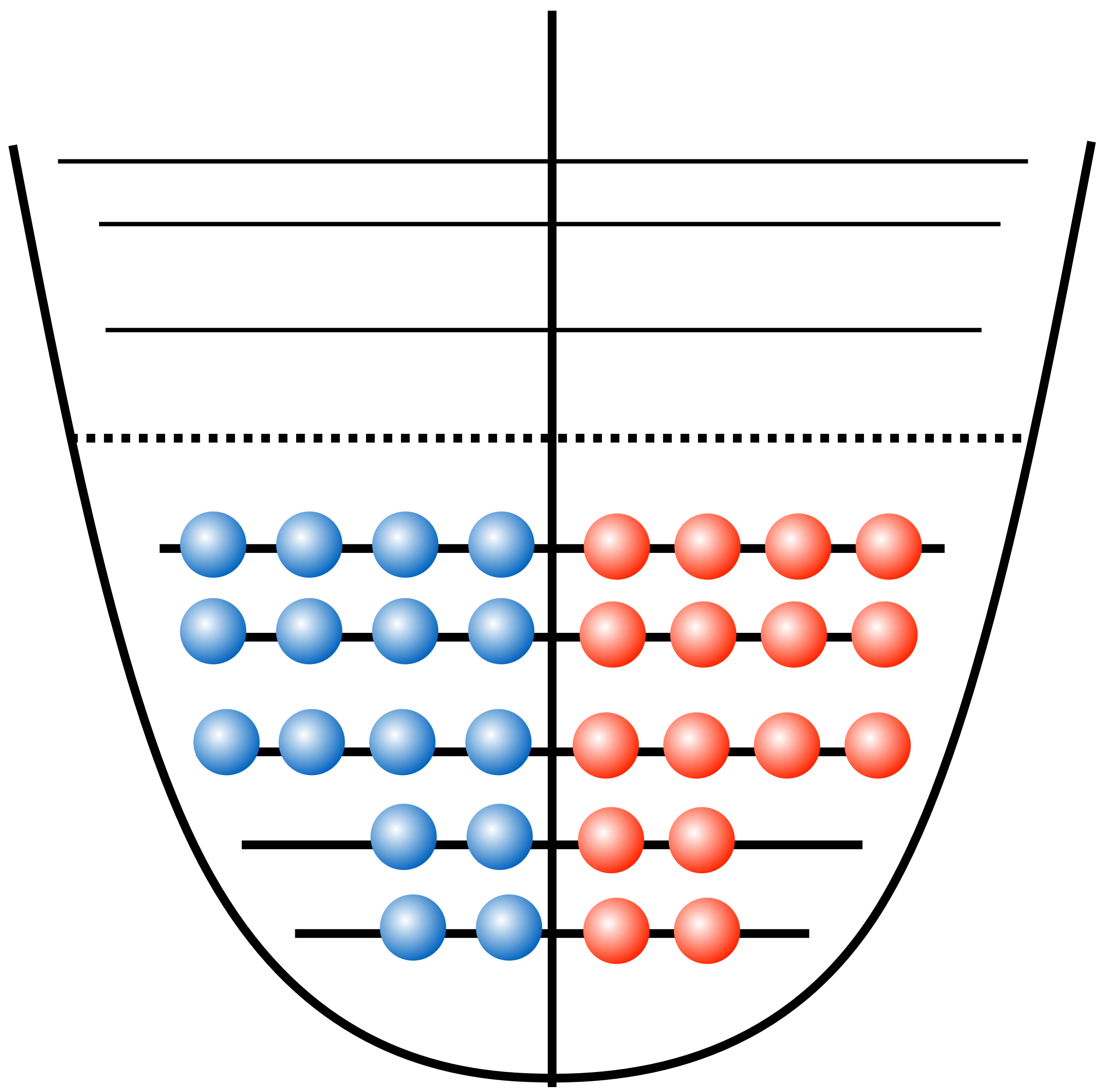
Part 2
Physics of quenching and spin-orbit coupling
Extension to RI-beam experiments

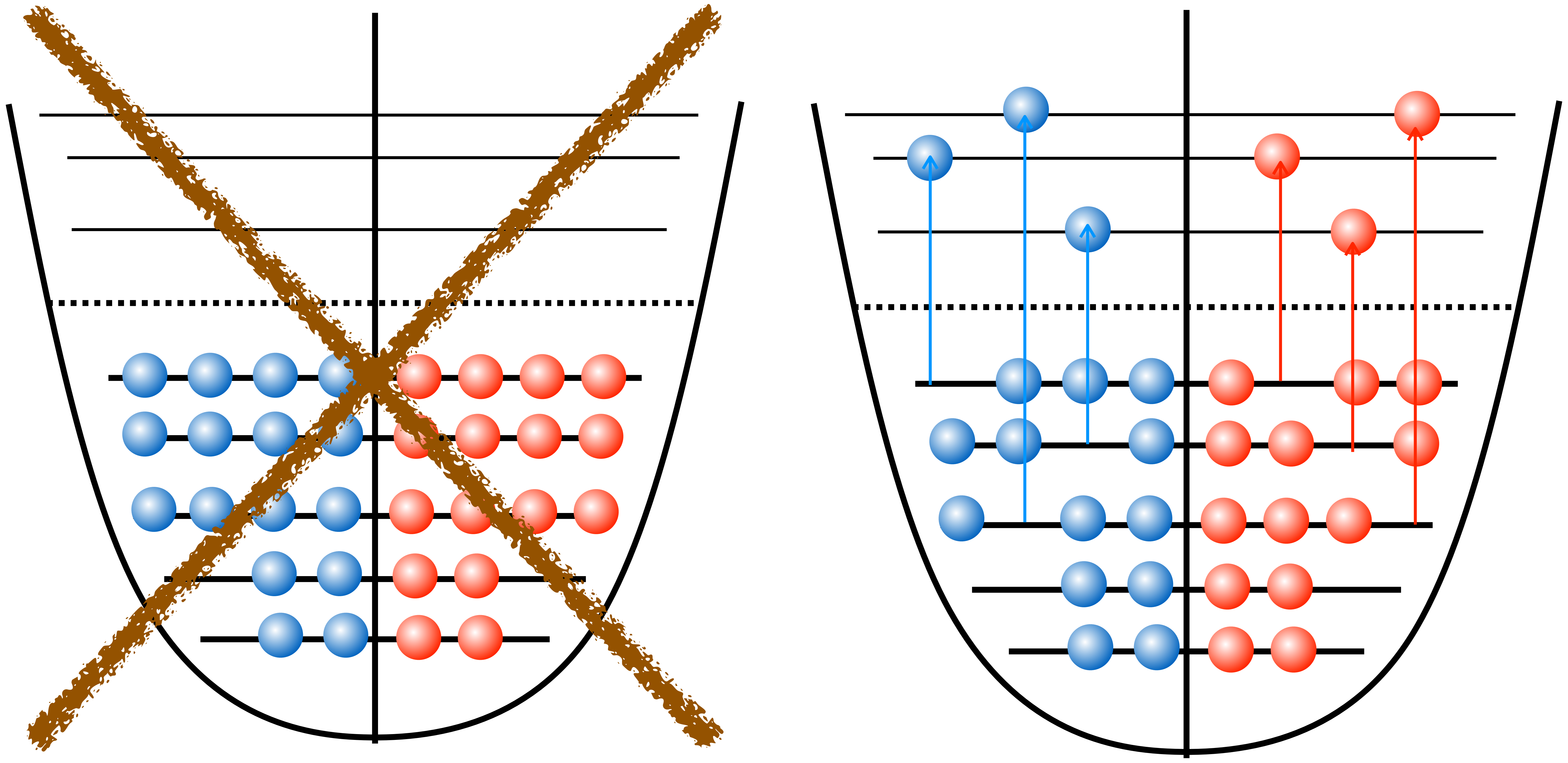
Occupation probabilities of nucleons

Fermi-gas model
(naive) Independent particle model
tell that the nucleons occupy the orbits from the lowest one.



Occupation probabilities of nucleons

Fermi-gas model
(naive) Independent particle model
tell that the nucleons occupy the orbits from the lowest one.
But this is not the case!

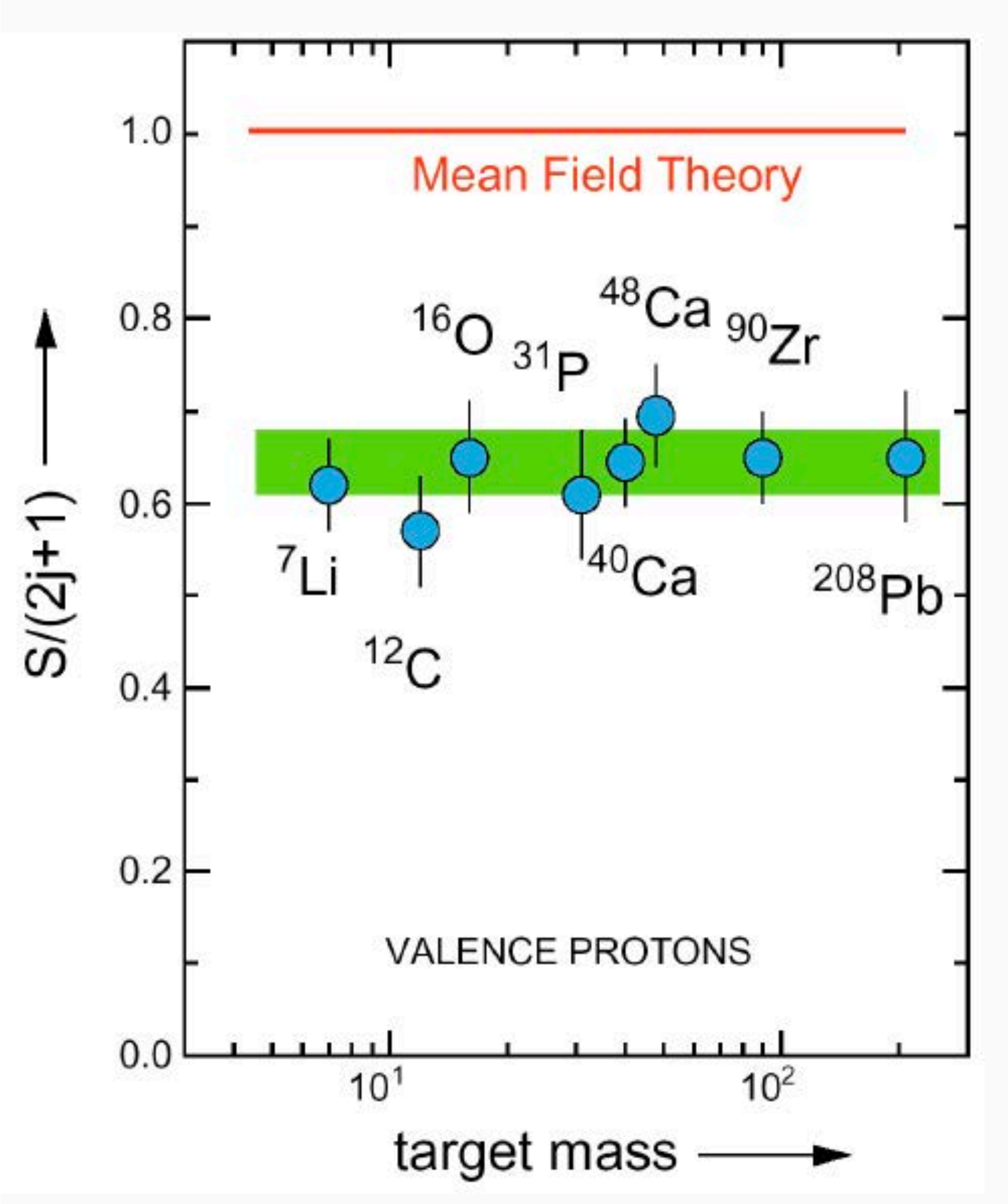


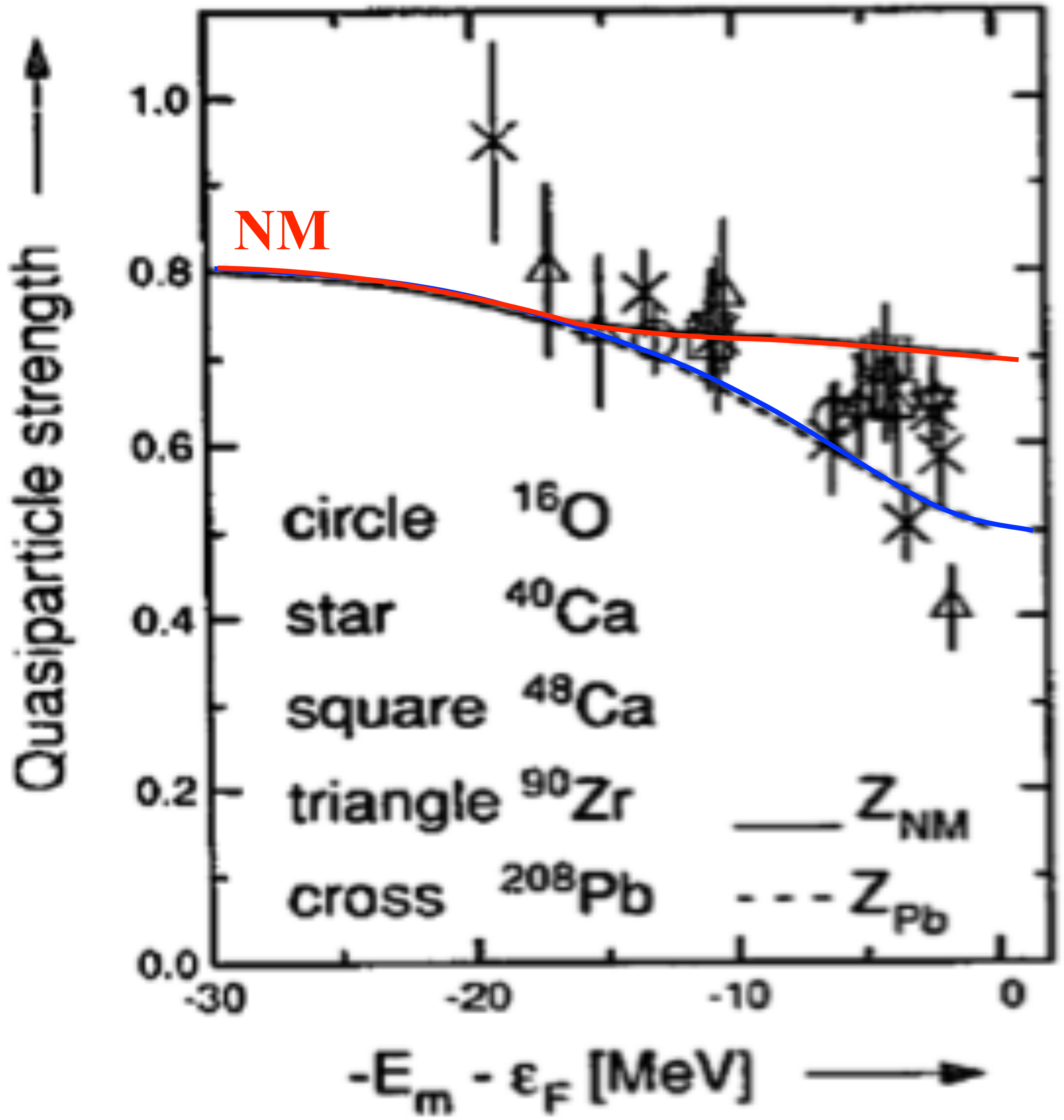
Occupation probabilities of nucleons

(*e,e'p*) Reaction

Lapikas, NPA 553, 297c (1993)

Single-particle strengths are ~65% of the independent particle values.





RMP Colloquia

Rev. Mod. Phys. 69, 981 (1997)

Independent particle motion and correlations in fermion systems

Vijay R. Pandharipande

Department of Physics, University of Illinois, Urbana, Illinois 61801

Ingo Sick

Department of Physics and Astronomy, Universität Basel, CH-4056 Basel, Switzerland

Peter K. A. deWitt Huberts

NIKHEF-K, NL 1009AJ Amsterdam, The Netherlands

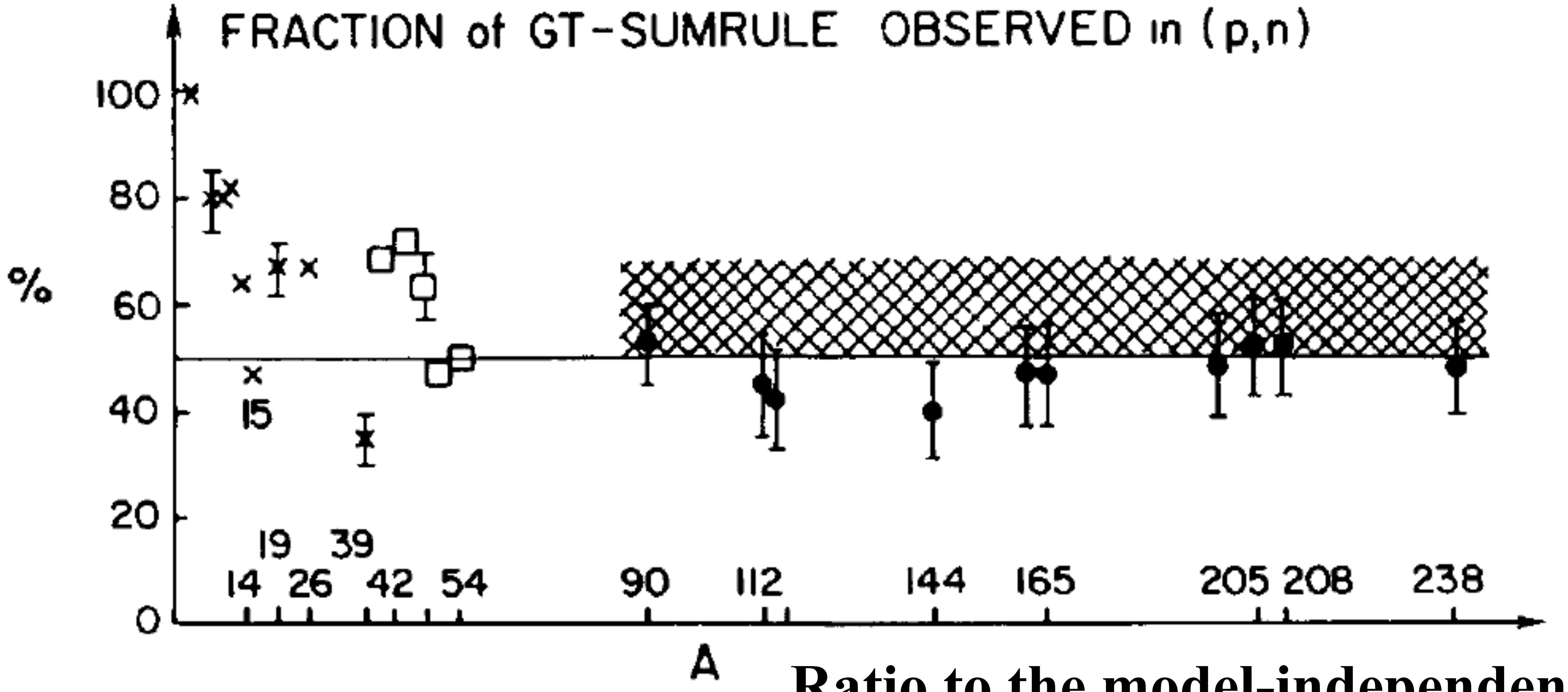
The independent-particle model explains many features of atomic nuclei and other fermion systems. The low-energy states of nearly closed-shell systems can be interpreted as having *quasiparticles* in single-particle orbitals. The difference between physical particles and quasiparticles results from the effects of correlations in the system. In this Colloquium the authors consider the consequences of these correlations. They discuss in particular, mainly for the case of nuclei, the quasihole strength z (spectroscopic factor) that gives the probability of the quasiparticle's being a physical particle. Results

from both theory and experiment indicate that $z \sim 0.65$ and imply that only $\sim 2/3$ of the time a nucleon acts as an independent particle bound in an average potential. The fraction of $\sim 1/3$ of correlated nucleons is larger than believed in the past. [S0034-6861(97)00703-4]

Effects of quenching

Quenching of Gamow-Teller strengths

Carl Gaarde, Nucl. Phys. A **507**, 79 (1990)



Ratio to the model-independent Ikeda sum rule

K. Ikeda et al. Phys. Lett. **3**, 271 (1963).

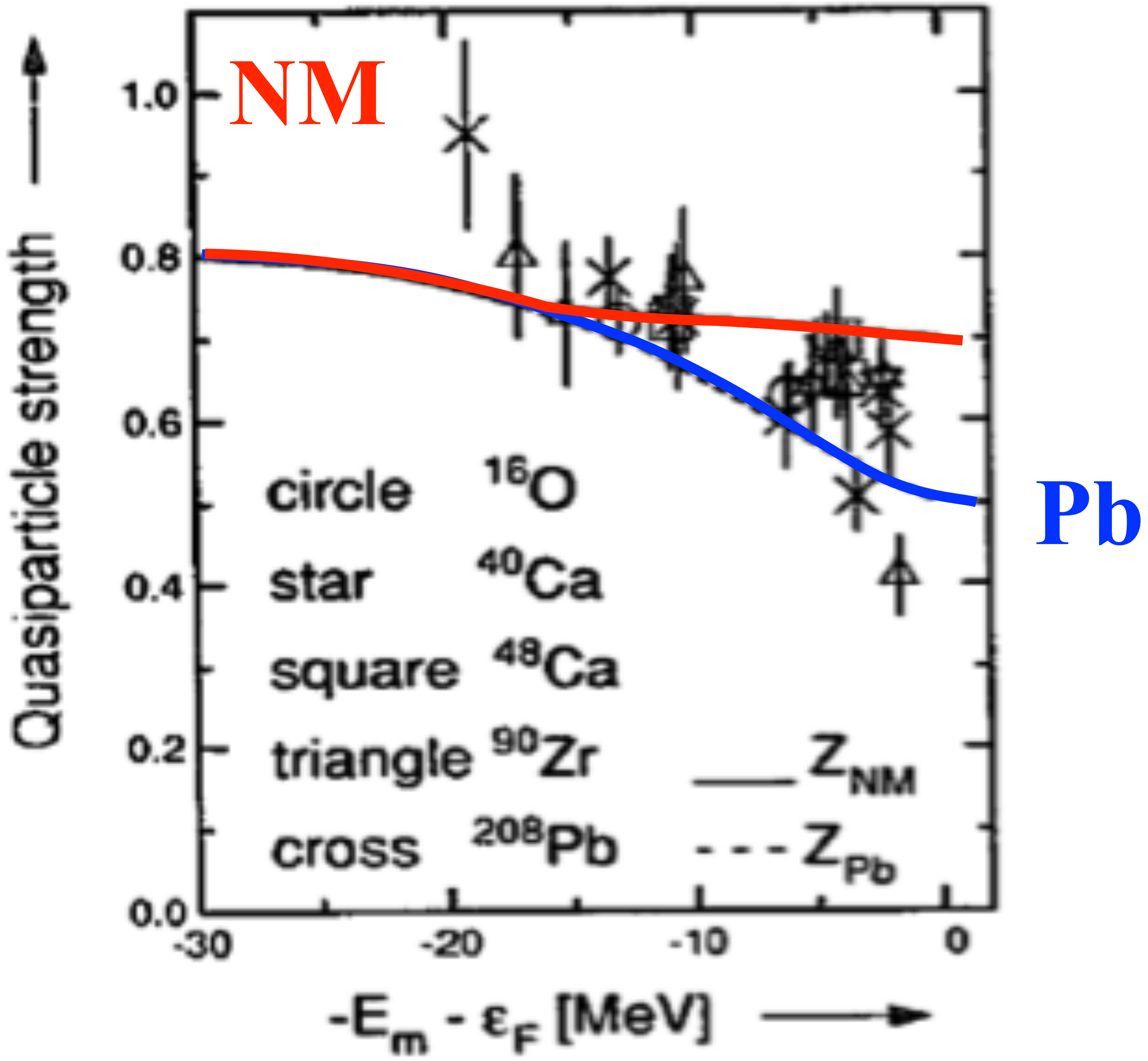
Δ admixture in nuclear wave functions

Tensor force effects

Sakai, Wakasa, Yako
→ dominance of the tensor force effects

Impact on broad sciences
e.g. axial-vector coupling constant used in the 0νββ matrix elements

Origins of the quenching: a variety of correlations



SRC: repulsive core

connection to changes of quark-gluon structure of nucleons in a medium

(probably) universal

5%?

Tensor correlations (both short and long ranges)

interconnection between low- and high-momentum phenomena in nuclei

approximately universal

10%?

LRC: pairing and coupling to giant resonances

should be isotope dependent

15–20%

Surprise!

Nucleon removal reactions with nuclear targets (^{9}Be, ^{12}C) at several tens of MeV

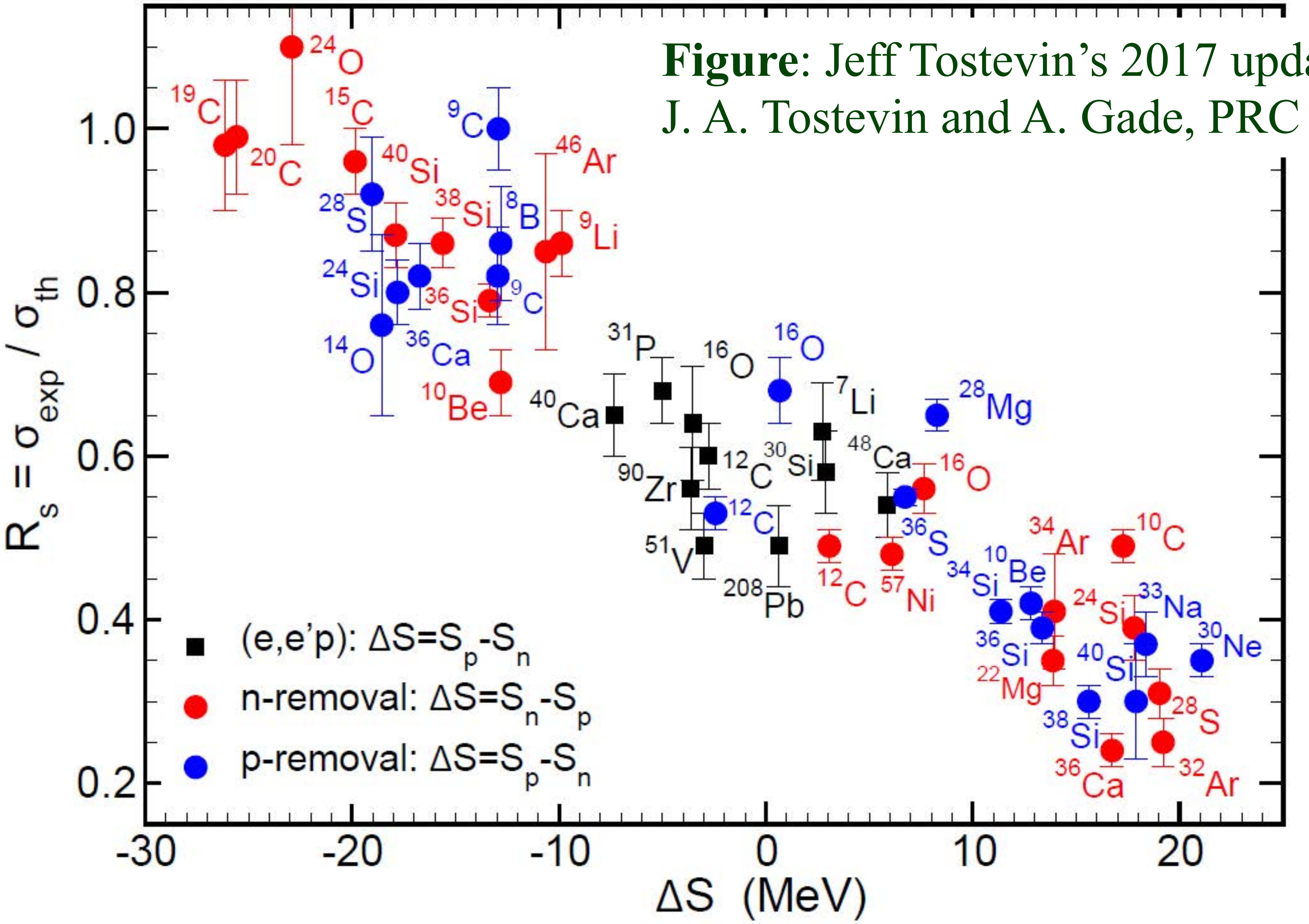


Figure: Jeff Tostevin's 2017 update from
J. A. Tostevin and A. Gade, PRC 90, 057602 (2014)

Physics? or
due to complicated reaction mechanism(s)?

Application of the (*p*,*pN*) reaction to the quenching studies

Long debates on the applicability of (*p*,*pN*)

"Hadron-induced reaction is dirty and cannot be used in quantitative discussions."

Workshop on QuasiFree Scattering w/ RI Beams (QFS-RB)

The first workshop on Quasi-free scattering with RI beam (QFS-RB)
7–11 April, 2008, Trento

Aim and Purpose
The workshop brought together experts working in the field of quasi-free scattering using both proton and electron beams on stable nuclei with those who wish to apply the quasifree scattering techniques using radioactive beams. The main purpose of the workshop was to review the experimental and theoretical status of the physics studied with quasi-free knockout reactions, including the reaction theory, aiming at a critical assessment on the potential of applying this technique to investigate properties of neutron-proton asymmetric nuclei and nuclear matter.

1st: Trento (Italy)

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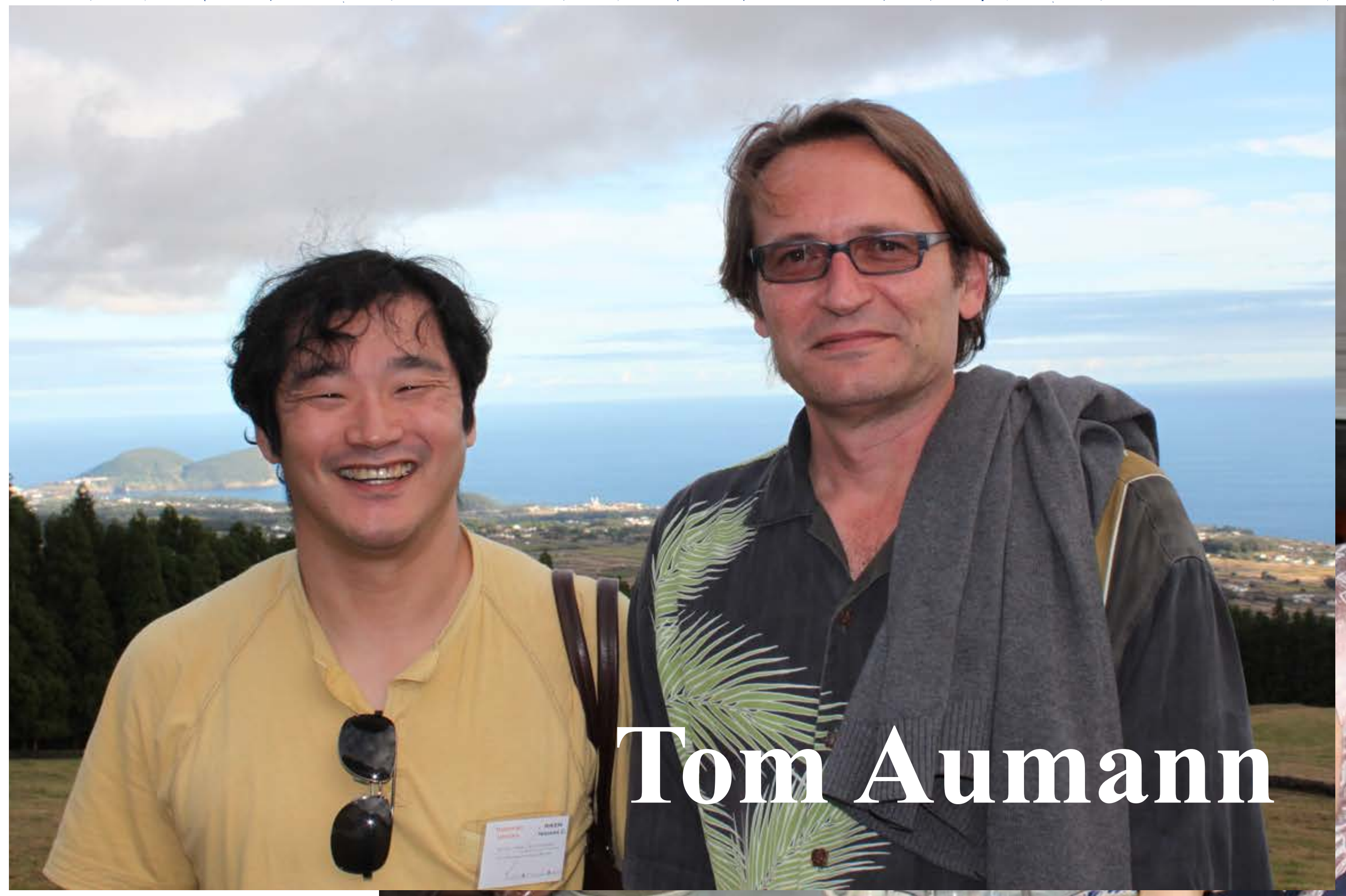
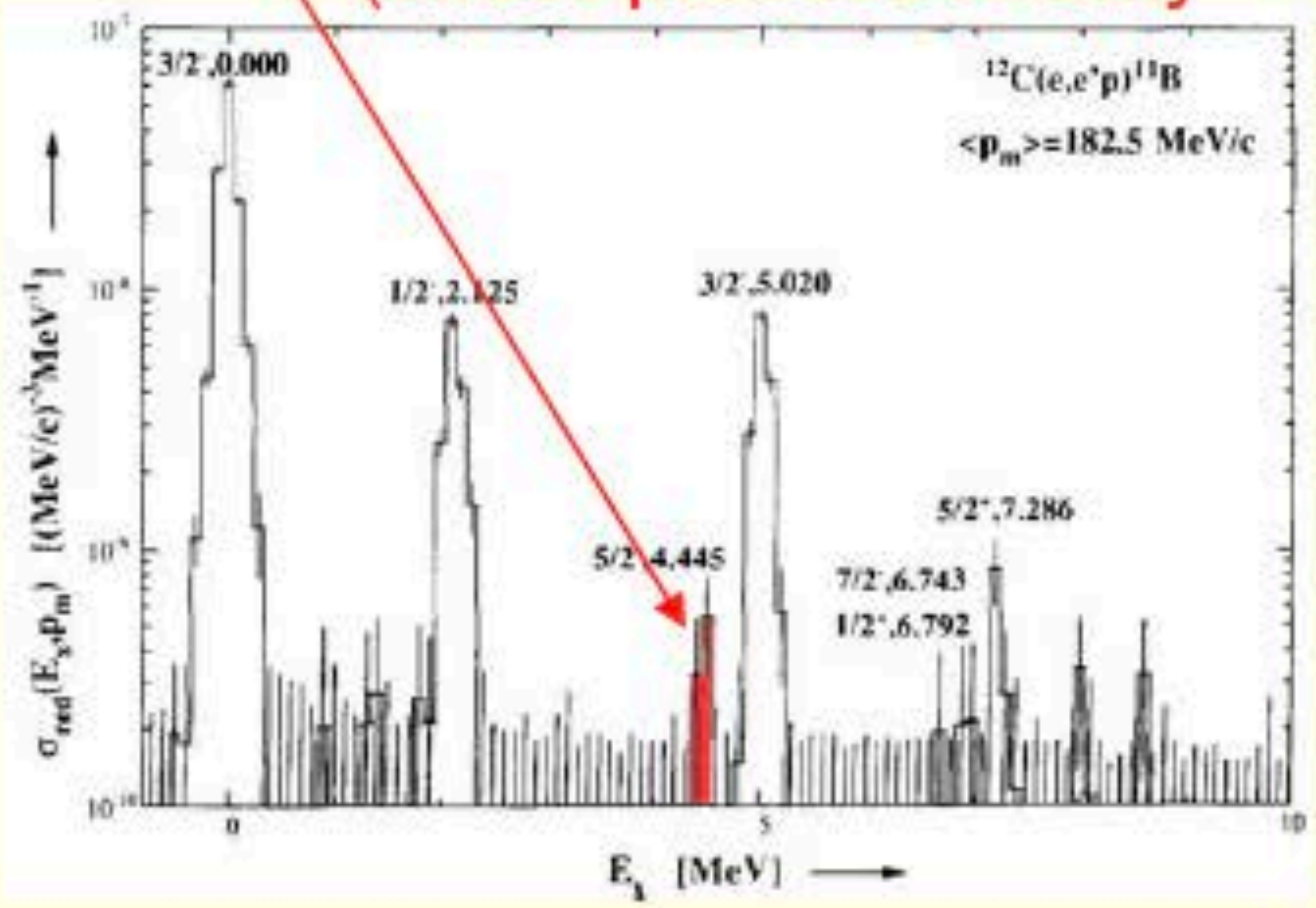


- **1st: Trento (Italy)**
- **2nd: Terceira (Portugal)**
- **3rd: York (UK)**
- **4th: Sao Paulo (Brazil)**
- **5th: Lefkada (Greece)**
- **6th: Hida Takayama (Japan)**

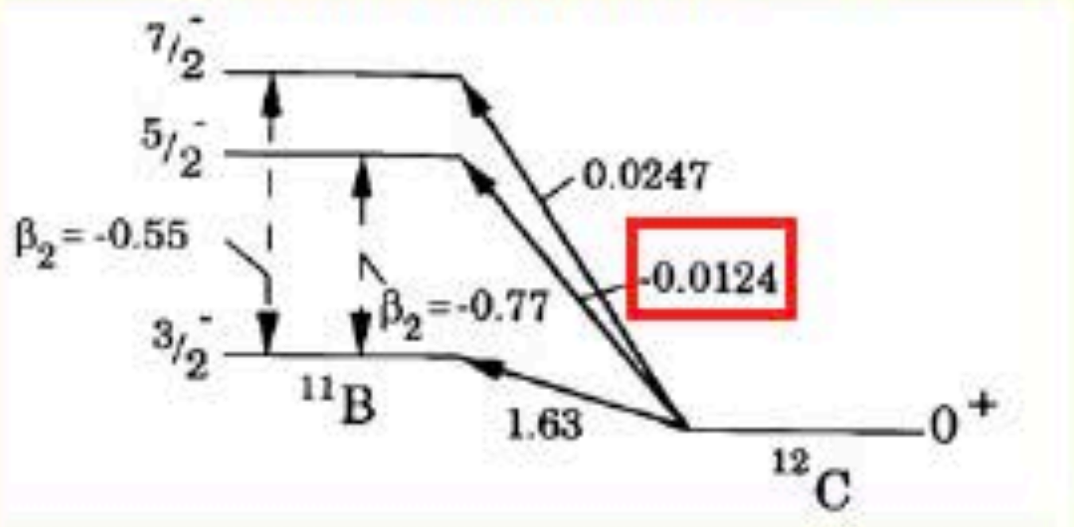
Contributions from multi-step processes

Excitation of 5/2⁻ (4.45MeV) state
by $^{12}C(e,e'p)^{11}B$

5/2⁻ : multistep dominant
(direct process is only ~1%)

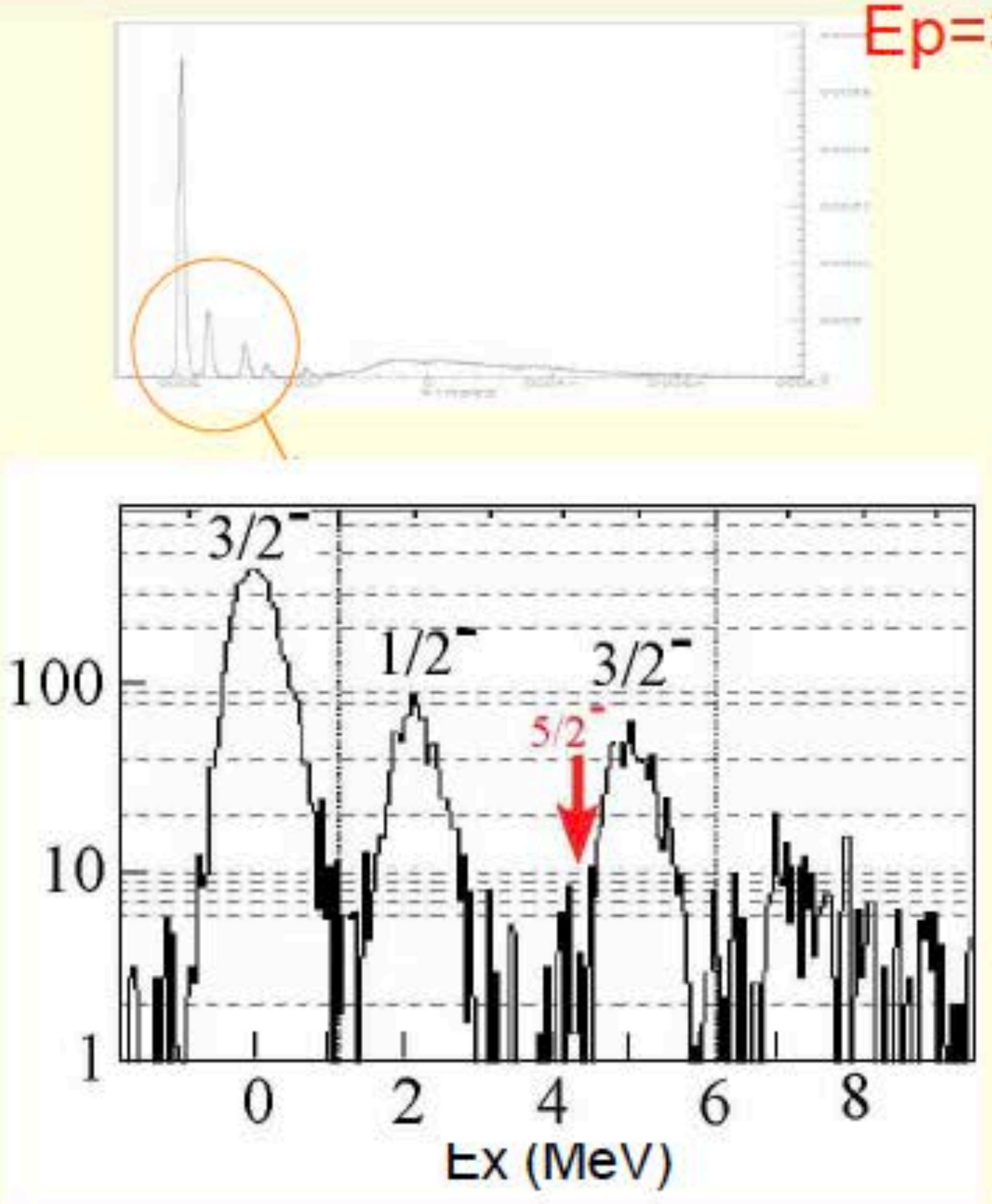


Reaction mechanism



In the case of $^{12}C(p,2p)$

Ep=392MeV



Similar result with (*e*,*e*'*p*) spectrum

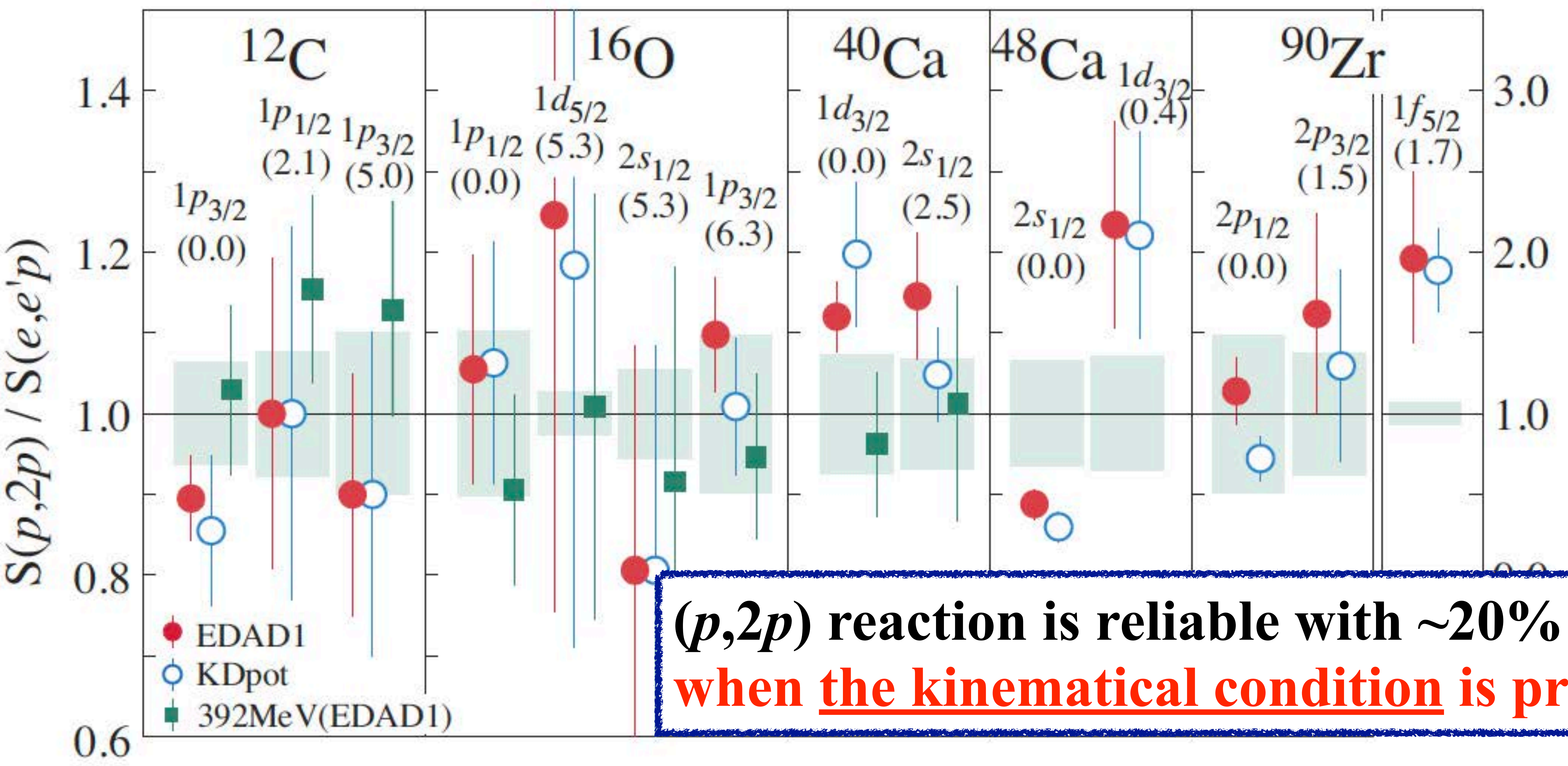
T. Noro,
1st QFS-RB

Application of the (*p*,*pN*) reaction to the quenching studies

Long debates on the applicability of (*p*,*pN*)

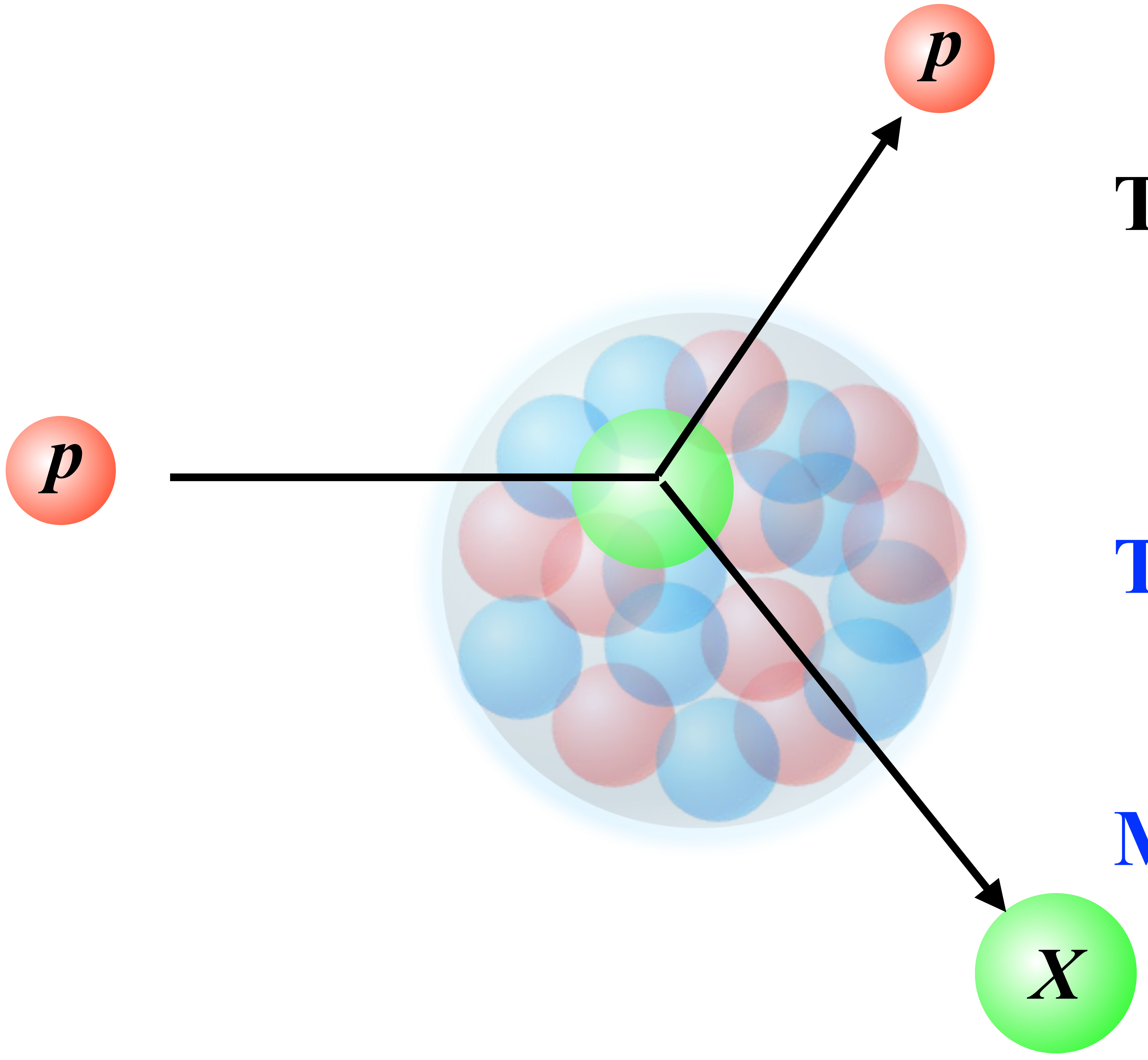
"Hadron-induced reaction is dirty and cannot be used in quantitative discussions."

(*p*,2*p*) @200 MeV: T. Noro et al., PTEP 2023 093D01



(*p*,2*p*) reaction is reliable with ~20% accuracy,
when the kinematical condition is properly chosen.

What does "quasi-free" means?



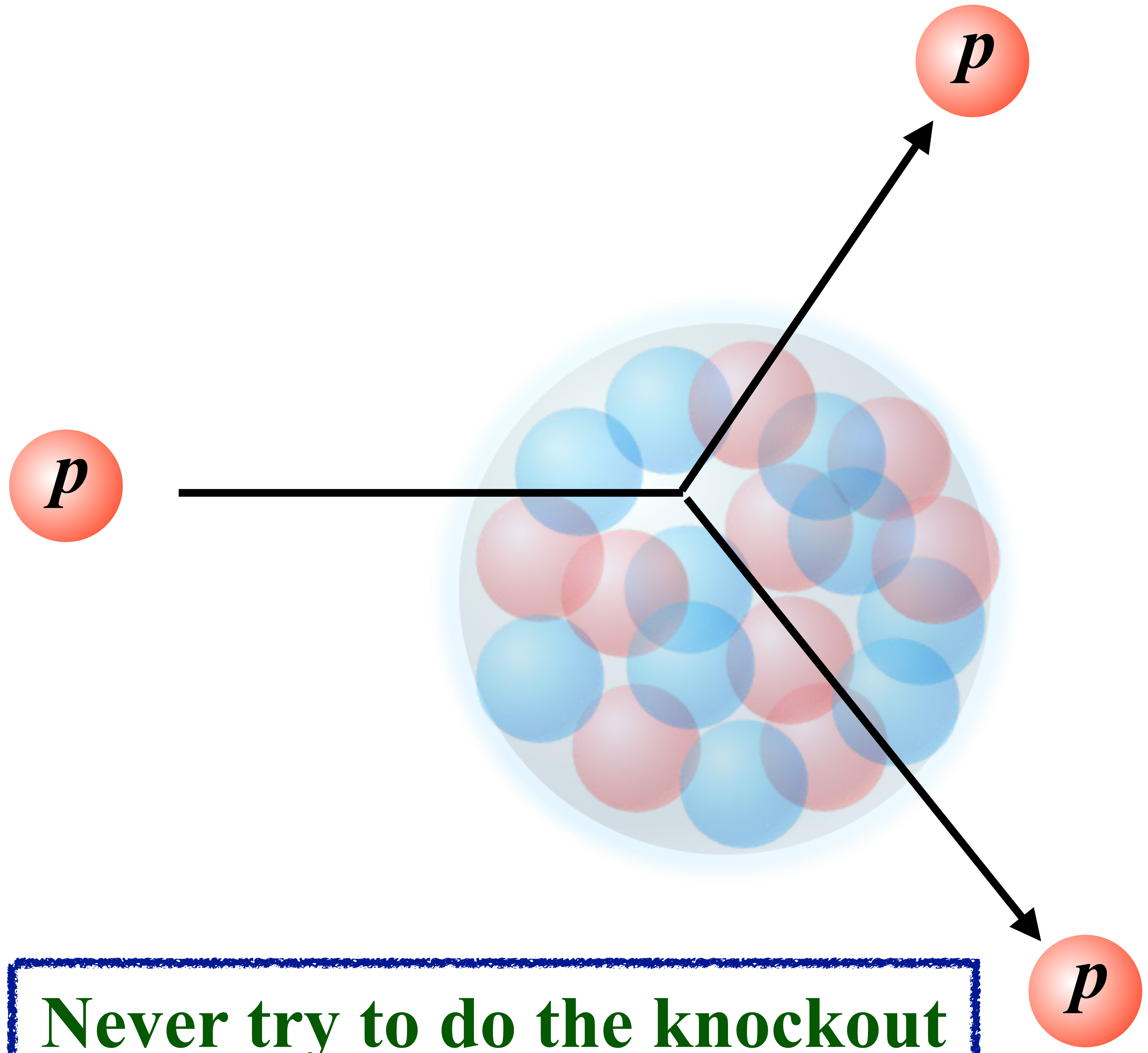
Decoupling between **the reaction dynamics** and **the nuclear structure effects.**

The reaction can be described as the *p-X* elastic scattering in the nuclear medium.
→ simple reaction mechanism

The other part of the nucleus (residual nucleus) can be treated as a spectator.

Motion of the knocked-out particle in the initial state can be reconstructed using the momenta of two protons in the final state.

Quasi-free condition



$k_p \gg$ **typical momentum in a nucleus (200 MeV/c)**

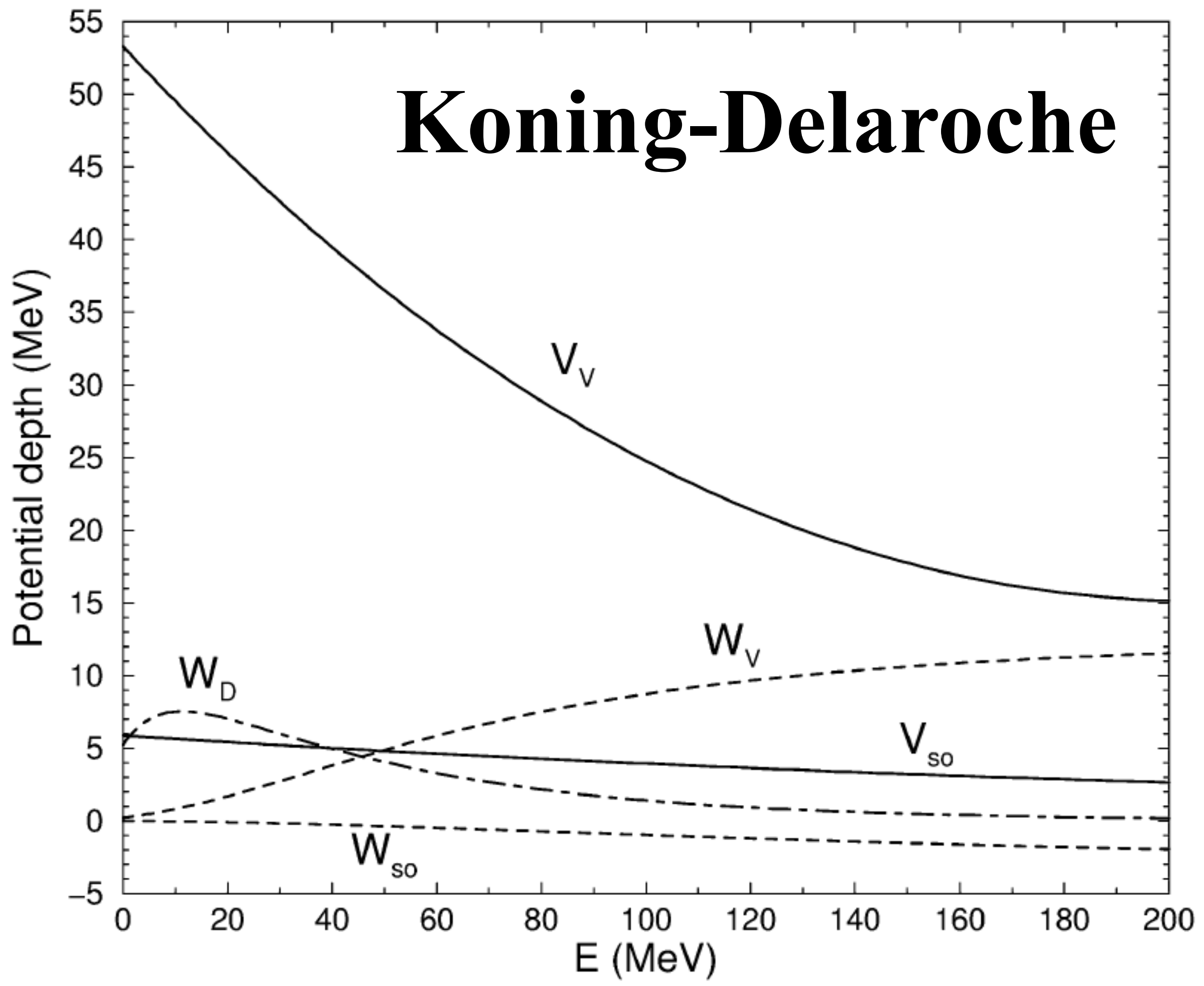
(p,2p) reaction @200 MeV, $\theta_1=\theta_2=40$ deg

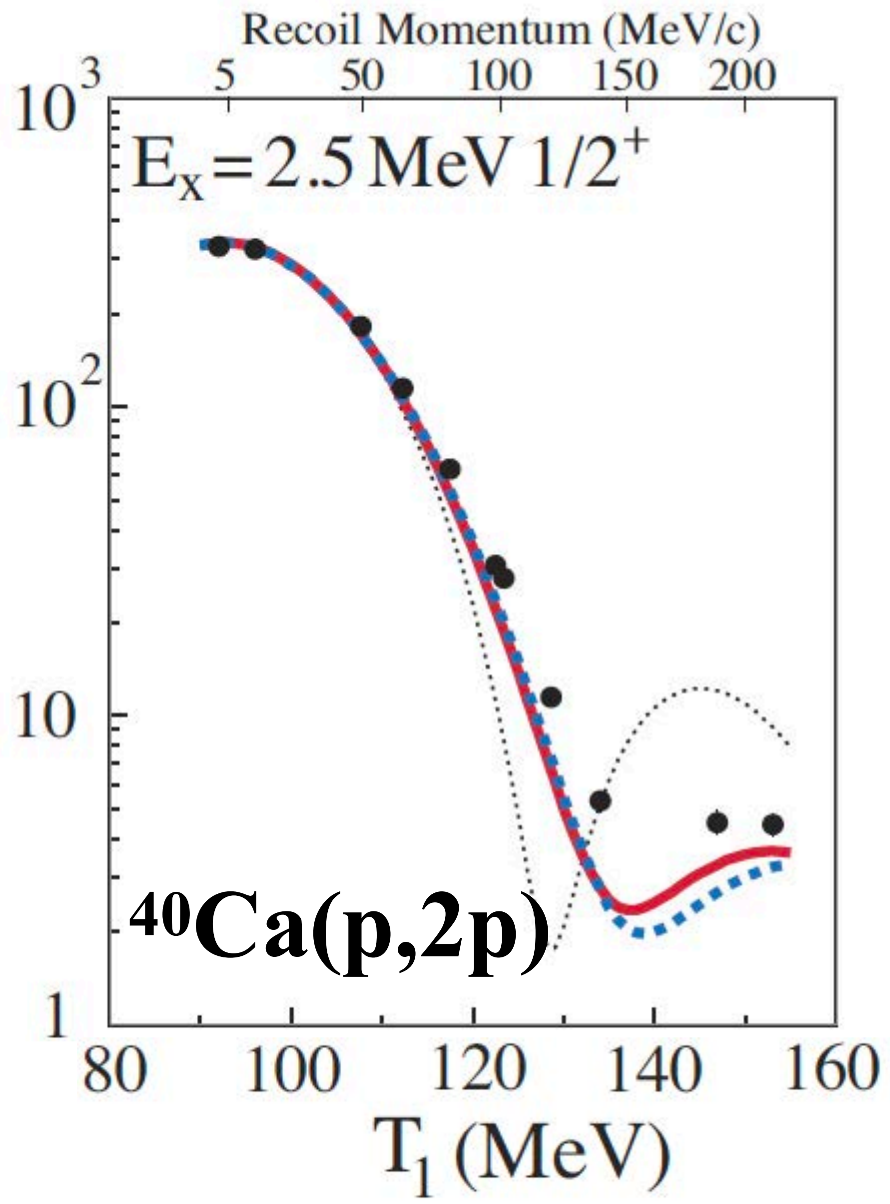
$k_{\mathrm{beam}} = 644$ **MeV/c**

q ~ 440 MeV/c

$k_X \sim 440$ **MeV/c**

$T_p \gg V_{\mathrm{opt.}}$





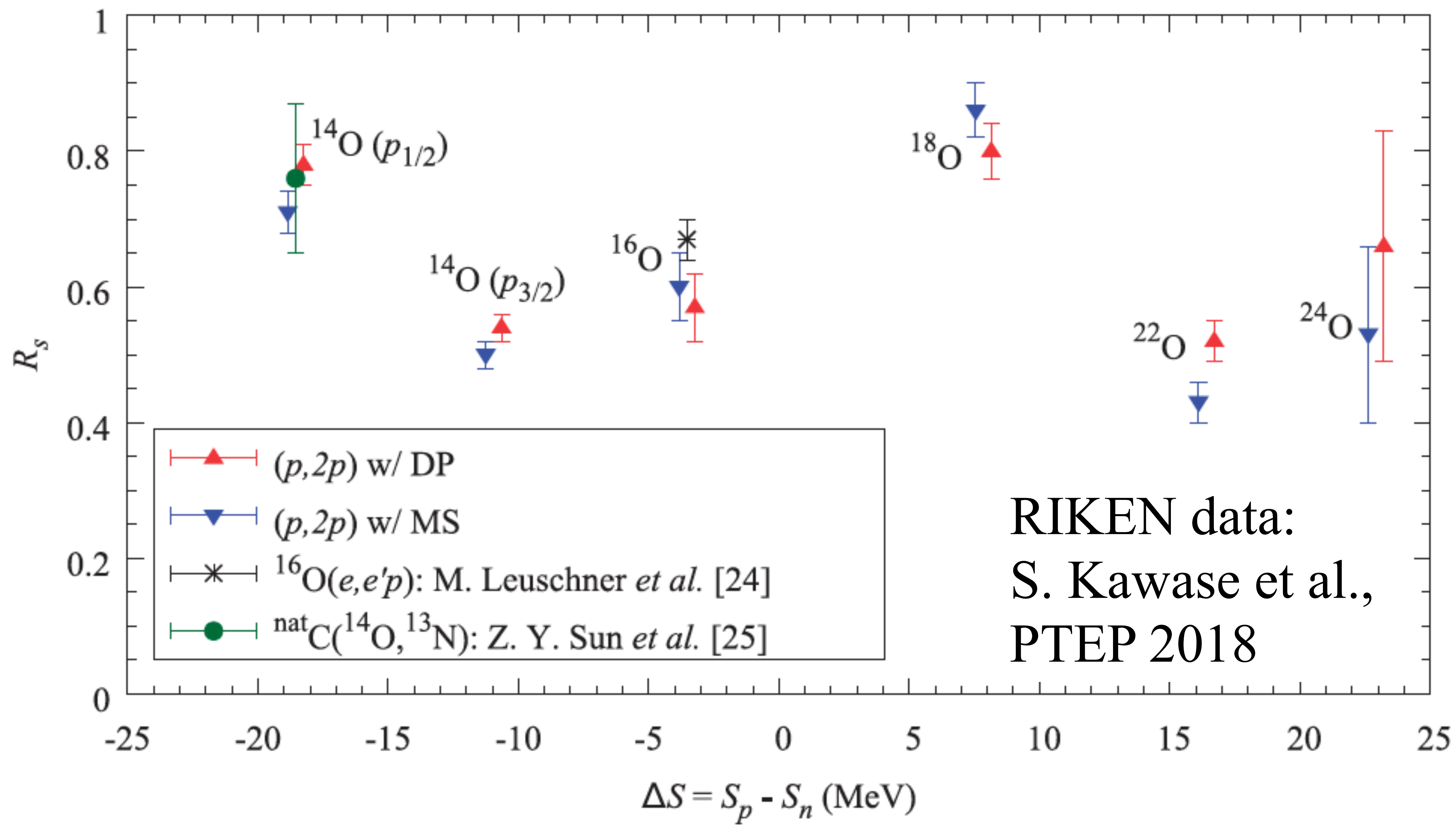
Never try to do the knockout experiments below 100 MeV.

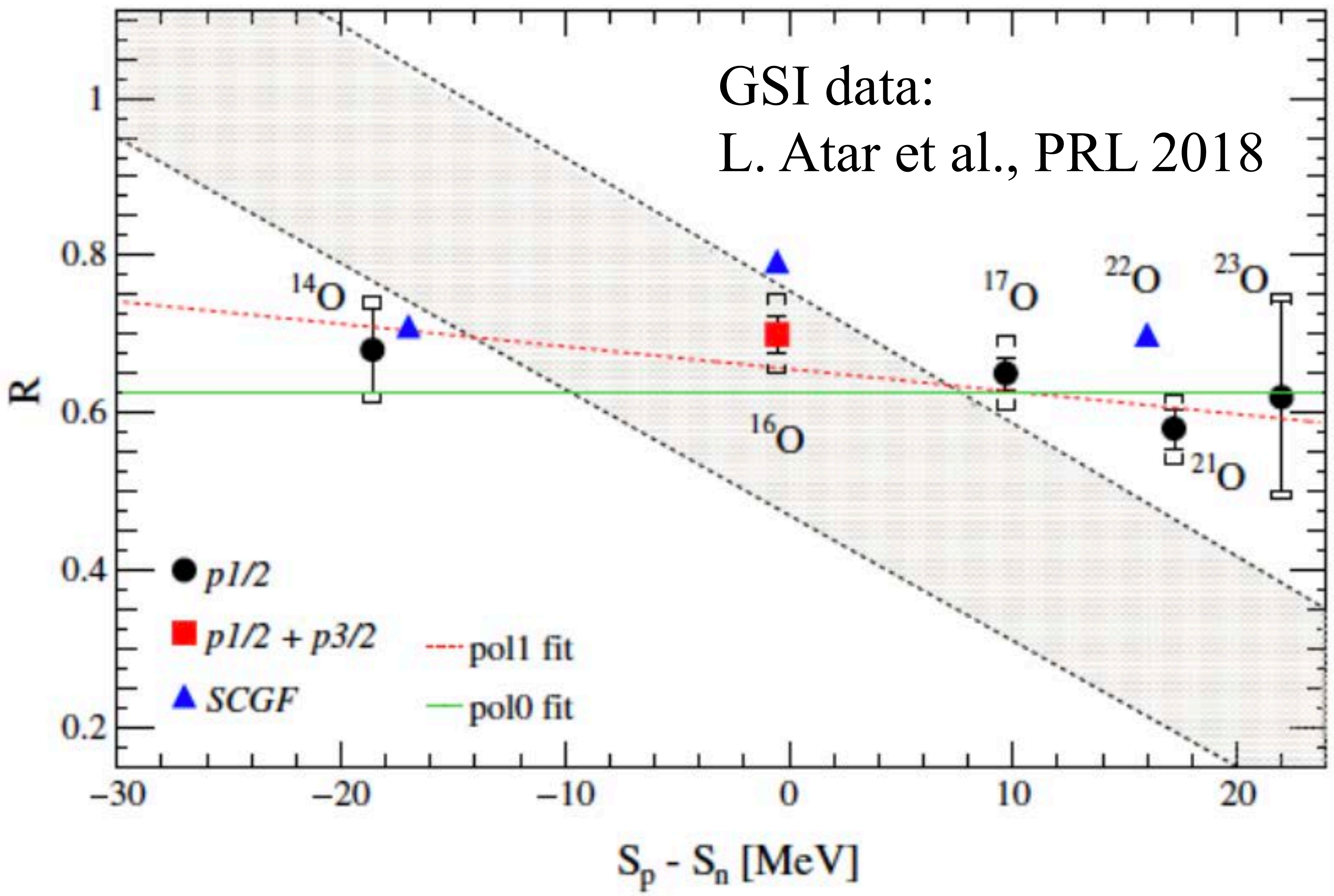
The above are necessary conditions, but not sufficient conditions

c.f. Test of the quasi-free condition:

A.W. Stetz, Physical Review C **21** 1979 (1980).

Spectroscopic factor from (*p*,2*p*) experiments

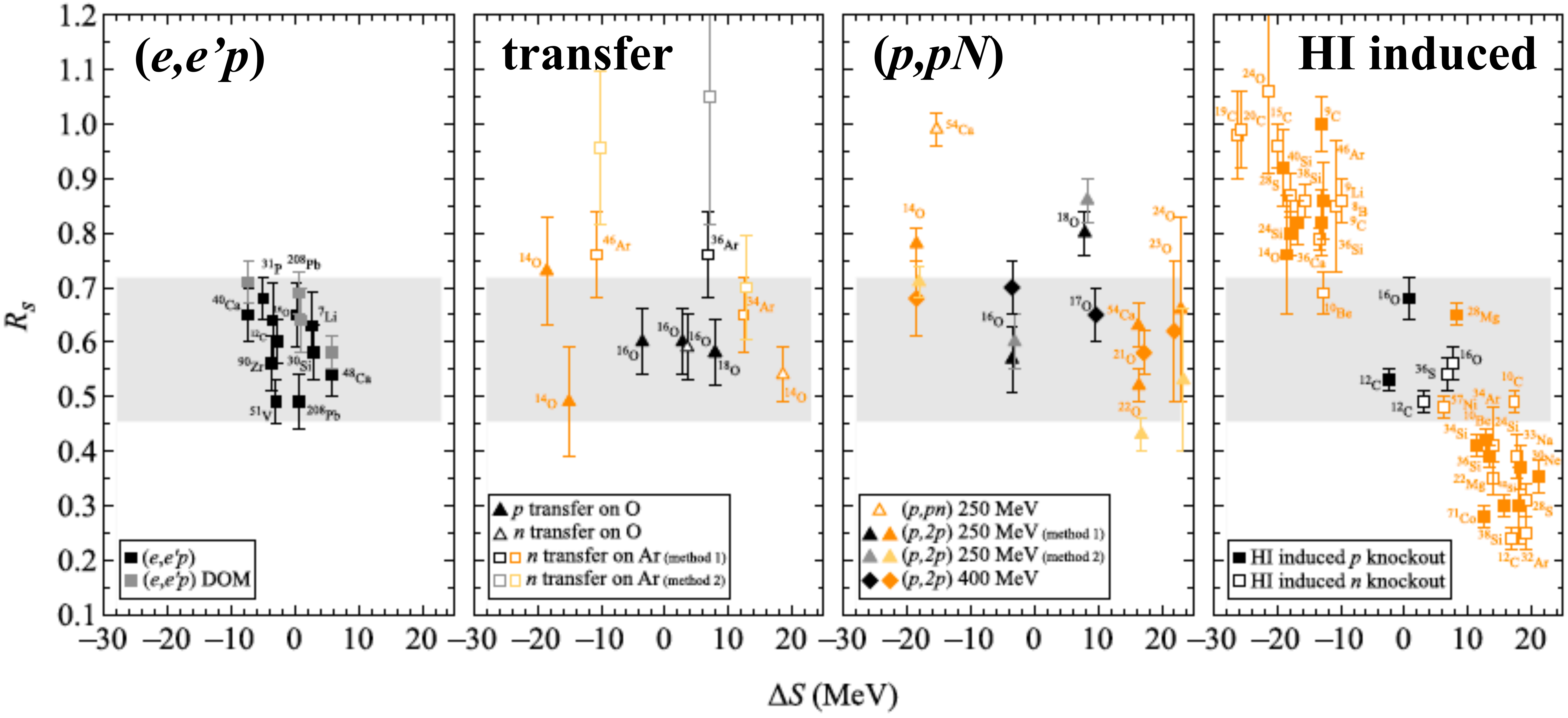




No strong ΔS dependences

Current understandings of spectroscopic factor

T. Aumann, A. Obertelli et al., PPNP 118, 103847 (2021).



Current understandings of spectroscopic factor

Progress in Particle and Nuclear Physics 118 (2021) 103847

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/ppnp

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Review

Quenching of single-particle strength from direct reactions with stable and rare-isotope beams

Check for updates

T. Aumann [a,b], C. Barbieri [c,d,e], D. Bazin [f,g], C.A. Bertulani [h], A. Bonaccorso [i], W.H. Dickhoff [j], A. Gade [f,g], M. Gómez-Ramos [a,k], B.P. Kay [l], A.M. Moro [k,m], T. Nakamura [n], A. Obertelli [a,*], K. Ogata [o,p], S. Paschalis [q], T. Uesaka [r]

Possible access to isospin dependences of short-range, tensor, and long-range correlations

Sunji's experiment may shed a new light.

Independently of the origin of the observed trend, we can conclude that there are inconsistencies between the direct-reaction model conclusions. Reviewing the state-of-the-art reaction studies, we conclude that the problem cannot be resolved at this stage. It is of utmost importance to further understand the different reaction mechanisms by dedicated key experiments hand in hand with theory developments in the near future.

(*p*,2*p*) reaction in RI beam experiments

The (*p*,2*p*) reaction is one of the most powerful experimental tool in RI-beam experiments.

High experimental efficiency
comparable to or better than proton beam experiments.

Ease of detecting decay particles

Unique physics cases

Suitable experimental tool
at RIBF, RAON, HIAF, FAIR etc.

Experimental merits of (p,2p) reaction in inverse kinematics

Decoupling of the reaction dynamics and the nuclear structure effects to be probed

ability to investigate low-momentum phenomena using a high-energy (several hundreds MeV) RI beams at inflight facilities.

Particles in the final state have large kinetic energies

Ease of particle detection

→ Use of a thick target (e.g. MINOS)

Relatively large cross section (~ several tens of mb)

~ several % of all the reaction channels

Large phase space volume in the 3-body final state can be covered relatively easily.

Best we can do in pursuit of the highest possible luminosity

"Mean free path" target

On average, 63% of the beam particles react with the target.

Thicker targets become less efficient.

$$\sigma_R \sim 1\mathrm{b} = 10^{-24}\ \mathrm{cm}^2 \quad \rightarrow \quad \lambda_{mfp} \sim 10^{24}\ /\mathrm{cm}^2 \sim 1.6 \times N_{Avogadro}$$

Hydrogen : 1.5 g/cm^2 ~ 20 cm (liquid)

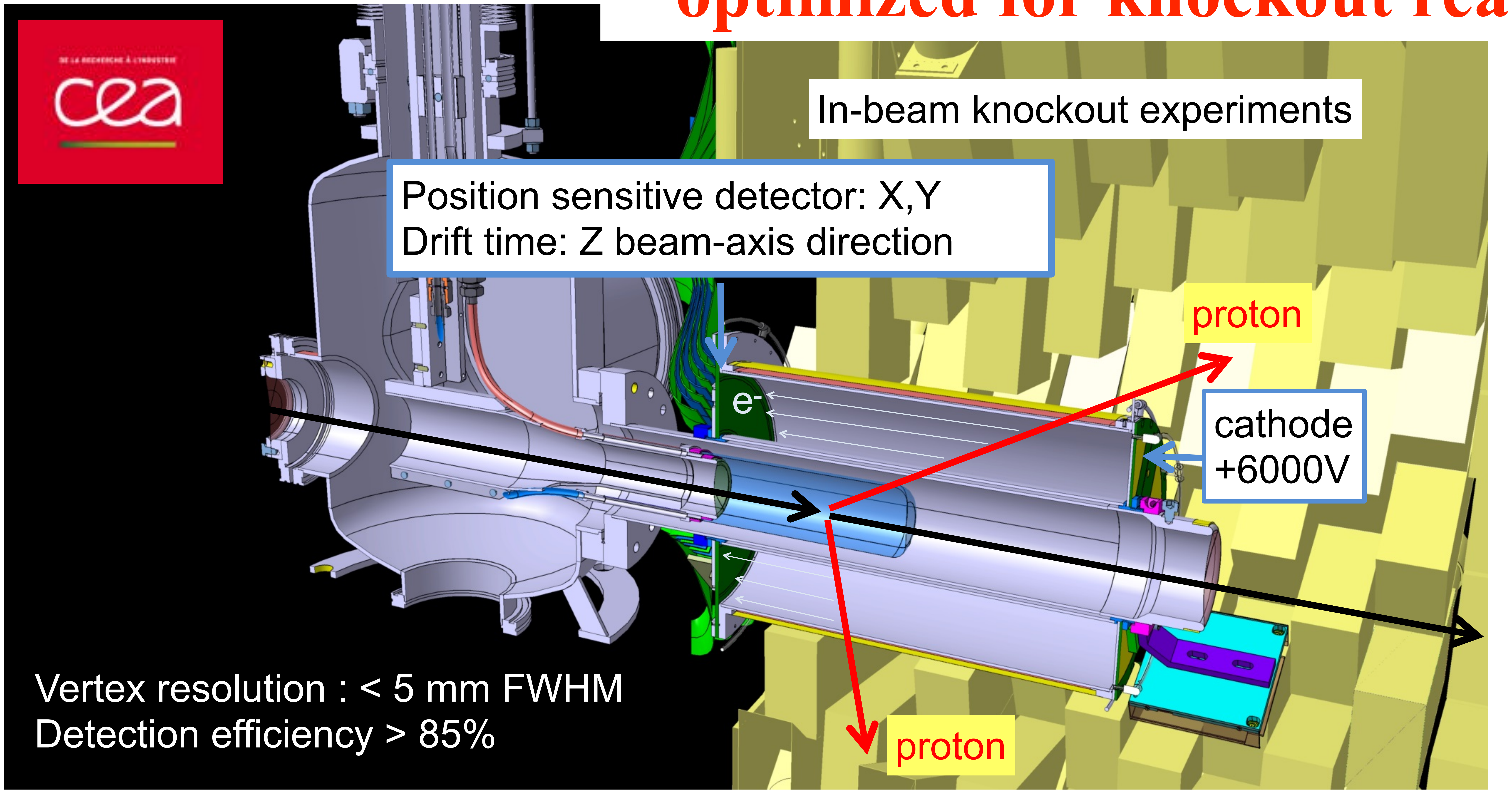
Carbon : 18 g/cm^2 ~ 9 cm

Lead : 300 g/cm^2 ~ 26 cm

Except for hydrogen, a mean free path target is thicker than a stopping range of the beam particle.

MINOS

The FIRST “mean-free-path" target, optimized for knockout reaction.



A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

http://minos.cea.fr

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Experimental merits of (*p*,2*p*) reaction in inverse kinematics

Decoupling of the reaction dynamics and the nuclear structure effects to be probed

ability to

(several h

Particles in th

→ Ease o

Use of

Relatively lar

~ several

Normal kinematics

I_{beam} ~ 10^{11} cps

N_{target} ~ 10^{20} cm^{-2}

ΔE_{out} ~ 10 MeV

$\Delta\Omega_{out}\Delta\Omega_{ko}$ ~ 10^{-4} sr^2

↓

0.1 counts/s

σ=10 μb/MeV/sr^2

Inverse kinematics

I_{beam} ~ 10^{5} cps

N_{target} ~ 10^{23} cm^{-2}

ΔE_{out} ~ 100 MeV

$\Delta\Omega_{out}\Delta\Omega_{ko}$ ~ 1 sr^2

↓

(10 counts/s)

~ 1 counts/s

Large phase s

can be covered relatively easily.

The whole momentum distribution can be covered in a single setting!

Inverse kinematics (*p*,*pN*) reaction experiments

HIMAC

T. Kobayashi et al., AIP Conf. Proc. 891, 108 (2007).

GSI

V. Panin et al., PLB 753; V. Panin et al., PLB 797; and his Ph.D thesis
L. Atar et al., PRL 120
C. Lehr et al., PLB 827; F. Wamers et al., PRC 109

RIBF

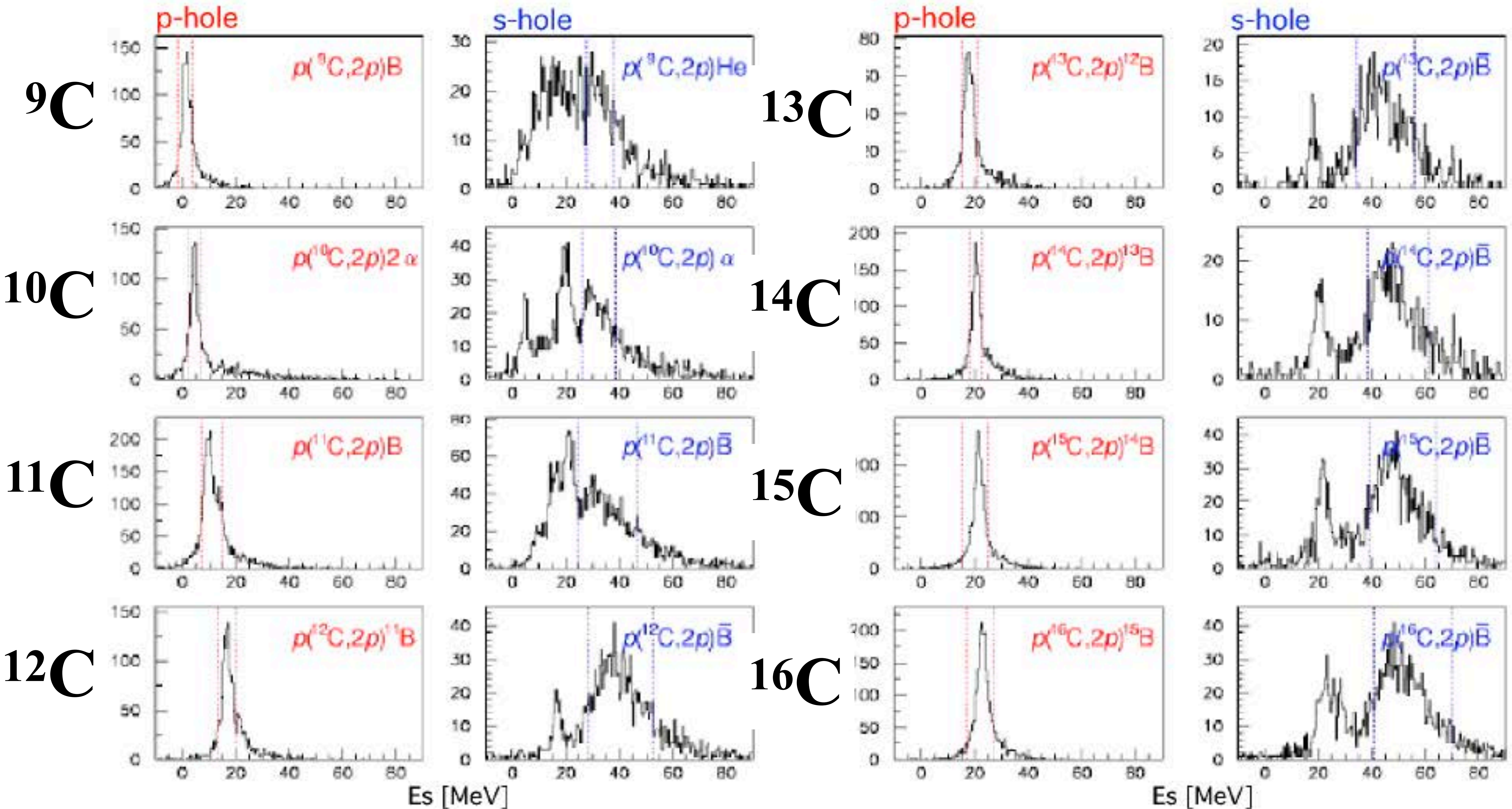
S. Kawase et al., PTEP 2018; R. Tang et al., PRL 124
Y. Kubota et al., PRL 125; A. Corsi et al., PLB 840; Z. Yang et al., PRL 126
P. Andre et al., PLB 857; B. Monteagudo PRL 132; Y. Sun Nat. Comm. 7
T. Pohl et al., PRL 130
Y. Kondo et al., Nature 620; Holl PRC 105; Kahlbow PRL133
Many SEASTAR results

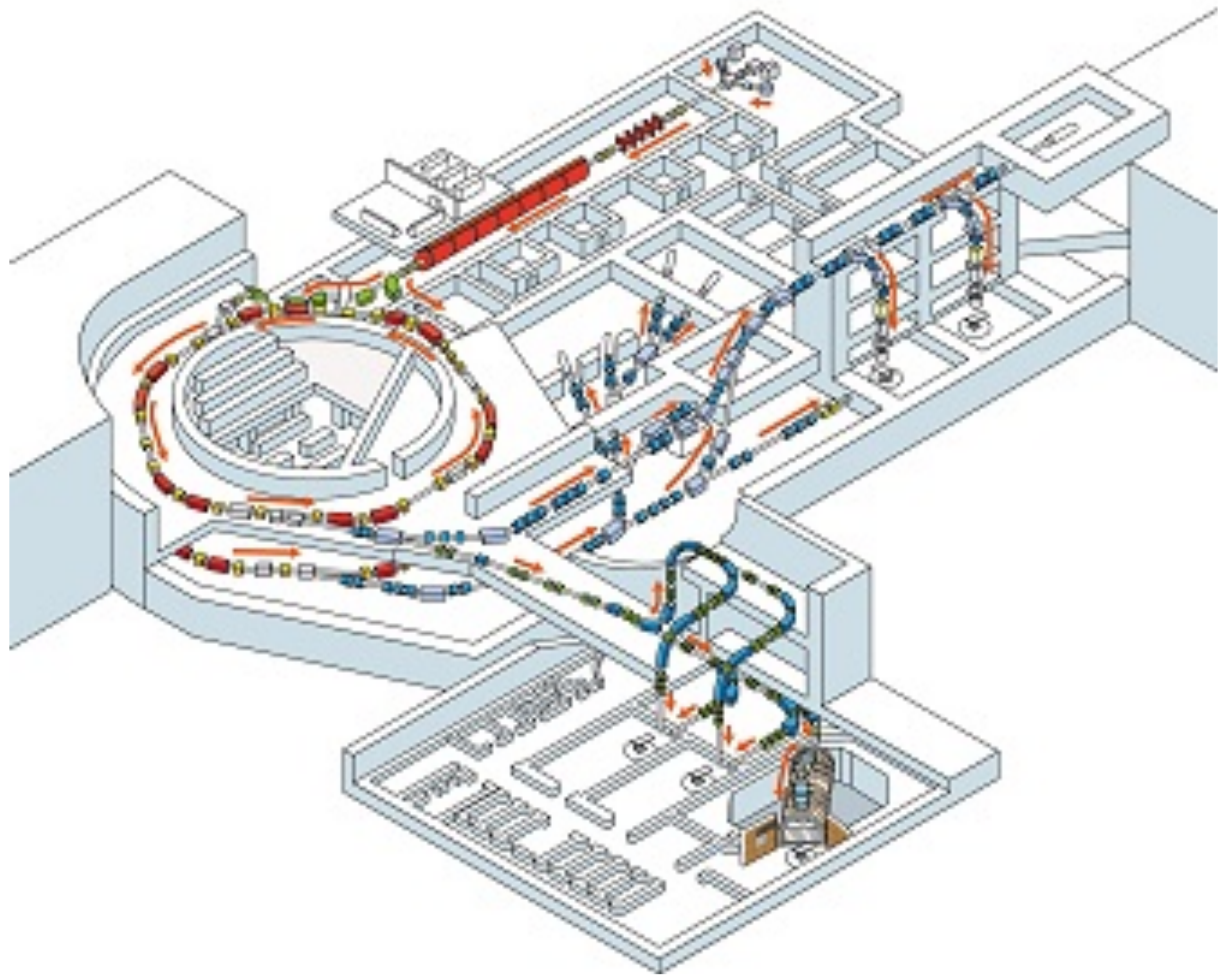
Pioneering experiment at HIMAC

(p,2p) Reactions on Carbon Isotopes: $p(^{9-16}C,2p)\,^{8-15}B$ at 250AMeV

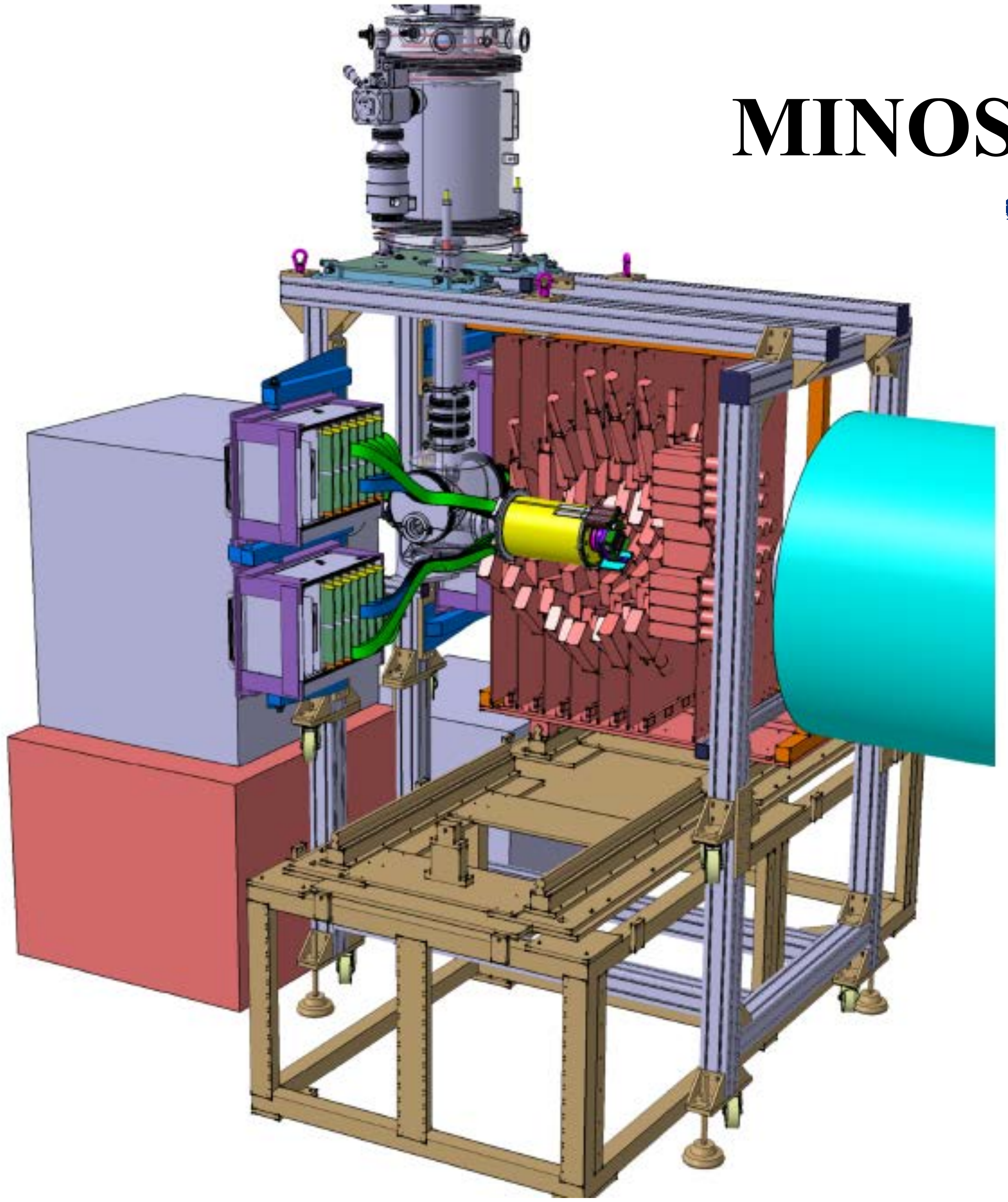
AIP Conf. Proc. **891**, 108 (2007);

Toshio Kobayashi, Kazutaka Ozeki[1], Kiwamu Watanabe, Yohei Matsuda, Yoko Seki, Tokukazu Shinohara, Toshiya Miki, Yuki Naoi, Hideki Otsu[2], Shigeru Ishimoto[3], Shoji Suzuki[3], Yutaka Takahashi[4], and E. Takada[5]





SEASTAR



MINOS+DALI2

C. Santamaria et al., PRL 115, 192501 (2015): ^{66}Cr, ^{70}Fe, ^{72}Fe
S. Chen et al., PRC 95, 41302 (2017): Se isotopes
N. Paul et al., PRL 118, 032501 (2017): ^{110}Zr
F. Flavigny et al., PRL 118, 242501 (2017): ^{98,100}Kr
L. Olivier et al., PRL 119, 192501 (2017): 79Cu
C. M. Shand et al., PLB 773, 492 (2017): ^{81,82,83,84}Zn
M. L. Cortés et al., PRC 97, 44315 (2018): Ni and Zn isotopes
X. Y. Liu et al., Physics Letters B 784, 392 (2018): ^{65,67}Mn
H. N. Liu et al, PRL122, 072502 (2019): ^{52}Ar
Z. Elekes et al., PRC 99, 014312 (2019): ^{76}Ni
R. Taniuchi et al., Nature 569, 53—58 (2019): ^{78}Ni
S. Chen et al., PRL 123, 142501 (2019): ^{53}Ca
M.L. Cortés et al., PLB 800, 135071 (2020): ^{62}Ti
Y.L. Sun et al., PLB 802, 135215 (2020): odd-K isotopes
T. Lokotko et al., PRC 101, 034314 (2020): ^{69,71,73}Co
C. Lizarazo, et al., PRL 124, 222501 (2020): $^{92, 94}$Se:
M. L. Cortés et al., PRC 102, 064320 (2020): ^{50}Ar
M.M. Juhász et al., PLB 814, 136108 (2021): ^{51}Ar
F Browne et al., PRL 126, 252501 (2021): ^{54}Ca
BD Linh et al., PRC 104, 044331 (2022): ^{47,49}Cl

T Koiwai et al., PLB 827, 136953 (2022): ^{55}K, ^{55}Ca, ^{57}Ca
R-B Gerst et al. PRC 105, 024302 (2022): ^{94,95,96}Kr
Z. Elekes, et al., PRC 106, 064321 (2022): $^{59, 61}$V
M Enciu et al, PRL 129, 262501 (2023): ^{52}Ca
S Chen et al. PLB 843, 138025 (2023): ^{56,58}Ca
P.J. Li et al. PLB 855, 138828 (2024): neutron-rich Ca
M. Begala et al., PRL 113, 064312 (2026): ^{46,47}S
F. Browne et al. PRC 114, 014316 (2026): ^{54}Ca

Inverse kinematics (*p*,*pN*) reaction experiments

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P. Andre et al., PLB 857; B. Monteagudo PRL 132; Y. Sun Nat. Comm. 7
T. Pohl et al., PRL 130
Y. Kondo et al., Nature 620; Holl PRC 105; Kahlbow PRL133
Many SEASTAR results

from single 3-day beamtime (SAMURAI18) discussed in Part 4

Proper expression for cross section in inverse kinematics

In knockout reactions with 5 degrees of freedom, the expression in normal kinemaitcs is

$$\frac{d\sigma}{dE_{\rm out}d\Omega_{\rm out}d\Omega_X}$$

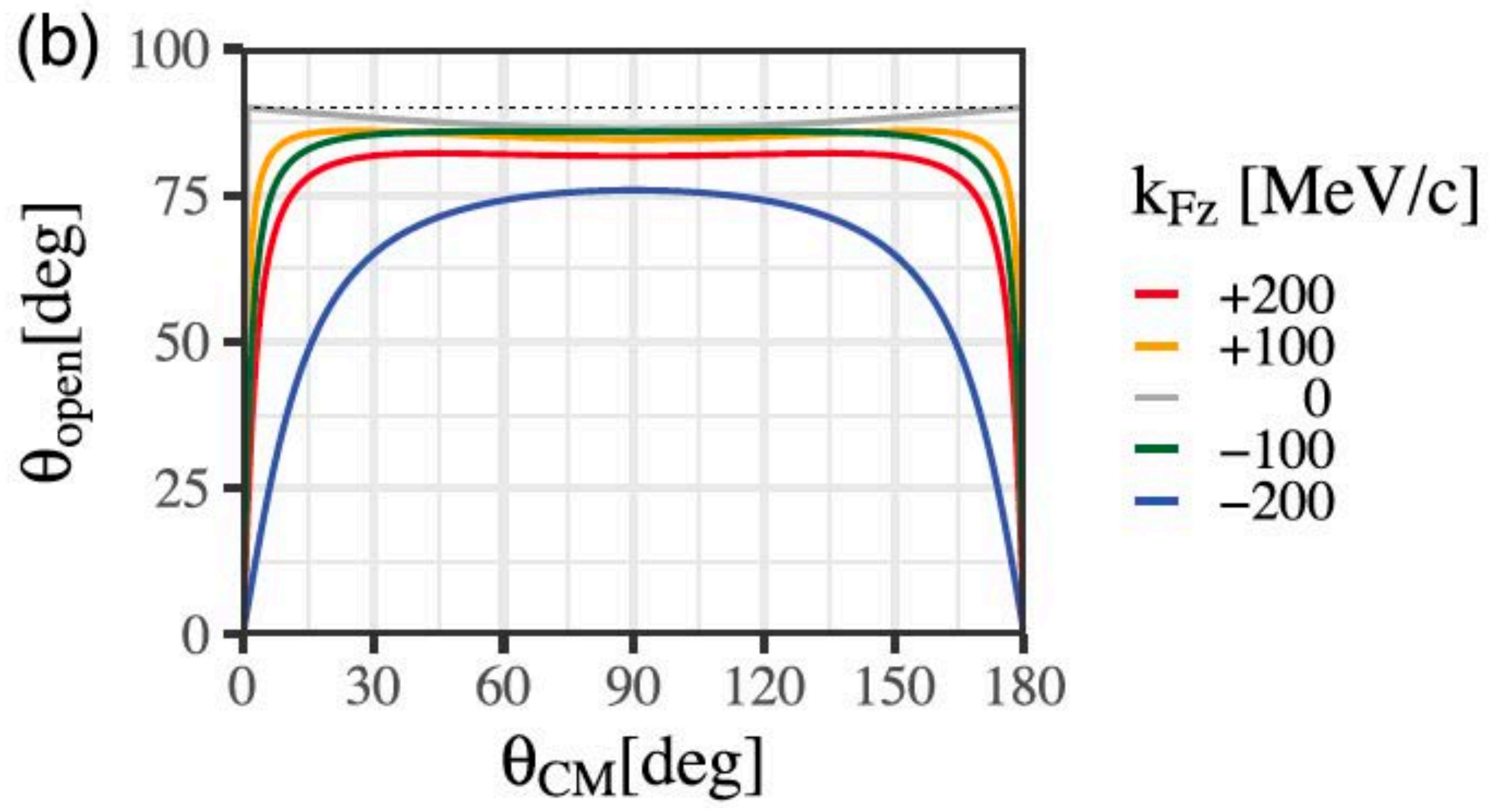
The expression cannot be used in inverse kinematics because $\theta_{\rm out}$ and θ_X are dependent each other.
Instead, you should use

$$\frac{d\sigma}{dE_{\rm out}dE_X d\phi_X d\Omega_{\rm out}}$$

K. Ogata et al., CPC 297, 109508 (2024).

c.f. This expression cannot be used in normal kinematics because E_{out} and E_X are dependent each other

See page 23 of TU, PTEP **2024**, 083D01.



Physics of nuclear spin-orbit coupling

The strong spin-orbit coupling is a unique feature of nuclear shell structure.
Magic numbers larger than 28 originates from the strong spin-orbit coupling.

However its microscopic origins are hardly understood.


EPJ Plus

EPJ.org

Eur. Phys. J. Plus (2016) **131**: 403 DOI 10.1140/epjp/i2016-16403-1

Spins in exotic nuclei: RI beam experiments with polarized targets

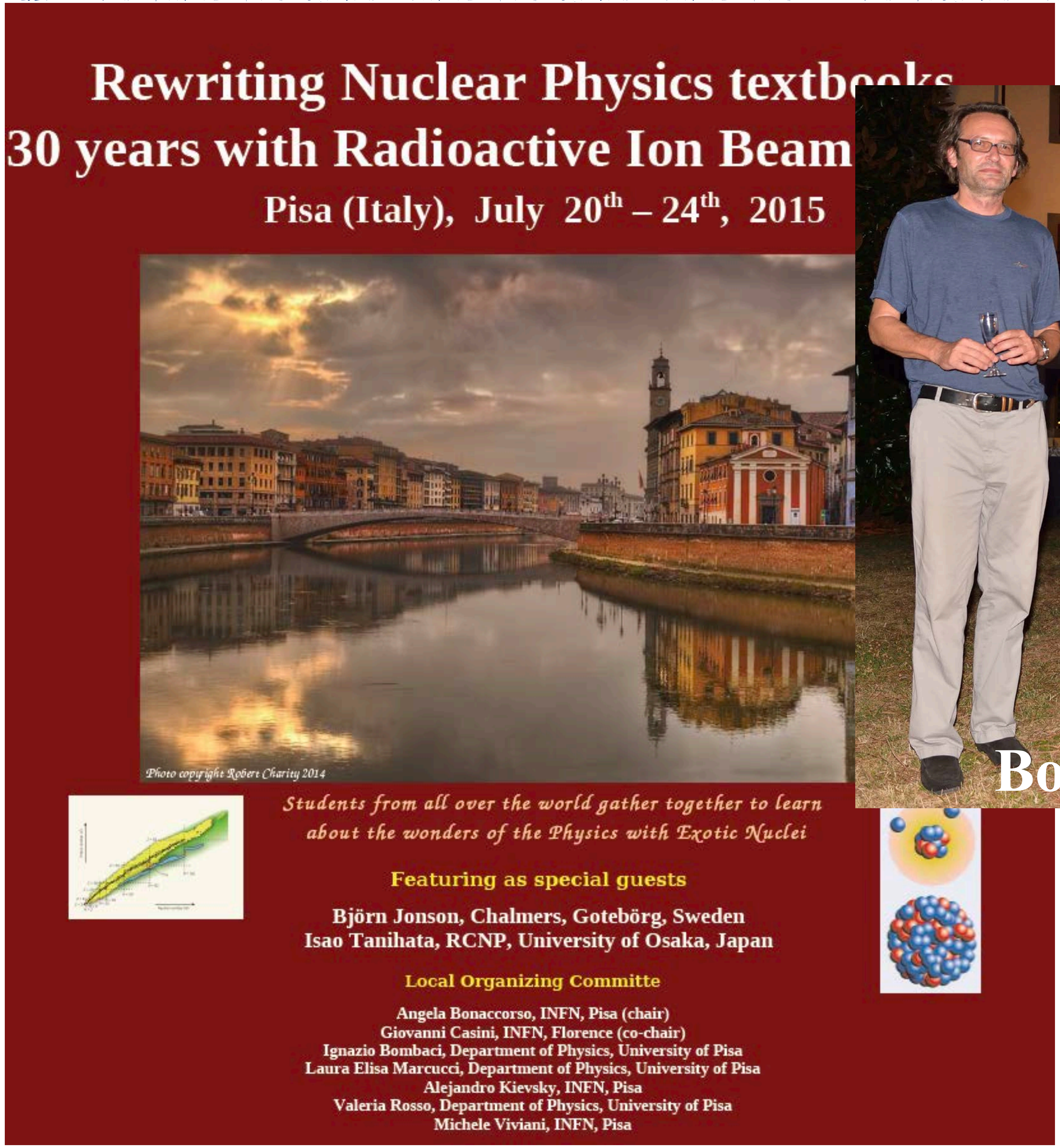
T. Uesaka

Società Italiana di Fisica

Springer

T. Uesaka,
European Physics Journal Plus **131**:403 (2016).

Pisa School



Rewriting Nuclear Physics textb
30 years with Radioactive Ion Beam
Pisa (Italy), July 20th – 24th, 2015
Photo copyright Robert Charity 2014
Students from all over the world gather together to learn about the wonders of the Physics with Exotic Nuclei
Featuring as special guests
Björn Jonson, Chalmers, Goteborg, Sweden
Isao Tanihata, RCNP, University of Osaka, Japan
Local Organizing Committe
Angela Bonaccorso, INFN, Pisa (chair)
Giovanni Casini, INFN, Florence (co-chair)
Ignazio Bombaci, Department of Physics, University of Pisa
Laura Elisa Marcucci, Department of Physics, University of Pisa
Alejandro Kievsky, INFN, Pisa
Valeria Rosso, Department of Physics, University of Pisa
Michele Viviani, INFN, Pisa

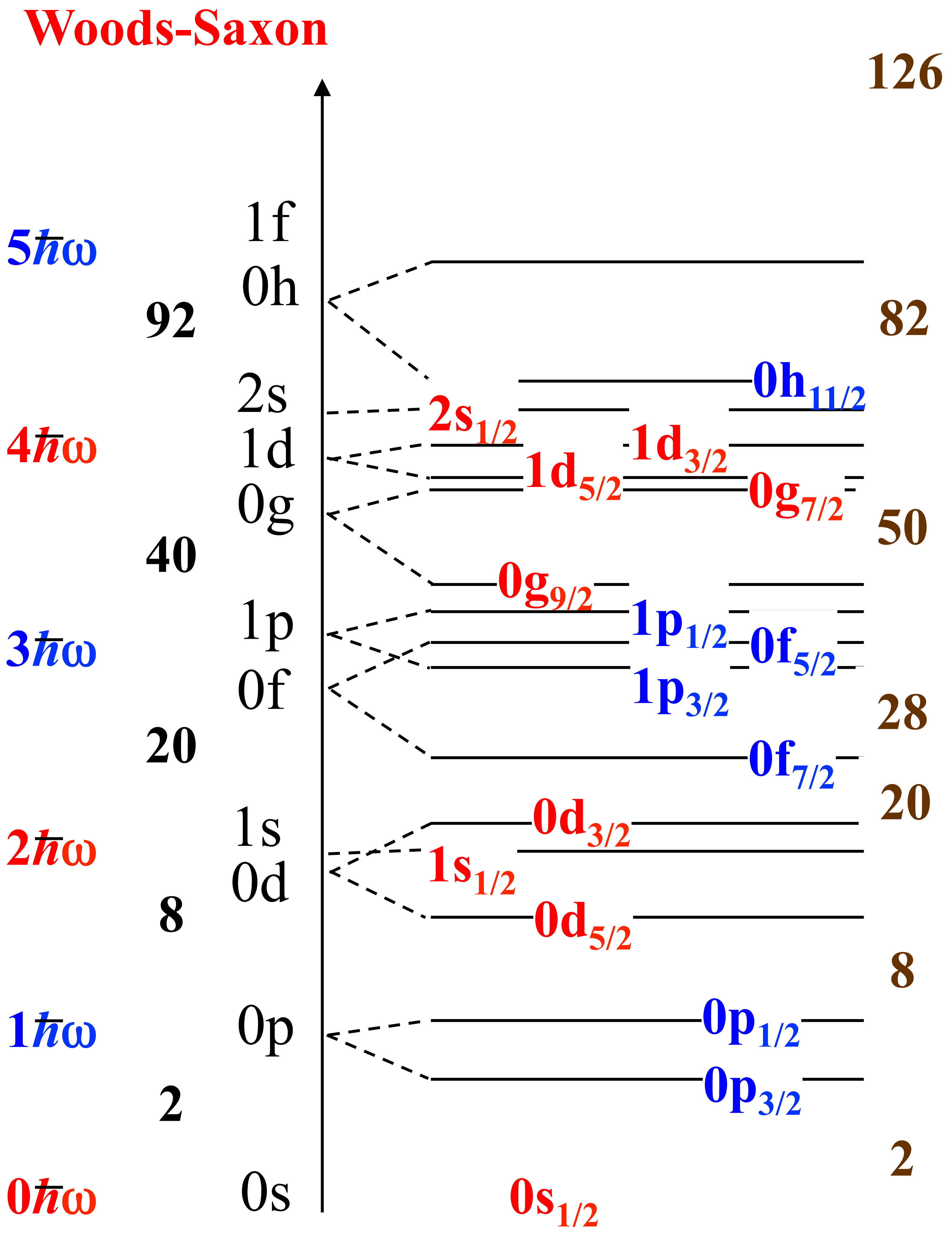
Angela
Bonnacorsso

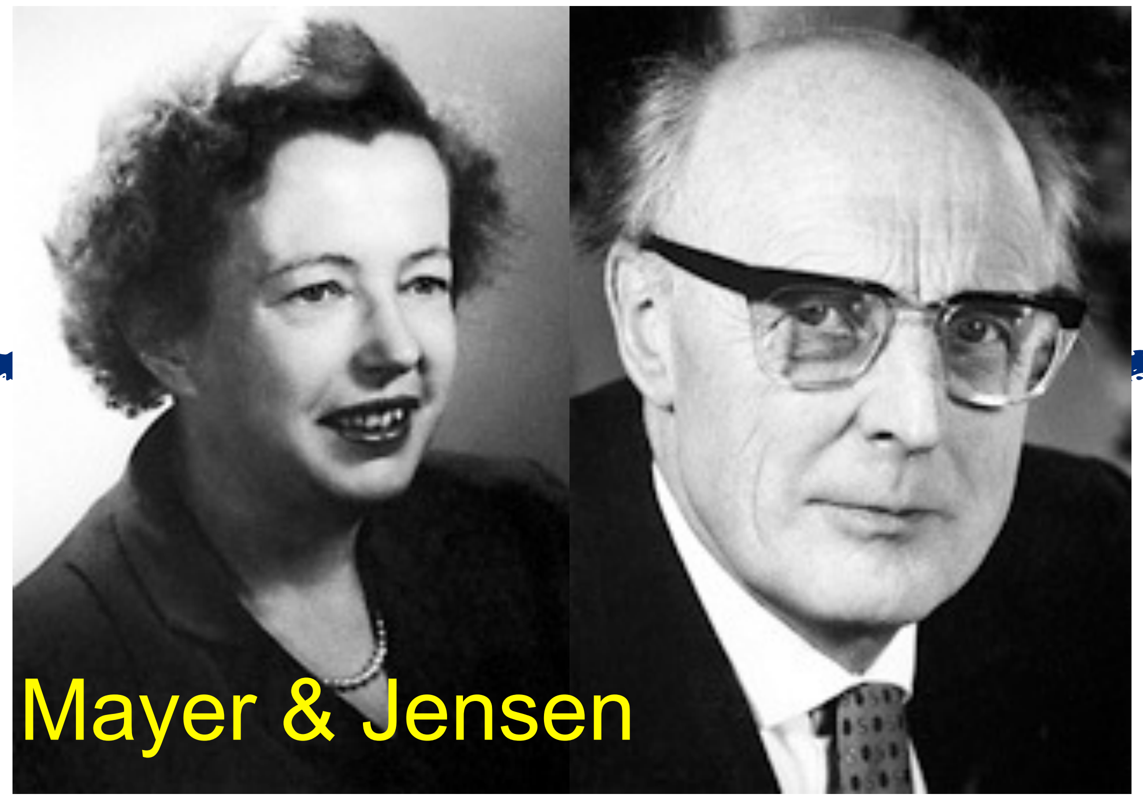
David Brink
me

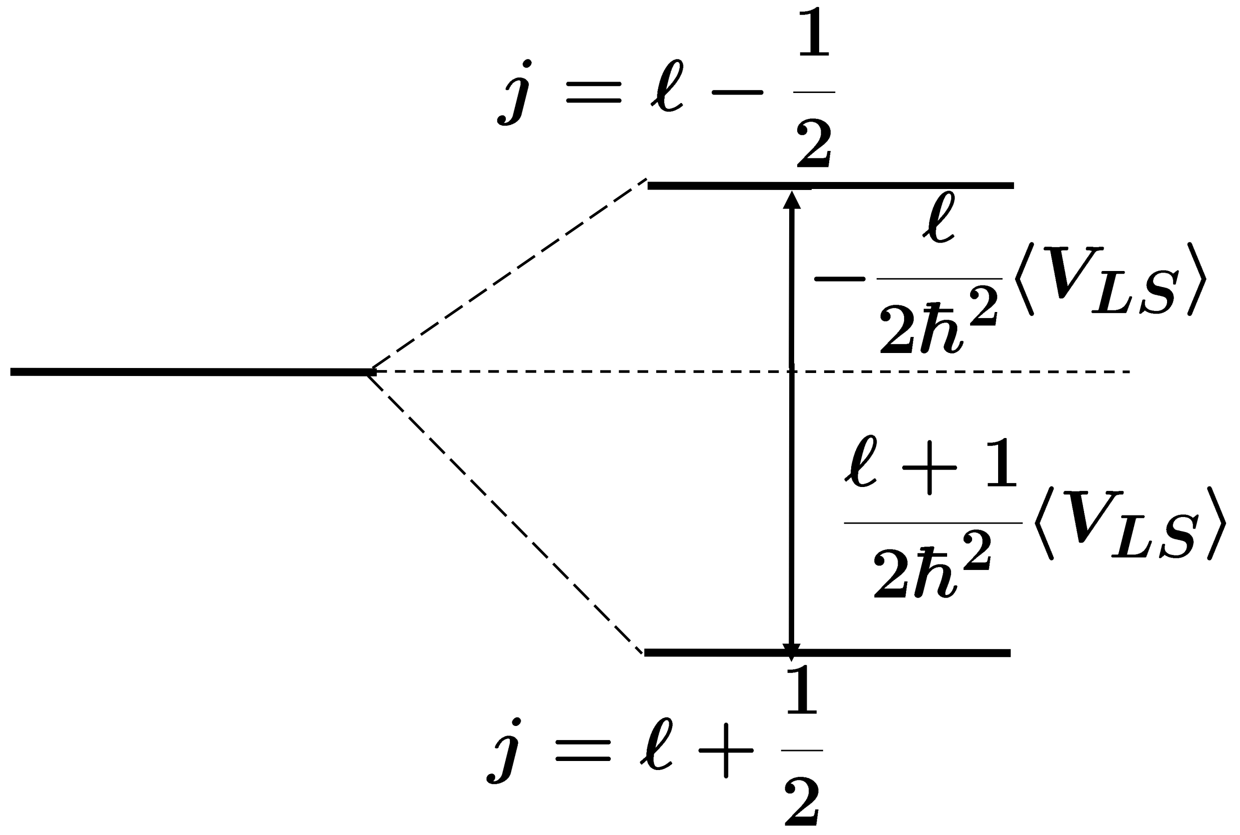
Bjorn Jonson
me

Strong Spin-Orbit Coupling

is essential in the formation of magic numbers in nuclei







Spin-orbit splitting

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

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.

The FIRST Polarization Study

Mayer & Jensen claimed in 1948

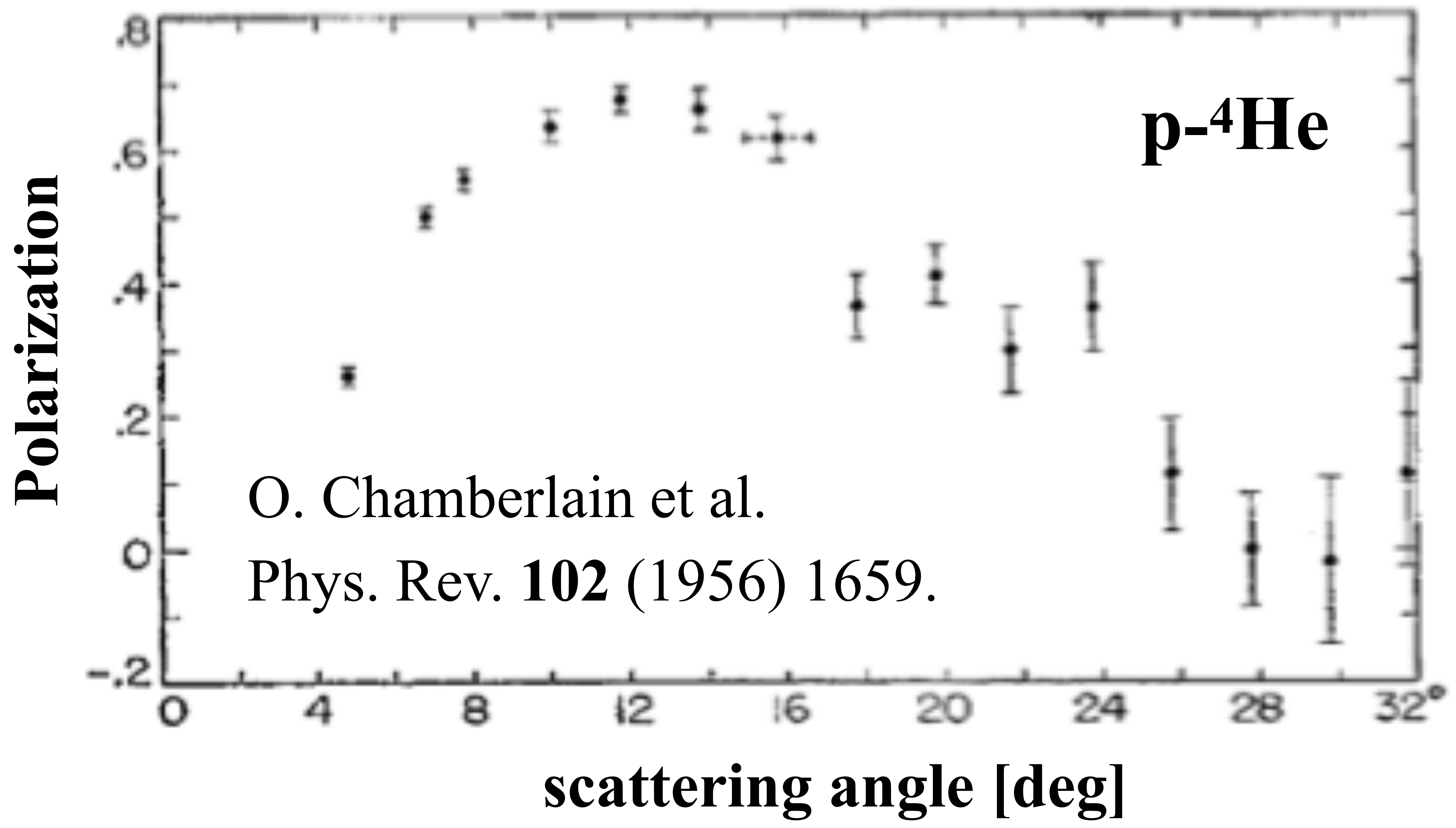
Strong spin-orbit coupling:

necessary to account for the magic numbers

one-order of magnitude stronger than the Thomas term

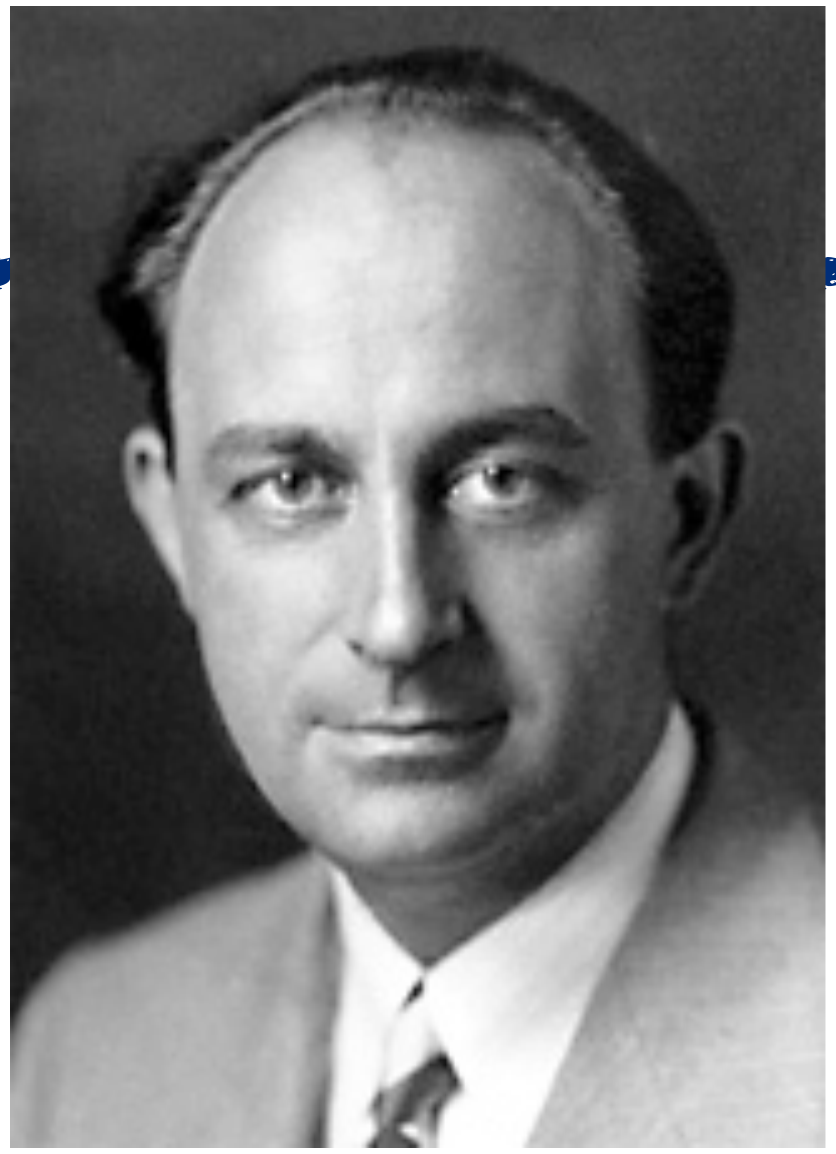
Several groups tried to measure spin asymmetry A_y

for p- A elastic scattering



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

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.

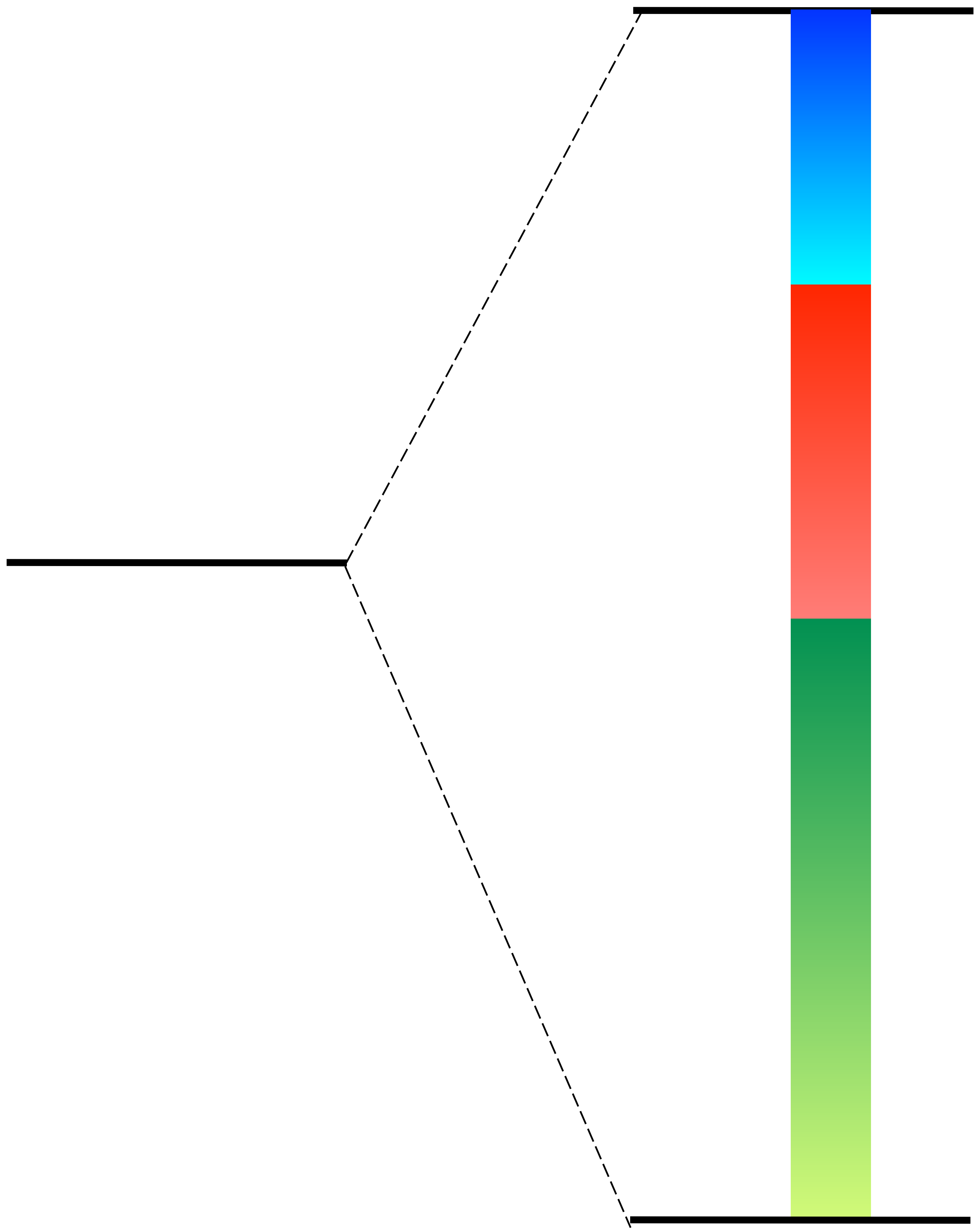
E. FERMI

University of Chicago - Institute for Nuclear Studies - Chicago

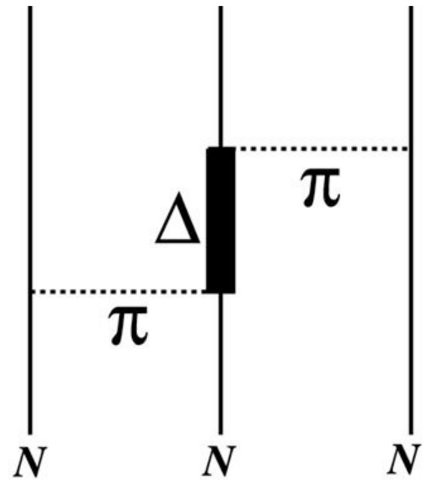
(ricevuto il 22 Febbraio 1954)

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.



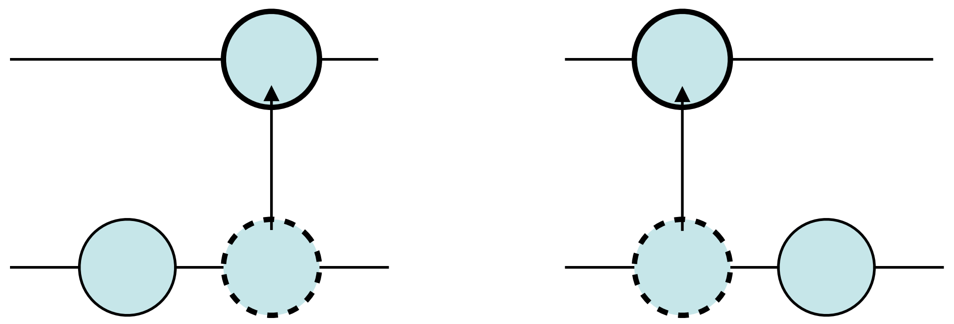
3N force



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

Tensor force

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

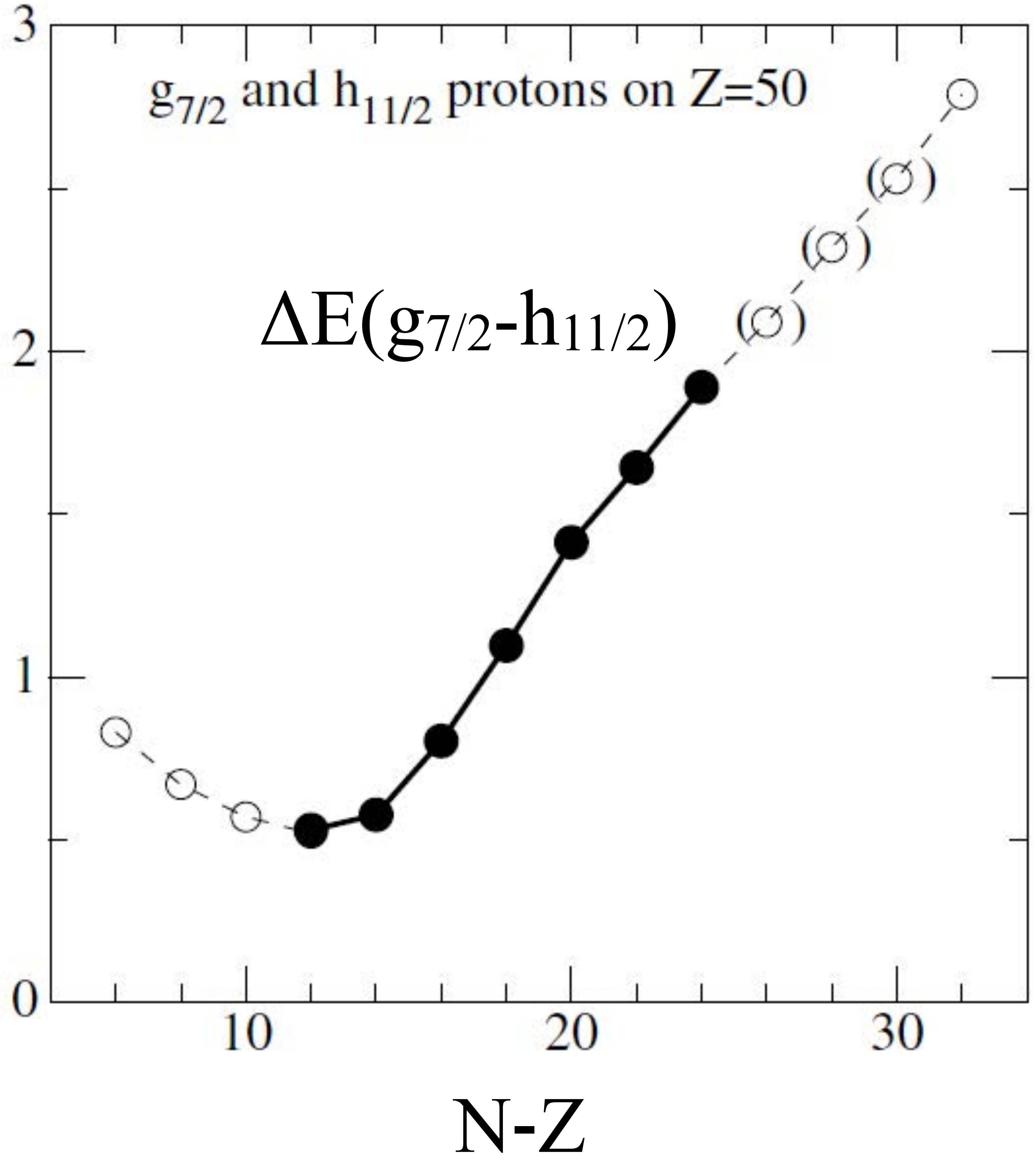


NN LS interaction
σ and ω exchange
isoscaler in nature

Neutron-number dependences of LS splitting

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

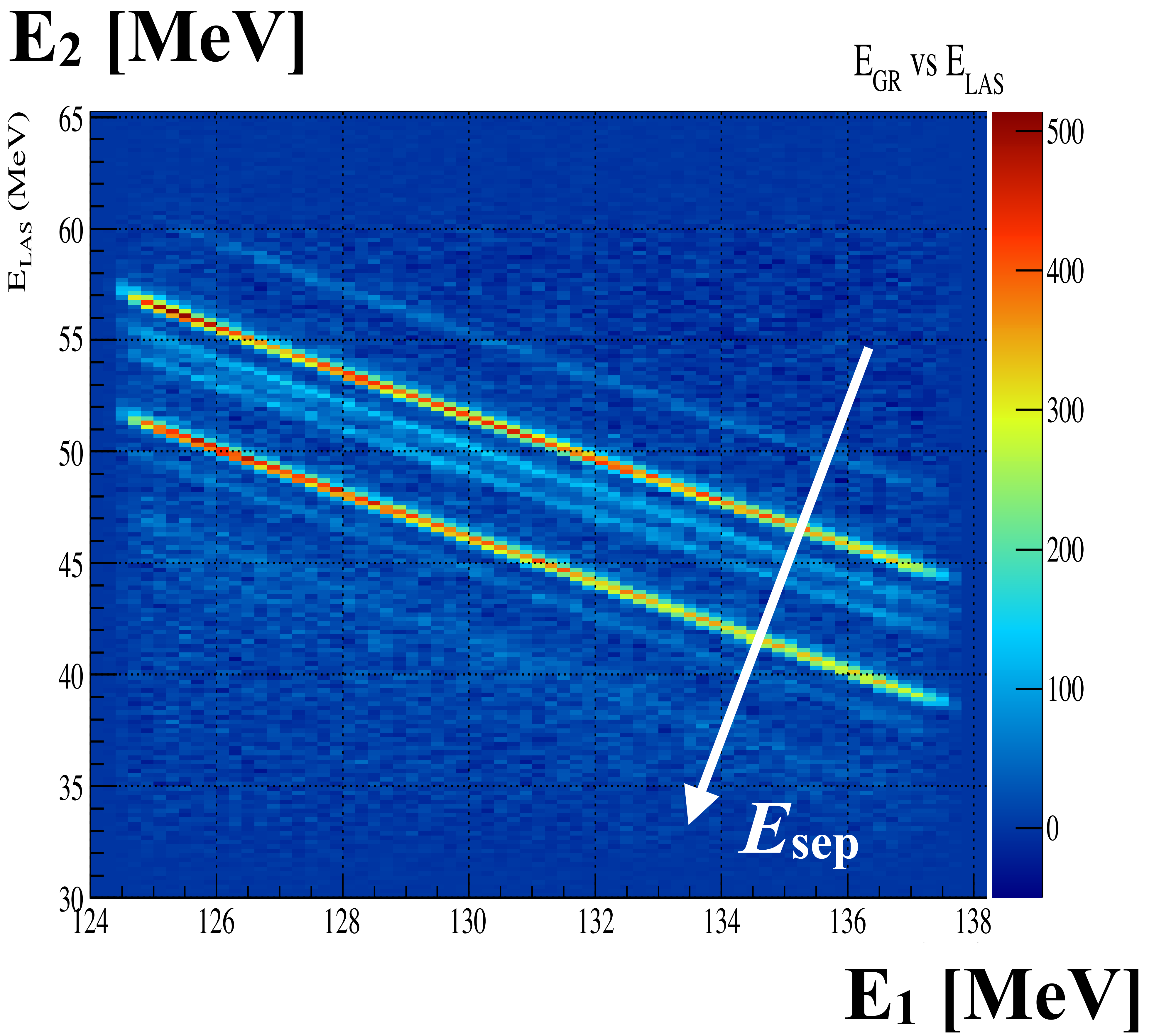
Sn isotopes



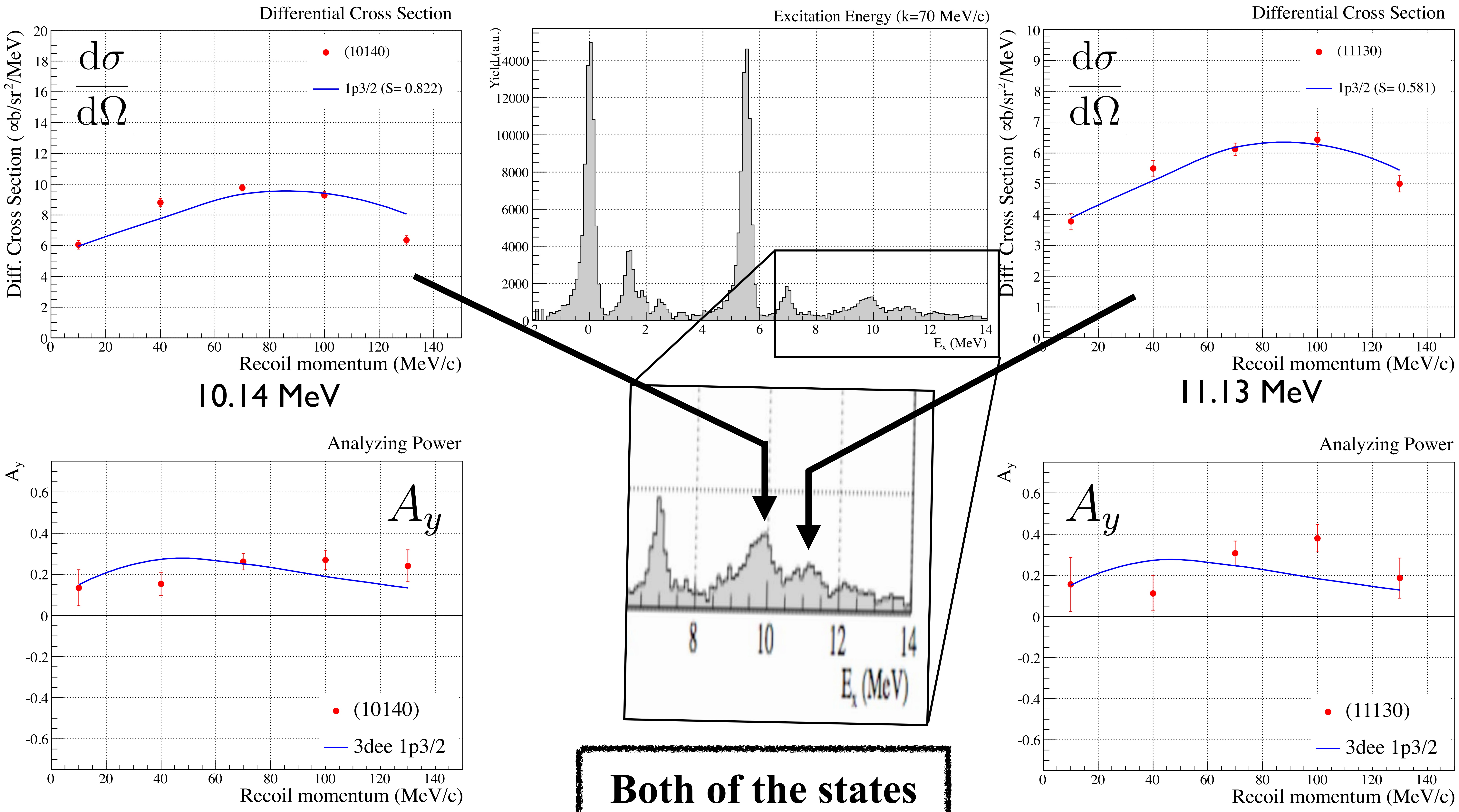
Spin observables: ^{18}O(p,2p) experiment @RCNP

Kawase et al.

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



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

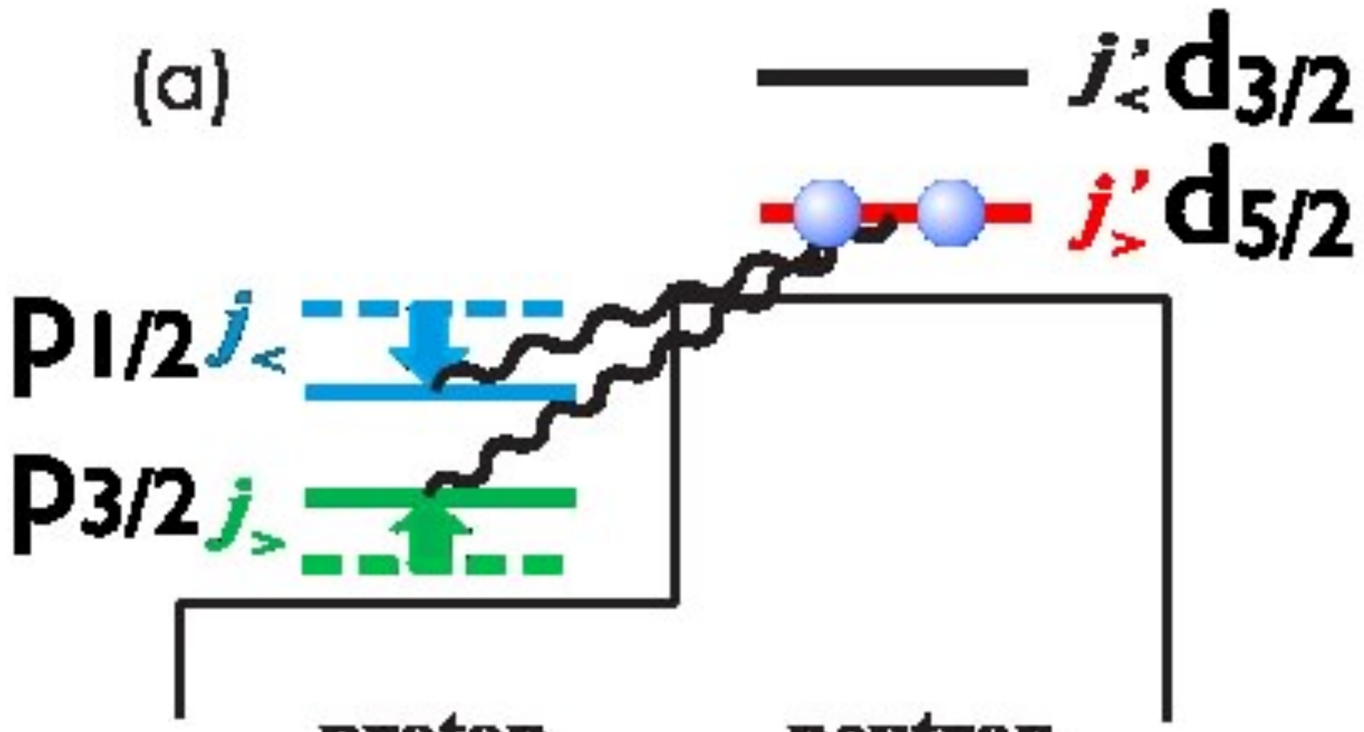


Both of the states are $p_{3/2}$-hole states.

Spin-orbit splitting in ^{18}O

8	O -2 -218.79 -182.95 -118.56 15.9994 0.078%	O12 0.40 MeV 0+ 2p	O13 8.58 ms (3/2-) ECp	O14 70.606 s 0+ EC	O15 122.24 s 1/2- EC	O16 0+ 99.762	O17 5/2+ 0.038	O18 0+ 0.200	O19 26.91 s 5/2+ β-	O20 13.51 s 0+ β-	O21 3.42 s (1/2,3/2,5/2)+ β-	O22 2.25 s 0+ β-	O23 82 ms β-n	O24 61 ms 0+ β-n

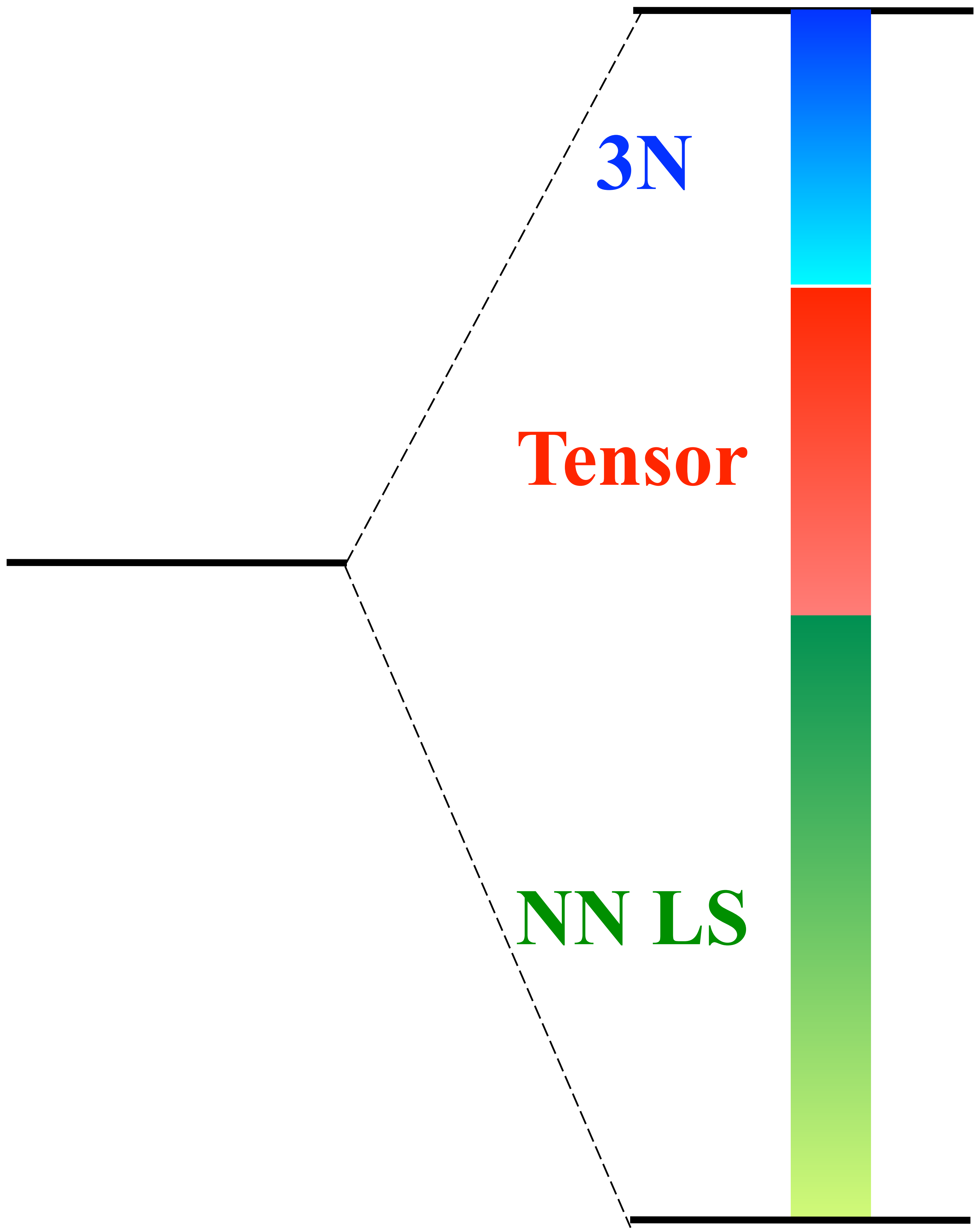
Tensor force effect!

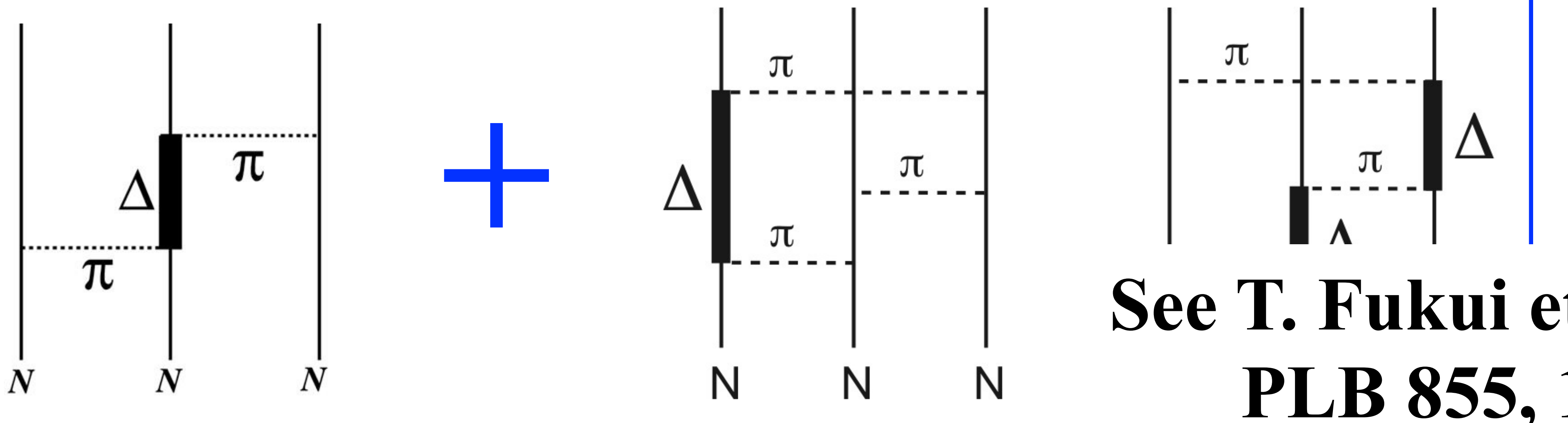


T. Otsuka *et al.*, Phys. Rev. Lett., 95,232502 (2005).

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

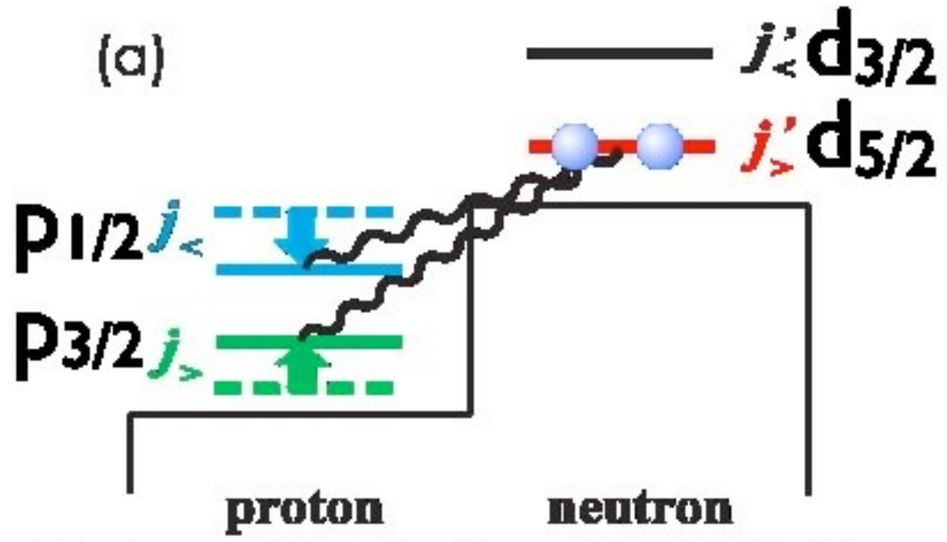
Spin-orbit splittings in Exotic Nuclei





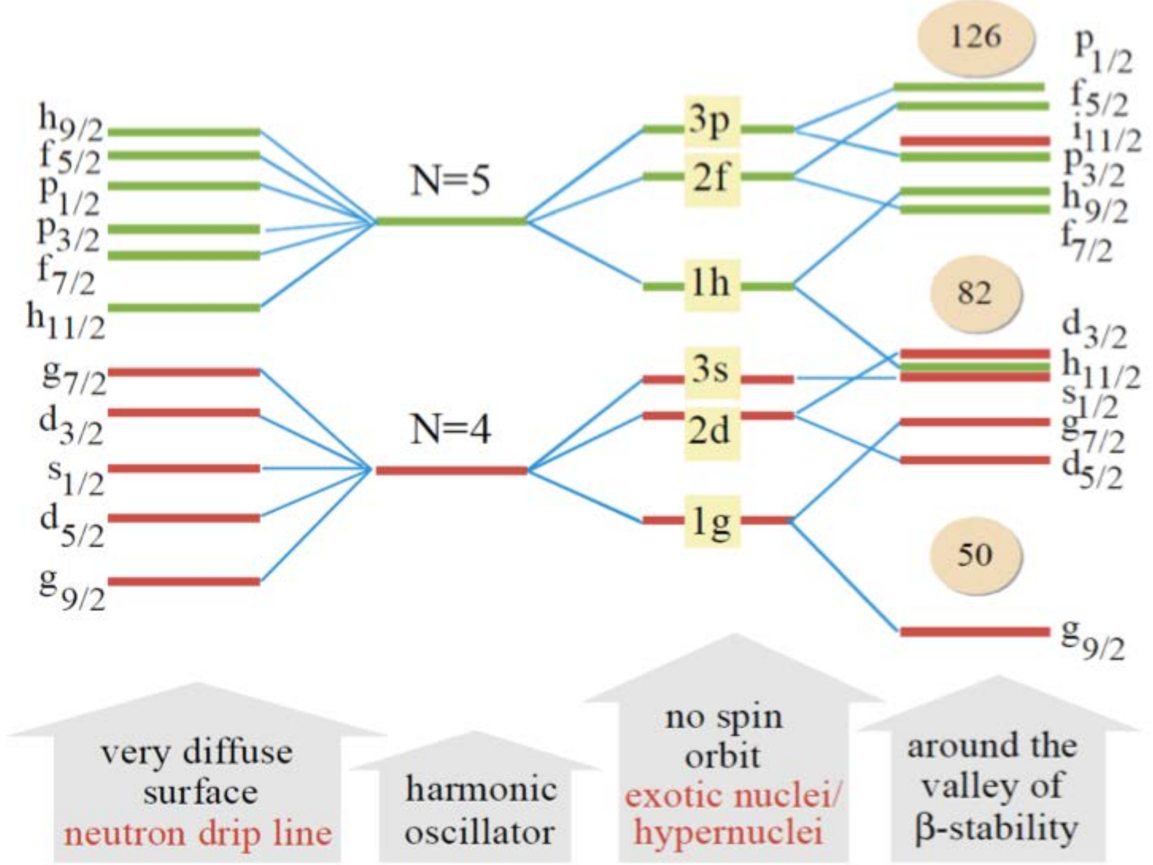
See T. Fukui et al. PLB 855, 138839 (2024).

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



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

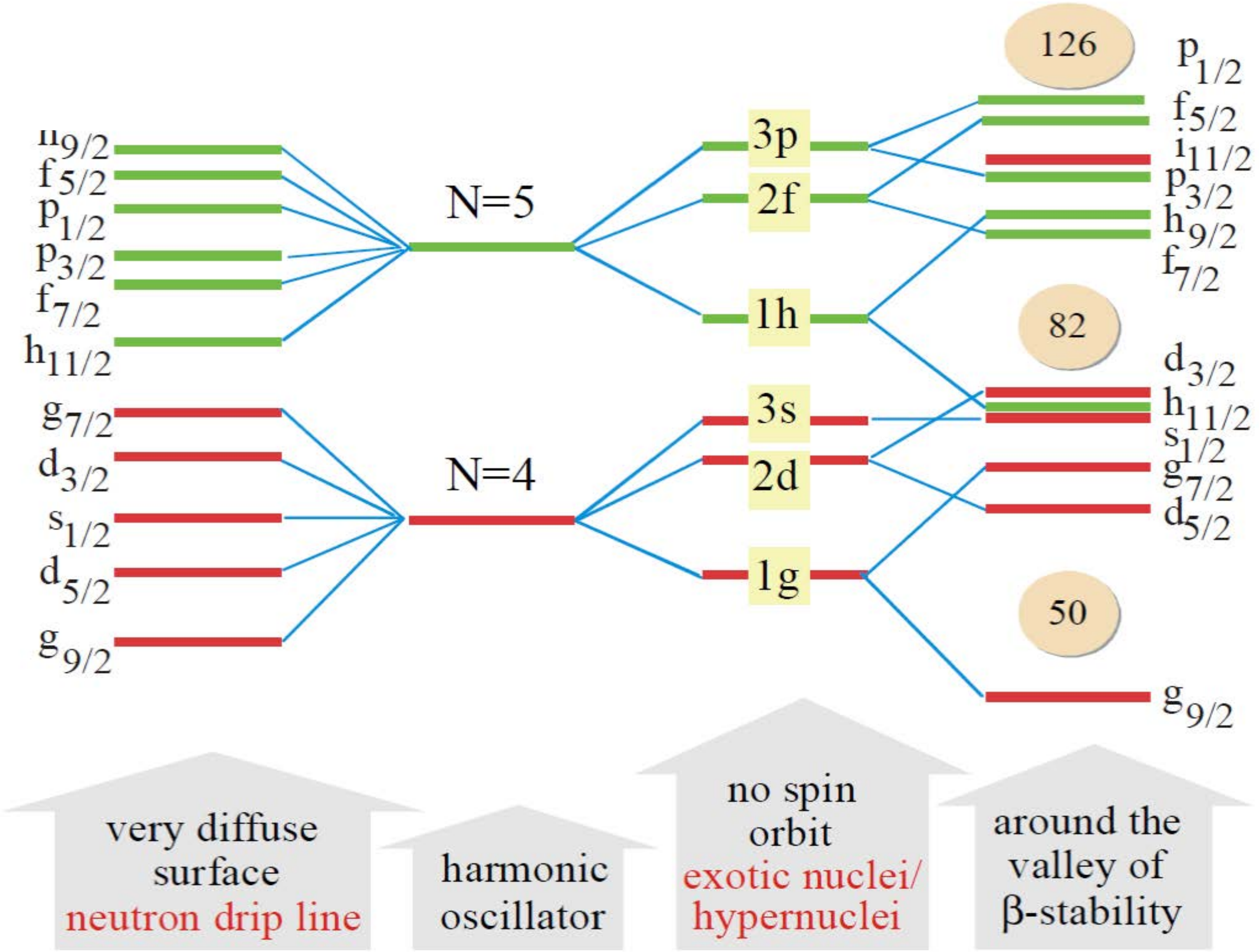
Mean-field effects



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

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

inconsistent

consistent

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

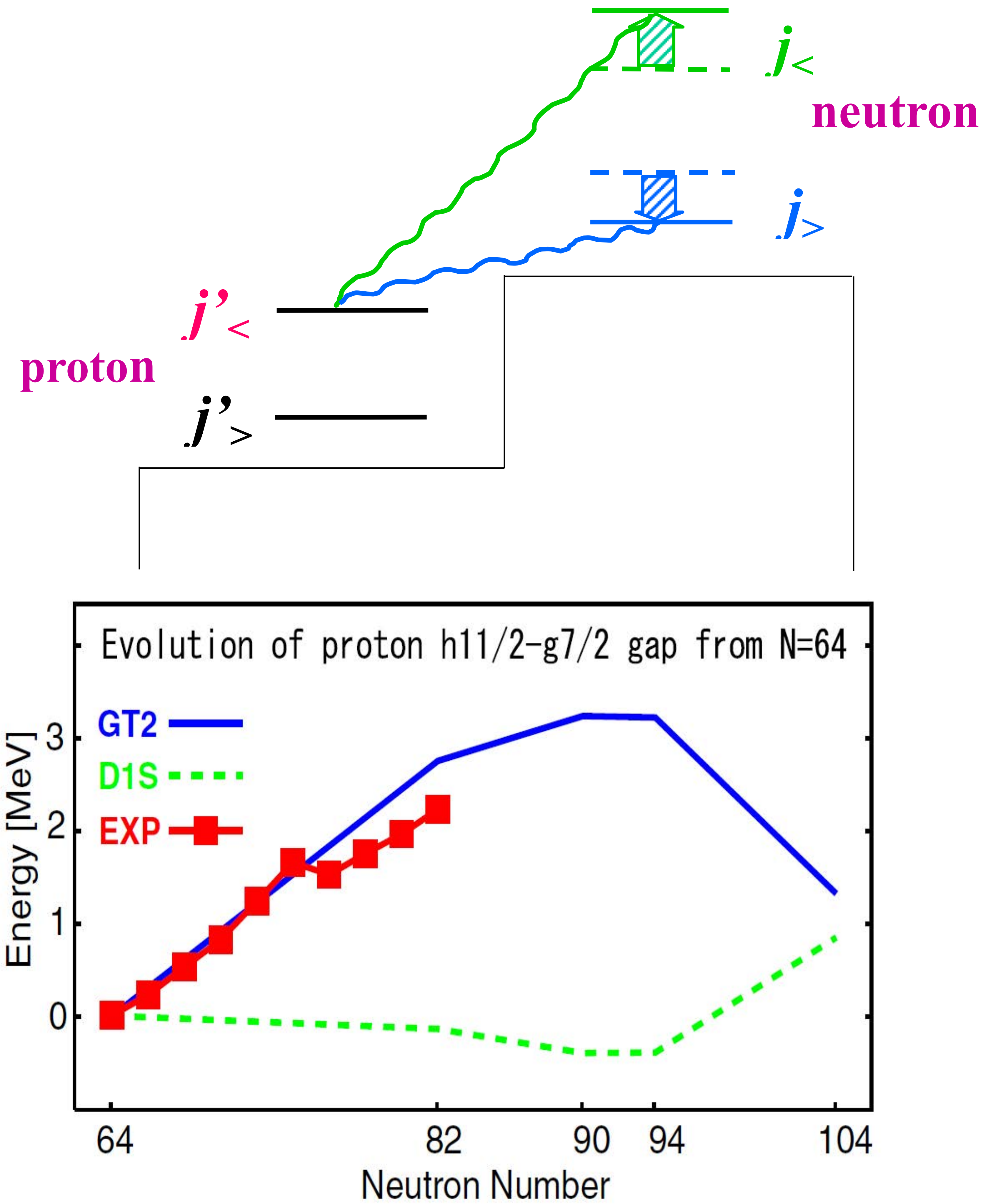
B. S. Pudliner et al.,
Phys. Rev. Lett. 76, 2416 (1996)

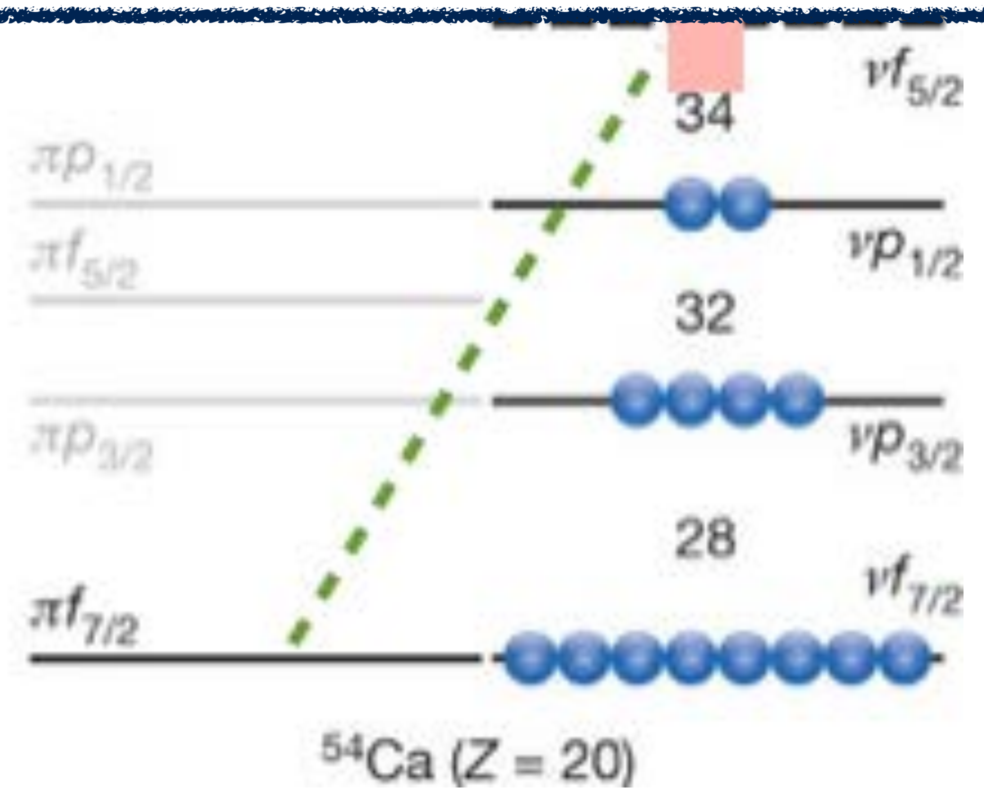
Tensor-force effects

First-order effects by T. Otsuka

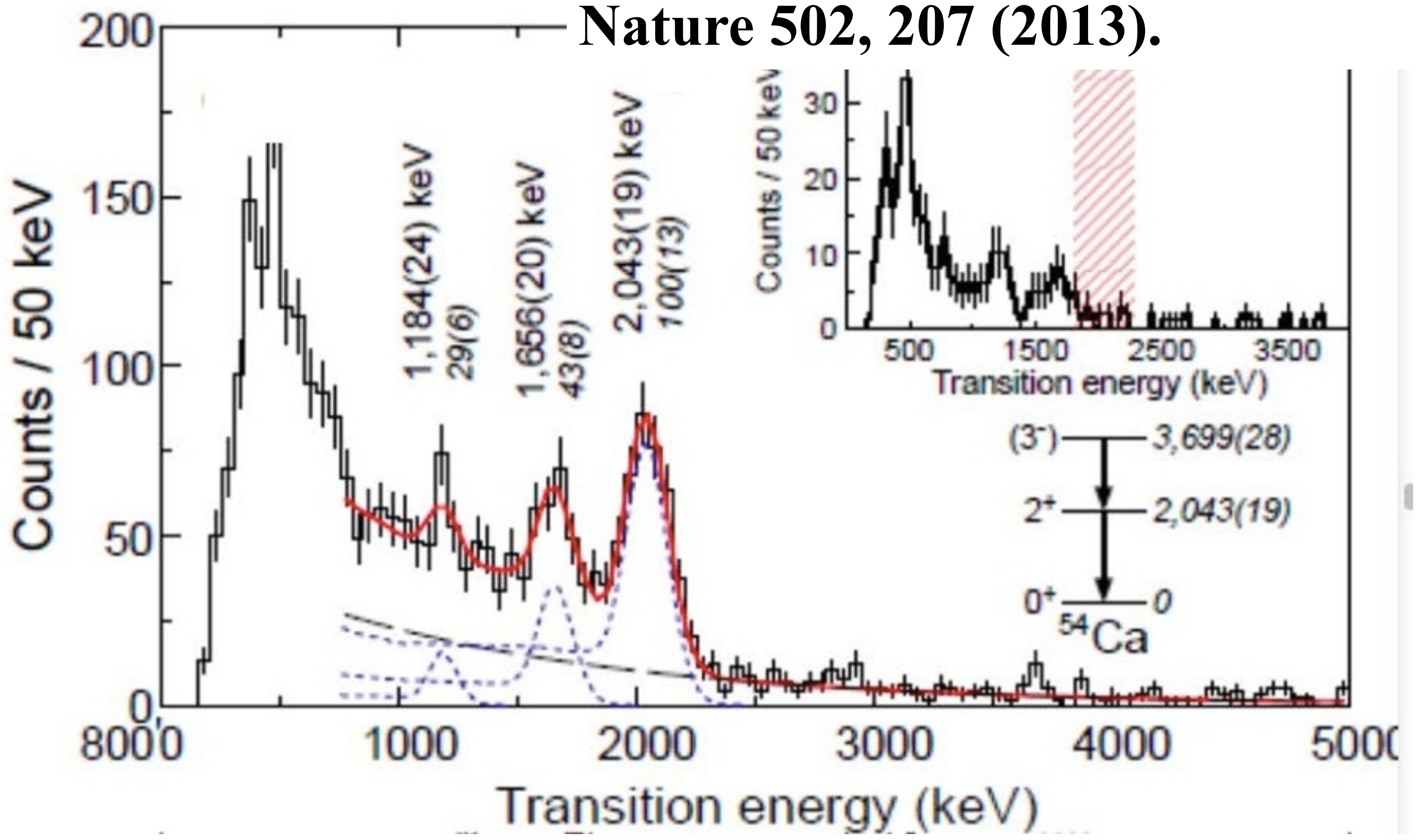
T. Otsuka *et al.*, Phys. Rev. Lett. 95, 232502

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



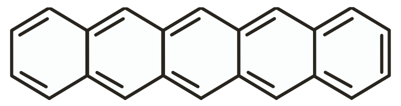


D. Steppenbeck, S. Takeuchi et al., Nature 502, 207 (2013).

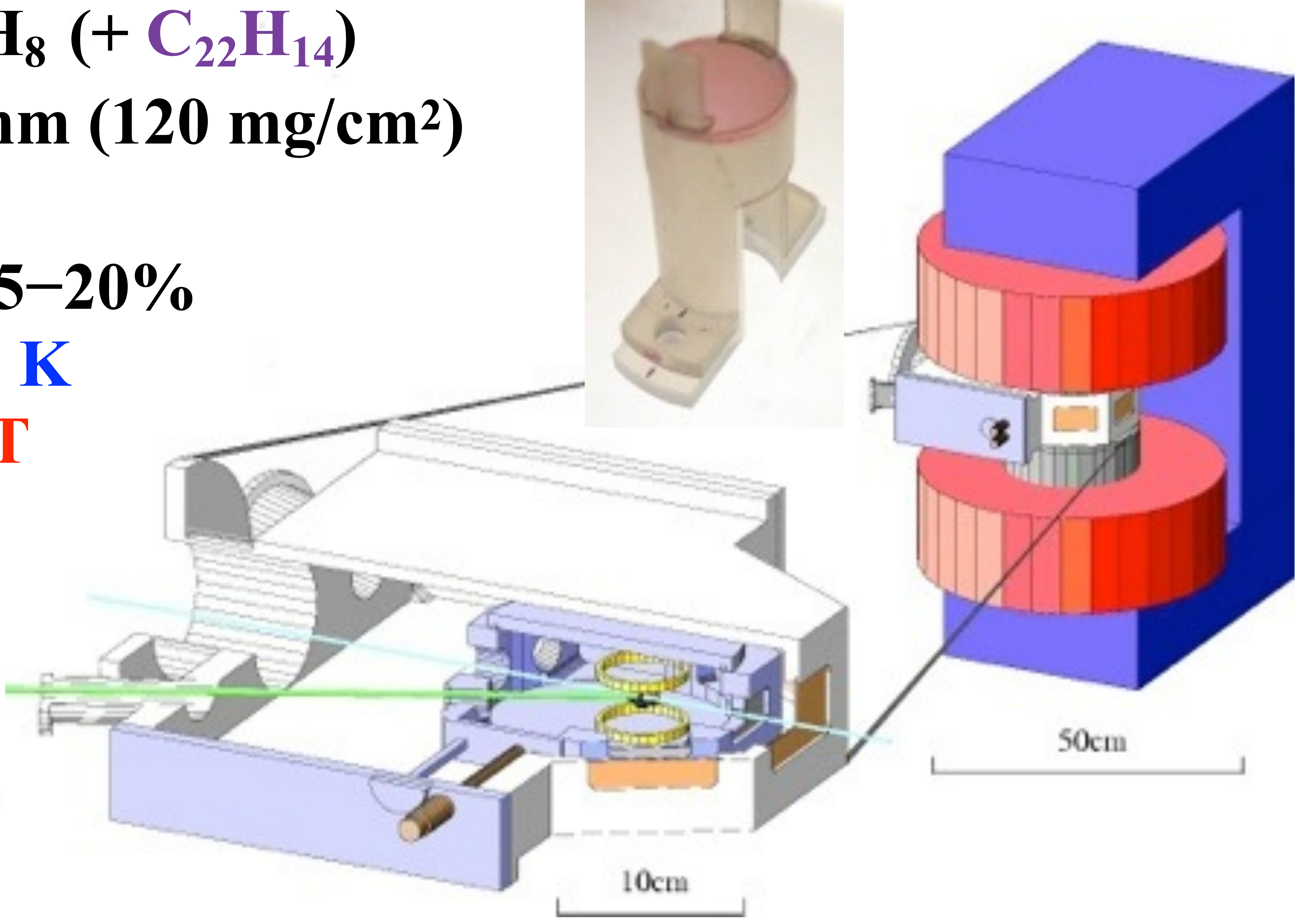


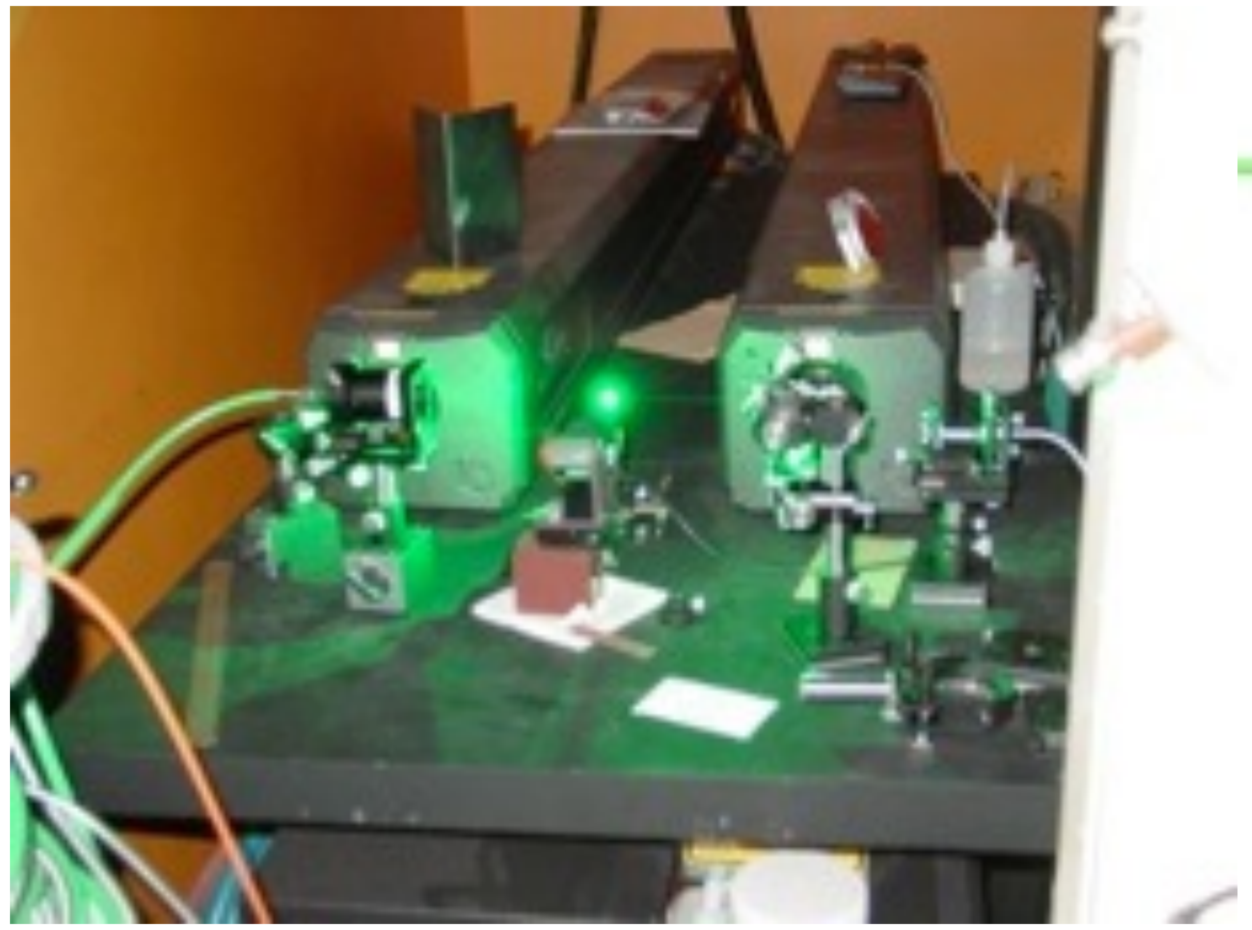
“TRIPLET” target at RIKEN-CNS

The FIRST Polarized Proton Target applicable to RI beam exp.



Material: $C_{10}H_8$ (+ $C_{22}H_{14}$)
Thickness: 1 mm (120 mg/cm²)
Size: ϕ14 mm
Polarization: P=15−20%
Temperature: 100 K
Mag. field: 0.1 T

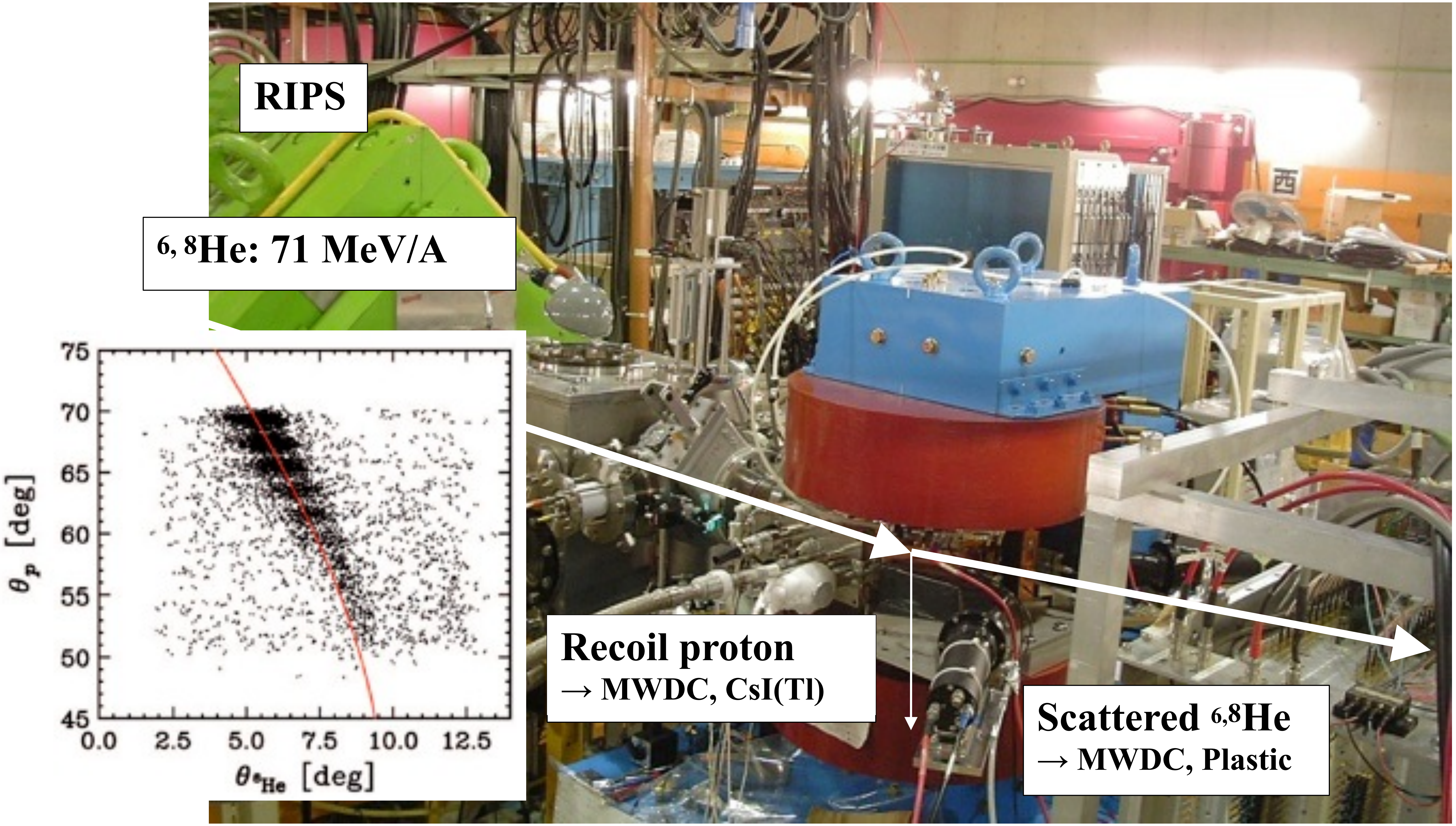




T. Wakui et al., NIM A 550 (2005) 521.
TU, M. Hatano et al., NIM A 526 (2004) 186.
A. Obertelli and TU, EPJ A 47 (2011) 105.

Experiments at RIPS, RIKEN

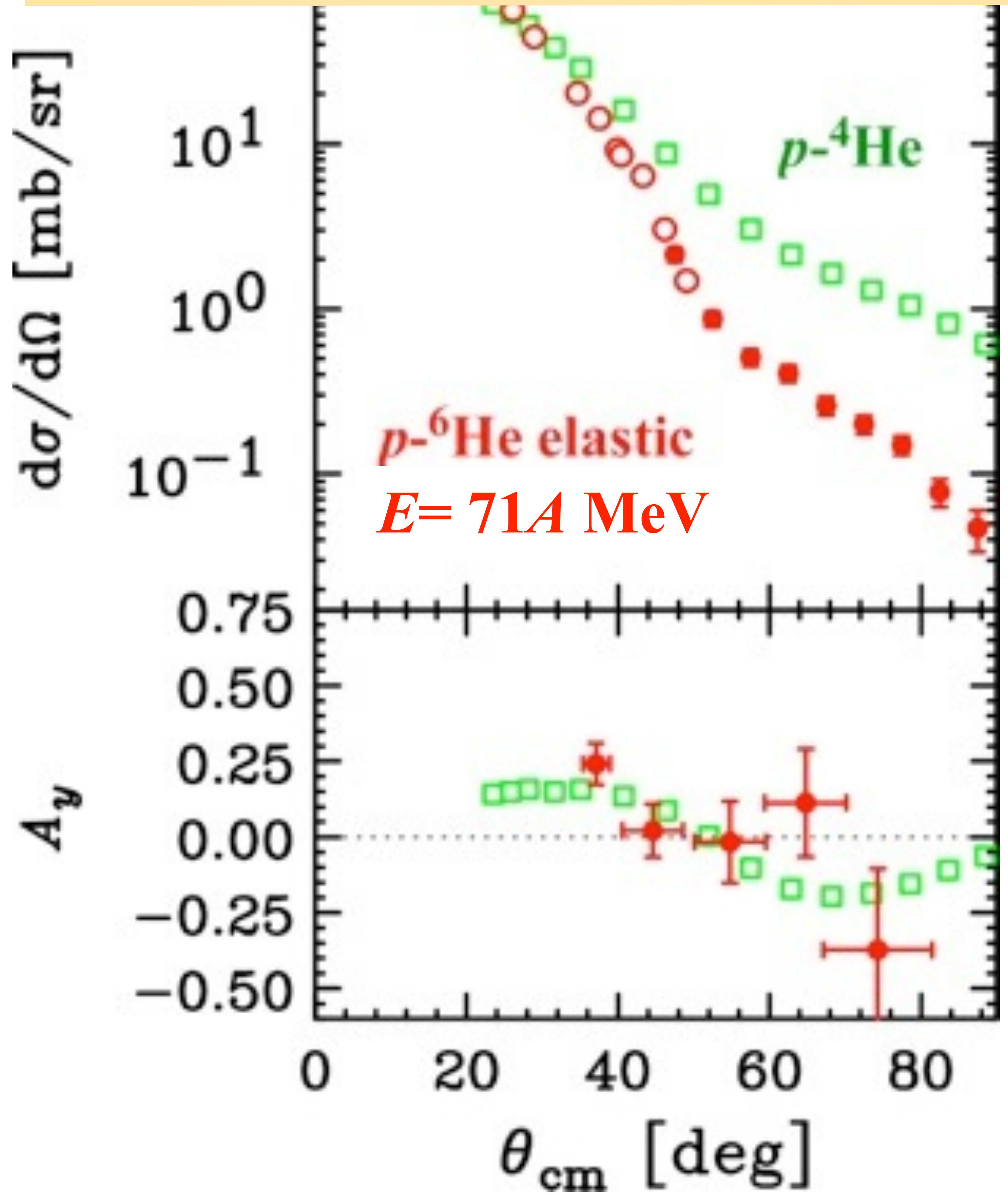
p-^{6}He @ 71 MeV/u in : 2.5×10^{5} pps
p-^{8}He @ 71 MeV/u in : 1.7×10^{5} pps

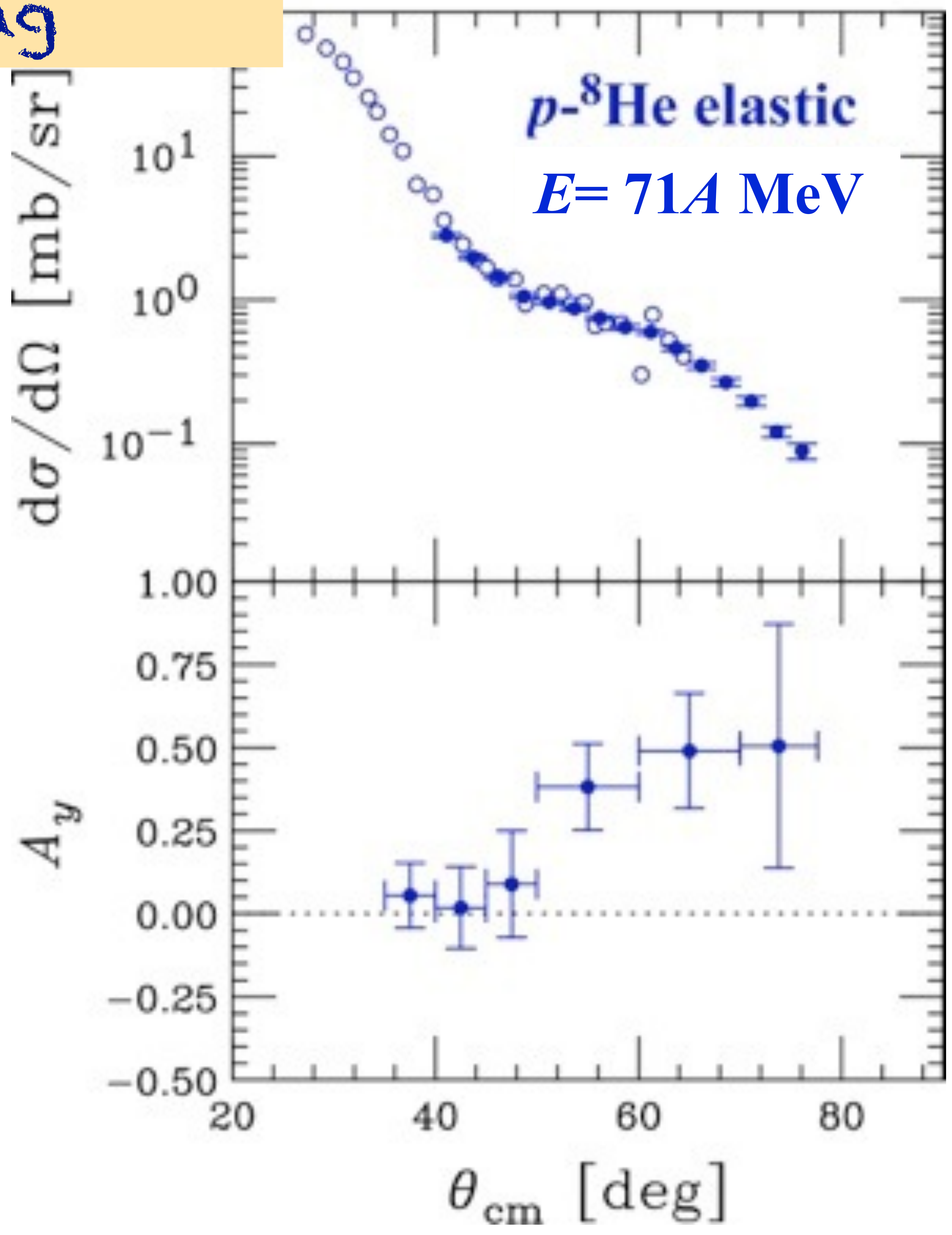


Results of $d\sigma/d\Omega$, A_y

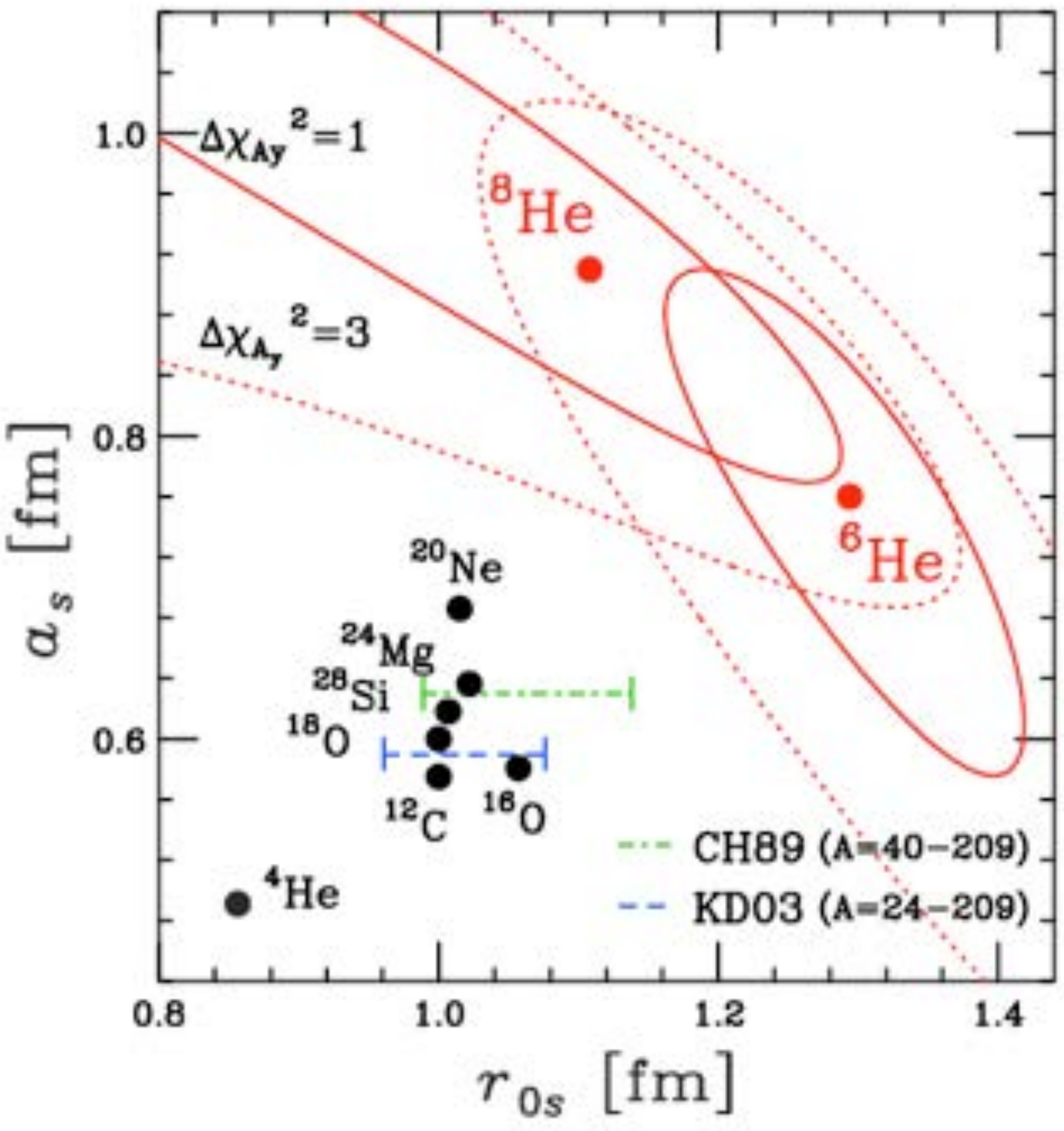
T. Uesaka et al., PRC **82** (2010) 021602(R).
S. Sakaguchi et al., PRC **84** (2011) 024604.
S. Sakaguchi et al., PRC **87** (2013) 021601(R).

The FIRST SPIN ASYMMETRY DATA
taken in RI-beam Scattering





Radius and diffuseness parameters



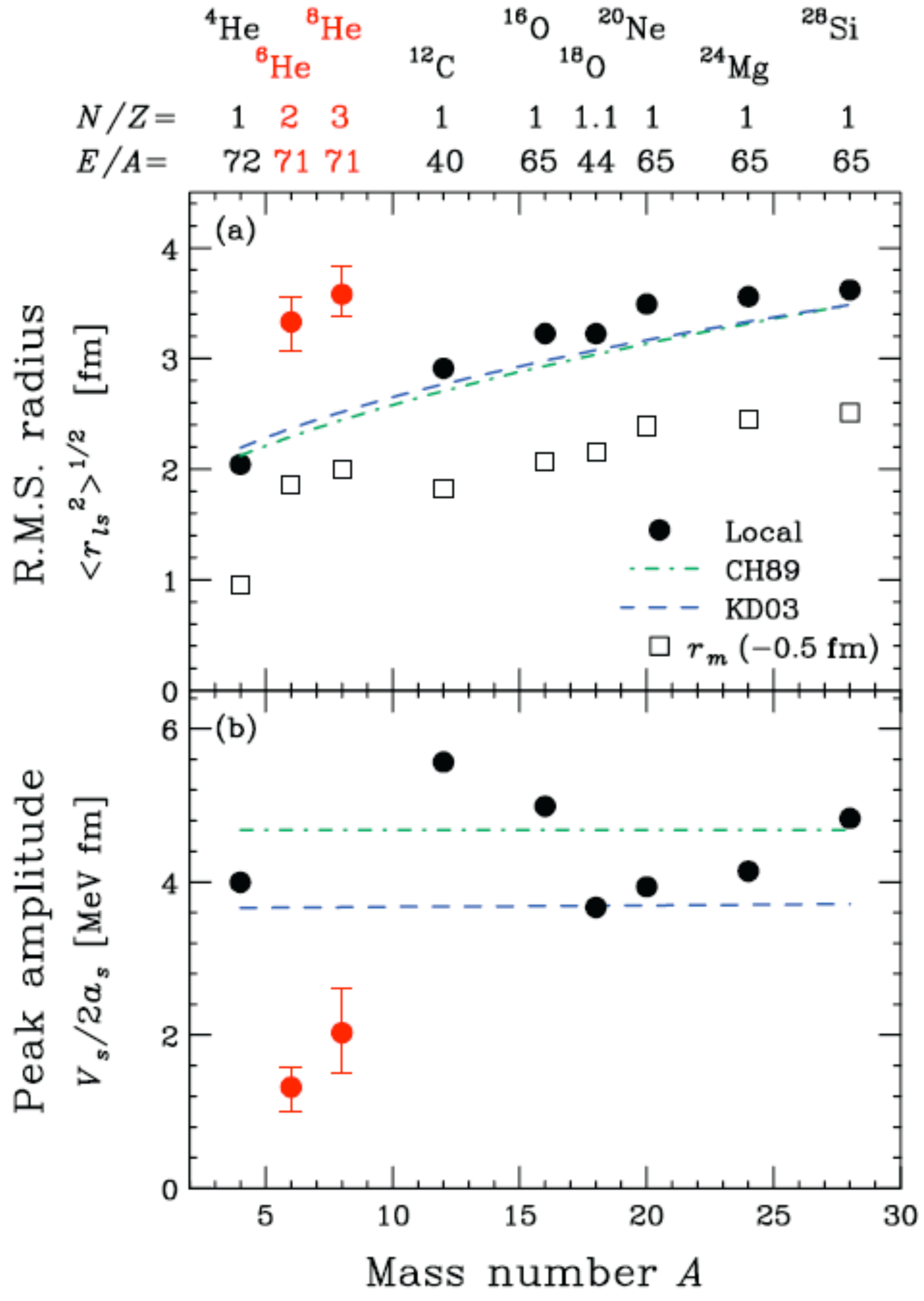
S. Sakaguchi, TU et al.
PRC 87 ('13) 021601(R)

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!



I am eager to conduct (*p*,2*p*) experiments with the polarized target at the earliest opportunity.

Recent progress of the polarization: P=60% at 300K

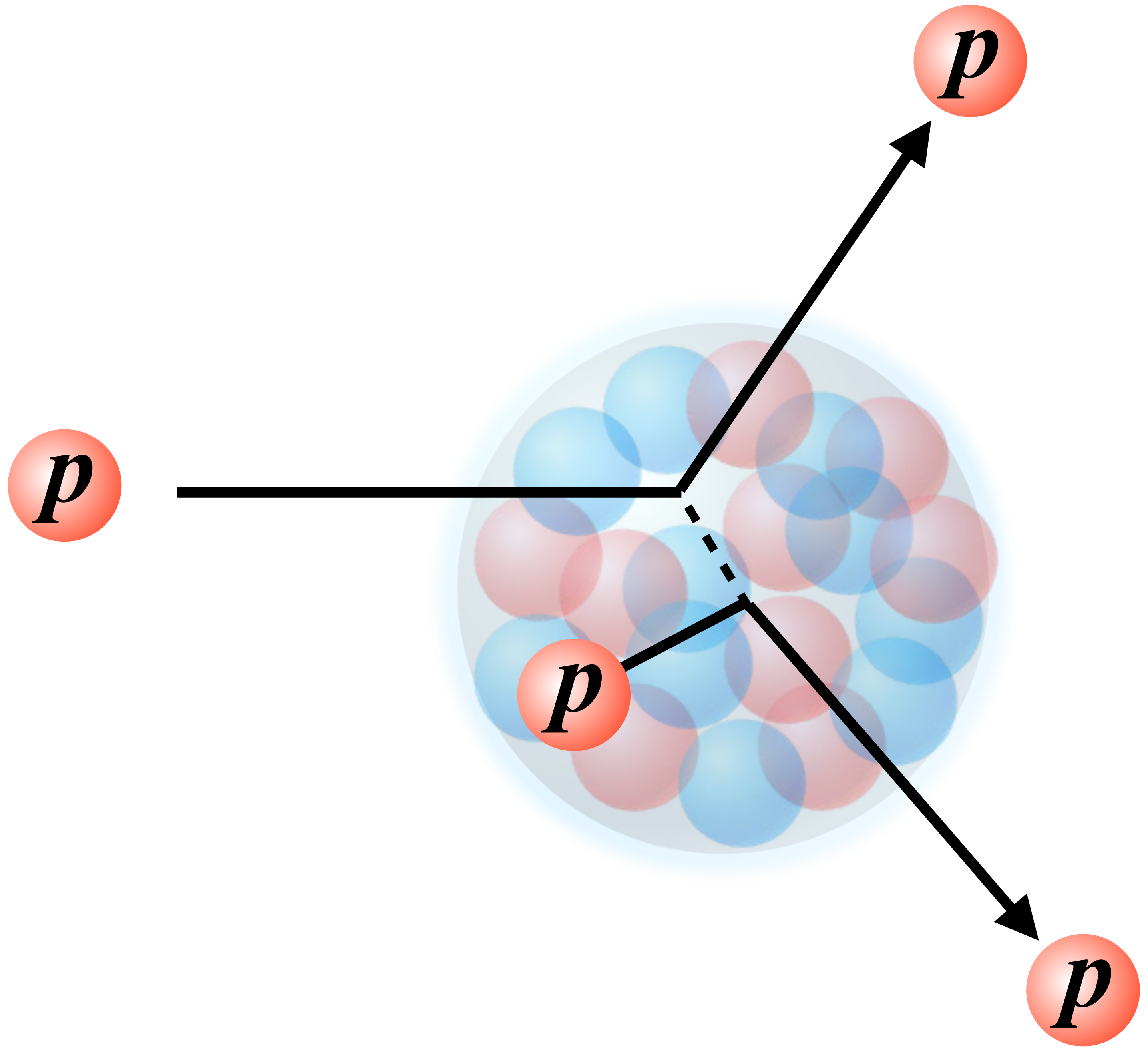
K. Tateishi et al, Chem. Phys. Lett. **885**, 142606 (2026).

Two topics more

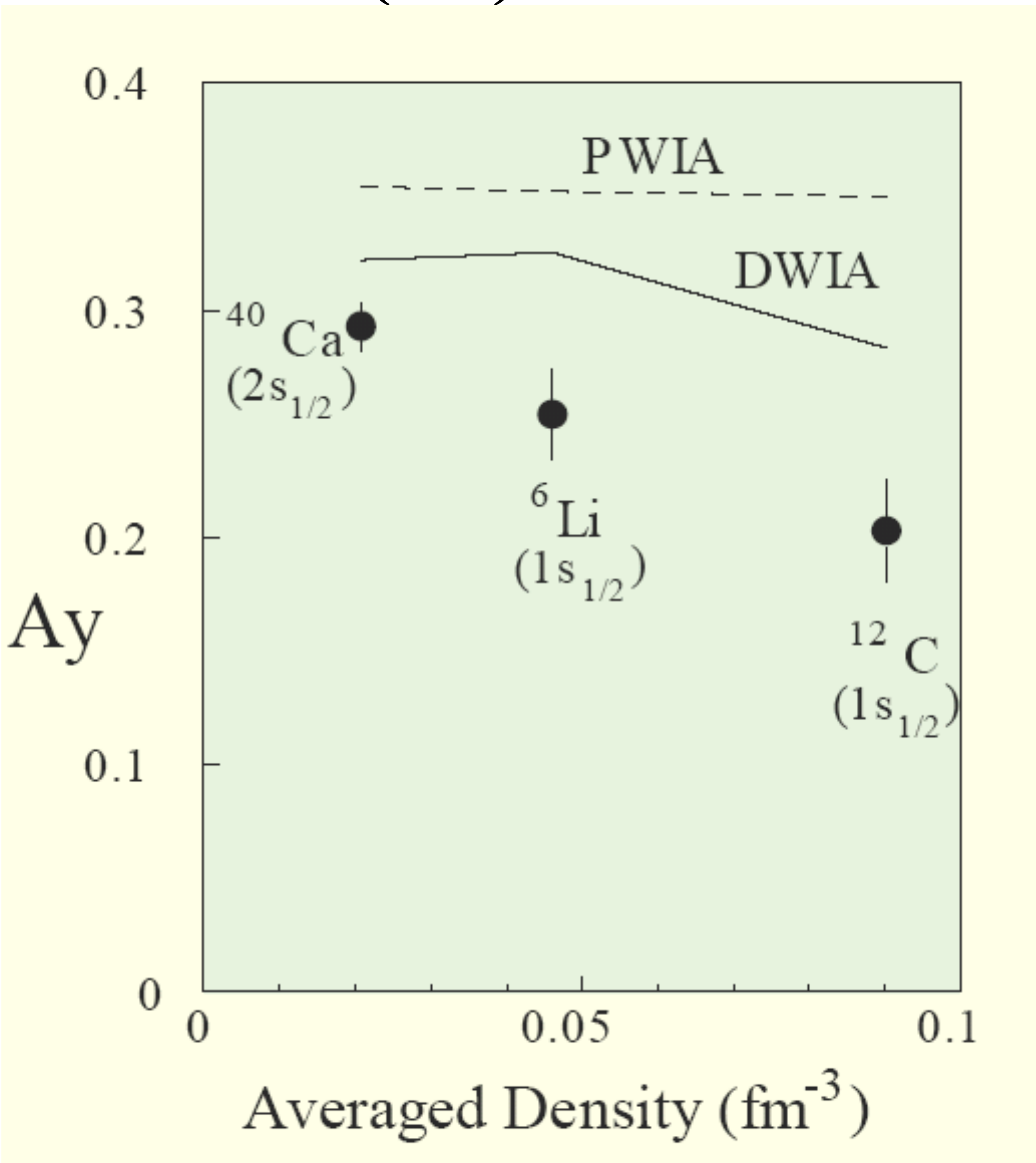
(p,2p) is the p-p elastic scattering in the nuclear medium.

How does the nuclear medium affect the p-p scattering amplitudes?

- Pauli blocking effects
- Multi-nucleon force effects
- Modification of mesons in nuclear medium
  (partial restoration of chiral symmetry)



K. Hatanaka, T. Noro et al.,
PRL 78 ('97) 1014.



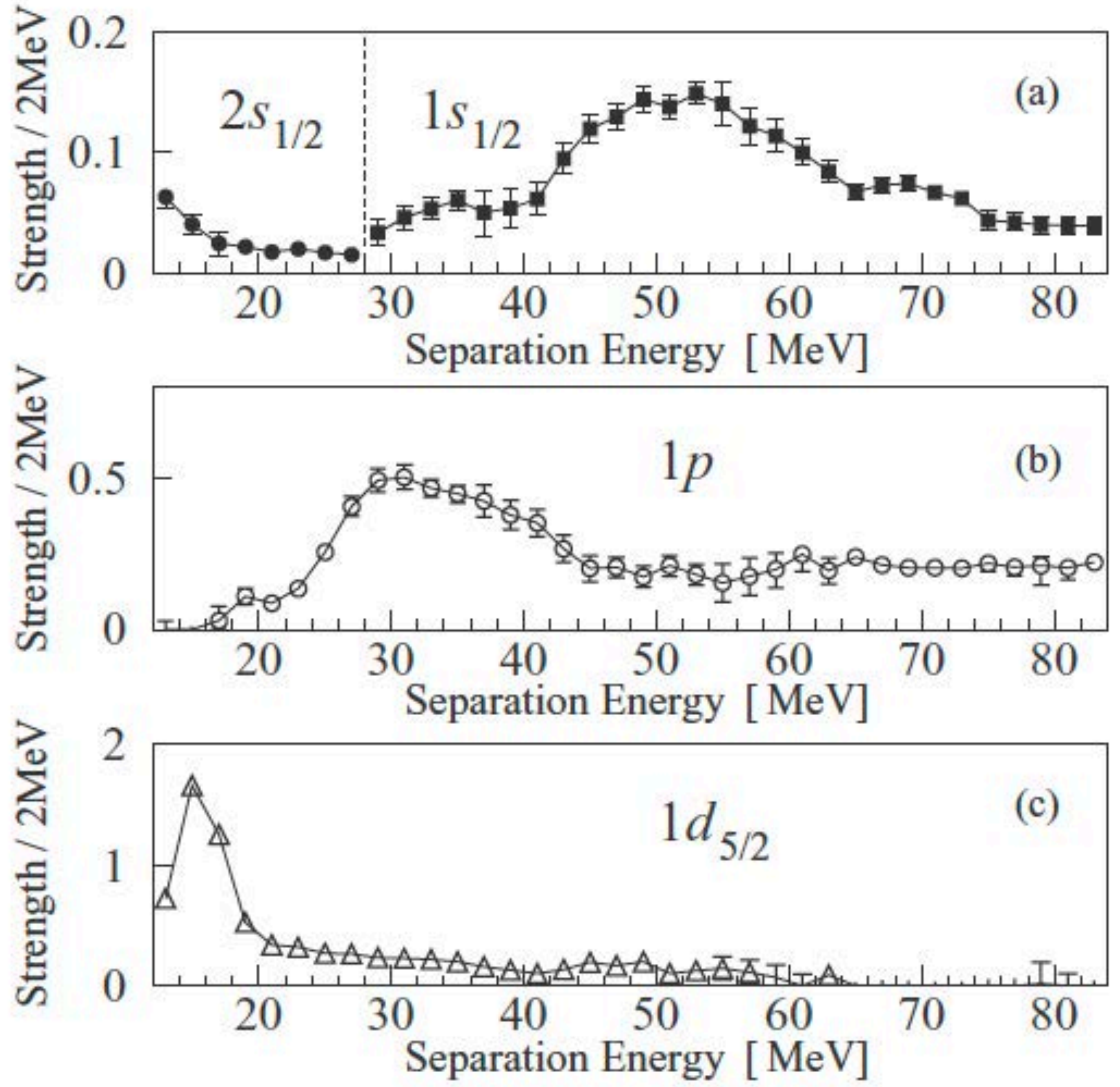
Spectroscopy of deep hole $0s_{1/2}$ states

Y. Yasuda et al., PRC 81, 044315 (2010).

PHYSICAL REVIEW C **81**, 044315 (2010)

Spectroscopic factors and strength distributions for the deeply bound orbitals in ^{40}Ca obtained from the $(\vec{p},2p)$ reaction at 392 MeV

Y. Yasuda,[1,*] H. Sakaguchi,[1,†] S. Asaji,[2] K. Fujita,[3,‡] Y. Hagihara,[2] K. Hatanaka,[3] T. Ishida,[2] M. Itoh,[3,§] T. Kawabata,[4,‖] S. Kishi,[1] T. Noro,[2] Y. Sakemi,[3,§] Y. Shimizu,[3,¶] H. Takeda,[5] Y. Tameshige,[3,**] S. Terashima,[1,††] M. Uchida,[3,‡‡] T. Wakasa,[2] T. Yonemura,[2] H. P. Yoshida,[3,§] M. Yosoi,[3] and J. Zenihiro[1,†]



	IPSM limit	Present work	Fabrocini *et al.* [6]	Bisconti *et al.* [7]
$2s_{1/2}$	2	$0.60 \pm 0.10(\pm 0.02)$	0.86	0.87
$1d$	10		0.87	
$1d_{3/2}$	4	$0.78 \pm 0.13(\pm 0.01)$		0.85
$1d_{5/2}$	6	$0.94 \pm 0.17(\pm 0.06)$		0.86
$1p$	6	$0.49 \pm 0.10(\pm 0.06)$	0.58	
$1p_{1/2}$	2			0.81
$1p_{3/2}$	4			0.82
$1s_{1/2}$	2	$0.78 \pm 0.14(\pm 0.05)$	0.55	0.78

Summary of Part 2

Quenching of the single-particle strengths

35% reduction of the single-particle occupation below the Fermi level is one of the most basic features of nuclear many-body systems.

The reduction is due to short-range, tensor, and long-range correlations.

Isospin dependence of the quenching should be further investigated using RI beams.

See PPNP 118, 103847 (2021).

There are plenty of reasons to use (*p*,*pX*) reactions in RI-beam experiments

Use of thick targets, recoil particle detection

← decoupling between the reaction dynamics and the nuclear structure effects

The strong spin-orbit coupling is another distinct feature of nuclear systems, and **its evolution in nuclei far from the stability line is the interesting subject to be investigated using knockout reactions with a polarized target.**