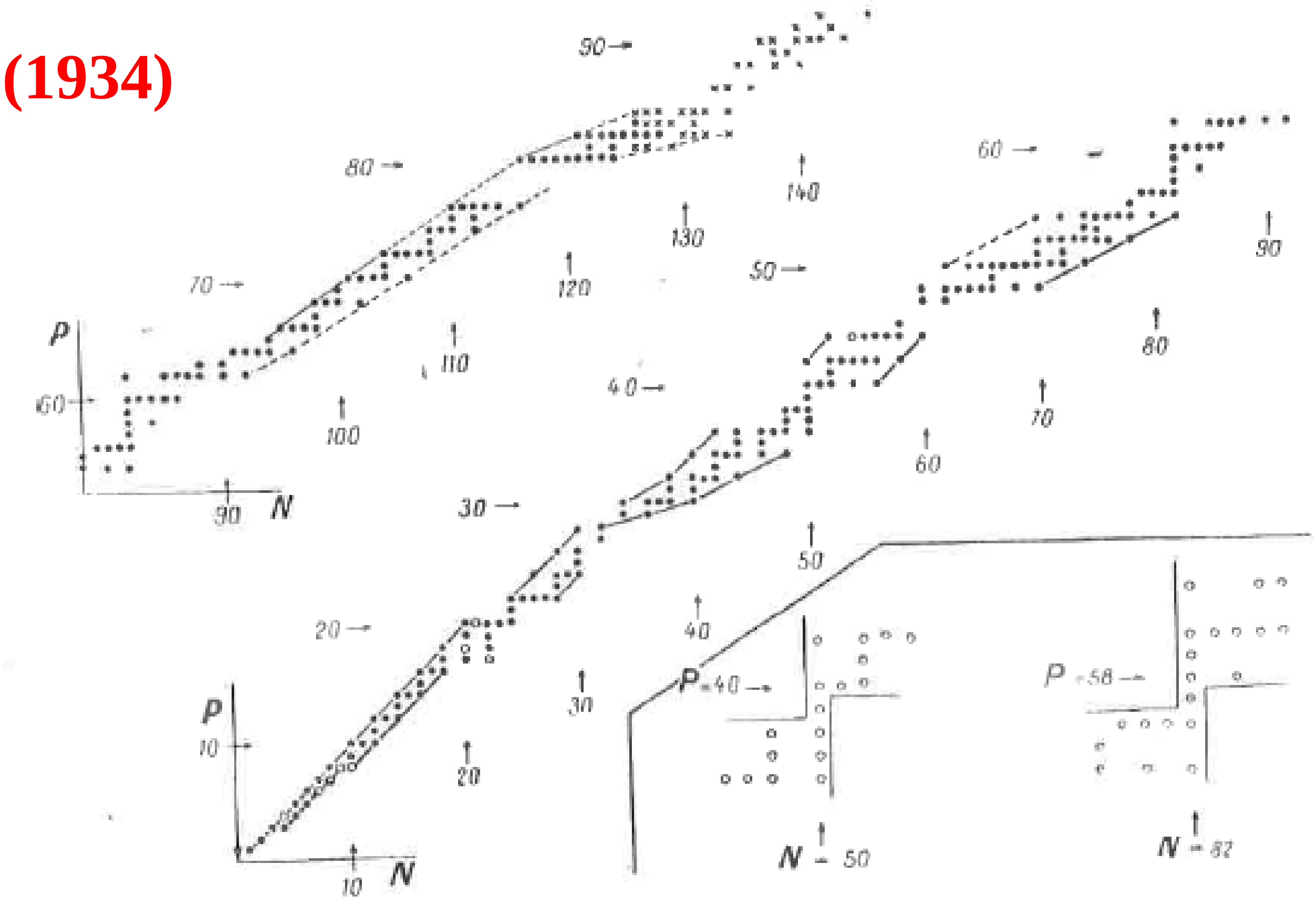
Spin in Nuclear Physics

Masaki Sasano
RIKEN Nishina Center for Accelerator-Based Science

At the beginning of nuclear physics.

Guggenheimer (1934)

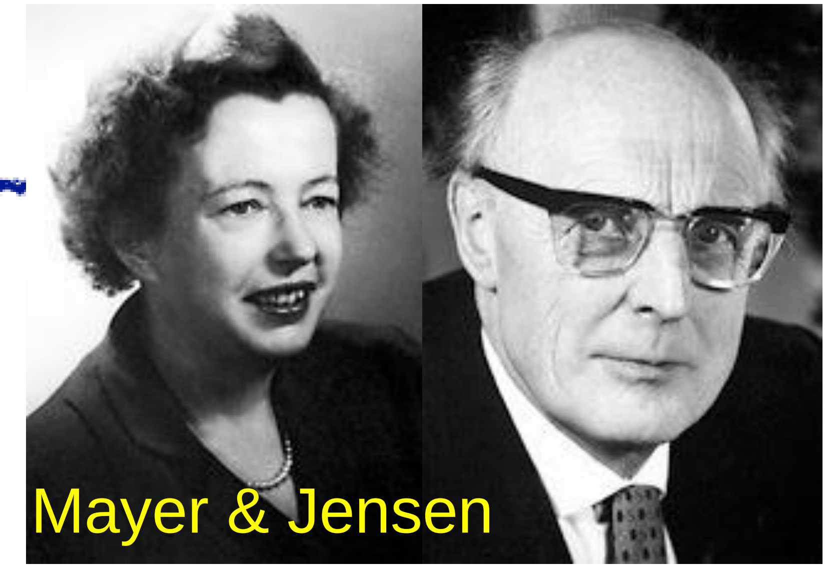


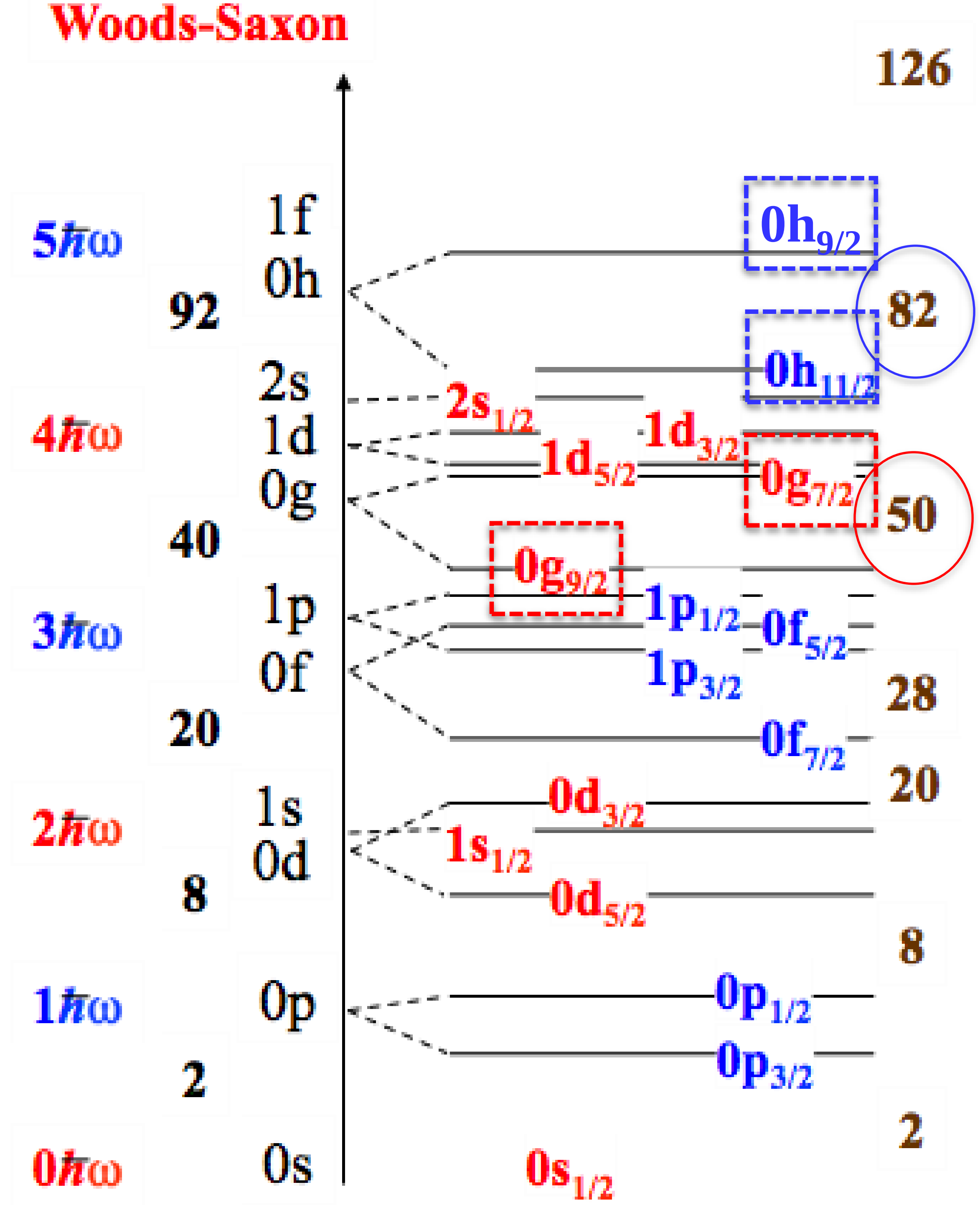
Basic ingredients are protons and neutrons (fermions), not α
Long isotonic chains of N=50 and 82 in natural abundance
→ Neutron magic number 50, 82
→ Do not exist in atomic shells

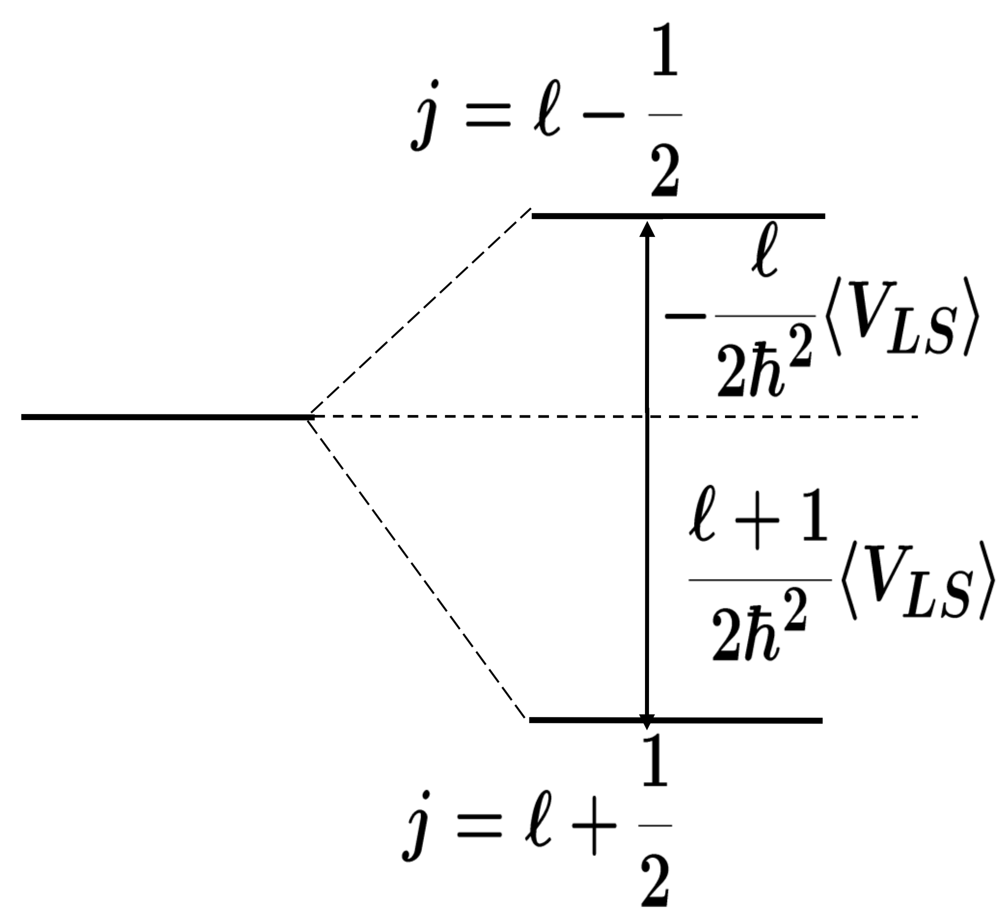
Cf. Isotope separation by mass separarator (Aston, 1919)
Discovery of neutron (Chadwick, 1932)

Strong Spin-Orbit Coupling

is essential in the formation of magic numbers in nuclei (1948)







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

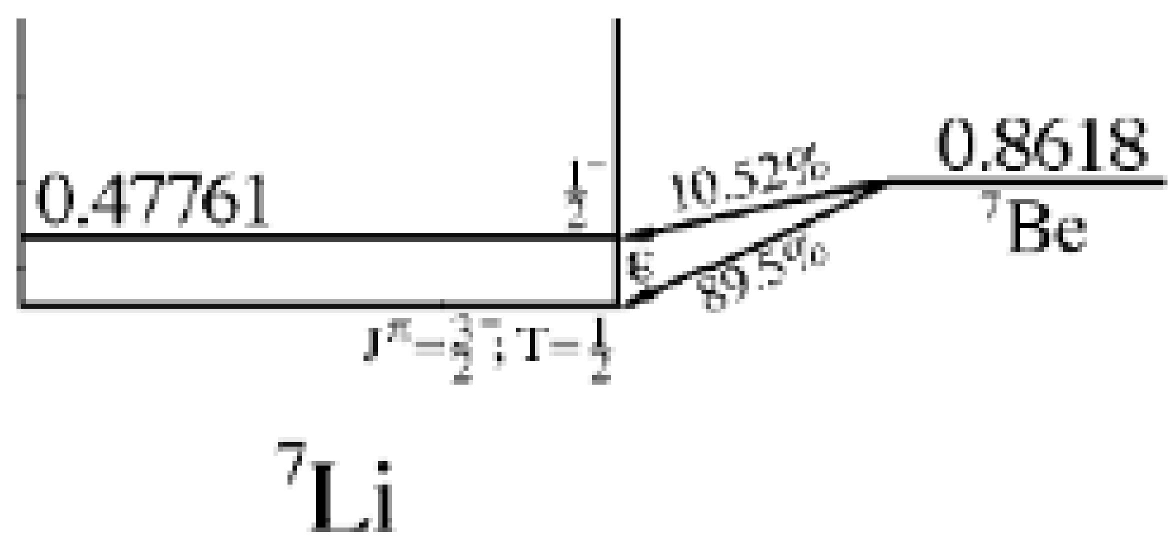
Also explains $J^\pi = l+1/2$ for g.s. of even-odd nuclei

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 case of that in atoms.

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

→ in inversion doublet
a state with J = L + 1/2
is more stable
than the case
by the Thomas effect



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

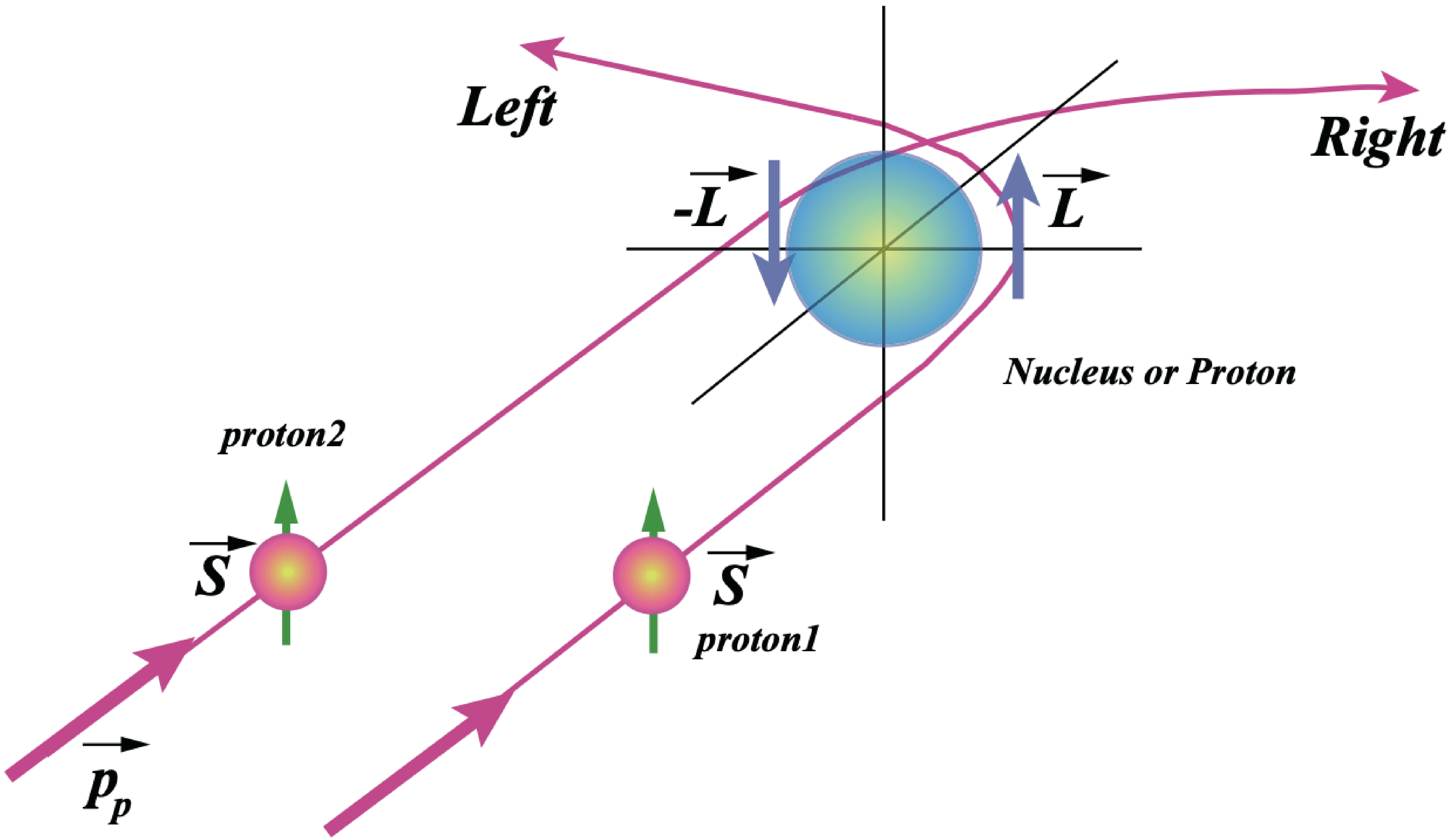
MARIA GOEPPERT MAYER
Argonne National Laboratory, Chicago, Illinois

(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.

Polarization experiment was necessary

Spin-orbit coupling in nuclear reaction

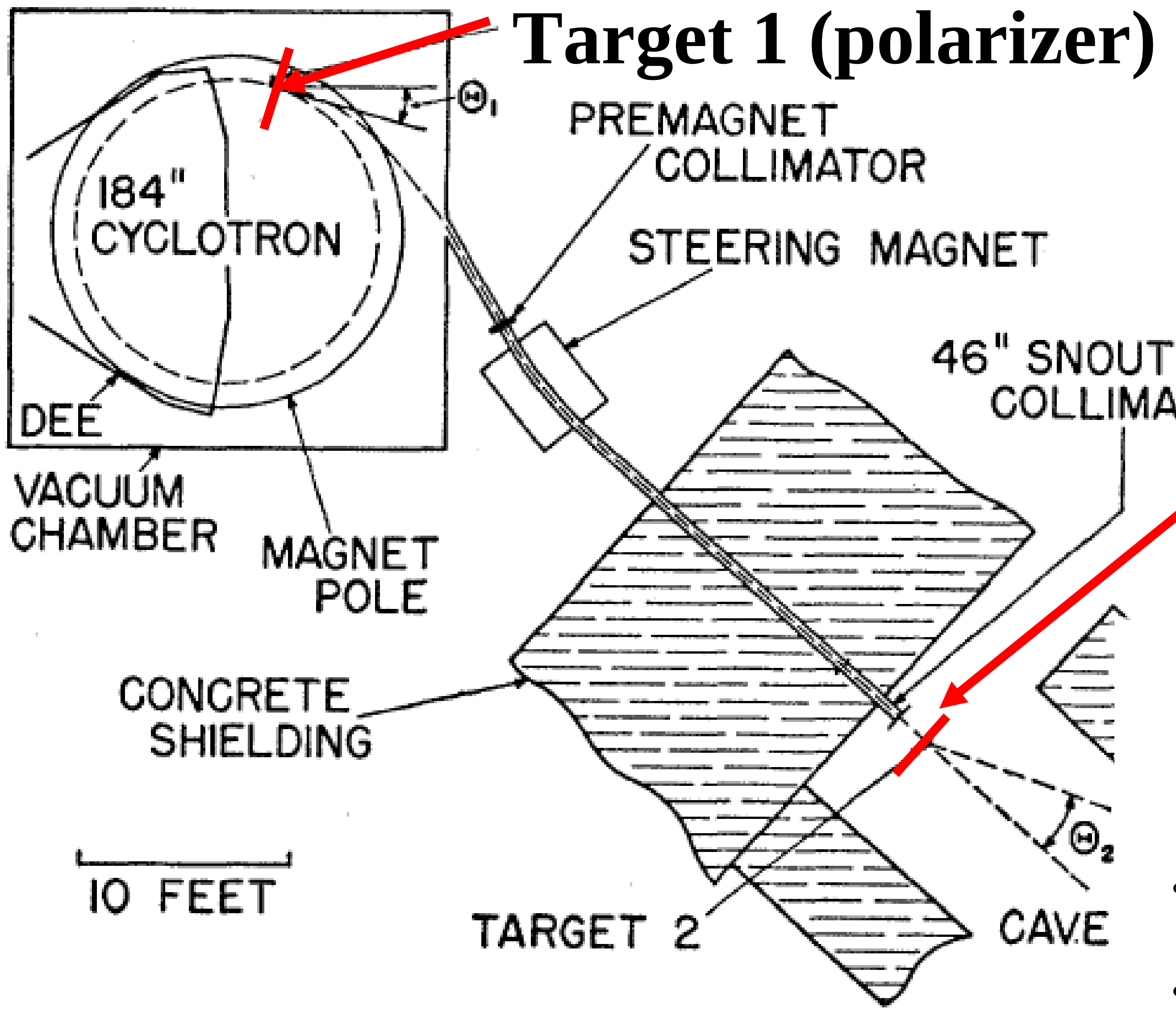


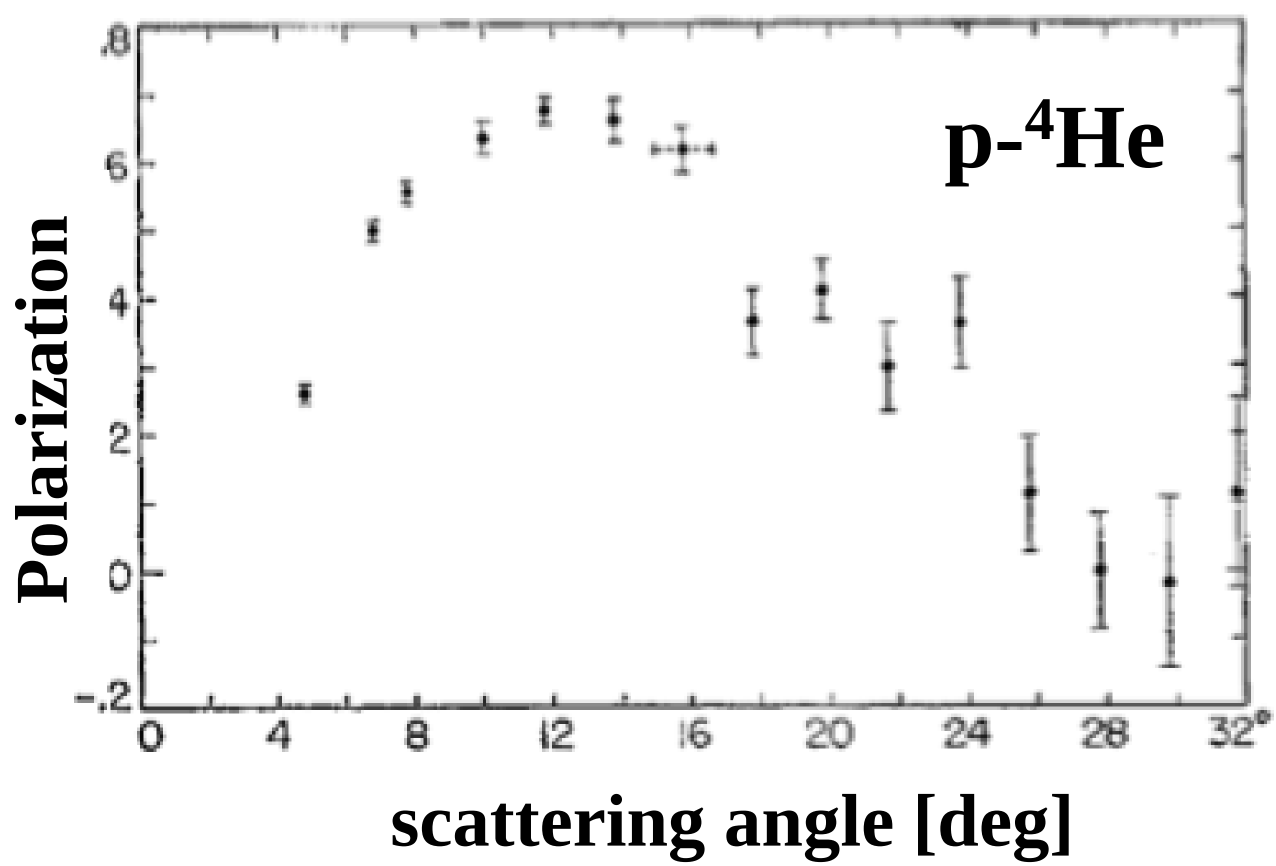
The FIRST Polarization Study

Double scattering method

O. Chamberlain et al.
Phys. Rev. 102 (1956) 1659.

Triple scatterings were also studied!





Direct evidence of spin-orbit force in nuclear scattering

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.

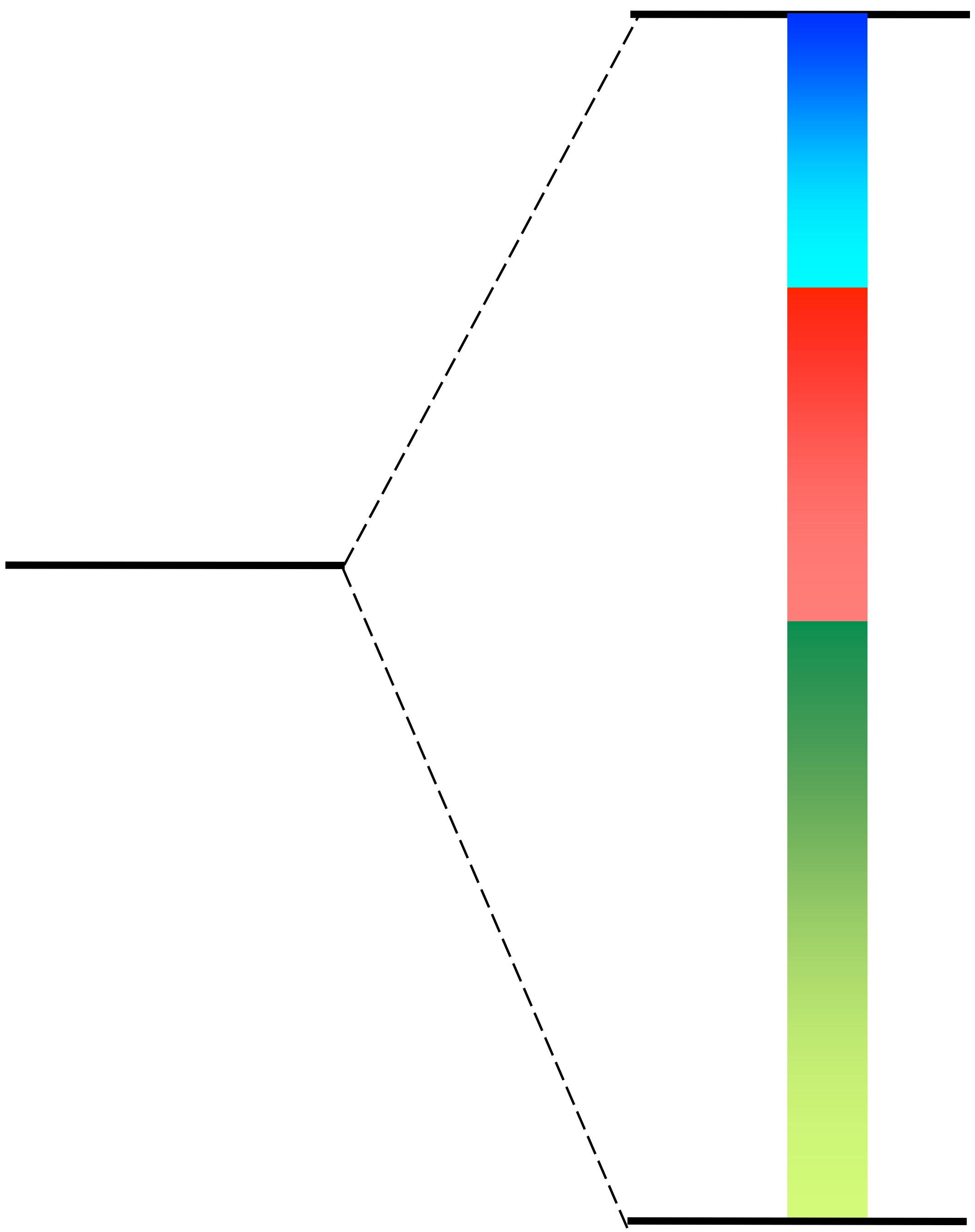
E. FERMI

University of Chicago - Institute for Nuclear Studies - Chicago

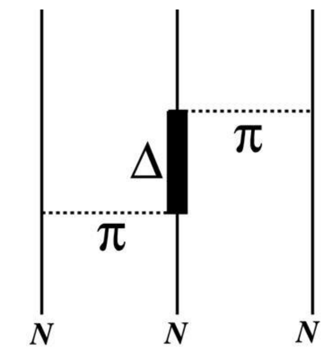
(ricevuto il 22 Febbraio 1954)

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.



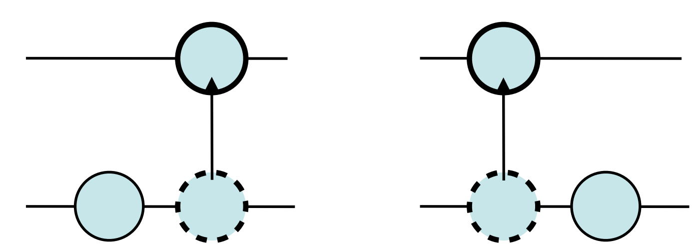
3N force



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

Tensor force

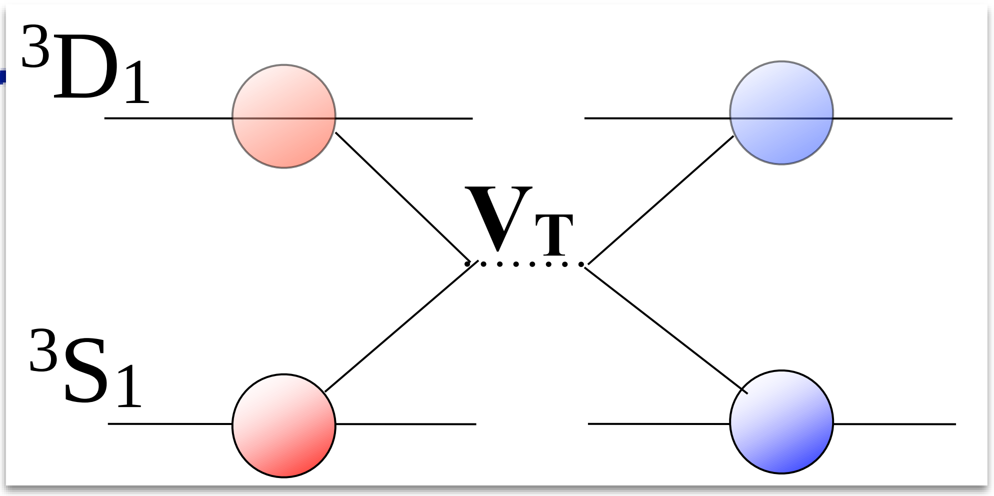
Wigner & Feingold, PR 79 (1950) 221.
Arima & Terasawa, PTP 23 (1960) 87.



NN LS interaction
σ and ω exchange

Tensor force and saturation

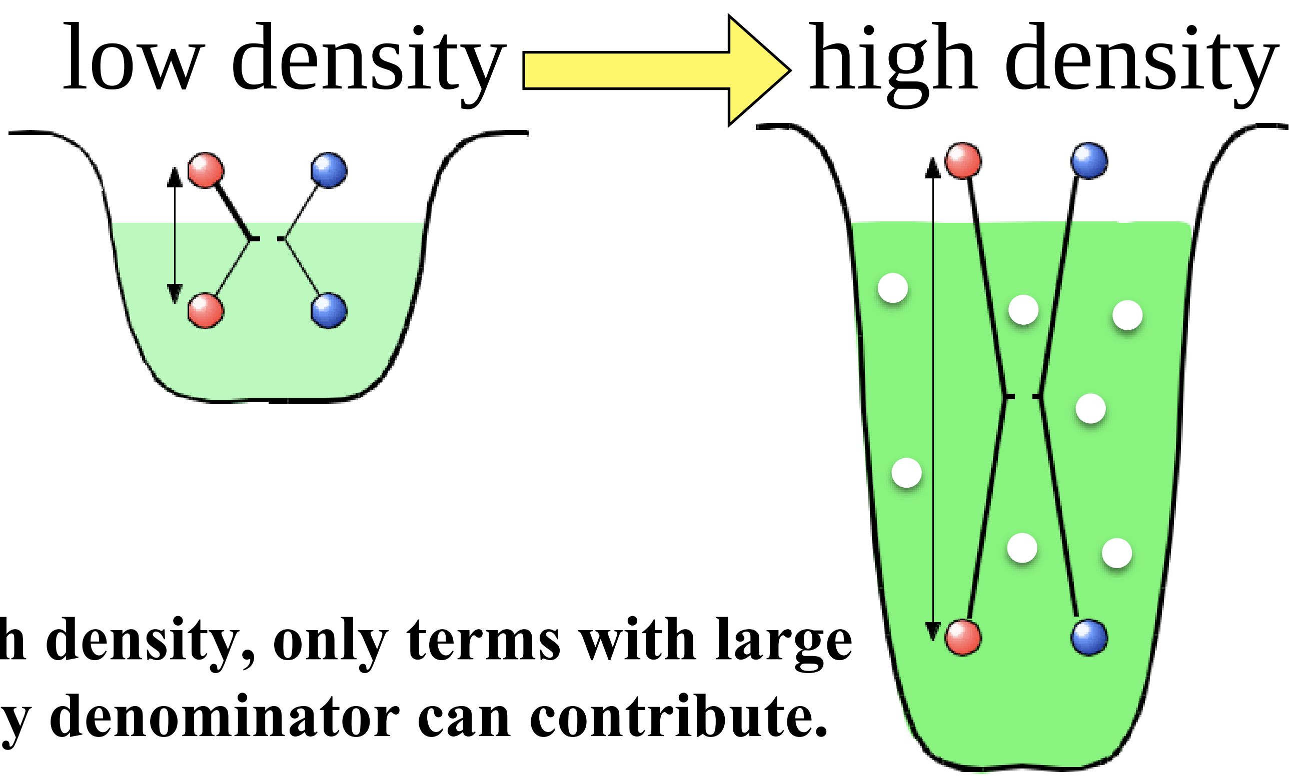
Saturates the nuclear density through the second-order perturbation effect :



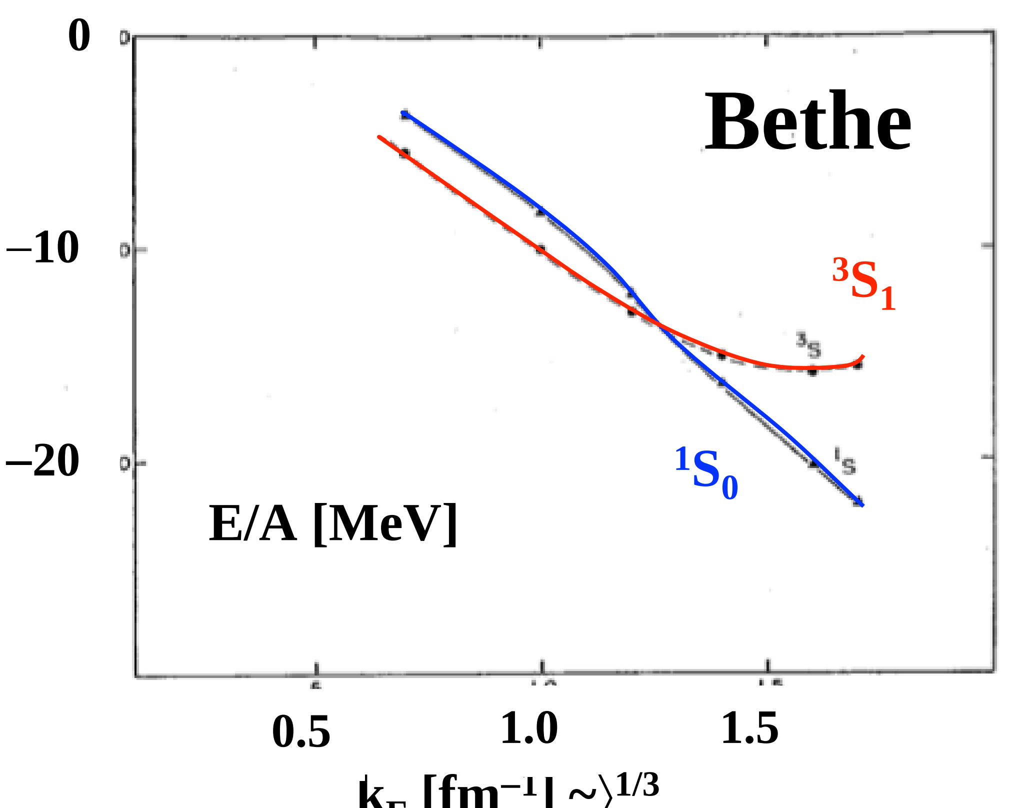
Attraction by pn tensor

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

Energy denominator

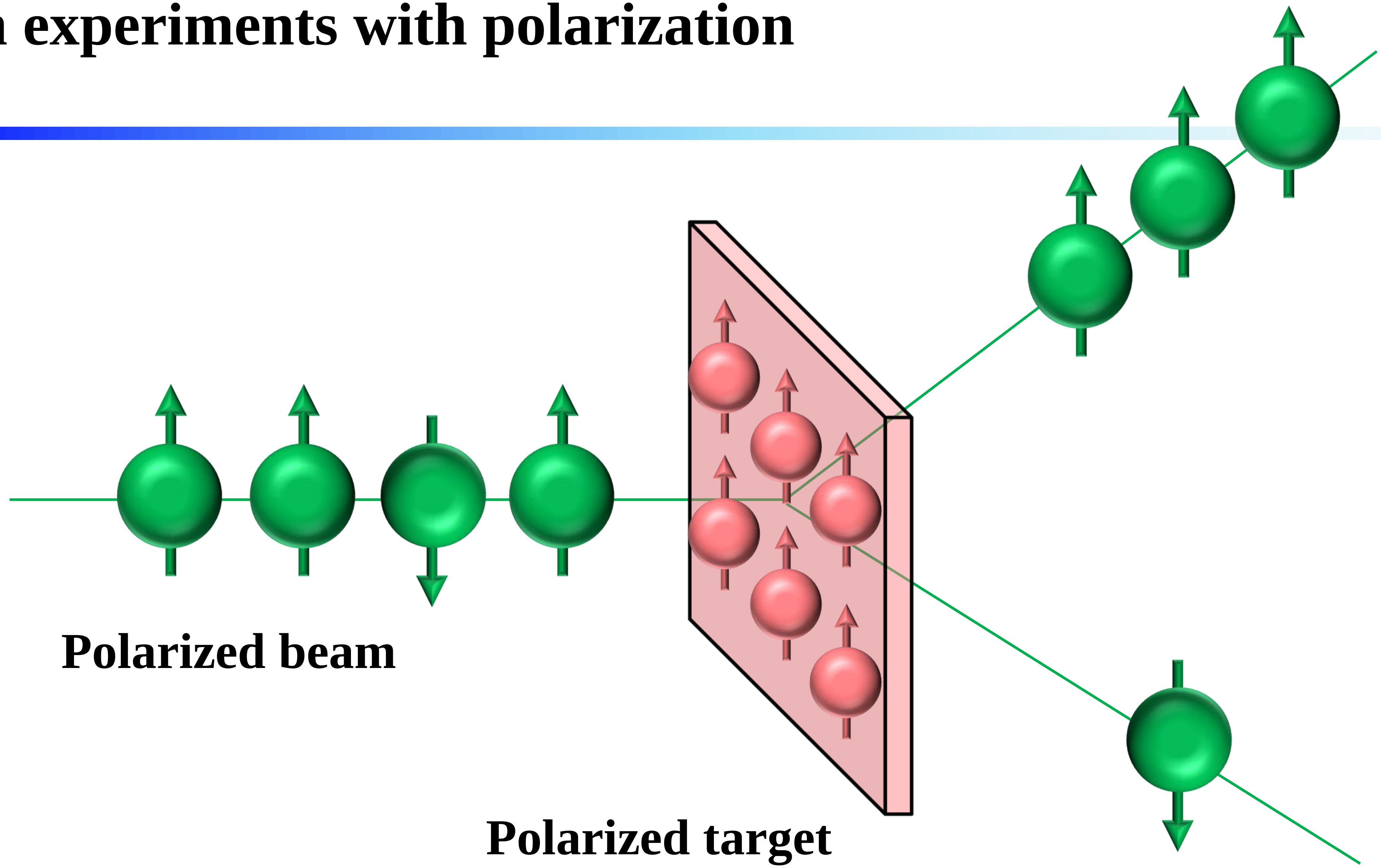


At high density, only terms with large energy denominator can contribute.



spin plays an essential role also in the understanding of nuclear matter

Beam experiments with polarization



- Differential cross sections (σ)
- Analyzing power (A_{ij}) : spin-orbit coupling ($L \cdot S$)
- Spin correlation (C_{ij}) : spin-spin coupling ($s \cdot S$)
- Spin transfers (D_{ij}) : spin responses

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

Dynamic Nuclear Polarization (DNP) Method

Standard technique to polarize nuclei in solid

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

Kastler

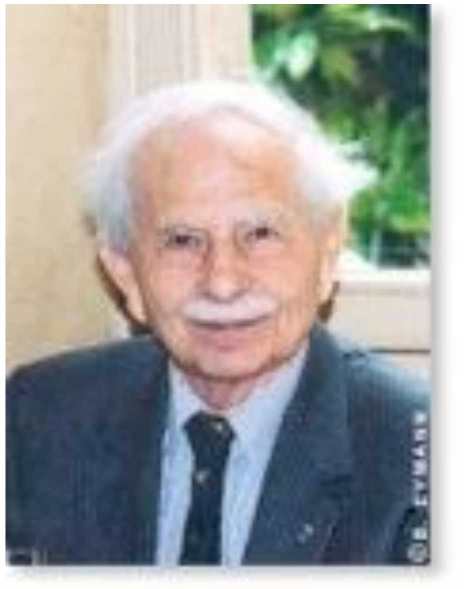
Brute Force Method

HD target (only for photon/neutron beams)

Nuclear Reaction Method

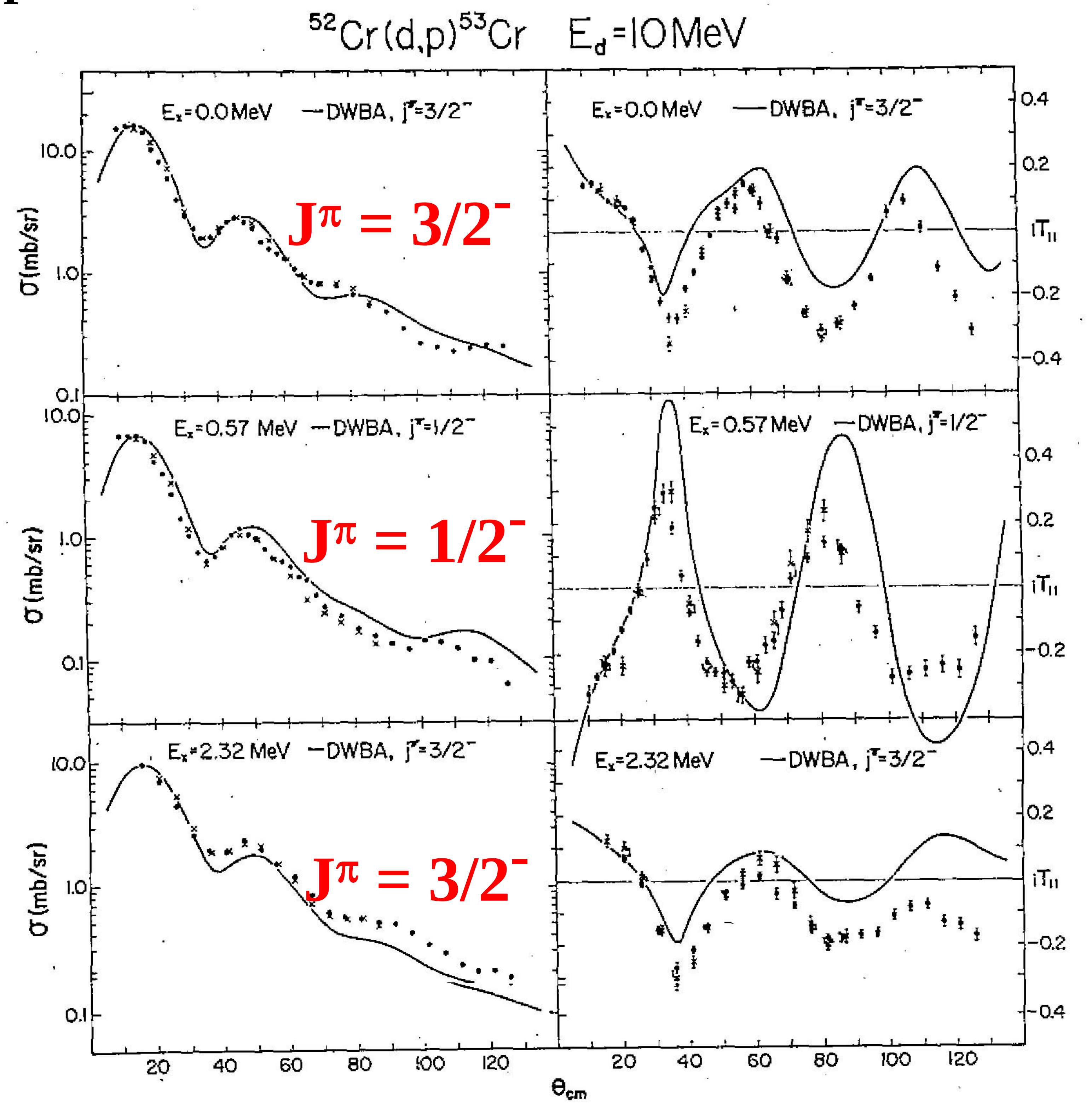
Standard method to polarize RIs

Abragam



(d,p) reactions with a polarized deuteron beam

Using a polarized ion source based on atomic beam method, coupled with Tandem

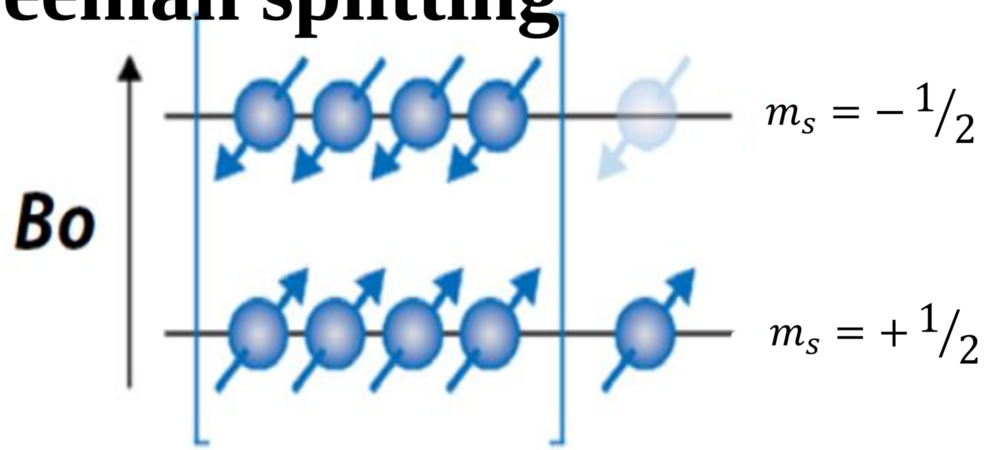


D.C. Kocher and W. Haeberli Nucl. Phys. A 196 ('72) 225.

How to polarize nuclear spins in solid

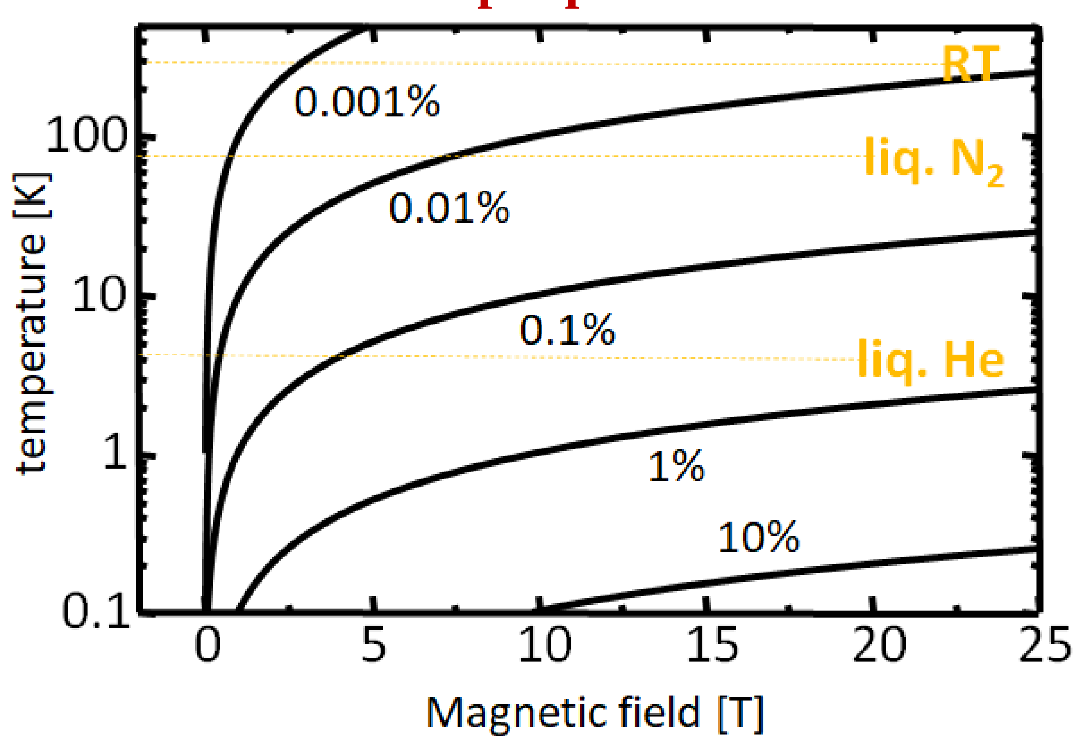
Note $\mu_N \ll \mu_e$

Zeeman splitting



Zeeman energy of proton
E = 1.6 μeV @ 9.4 T
Room temperature
E = 39 meV

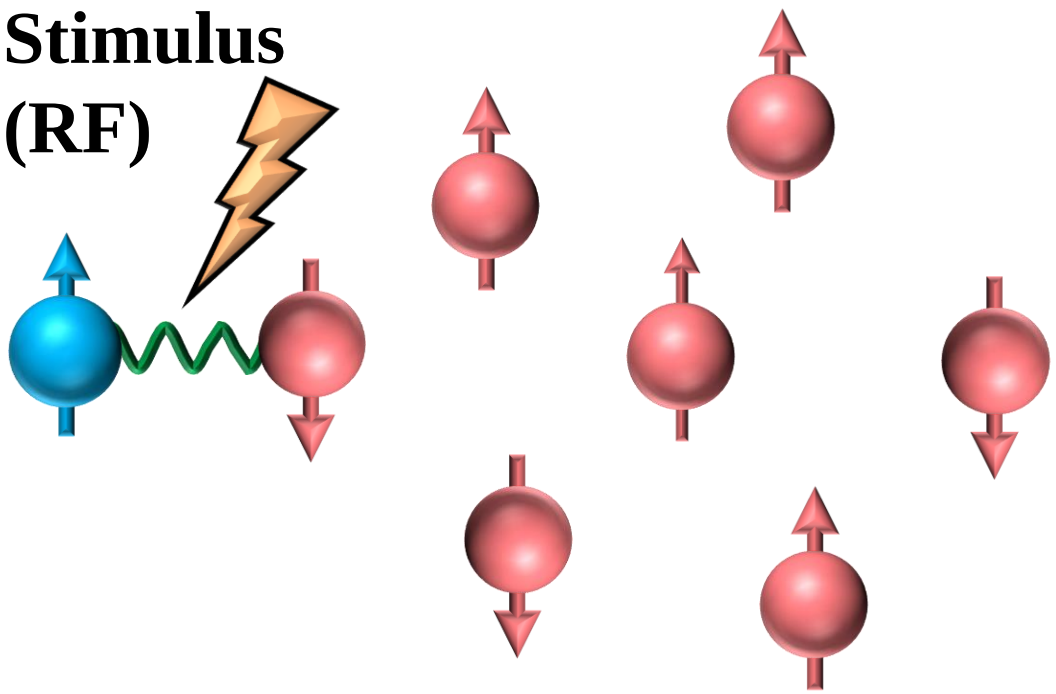
[1]H spin polarization



Dynamical methods

Stimulus (RF)

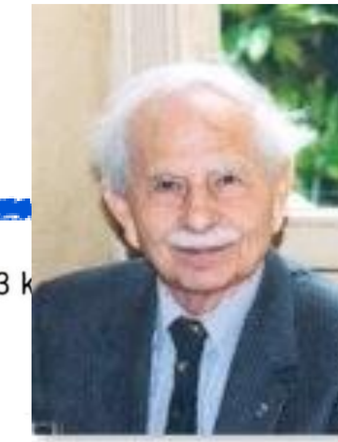
Polarized electrons



Nuclear Spins

electron spin polarization is transferred to nuclear spin polarization using RF

DNP has driven Spin Physics

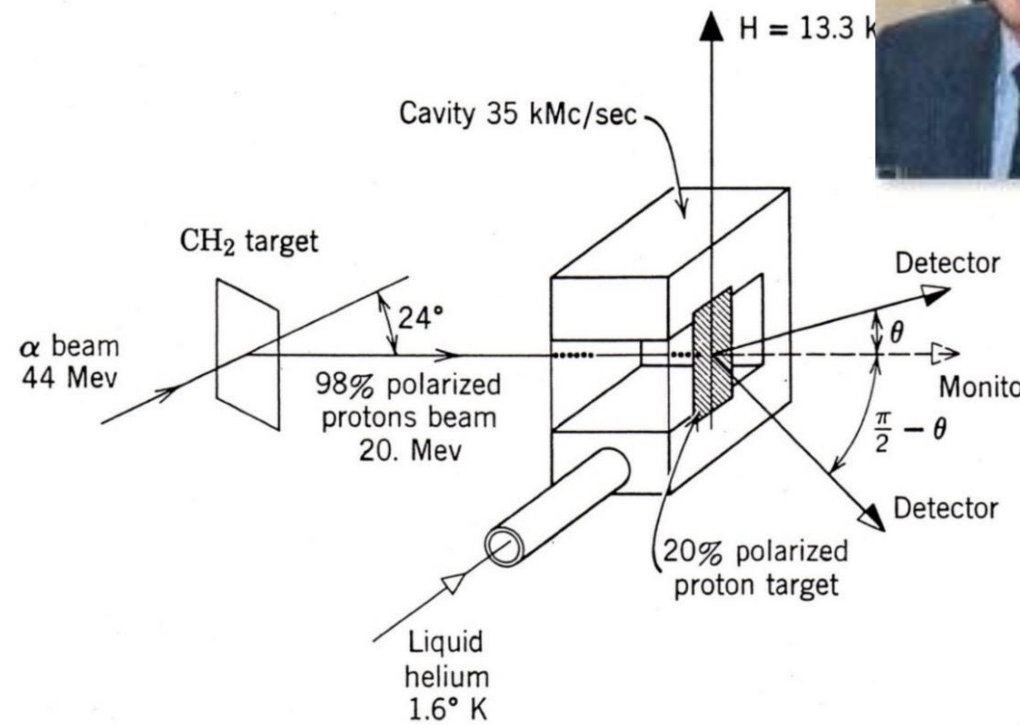


The first experiment with a polarized target

1962 at Saclay

by A. Abraham, M. Borghini et al.

C_{nn} for *pp* scattering at 20 MeV



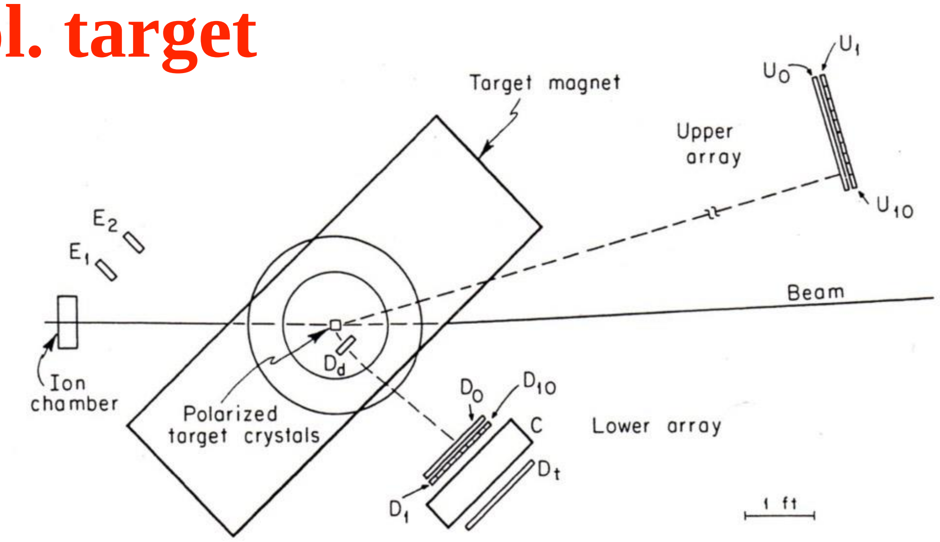
Protons in $La_2Mg_3(NO_3)_{12}$ $24H_2O$ (LMN) were polarized.

The first high-energy experiment with a pol. target

1963 at Berkeley (Bevatron)

by O. Chamberlain, C. Jeffries et al.

Spin asymmetry in π-p scattering

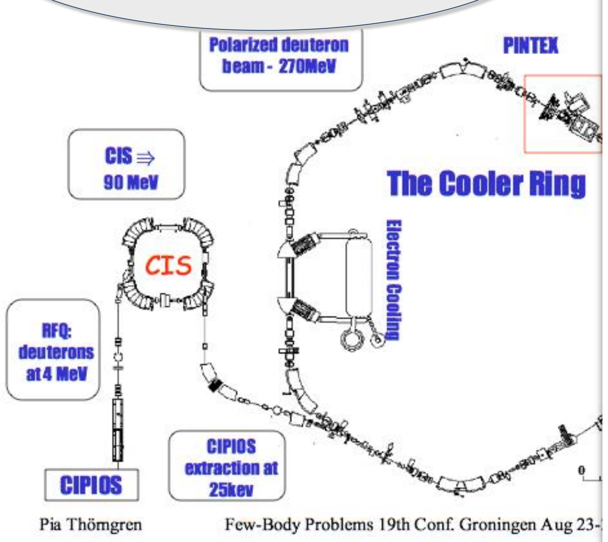


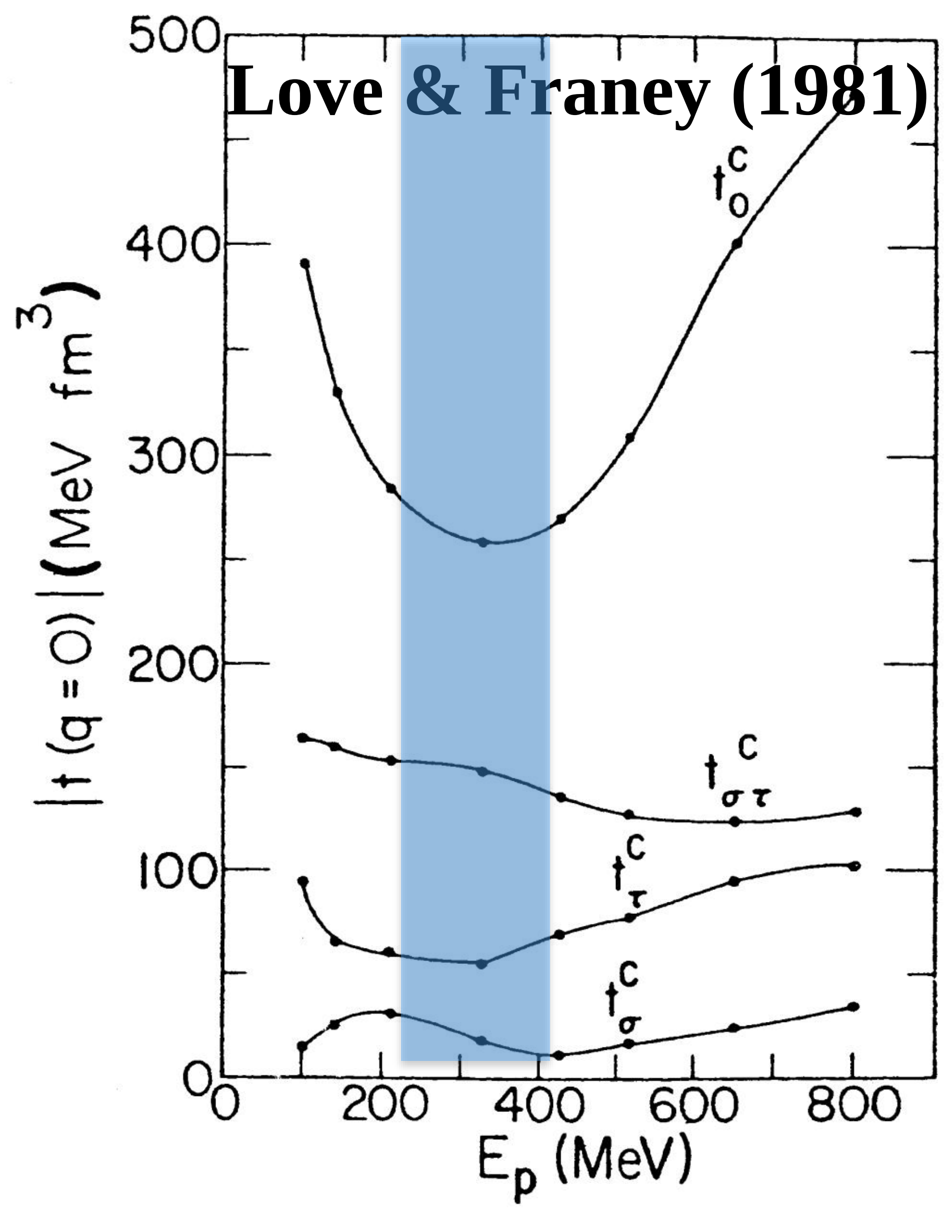
Experimental setup for π-p scattering at Berkeley

Intermediate beam energy facilities: Exploiting the natures of NN interaction for spin physics

RIKEN

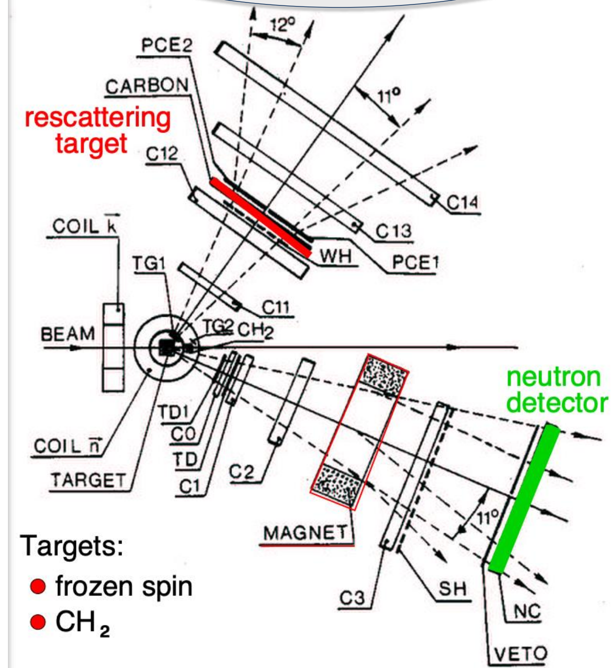
IUCF



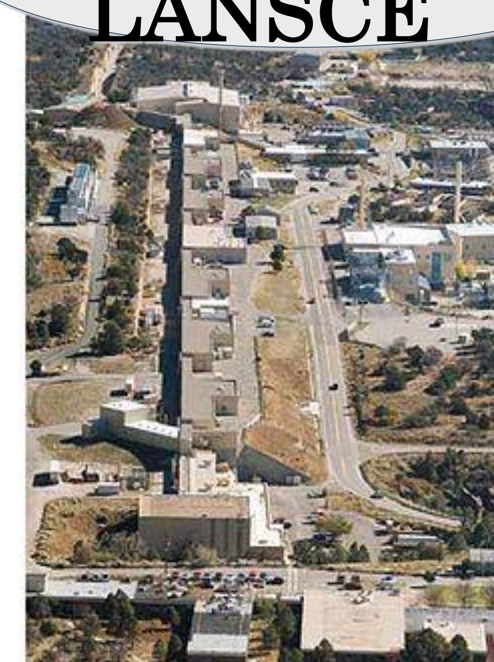


- Phenomena at shorter distances
- Nuclear transparency
- Suitable for spin-isospin channel

Saturne II

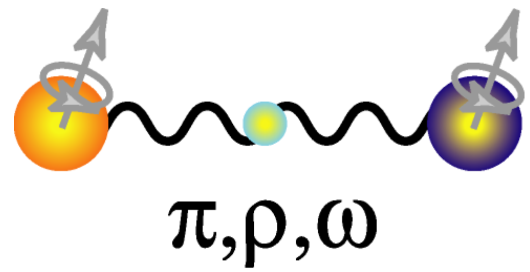


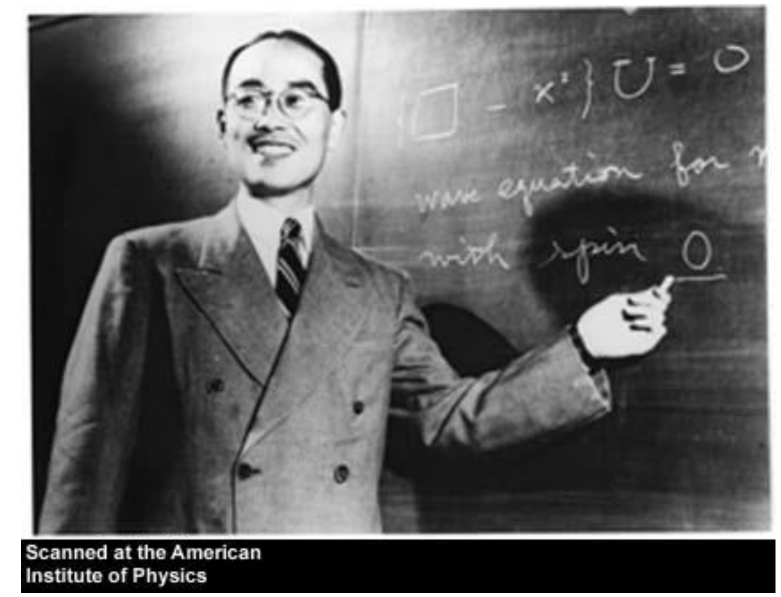
LAMPF
LANSCE



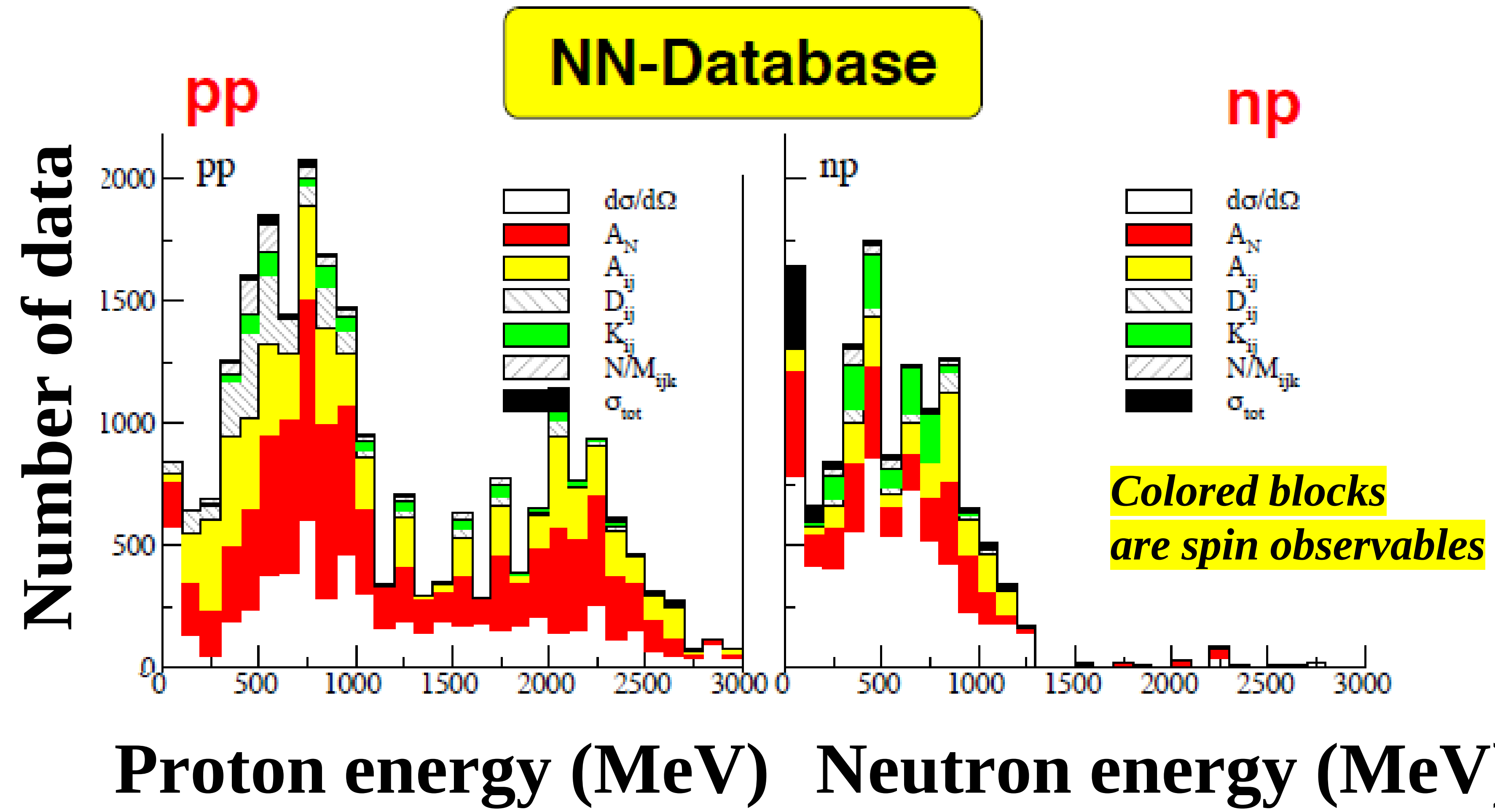
Establishment of 2NF

Yukawa's Meson Theory
Proc. Phys. Math. Soc. Jpn.
17, 48 (1935)



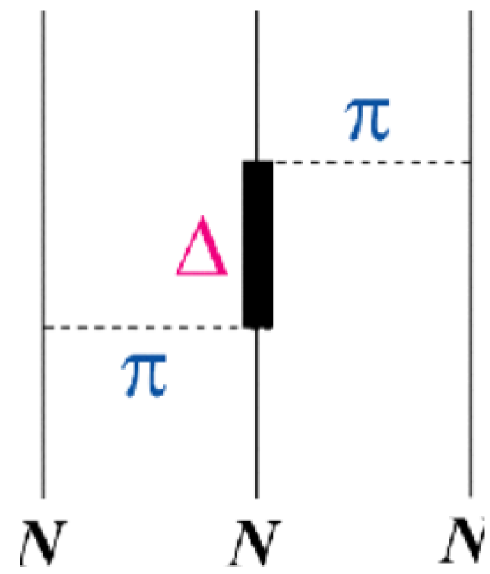


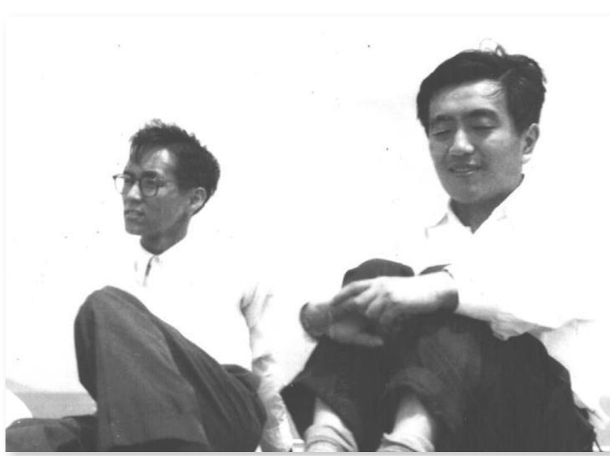
After
~60 years



1990's Realistic Modern Nucleon-Nucleon Forces (2-Nucleon F)
reproduce 3500 NN scattering exp. data with high precision, $\chi^2 \sim 1$.

Direct evidence of 3NF in *d-p* scattering (2000s)

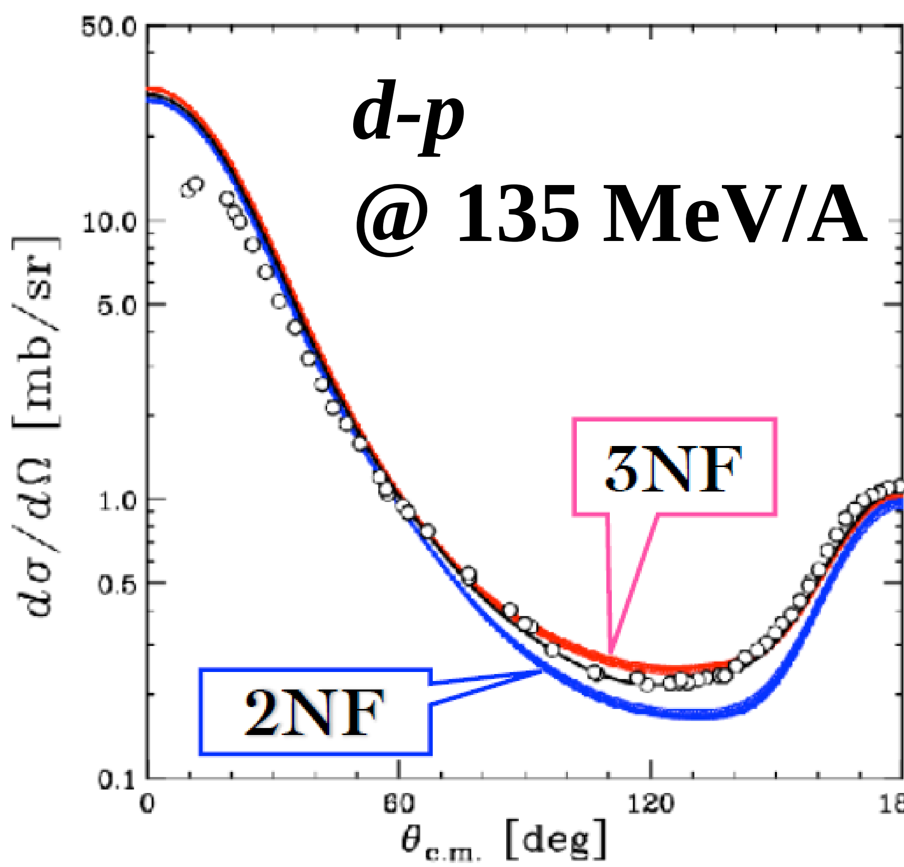


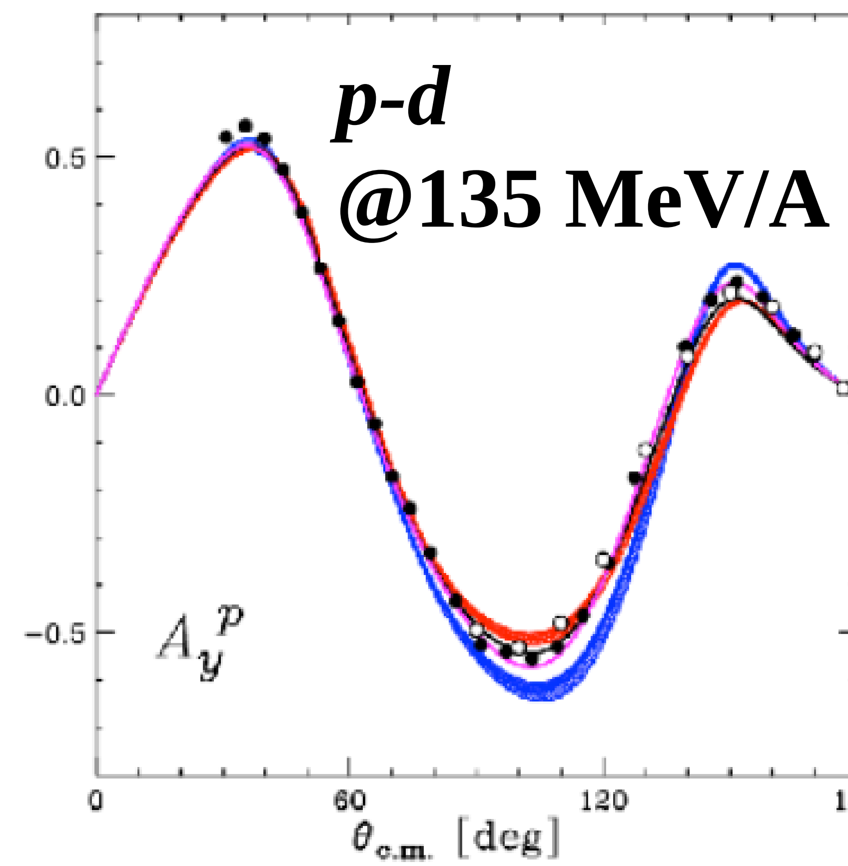


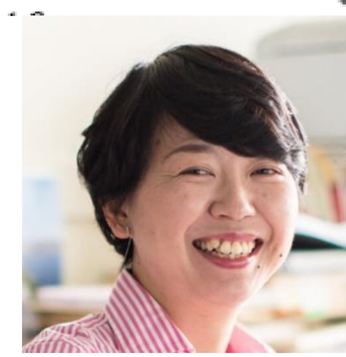
Fujita & Miyazawa
3NF (1957)

NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18

K. Sekiguchi et al. PRC 65, 034003 (2002)
K. Sekiguchi et al. PRL 95, 162301 (2005)
Calculations by Bochum-Cracow Gr.





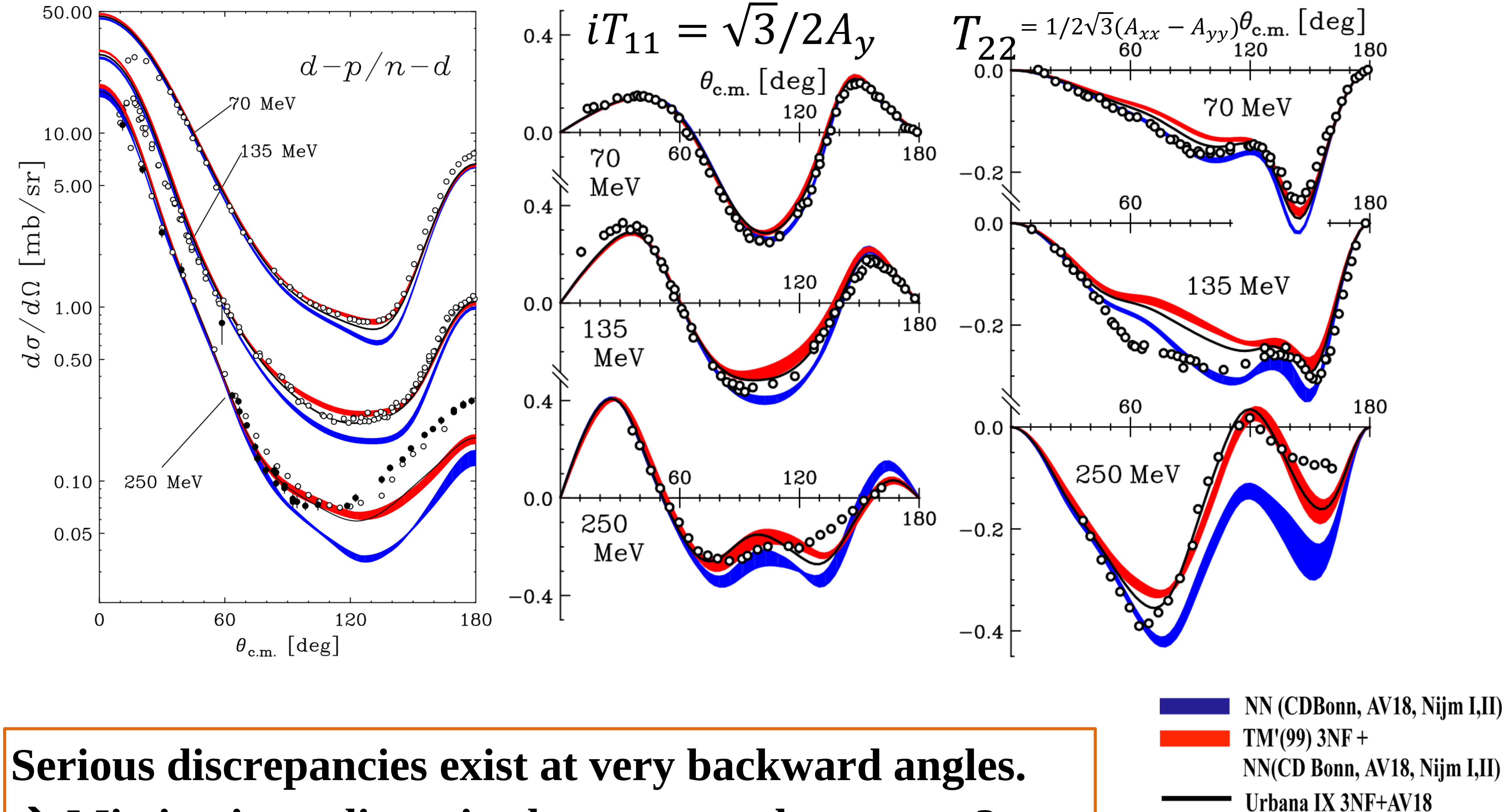


Plenary talk by K. Sekiguchi (Nov. 29th)

Both the experimental and theoretical progresses were crucial:
- **Beam energy & accurate cross section/spin observable measurement**
- **precise 2NF models (CDBonn, AV18, Niijm I, II) and Faddeev calculation**

Energy Dependent Study for *dp* Scattering
- Cross Section & Analyzing Powers -

K. Hatanaka et al., Phys. Rev. C, 66, 044002 (2002)
Y. Maeda et al., Phys. Rev. C 76, 014004 (2007)
K. S. et al., Phys. Rev. C 83, 061001 (2011)
K. S. et al., Phys. Rev. C 89, 064007 (2014)



Serious discrepancies exist at very backward angles.
→ Missing ingredients in short-range phenomena?

Plenary talk by K. Sekiguchi (Nov. 29th)

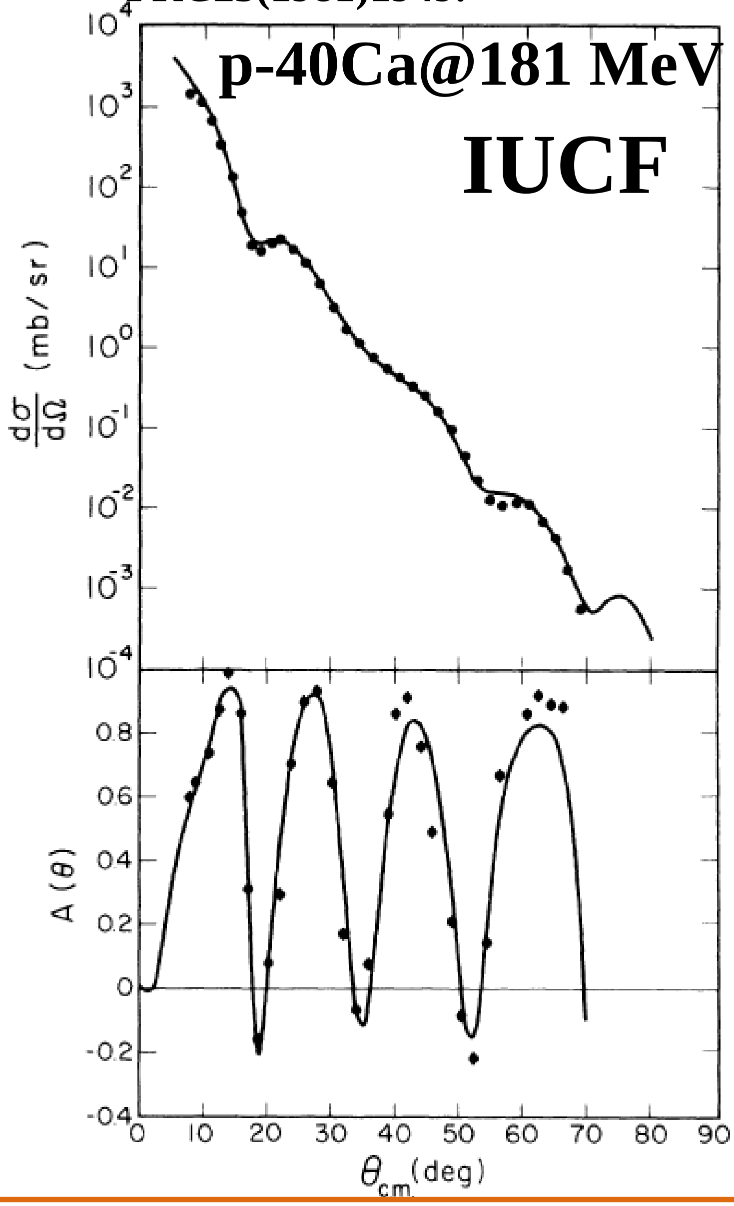
p-nucleus elastic scattering at intermediate energies

Nuclear transparency
→ probing the whole volume

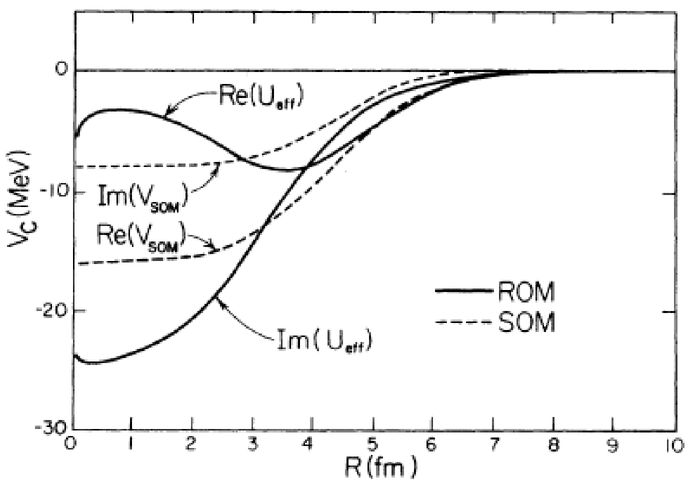
Arnold, Clark, Mercer, Schwandt, PRC23(1981)1949.

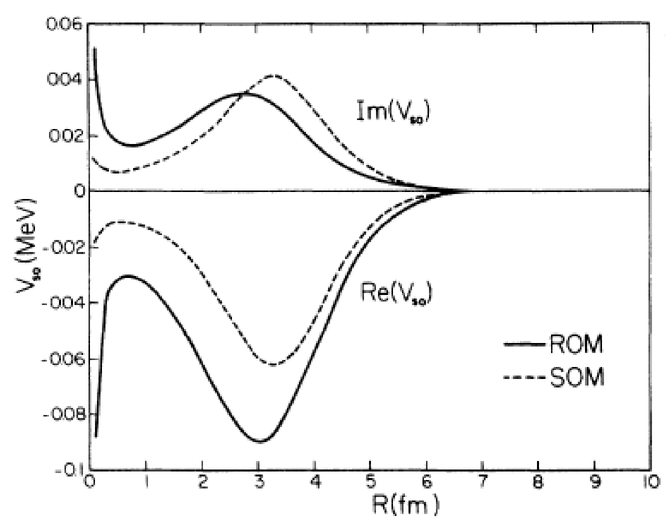
p-40Ca@181 MeV

IUCF

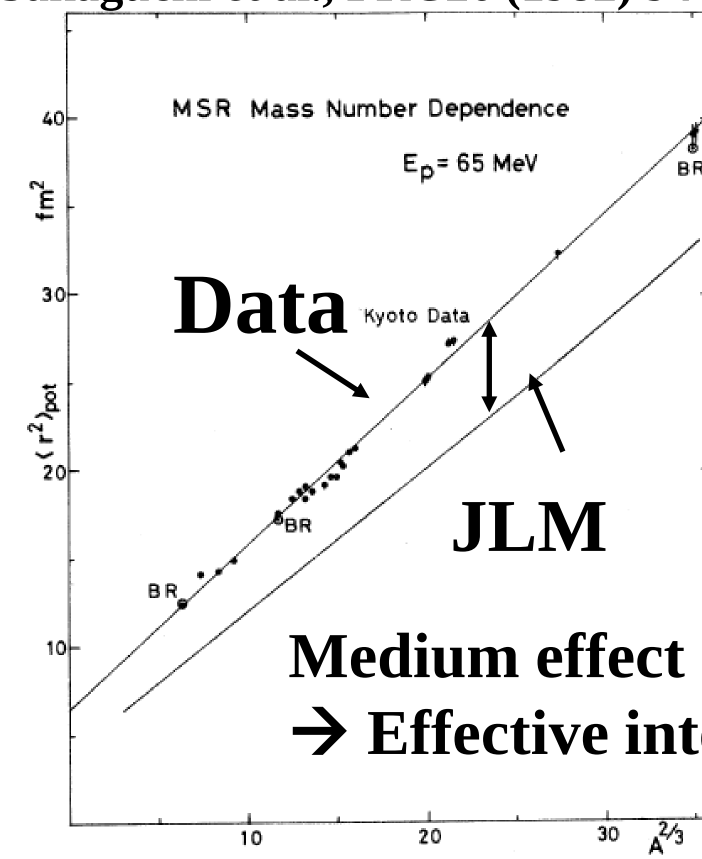


Wine bottle bottom shape





Sakaguchi et al., PRC26 (1982) 944



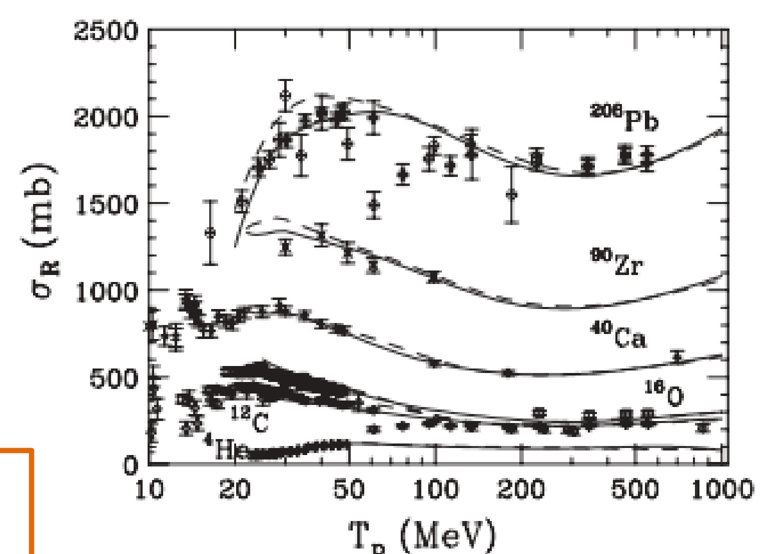
pol p study @RCNP started

Data

JLM

Medium effect
→ Effective interaction model

Global optical potential



E. D. Cooper, S. Hama, and B. C. Clark, PRC **80**, 034605 (2009).

Spin observable (Ay)
→ the reaction & effective-interaction models

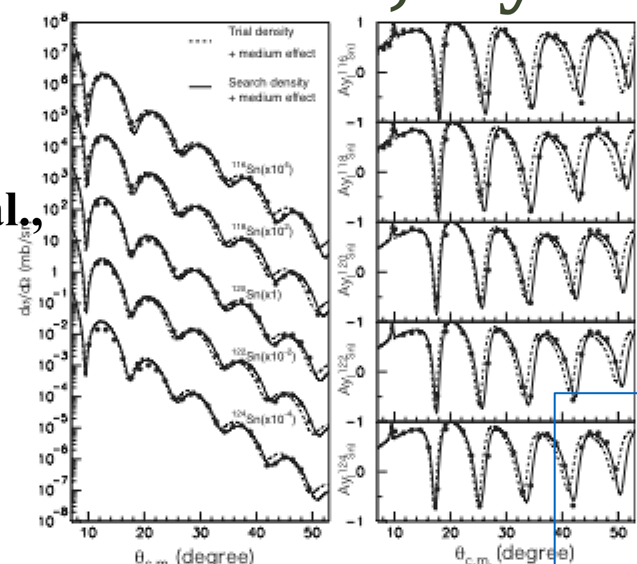
Now, …

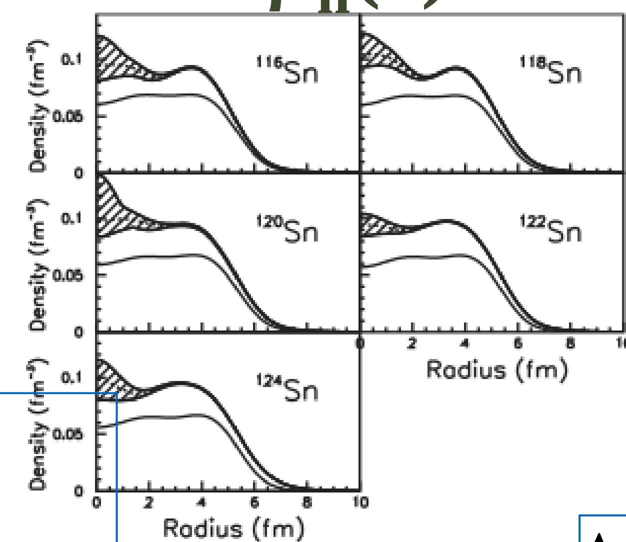
<u>Stable nuclei</u> : ρ_p is known from electron scatterings

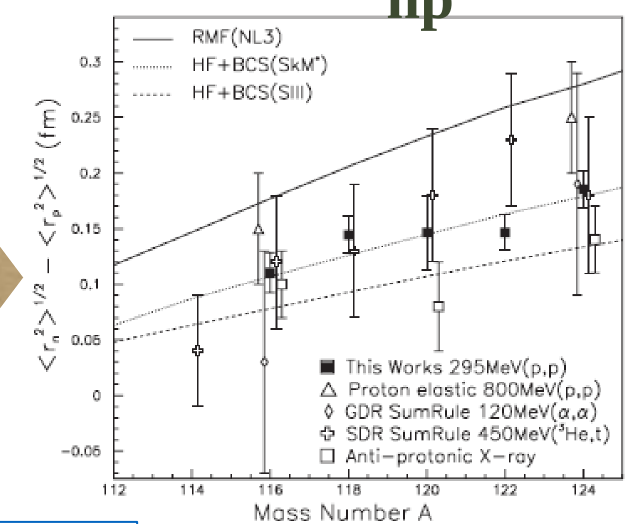
$d\sigma/d\Omega$, Ay $\rho_n(r)$ Δr_{np}

Sn

S.Terashima et al., Phys. Rev. C 77, 024317 (2008)





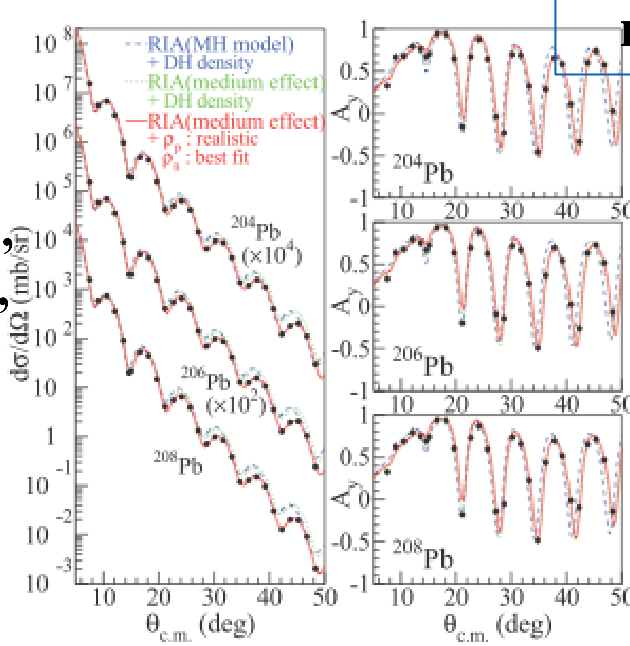


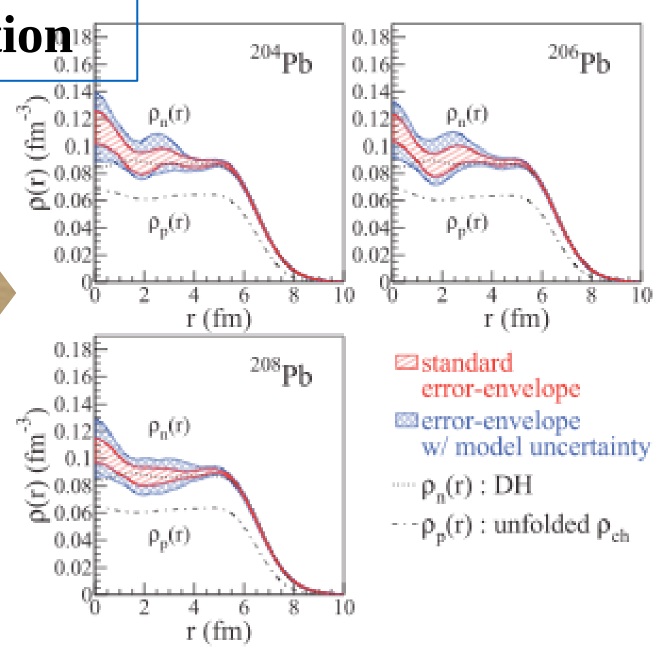
RIA
+
Medium modification

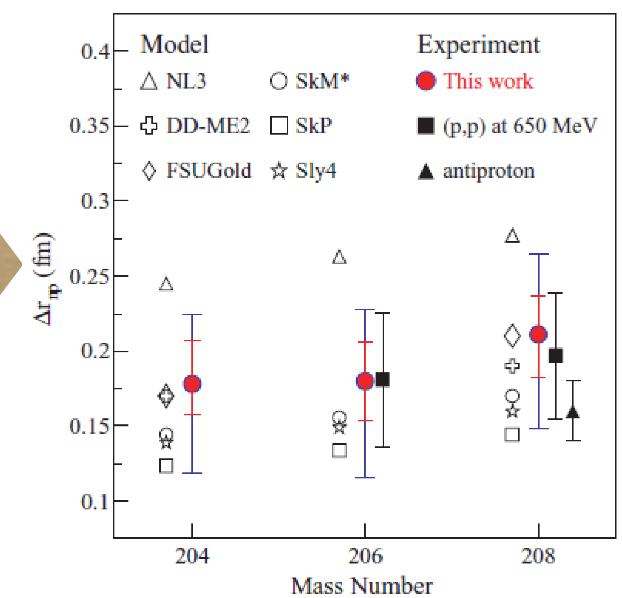
$\Delta r_n/r_n < 0.5\%$

Pb

J.Zenihiro et al., Phys. Rev. C 82, 044611 (2010)



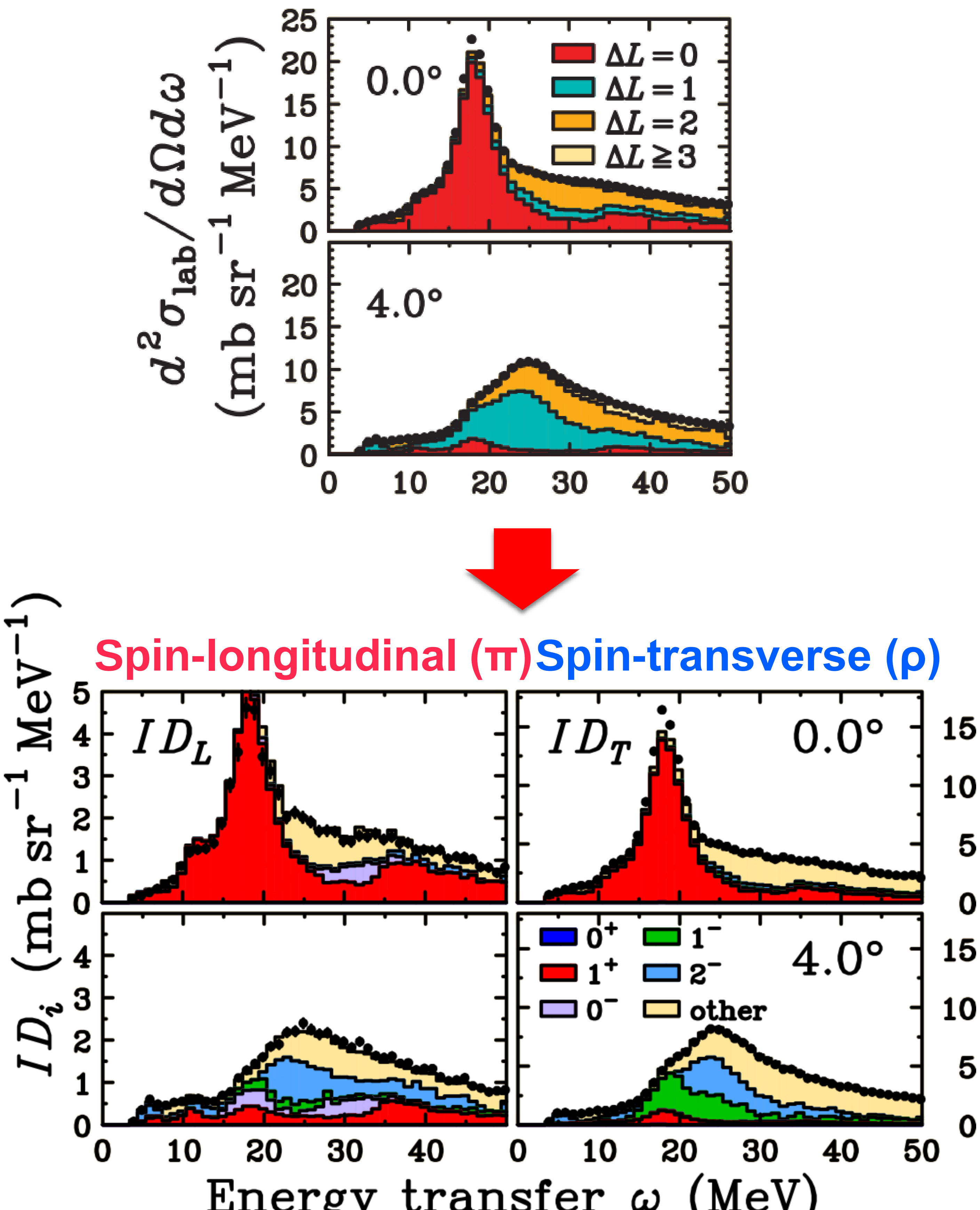


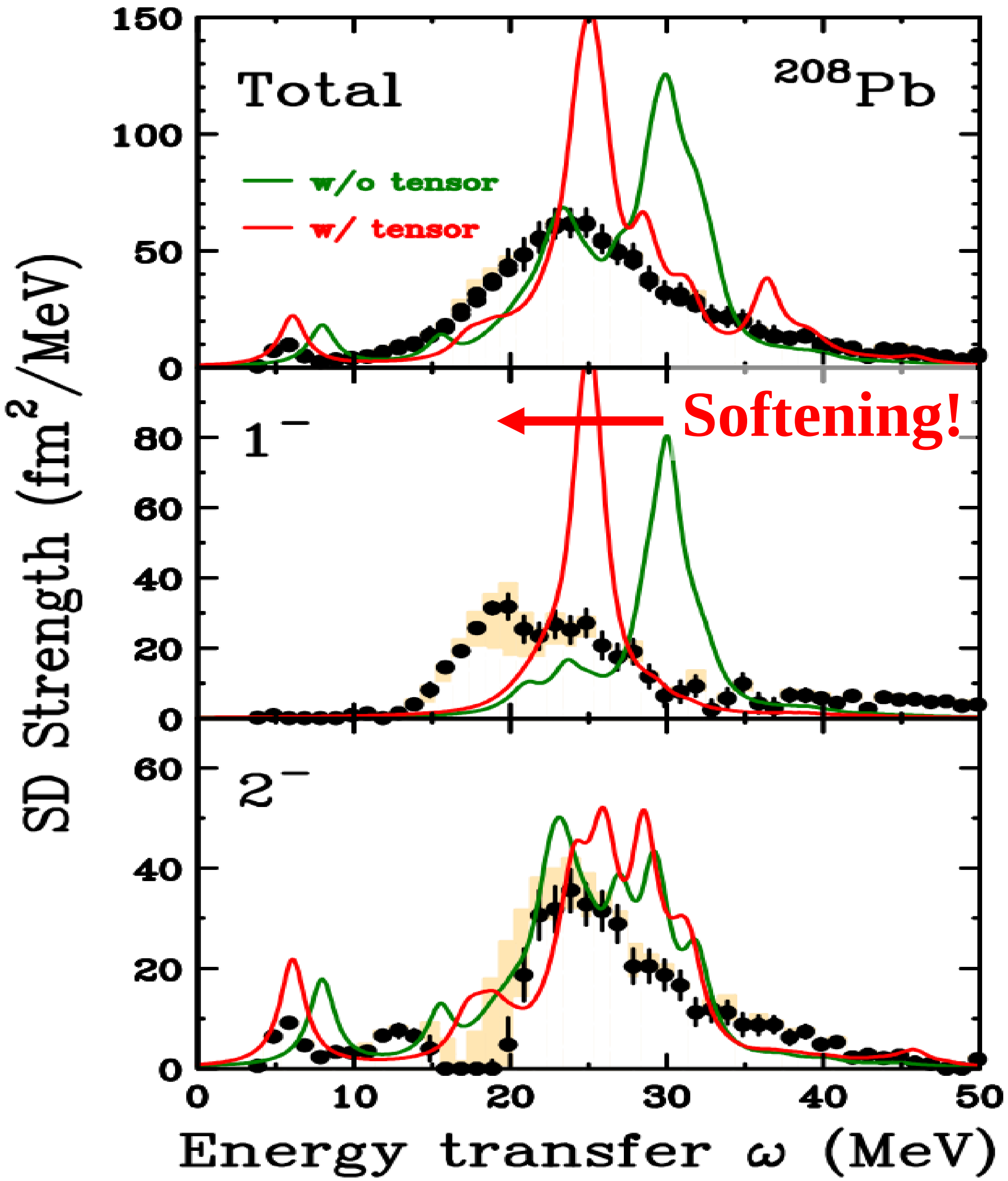


In combination with e-scatt.,
the neutron skin thickness is precisely obtained.

Spin transfers →
J^{π} decomposition of Spin Dipole giant resonance in ^{208}Pb(*p*,*n*)

T.Wakasa. et al., Phys. Rev. C 85, 064606 (2012).





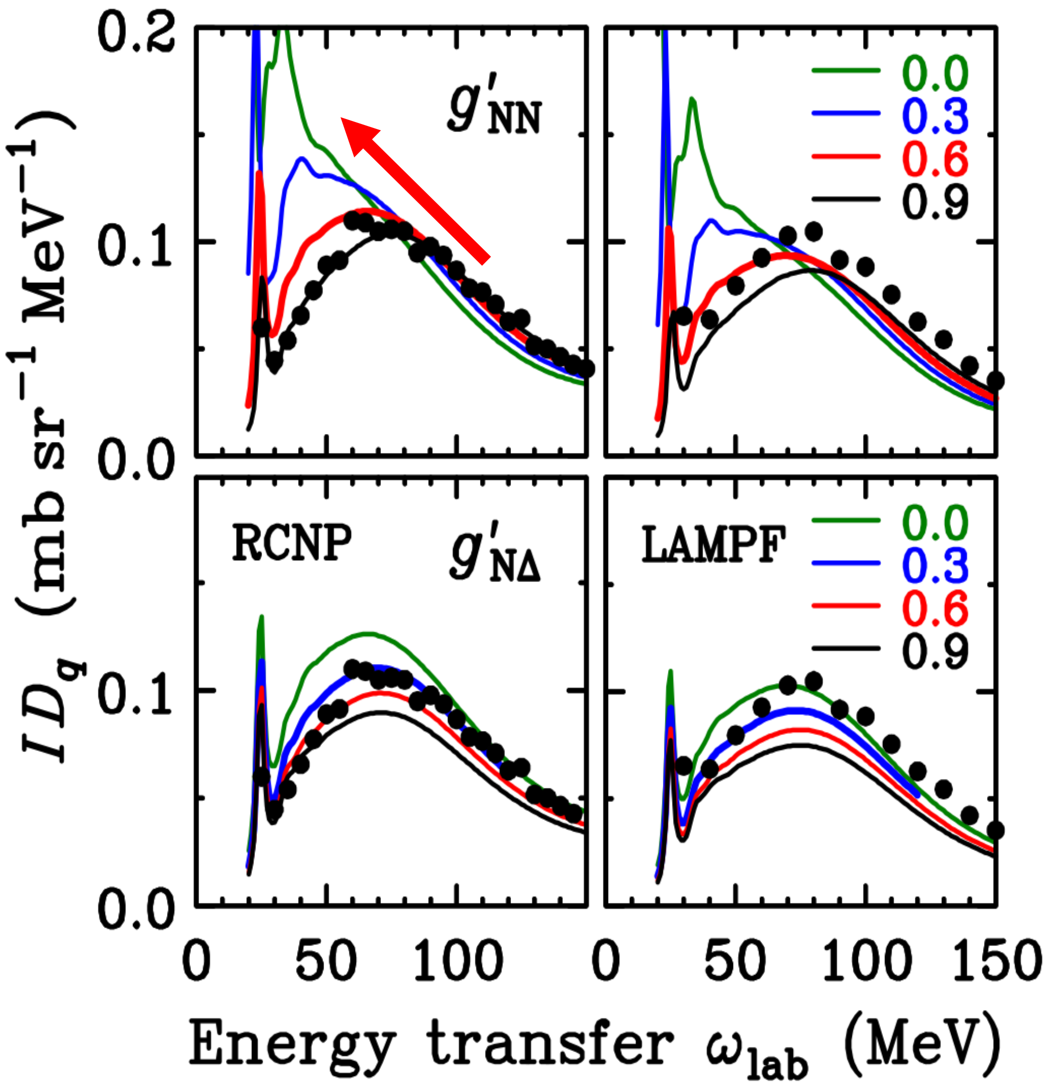
Softening on 1^- by tensor correlation
Has been found

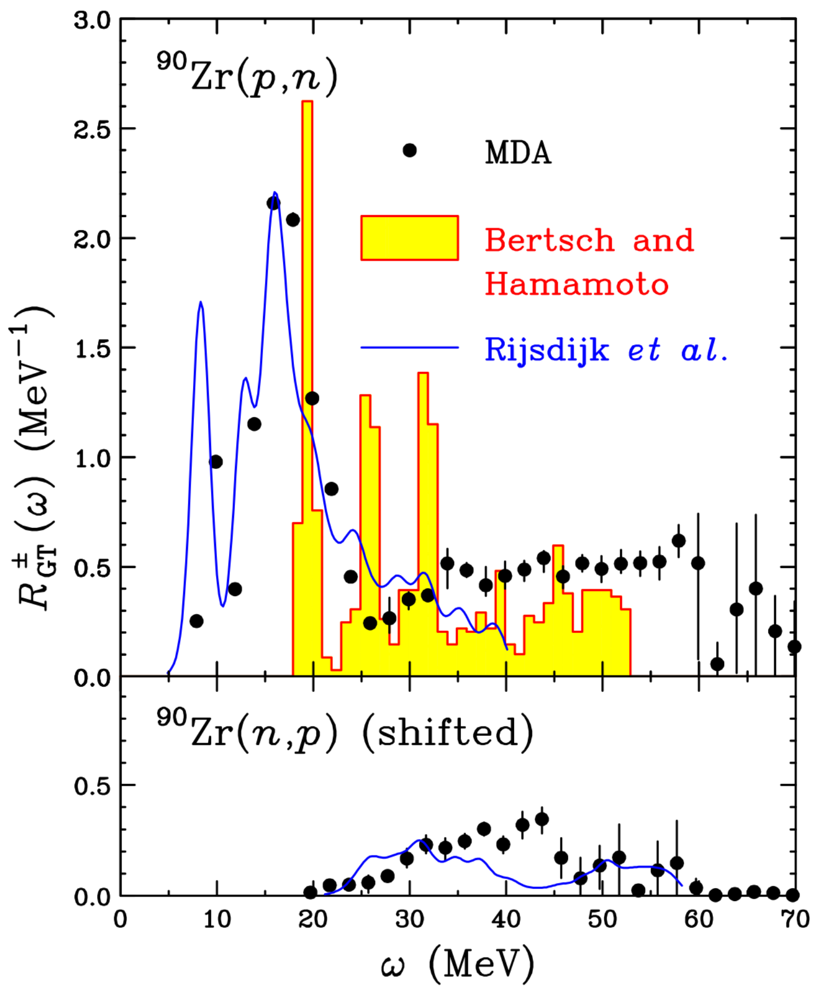
Study of pionic mode and GTGR

M. Ichimura,
H. Sakai, TW, PPNP 56, 446 (2006).

- **T. Wakasa et al.,** ***PRC 55, 2909 (1997).***
- **K. Yako, TW, et al.,** ***PLB 615, 193 (2005).***

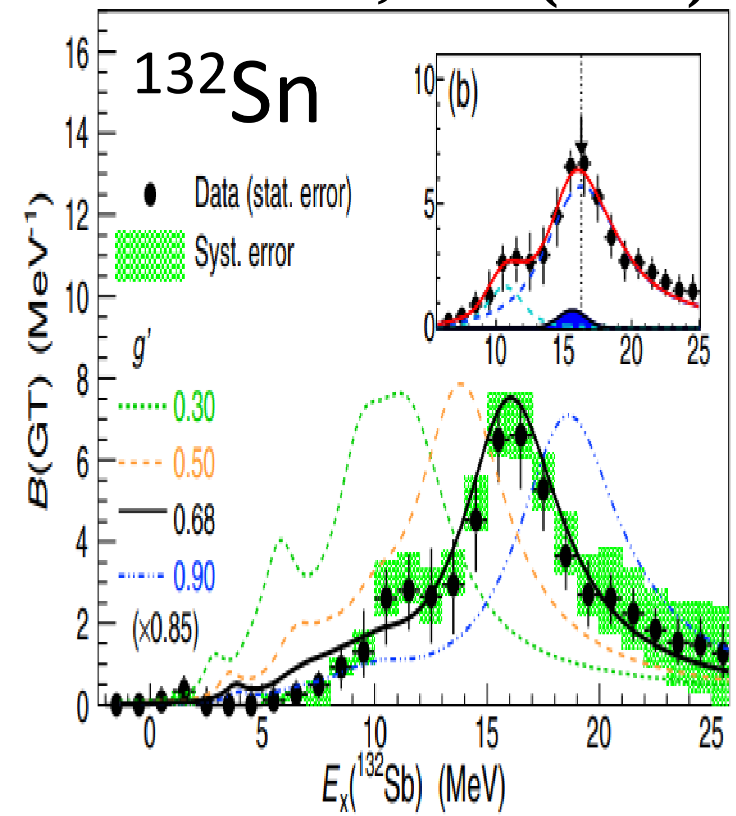
^{12}C(p,n) at q=1.7 fm^{-1}





M. Ichimura

MS et al., PRL(2018)



$$g'_{NN} \approx 0.7, \quad g'_{N\Delta} \approx 0.3$$

$q \simeq 1.7\,\mathrm{fm}^{-1}$

↔

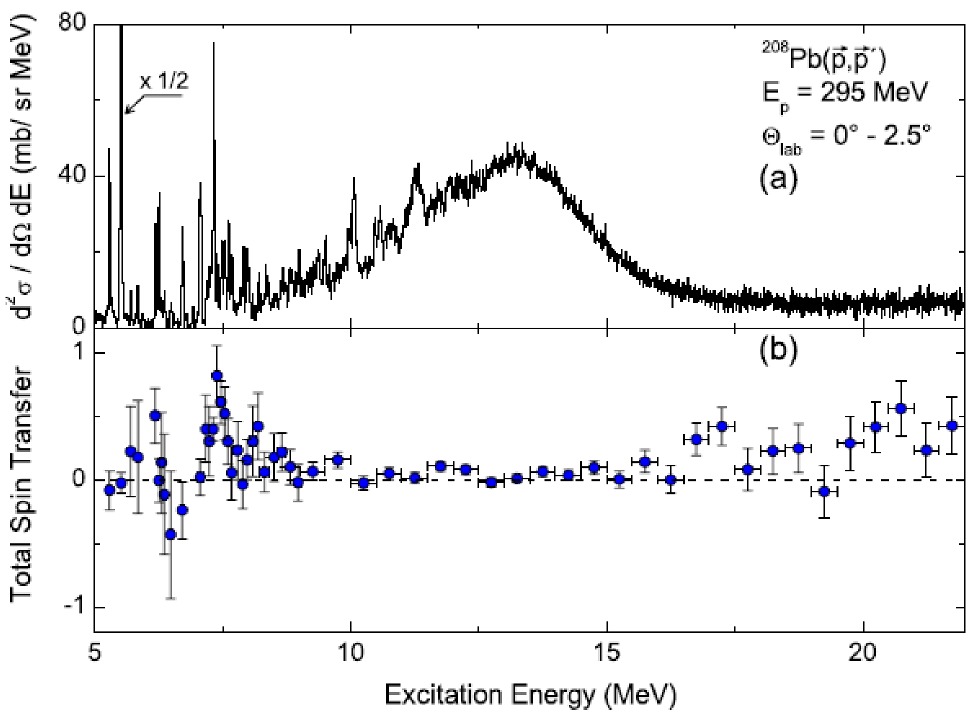
$$g'_{NN} = 0.6 \pm 0.1, \quad g'_{N\Delta} = 0.35 \pm 0.16$$

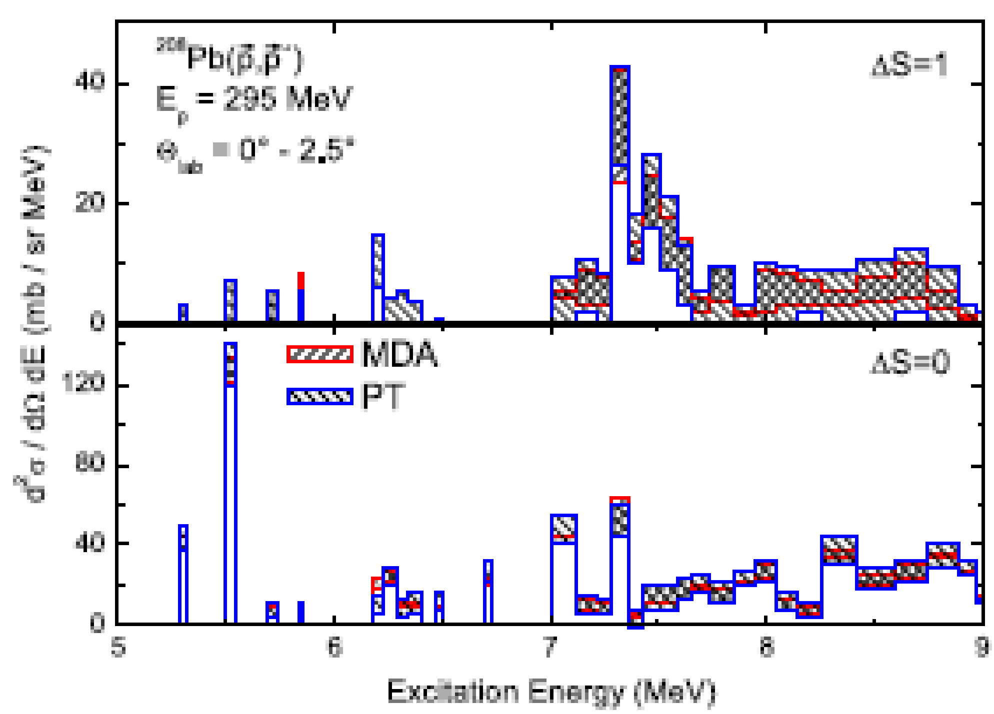
$q = 0\,\mathrm{fm}^{-1}$

Dipole polarizability of ^{208}Pb

A. Tamii et al., PRL107, 062502 (2011)

Spin transfers
& high-resolution measurement
@ RCNP





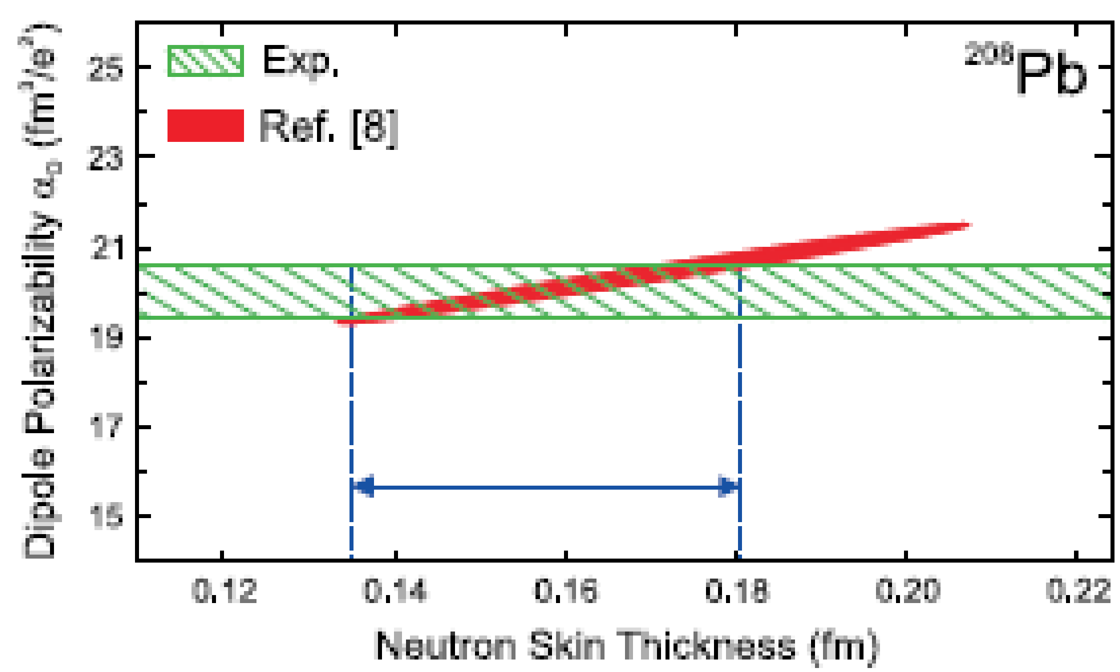


FIG. 5 (color online). Extraction of the neutron skin in ^{208}Pb based on the correlation between r_{skin} and the dipole polarizability α_D established in Ref. [8].

D-like correlation in the ground state

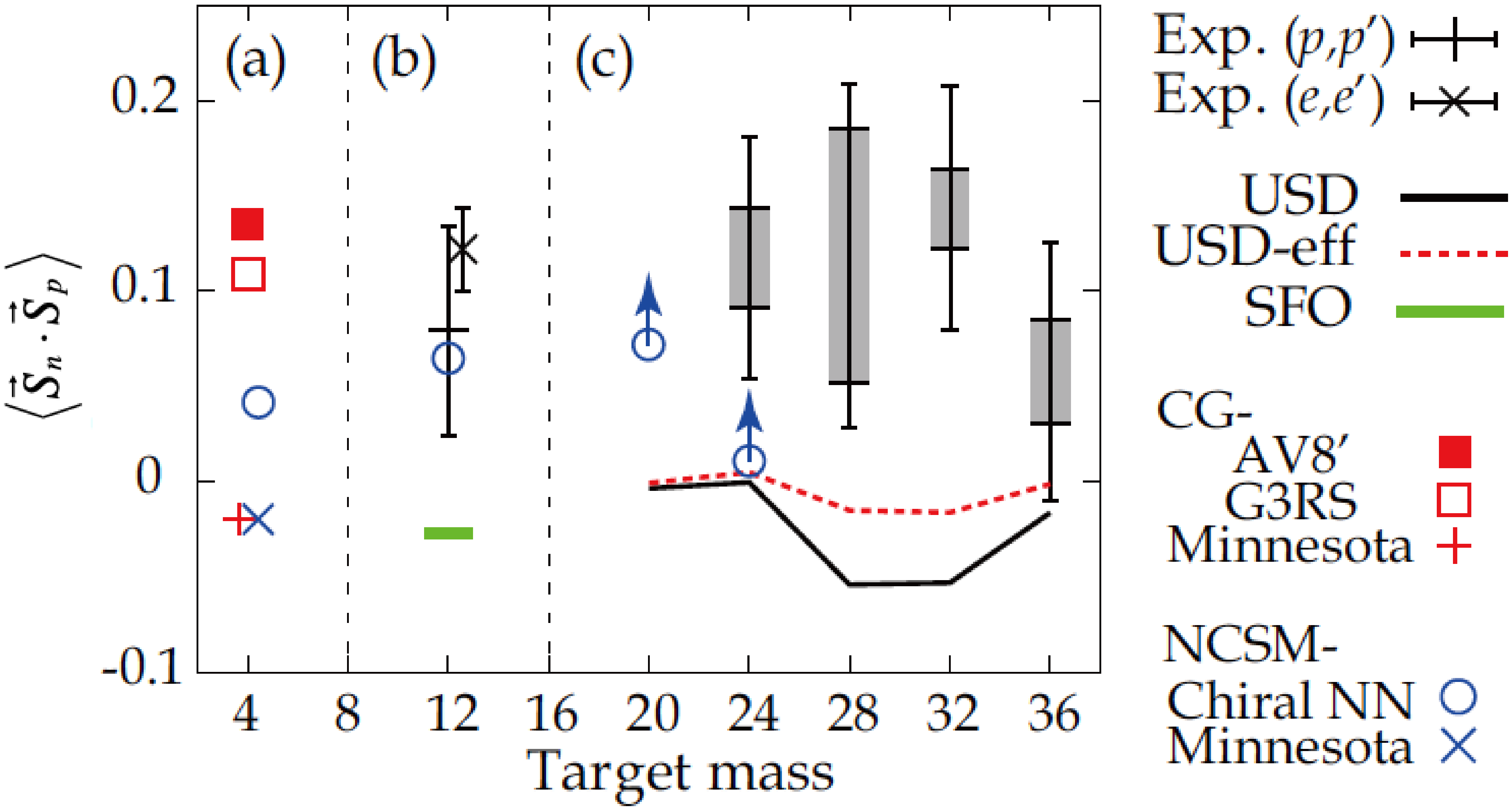
H. Matsubara et al., PRL115, 102501 (2015)

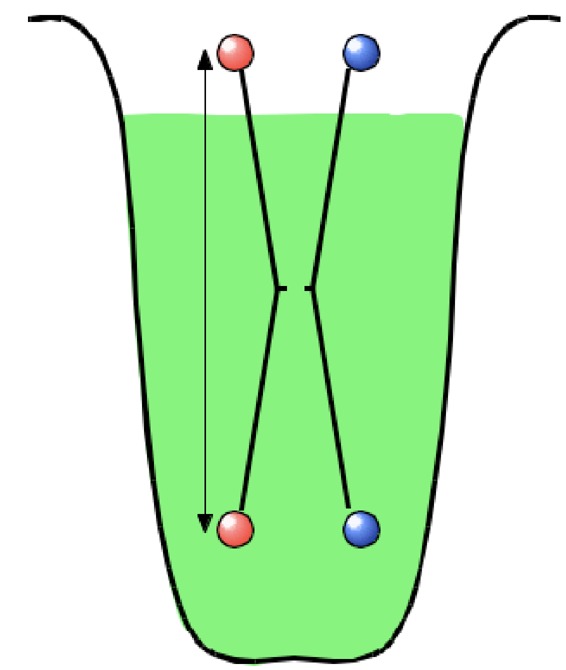
Isoscalar M1 Isovector M1

$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = \frac{1}{16}\left(\sum\left|M\left(\vec{\sigma}\right)\right|^2 - \sum\left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)$$

a measure of D-like correlation

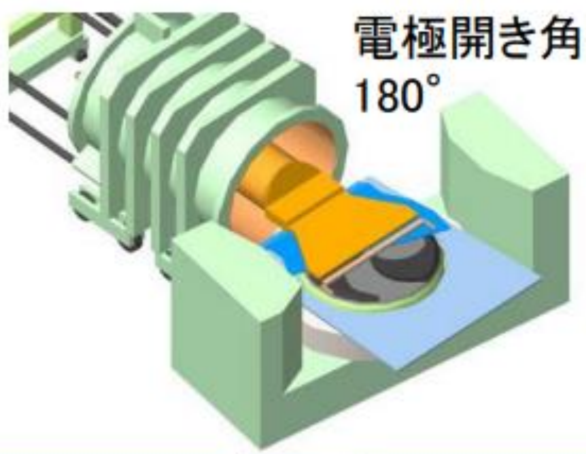
IS - IV



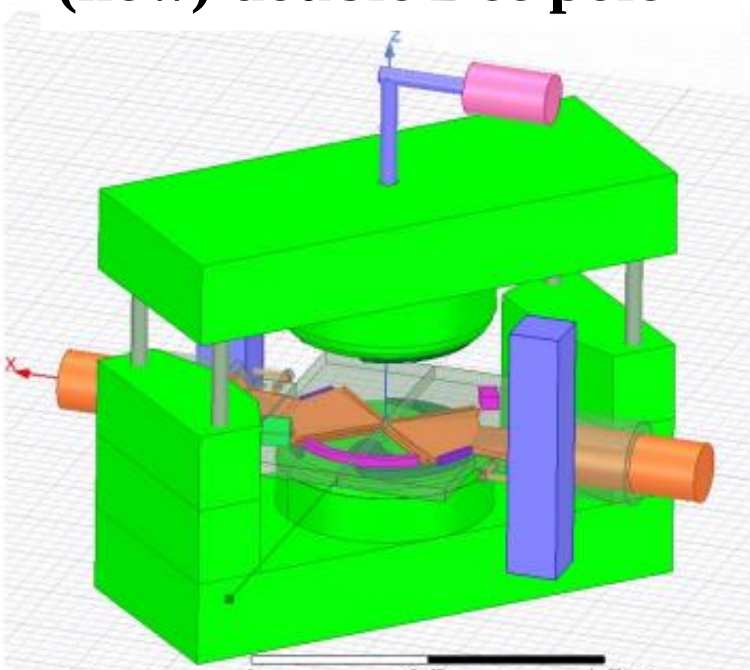


Boosting spin physics at RCNP w/ upgrade RCNP AVF and HIPIS

(prev.) single Dee pole



(now) double Dee pole

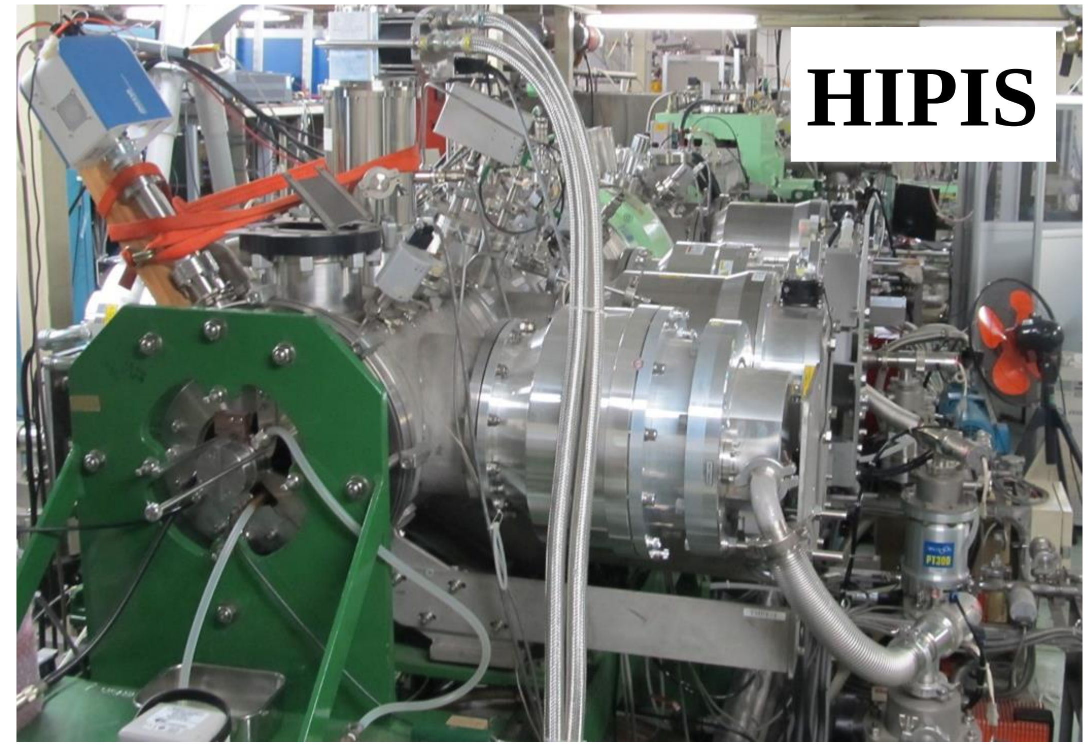


Larger turn separation
Larger energy gain

Done in 2022

Extraction voltage
→ 50 KV

Overhaul



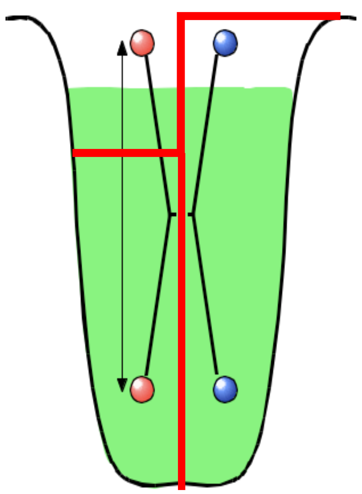
甲南大学

Beam intensity (x10) → 1uA
Polarization → 70%

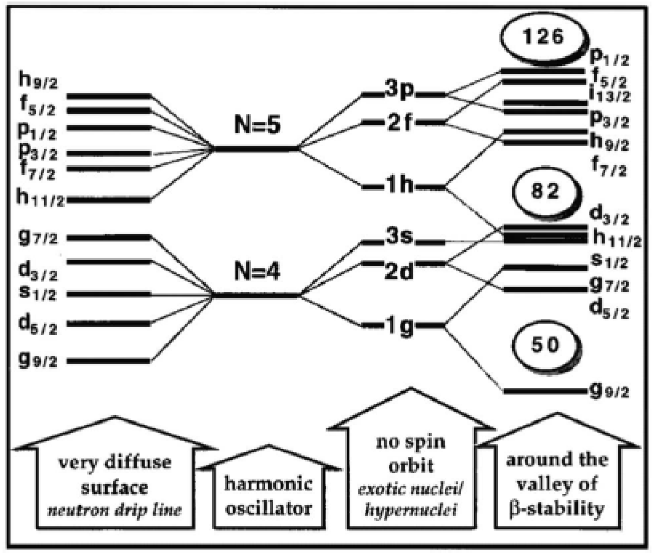
Photos and figure : In the courtesy of Kanda, RCNP
(Overhaul : Prof. Matsuda and students of Konan University)

The advent of RI beam facilities
→ Spin and unstable nuclei

Weaker density saturation

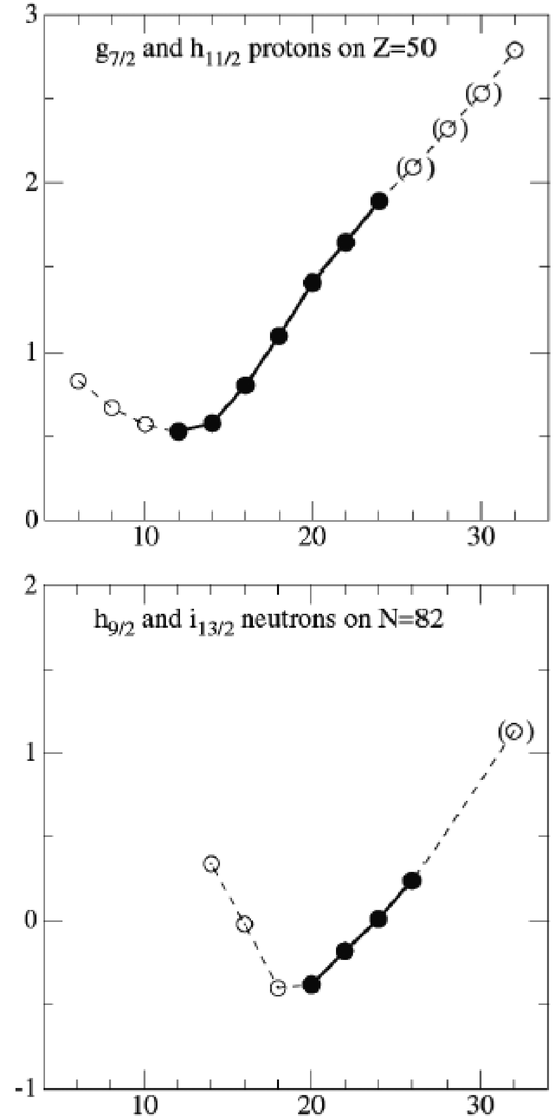


Weaker S. O. splitting



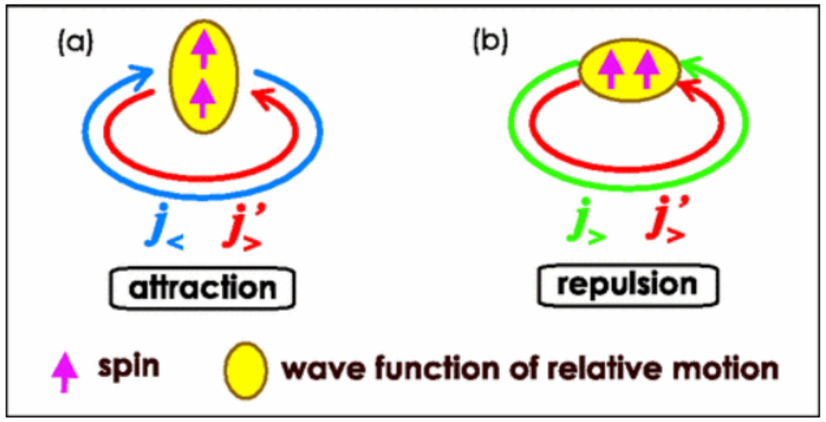
J. Dobaczewski, W. Nazarewicz, T.R. Werner, J.F. Berger, C.R. Chinn, J. Decharg´e, PRC 53, 2809 (1996).

S.O. splitting along isotop(n)es



J. P Schiffer et al., PRL92, 162501 (2004)

1st order effect of Tensor on shell structure



T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi
Phys. Rev. Lett. **95**, 232502

Polarization of unstable nuclei (developed in 1960s)

^{17}F(g.s.;5/2+), β+ emitter with 66 s

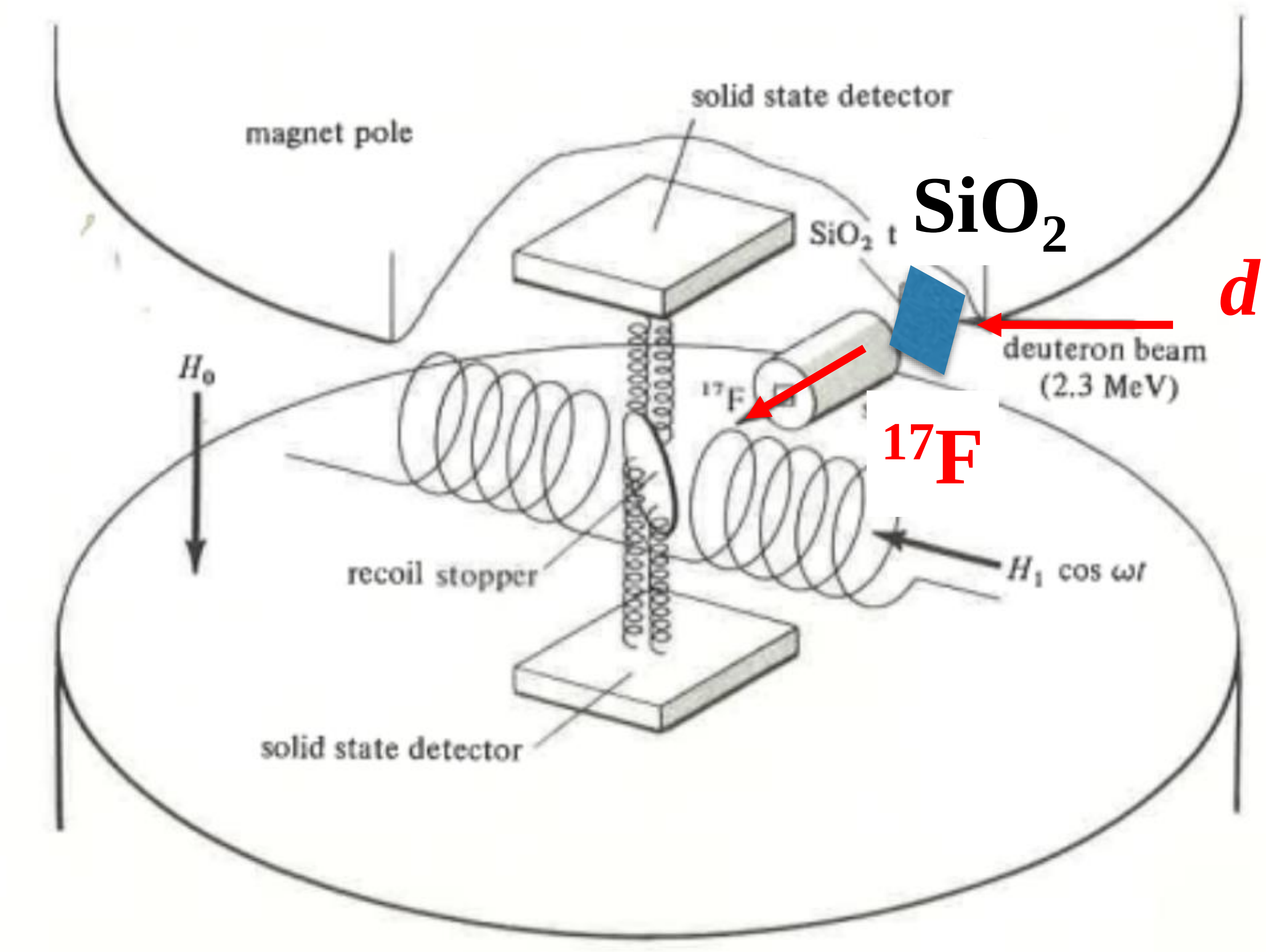


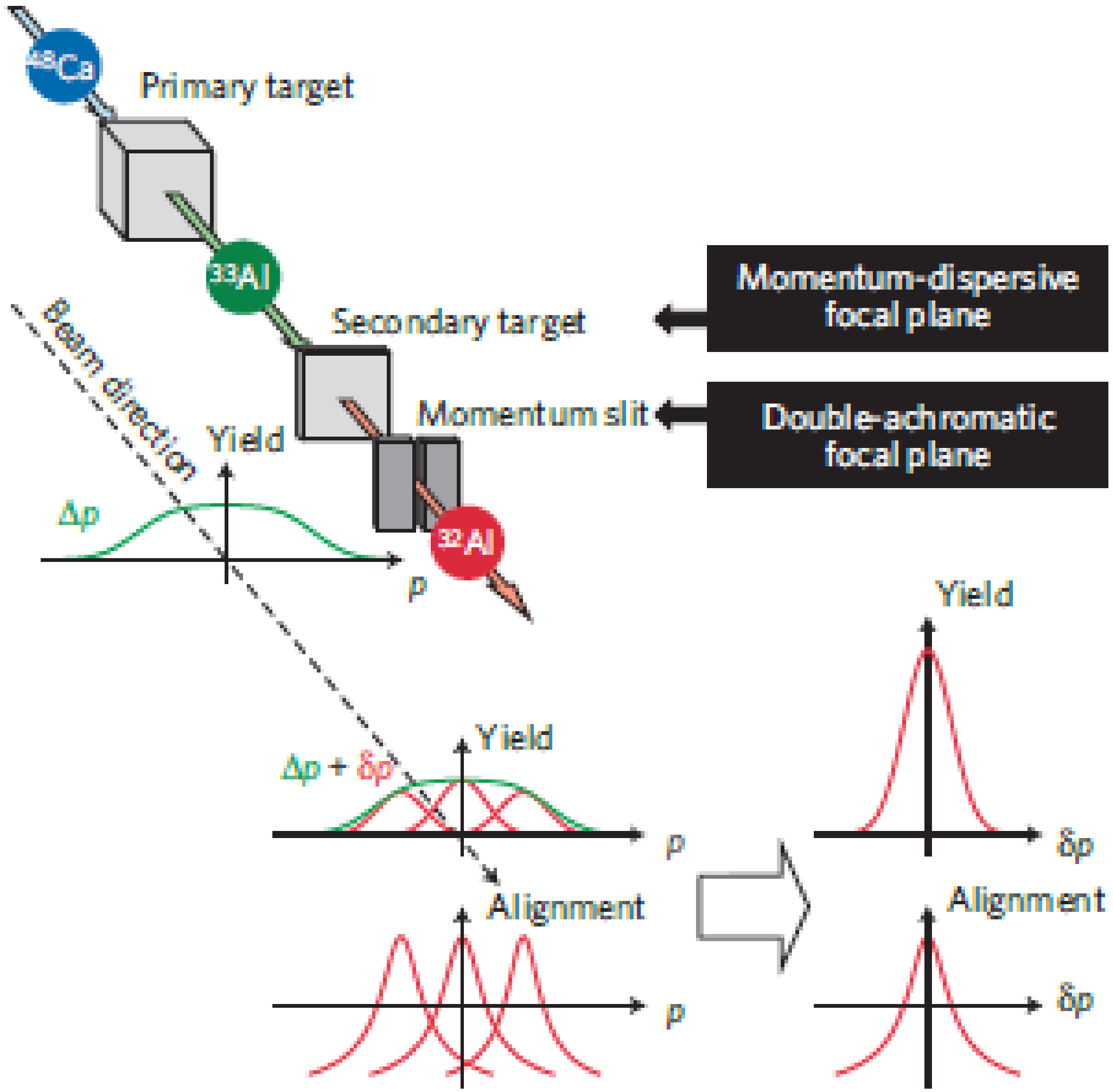
Fig. 6-24 A schematic drawing of the NMR experiment for ^{17}F.

$^{18}O(d,p)^{17}F$

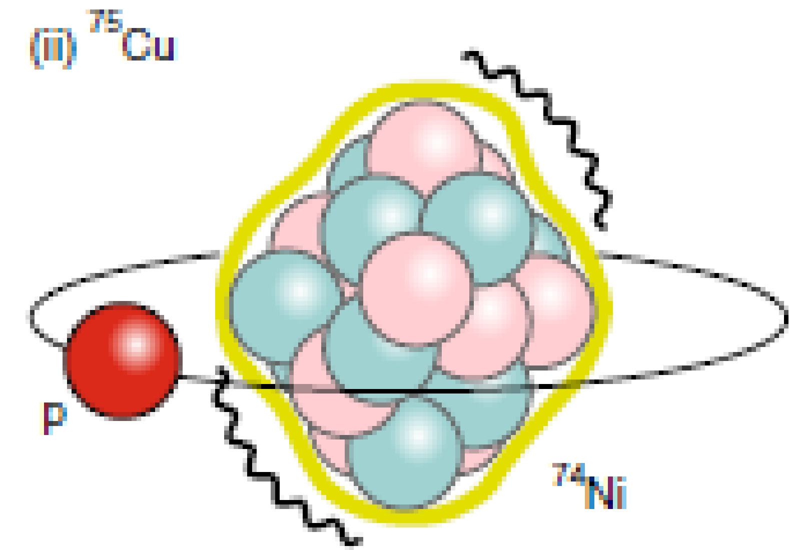
Sugimoto et al.

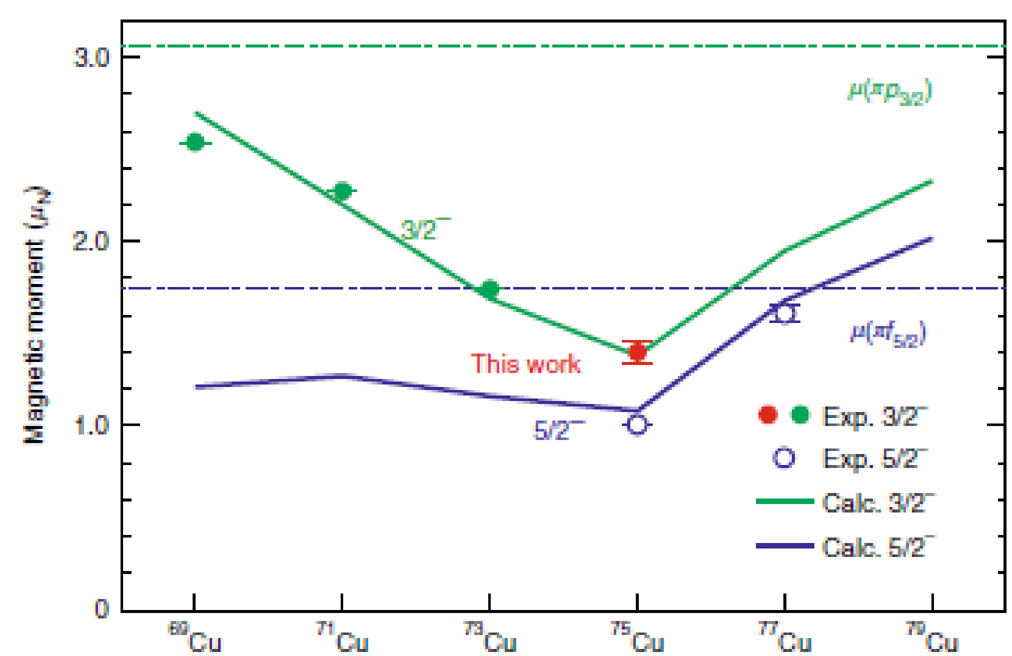
→ Measure magnetic moments of unstable nuclei

RI spin alignment with dispersion matching



Ichikawa et al.,
Nature Physics 8, 918-922 (2012)

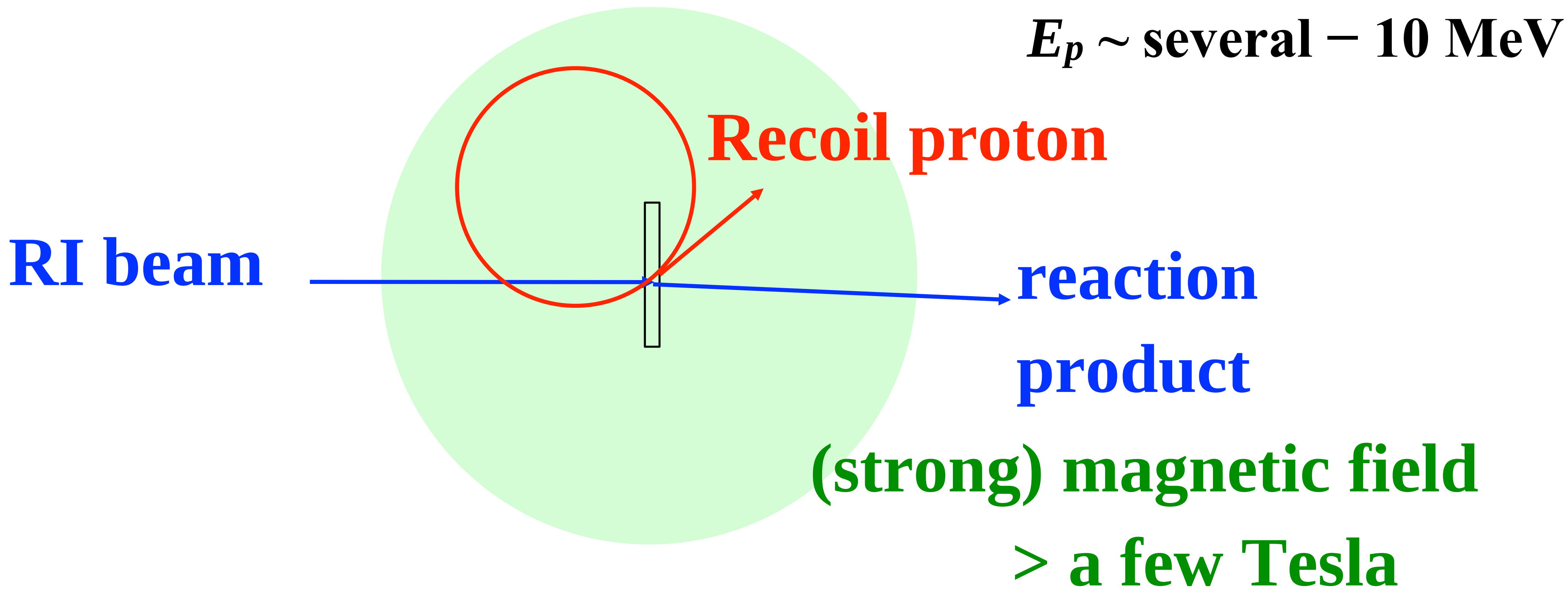




Ichikawa et al.,
Nature Physics 15, 321-325 (2019)

Polarized target for RI-beam experiments

is difficult because of the inverse kinematics

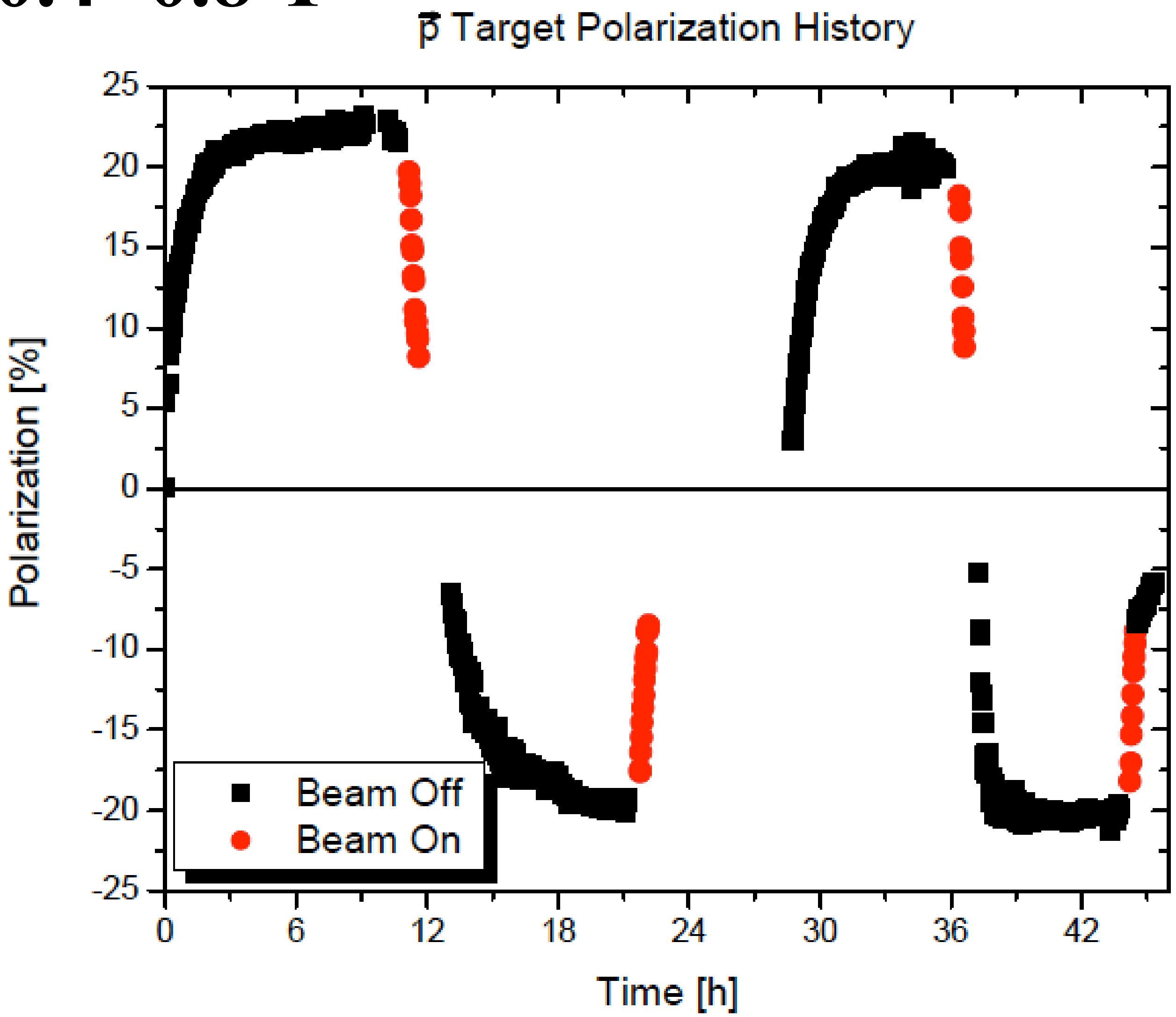


Should be operated in a low-magnetic field (< 0.5 T).

ORNL-PSI Polarized Proton Target

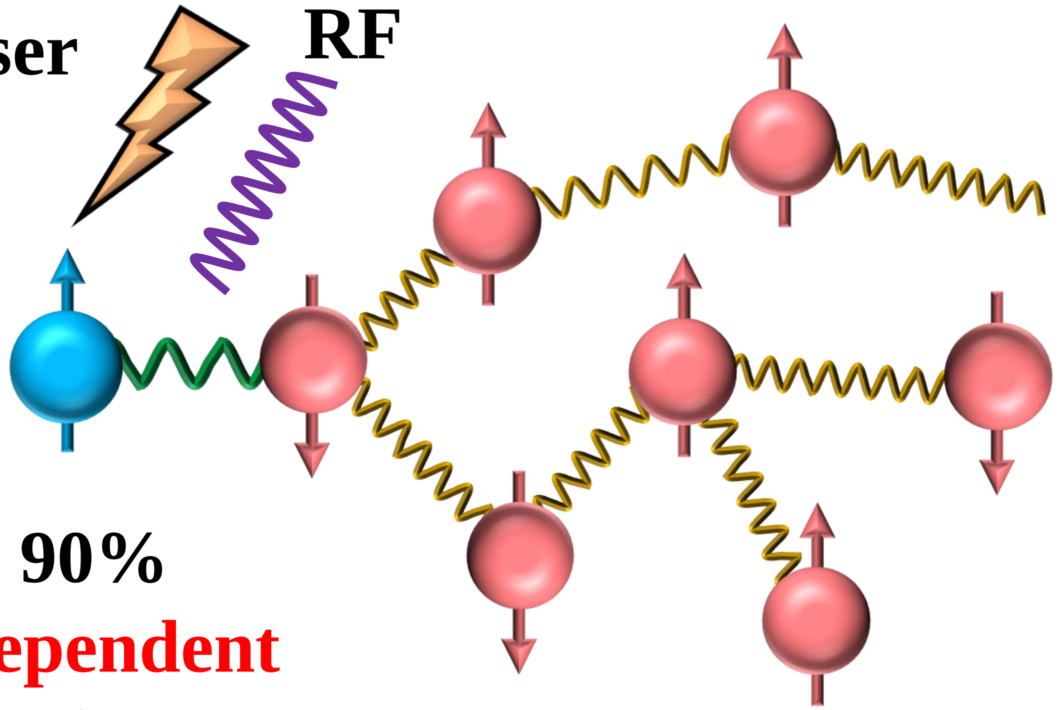
Spin-frozen operation of traditional DNP target
another promising way to prepare pol. target for RI-beam exp.

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



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

Triplet-DNP：solid polarized proton target at low magnetic field

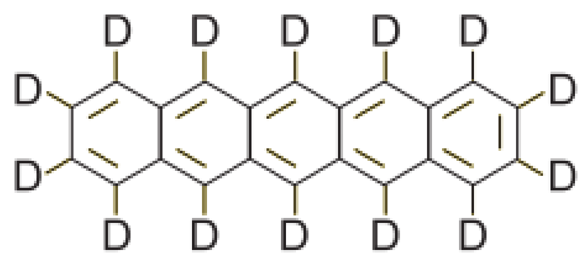


Environment: **0.3 T, 100 K**

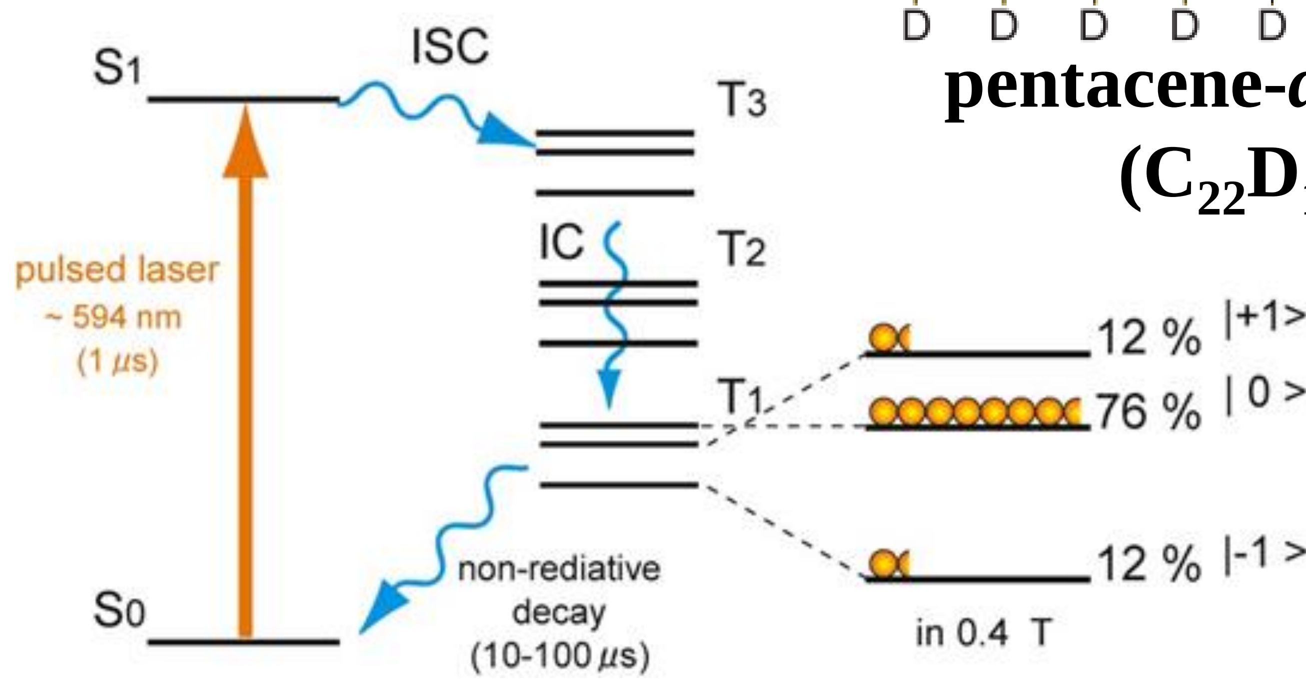
Polarization：^{1}H (20-30%)

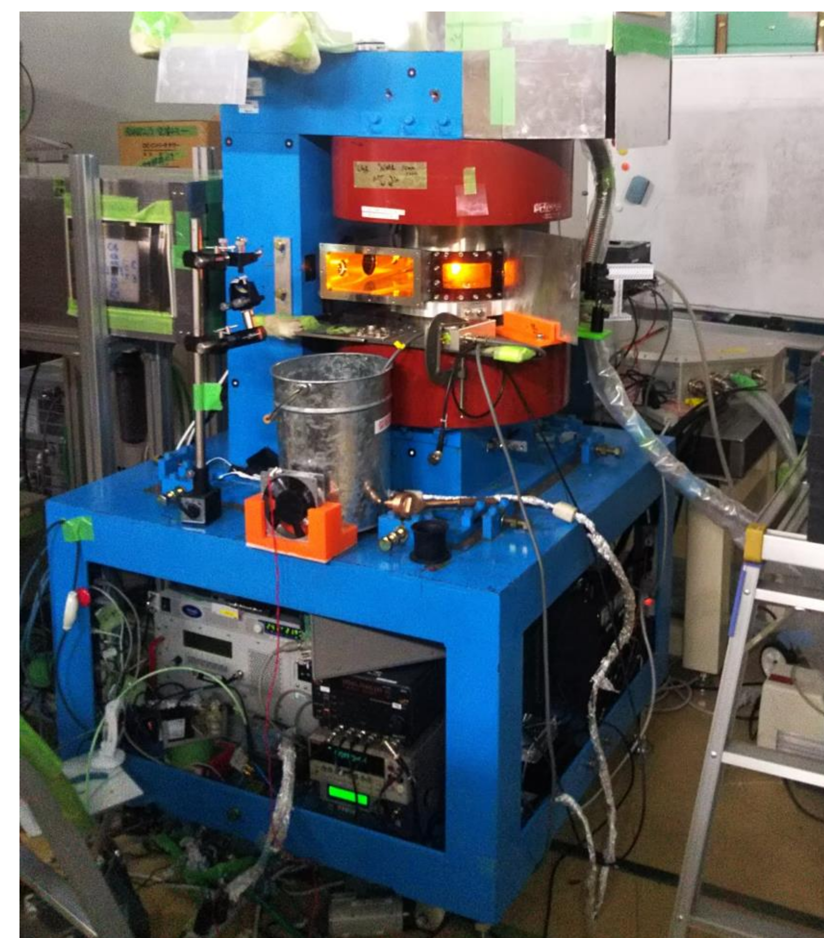
Pe = 90%
(independent of B, T)

(In conventional DNP, Pe depends on B and T)



pentacene-d_{14}
($C_{22}D_{14}$)



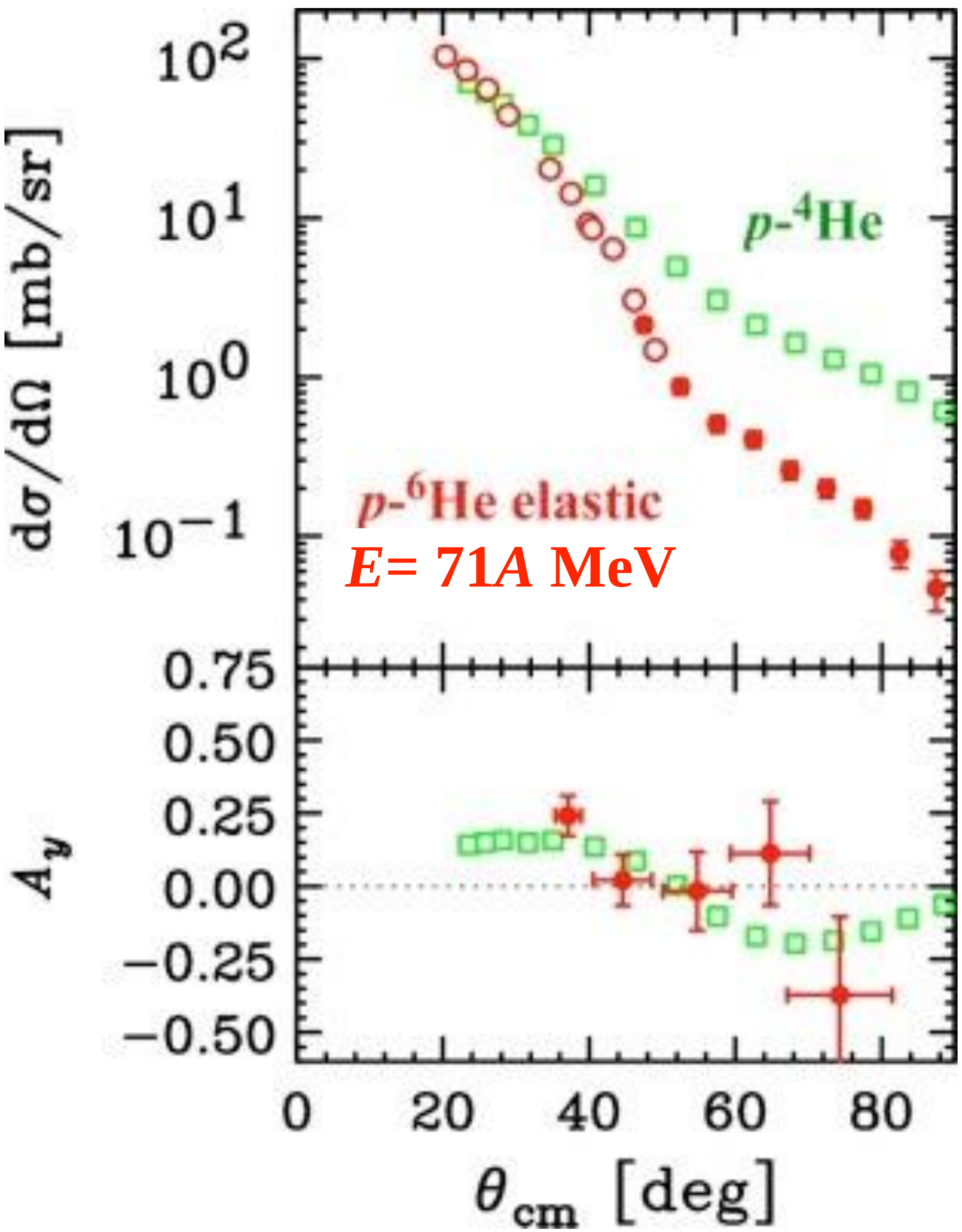


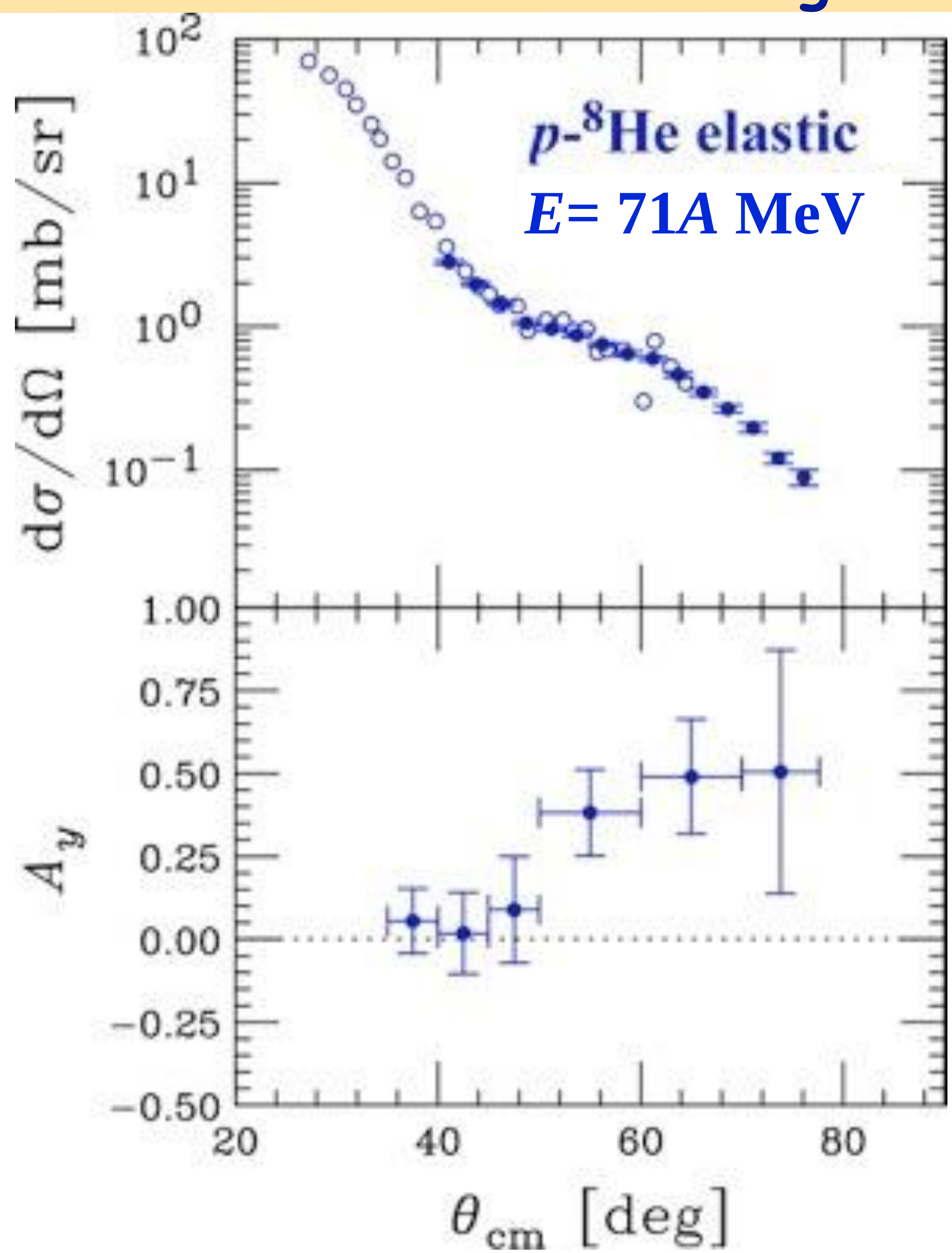
K. Tateishi
(RIKEN)

dσ/dΩ, A_y for p+^{4}He/^{8}He

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).

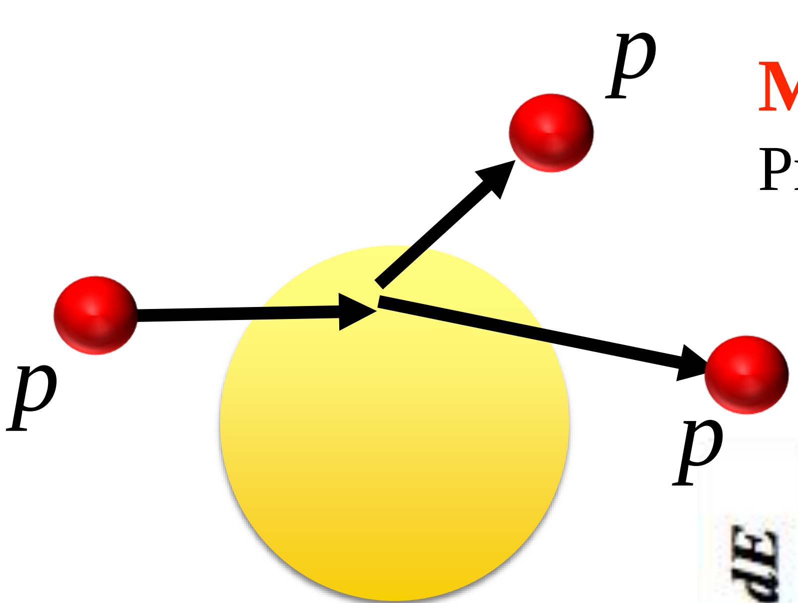
The FIRST SPIN ASYMMETRY DATA taken in RI-beam Scattering





→ **Indicating shallow S.O. potential**

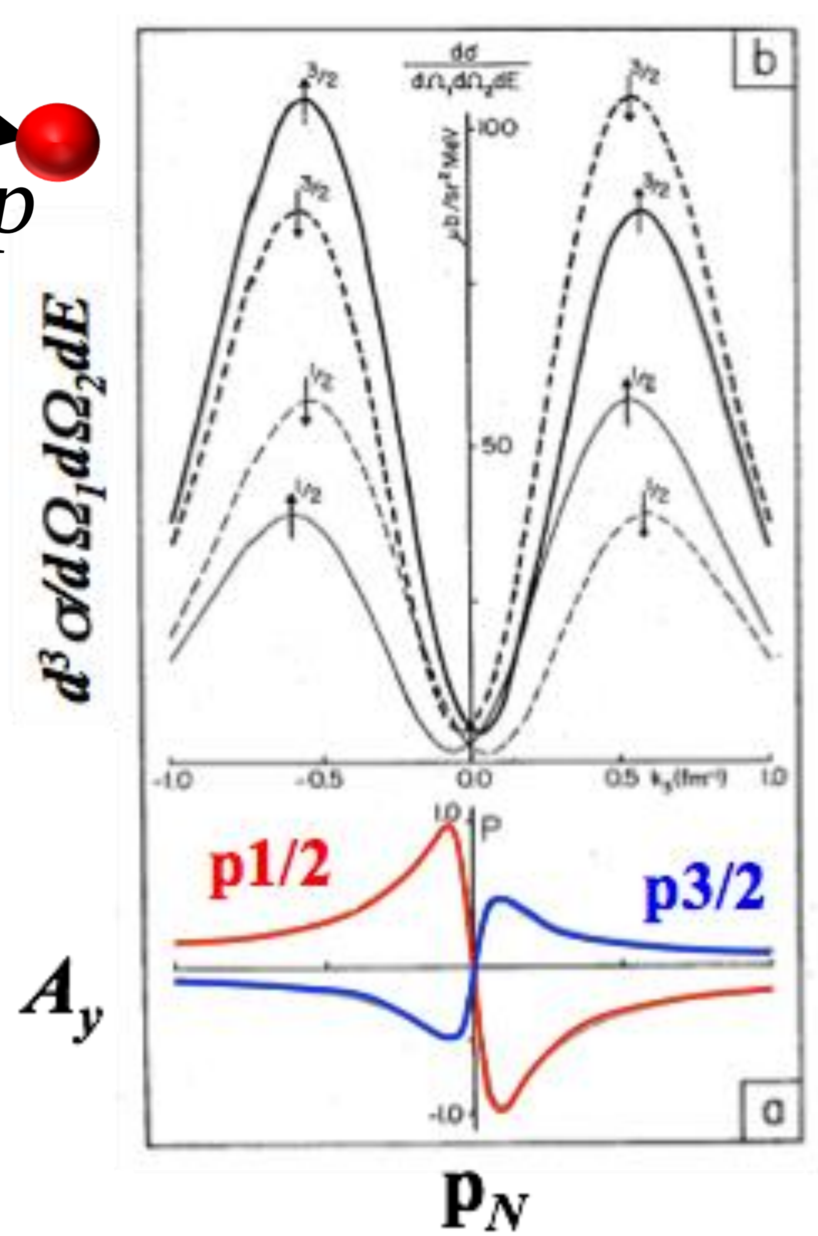
Future application of triplet DNP: Spin Polarization in ($\vec{p}$,pN) in inverse kinematics



(p,pp) reaction

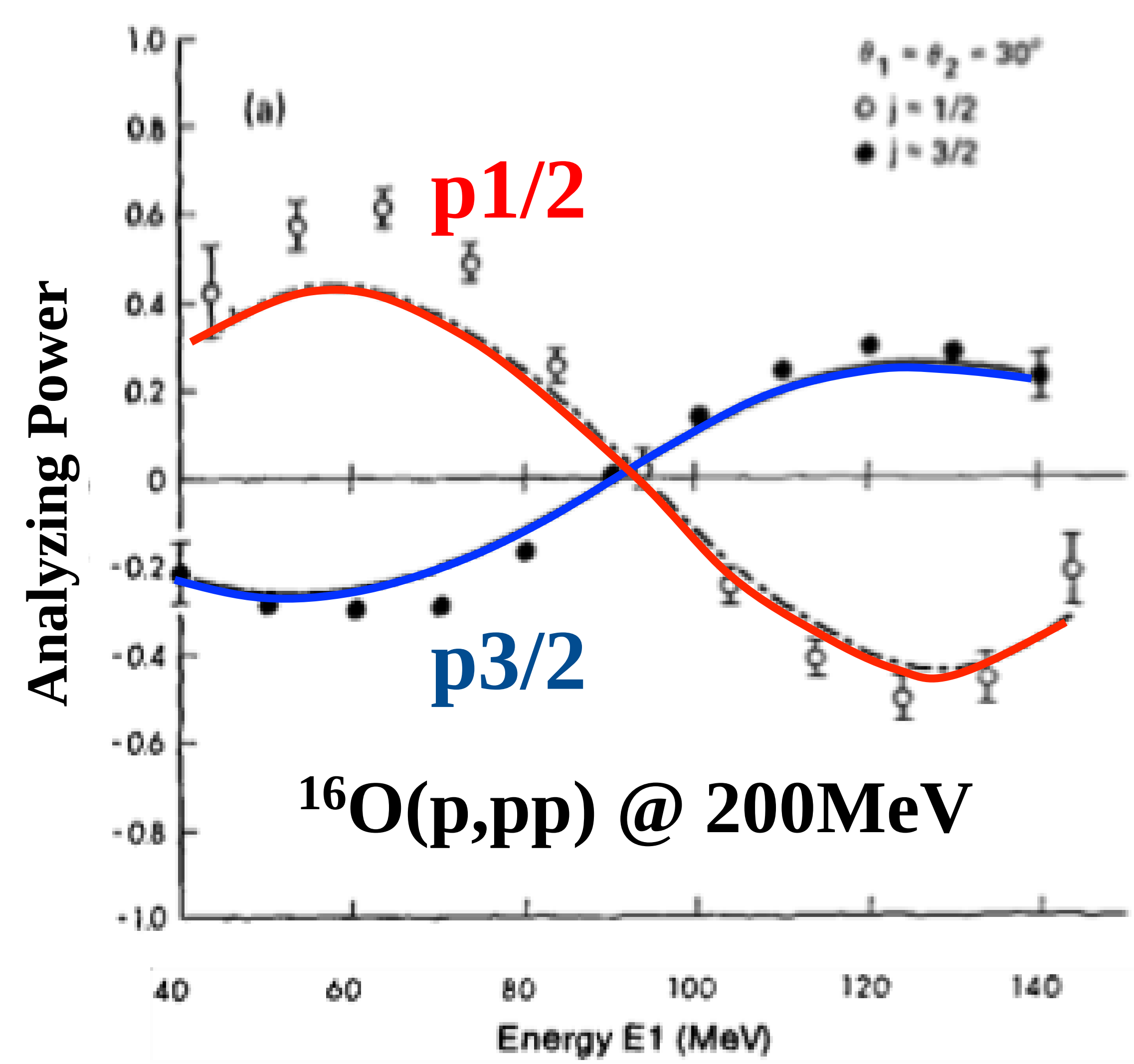
Maris effect

Proposed by Maris & Jacob



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

Demonstrated at TRIUMF
by Kinching et al.

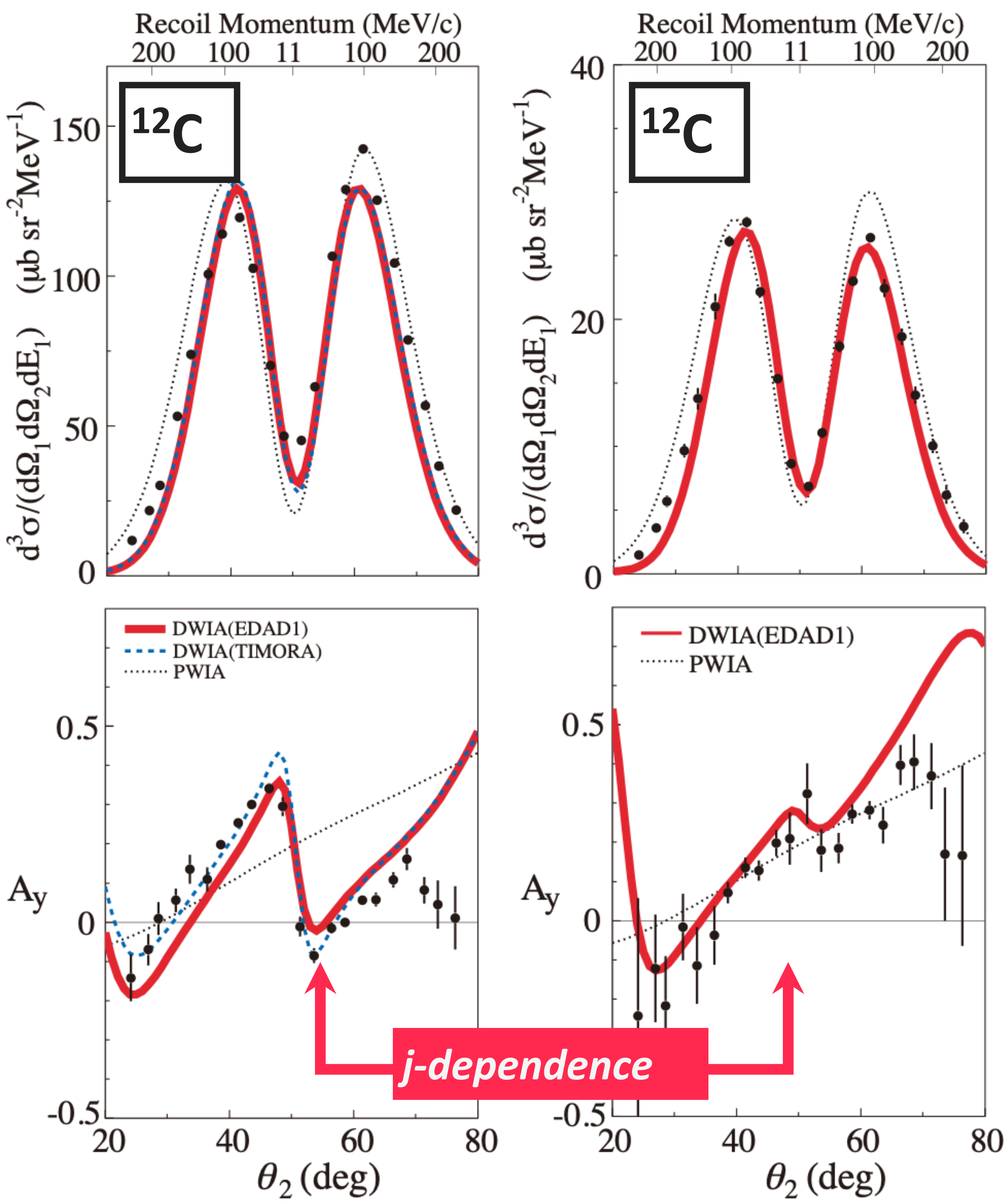


P. Kinching et al., NPA 340 (1980) 423.

Normal kinematics data by Kyushu gr. @ RCNP

T. Noro, T. Wakasa et al., et al., PTEP ptaa109 (2020).

$p_{3/2}$ (l=1, j=3/2) ***$p_{1/2}$ (l=1, j=1/2)***



PTEP

Prog. Theor. Exp. Phys. **2012**, 00000 (13 pages)
DOI: 10.1093/ptep/0000000000

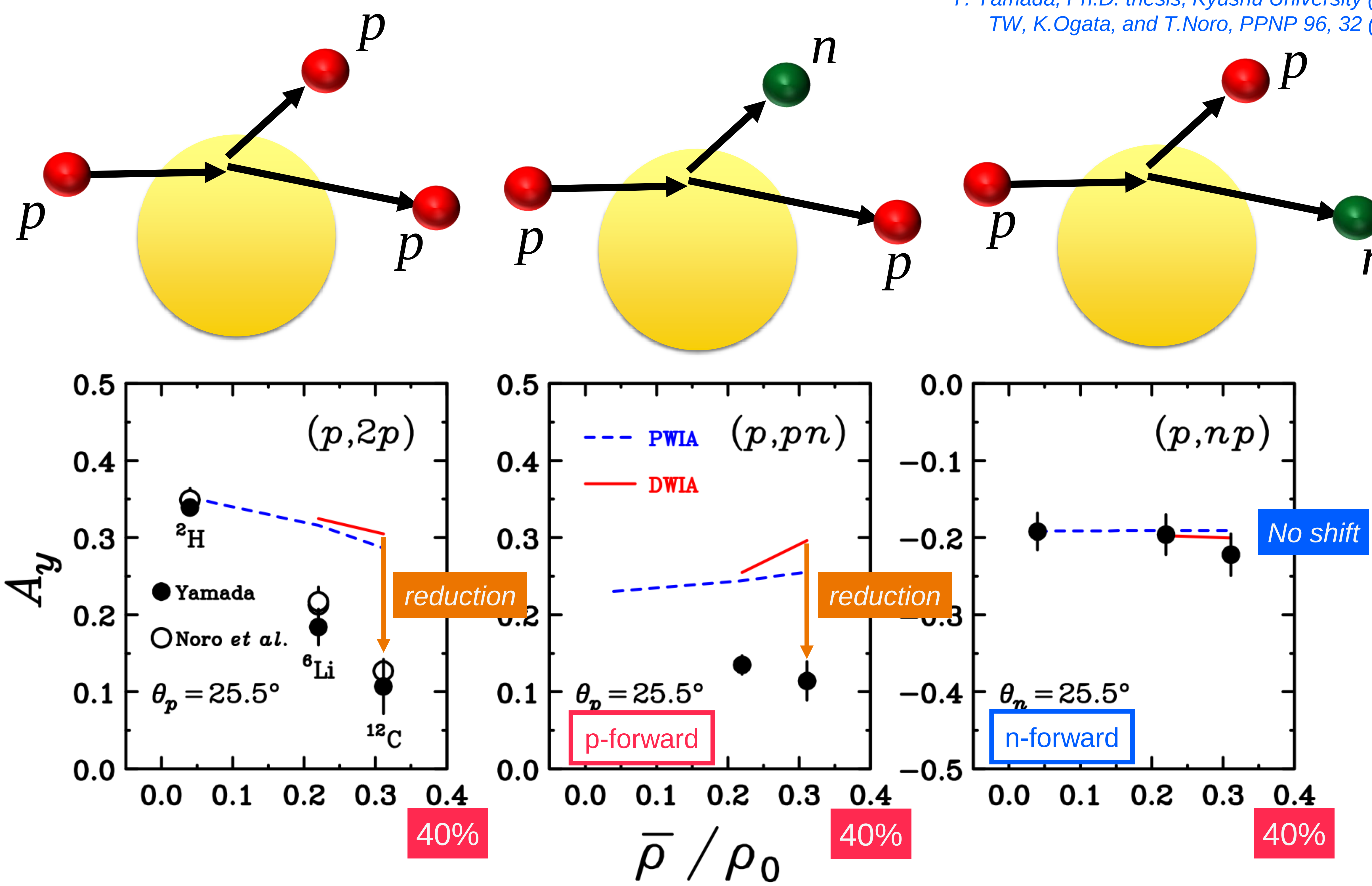
Experimental study of $(p, 2p)$ reactions at 197 MeV on ^{12}C, ^{16}O, ^{40,48}Ca, and ^{90}Zr nuclei leading to low-lying states of residual nuclei

DWIA

● exp. data

A_y puzzle for $1s_{1/2}$ knockout (p,pN)

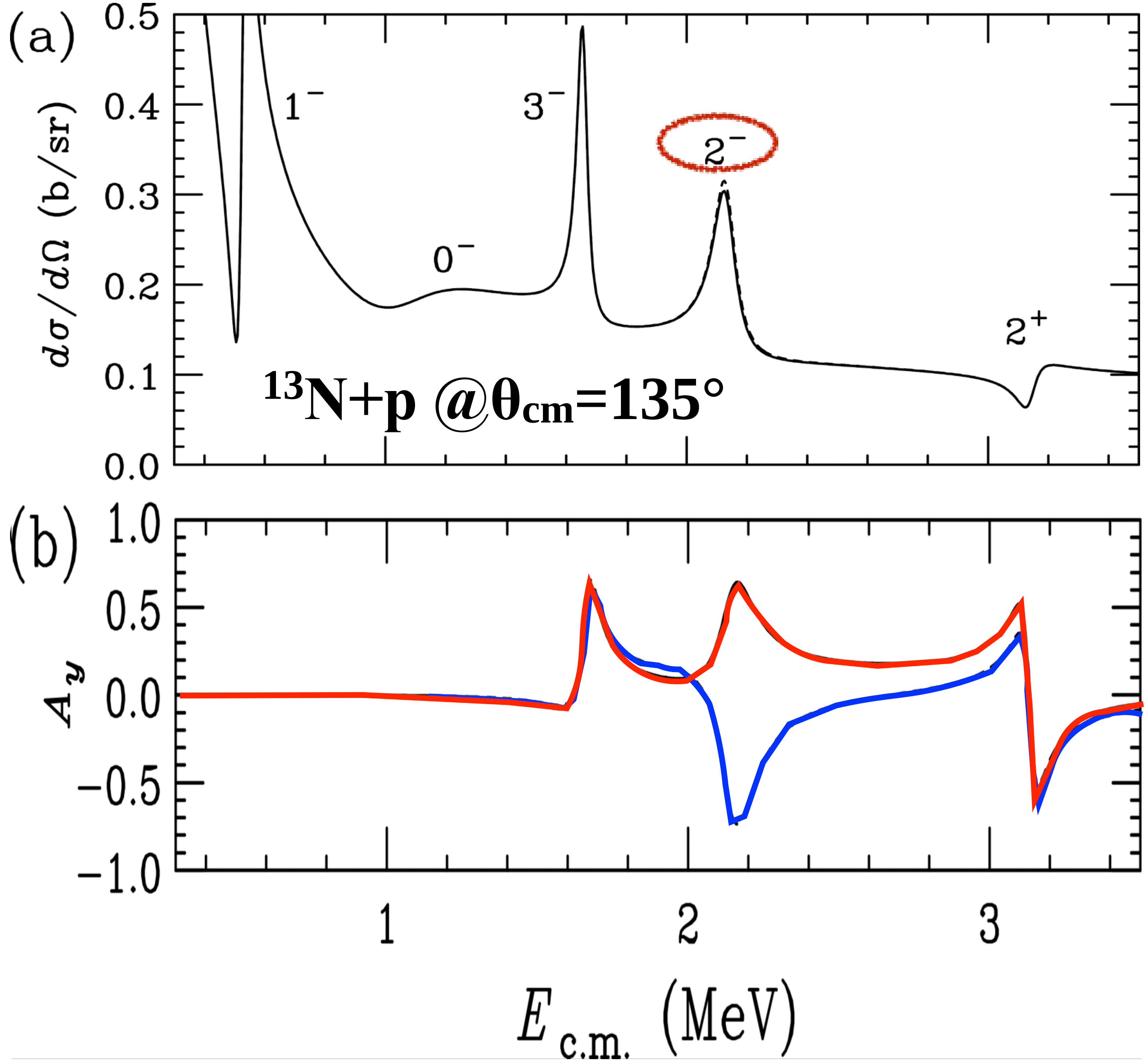
Y. Yamada, Ph.D. thesis, Kyushu University (2010).
TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).



Nuclear medium effects on 2NF depend on isospin (charge) transfer
→ Interesting to see the (N-Z)/A dependence with RI beams

Polarization in Resonant Scattering

Sensitivity test with R-matrix calculations



Two possibilities:

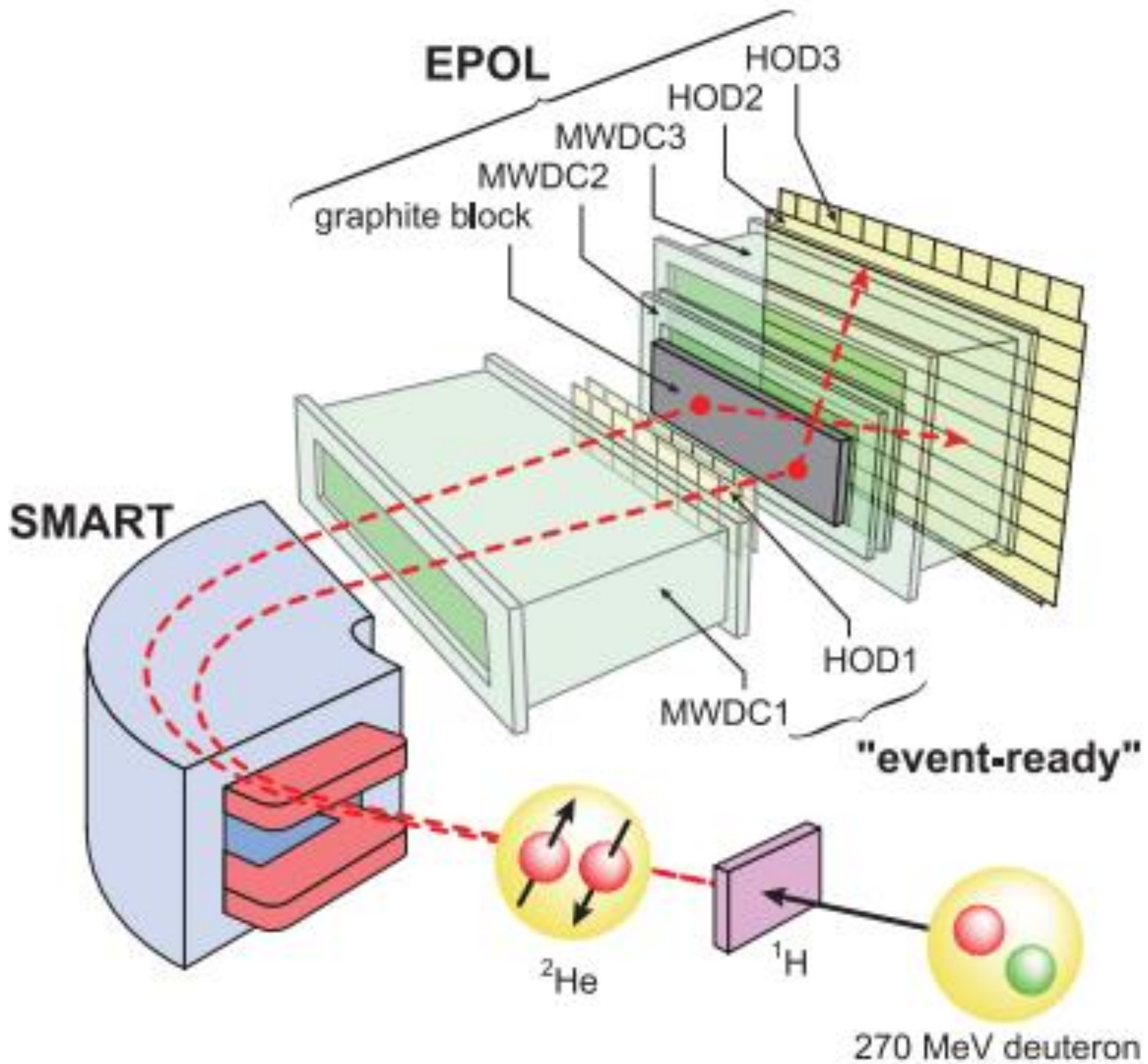
1) $^{13}N(1/2^-)$ + $\pi d_{5/2}$

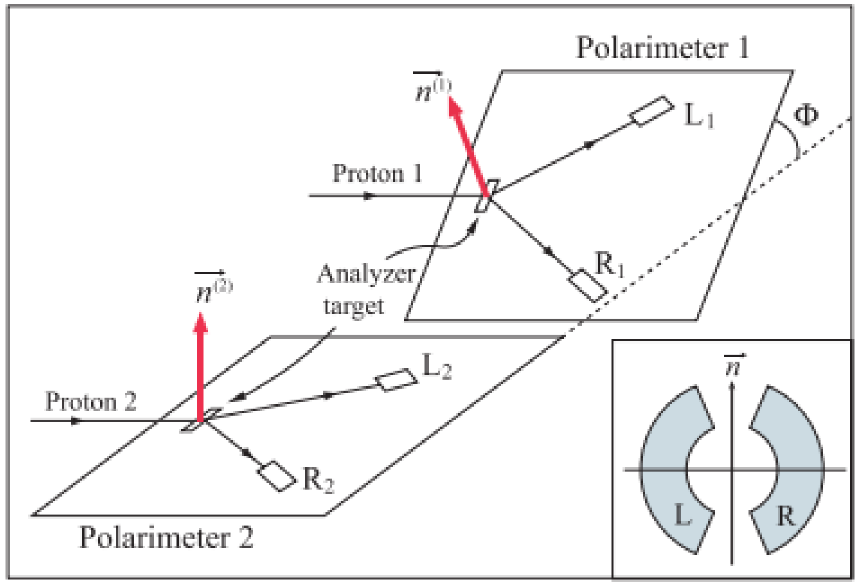
2) $^{13}N(1/2^-)$ + $\pi d_{3/2}$

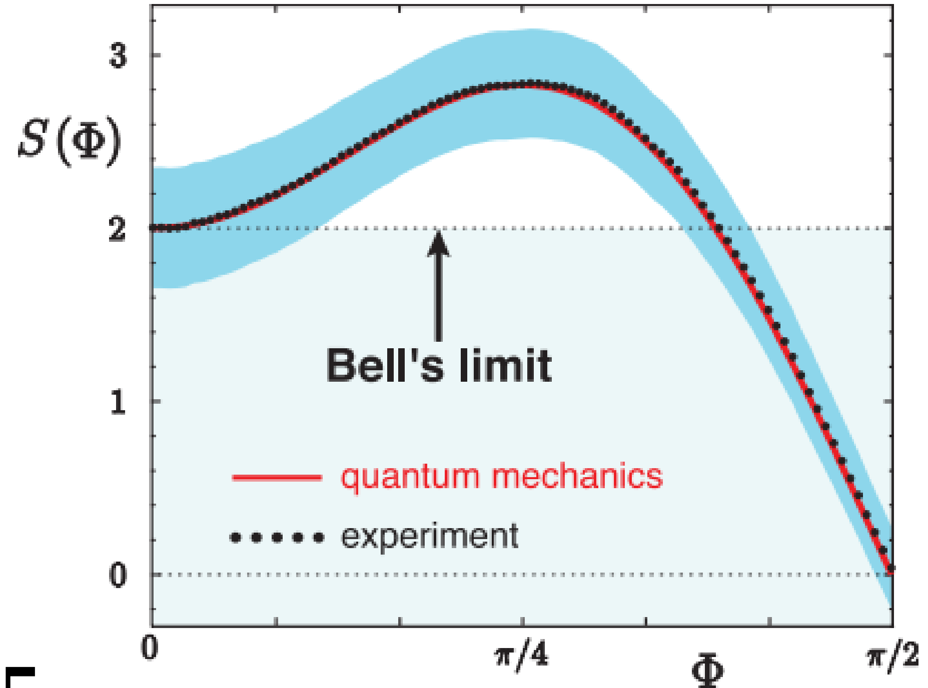
No difference in cross section . . .

A_y is sensitive to the configuration!

Spin correlation between ejectiles from RI : an EPR experiment







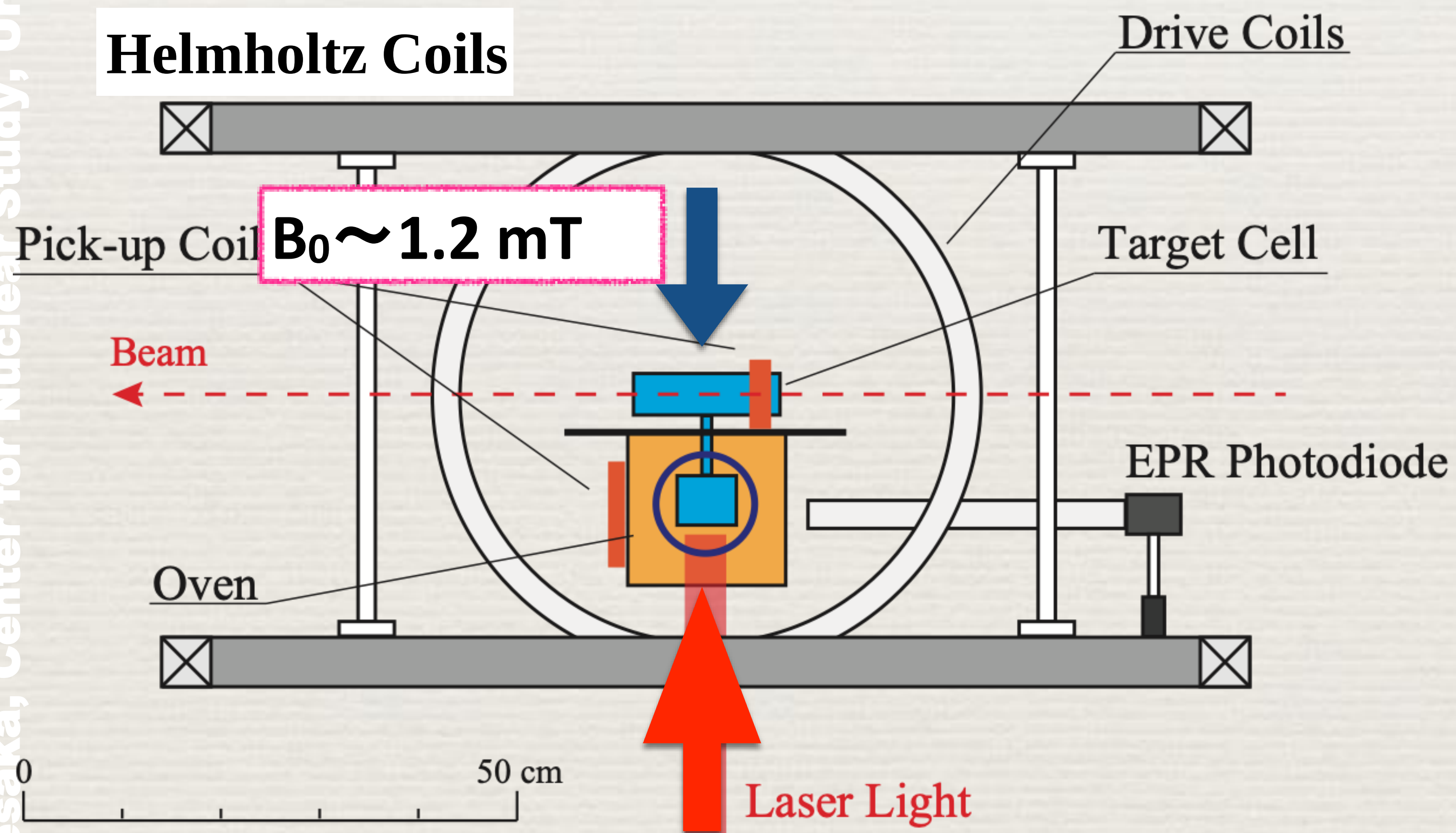
Sakai, Saito, et al., PRL97 (2006) 150405

QM is supported.

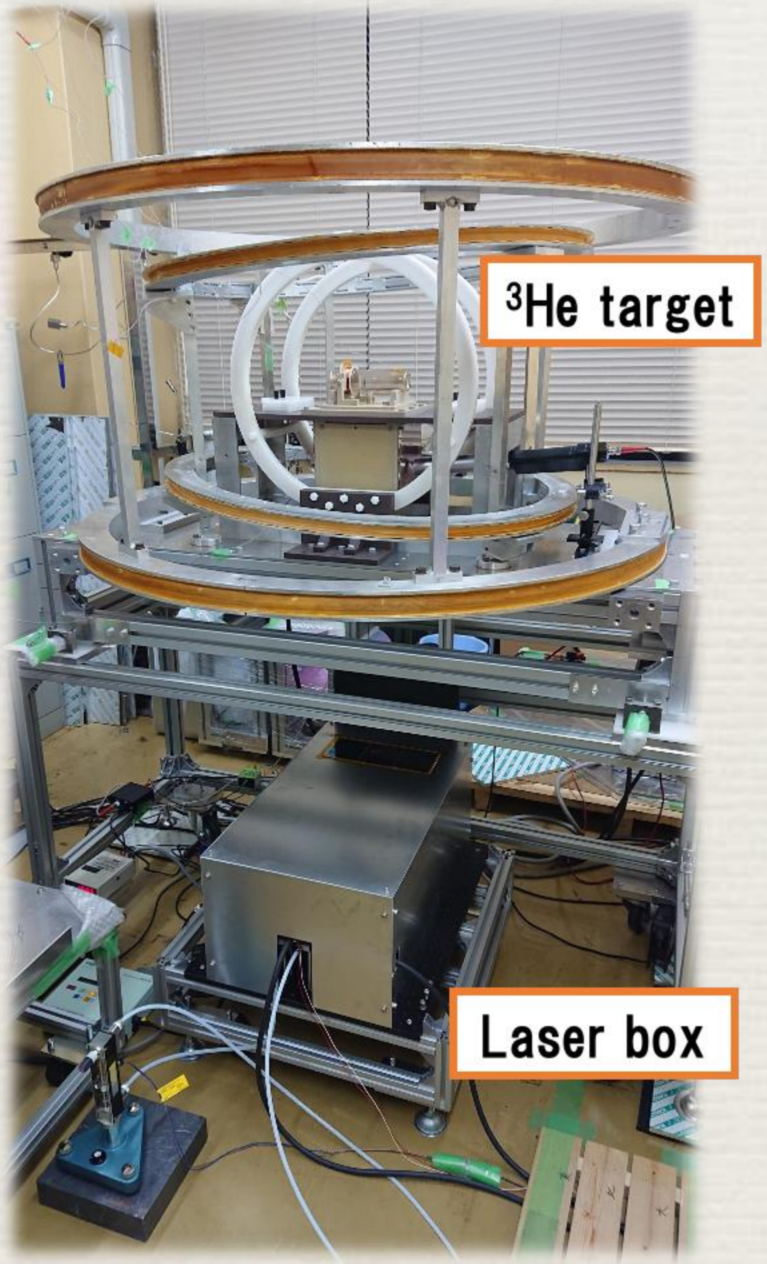
Spin correlation measurement of unbound nuclei (^{2}He)

Polarized ^{3}He Target System

- Polarization Method :
  - (Alkali-Hybrid) Spin Exchange Optical Pumping
- Polarization (current) : 60%, Relaxation time : about 40 hrs
- Calibration of absolute values : EPR & neutron-transmission

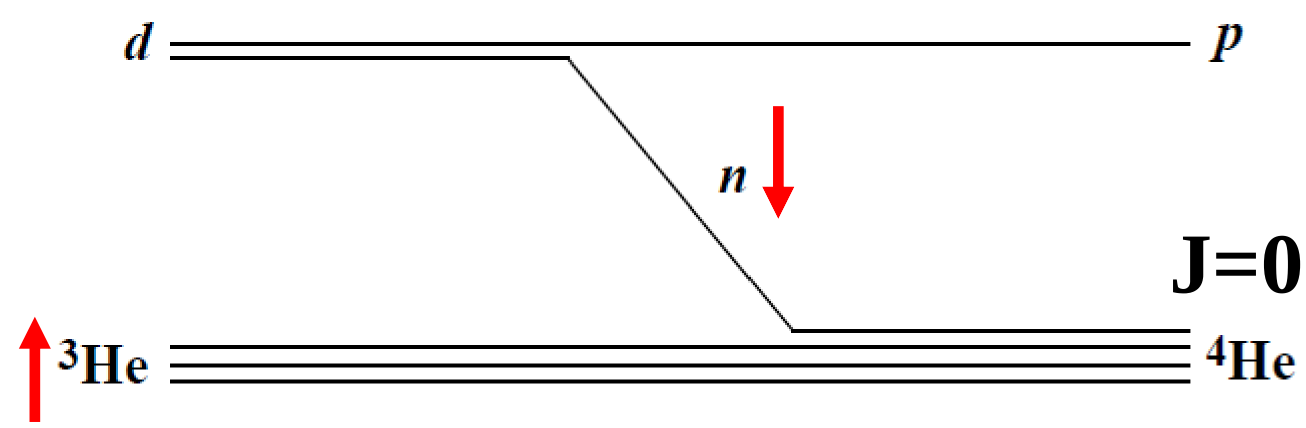


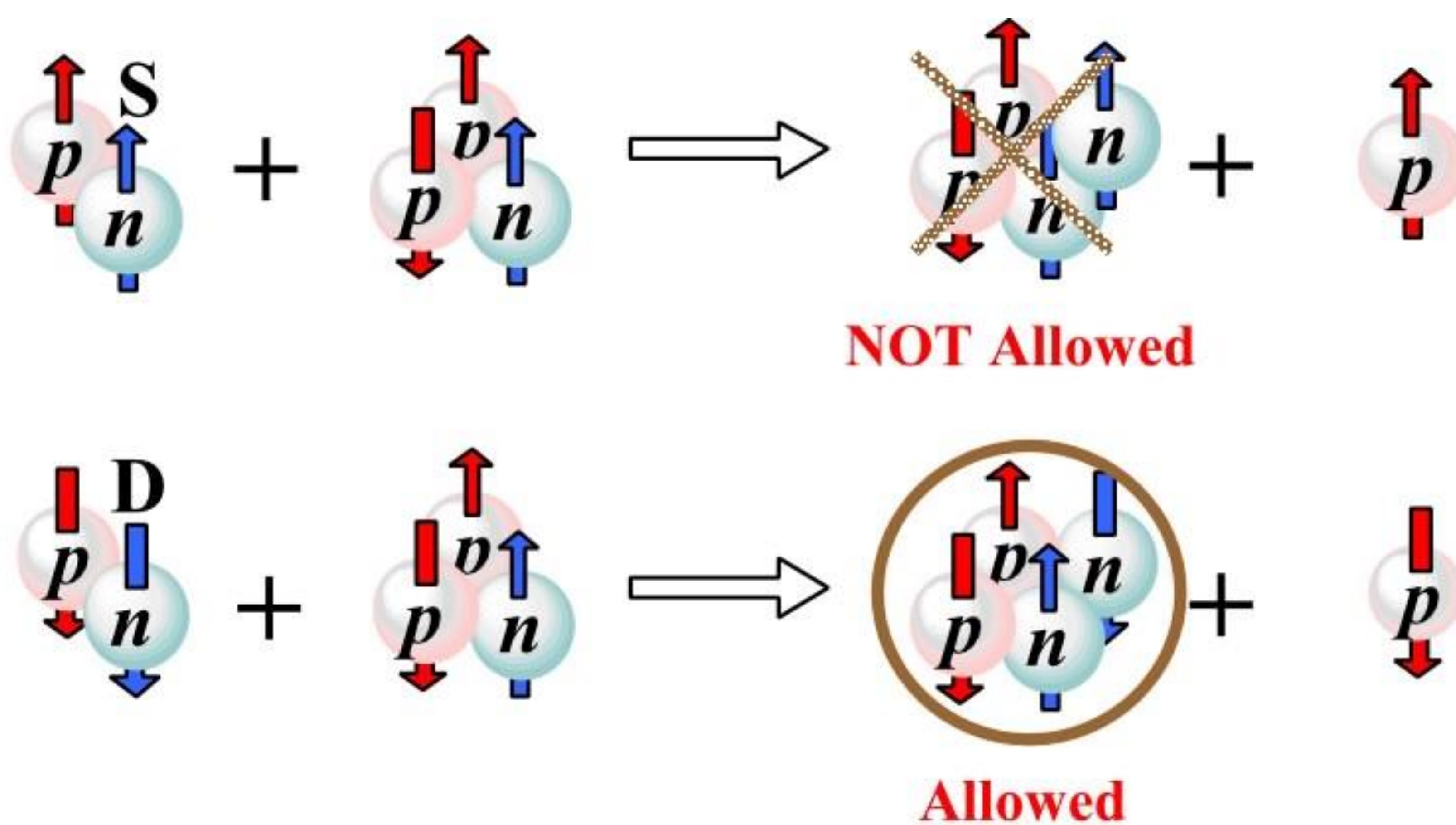
Diode Laser + VBG (Volume Bragg Grating)
Power : 80W
Wavelength : 794.7 nm
width : 0.2 nm (FWHM)



$^3He(d,p)^4He$ Reaction : D-state filter

- Neutron exchange process:





T. Uesaka et al., Phys. Lett. B **467** (1999) 199.

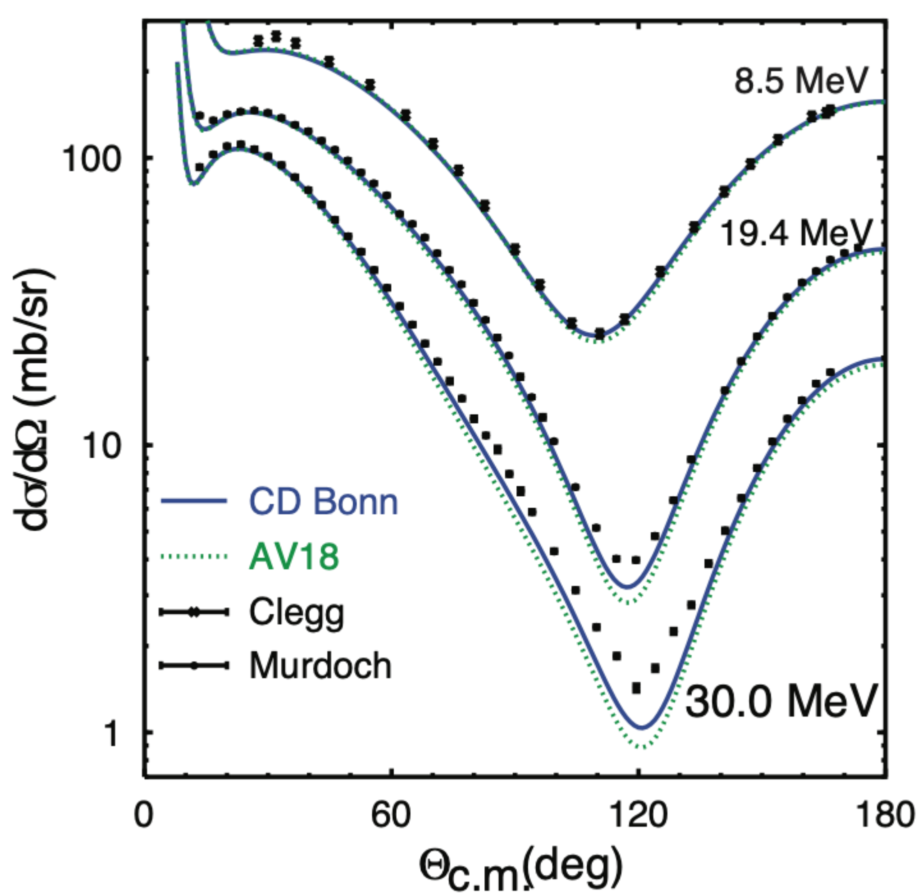
p-^{3}He scattering

Theory in Progress

Calculations above 4-nucleon breakup threshold energy open new possibilities of 3NF study in 4N-scattering.

up to 35 MeV

A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)

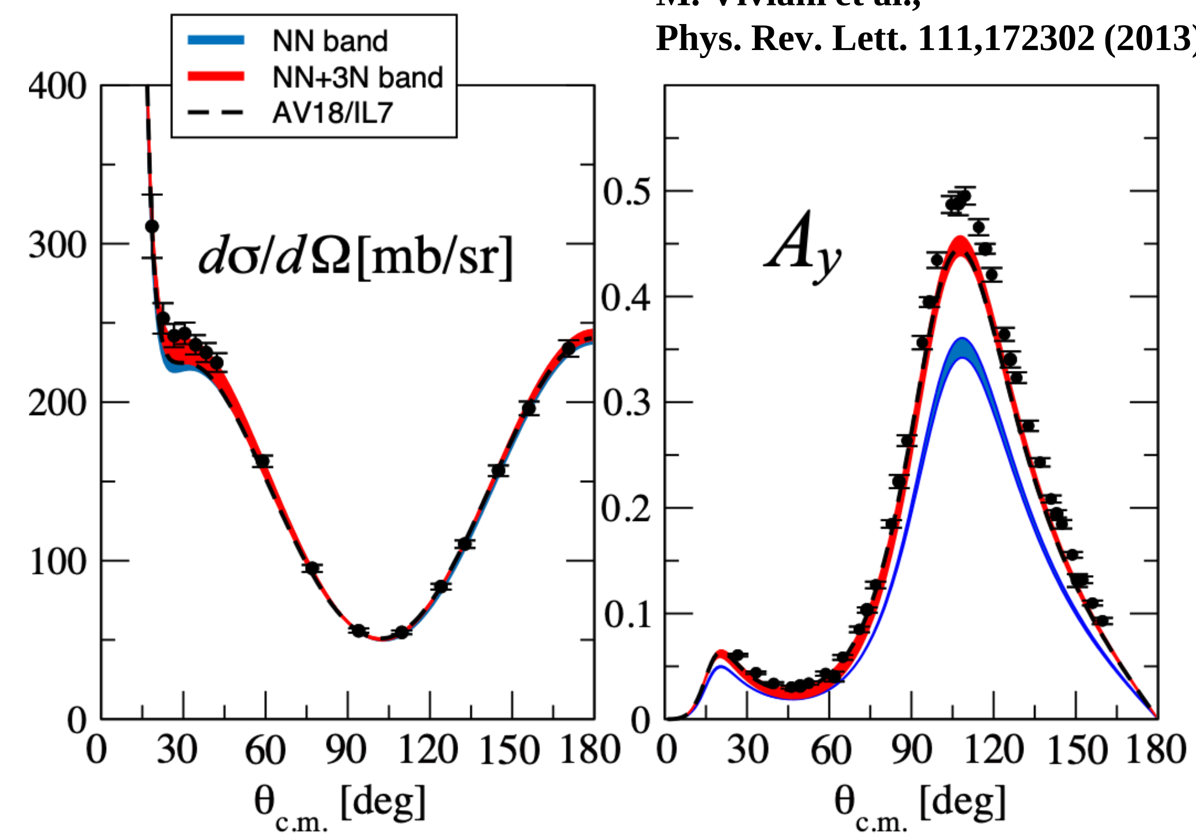


Discrepancies in cross section minimum
at higher energies

New rooms for 3NF study

at 5.54 MeV

M. Viviani et al.,
Phys. Rev. Lett. 111,172302 (2013)



- No signature of 3NFs in cross section
- ***Ay(p)*** **puzzle :** 3NFs sensitive to *p*-shell nuclei improve the agreement to the data.

How about spin observables at higher energy?

Summary

- Spin physics stared from the puzzles of the magic numbers and the strong spin-orbit split
- The development of the polarization experiment techniques is important especially for
  - beam polarization (atomic beam method)
  - Target polarization (DNP, triplet DNP)
- Collaboration between experimentalists and theorists led to important findings
  - Understanding of the origin of spin-orbit splitting
  - 2NF establishment
  - 3NF discovery
  - Optical potential model
  - Pion mode enhancement
  - Deuteron correlation ...
- RCNP is trying to boost their spin physics
- At RIBF, Uesaka laboratory is working for future polarization experiments with RI beam

Thanks for

- **T. Uesaka, K. Tateishi, H. Sakai, D. Suzuki (RIKEN)**
- **K. Sekiguchi (Titech)**
- **T. Wakasa (Kyushu)**
- **A. Tamii, H. Kanda, M. Fukuda, T. Yorita, N. Aoi (RCNP)**
- **J. Zenihiro (Kyoto)**

and many pioneers of spin physics