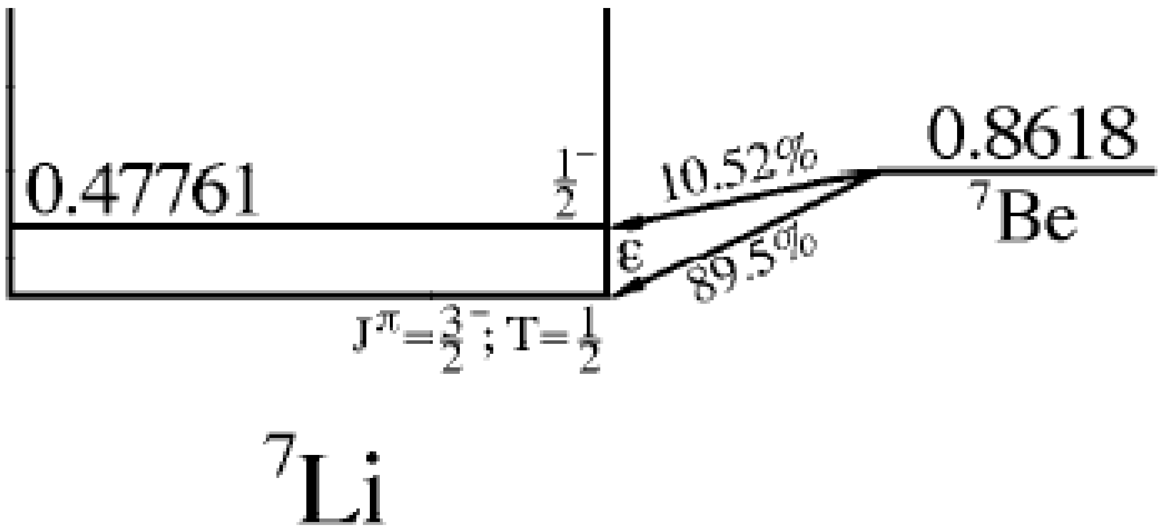


The first study of Nuclear Spin-Orbit Coupling

D.R. Inglis, Phys. Rev. 50 (1936) 783.
Investigation of spin-orbit coupling in nuclei,
taking an analogy to the atomic spin-orbit coupling.

He considered that
the magnetic term should be negligibly small, and
the Thomas term is dominating

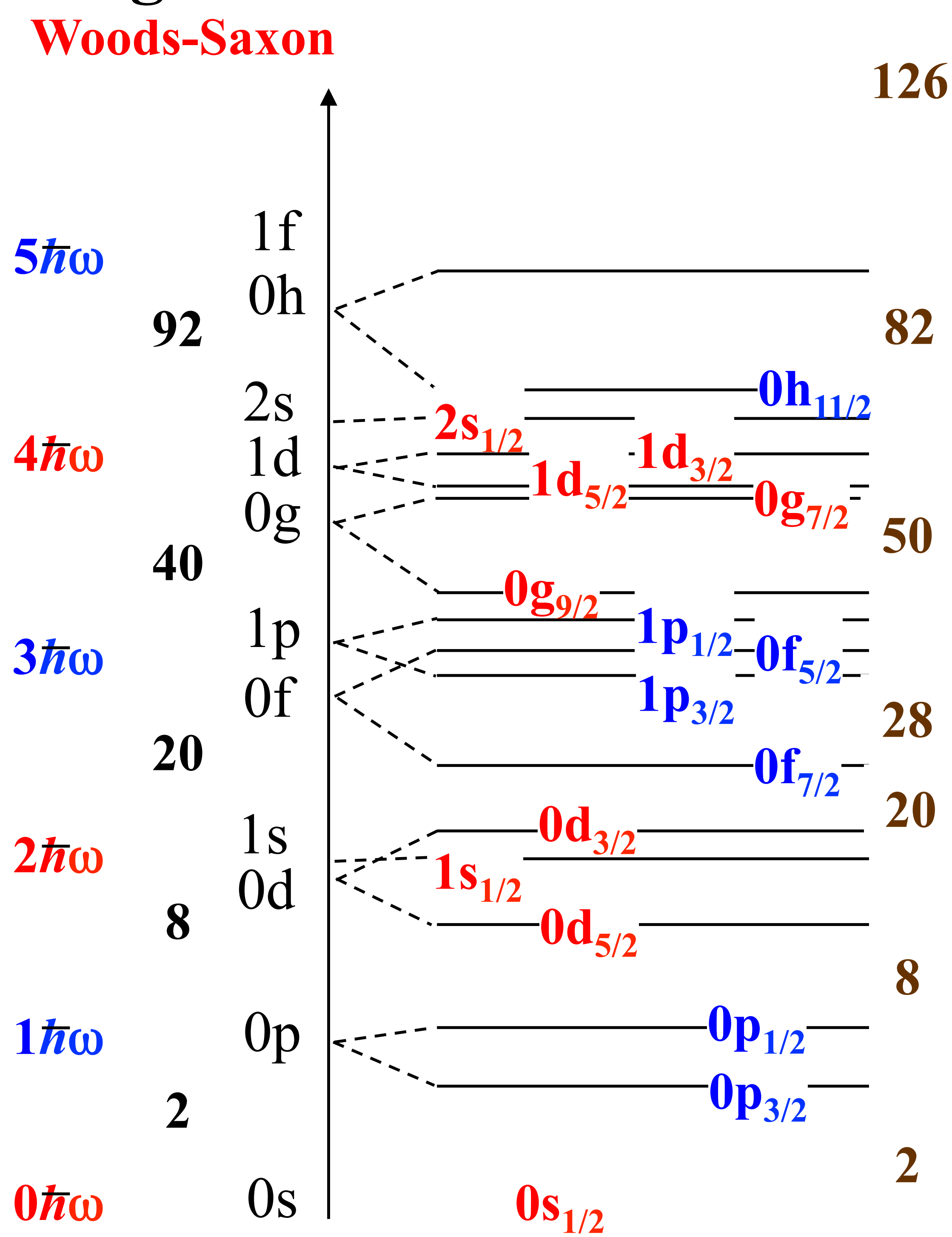
→ Inversion doublet
a state with J = L + 1/2
is more stable.

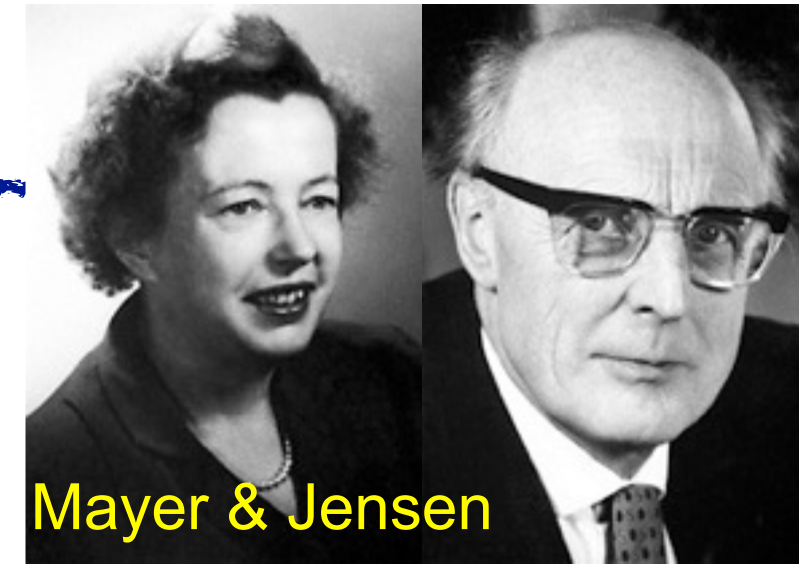


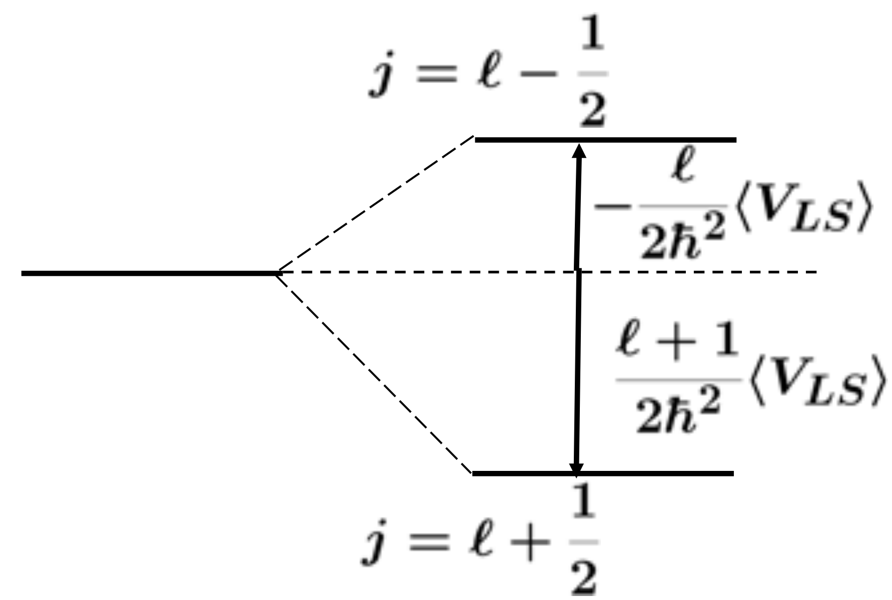
But, the Thomas term is
too weak to explain magic numbers.

Strong Spin-Orbit Coupling

is essential in the formation of magic numbers in nuclei







Spin-orbit splitting

$$\Delta E_{LS} = \frac{2\ell+1}{2\hbar^2}\langle V_{LS}\rangle$$

Terminology around spin-orbit ・・・

Spin-orbit splitting

Energy interval between a spin doublet

Spin-orbit coupling

Coupling between spin and orbital angular momentum that produces a spin-orbit splitting

Spin-orbit potential

One-body potential to model spin-orbit coupling

Usually written in the form proportional to a first derivative of a density distribution

Spin-orbit force

A term proportional to L・S in the nuclear interactions

Origin of the strong spin-orbit coupling?

PHYSICAL REVIEW VOLUME 78, NUMBER 1 APRIL 1, 1950

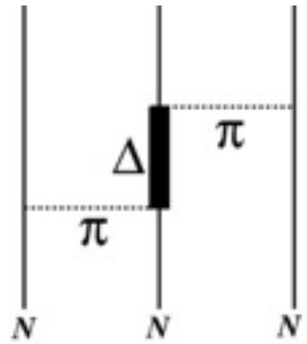
Nuclear Configurations in the Spin-Orbit Coupling Model. I. Empirical Evidence

MARIA GOEPPERT MAYER
Argonne National Laboratory, Chicago, Illinois
(Received December 7, 1949)

There is no adequate theoretical reason for the large observed value of the spin orbit coupling. The Thomas splitting has the right sign, but is utterly inadequate in magnitude to account for the observed values. A proper type of meson potential can be made to predict splitting qualitatively similar to the Thomas splitting, and therefore qualitatively similar to the observed, but greater in magnitude than the Thomas splitting, although usually somewhat less than the observed value.

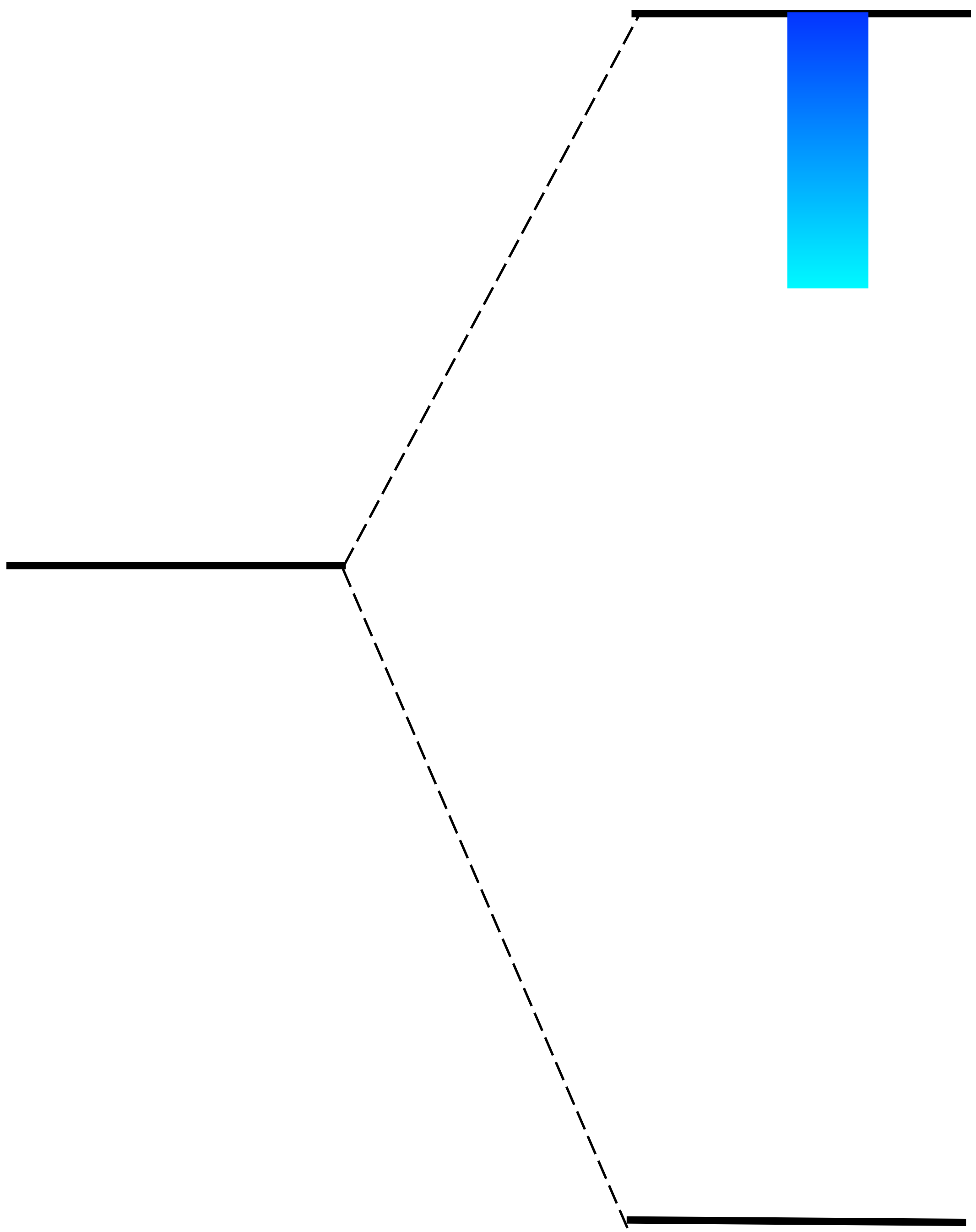
Microscopic origins of spin-orbit coupling

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.



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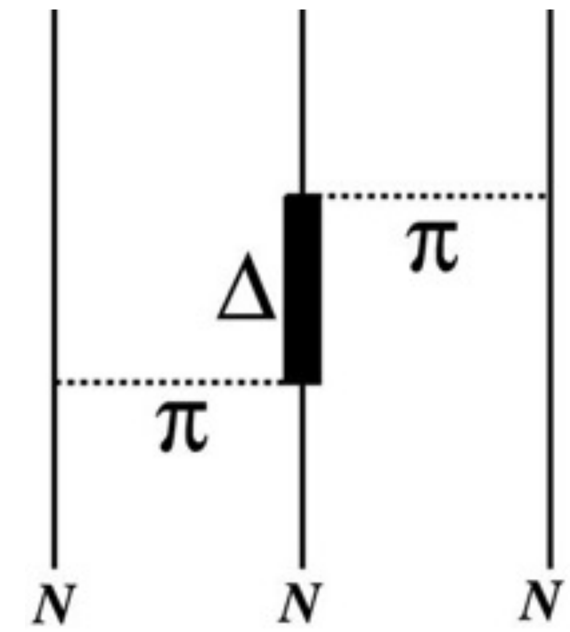
Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Pion Theory of Three-Body Forces

Jun-ichi FUJITA and Hironari MIYAZAWA

Department of Physics, University of Tokyo, Tokyo

(Received October 27, 1956)



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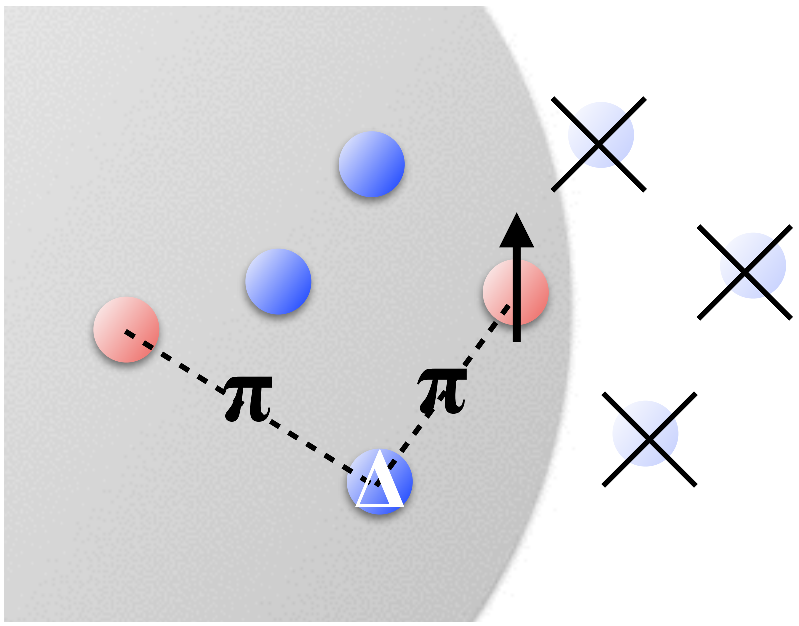
Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Spin-Orbit Coupling in Heavy Nuclei

Jun-ichi FUJITA and Hironari MIYAZAWA

Department of Physics, University of Tokyo, Tokyo

(Received October 27, 1956)



Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

Spin-Orbit Coupling in Heavy Nuclei

Jun-ichi FUJITA and Hironari MIYAZAWA

Conclusions of this paper are:

i) The meson-theoretical two-body spin-orbit coupling has the effect about two or three times as large as the Thomas term. Of course, it may be somewhat increased because of the ambiguity with radial dependence of the interaction in the small distance between two nucleons and possible correlations between their positions.

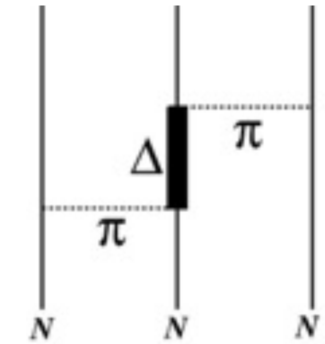
ii) Our spin-orbit coupling derived from the meson-theoretical three-body force is about 4.3 times larger than the Thomas term. The existence of the correlations may also increase this magnitude further. It is probable that the higher-order corrections for three-body forces have a large effect.

iii) The experimental spin-orbit coupling[3)] is 40 times larger than the Thomas term with the magnitude as evaluated in Sec. 2. The net effect of Thomas term, two-body spin-orbit coupling and many-body interaction, which have the common correct sign, seems to be only about one fifth of the experimental one. Although we have underestimated the effects of many-body forces or two-body spin-orbit couplings because of the roughness of the Fermi gas model and the ambiguity in the small distance region, a considerable fraction of the strong spin-orbit coupling should probably be attributed to some other causes.

* This kind of spin-orbit coupling was suggested by Prof. Y. Nambu in private communication.

Microscopic origins of spin-orbit coupling

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.

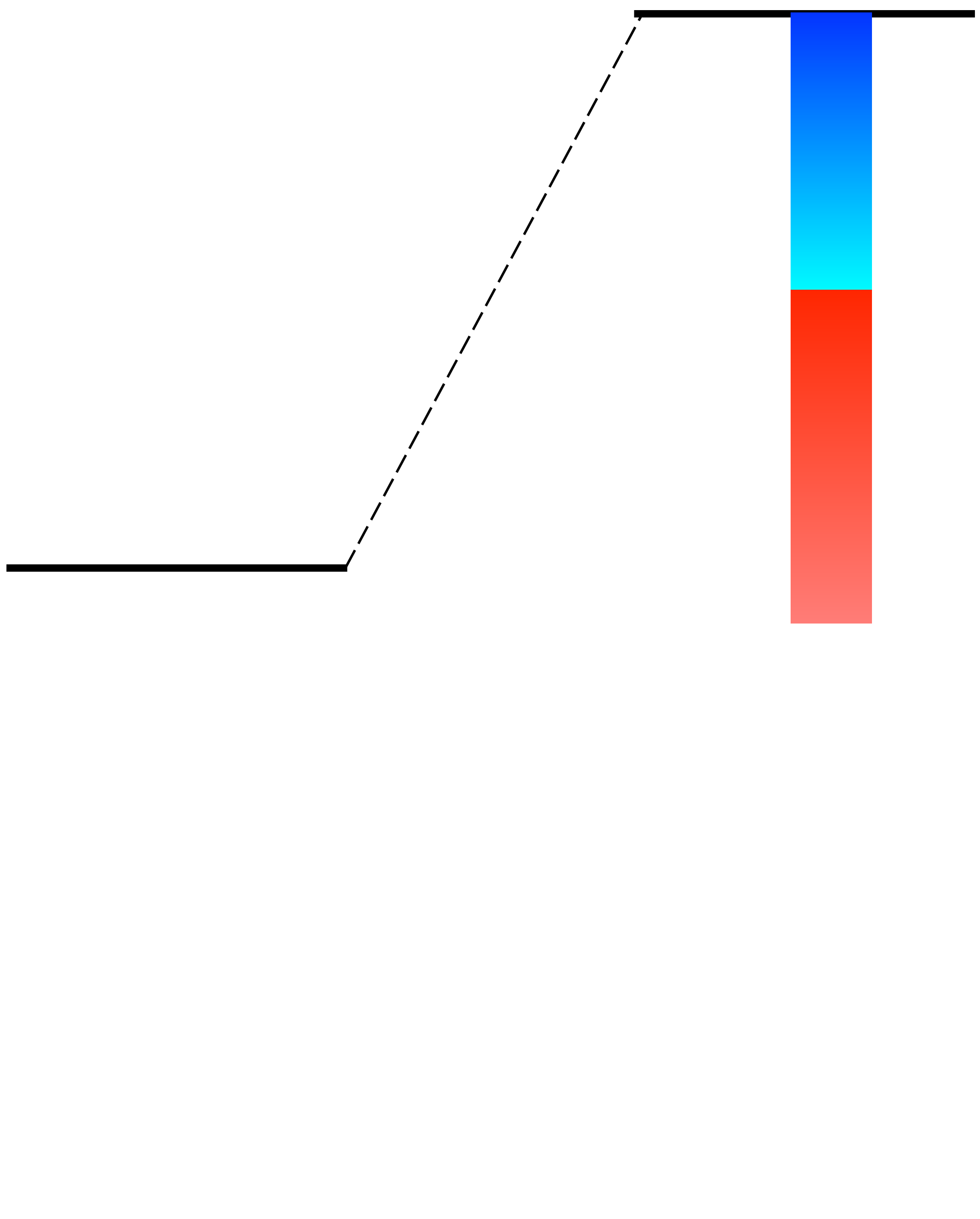


3N force

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

Tensor force

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



Tensor Force Effects

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Progress of Theoretical Physics, Vol. 23, No. 1, January 1960

Spin-Orbit Splitting and Tensor Force. I*

Tokuo TERASAWA**

The Institute for Solid State Physics, University of Tokyo, Tokyo

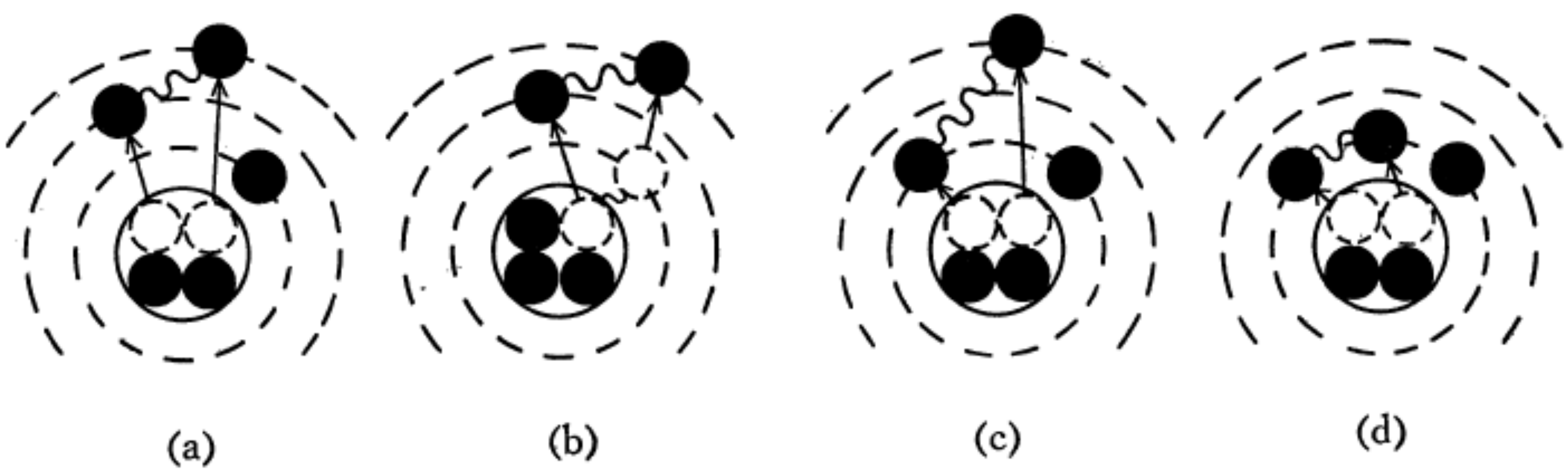
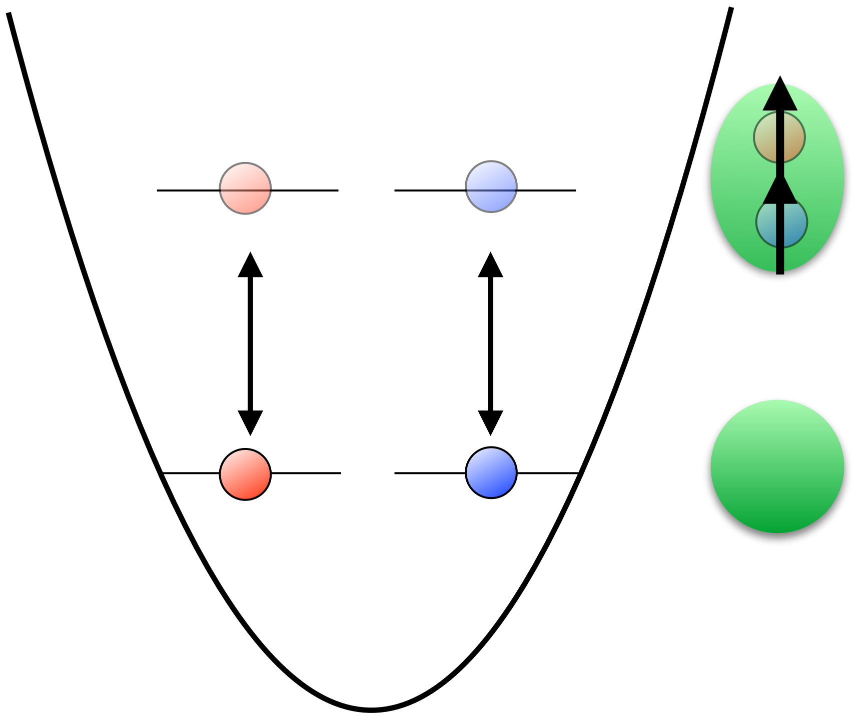


Fig. 1. Figures (a), (b), (c) and (d) show configurations (I), (II), (IIIa) and (IIIb) in He^5, respectively.

A Key to understand Tensor-force effects in nuclei

Core polarization/
Configuration mixing/
2particle-2hole excitation

Different wording, but the same meaning



A virtually excited *p-n* pair is mixed in the ground state.

This is the origin of nuclear stability (⇔unstableness of exotic nuclei), saturation property, quenching of spectroscopic factors. . .

Schrödinger equation for deuteron

$$\left[-\frac{\hbar^2}{M}\frac{1}{r}\frac{d^2}{dr^2}r - \frac{\hbar^2}{M}\frac{\ell(\ell+1)}{r^2} + V_{\rm c} + V_{\ell s}\ell\cdot s + V_{\rm t}S_{12}\right]\varphi_d = \varepsilon_d\varphi_d$$

In deuteron, a D-state, where p-n relative orbital angular momentum (L) is two, is mixed to a S-state with L=0.

origin of deuteron quadrupole moment

$$r\varphi^d_{\nu_d} = u(r)\mathcal{Y}_0^{\nu_d} + w(r)\mathcal{Y}_2^{\nu_d}$$

$$\mathcal{Y}_\ell^{\nu_d} = \sum_\mu (2\ 1\ \nu_d{-}\mu\ \mu|1\ \nu_d)Y_\ell^{\nu_d-\mu}\chi_\mu$$

Tensor operator mixes the state with the same J but different L by a unit of two.

$$S_{12}\begin{pmatrix}\mathcal{Y}_{J-1,J}\\ \mathcal{Y}_{J,J}\\ \mathcal{Y}_{J+1,J}\end{pmatrix} = \frac{1}{2J+1}\begin{pmatrix}-2(J-1) & 0 & 6\sqrt{J(J+1)}\\ 0 & 2(2J+1) & 0\\ 6\sqrt{J(J+1)} & 0 & -2(J+2)\end{pmatrix}\begin{pmatrix}\mathcal{Y}_{J-1,J}\\ \mathcal{Y}_{J,J}\\ \mathcal{Y}_{J+1,J}\end{pmatrix}$$

Schrödinger equation for deuteron (*cont.*)

$$\left[-\frac{\hbar^2}{M}\frac{1}{r}\frac{d^2}{dr^2}r - \frac{\hbar^2}{M}\frac{\ell(\ell+1)}{r^2} + V_{\mathrm{c}} + V_{\ell s}\ell\cdot s + V_{\mathrm{t}}S_{12}\right]\varphi_d = \varepsilon_d\varphi_d$$

S-state $\left[\frac{\hbar^2}{M}\frac{d^2}{dr^2} - (V_{\mathrm{c}} - \varepsilon_d)\right]u(r) = \sqrt{8}V_T w(r)$

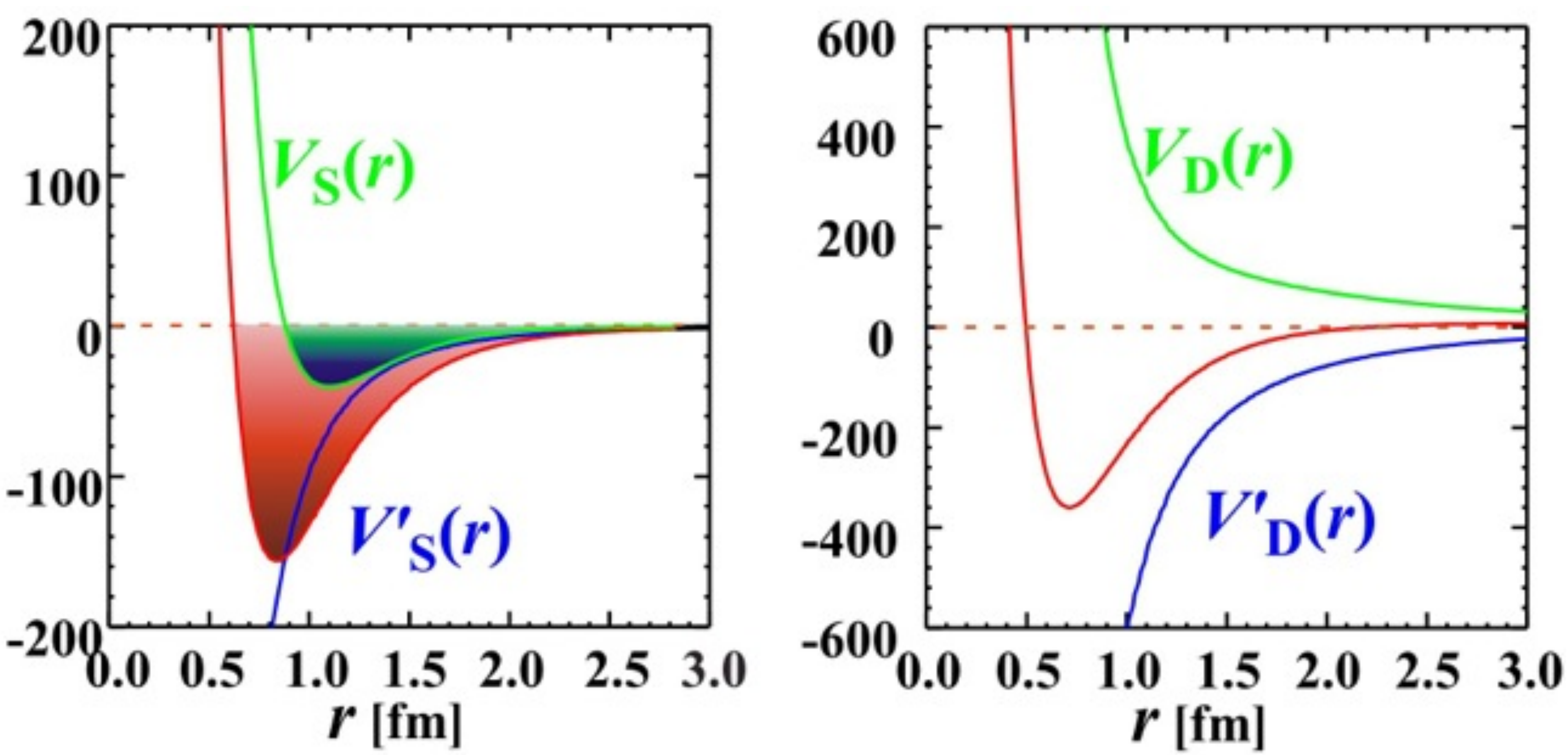
D-state $\left[\frac{\hbar^2}{M}\frac{d^2}{dr^2} - (\frac{\hbar^2}{M}\frac{6}{r^2} + V_{\mathrm{c}} - 3V_{\ell s} - 2V_{\mathrm{t}} - \varepsilon_d)\right]w(r) = -\sqrt{8}V_T u(r)$

Schrödinger equation for deuteron (*cont.*)

$$\left[-\frac{\hbar^2}{M}\frac{1}{r}\frac{d^2}{dr^2}r - \frac{\hbar^2}{M}\frac{\ell(\ell+1)}{r^2} + V_\mathrm{c} + V_{\ell s}\ell\cdot s + V_\mathrm{t}S_{12}\right]\varphi_d = \varepsilon_d\varphi_d$$

S-state $\left[\frac{\hbar^2}{M}\frac{d^2}{dr^2} - \left(V_\mathrm{c} + \sqrt{8}V_T\frac{w(r)}{u(r)} - \varepsilon_d\right)\right]u(r) = 0$

D-state $\left[\frac{\hbar^2}{M}\frac{d^2}{dr^2} - \left(\frac{\hbar^2}{M}\frac{6}{r^2} + V_\mathrm{c} - 3V_{\ell s} - 2V_\mathrm{t} - \sqrt{8}V_T\frac{u(r)}{w(r)} - \varepsilon_d\right)\right]w(r) = 0$



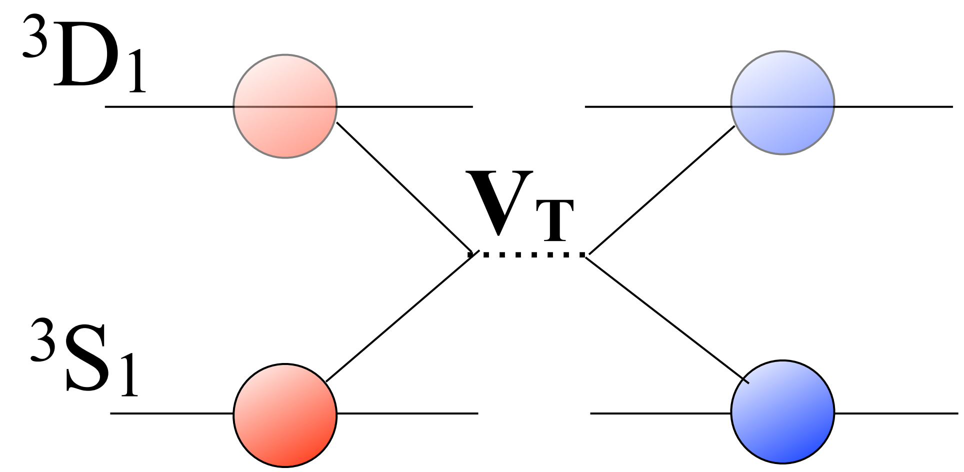
$V_{\mathrm{S,D}}(r)$ w/o mixing

$V'_{\mathrm{S,D}}(r)$ **contribution of the mixing**

Sum

Tensor force and saturation

Attraction due to tensor force is a second-order perturbation effect.



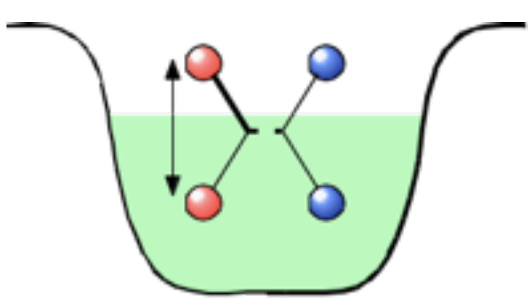
***Q*=1 *m*: unoccupied**
***Q*=0 *m*: occupied**

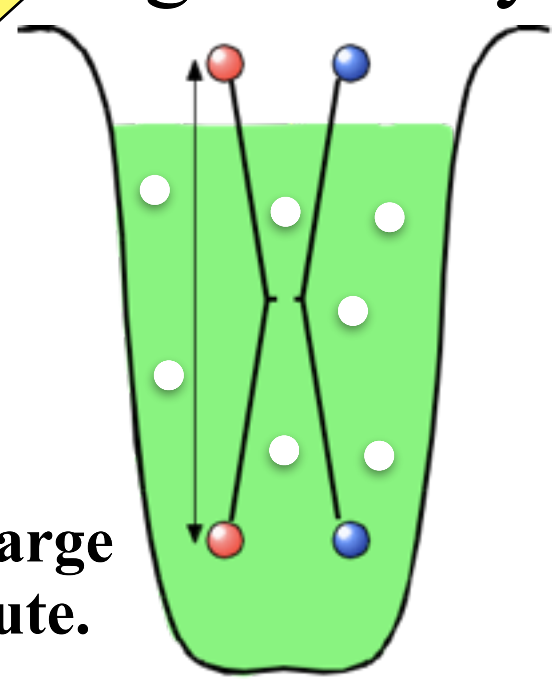
$$\Delta E = \sum_m \frac{\langle {}^3S_1 | V_T | {}^3D_{1;m} \rangle \boxed{Q} \langle {}^3D_{1;m} | V_T | {}^3S_1 \rangle}{\boxed{E_m - E_0}}$$

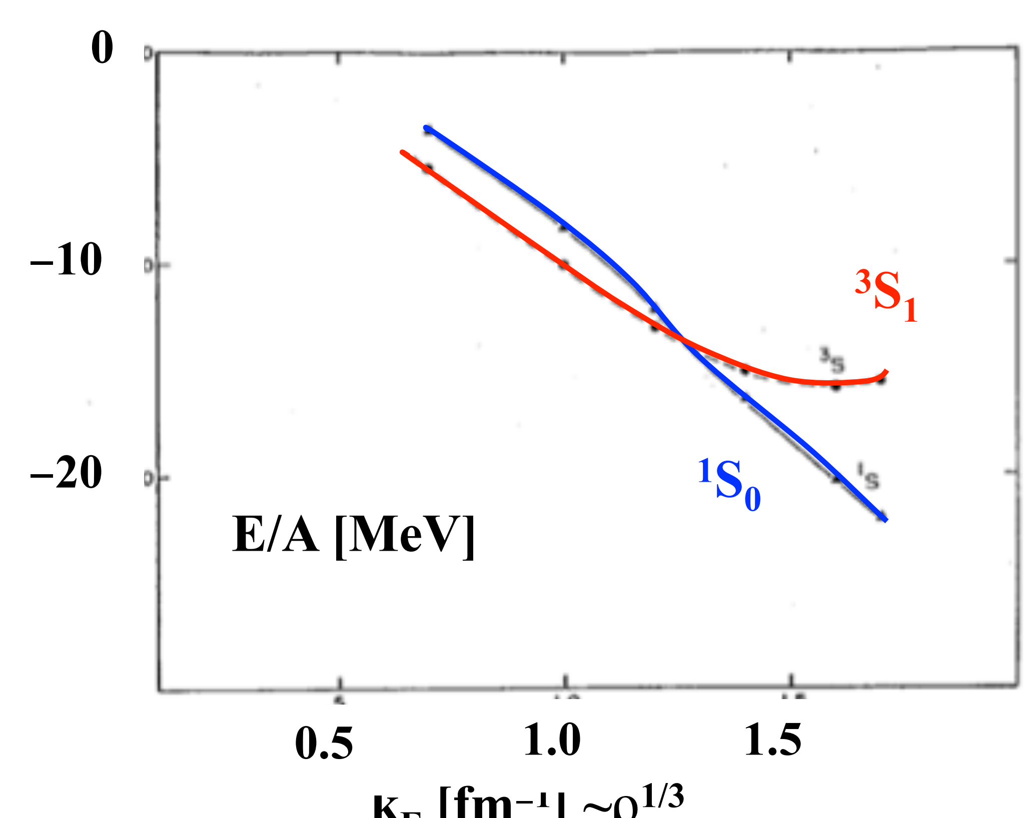
Energy denominator

H.A. Bethe, Ann. Rev. Nucl. Sci. 21, 93 (1971)

low density → high density





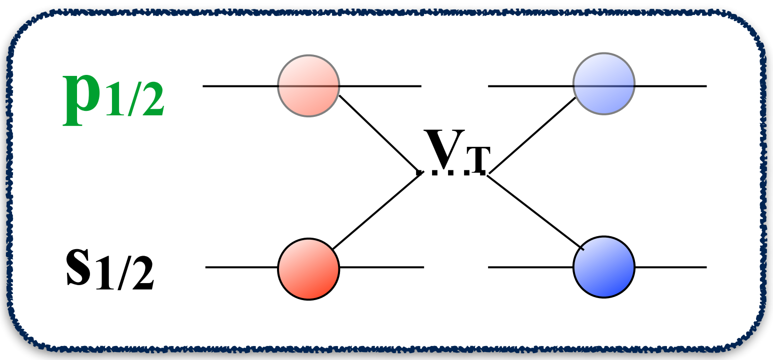


At high density, only terms with large energy denominator can contribute.

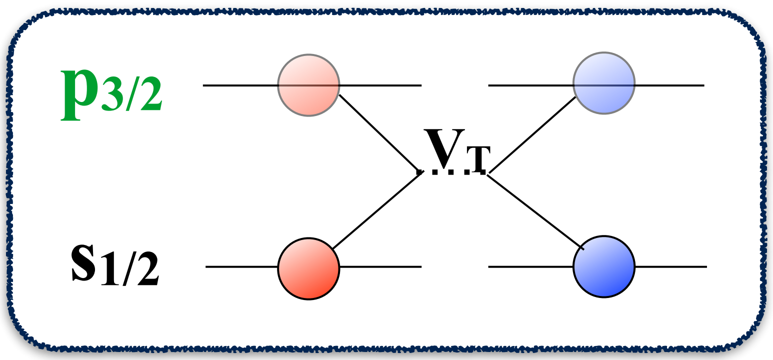
Tensor Force Effect to Spin-Orbit Coupling

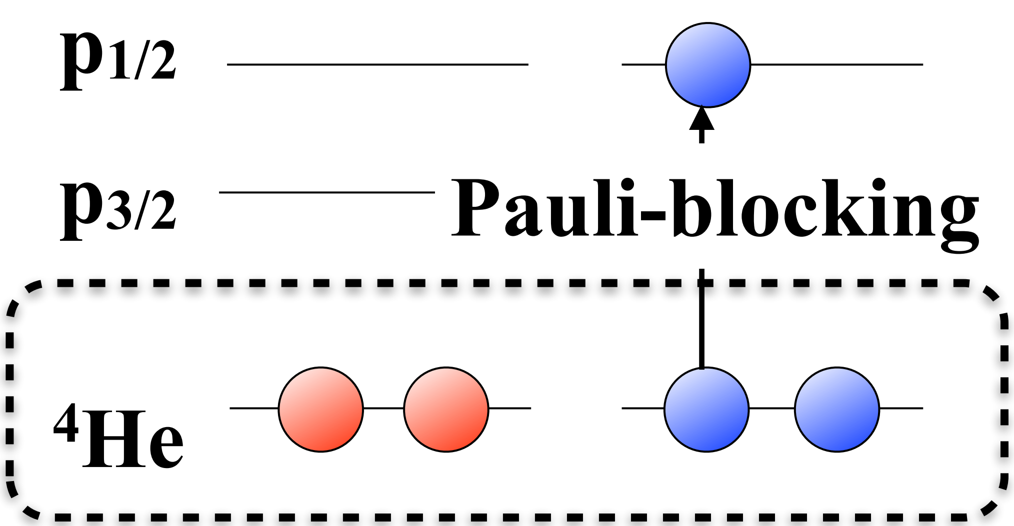
Case of ^{5}He : ^{4}He+ one neutron in *p*-shell

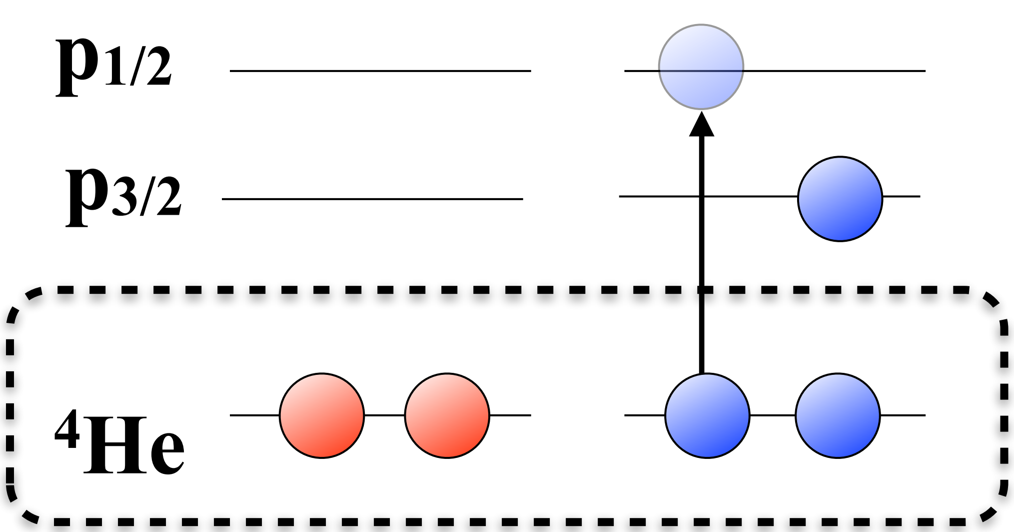
From angular-momentum algebra, it can be shown that



is more attractive than

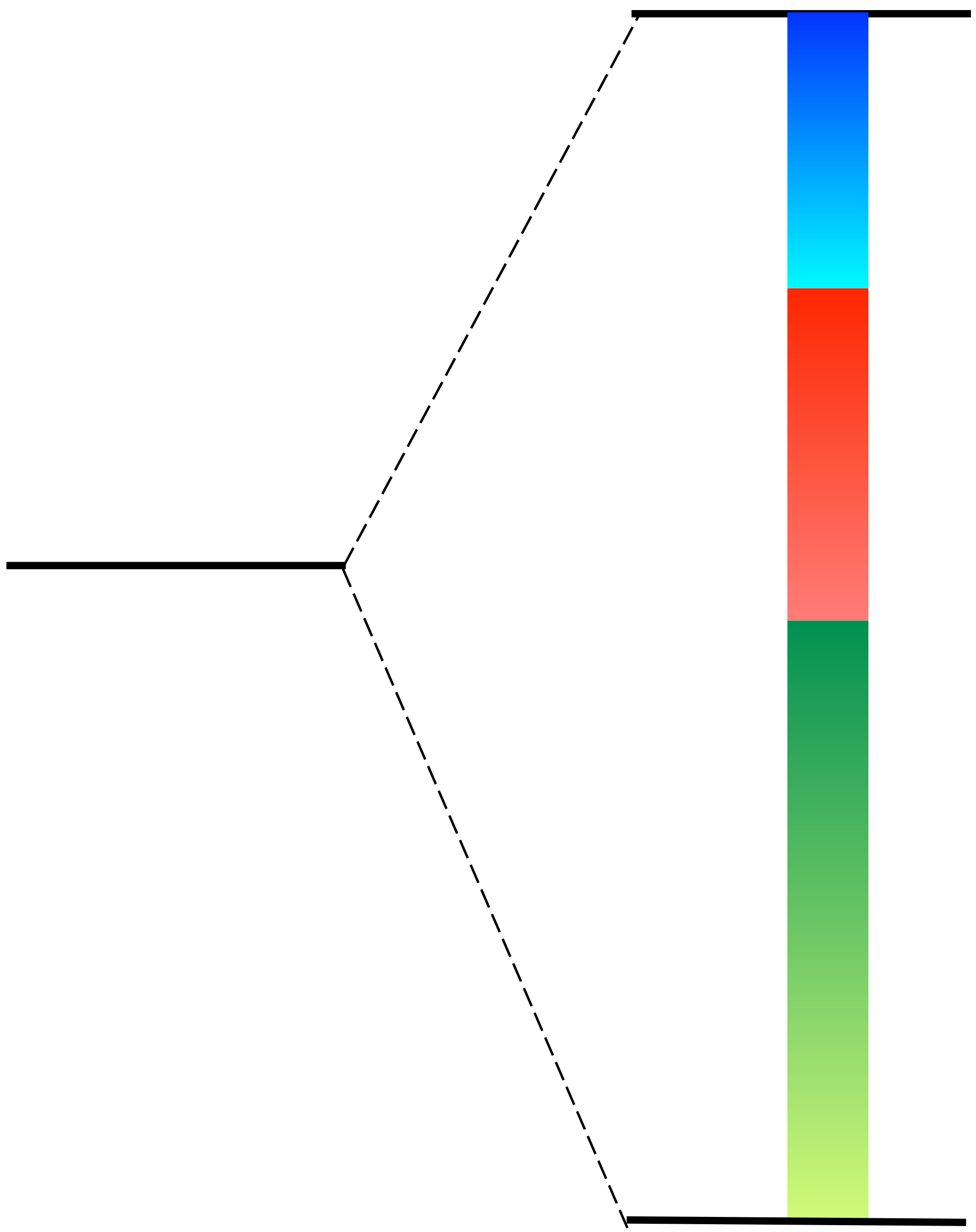


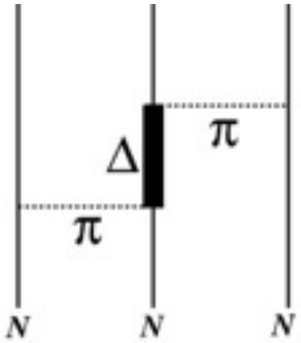




Microscopic origins of spin-orbit coupling

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.



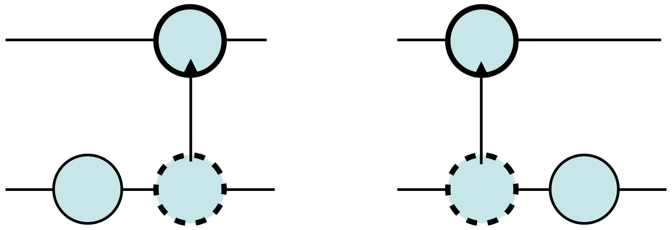


3N force

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

Tensor force

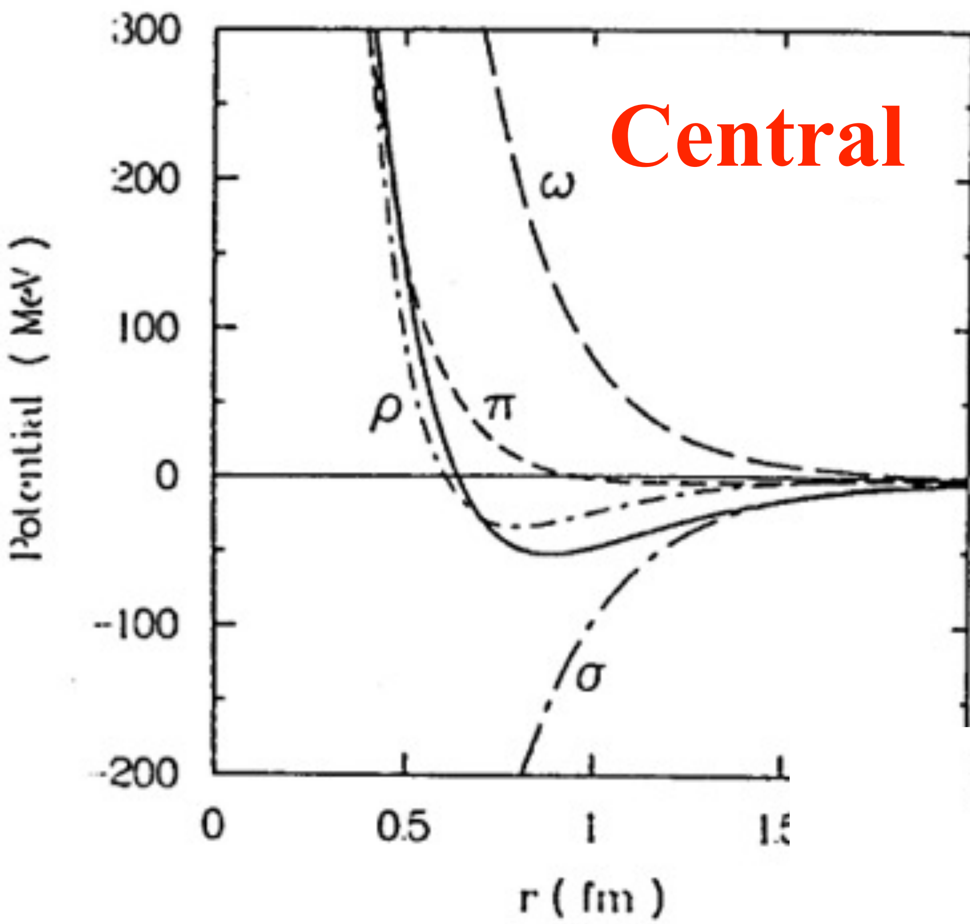
Wigner & Feingold, PR 79 (1950) 221.
Terasawa, PTP 23 (1960) 87.

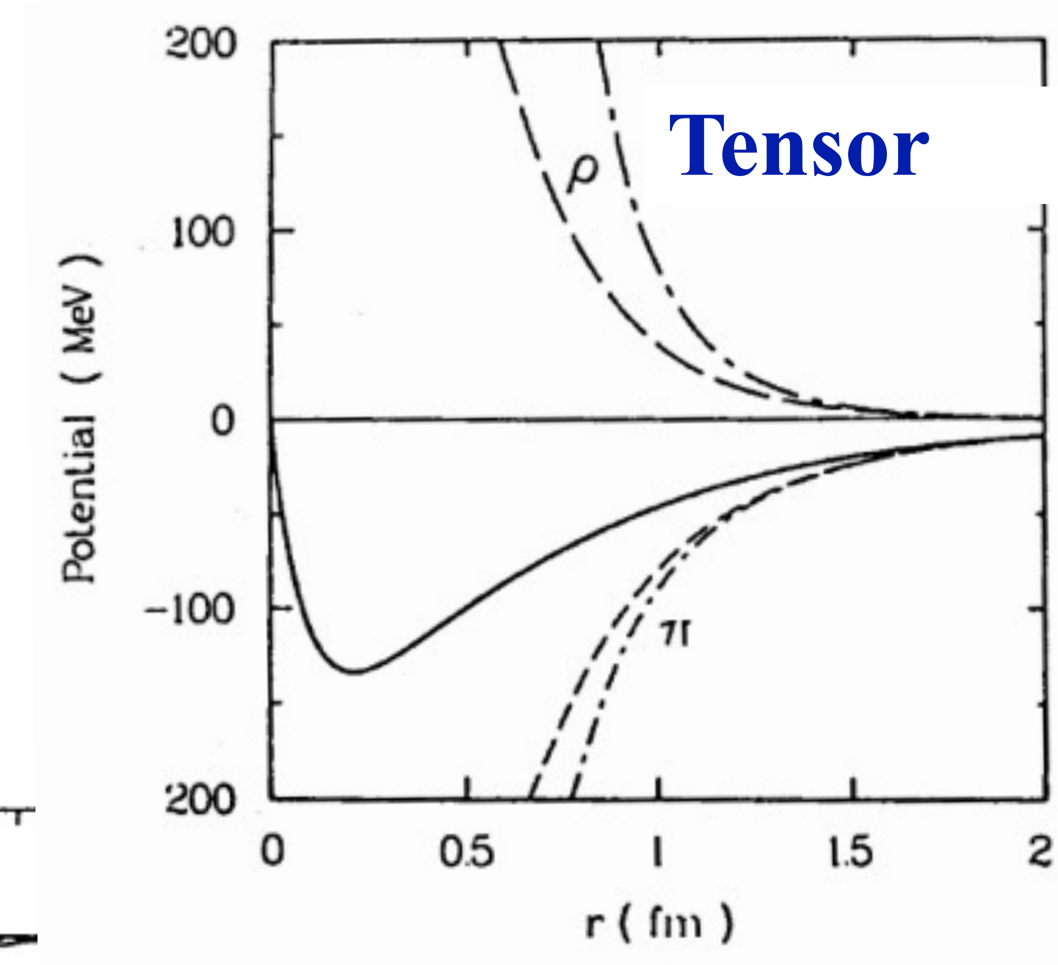


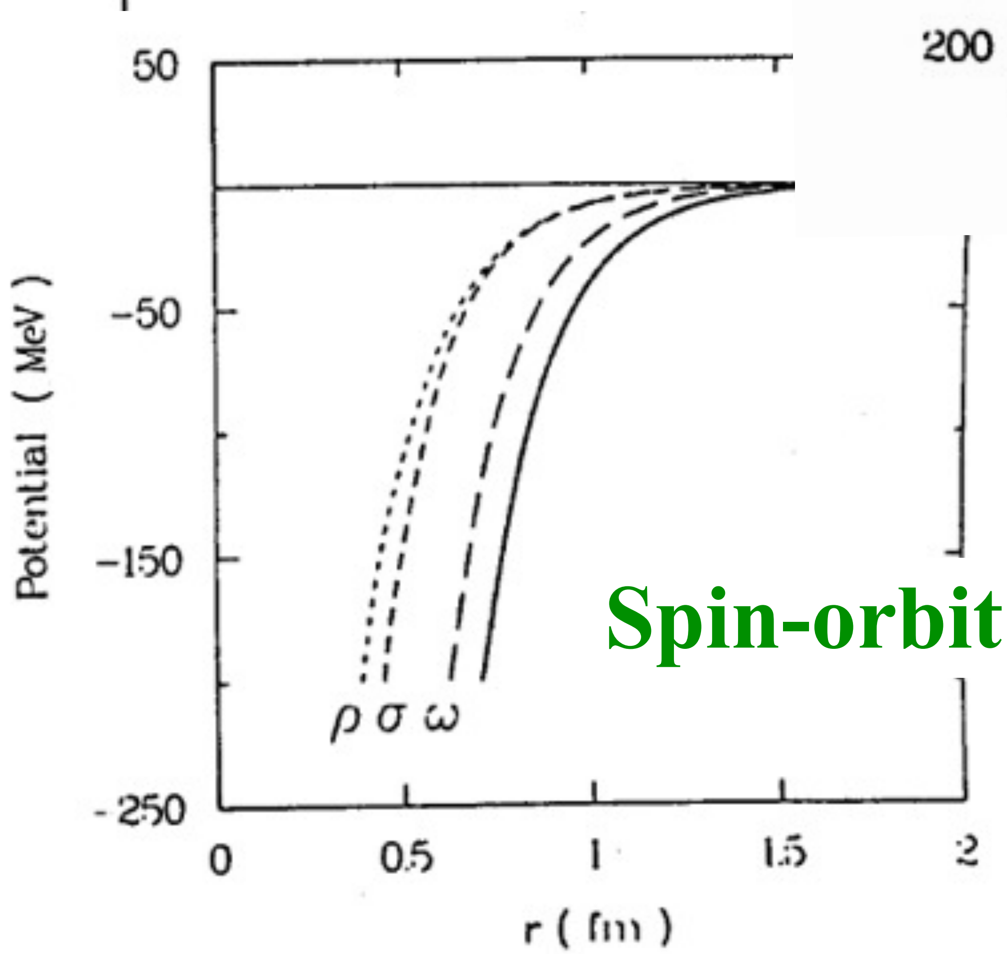
NN LS interaction
σ and ω exchange
isoscaler in nature

R. Machleidt, Adv. Nucl. Phys. **19** (1989) 189.

Contributions from each meson





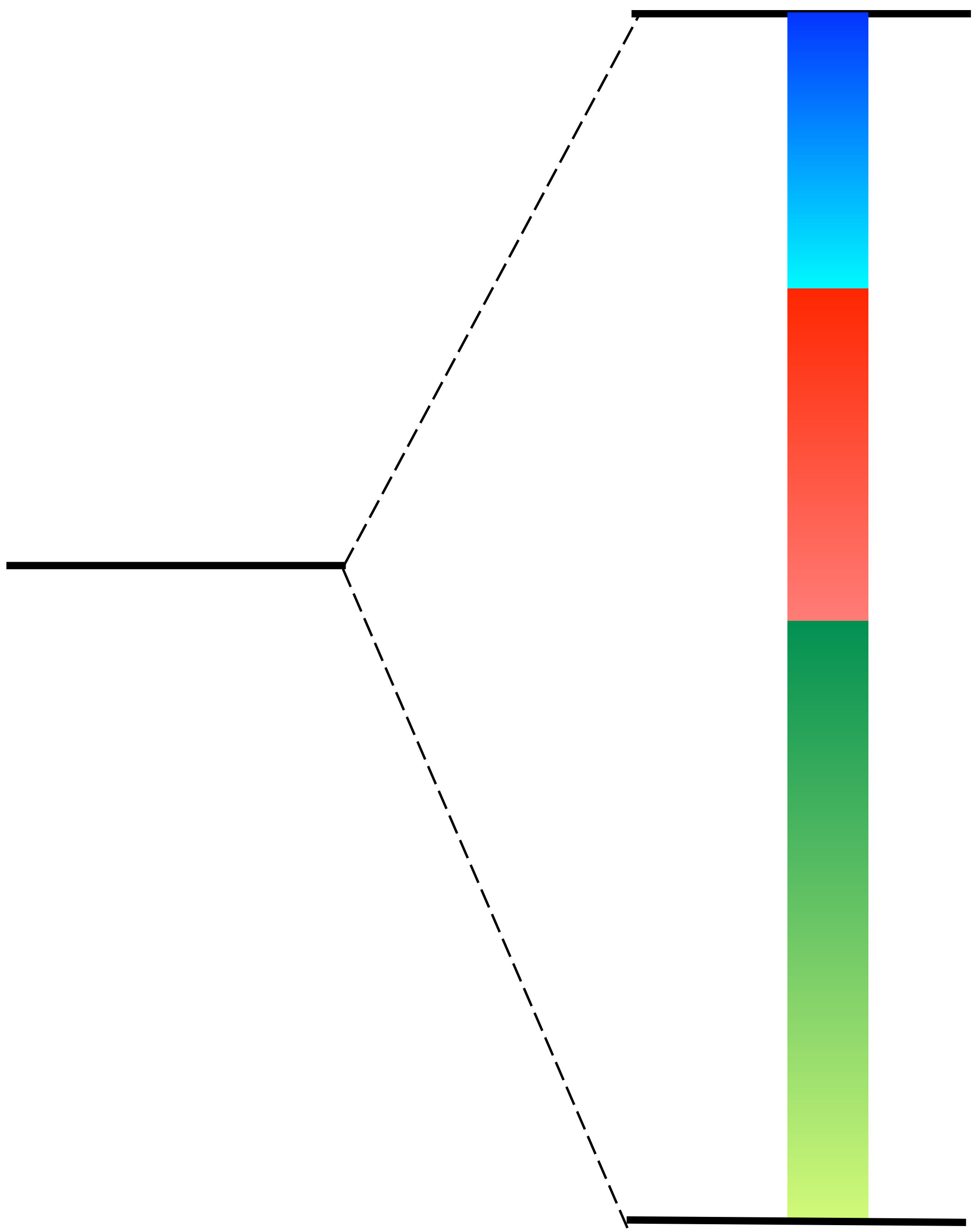


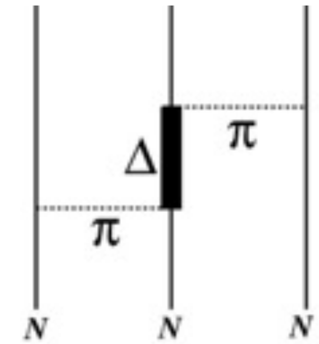
σ → attractive
ω → repulsive

π → attractive
ρ → repulsive

Microscopic origins of spin-orbit coupling

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

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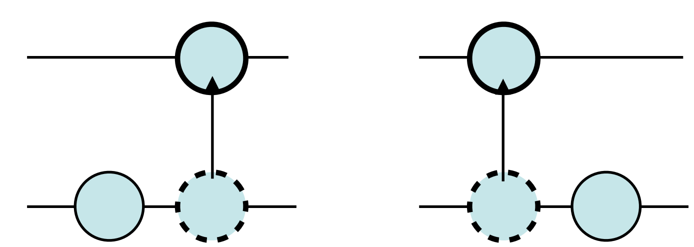
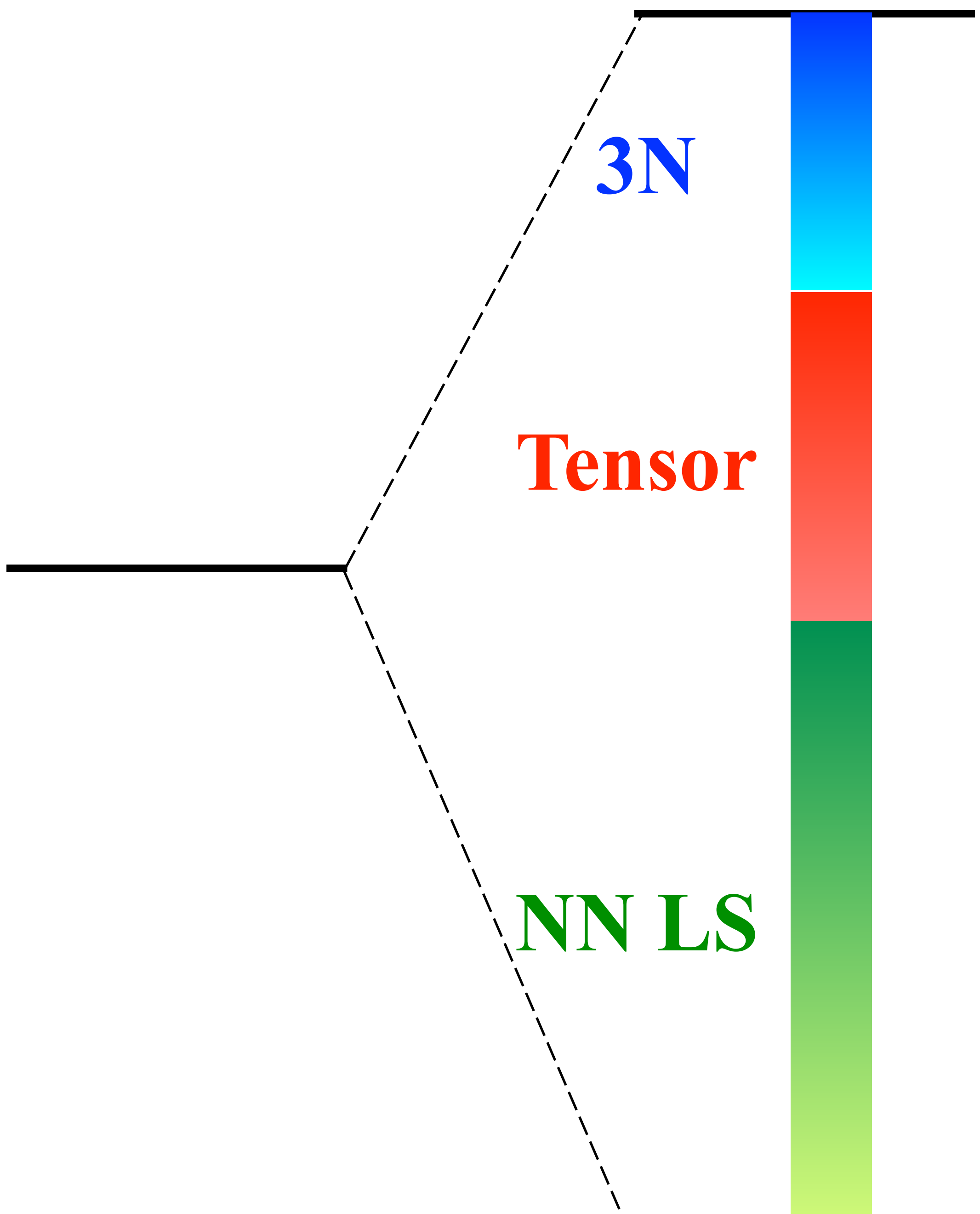
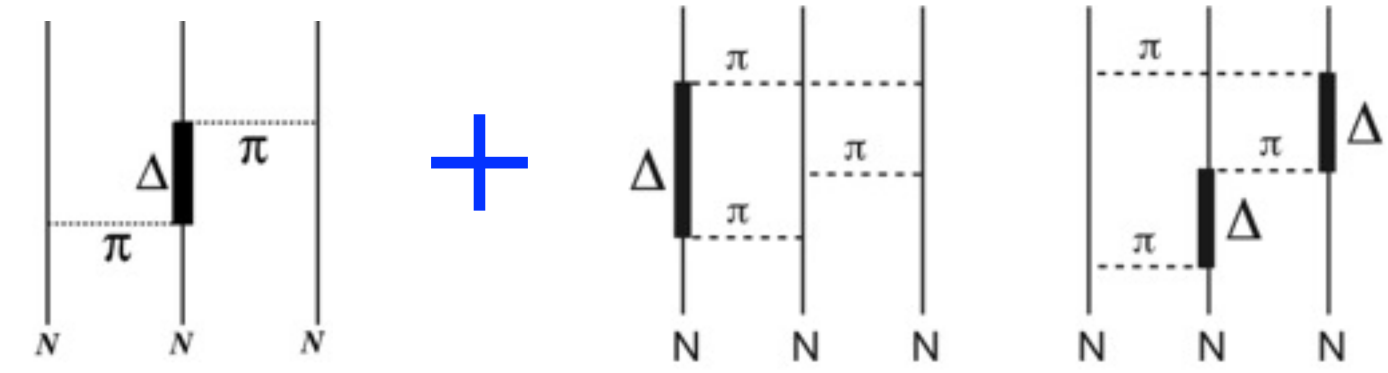


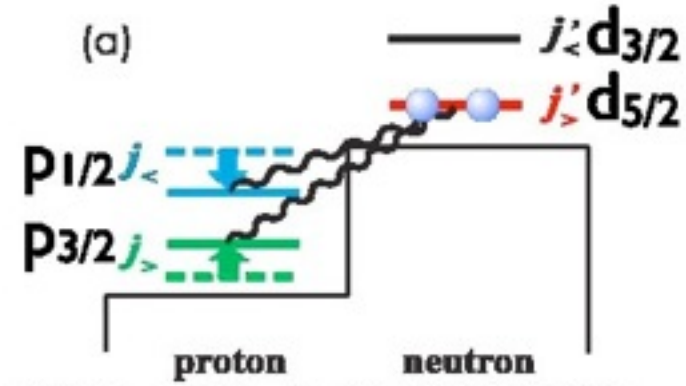
NN LS interaction
σ and ω exchange
isoscaler in nature

Spin-orbit splittings in Exotic Nuclei



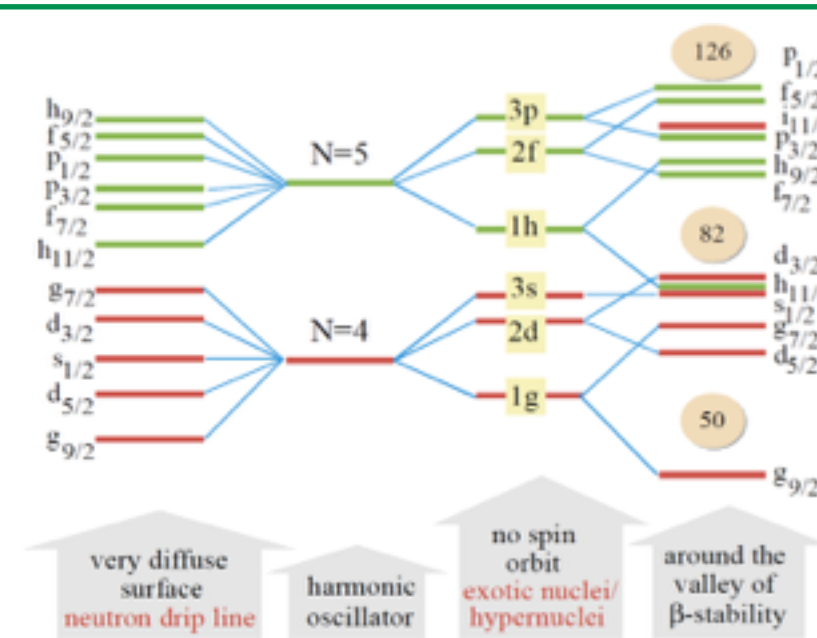


First-order tensor effect by Otsuka
2p2h+Pauli-blocking



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

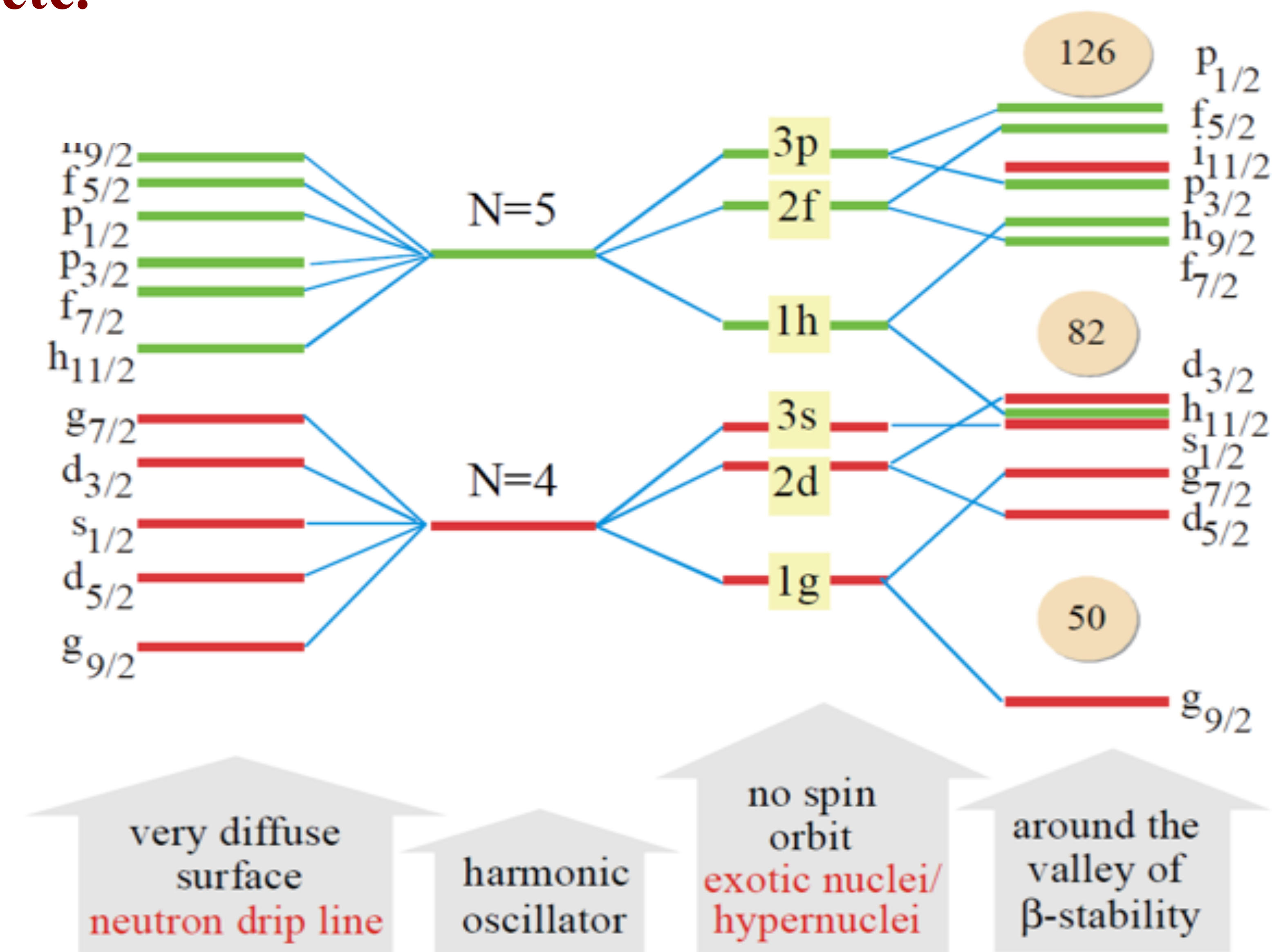
Mean-field effects



Mean-field effect

Weakening of spin-orbit coupling
due to diffuse surface etc.

$$V_{LS} \sim \frac{1}{r}\frac{d}{dr}\rho$$



J. Dobaczewski et al.,
Phys. Rev. C 53, 2809 (1996)

Theoretical Predictions for Exotic Nuclei

Three nucleon force effect gets weaker in ^{7}n than in ^{15}N.

TABLE I. Comparison of microscopic and Skyrme-model energies.

	^{8}n(0^+) (MeV)	^{7}n SOS (MeV)	Magic nuclei $\lvert\Delta E/E\rvert_{\rm rms}$%	^{15}N SOS[a] (MeV)	$W_{\ell s}$ (MeV^5)
GFMC	−37.6(3)	1.1(3)			
CVMC	−35.5(1)	1.4(1)	—	6.1[b]	
SkM	−47.4	3.0	1.1	6.3	130
FPS-21	−42.2	3.0	1.1	6.7	110
Skyrme 1′	−38.7	2.9	1.8	6.9	120
FPS	−32.5	3.5	1.2	6.7	110

inconsistent

consistent

[a]Experimental value 6.9 MeV deduced from Ref. [6].
[b]With Argonne v_{14}, Ref. [6].

In contrast, the three-body interaction and clusters give a very small contribution to the SOS in ^7n in CVMC calculations.

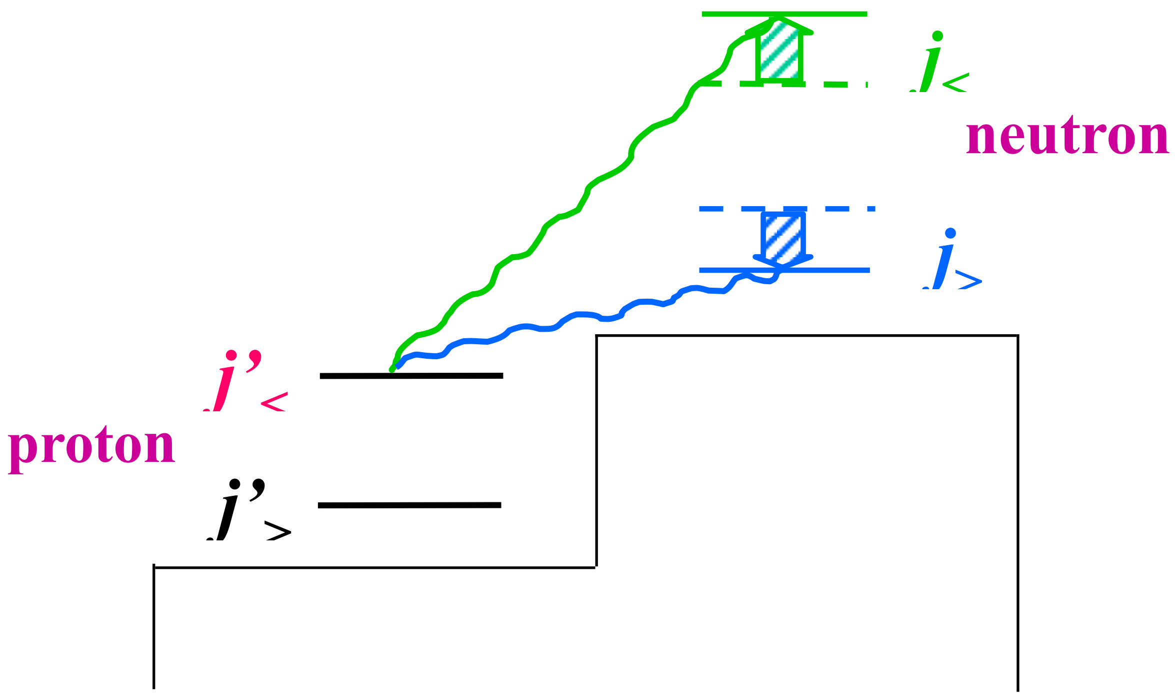
B. S. Pudliner et al.,
Phys. Rev. Lett. 76, 2416 (1996)

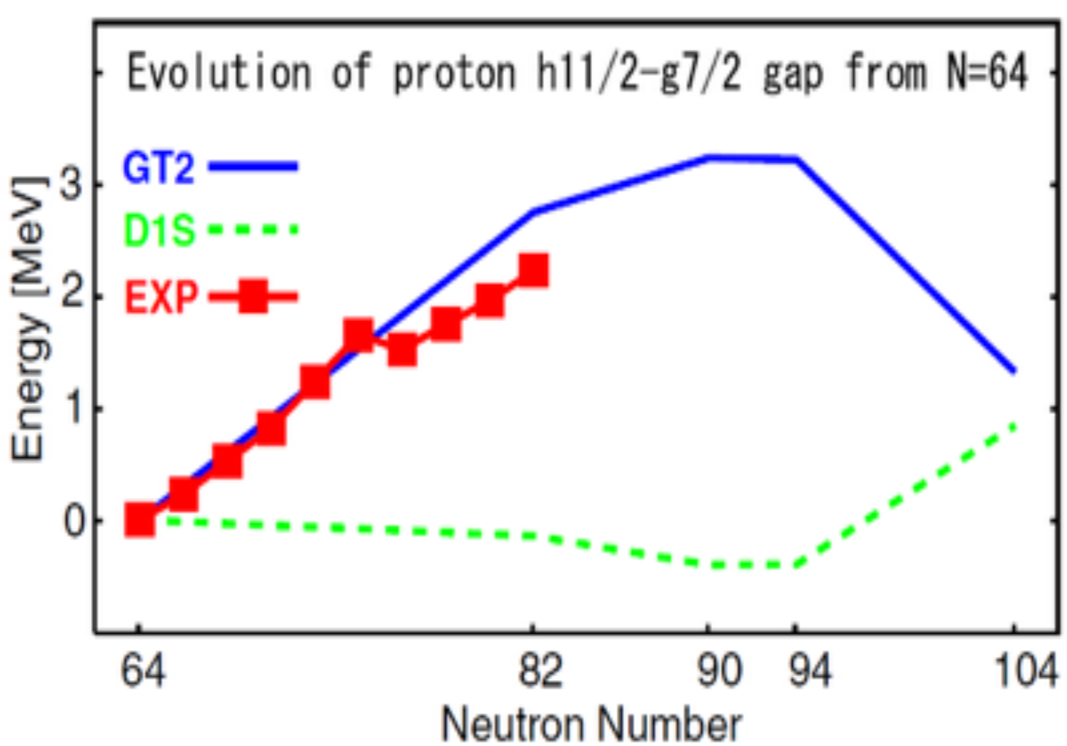
Tensor-force effects

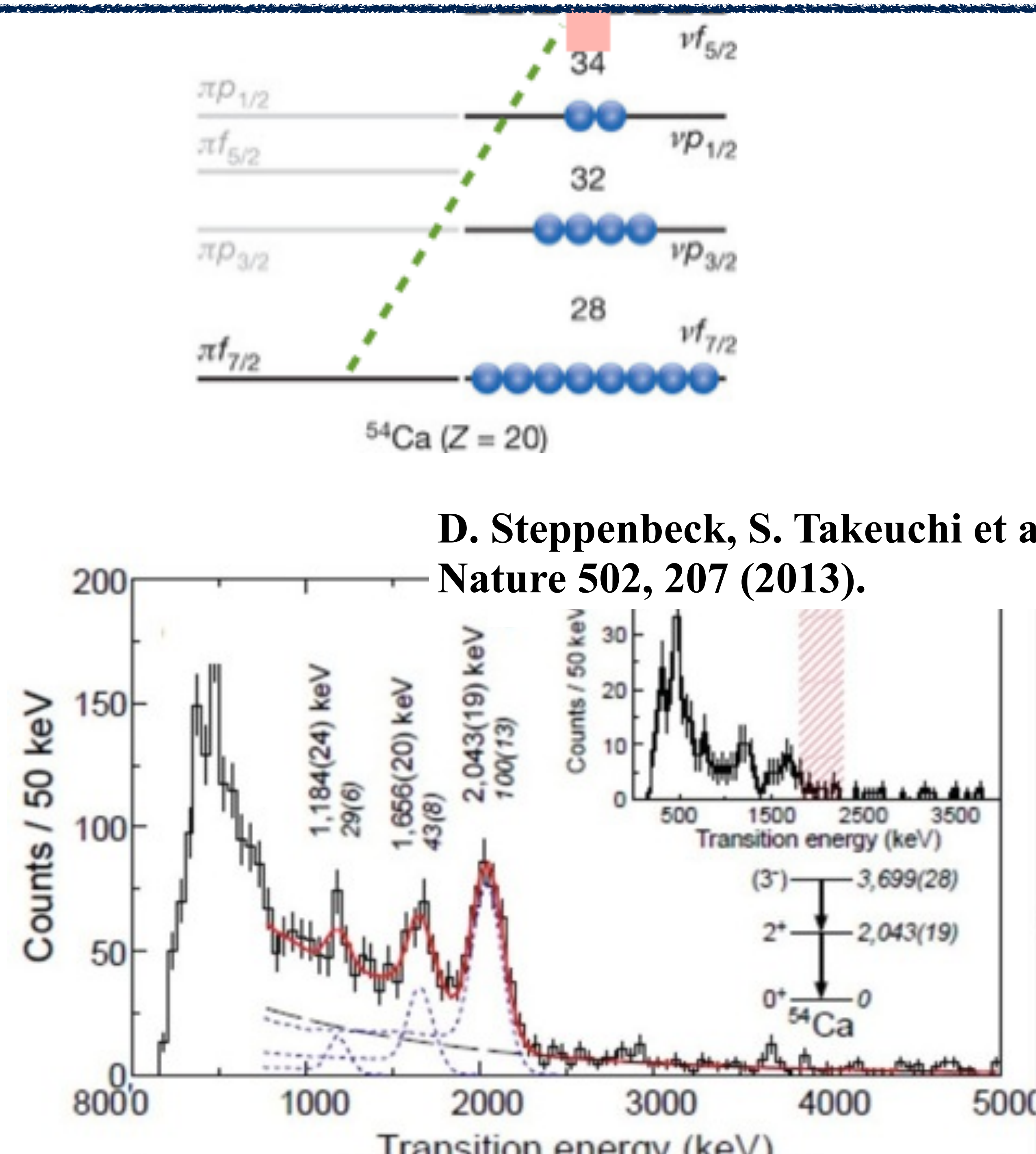
First-order effects by T. Otsuka

T. Otsuka *et al.*, Phys. Rev. Lett. 95, 2325

Second-order effects in exotic nuclei have not been discussed thoroughly.



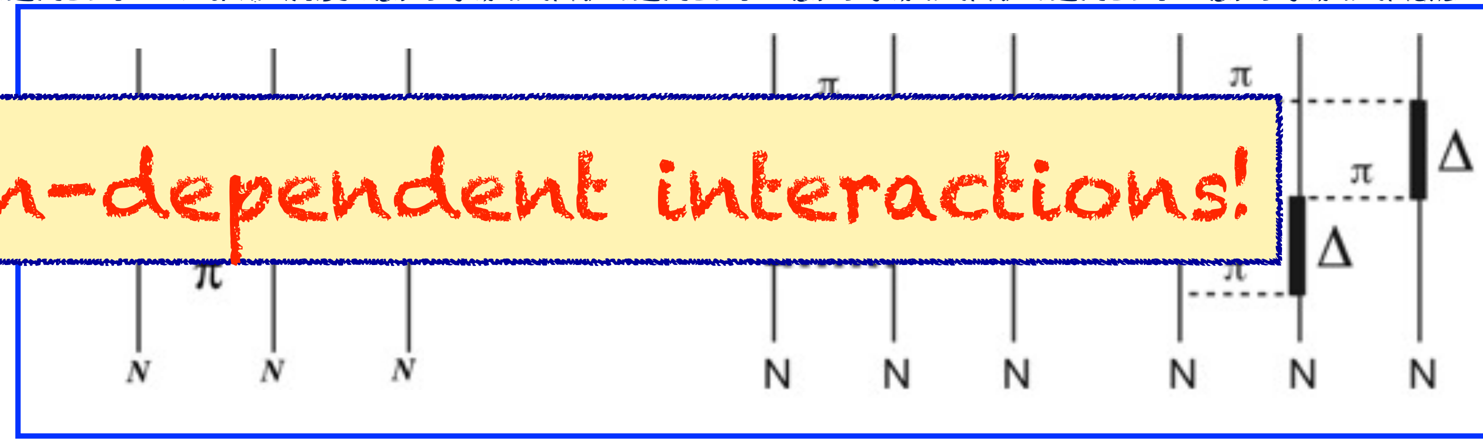


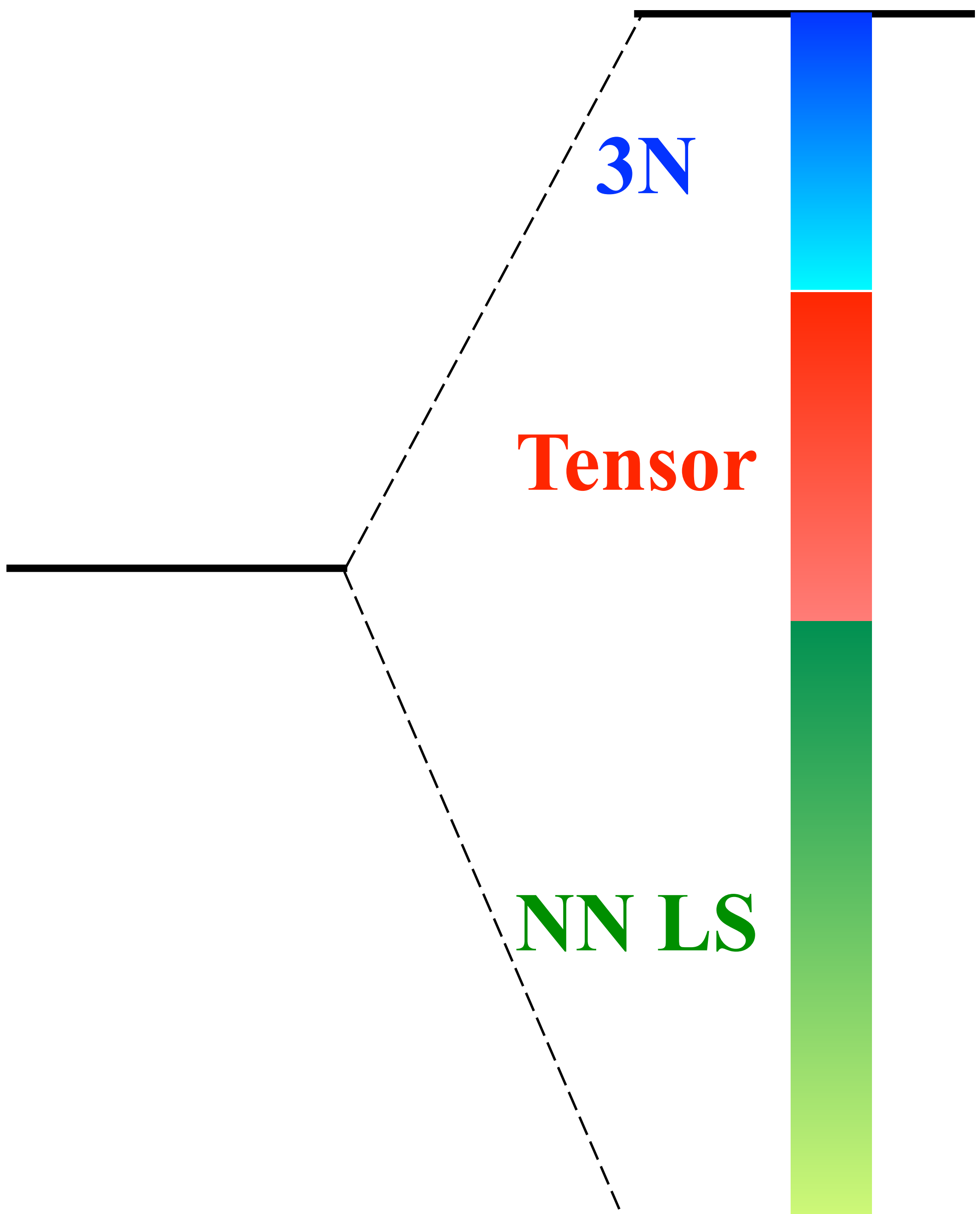


D. Steppenbeck, S. Takeuchi et al., Nature 502, 207 (2013).

Spin-orbit splittings in Exotic Nuclei

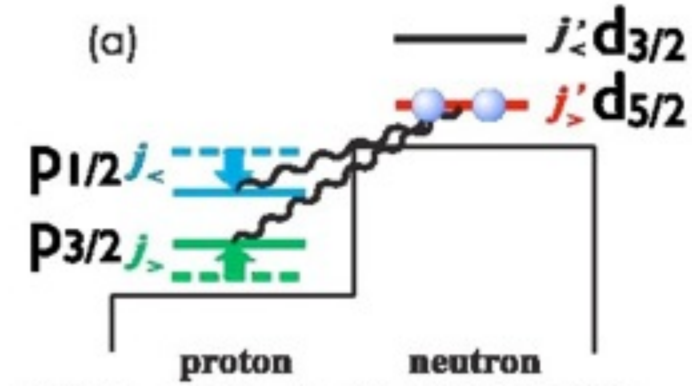
Interplay of the spin-dependent interactions!





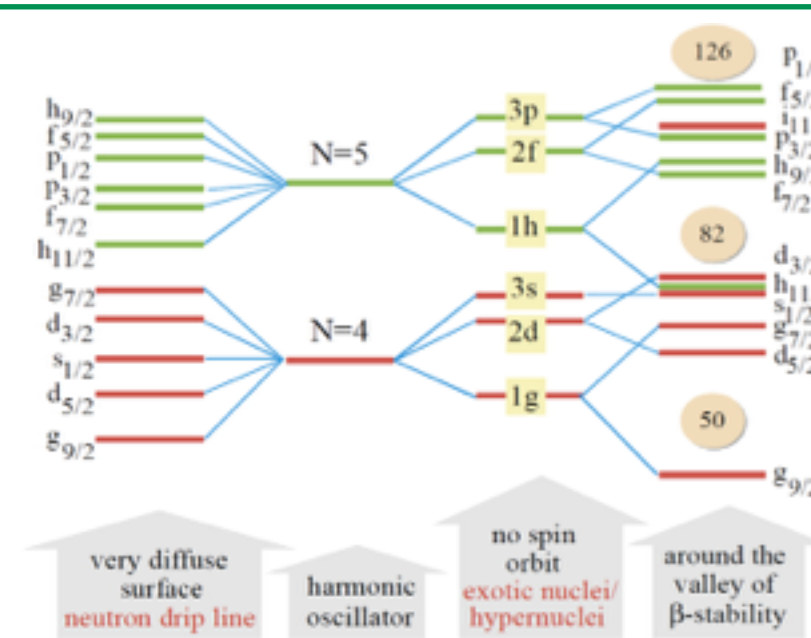
First-order tensor effect by Otsuka

2p2h+Pauli-blocking



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

Mean-field effects

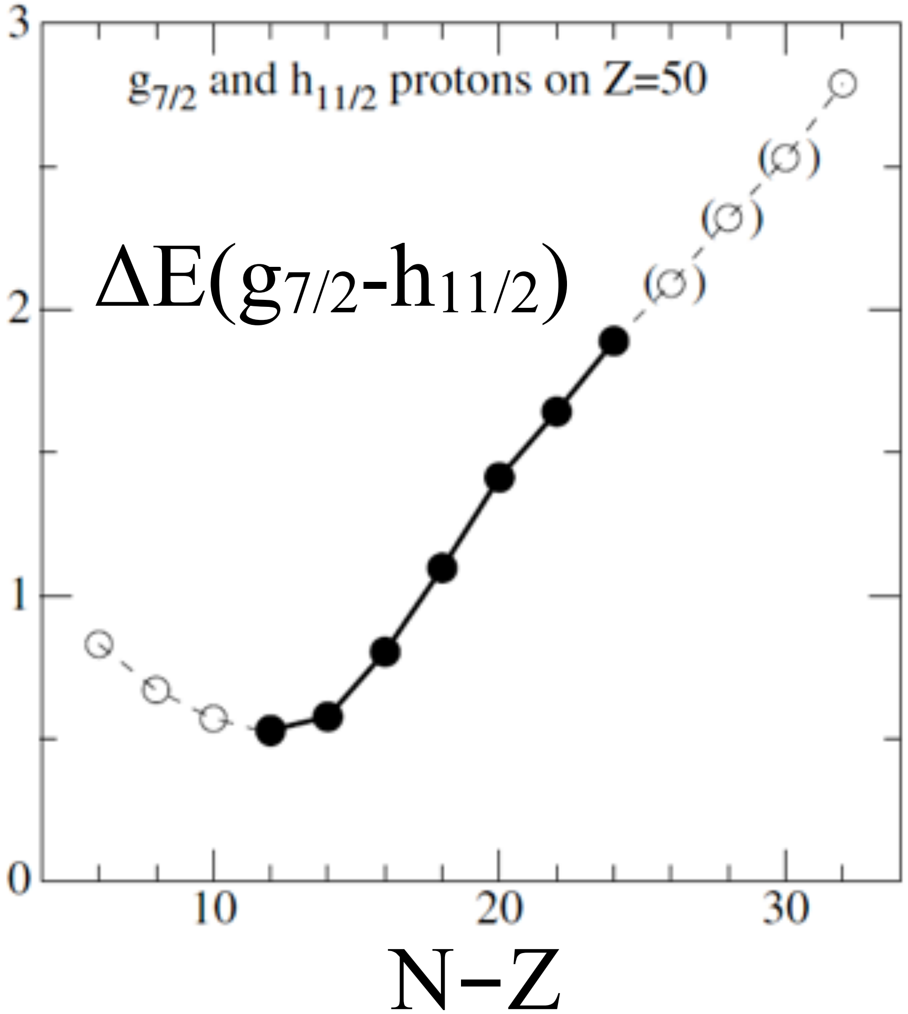


Neutron-number dependences of LS splitting

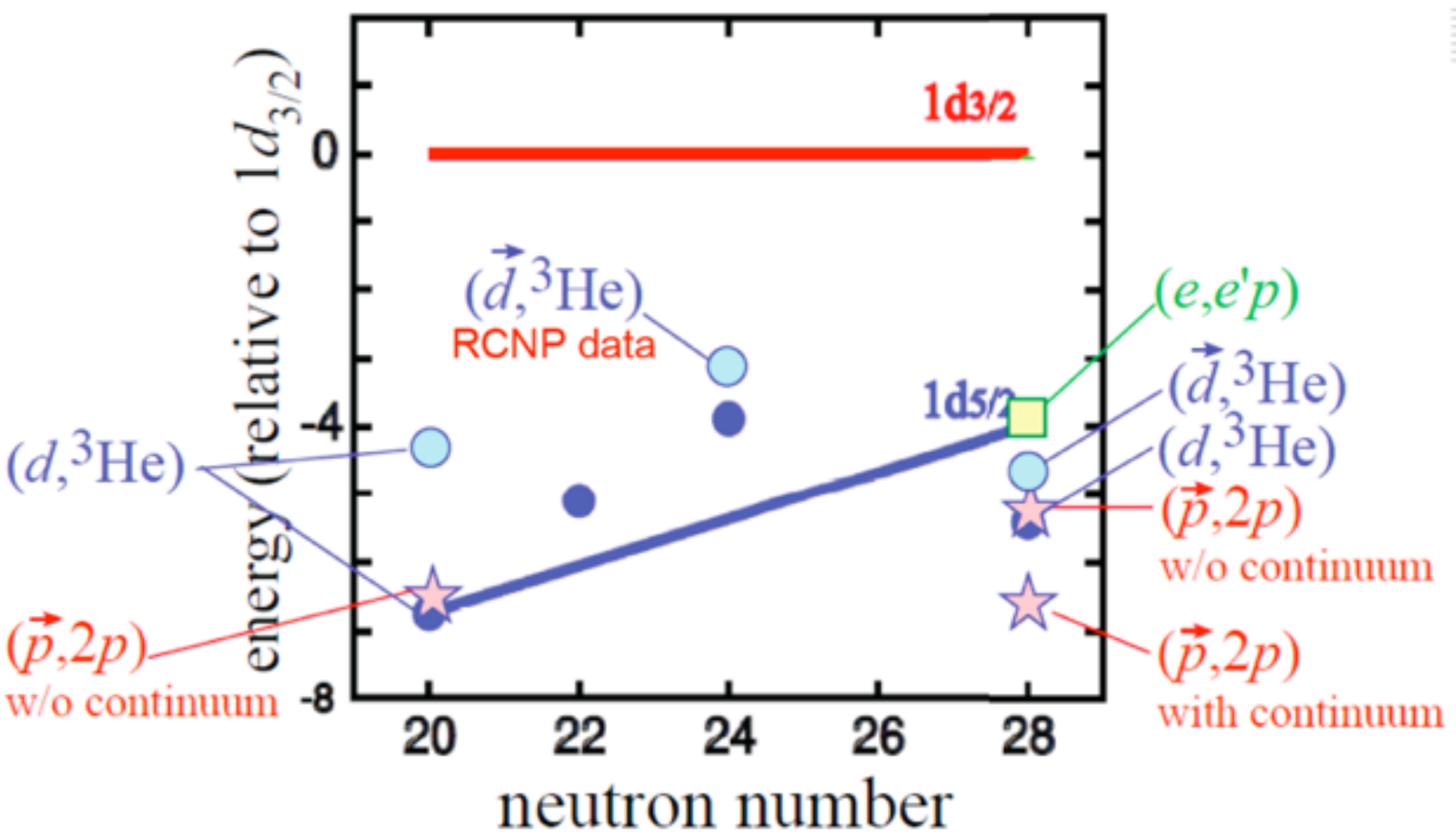
J. Schiffer et al.,
Phys. Rev. Lett. 92 (2004) 162501.

T. Noro et al.,
ECT* workshop, 2010

Sn isotopes



Ca isotopes



Why don't we extend this interesting research to unstable nuclei?

BREAK

Outline

Polarization Study of Exotic Nuclei

- **Polarized target for RI-beam experiments**

Proton elastic scattering

Experimental approaches to spin-orbit splitting in nuclei

- **Transfer reactions**
- **Knockout reactions**
- **Proton resonant scatterings**

I will show some examples.
But, so far, little has been done.
Much is left for future (you)!

How to Polarize Nuclei

Atomic Beam Method

Long history since 1950's

Adopted in many polarized p/d ion sources

Rabi

Optical Pumping Method

Polarized p/d ion sources (ex., RHIC)

^{3}He gas target (high density)

Polarization of heavy ions

Kastler

Dynamic Nuclear Polarization (DNP) Method

Standard technique to polarized nuclei in solid

Used in many high-energy labs (CERN, SLAC, JLab)

Brute Force Method

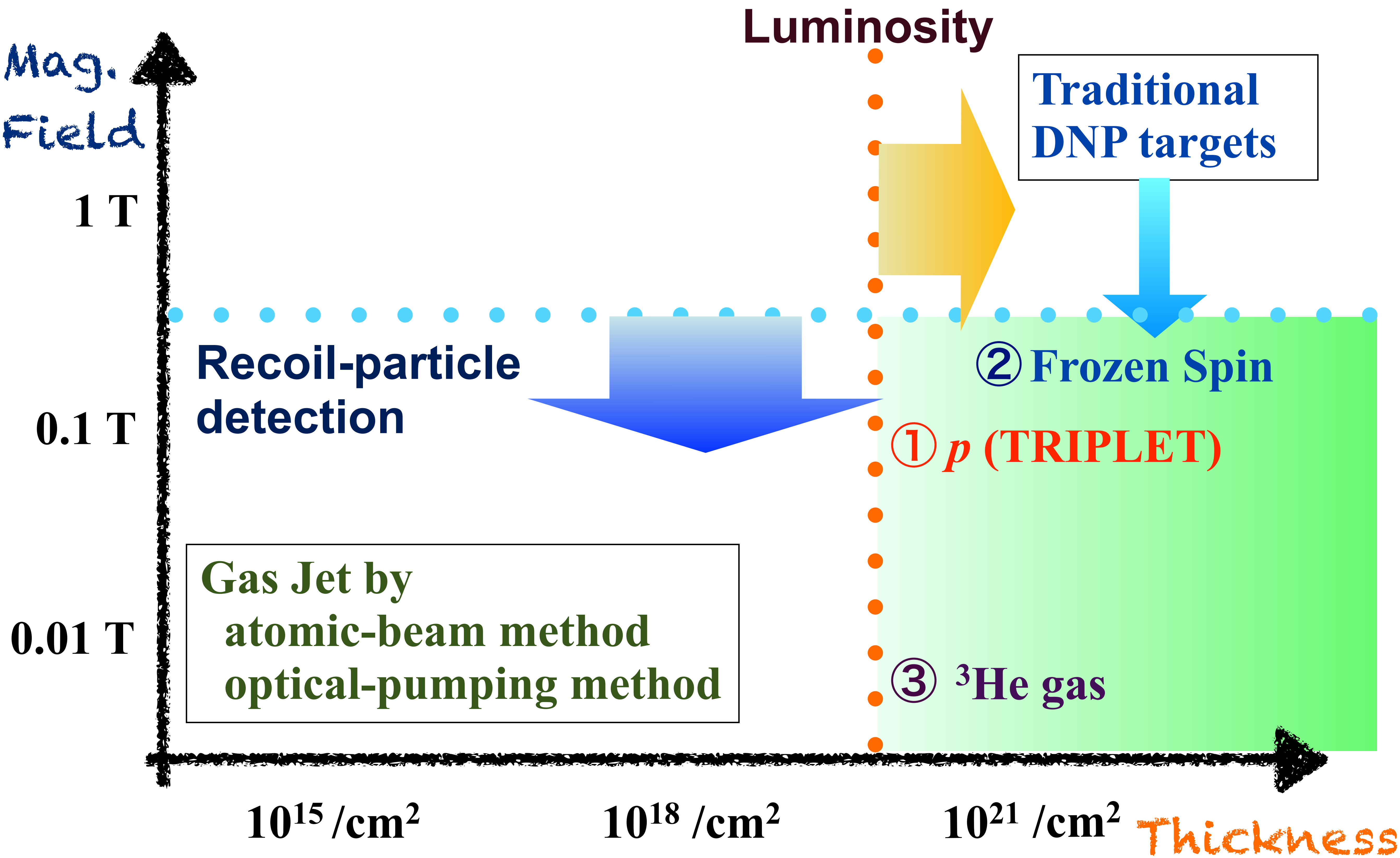
HD target (only for photon/neutron beams)

Nuclear Reaction Method

Standard method to polarize RIs

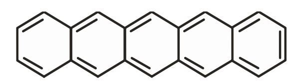
Abragam

Polarized Target in the market



"TRIPLET" target at RIKEN-CNS

The FIRST Polarized Proton Target applicable to RI beam exp.



Material: $C_{10}H_8$ (+ $C_{22}H_{14}$)

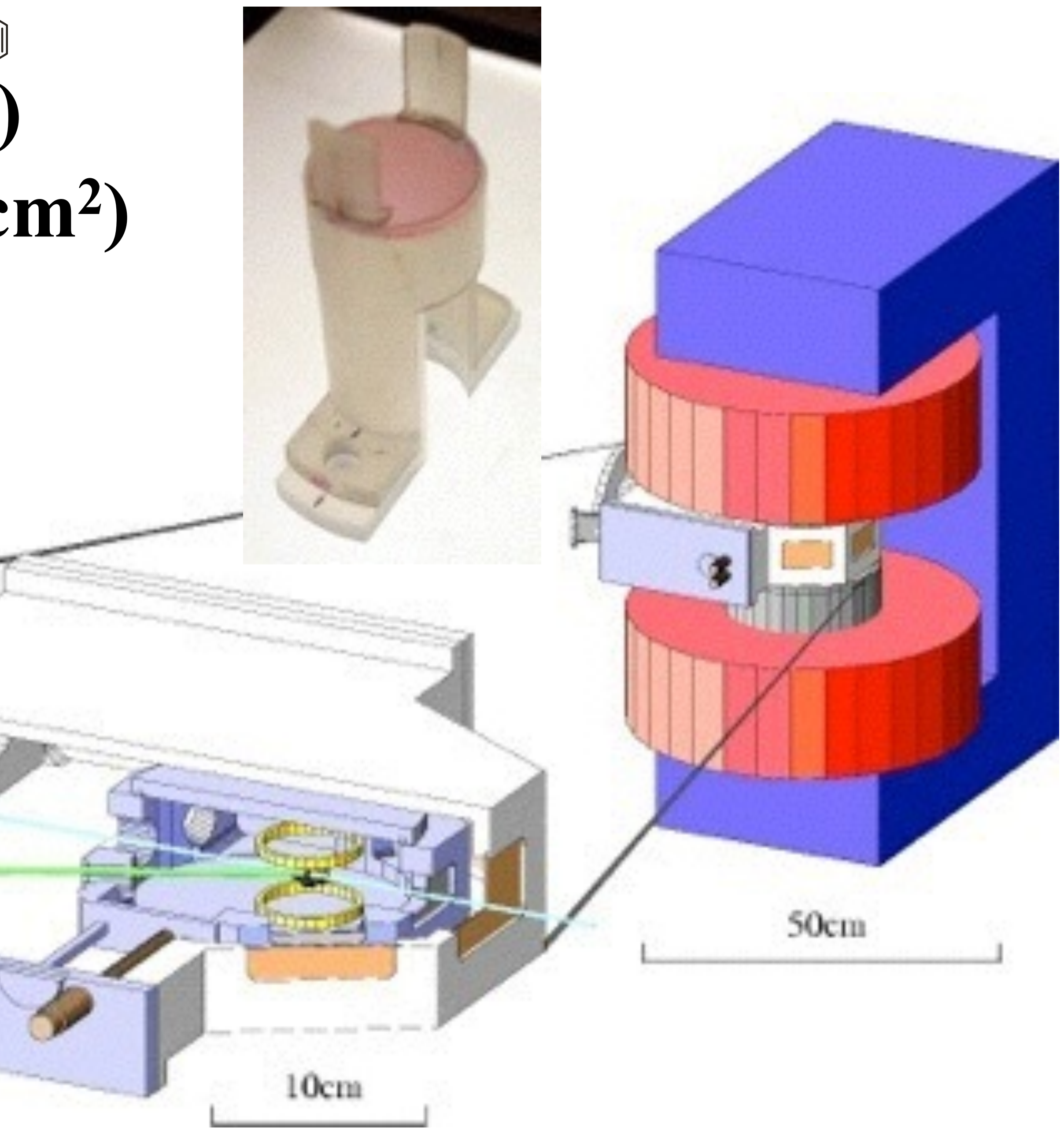
Thickness: 1 mm (120 mg/cm^2)

Size: ϕ14 mm

Polarization: P=15−20%

Temperature: 100 K

Mag. field: 0.1 T

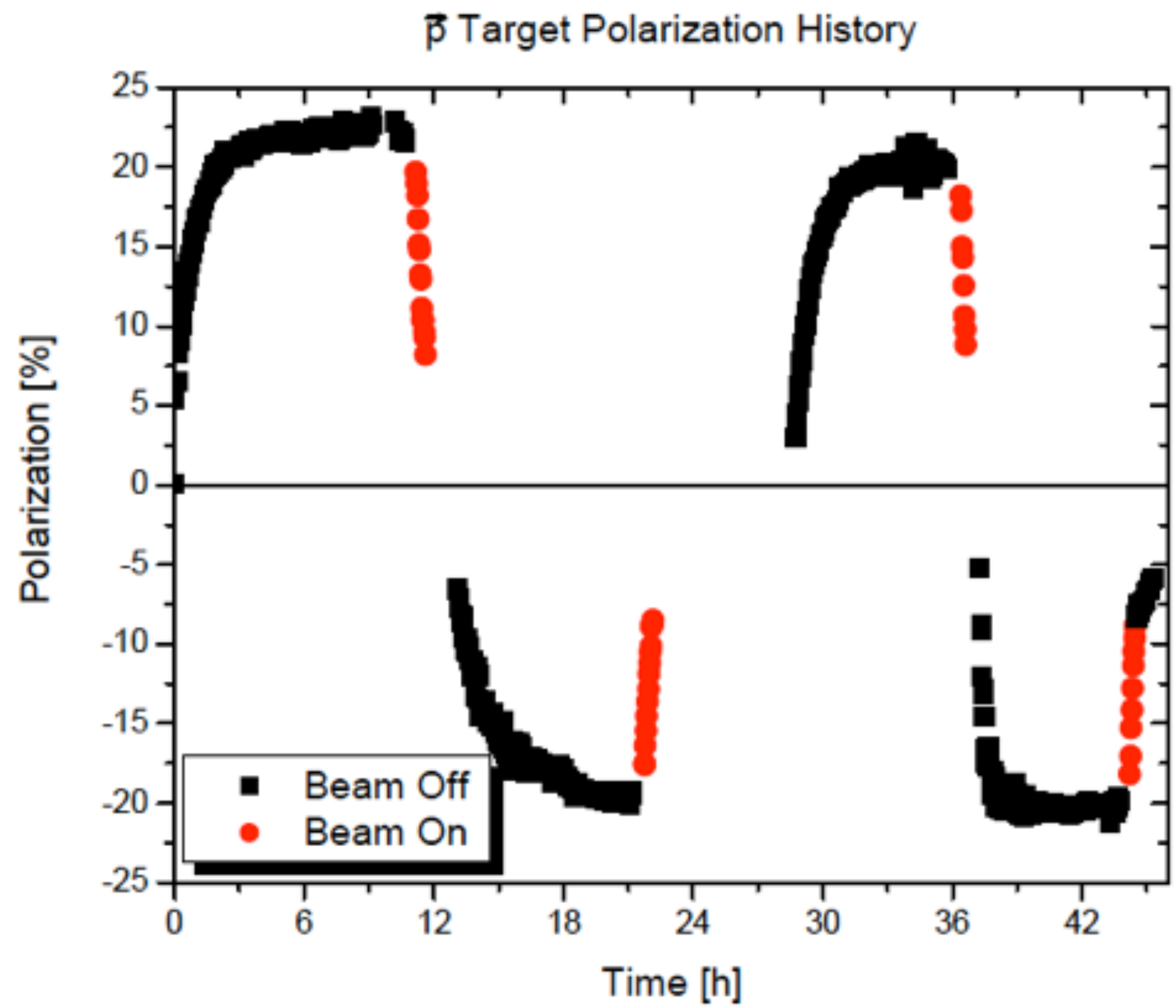


T. Wakui et al., NIM A <u>550</u> (2005) 521.
TU, M. Hatano et al., NIM A <u>526</u> (2004) 186.
A. Obertelli and TU, EPJ A <u>47</u> (2011) 105.

ORNL-PSI Polarized Proton Target

Spin-frozen operation of traditional DNP target
another promising way to prepare pol. target for RI-beam exp.

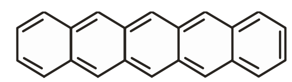
Target material	**polystyrene plastic (> 0.1 mg/cm^2)**
Frozen spin operation	**0.3K, 0.4−0.8 T**



J.P. Urrego-Blanco, A. Galindo-Uribarri et al., NIMB 261, 1112 (2007).

“TRIPLET” target at RIKEN-CNS

The FIRST Polarized Proton Target applicable to RI beam exp.



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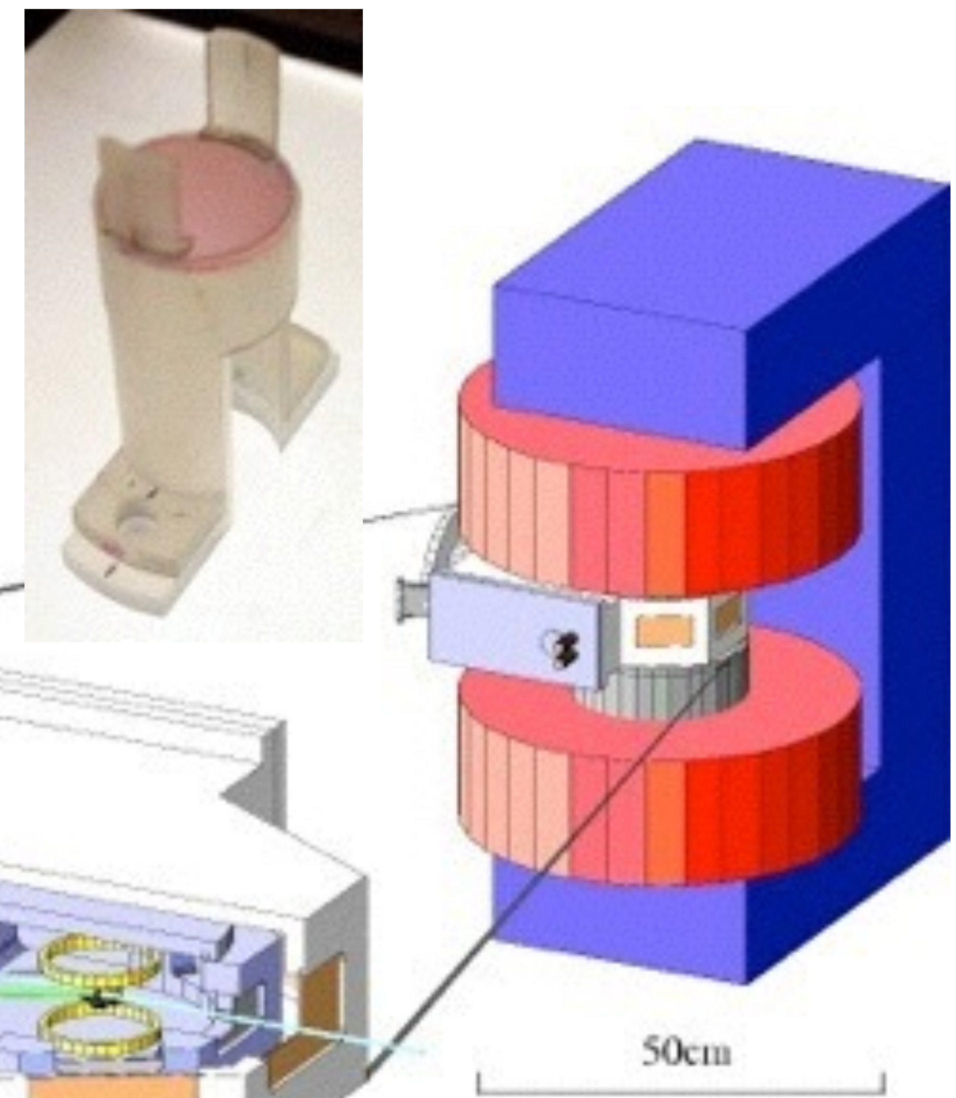

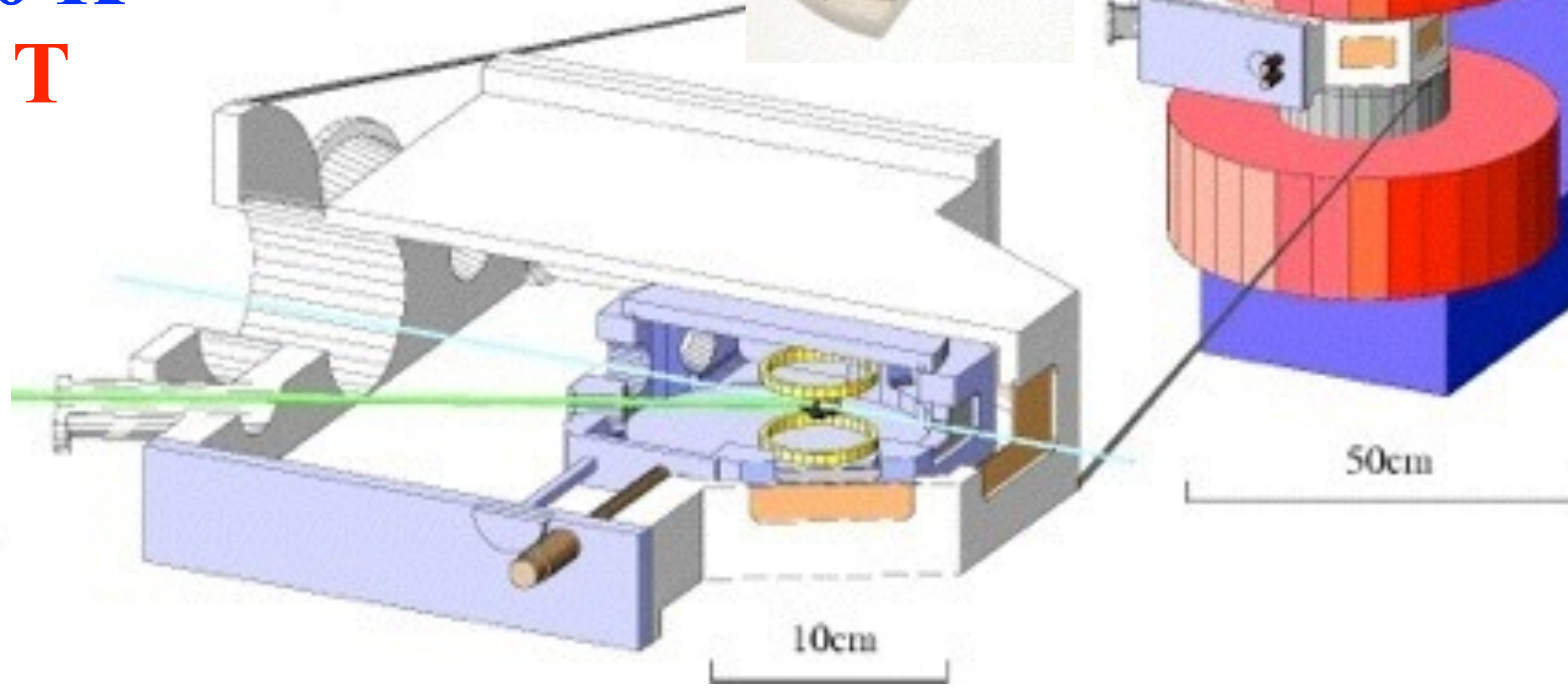

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TU, M. Hatano et al., NIM A <u>526</u> (2004) 186.
A. Obertelli and TU, EPJ A <u>47</u> (2011) 105.

Polarization in Proton Elastic Scattering

The FIRST Polarization Study

Mayer & Jensen claimed in 1948

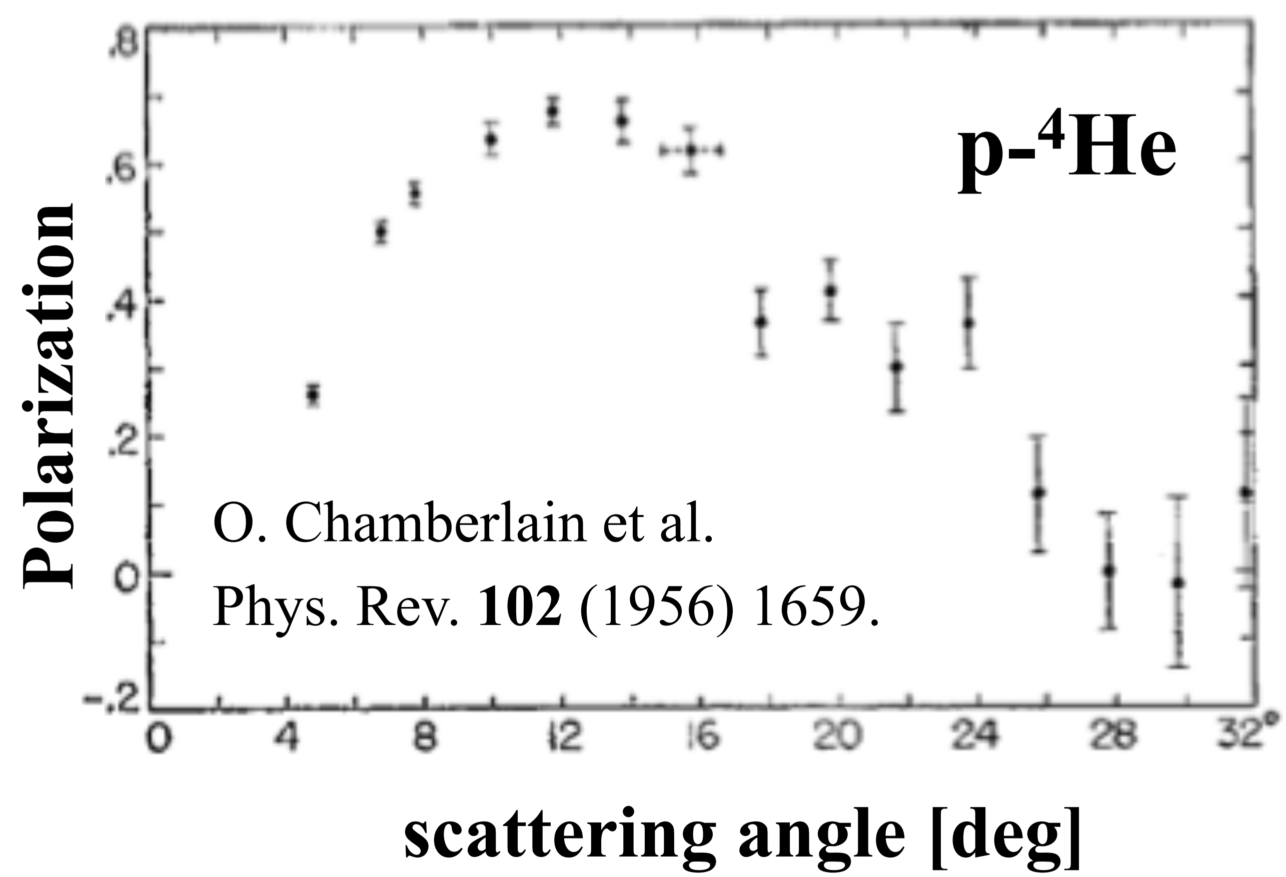
Strong spin-orbit coupling:

necessary to account for the magic numbers

one-order of magnitude stronger than the Thomas term

Several groups tried to measure spin asymmetry A_y

for p- A elastic scattering

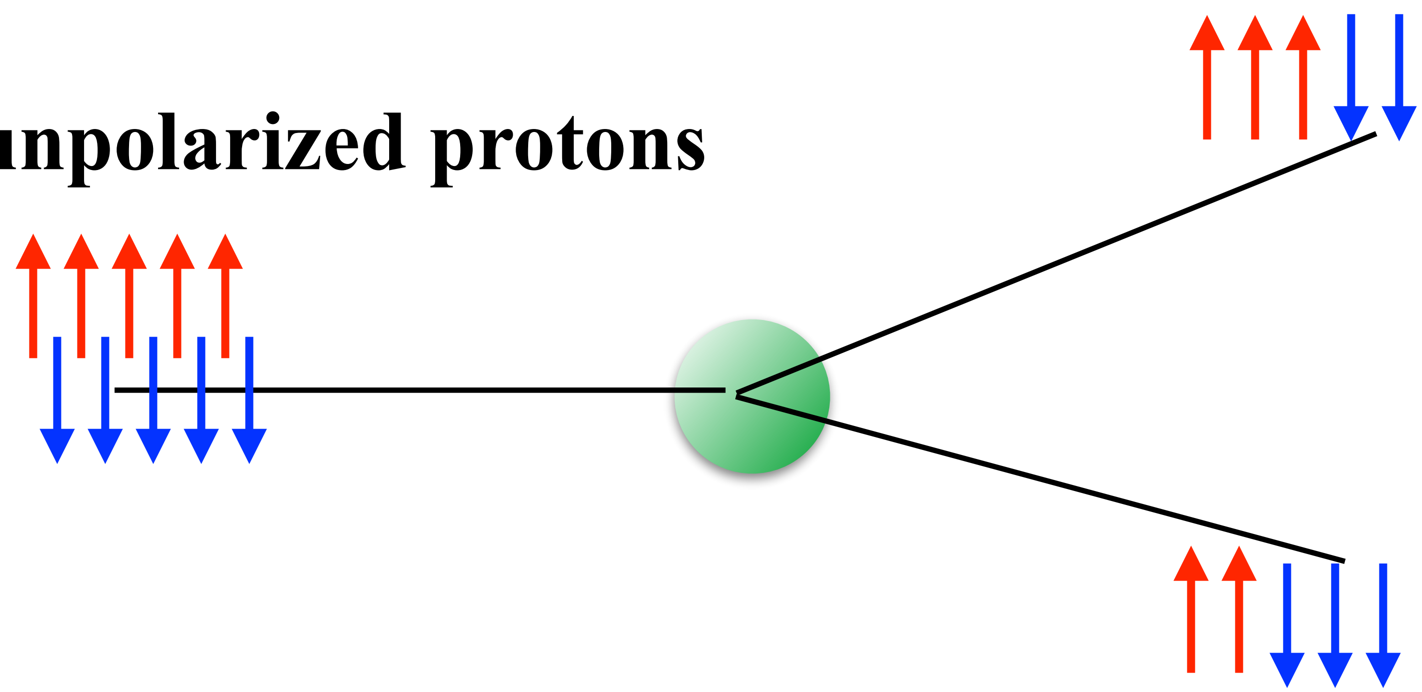


What is spin asymmetry (A_y)

A_y : spin asymmetry (analyzing power)

In elastic scattering, Ay is a measure of magnitude of LS coupling

unpolarized protons



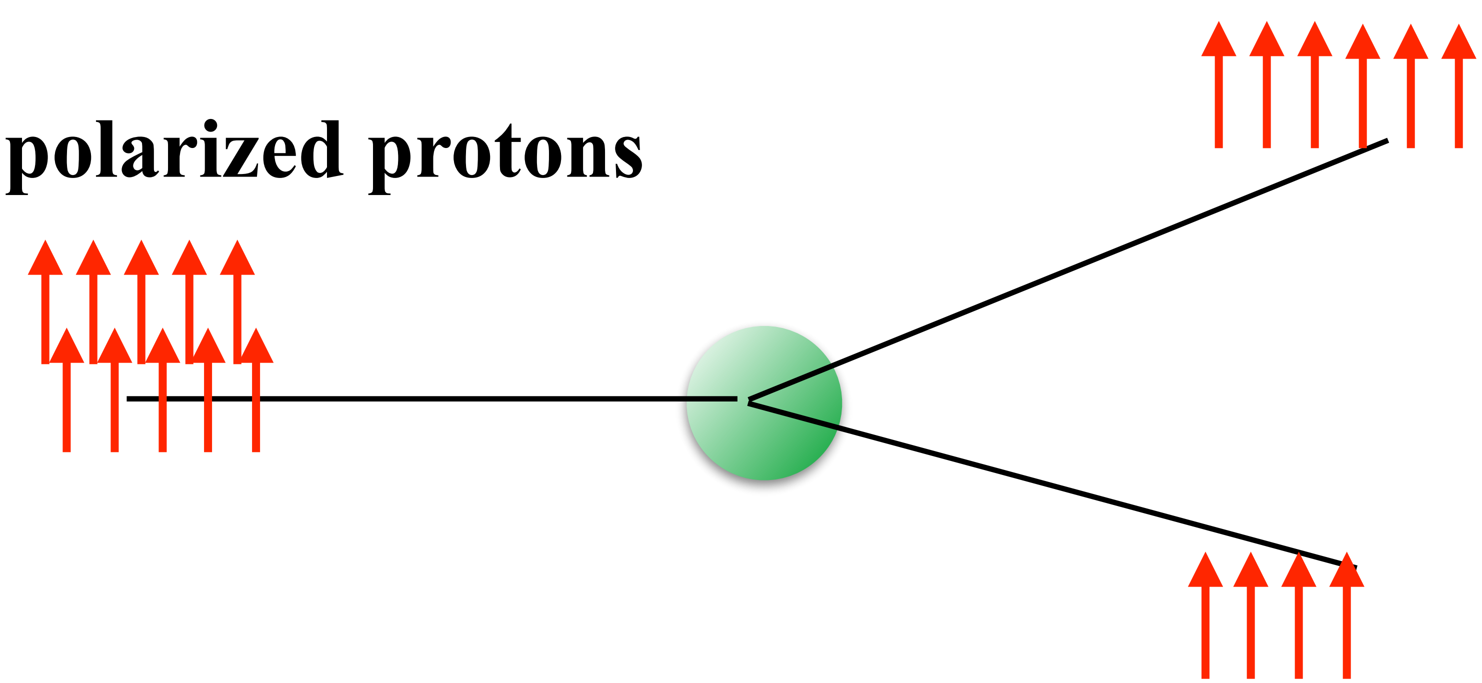
N_L=5

$$\frac{N_L - N_R}{N_L + N_R} = 0$$

no asymmetry

N_R=5

polarized protons



N_L=6

$$\frac{N_L - N_R}{N_L + N_R} = 0.2 = A_y$$

spin asymmetry

N_R=4

The FIRST Polarization Study

Mayer & Jensen claimed in 1948

Strong spin-orbit force:

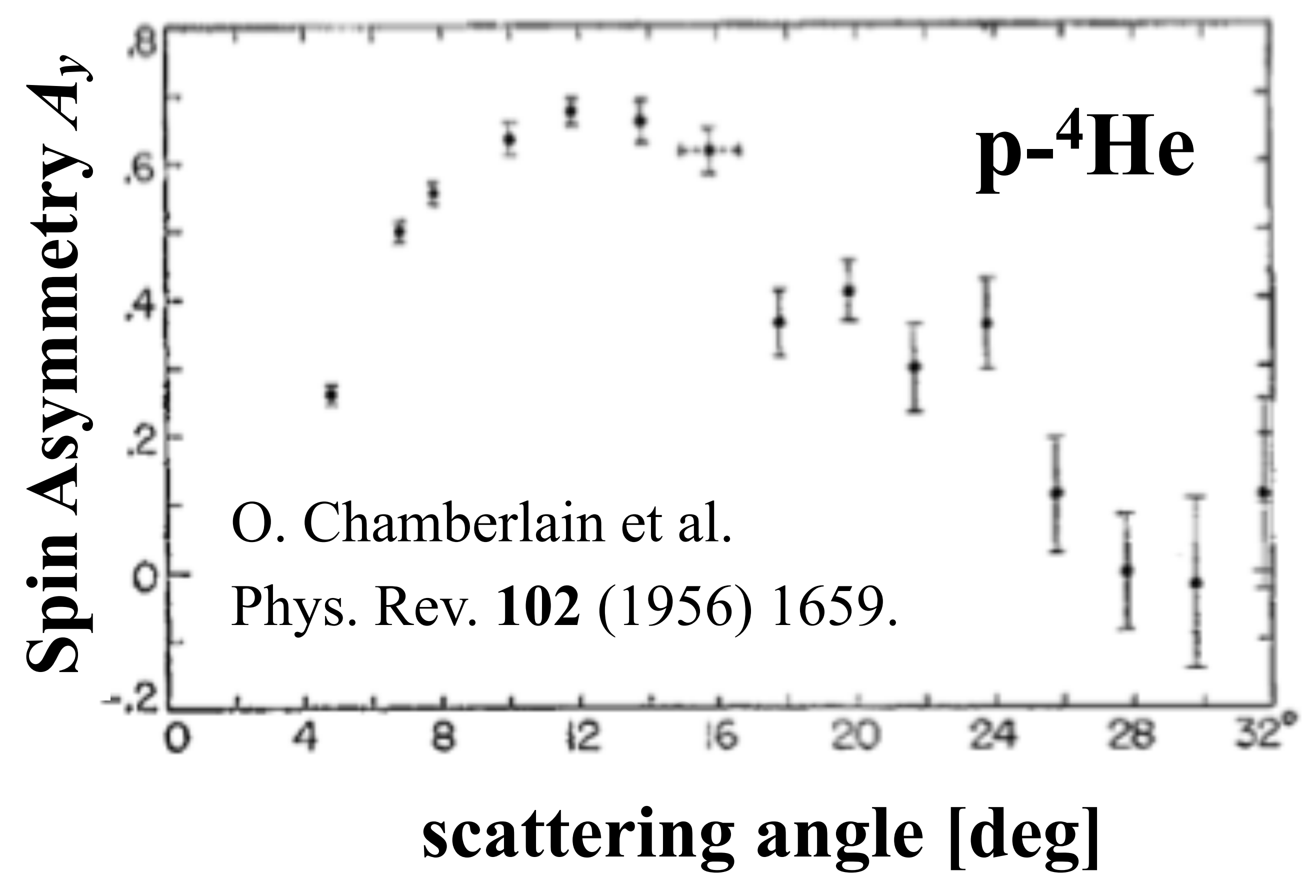
necessary to account for the magic numbers

one order stronger than the Thomas term

Several groups tried to measure spin asymmetry A_y

for p- A elastic scattering

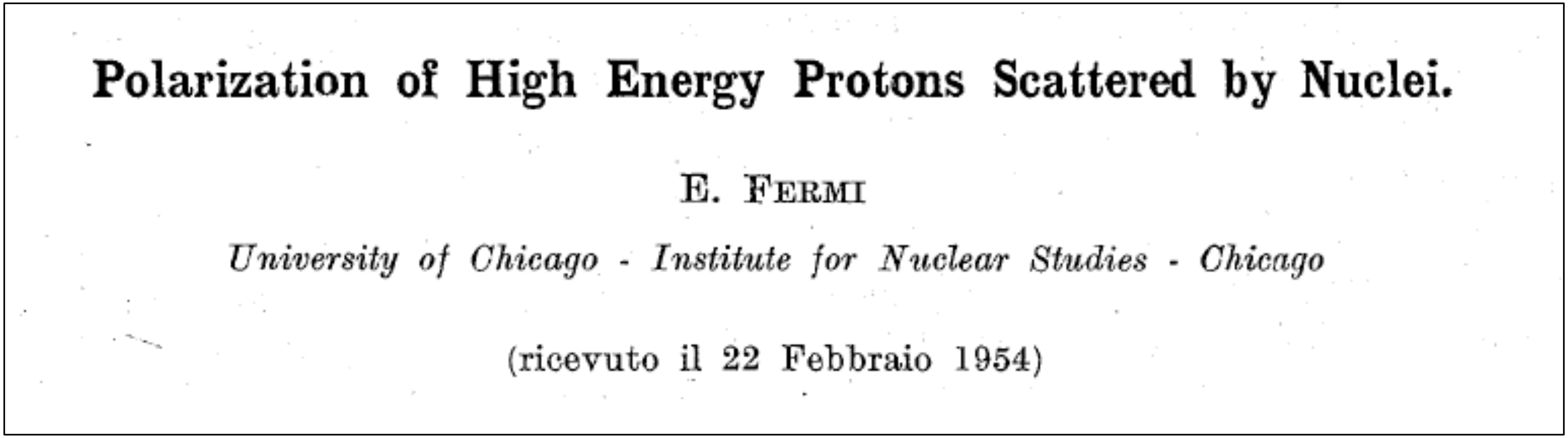
→ direct evidence of spin-orbit force



Theoretical analysis of the data

E. Fermi ,
Nuovo Cimento 10 (1954) 407.

V_{LS} deduced from the scattering experiment
is consistent with that required by the shell model



Polarization of High Energy Protons Scattered by Nuclei.

E. FERMI

University of Chicago - Institute for Nuclear Studies - Chicago

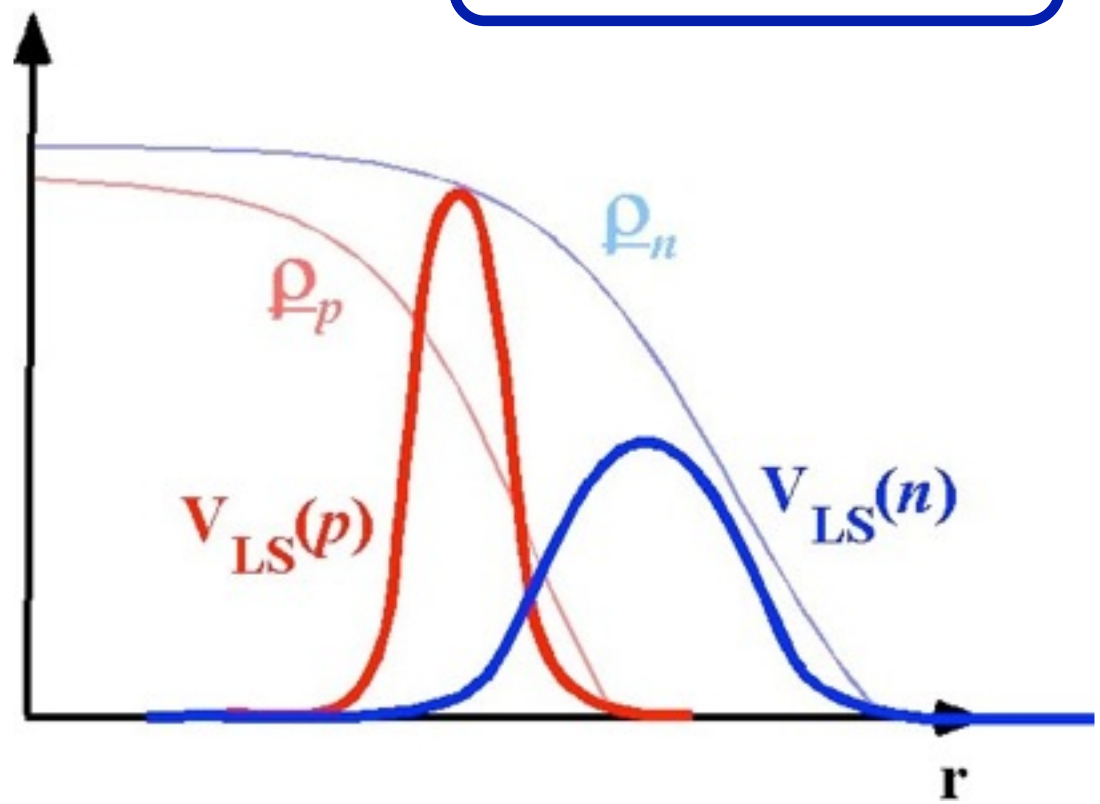
(ricevuto il 22 Febbraio 1954)

What we can expect in neutron-rich nuclei

Spin-orbit coupling: surface phenomena

$$V_{LS} \sim \frac{1}{r}\frac{d}{dr}\rho$$

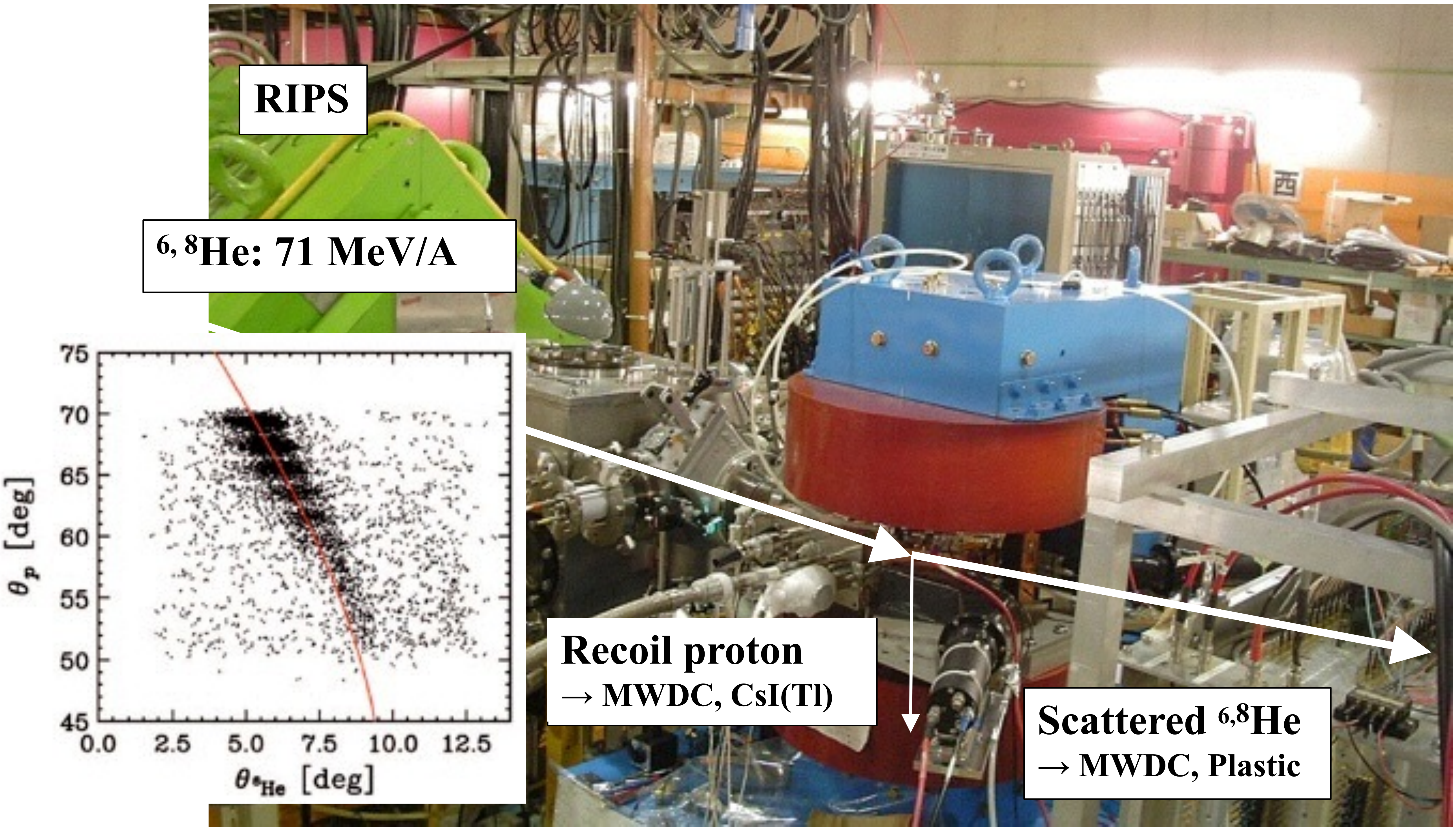
**1) could be modified
in neutron-rich nuclei
where neutron and proton
have different surfaces.**



**2) extended distribution of neutrons
may affect the shape of LS potential.**

Experiments at RIPS, RIKEN

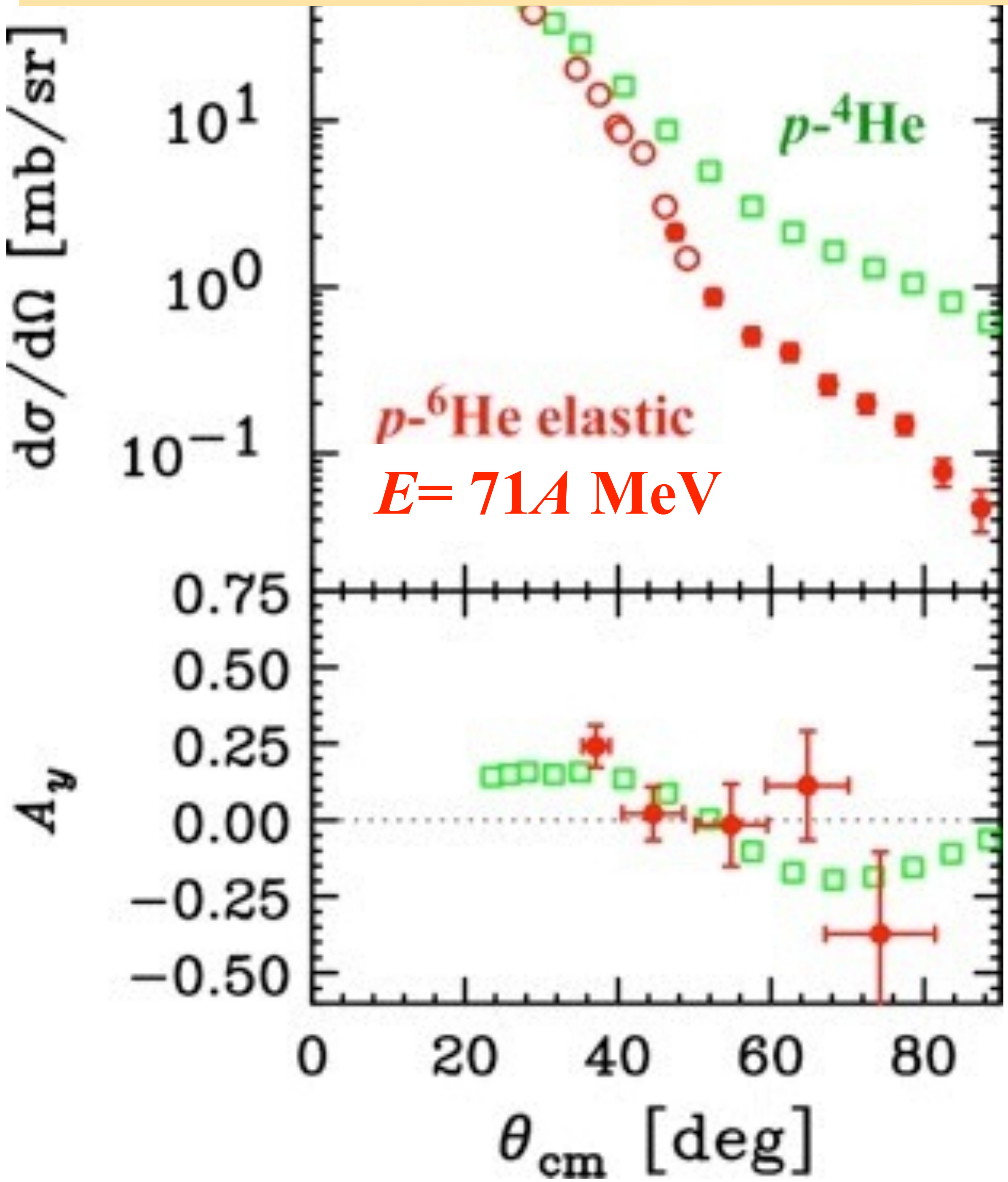
p-^{6}He @ 71 MeV/u in : 2.5×10^{5} pps
p-^{8}He @ 71 MeV/u in : 1.7×10^{5} pps

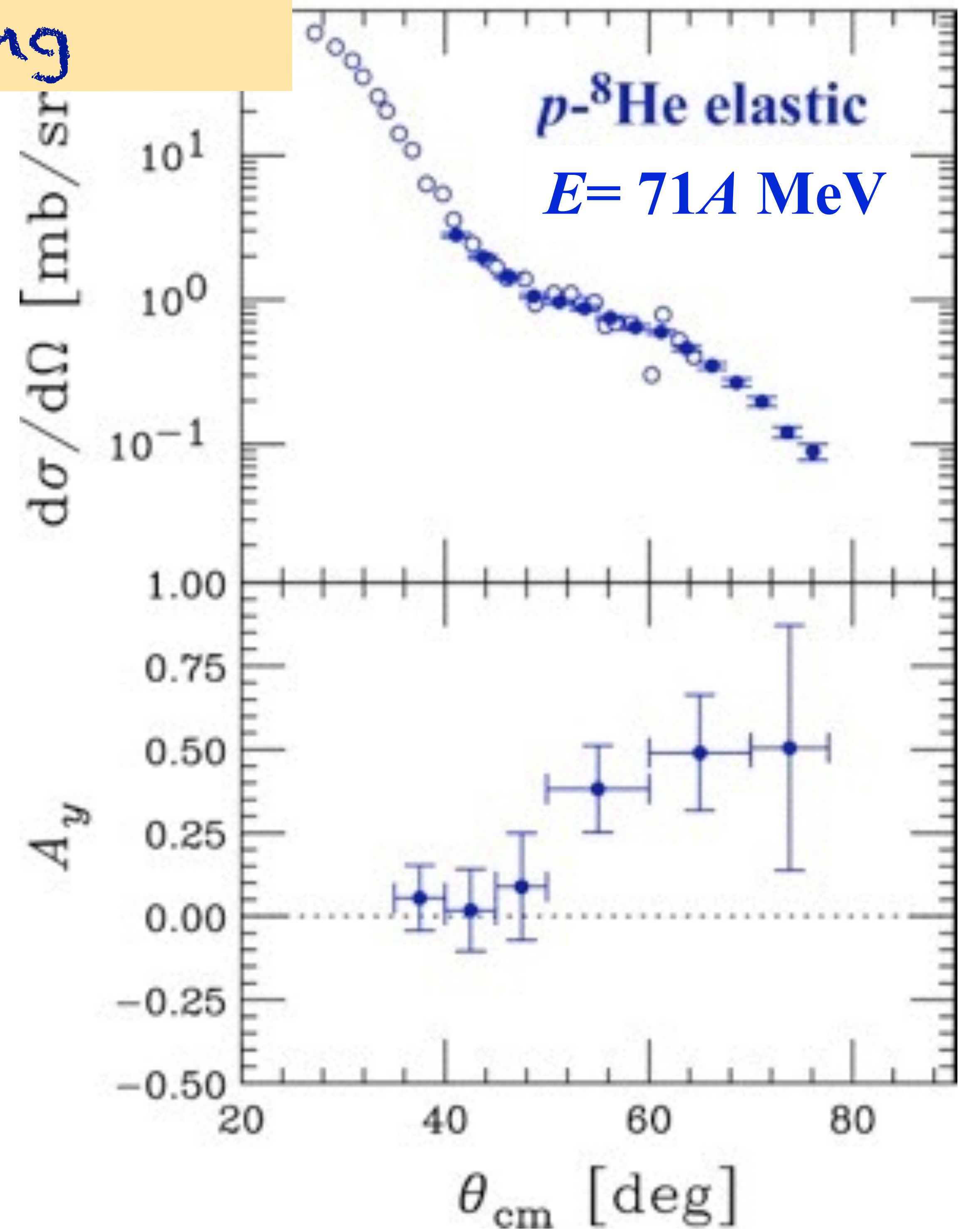


Results of dσ/dΩ, A_y

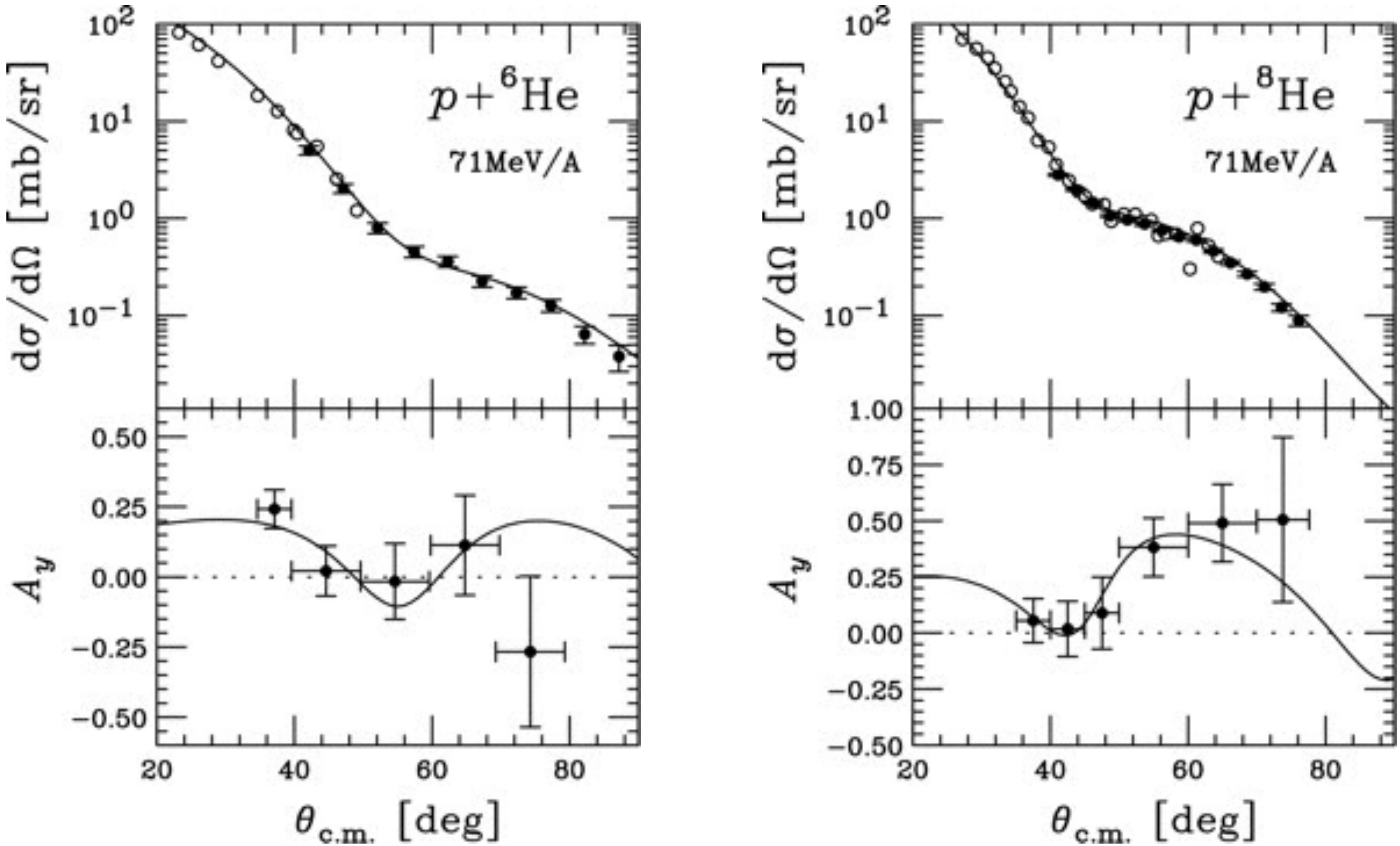
T. Uesaka et al., PRC **82** (2010) 021602(R).
S. Sakaguchi et al., PRC **84** (2011) 024604.
S. Sakaguchi et al., PRC **87** (2013) 021601(R).

The FIRST SPIN ASYMMETRY DATA
taken in RI-beam Scattering



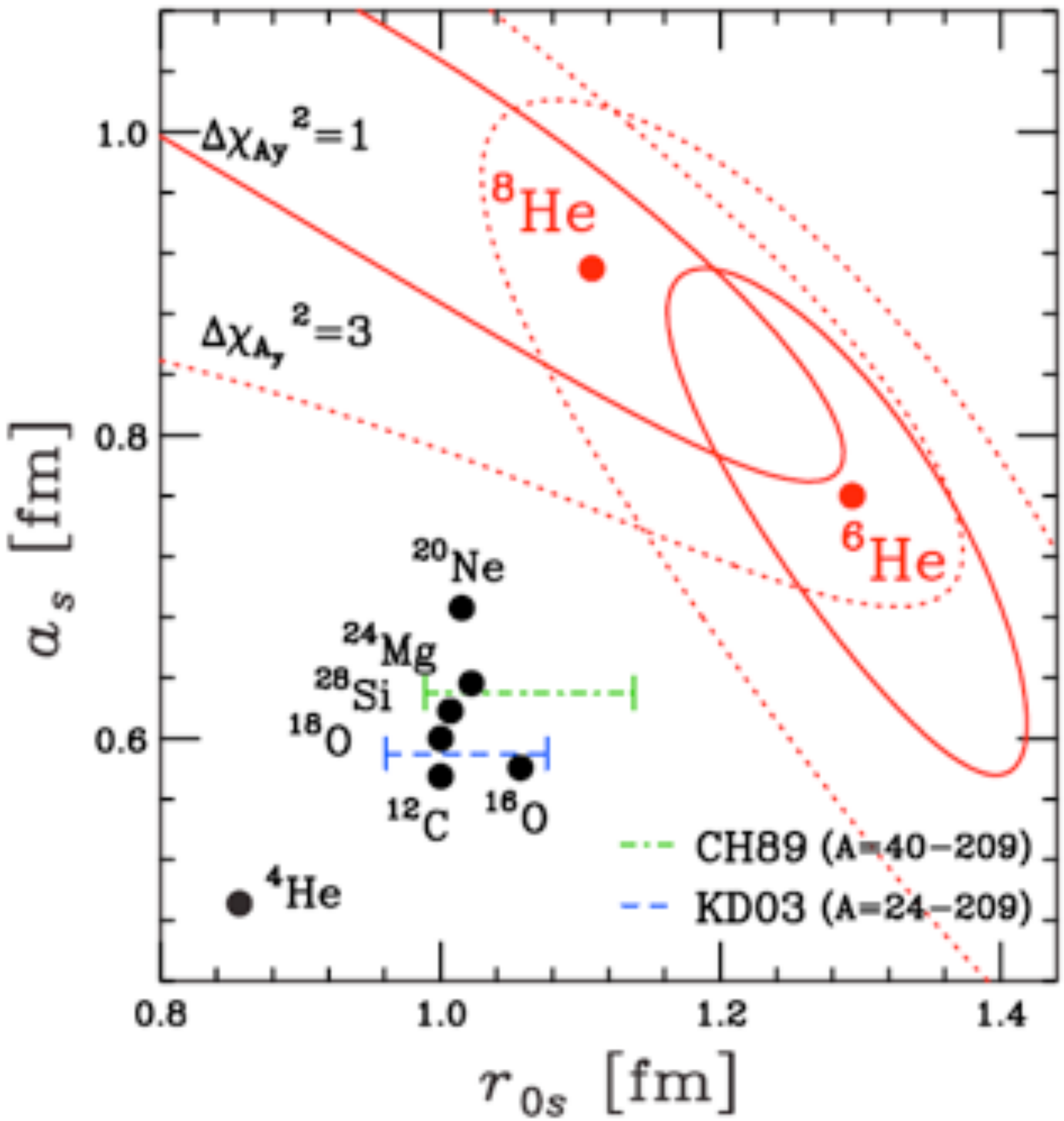


Phenomenological Optical Model analysis



→ Depths and radii of spin-orbit potentials

Radius and diffuseness parameters

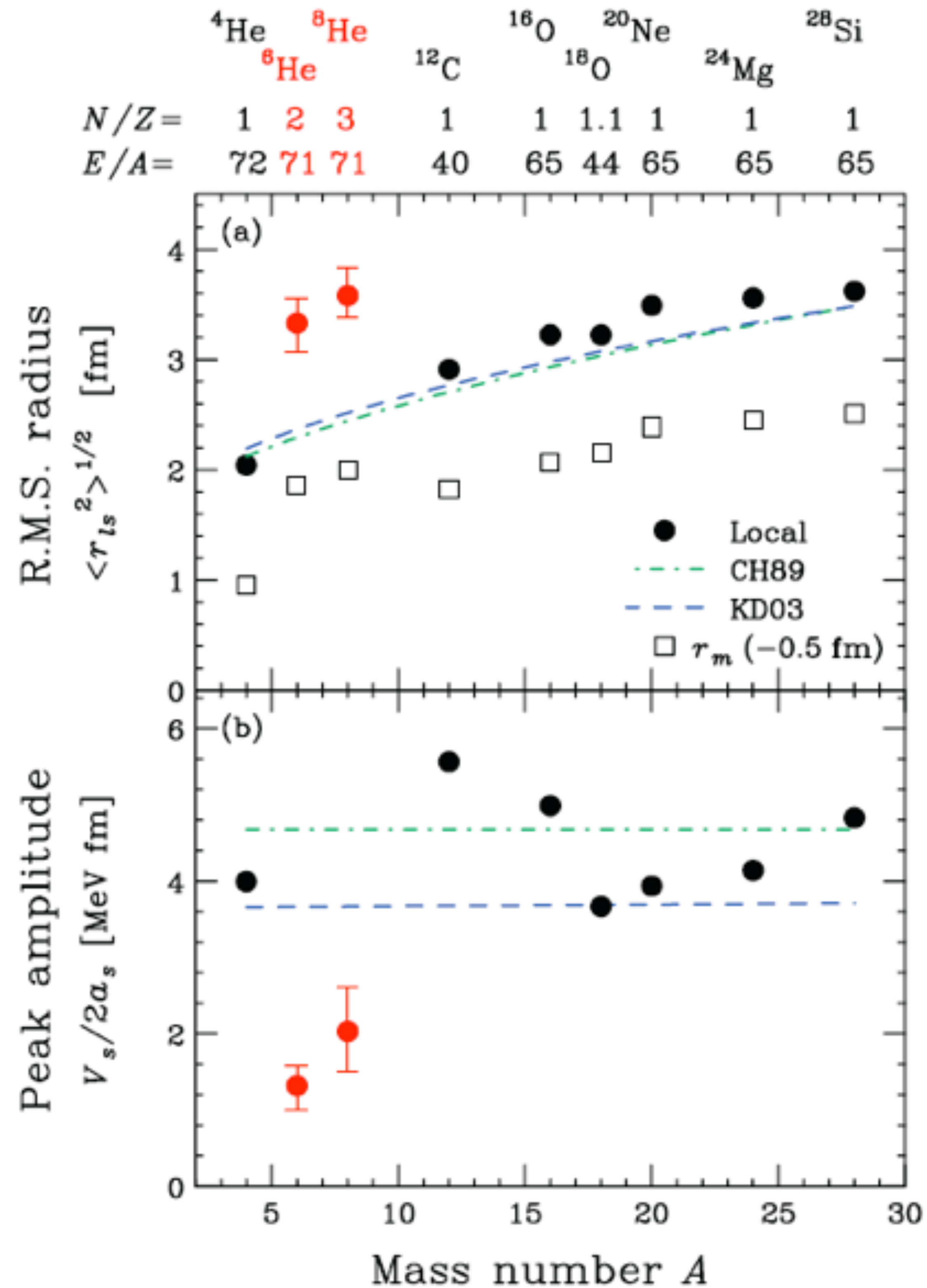


S. Sakaguchi, TU et al.
PRC 87 ('13) 021601(R)

SHALLOW Spin-orbit potential

S. Sakaguchi, TU et al.
PRC 87 ('13) 021601(R)

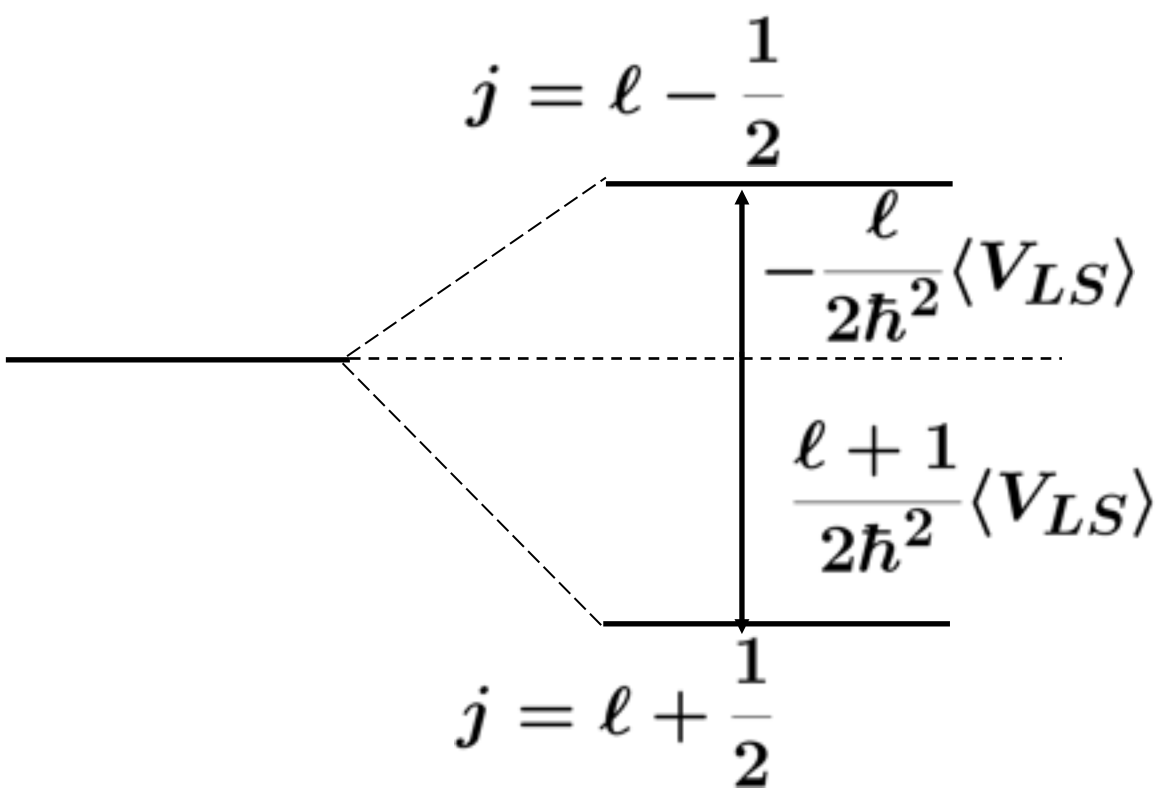
Spin-orbit potentials of ^{6,8}He are considerably shallower and have larger radii, compared with other light nuclei!

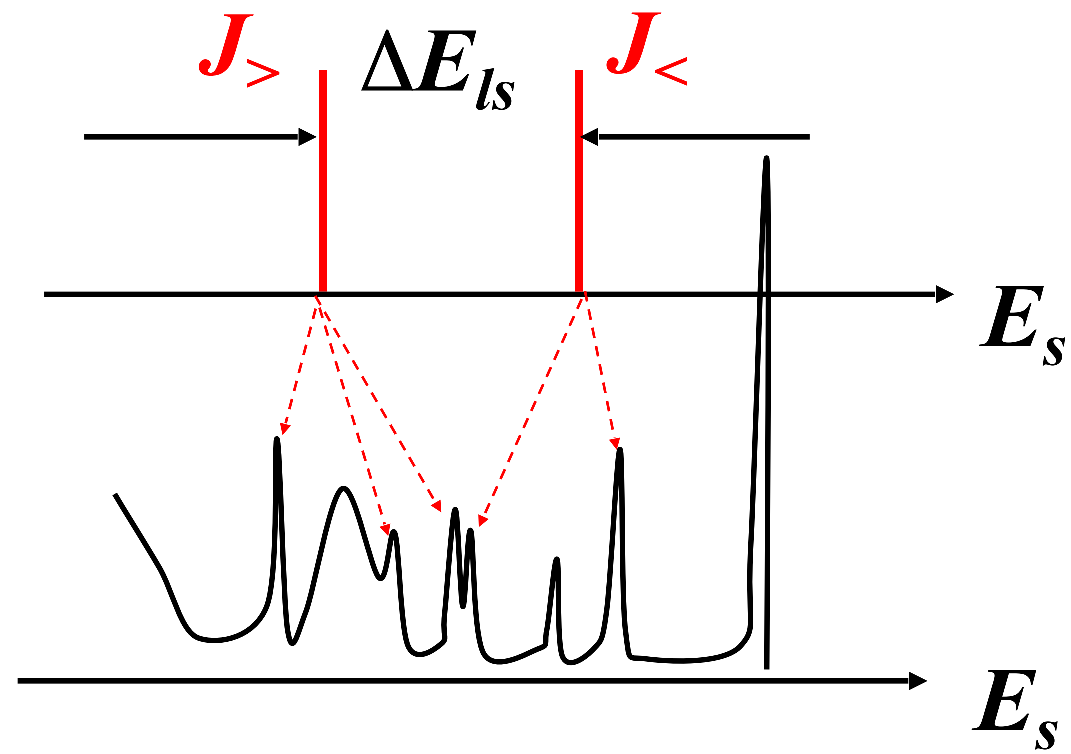


Direct experimental evidence for shallowing of spin-orbit potential.
Effectiveness of polarized protons!

Experimental study of spin-orbit splitting (on-going and future works)

Experimental study of spin-orbit splitting





Fragmented strength of single-particle levels with J=L+1/2 and J=L-1/2

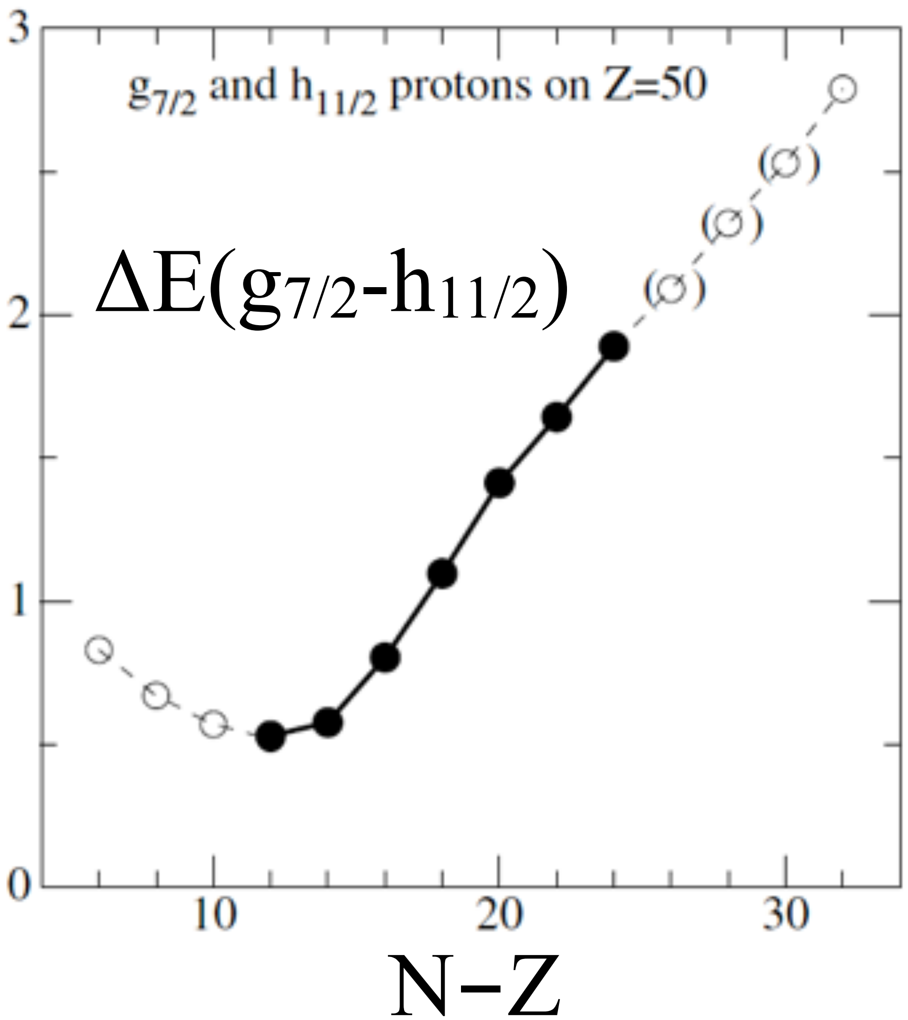
state-by-state assignment of L, J, and spectroscopic amplitudes

Experiments for stable targets

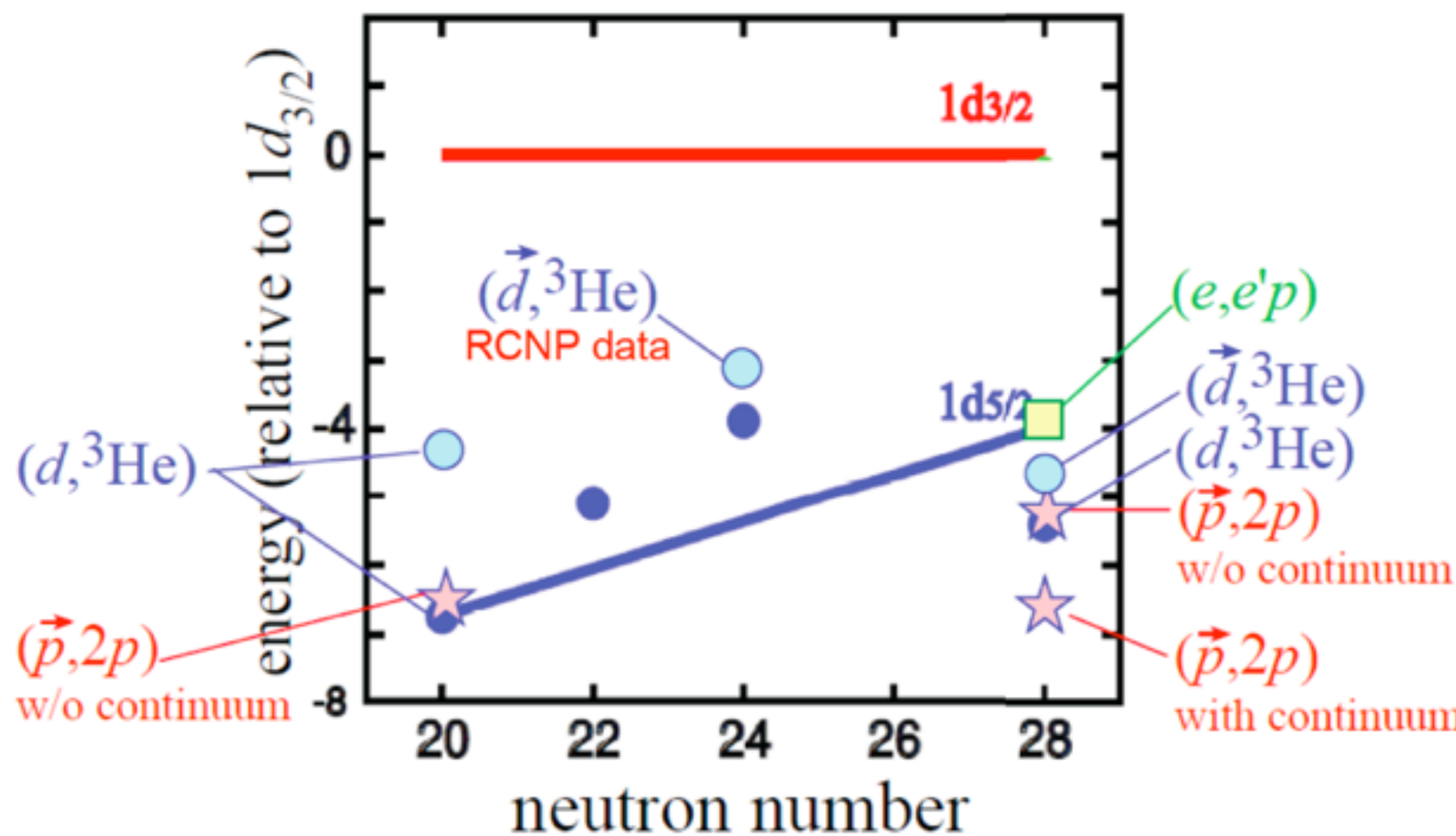
J. Schiffer et al.,
Phys. Rev. Lett. 92 (2004) 162501.

T. Noro et al.,
ECT* workshop, 2010

Sn isotopes



Ca isotopes



Experiments to investigate LS splitting

Reactions to selectively populate single-particle states

Transfer reactions: stripping reactions (d,p), (^{3}He,d) . . .

pickup reactions (p,d), (d,^{3}He/t). . .

→ Obertelli's lecture

Knockout reactions: (p,pN)

→ Charity's lecture

Proton resonant scattering

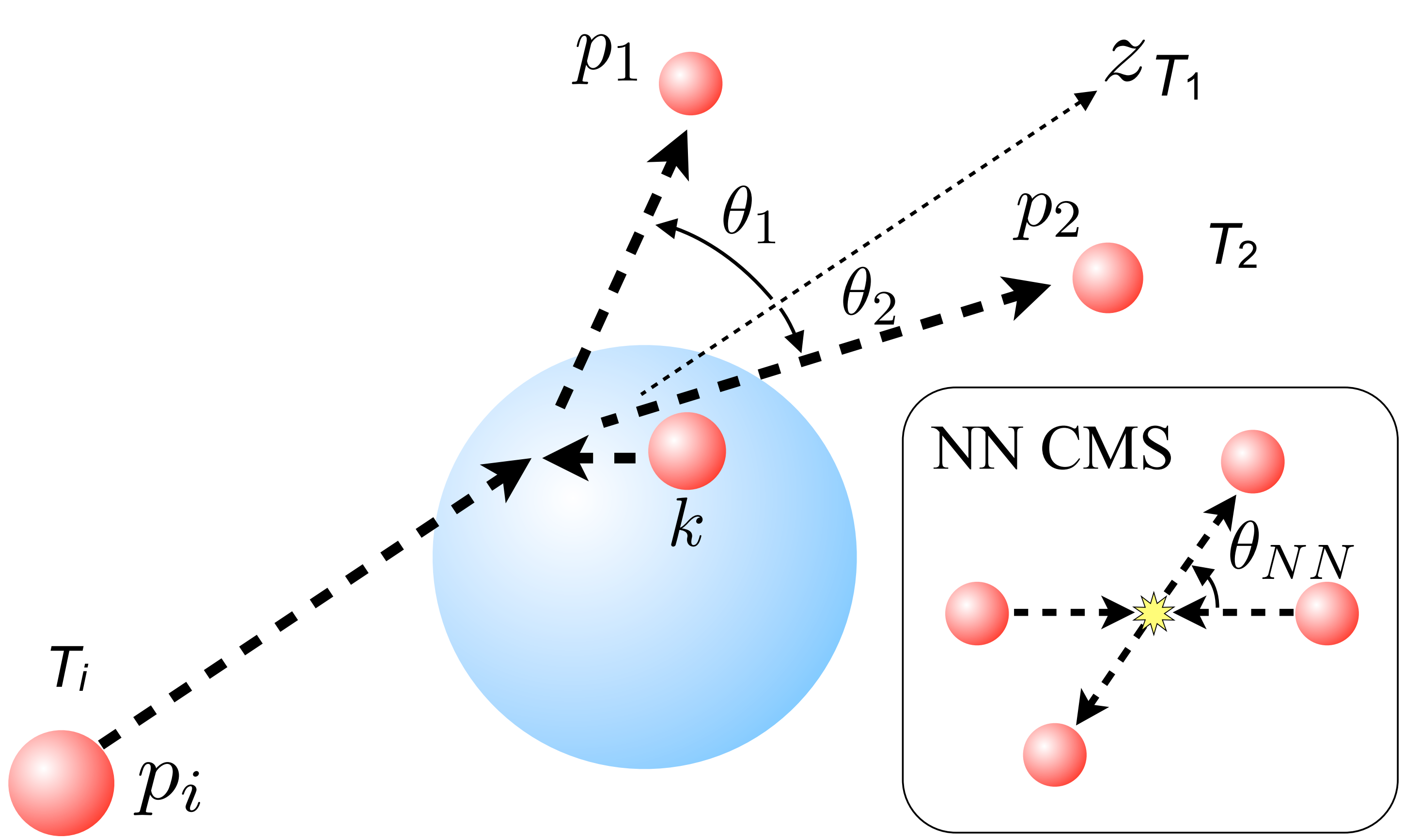
Observables to determine J^π, spectroscopic amplitude

$\boxed{\text{I will concentrate on how to determine “}J\text{”.}}$

(p,pN) Quasi-free Scattering

NN scattering in nuclear medium, without serious disturbance to the residual nucleus. Reaction mechanism is considered to be reasonably simple at E/A > 200 MeV.

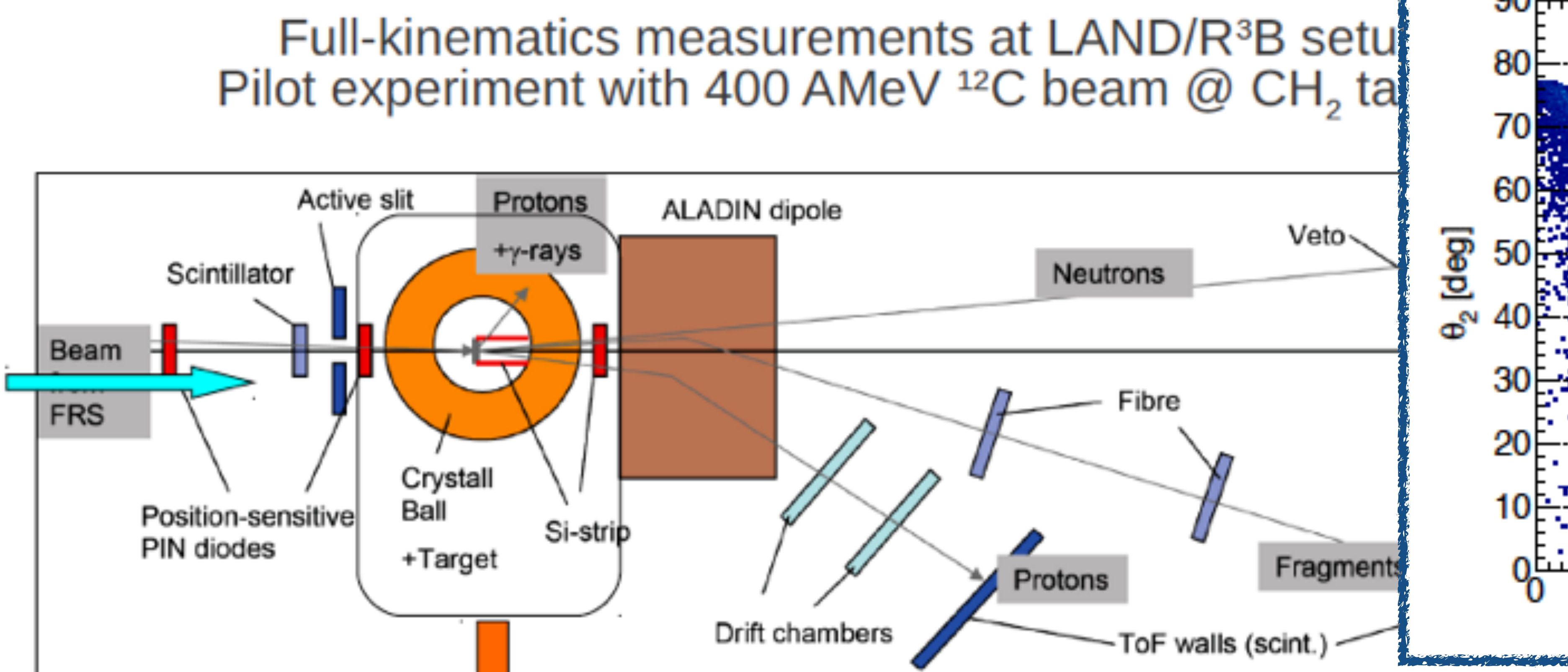
Selectively populate one-nucleon hole state and scattering observables are directly connected to properties of the nucleon (momentum distribution, spectroscopic factor, L, J, . . .).

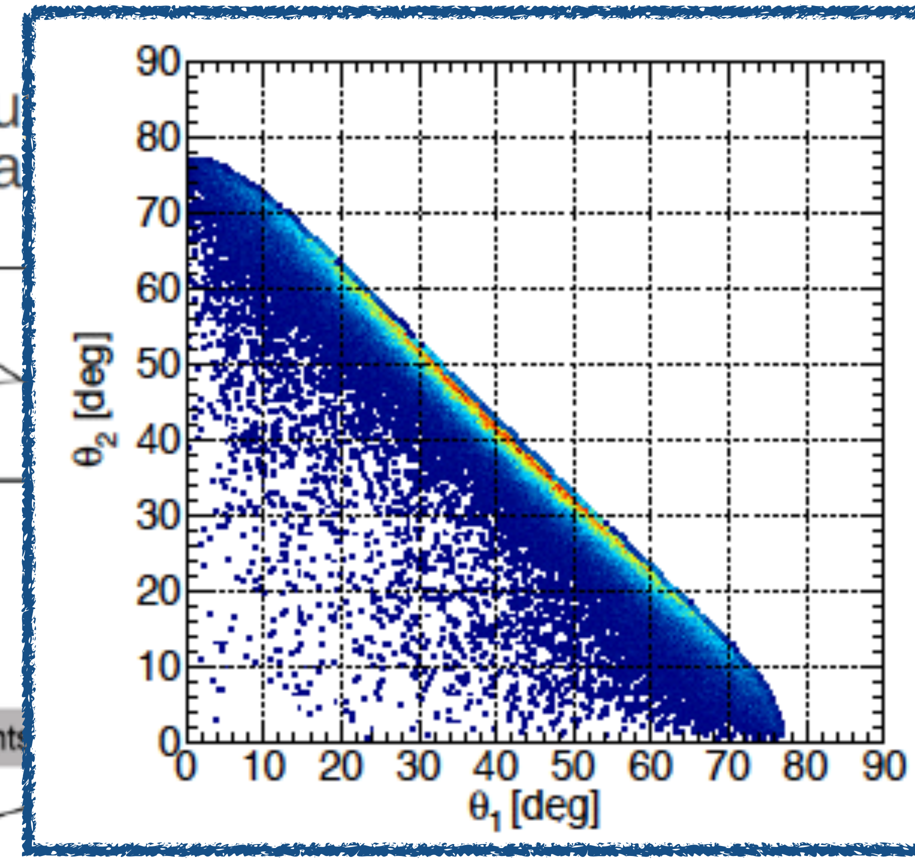


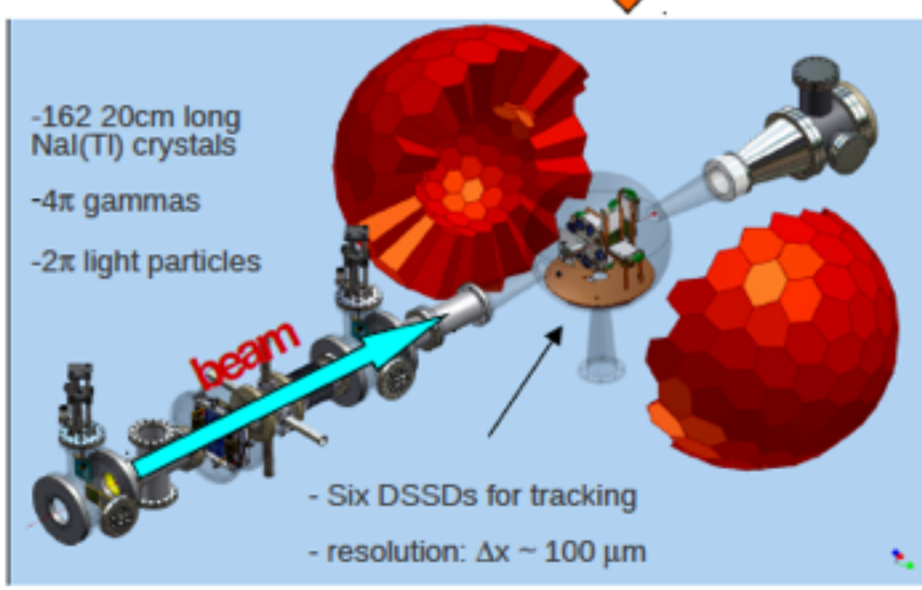
R3B @GSI	Aumann, Panin et al.
HIMAC	Kobayashi et al.
RIBF	Uesaka, Kawase, et al.

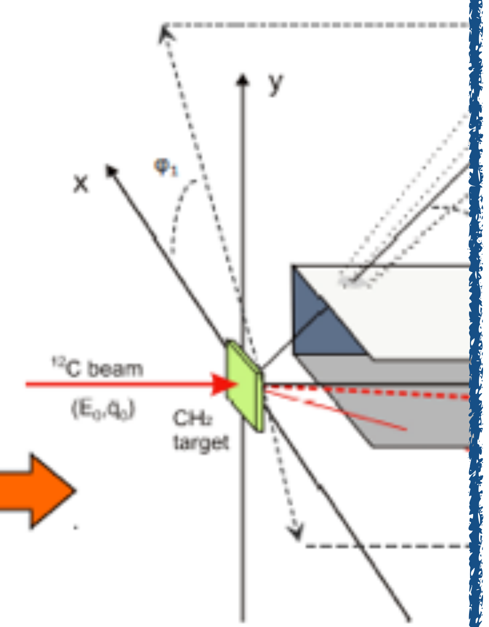
(p,pN) QFS experiments

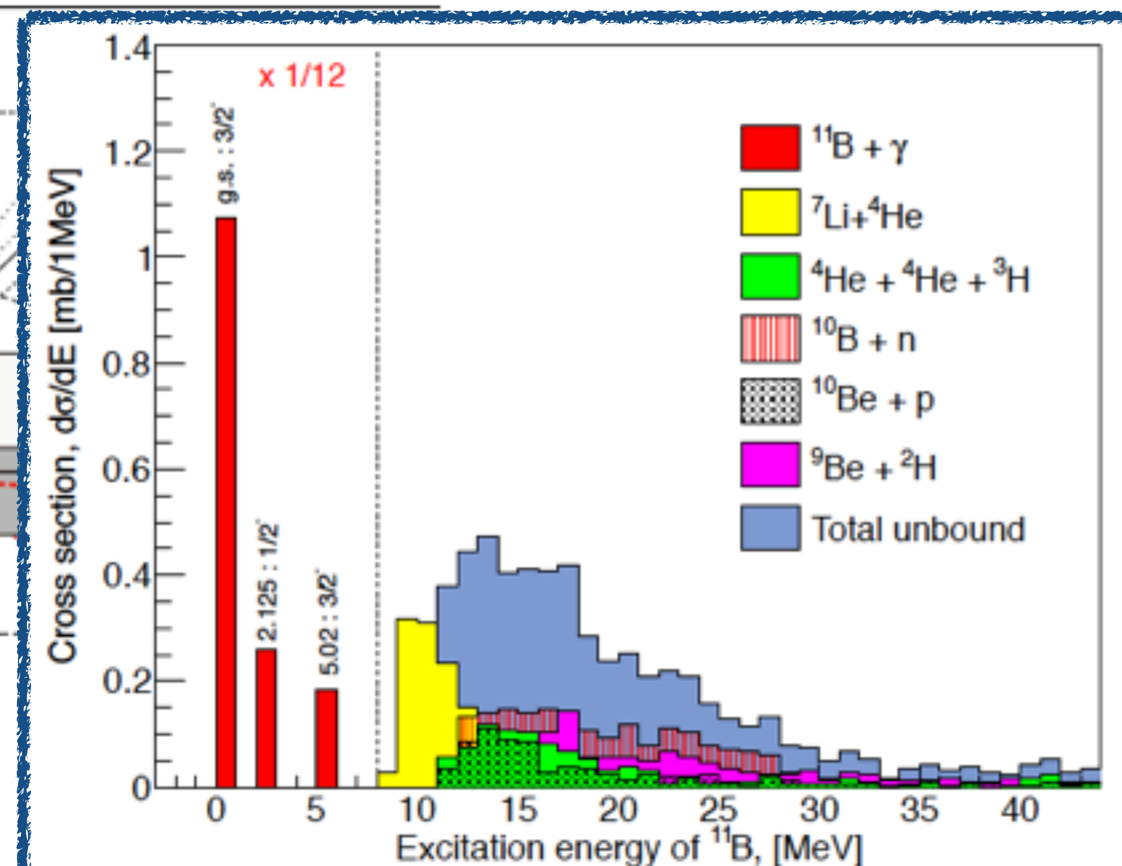
Panin, Aumann et al.









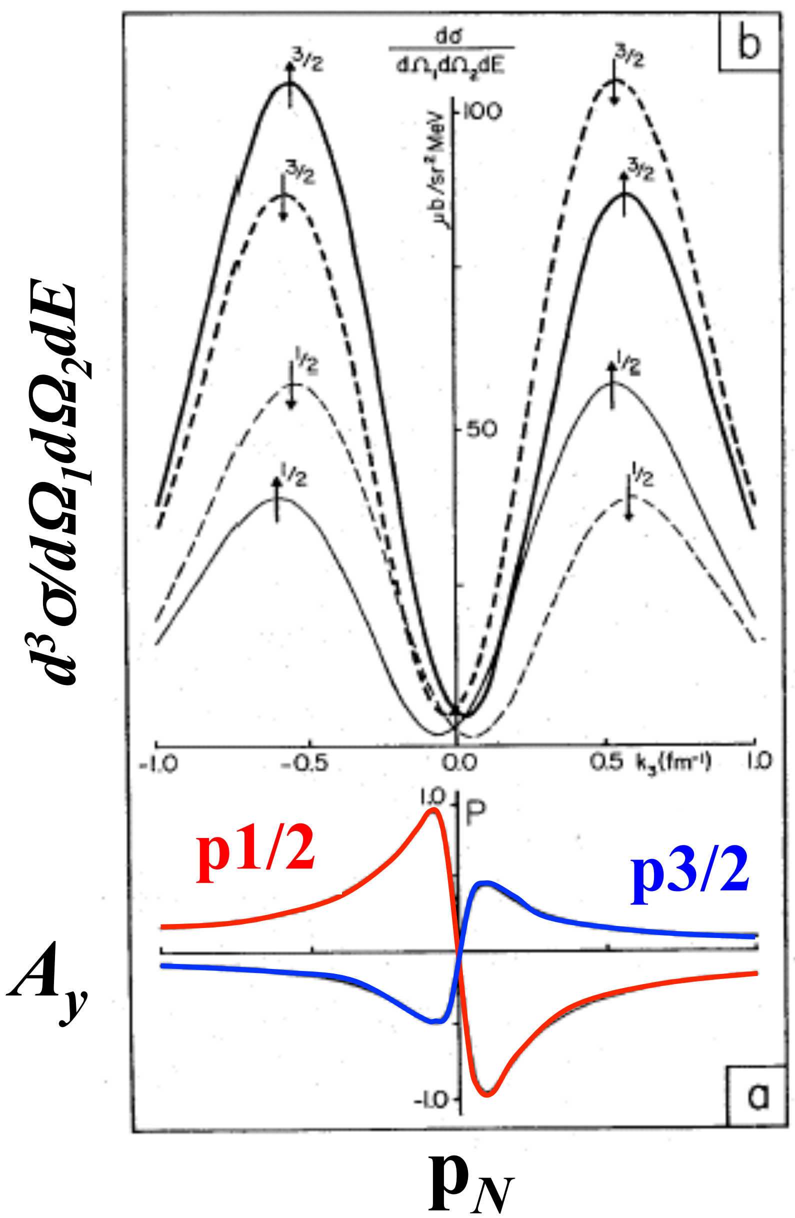


Courtesy of V. Panin

Spin Polarization in ($\vec{p}$,pN) Reaction

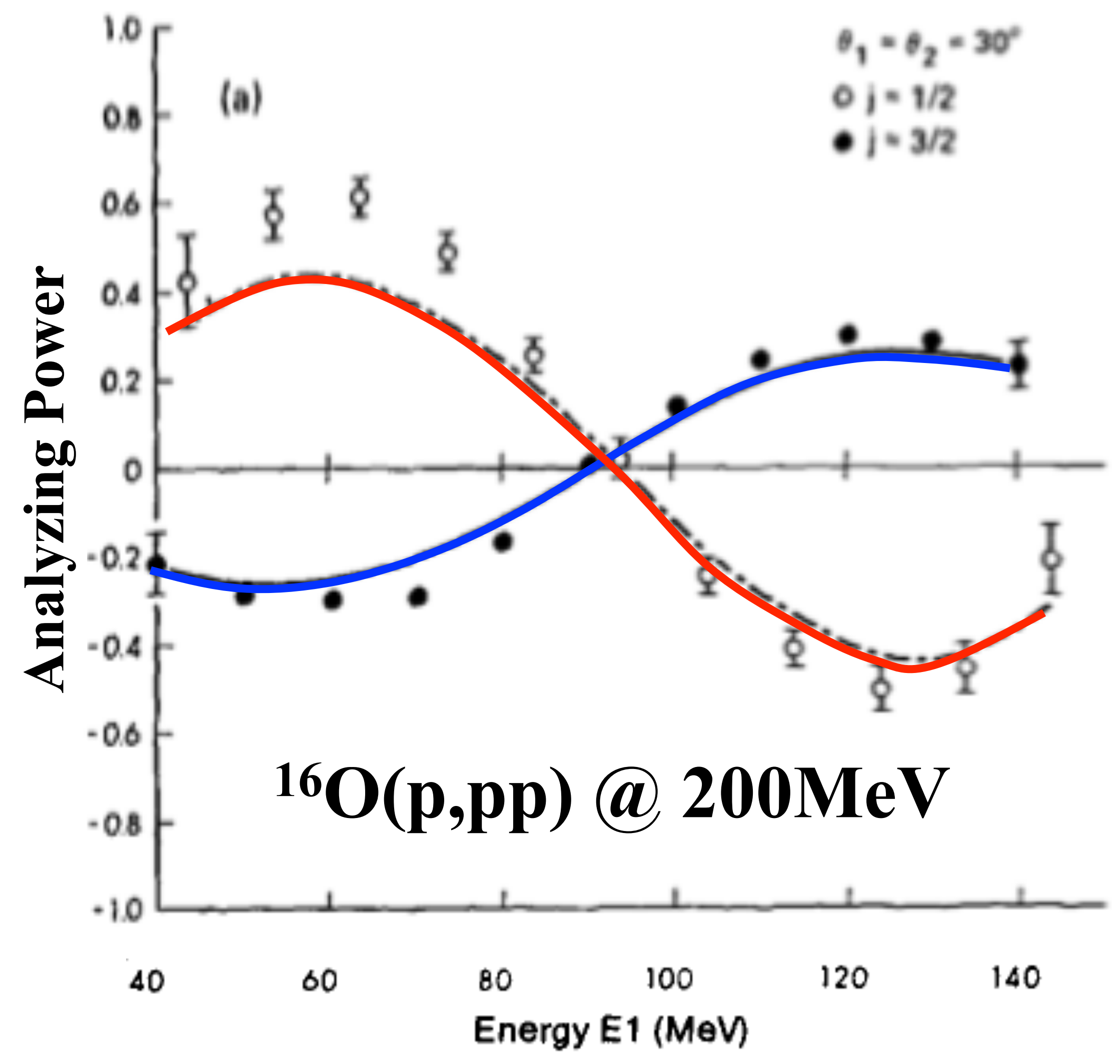
- **Momentum dependence of dσ/dΩ ⇒ L and spectroscopic amplitude**
- **Analyzing power (A_y) ⇒ J**

Proposed by Maris & Jacob



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

Demonstrated at TRIUMF by Kinching et al.



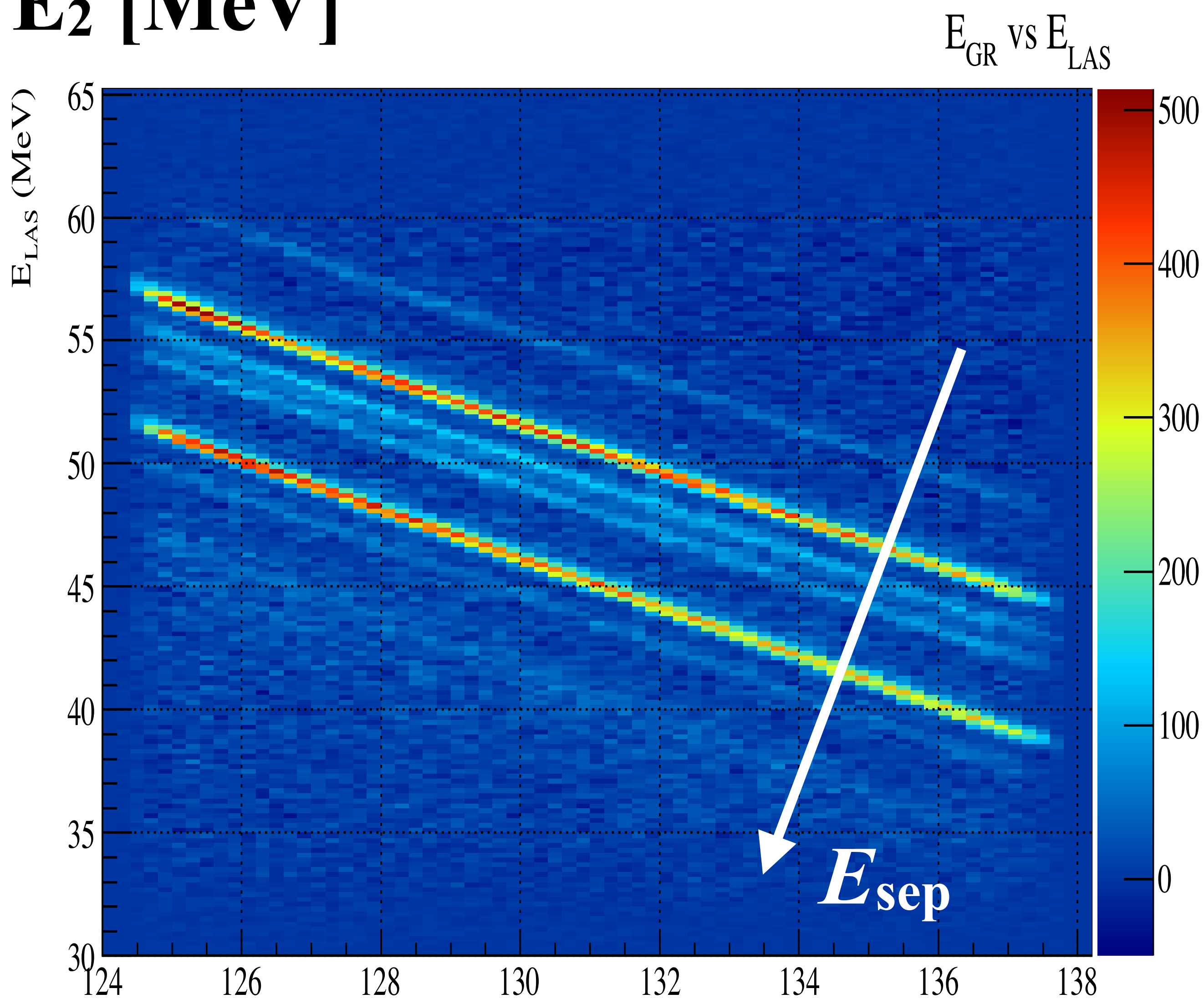
P. Kinching et al., NPA 340 (1980) 423.

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

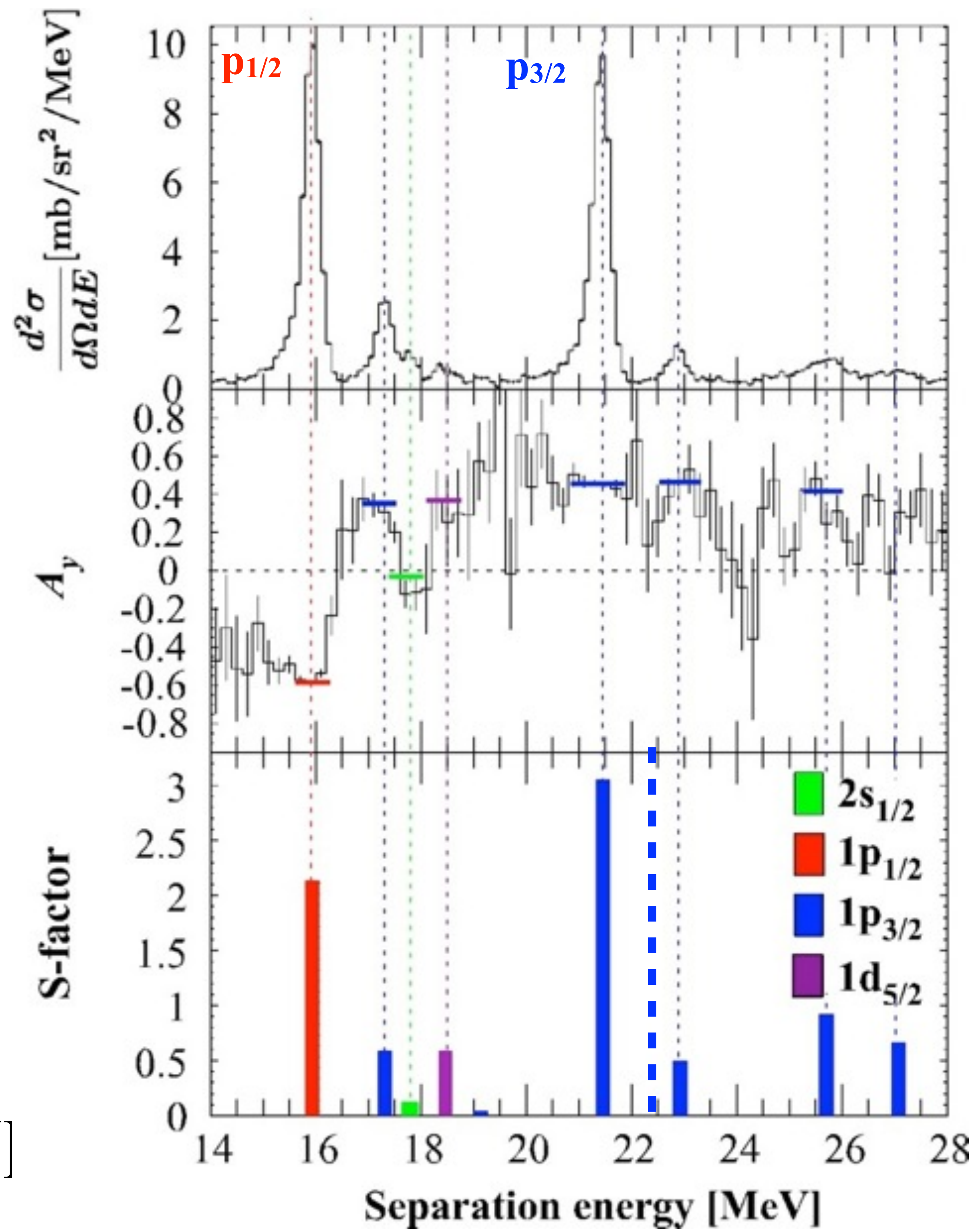
Kawase, TU et al.

$^{18}O(p,2p)^{17}N$ @ 200 MeV

E$_2$ [MeV]



E$_1$ [MeV]



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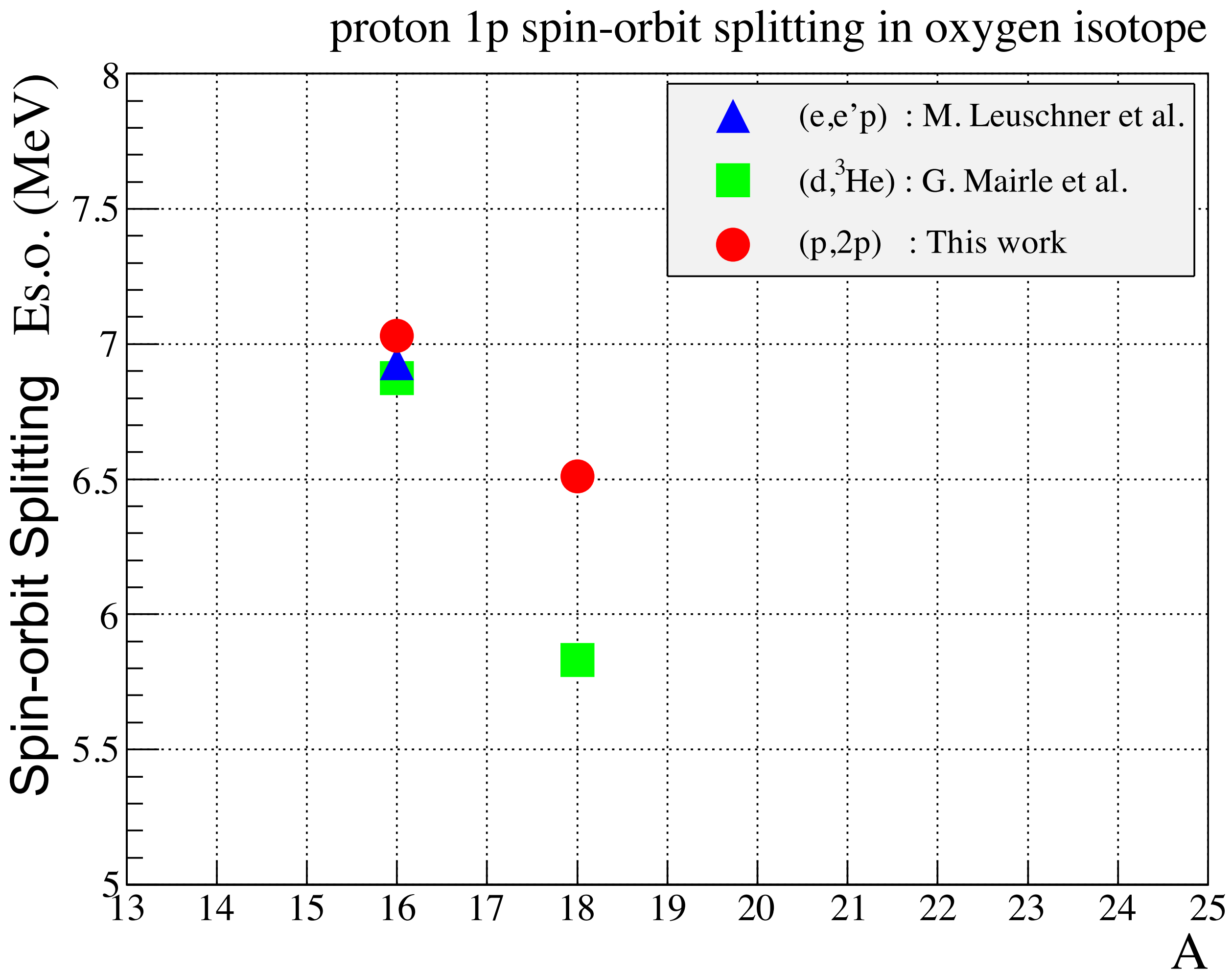
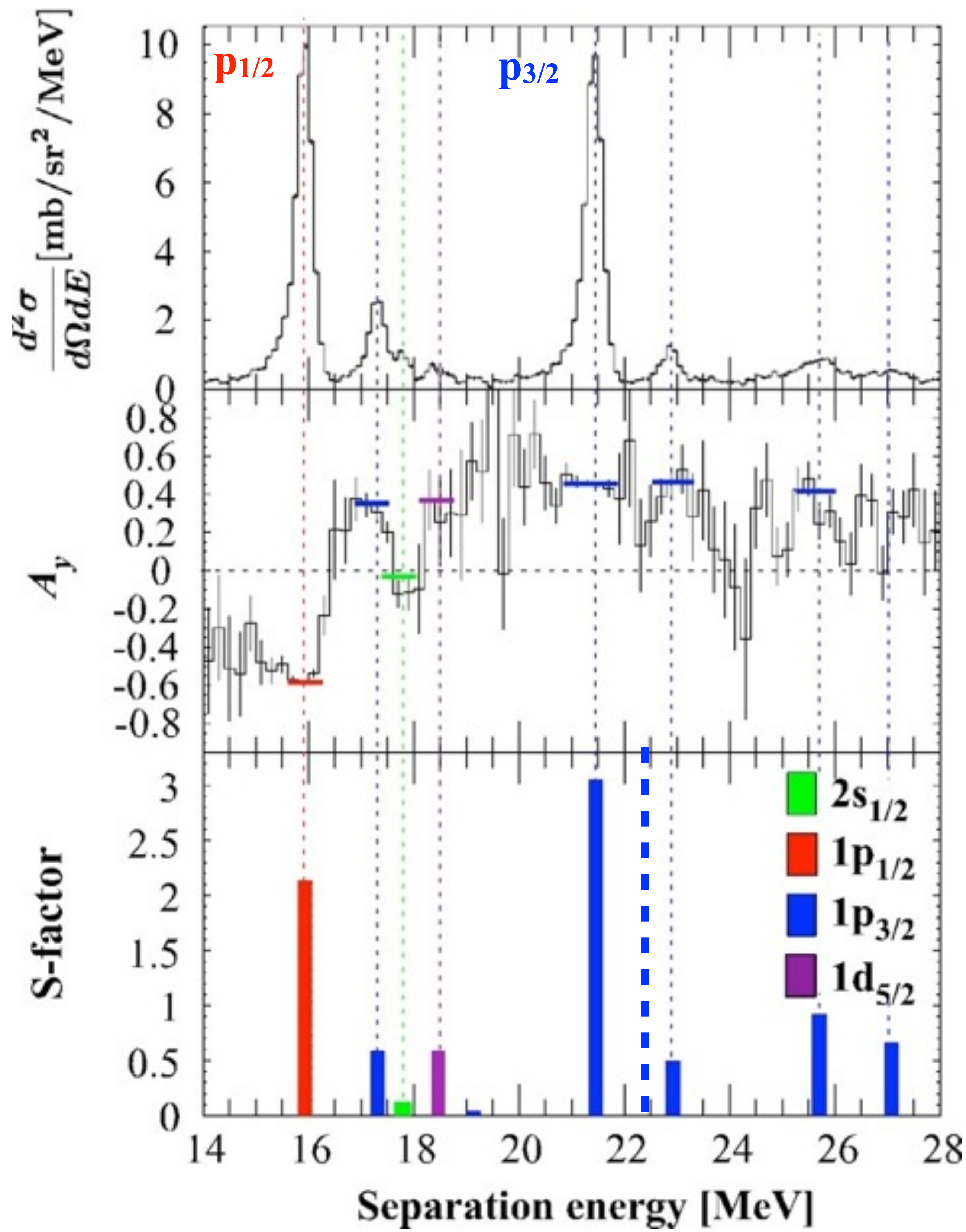


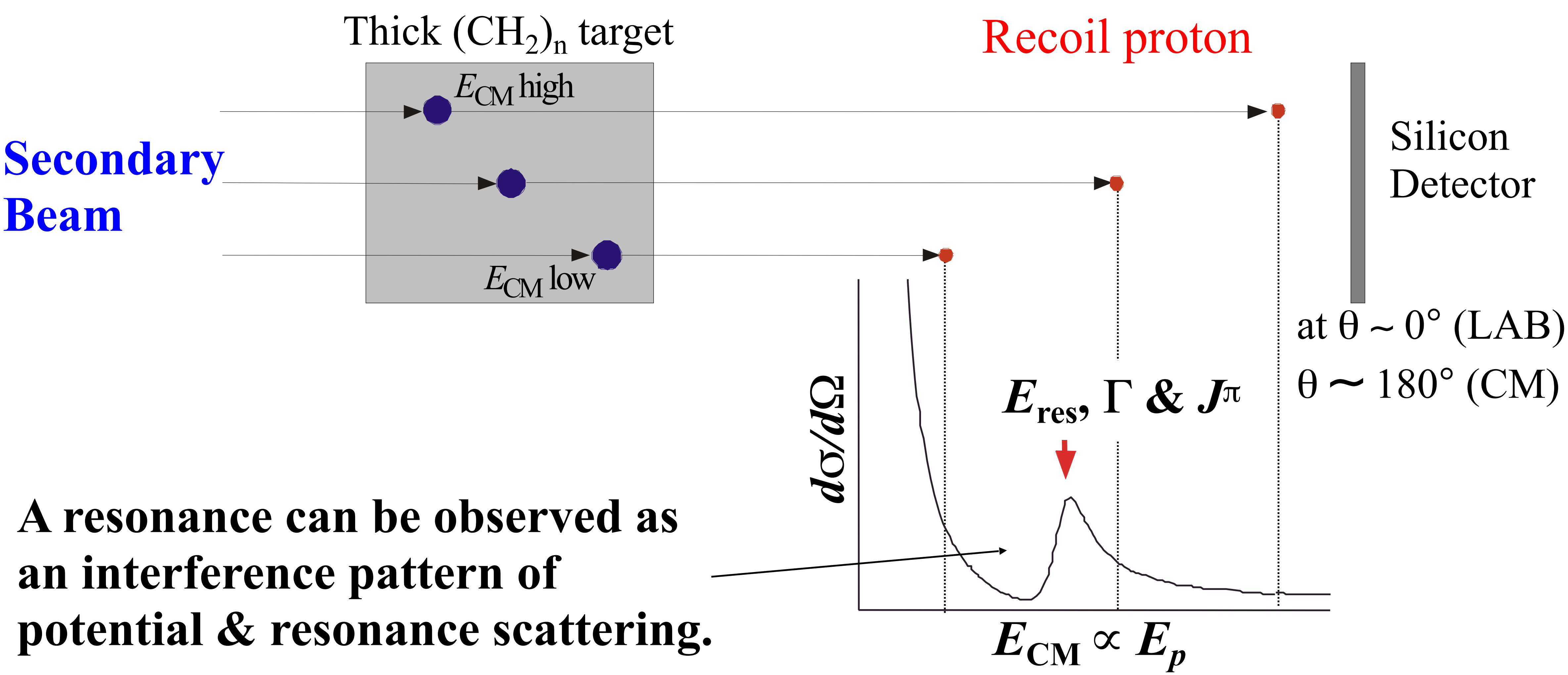


Proton resonant scattering of unstable nuclei

Low-energy secondary beams of < ~5 MeV/nucleon

Thick Target method in Inverse Kinematics (TTIK)

- **Excitation function can be obtained by using beam energy loss in the thick target**
- **Detection of recoil protons at forward angles**



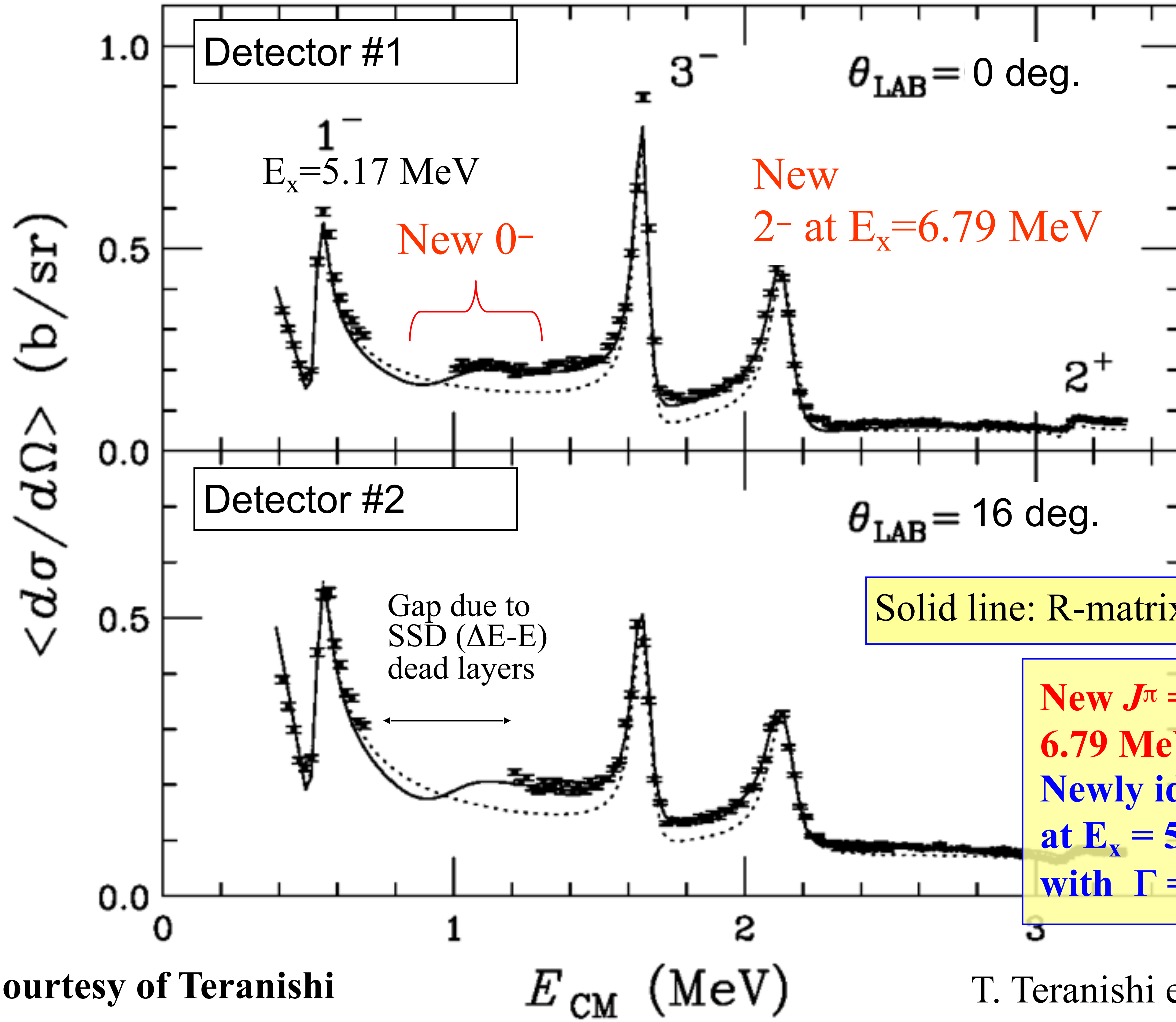
A resonance can be observed as an interference pattern of potential & resonance scattering.

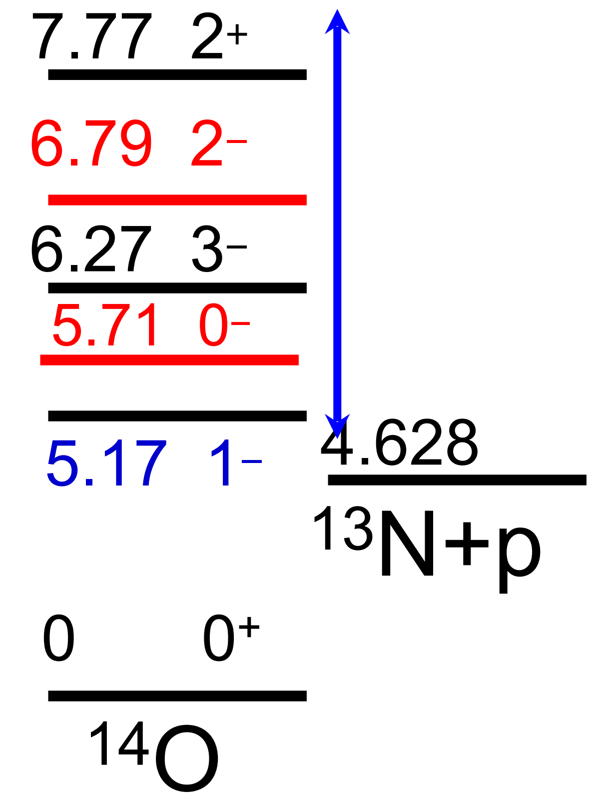
Courtesy of Teranishi

V.Z. Goldberg and A.E. Pakhomov, Phys. At. Nucl. 56, 1167 (1993).

Example: ^{13}N+p experiment at CRIB/CNS

E_x =
5—8 MeV





Solid line: R-matrix fitting → E_x, Γ, J^π

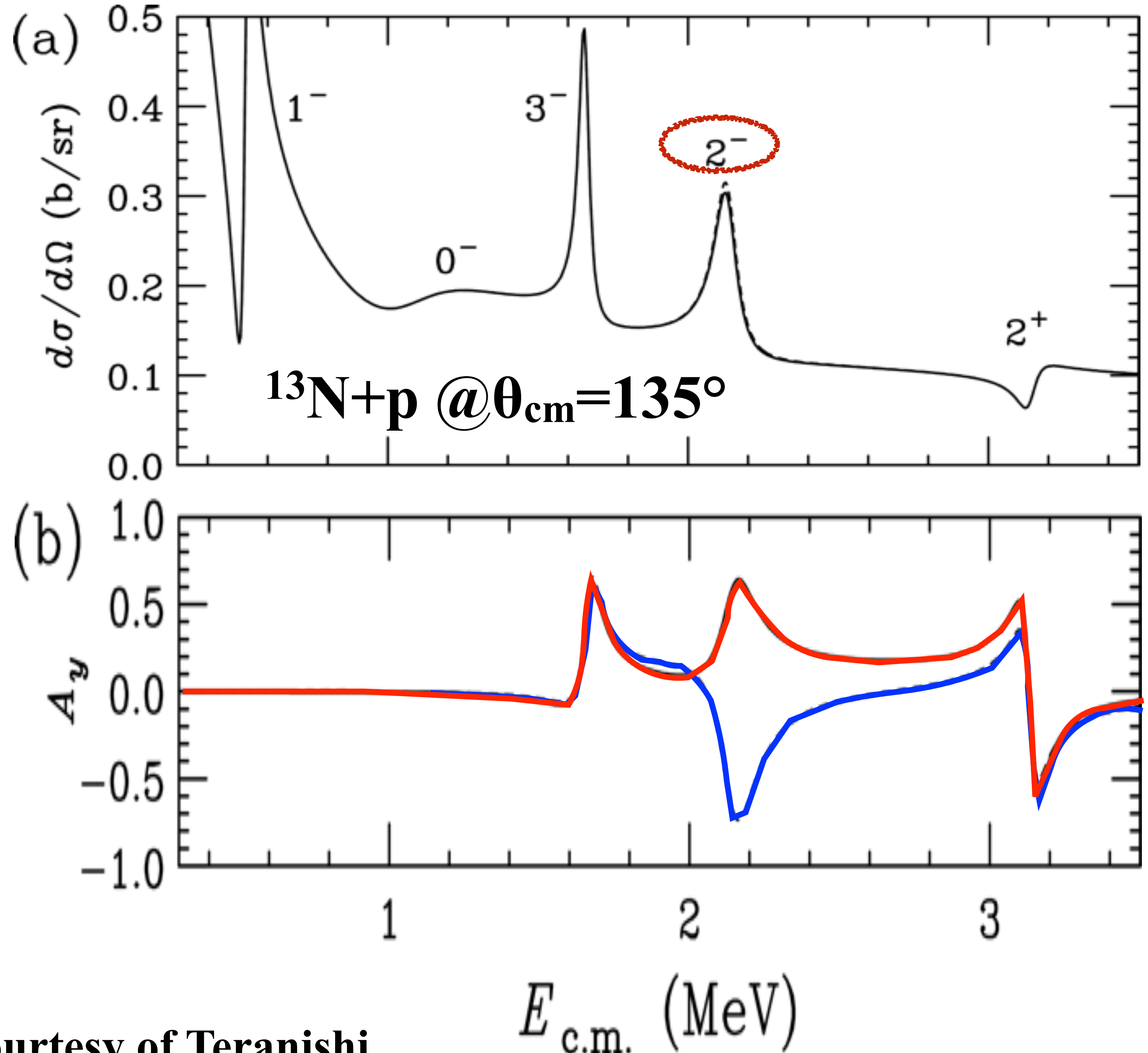
New J^π = 2⁻ assignment for 6.79 MeV level.
Newly identified 0⁻ level at E_x = 5.71(2) MeV with Γ = 400(100) keV

Courtesy of Teranishi

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

Polarization in Resonant Scattering

Sensitivity test with R-matrix calculations



Two possibilities:

1) $^{13}N(1/2^-) + \pi d_{5/2}$
2) $^{13}N(1/2^-) + \pi d_{3/2}$

No difference in cross section . . .

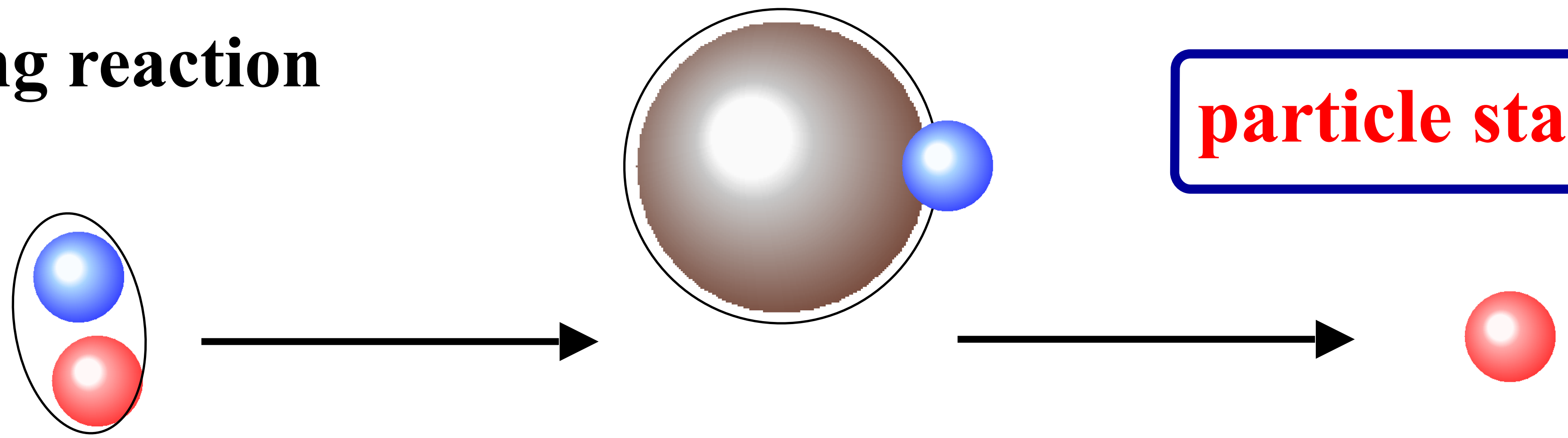
A_y is sensitive to the configuration!

T. Teranishi, S. Sakaguchi et al., AIP Conf. Proc. 1525, 552 (2013)

Courtesy of Teranishi

Transfer reactions

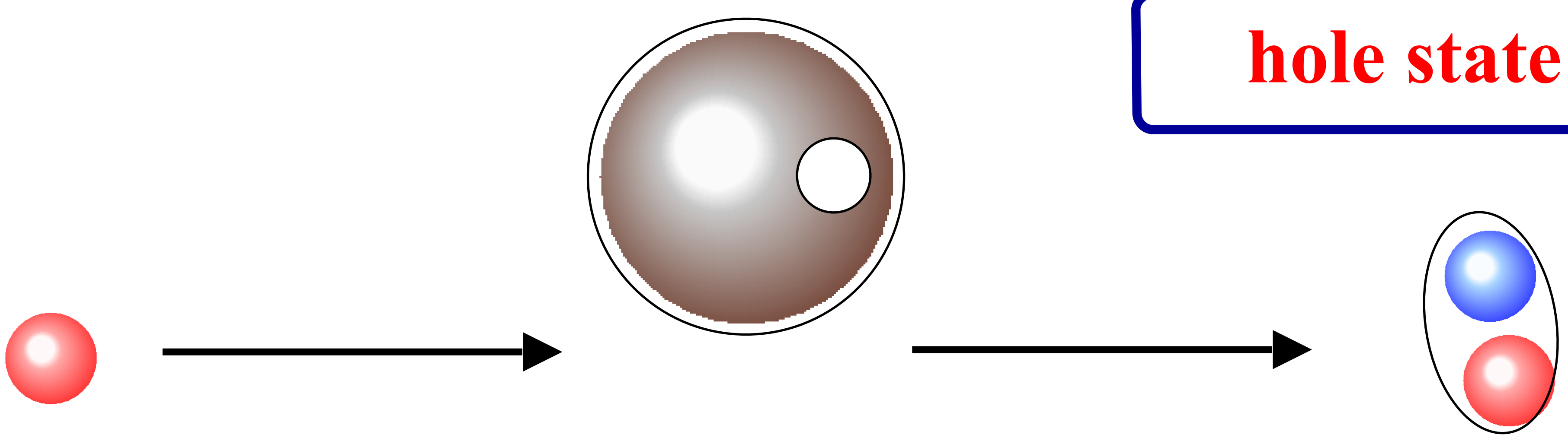
Stripping reaction



particle state

(d,p), (d,n), (^{3}He,d), (^{4}He, t/^{3}He)

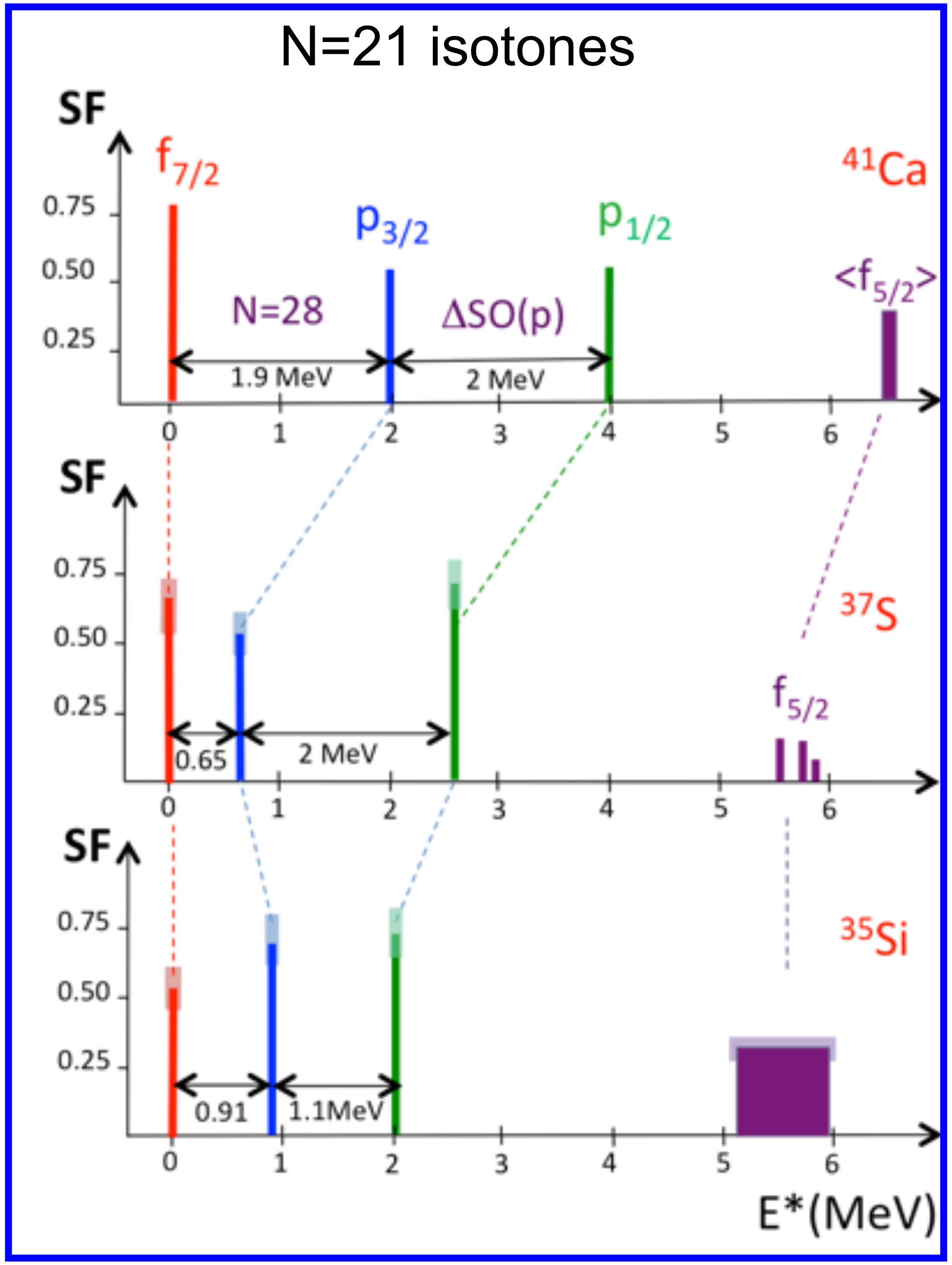
Pickup reaction

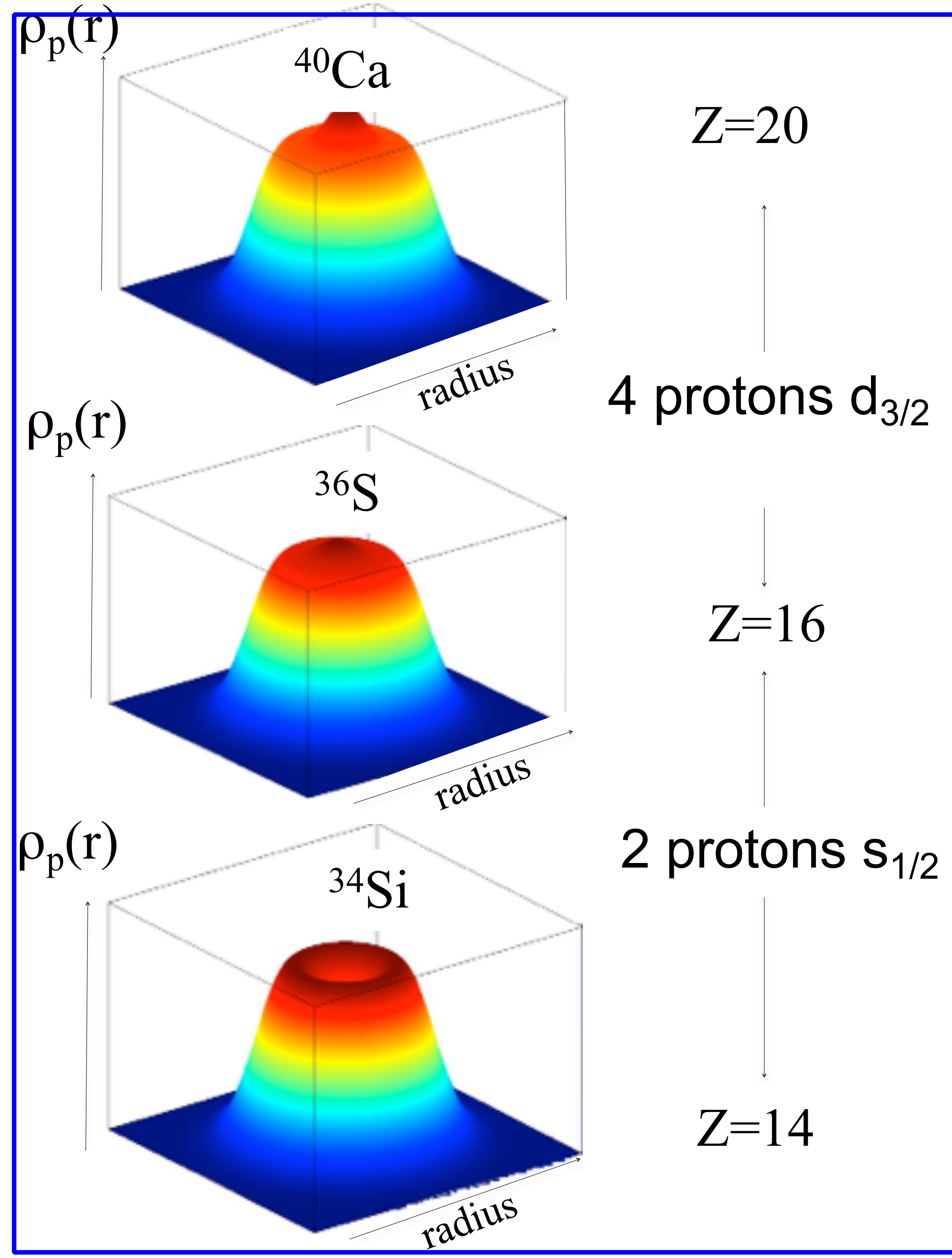


hole state

(p,d), (n,d), (d, ^{3}He), (^{3}He, ^{4}He)

Evolution of the $p_{3/2}$-$p_{1/2}$ SO splitting





No change in $p_{3/2}$-$p_{1/2}$ splitting between ^{41}Ca and ^{37}S

Large reduction of $p_{3/2}$-$p_{1/2}$ splitting between ^{37}S and ^{35}Si, no change of $f_{7/2}$-$f_{5/2}$

Courtesy of Sorlin

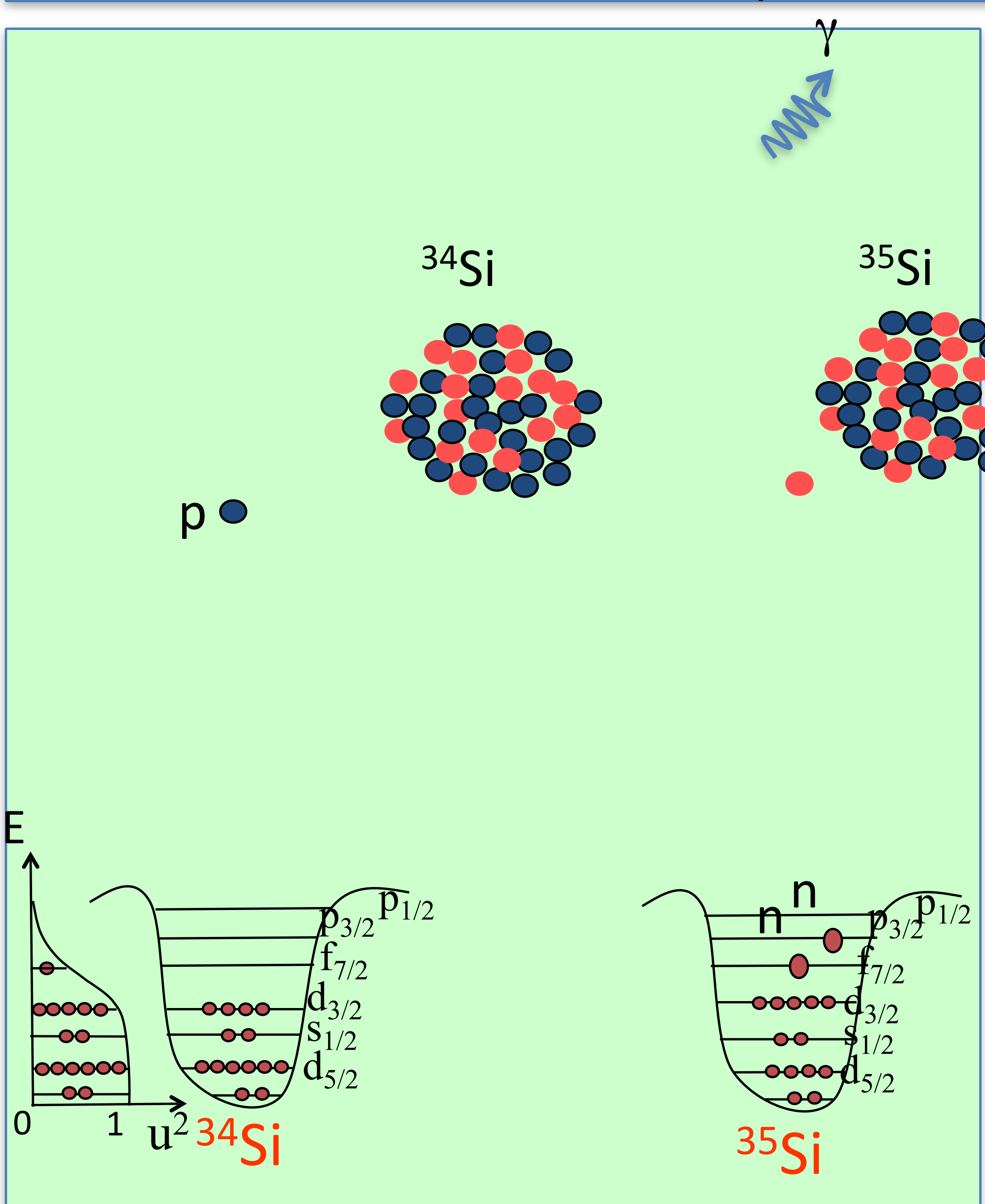
G. Burgunder et al., Phys. Rev. Lett. 112, 042502 (2014)

^{34}Si(d,p) reaction in inverse kinematics at GANIL

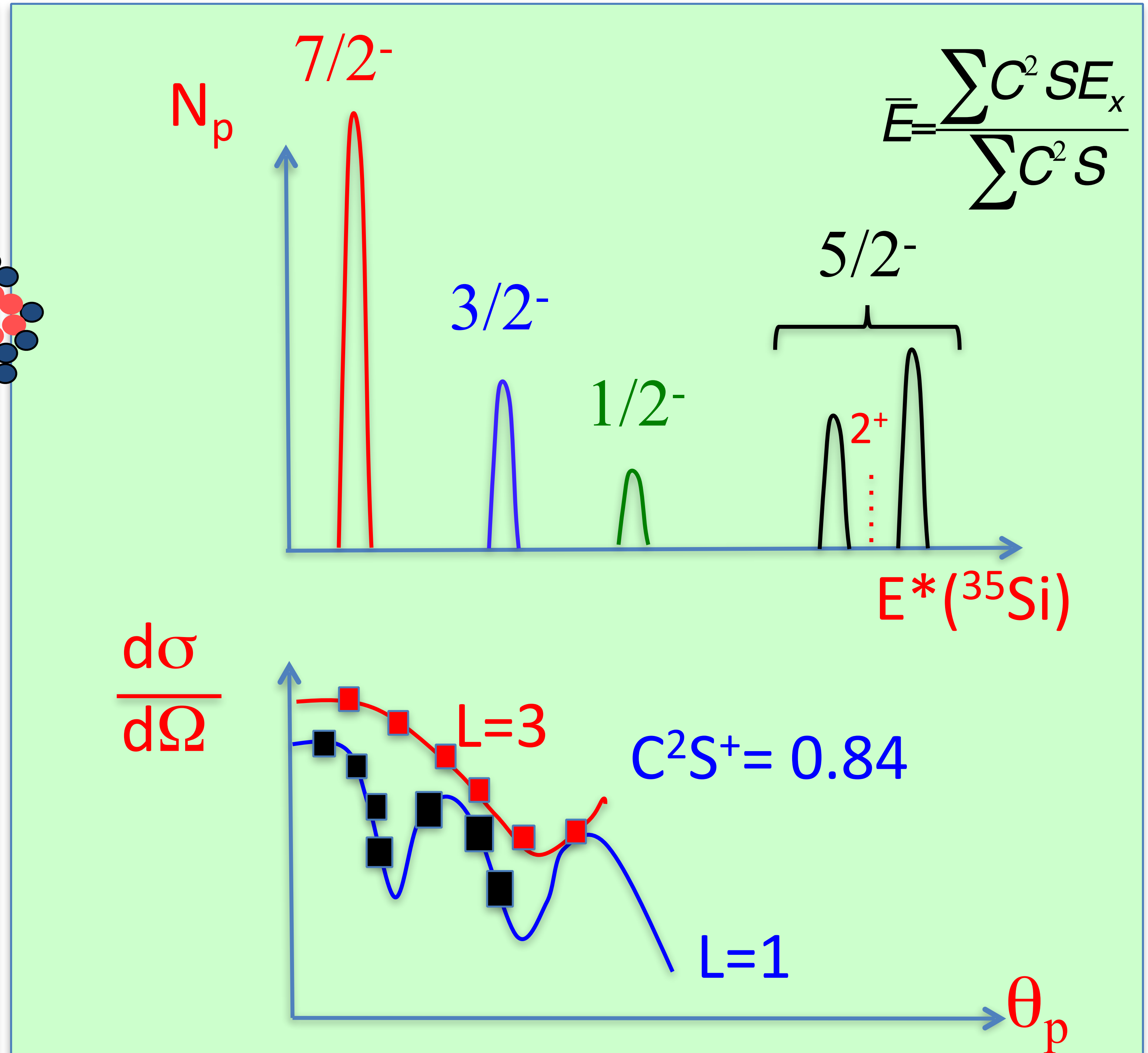
Transfer reaction (d,p) at $\beta \approx 0.15$

$$\frac{d\sigma(n,L,\theta)}{d\Omega} = \underbrace{(2j+1)\, C^2S^+}_{\textit{vacancy}} \; \underbrace{\frac{d\sigma_{AWBA}(n,L,\theta)}{d\Omega}}_{\textit{reaction theory}}$$

Proton energy -> (binding) energy of orbit
Proton angle -> orbital momentum L
Cross section -> vacancy of the orbit
Appropriate momentum matching required



Courtesy of Sorlin



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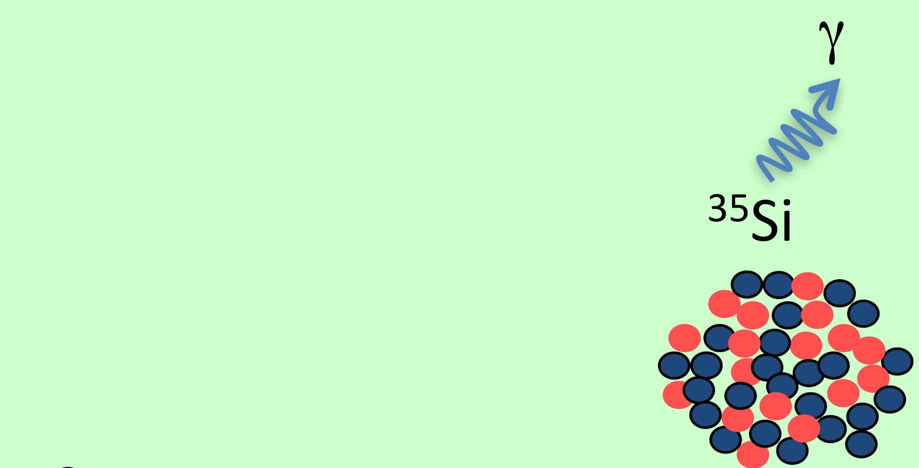
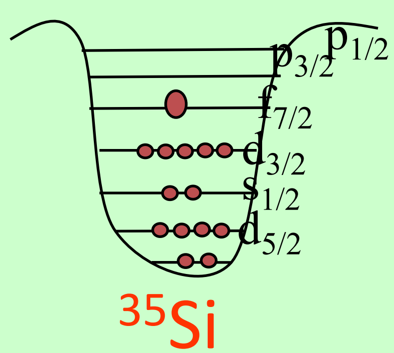
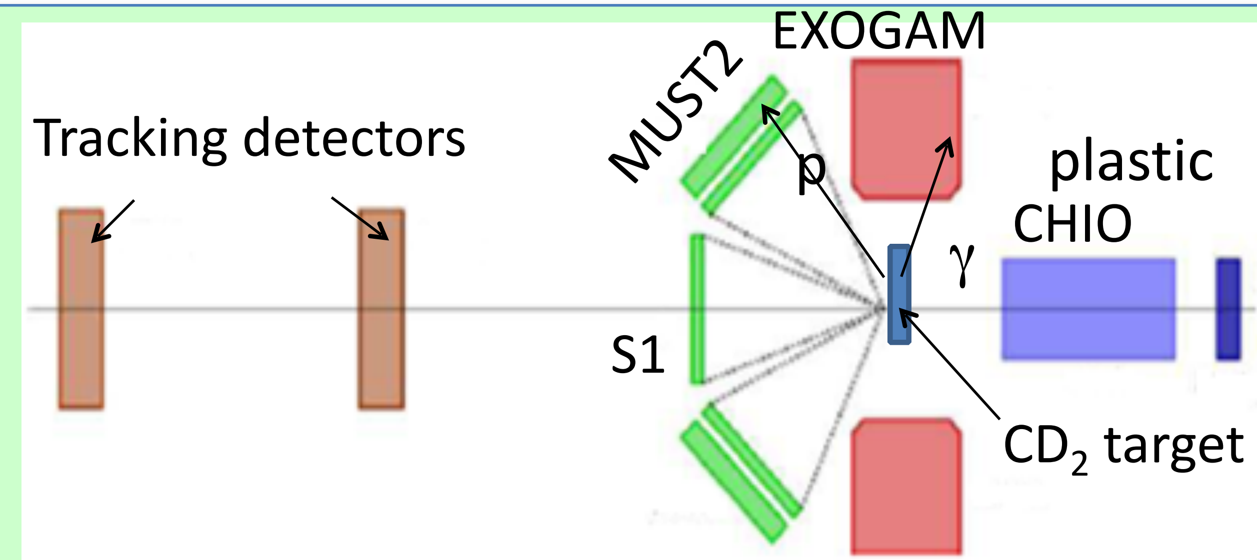
vacancy *reaction theory*

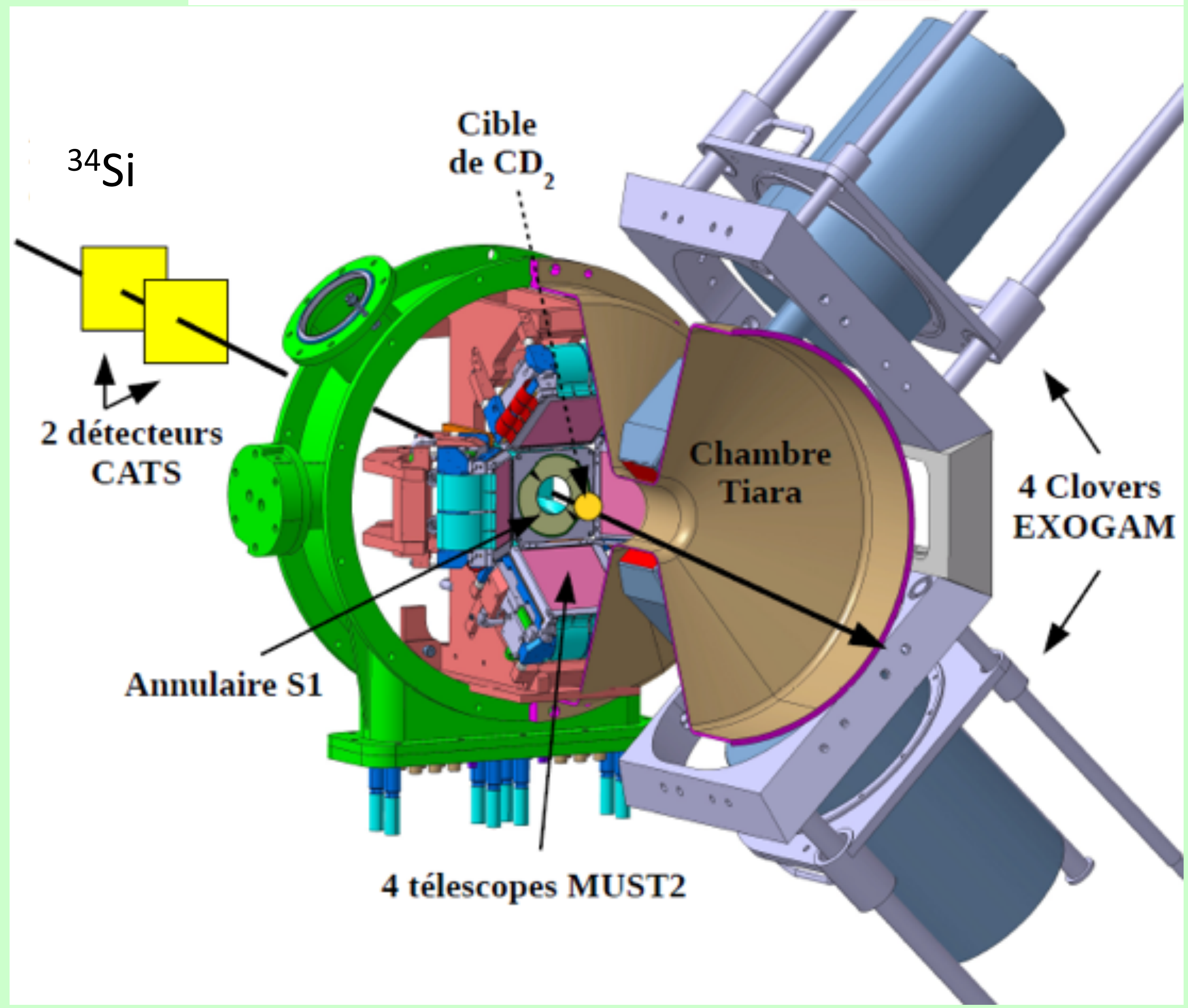




Courtesy of Sorlin

^{34}Si
10^5pps
20A.MeV
GANIL





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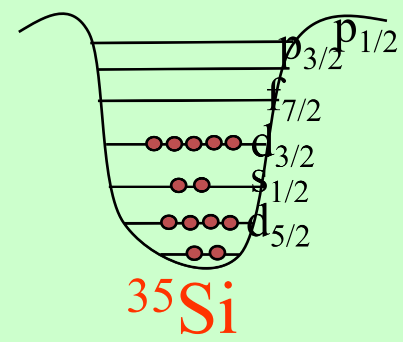

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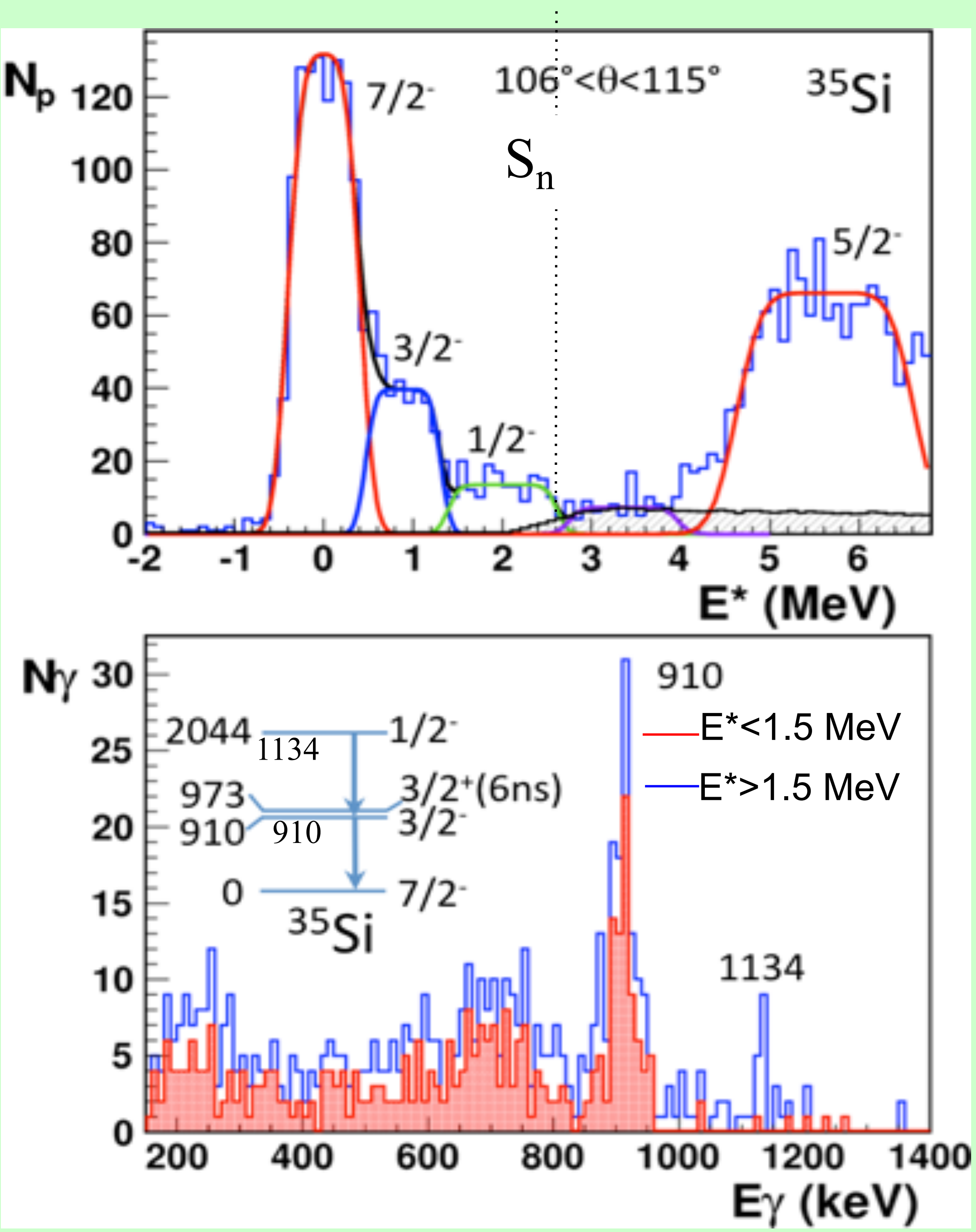
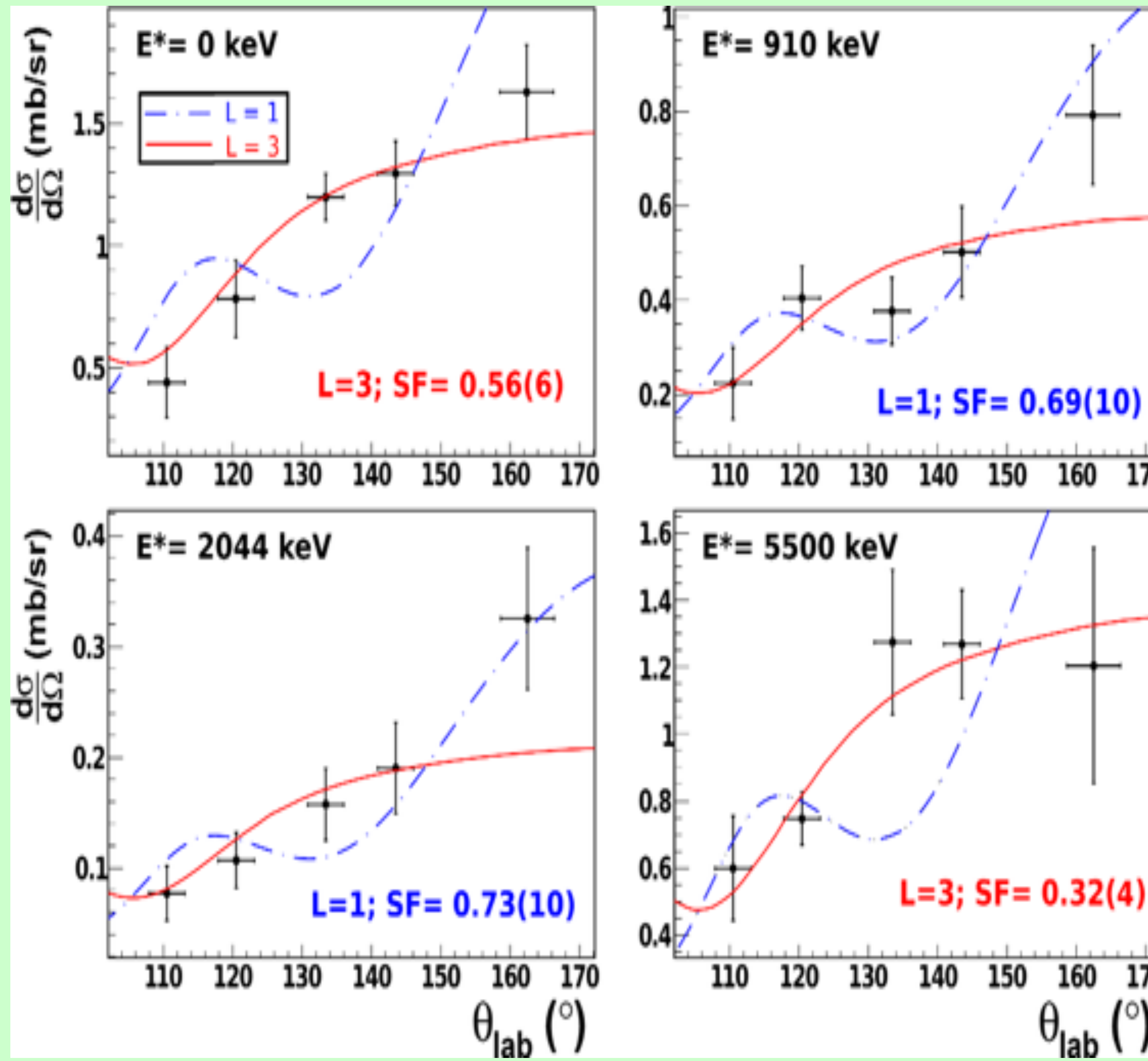




Polarization in transfer reactions

Major a

So far no polarization exp. has been done for transfer reaction of RI-beams.

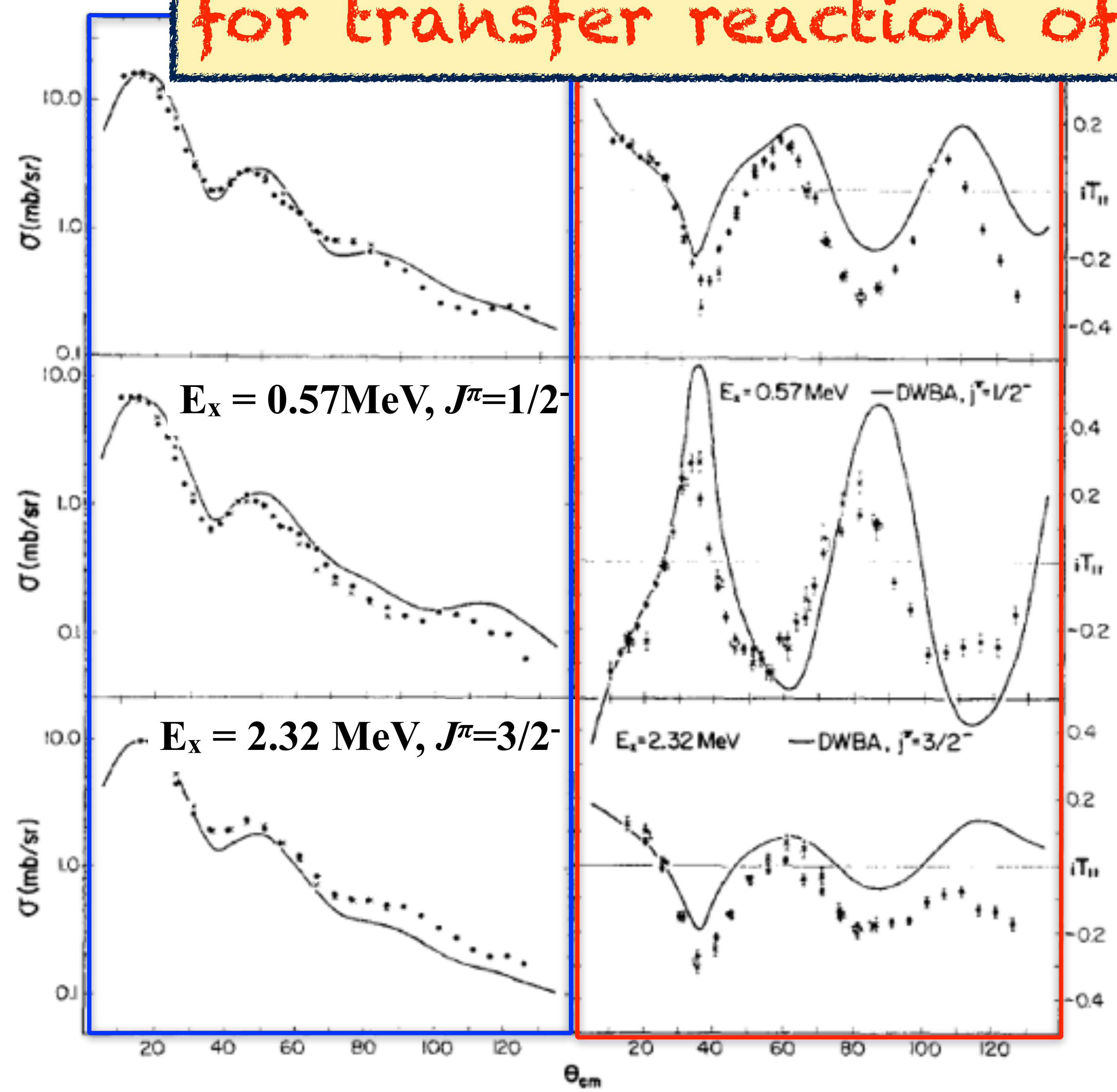


Fig. 2. Cross sections and vector analysing powers for $l_n = 1$ transitions in ^{52}Cr(d, p)^{53}Cr leading to final states of known spin. Solid symbols are data taken with poor resolution and crosses are data taken with good resolution.

dσ/dΩ:

Shape is almost same if ΔL is the same (ΔL=1 in the present case)

A_y (polarization data):

Phase is opposite depending on $J = L \pm 1/2$

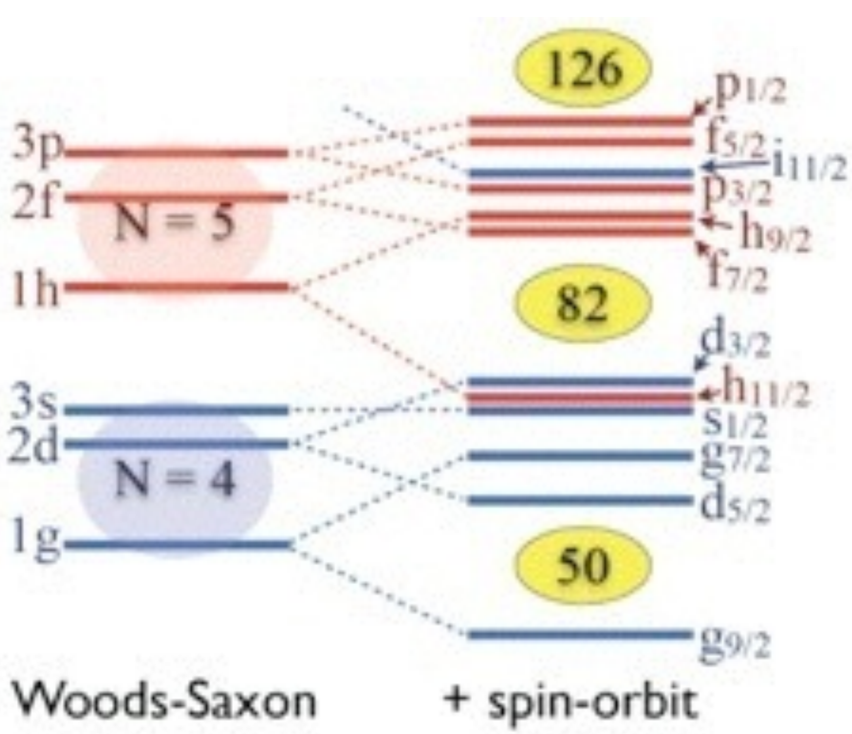
D.C. Kocher and W.Haeberli, Nucl. Phys. A 196, 225 (1972)

My First Message

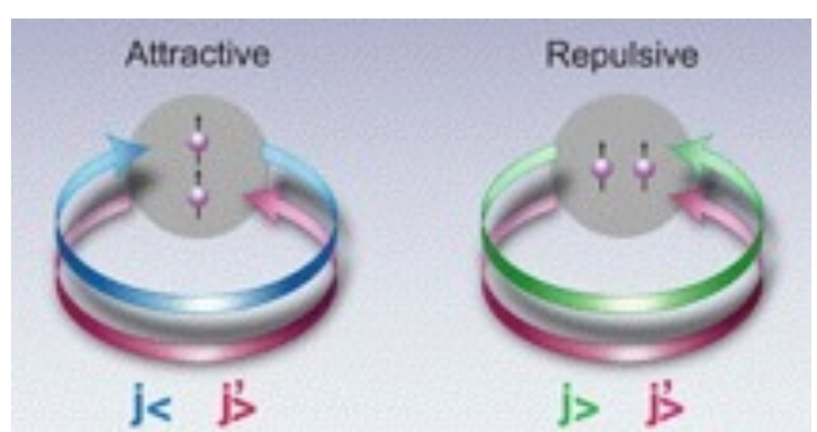
30-years research with radioactive isotope beams has revealed that "spin" plays more vital roles in exotic nuclei than expected!

Richness in nuclear structure is a manifestation of interplays among the spin-dependent interactions.

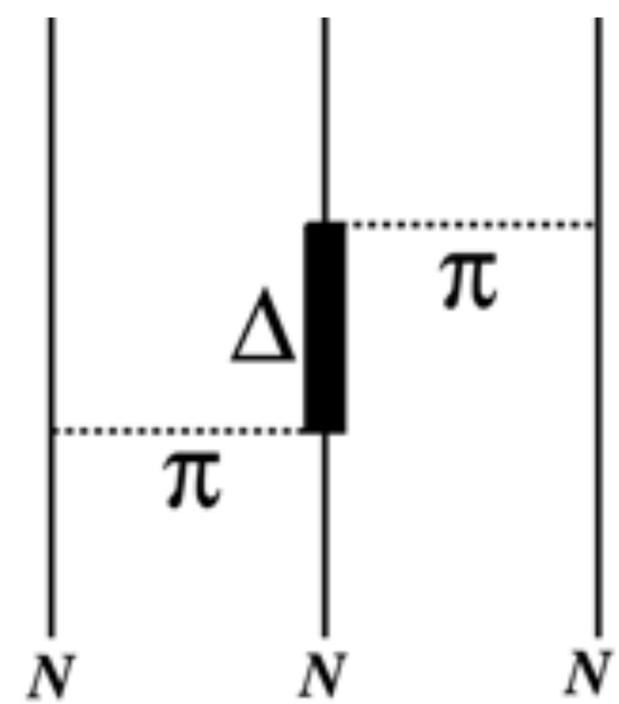
Spin-orbit force



Tensor force (pion exchange)

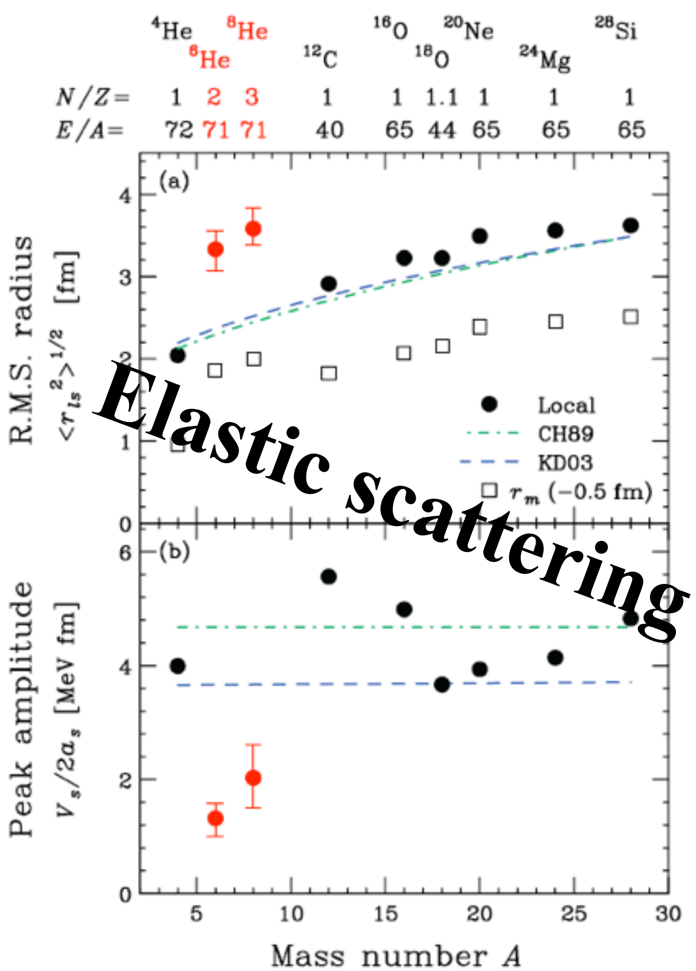


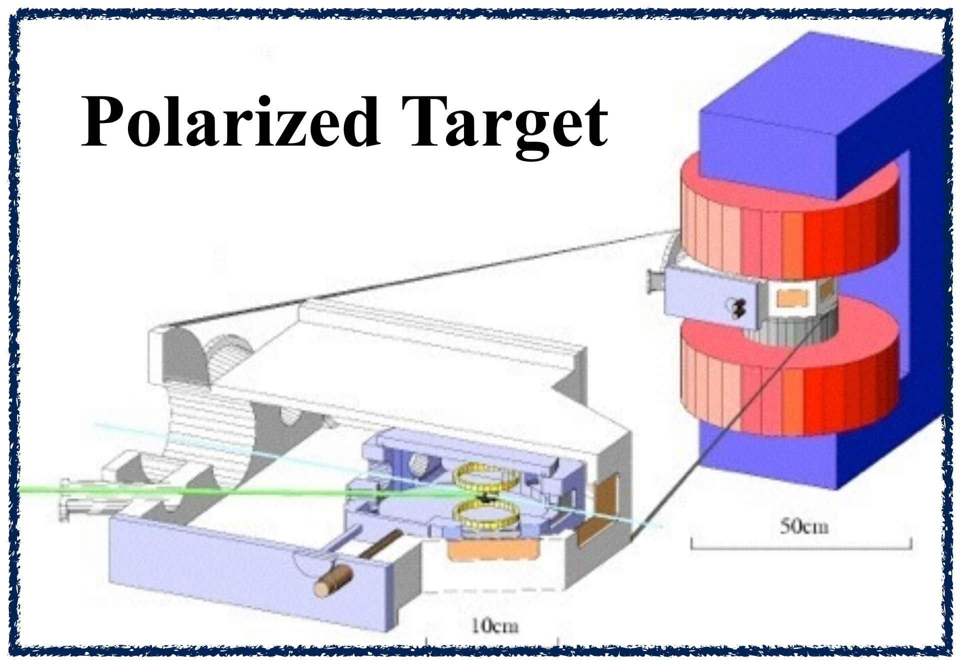
3N force



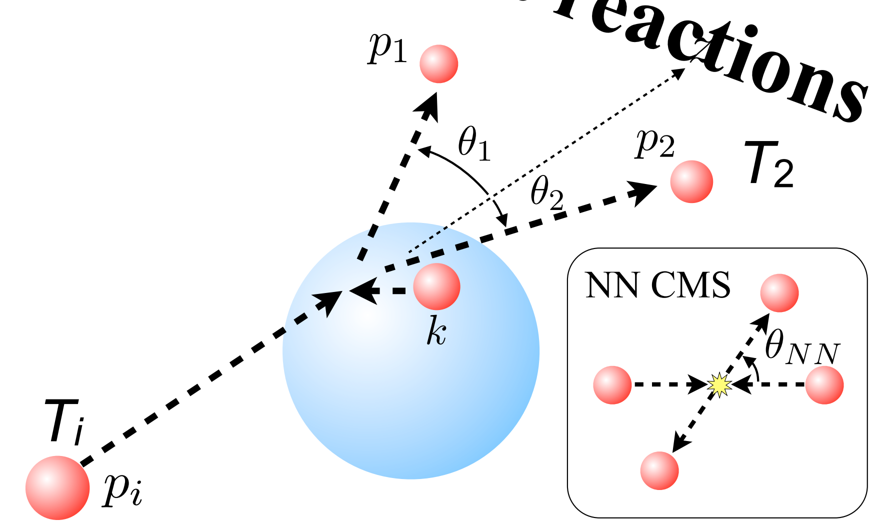
My Last Message

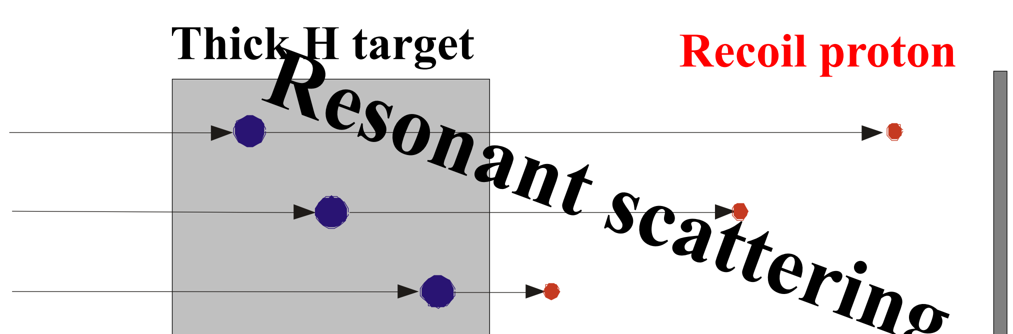
Experiments with polarized targets are essential in clarifying roles played by spin degrees of freedom in exotic nuclei.





Knockout reactions





Transfer reactions

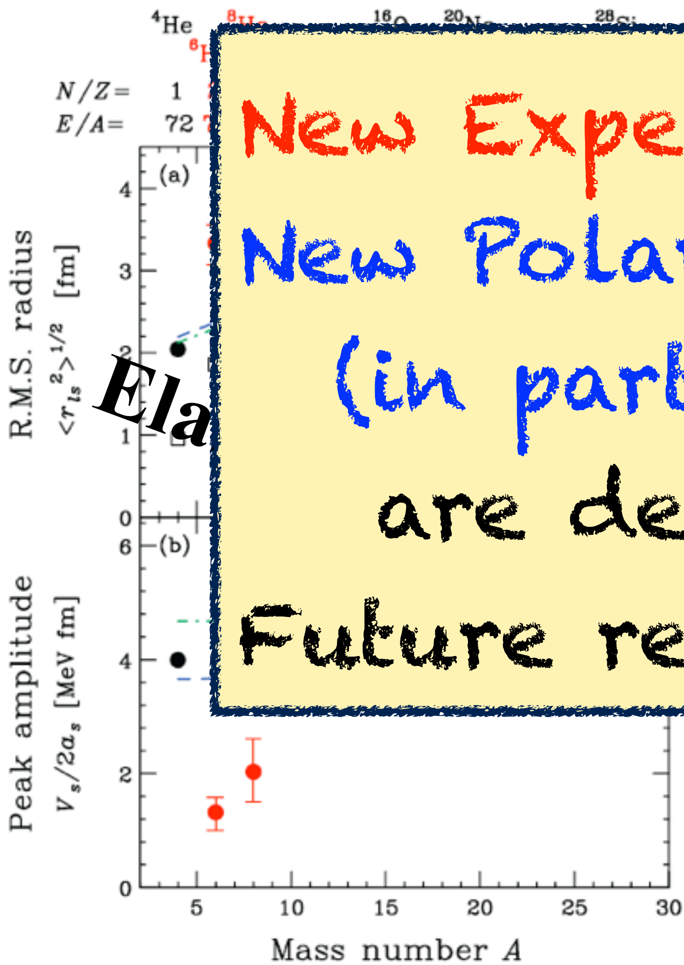
My Last Message

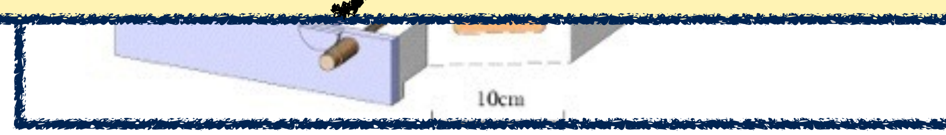
Experiments with polarized targets are essential in clarifying roles played by spin degrees of freedom in exotic nuclei.

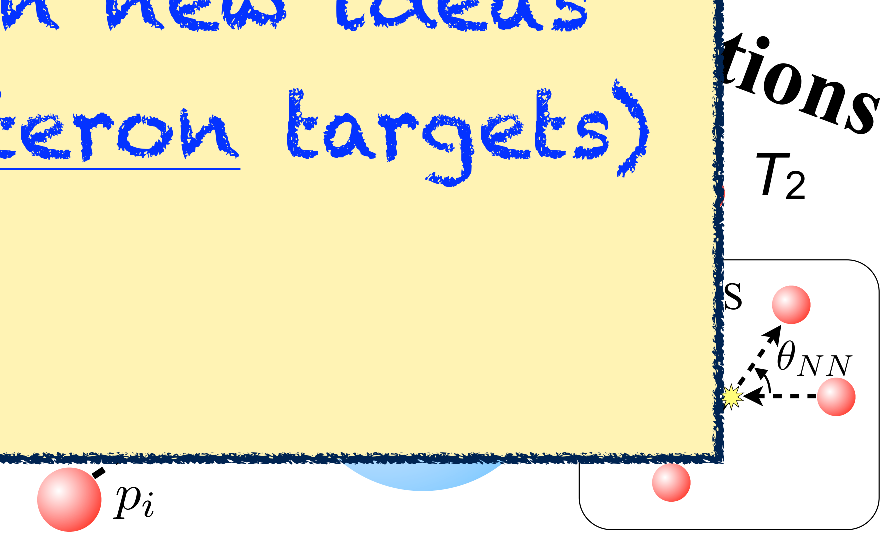
New Experiments

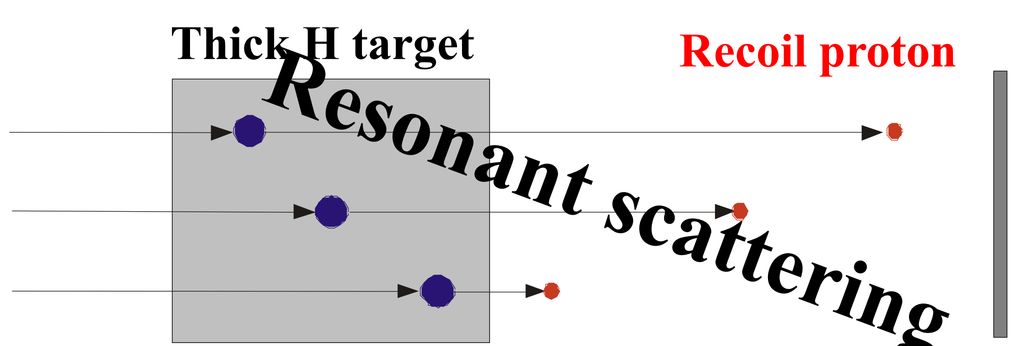
New Polarized Targets based on new ideas
(in particular polarized <u>deuteron</u> targets)
are definitely needed.

Future relies on you!









Transfer reactions