”短距離”で相互作用する核内２核子系の観測方法について

- TAGXでの^{3}He光分解測定の経験からー

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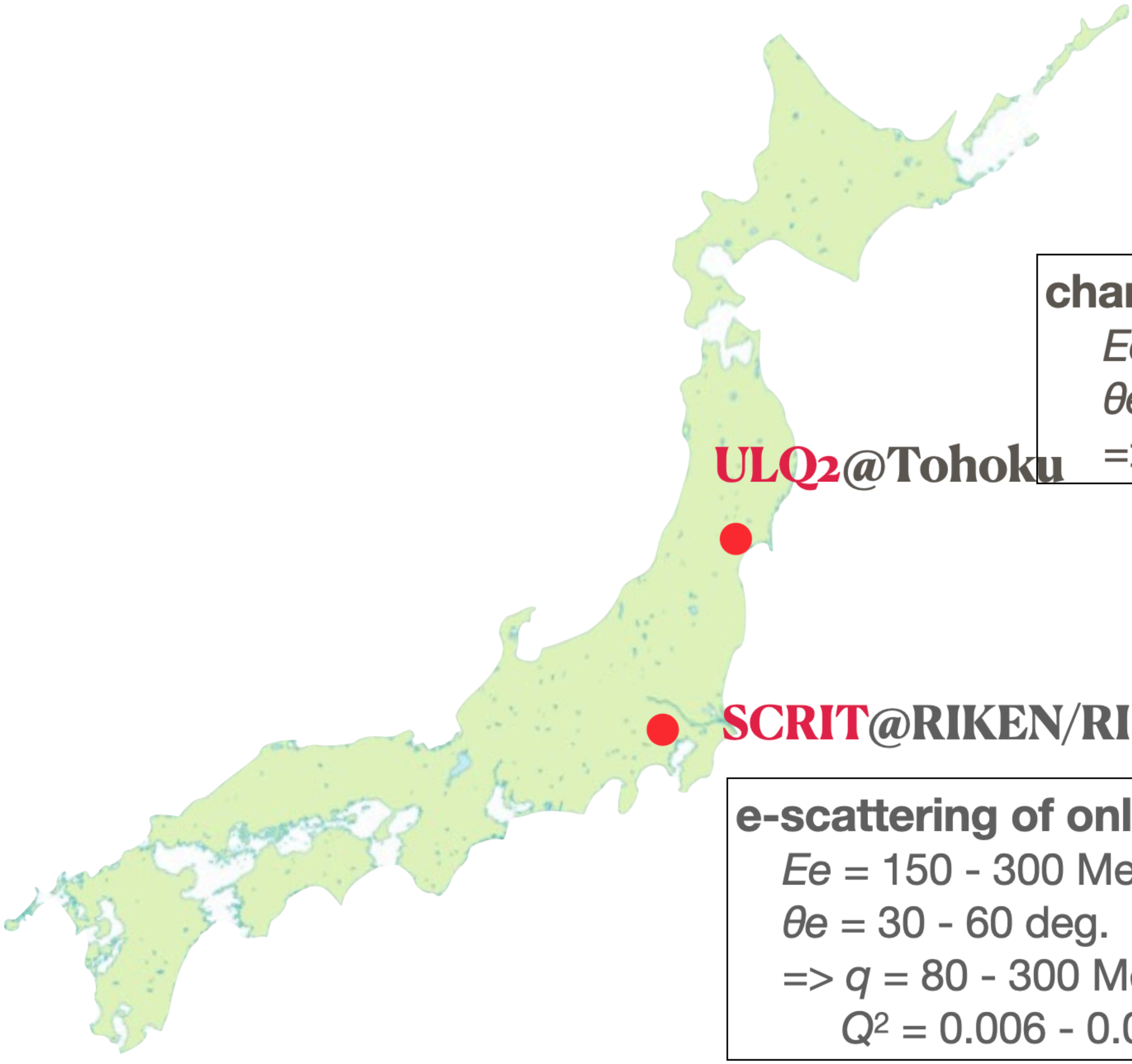
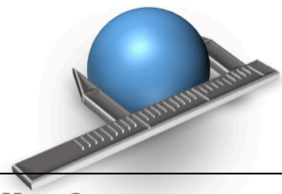
“Probing “Short-Range Correlations” in Nuclei

— Insights from TAGX Measurements of ^{3}He Photodisintegration”

Toshimi SUDA
Tohoku University





charge radii of proton and deuteron (neutron)

E_e = 10 - 60 MeV

θ_e = 30 - 150 deg.

=> $Q^2 = 3\text{x}10^{-5}$ - 0.013 (GeV/c)^2

lowest-ever Q^2 !!

e-scattering of online-produced exotic nuclei (~10^8/sec)

E_e = 150 - 300 MeV

θ_e = 30 - 60 deg.

=> q = 80 - 300 MeV/c

Q^2 = 0.006 - 0.09 (GeV/c)^2

world's first !!

“Two-nucleon” knockout exp. @ JLab

Nature 320, 1476, 2008

$^{12}C(e,e'pp)/^{12}C(e,e'p)$

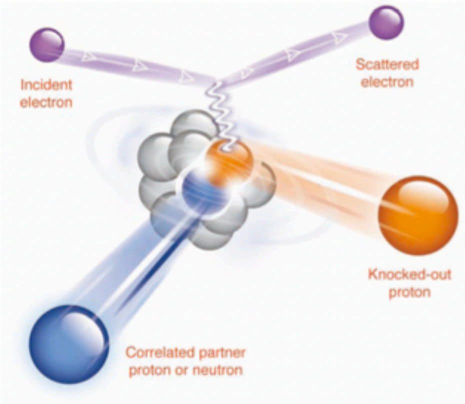


Fig. 1. Illustration of the $^{12}C(e,e'pN)$ reaction. The incident electron beam couples to a nucleon-nucleon pair via a virtual photon. In the final state, the scattered electron is detected along with the two nucleons that are ejected from the nucleus. Typical nuclear density is about 0.16 nucleons/fm^3, whereas for pairs the local density is approximately five times larger.

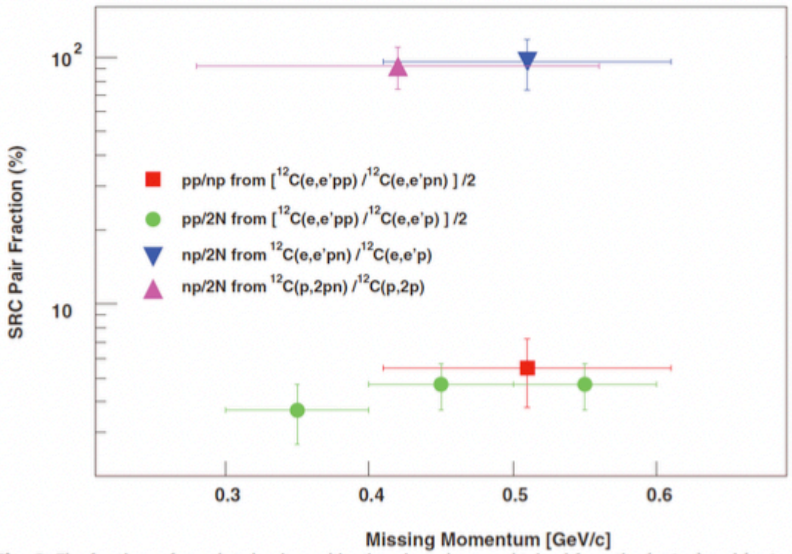
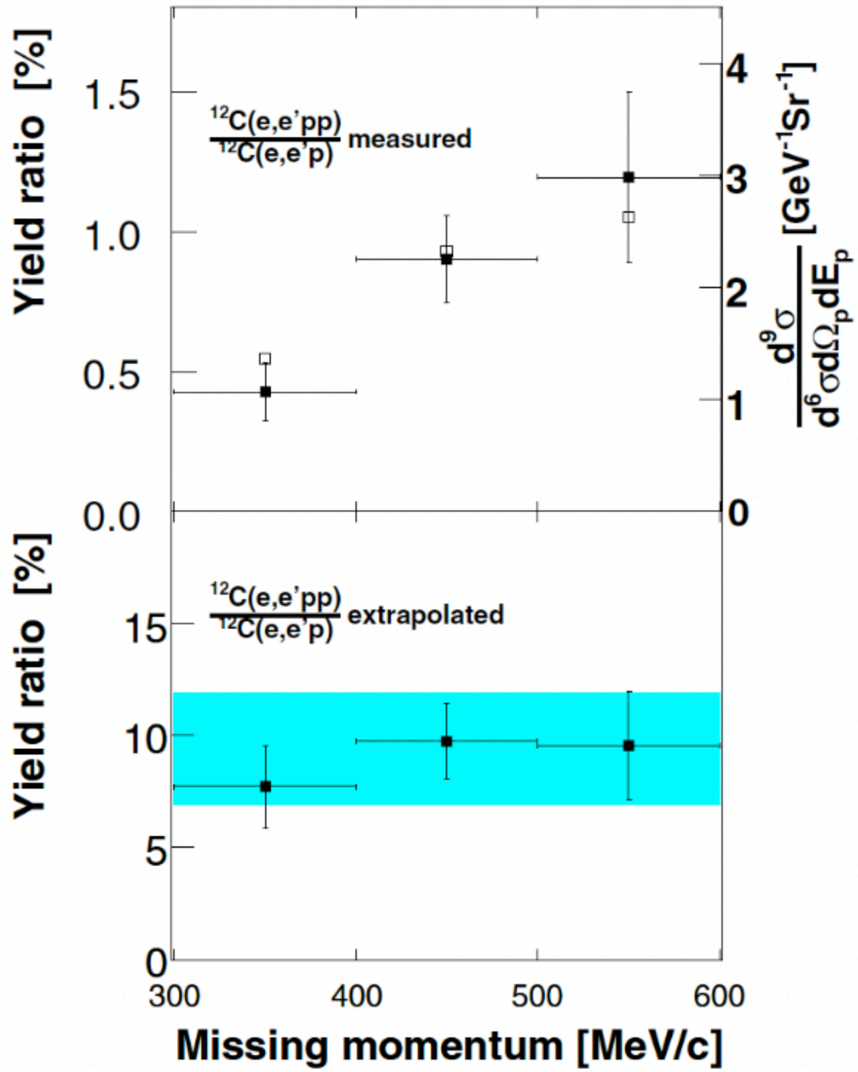
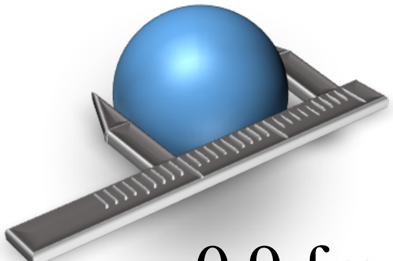


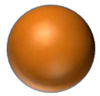
Fig. 2. The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in table S1.



Proton Size (ULQ2)

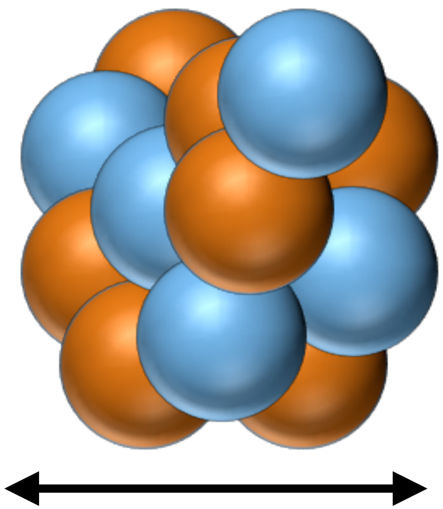


$r_p \sim 0.9$ fm



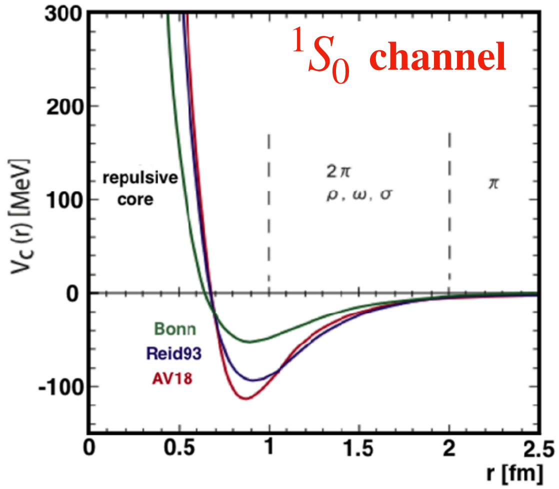
Neutron charge size?? (eD@ULQ2)

Nuclear size



$R \sim 1.2\ A^{1/3}$ fm

nucleon-nucleon force



Fermi momentum

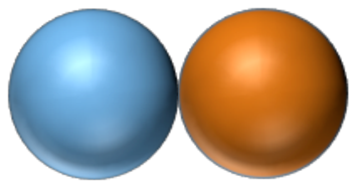
$k_f = 1.4\ \mathrm{fm}^{-1} = 270$ MeV/c

$\beta \sim 0.3$

nucleon density

$\rho_A = 0.16$ nucleon/fm^3

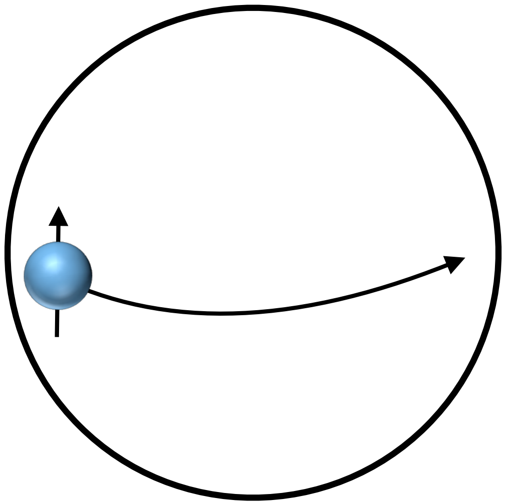
$\Delta L_{NN} \sim 1/\rho_A^{1/3} = 1.8$ fm

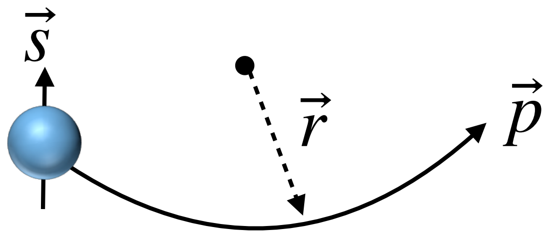


Independent particle picture
(独立粒子模型)

$$V_c(r) \rightarrow V_c(r) + V_{so}\vec{l}\cdot\vec{s}$$

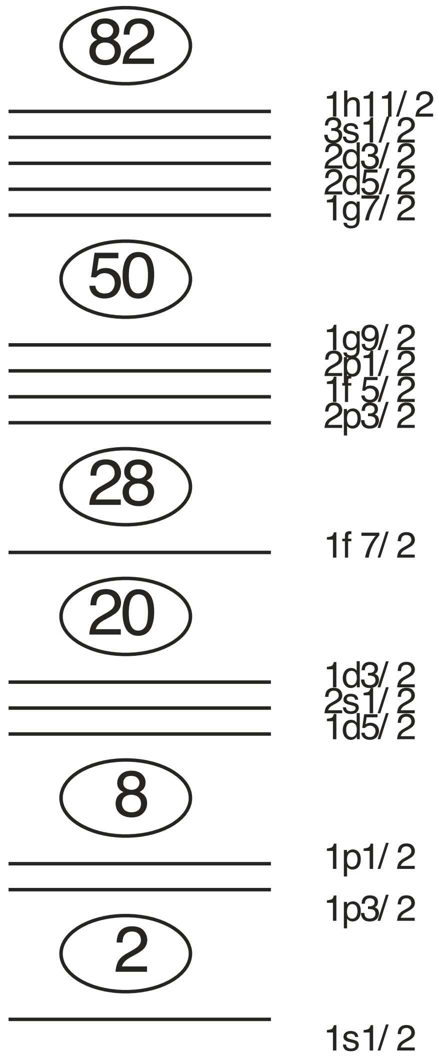
$$[-\frac{\hbar^2}{2m}\nabla^2 + V_c(r)]\,\psi(r) = E\,\psi(r)$$



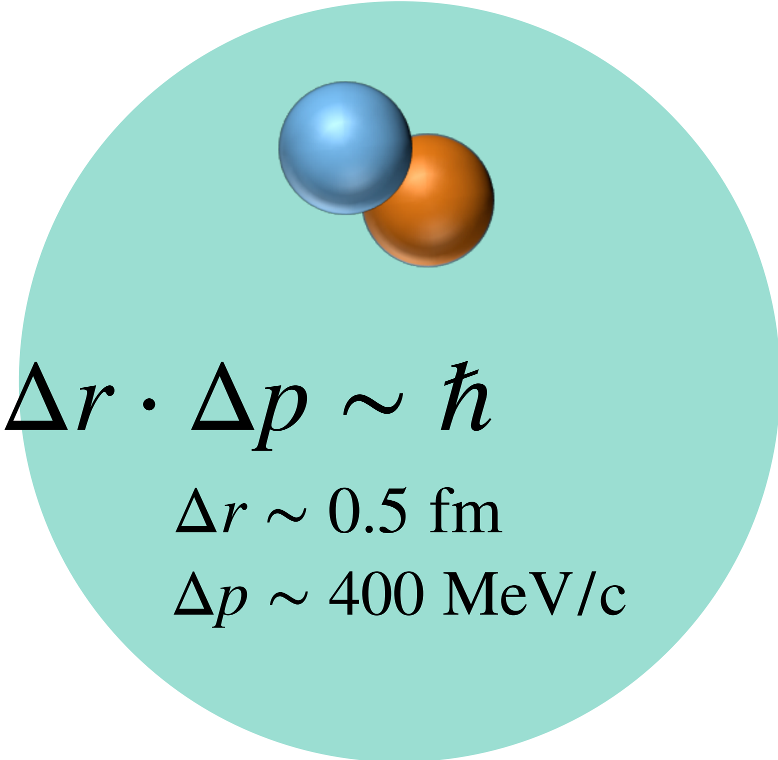


$$\vec{l} = \vec{r}\times\vec{p}$$

M.G.Mayer and J.Jensen



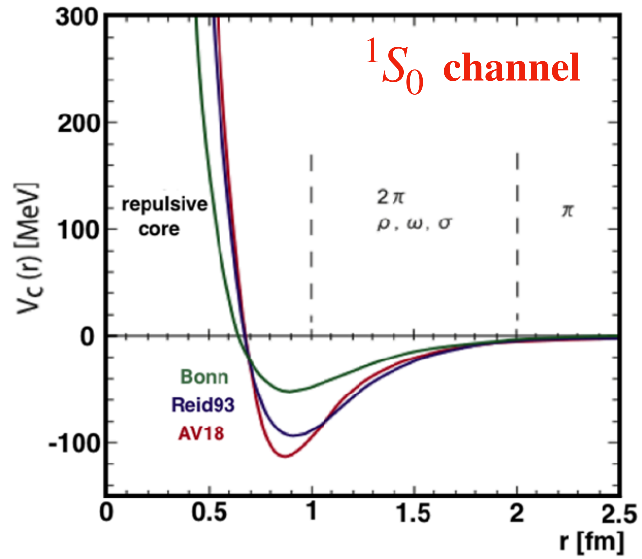
"beyond shell-model picture"??

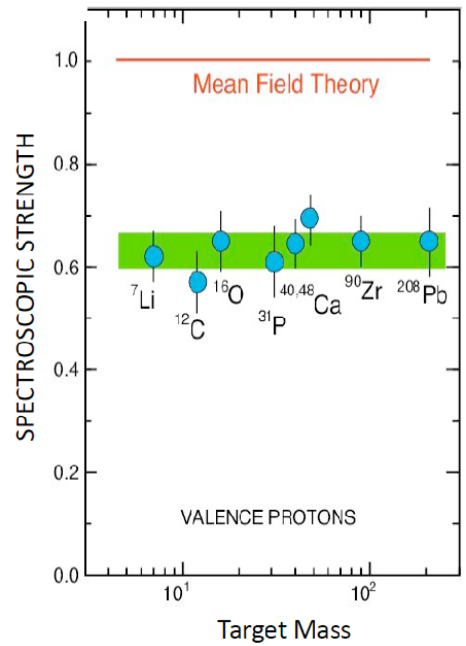


$$\Delta r \cdot \Delta p \sim \hbar$$

$$\Delta r \sim 0.5 \text{ fm}$$

$$\Delta p \sim 400 \text{ MeV/c}$$



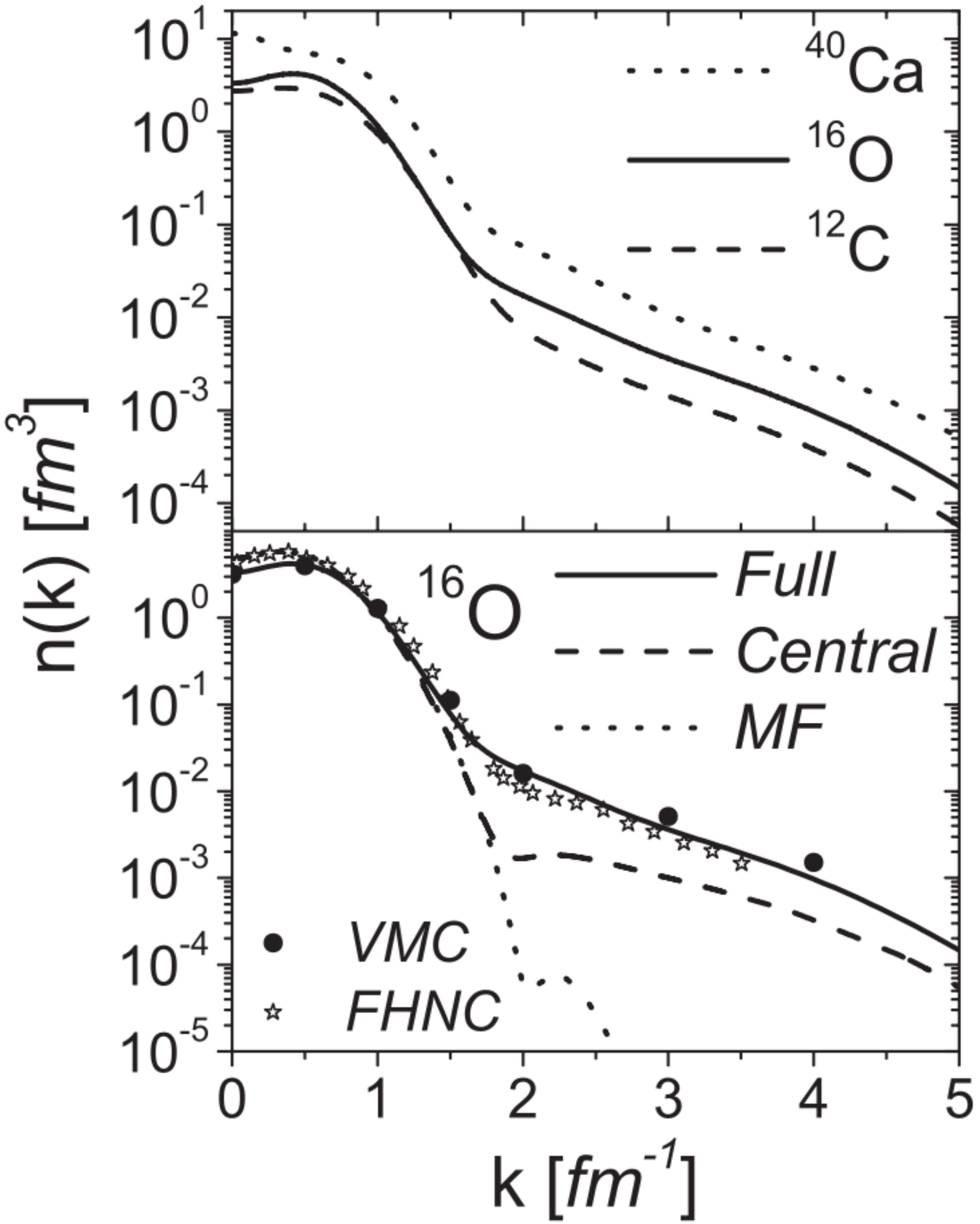


"collision" at short-distance may produced

=> high-momentum component

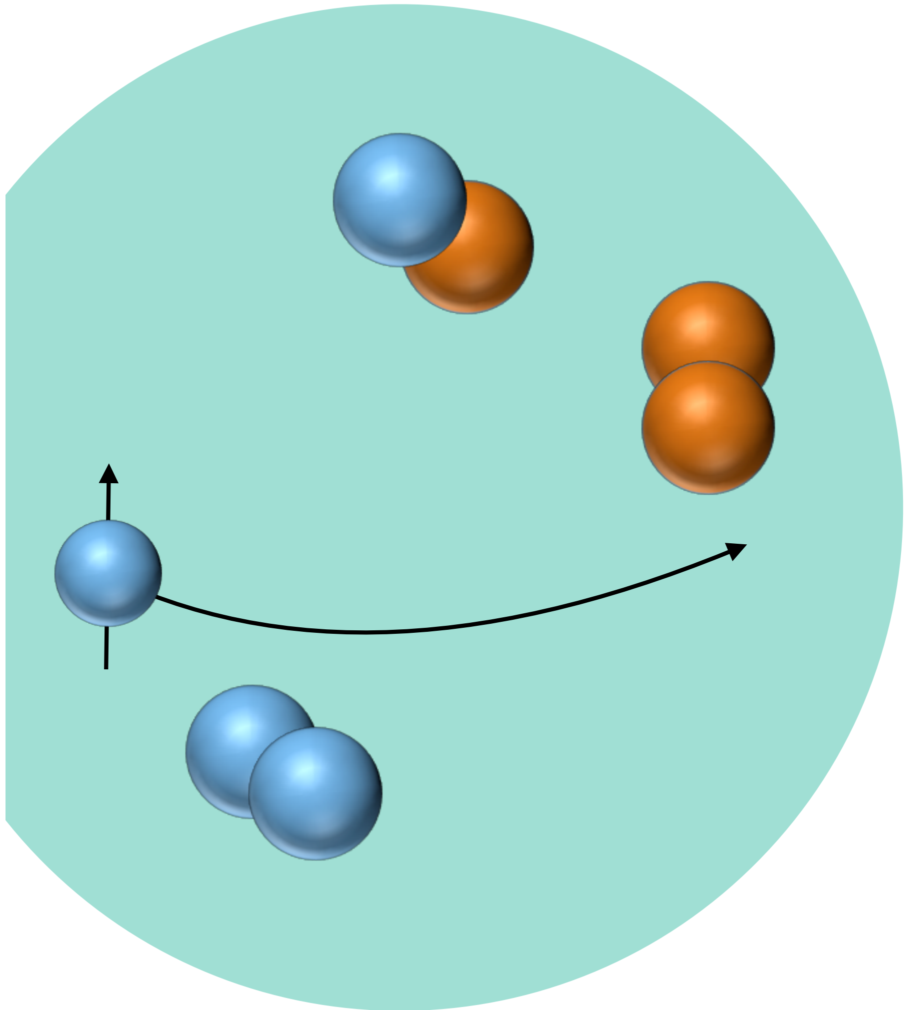
=> reduction of spectroscopic factor

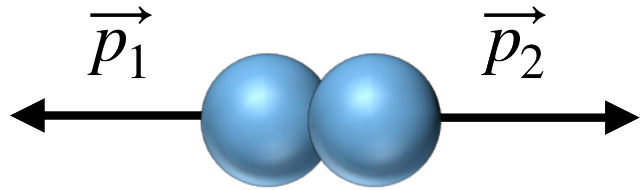
Single-particle momentum distribution in nuclei



Phys. Rev. Lett. 100 (2008), 162503.

two nucleons at short-distance in a nucleus?





$$\vec{p}_1 + \vec{p}_2 \sim 0$$

$$\vec{p}_1 - \vec{p}_2 \to \text{large}$$

many references;
J.S. Levinger : Phys. Rev. 84 (1951) 43.
K. Gottfried : Nucl. Phys. 5 (1958) 557.
J. Ryckebush et al. : Nucl. Phys. A624 (1997) 581

Such a “dynamic aspect” is beyond the shell-model picture.
Any effects beyond are included so far by “hands”.

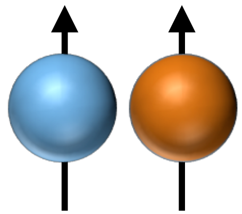
Two-nucleon system

antisymmetrized wave function

$$^{2T+1,2S+1}L_J$$

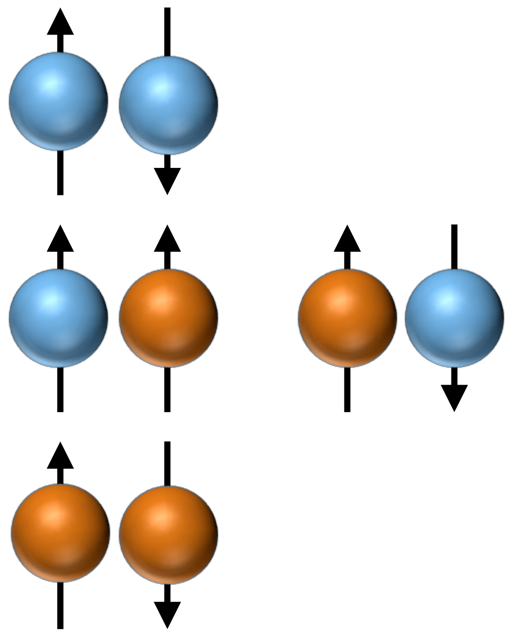
T : isospin
S : spin
L : orbital angular momentum
J : total angular momentum

deuteron



$^{13}S_1 + ^{13}D_1$

2N in a nucleus



$^{31}S_0$

$^{13}S_1 + ^{31}S_0$

$^{31}S_0$

how to access "correlated" two-nucleon in nuclei?

- high-*p* component of single nucleon
- observe an interacting-two-nucleon system directly

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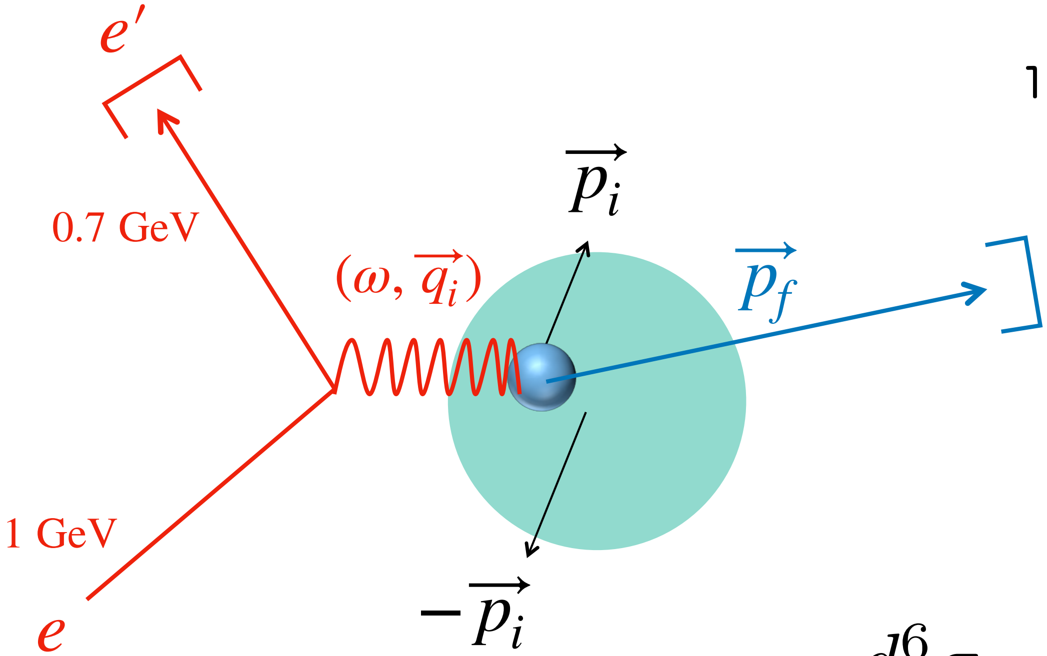
Quasi-elastic (e,e'p) scattering



1980~: Saclay, NIKHEF, MIT, Mainz, JLab

$$\vec{p_f} = \vec{p_i} + \vec{q}$$

$$\vec{p_m} \equiv \vec{p_i} = \vec{p_f} - \vec{q}$$

$$\frac{d^6\sigma}{dk_{e'}d\Omega_{e'}dp_p d\Omega_p} = K\frac{d\sigma_{ep}}{d\Omega}S(E_m, \vec{p}_m)$$

$\omega \sim 300$ MeV

$q \sim 750$ MeV/c

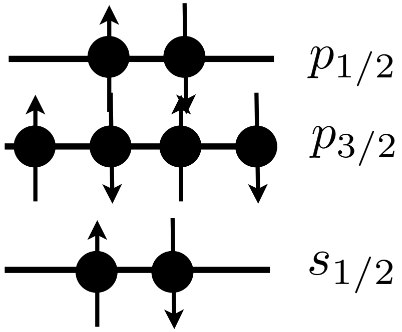
$$\omega \sim \frac{\vec{q}}{2m_p}$$

$$S(E_m, \vec{p}_m) = \rho(\vec{p}_m)n_\alpha\delta(Em - E_{tr})$$

$$\rho(p) = |\phi(p)|^2$$

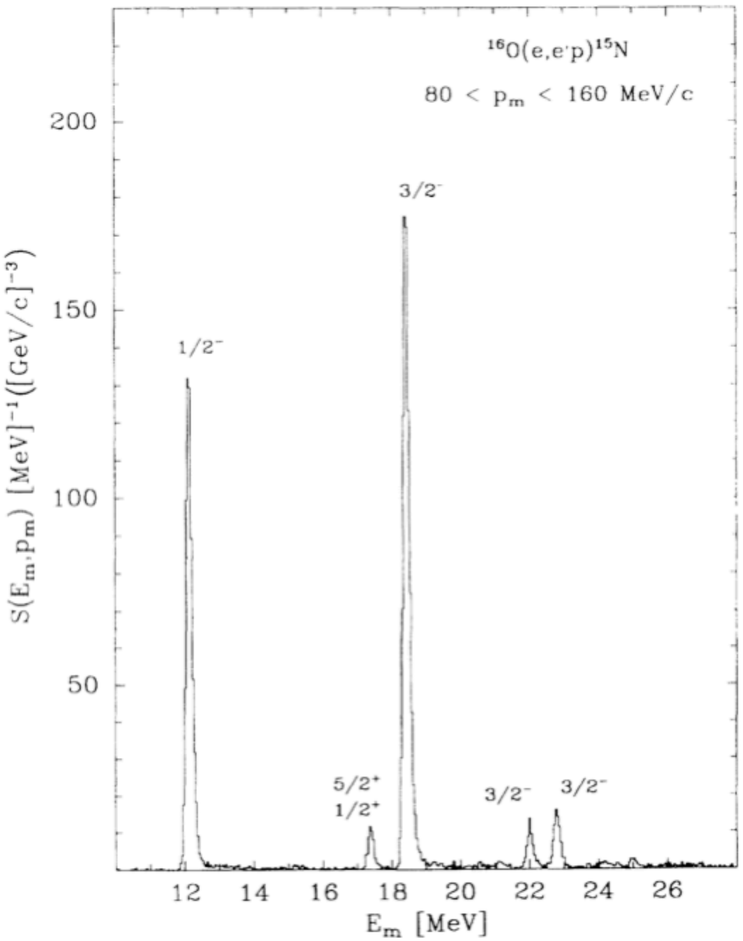
陽子運動量密度分布

$$\phi(\mathbf{p}) = \int \psi(\mathbf{r})e^{-i\mathbf{p}\cdot\mathbf{r}}d\mathbf{r}$$

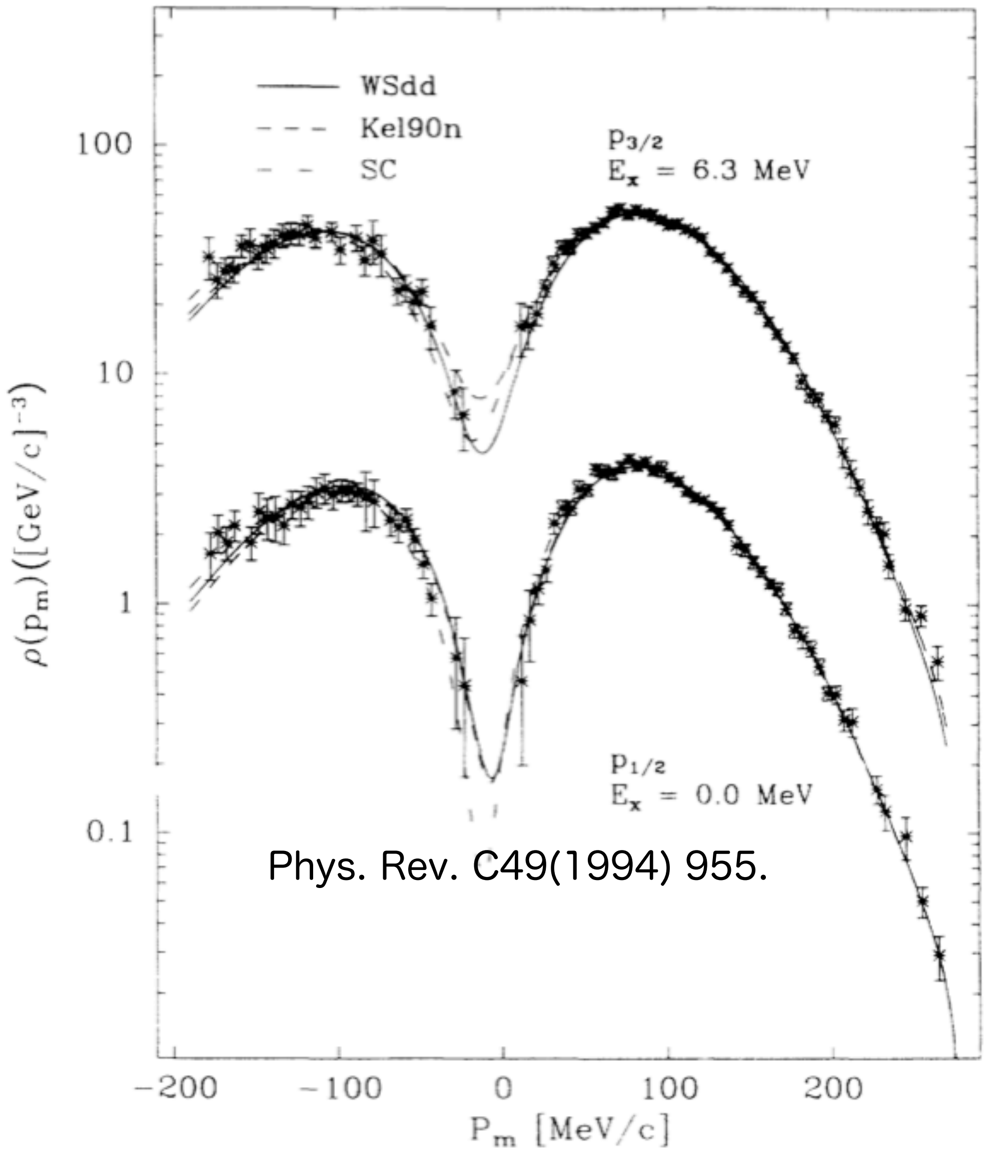


Quasi-elastic $^{16}O(e,e'p)$ @ NIHEF

E_{miss} distributions



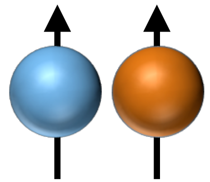
P_{miss} distributions



Phys. Rev. C49(1994) 955.

Success of shell-model pictures

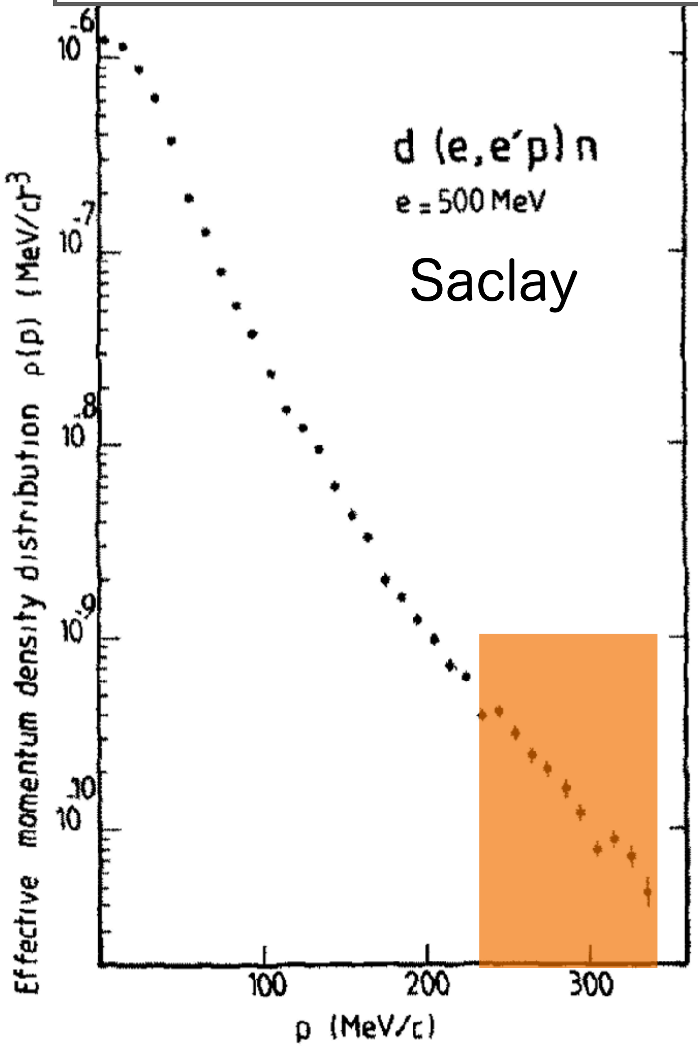
P_{proton} in deuteron by d(e,e'p)



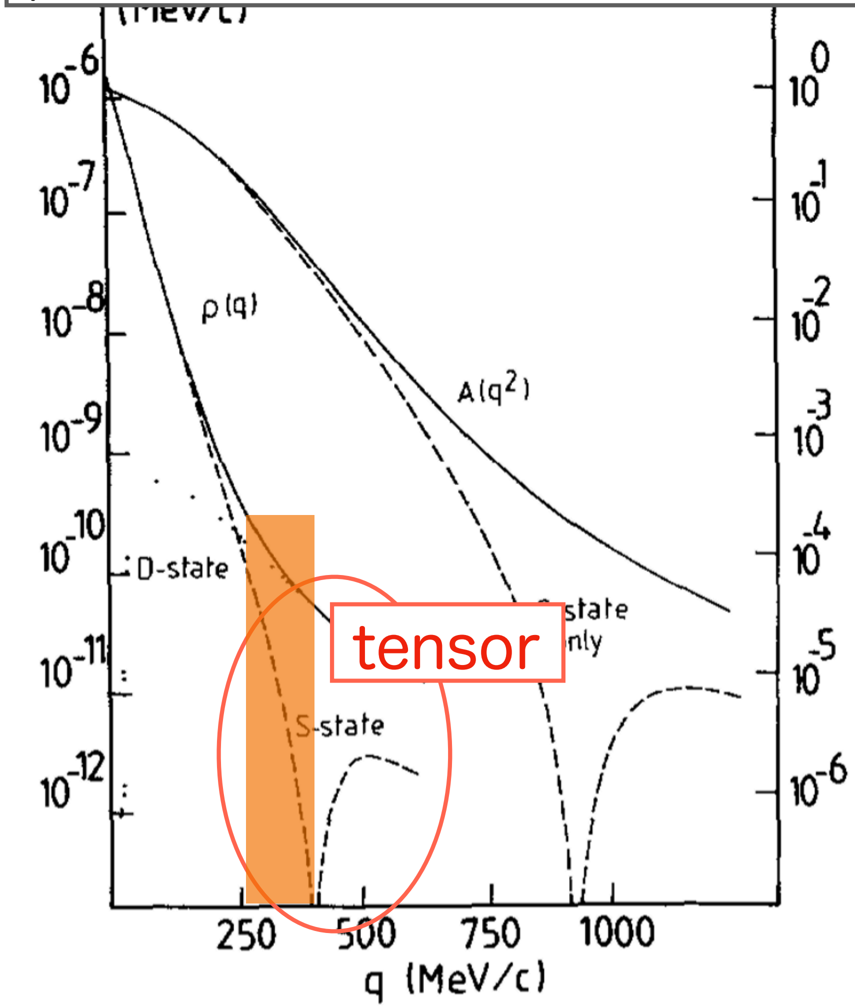
$^{13}S_1 + ^{13}D_1$

M. Bernheim et al.,
Nucl. Phys. A365 (1981) 349

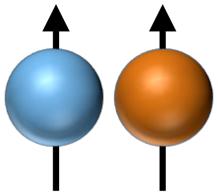
$\rho(p) = |\phi(p)|^2$



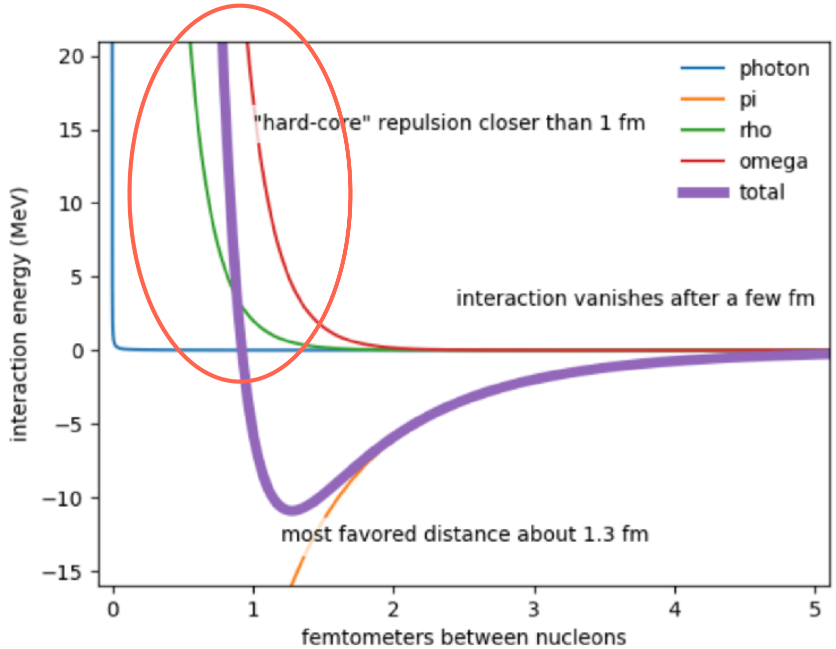
proton momentum distribution



P_{proton} in deuteron



$^{13}S_1 + ^{13}D_1$



"high-p" component in deuteron is
due to mainly
the well-established tensor interaction

- pion-exchange force

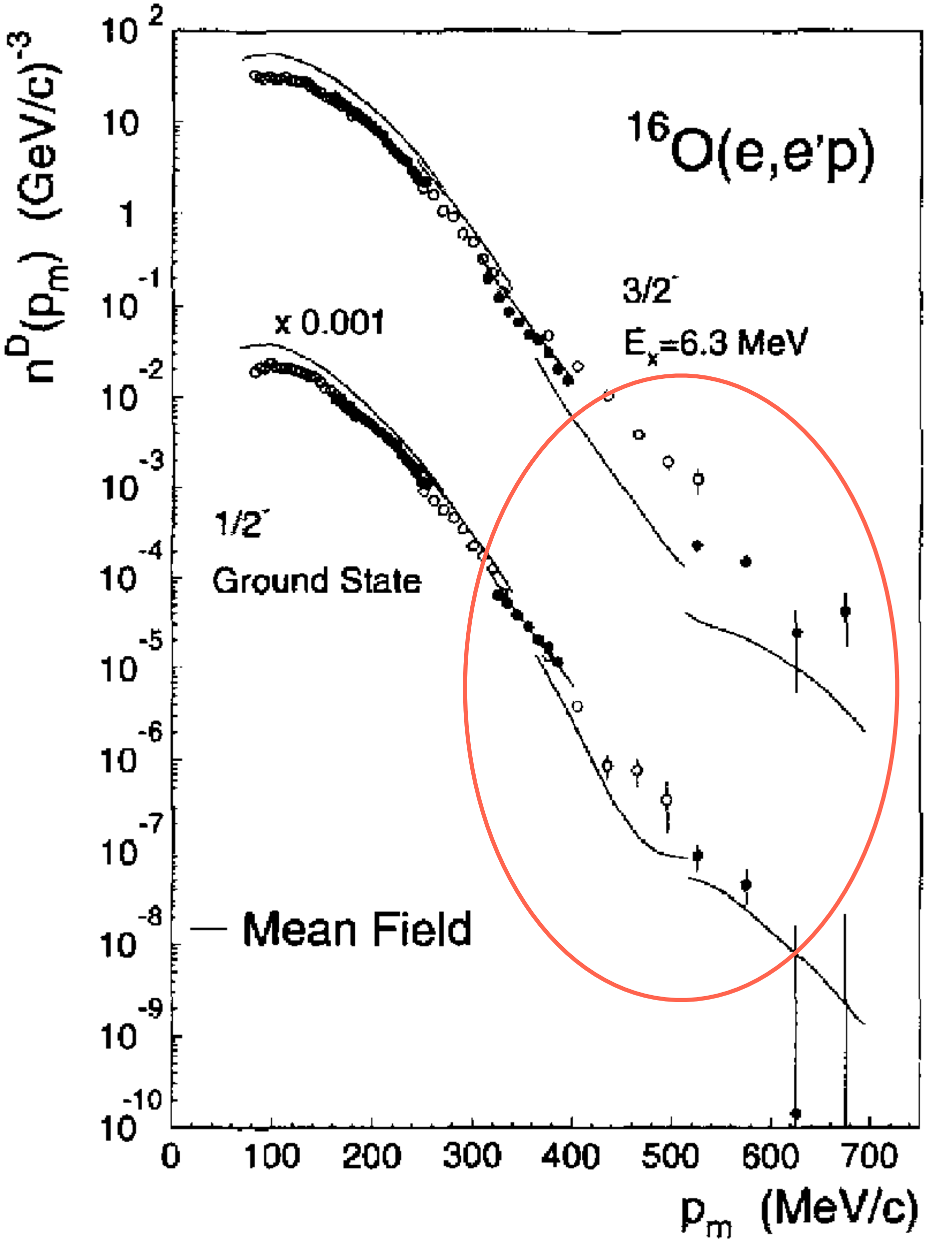
high-momentum does not necessarily imply "short-range" physics!!

high-momentum components in a nucleus?

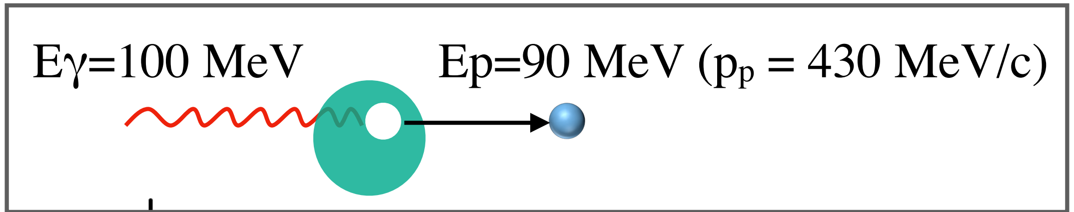
Eγ~ 60 - 100 MeV

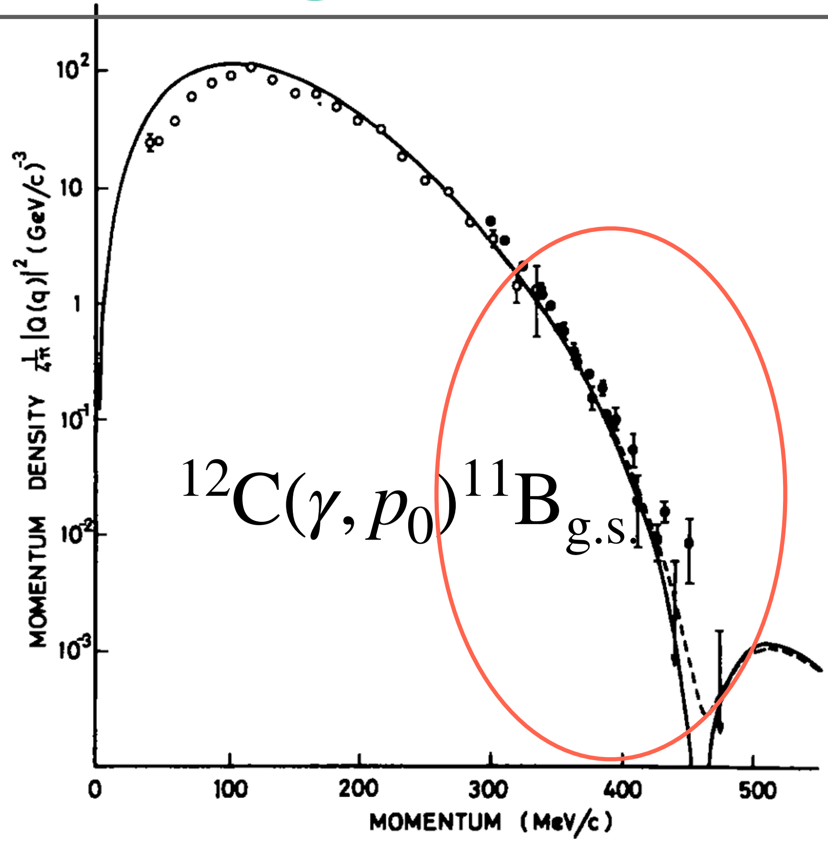
Mainz : (γ,p)
Sendai : (γ,p), (γ,n)

1980s



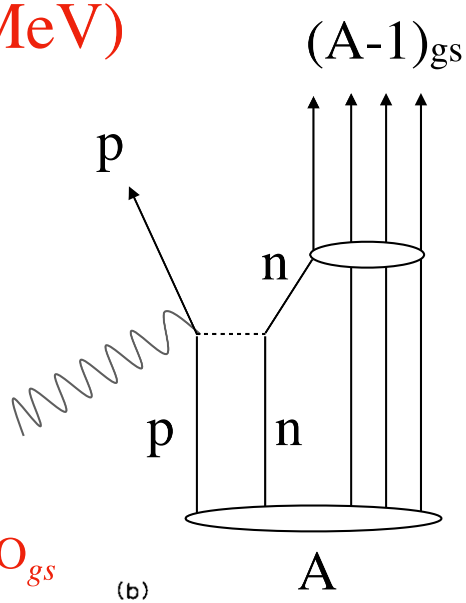
Phys. Lett. B344 (1995) 85





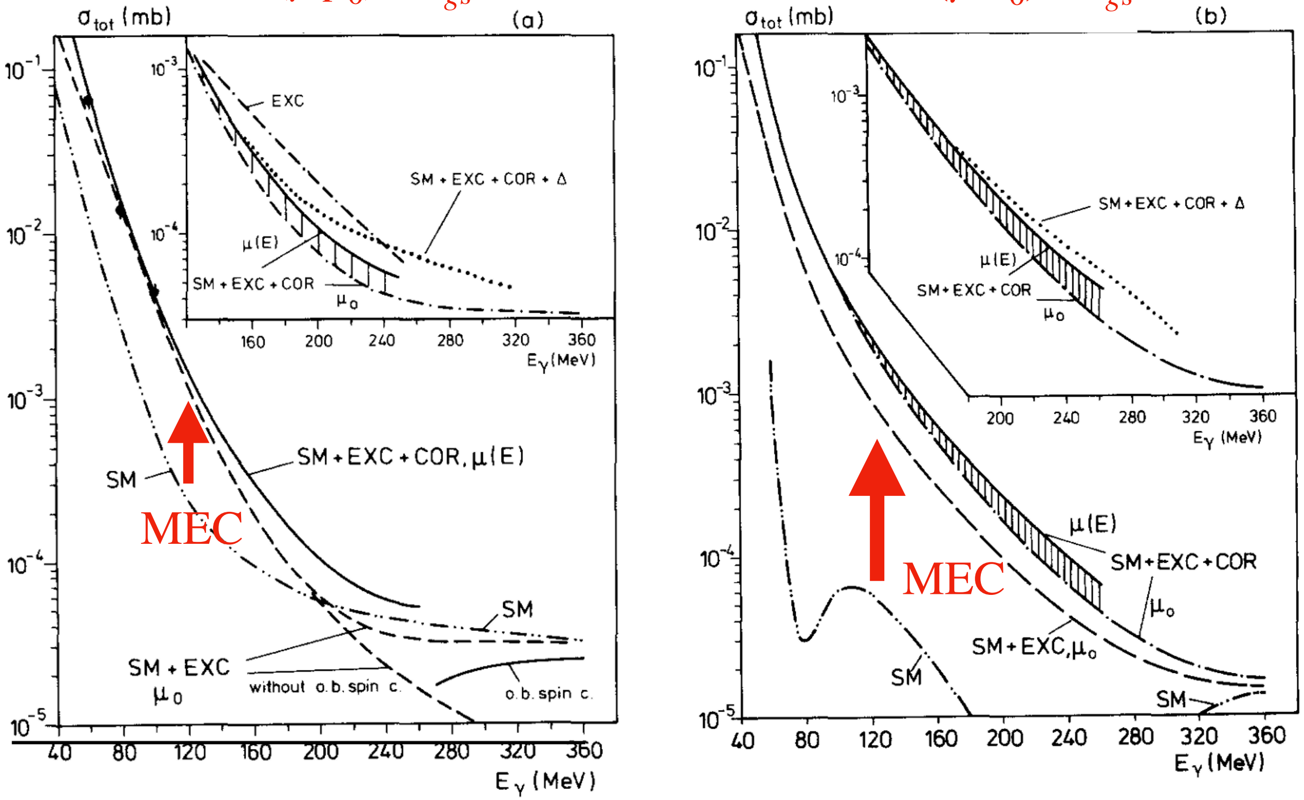
Nucl. Phys. A292 (1977) 53.

$\sigma(\gamma, p_0) \sim \sigma(\gamma, n_0)$!!! (Eγ ~ 100 MeV)



- single nucleon knockout: $\sigma(\gamma, p_0) \gg \sigma(\gamma, n_0)$
- importance of meson exchange current (MEC)

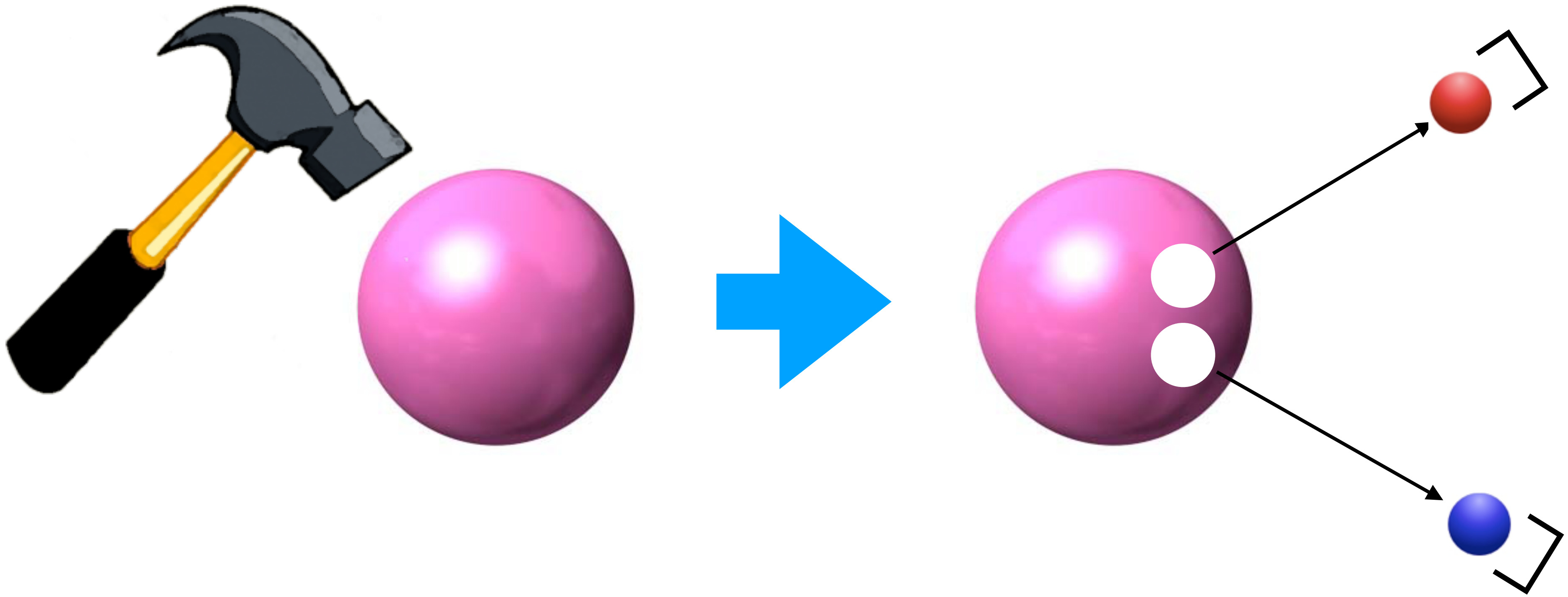
$^{16}O(\gamma, p_0)^{15}N_{gs}$ $^{16}O(\gamma, n_0)^{15}O_{gs}$



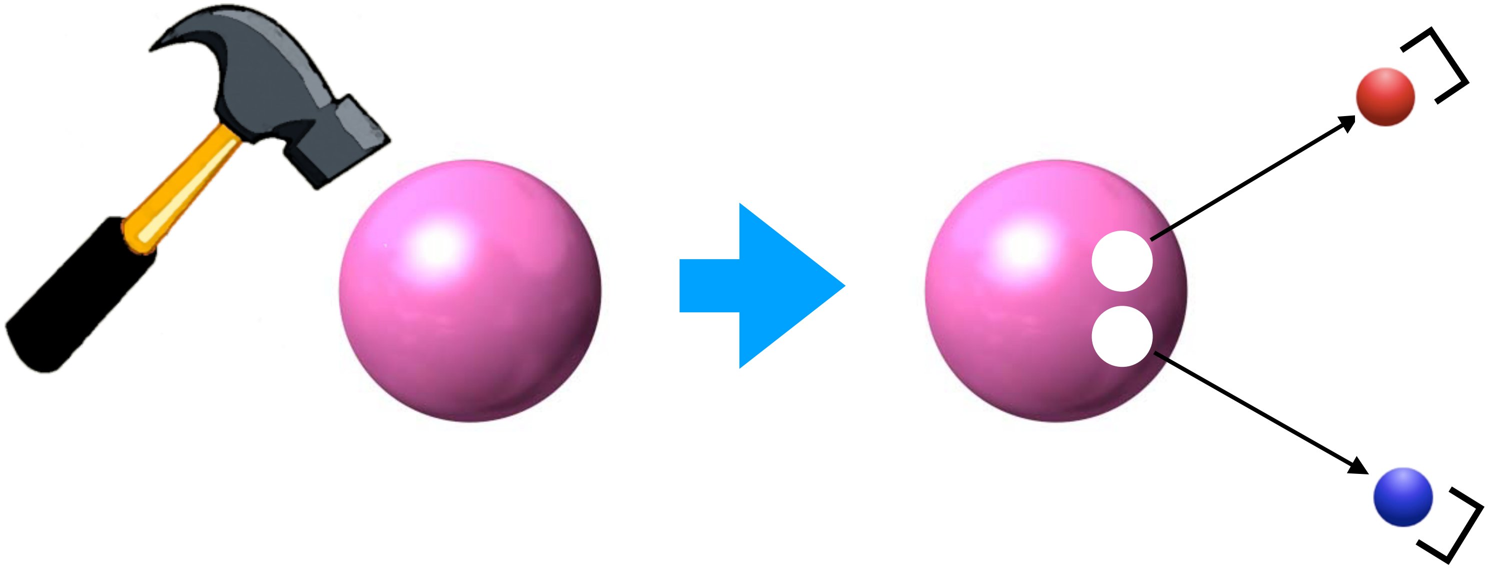
M. Gari and H. Hebach, Phy. Rep. 72 (1981) 1-55

how to access “correlated” two-nucleon in nuclei?

- high-*p* component of single nucleon
- observe an interacting-two-nucleon system directly



two-nucleon emission is a way for SRC study?



which probe should we use?

・electromagnetic probes : well-understood and “weak”

・hadronic probes: too strong and complex reaction mechanism

possible signal due to SRC may be very faint

“Two-nucleon” knockout exp. @ JLab

Nature 320, 1476, 2008

^{12}C(e,e’pp)/^{12}C(e,e’p)

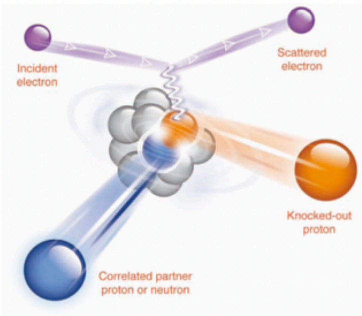
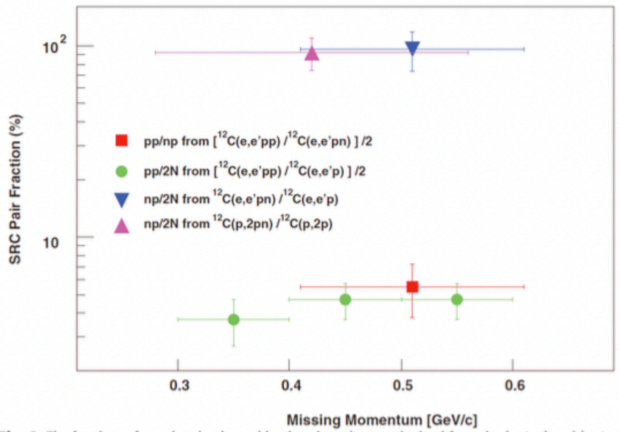


Fig. 1. Illustration of the ^{12}C(e,e'pN) reaction. The incident electron beam couples to a nucleon-nucleon pair via a virtual photon. In the final state, the scattered electron is detected along with the two nucleons that are ejected from the nucleus. Typical nuclear density is about 0.16 nucleons/fm^3, whereas for pairs the local density is approximately five times larger.

$$\frac{\sigma(e,e'pp)}{\sigma(e,e'pn)} \sim 1/100$$



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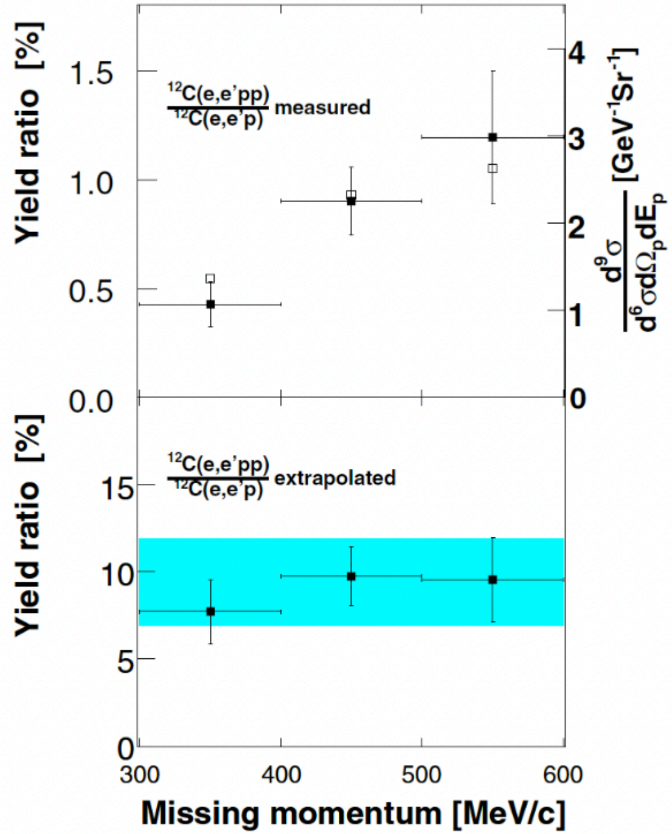


Kinematically incomplete measurements

+

there may be another way to interpret this results.

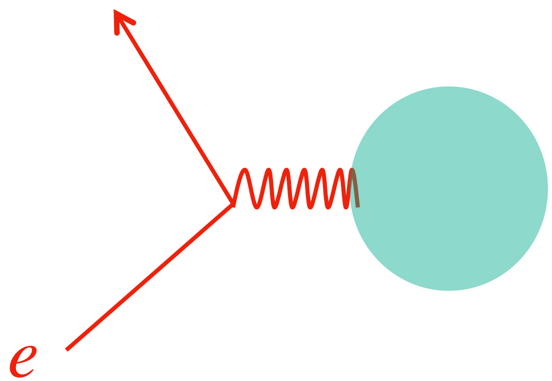
Basics of electromagnetic probes

interaction : $$H_{int} = \rho\phi - \vec{J}\cdot\vec{A}$$

$(\phi, \vec{A})$ photon

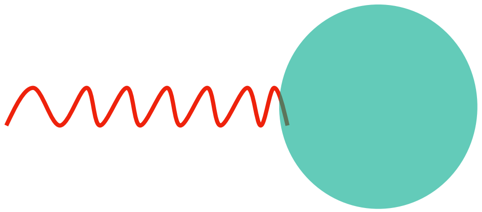
$(\rho, \vec{J})$ target

electron scattering (virtual photons)



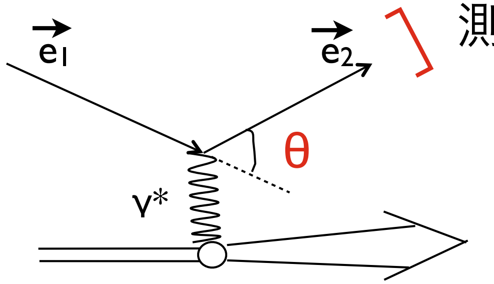
		operators
Charge	**(Longitudinal)**	$\rho = e$
Convection current	**(Transverse)**	$\vec{j}_{conv} = e\dfrac{\vec{p}}{m}$
Spin magnetization	**(Transverse)**	$\vec{j}_{spin} = \vec{\nabla}\times\vec{\mu}$

γ-ray (real photon)



		operators
Convection current	**(Transverse)**	$\vec{j}_{conv} = e\dfrac{\vec{p}}{m}$
Spin magnetization	**(Transverse)**	$\vec{j}_{spin} = \vec{\nabla}\times\vec{\mu}$

Nuclear response function in (ω,q) plane



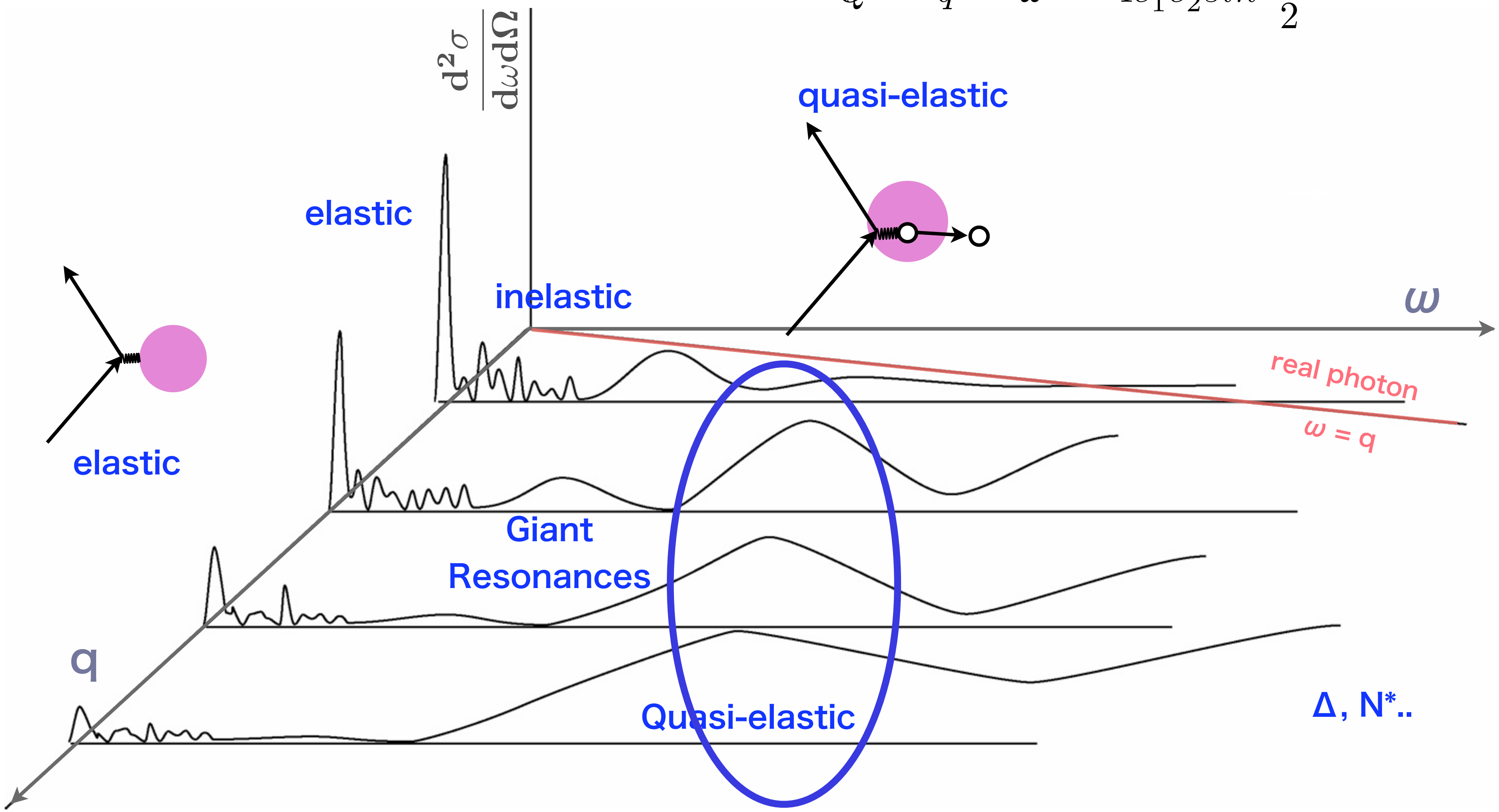
測定量 e_2, θ

kinematical valuables

$$\omega = e_1 - e_2$$ energy transfer

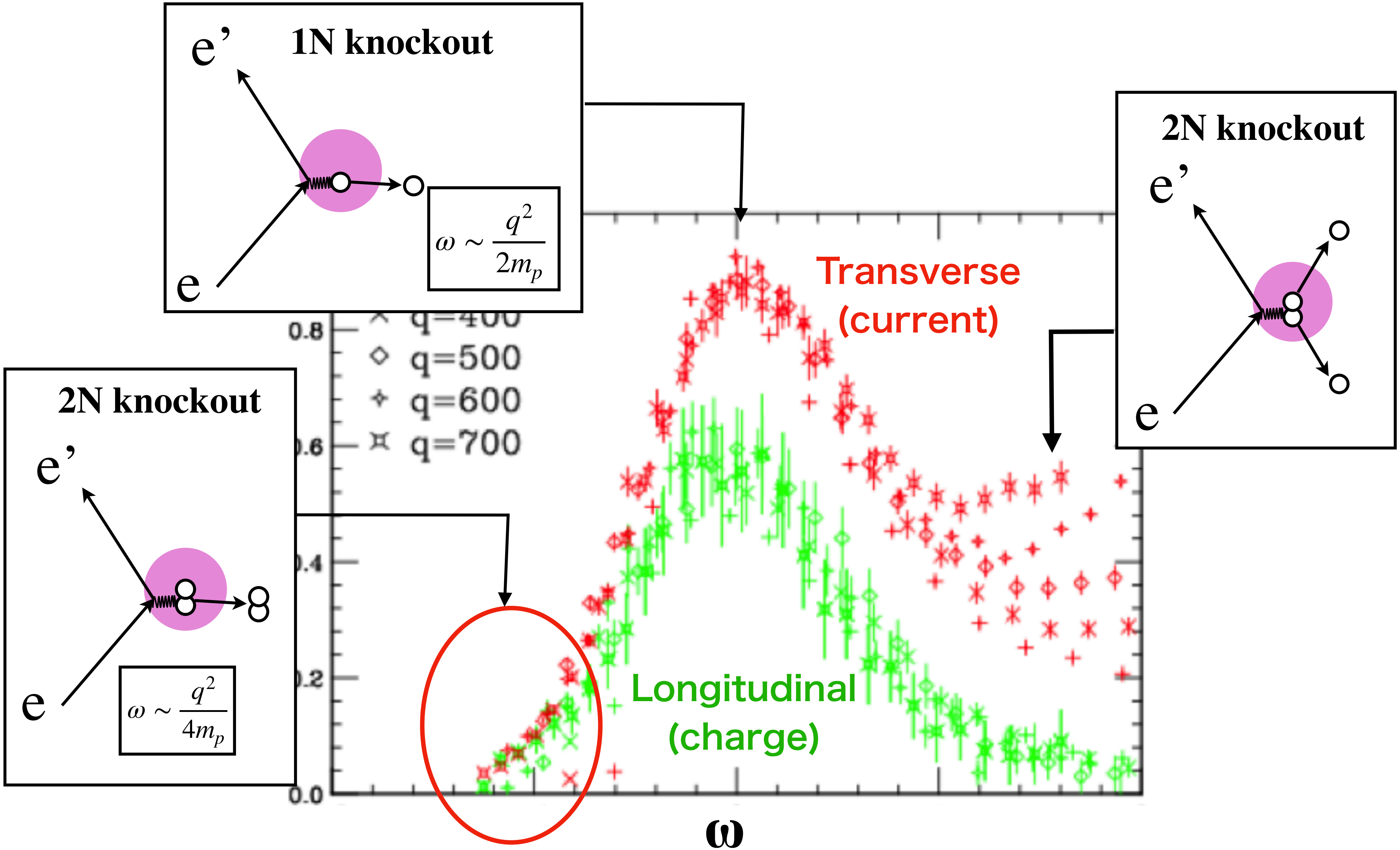
$$\vec{q} = \vec{e_1} - \vec{e_2}$$ momentum transfer

$$Q^2 = q^2 - \omega^2 = 4e_1^2 e_2^2 sin^2\frac{\theta}{2}$$



quasi-elastic region in A(e,e')

$$\frac{d^2\sigma}{d\Omega dE} = \sigma_L + v(\theta)\sigma_T$$ (Rosenbluth separation)



Current conservation

$$\vec{\nabla} \cdot \vec{J} = -i[H, \rho]$$

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m_i} + \sum_{i>j} (\vec{\tau_i} \cdot \vec{\tau_j})(\vec{s_i} \cdot \vec{s_j})\, V(\vec{r_i}, \vec{r_j})$$ two-body int.

$$\rho = \sum e_i \delta(\vec{(r)} - \vec{r_i})$$

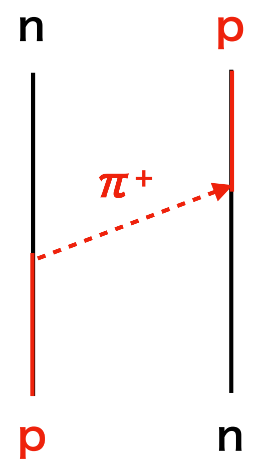
with the isospin-isospin interaction, $\vec{\tau_i} \cdot \vec{\tau_j}$,

a two-body current operator should appear for current conservation

$$\vec{J} = \vec{j_1} + \vec{j_2}$$

$$\vec{j_2} \;:\; [\tau_z, \vec{\tau_1} \cdot \vec{\tau_2}] = \tau_1^+ \tau_2^- - \tau_1^- \tau_2^+$$

two-body current operator
(meson-exchange current)



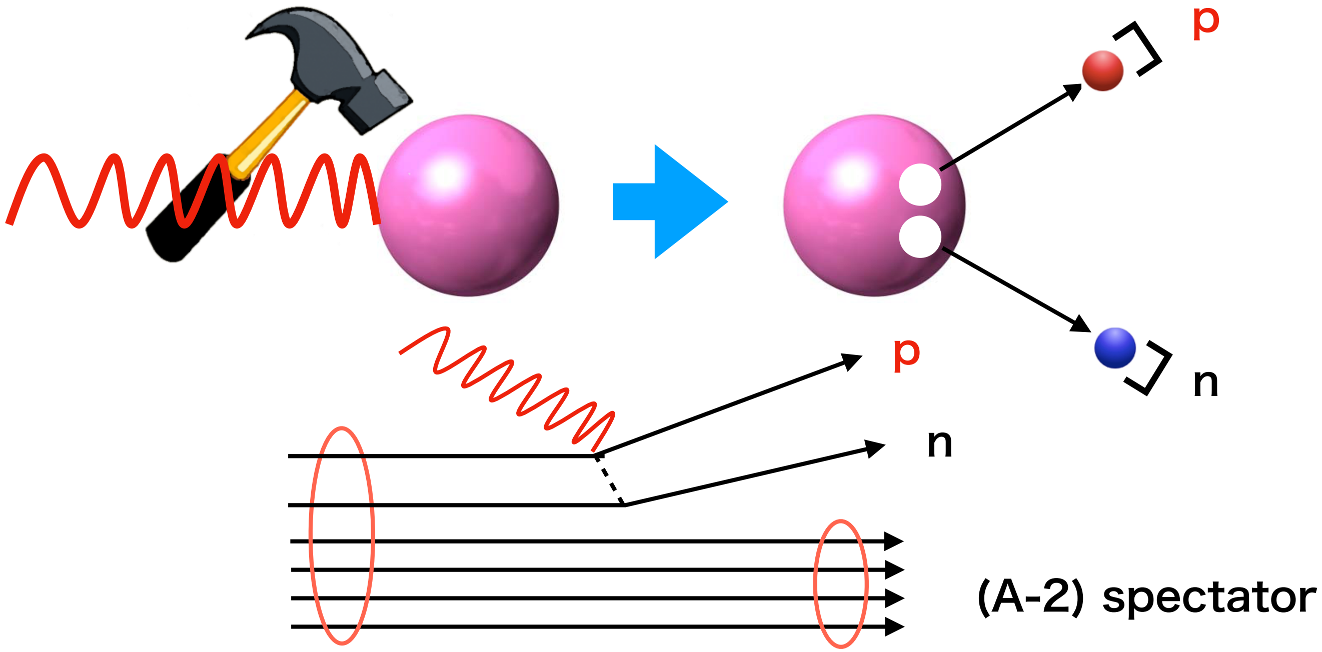
$$(\tau_1^+ \tau_2^- - \tau_1^- \tau_2^+)\,|pn> = |np>$$

$$(\tau_1^+ \tau_2^- - \tau_1^- \tau_2^+)\,|pp> = 0$$

$$(\tau_1^+ \tau_2^- - \tau_1^- \tau_2^+)\,|nn> = 0$$

the isospin-exchange force $\vec{\tau_i} \cdot \vec{\tau_j}$ in the nuclear force
inevitably introduces two-body currents

two-nucleon photoemission



two-body current operator allows two-nucleon emission
with the shell model wave function (independent particle model)

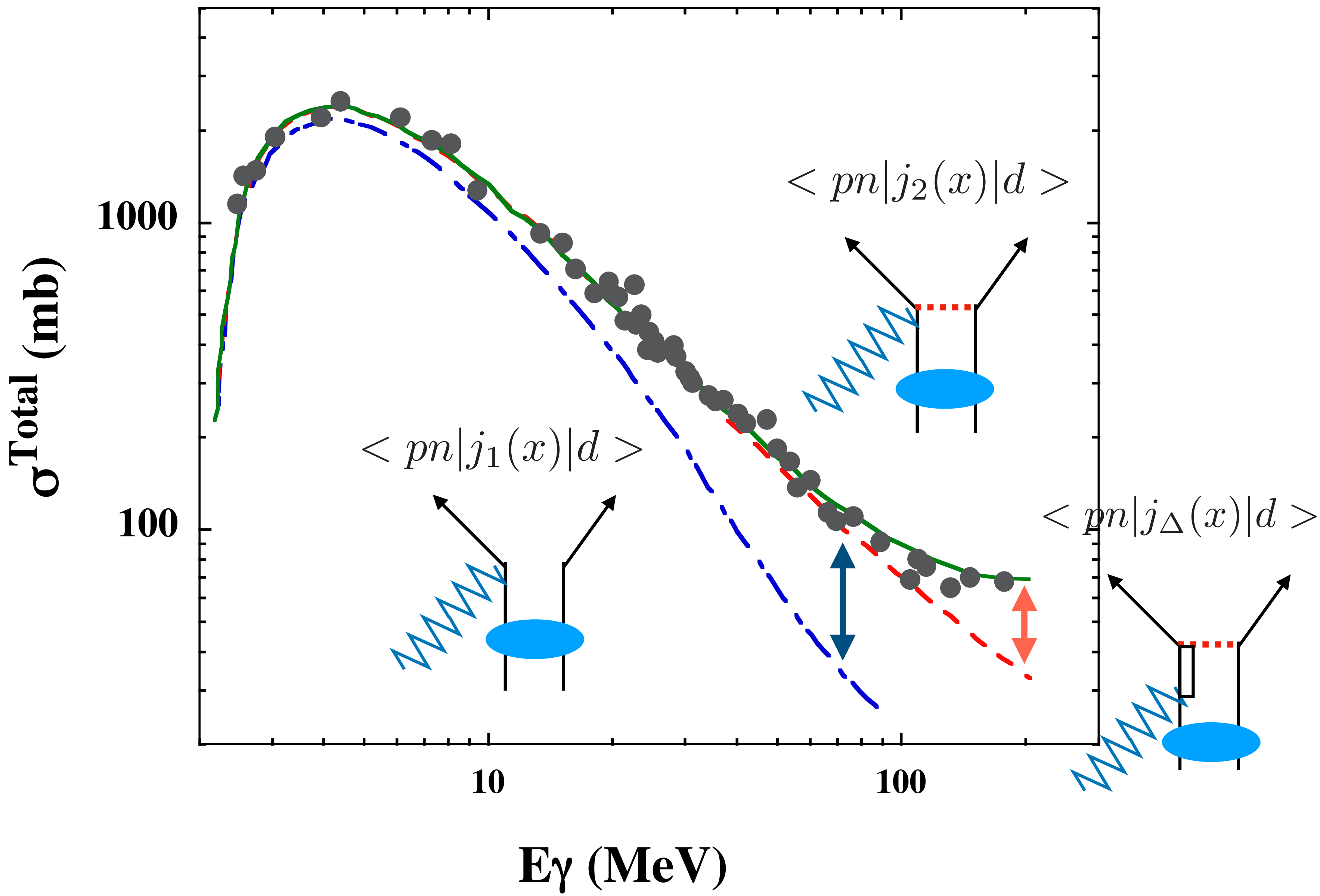
1) NO CORRELATION is required.
2) np pair only. no pp, nn pair

$$(\gamma, \mathrm{np}): \begin{cases} \sigma_{\mathrm{np}}^{\mathrm{total}} \approx \sigma_{\mathrm{np}}(\mathrm{EXC}) \approx 0.5\text{–}1\ \mathrm{mb}, \\ \sigma_{\mathrm{np}}(\mathrm{EXC}) \gg \sigma_{\mathrm{np}}(\mathrm{COR}); \end{cases}$$

$$(\gamma, \mathrm{nn}), (\gamma, \mathrm{pp}): \begin{cases} \sigma_{\left\{ \mathrm{nn} \atop \mathrm{pp} \right\}}^{\mathrm{total}} \approx \sigma_{\left\{ \mathrm{nn} \atop \mathrm{pp} \right\}}(\mathrm{COR}) \approx \sigma_{\mathrm{np}}(\mathrm{COR}) \approx 1\text{–}10\ \mu\mathrm{b}, \\ \sigma_{\left\{ \mathrm{nn} \atop \mathrm{pp} \right\}}(\mathrm{EXC}) \approx 0. \end{cases}$$

M. Gari and H. Hebach, Phy. Rep. 72 (1981) 1-55

Deuteron photodisintegration and meson exchange current



Electro-disintegration of deuteron at threshold and meson-exchange currents

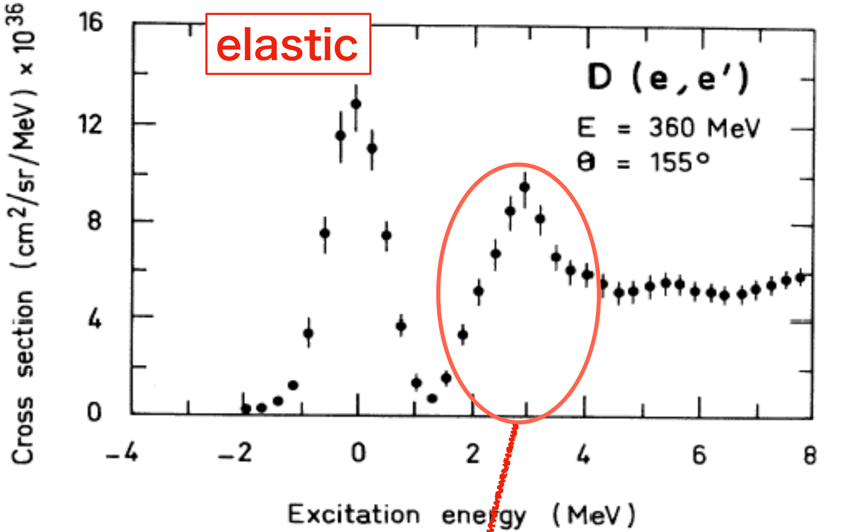
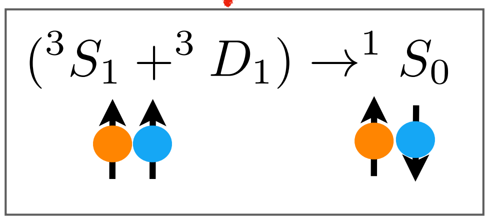
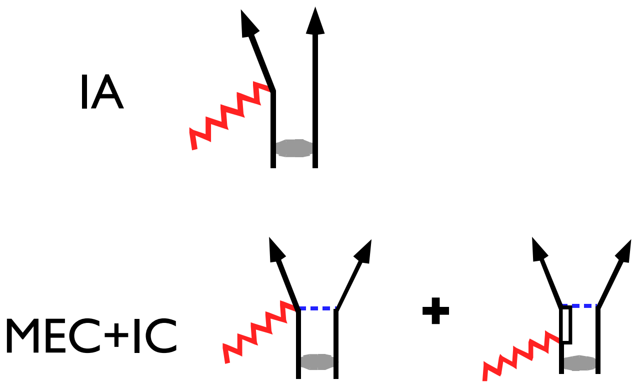


FIG. 1. Experimental spectrum for e-D scattering at 360 MeV and 155°, unfolded for radiative effects.



$$({}^3S_1 + {}^3D_1) \rightarrow {}^1S_0$$



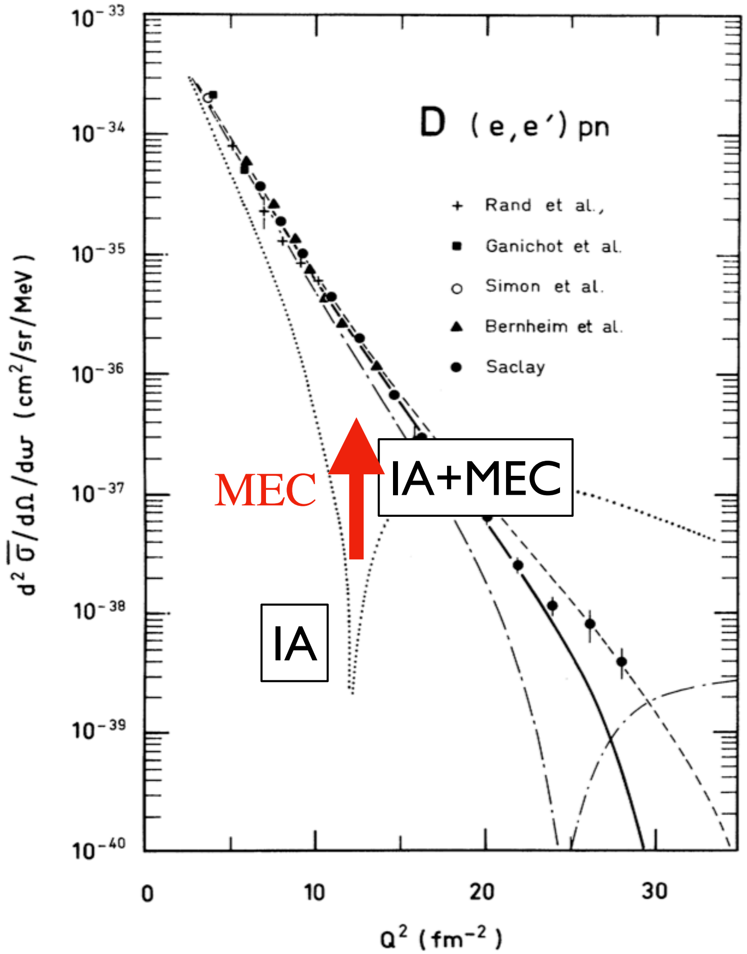
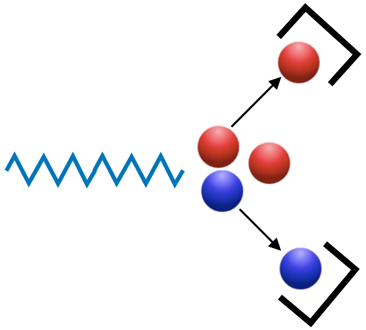


FIG. 2. Experimental cross sections from Ref. 3 and the present experiment. (The data of Rand *et al.* correspond to a different E_{np} and thus do not exactly match the present definition of $d^2\sigma/dQ\,d\omega$.) The dotted curve is the impulse-approximation result, the dash-dotted curve includes the pion-exchange contribution, and the dashed curve includes in addition the ρ-exchange contribution. The solid curve is the total result, in which the Δ-isobar contribution is also taken into account.

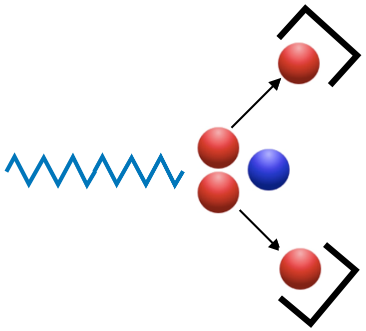
Photodisintegration of ^{3}He at 100 ≤ Eγ ≤ 600 MeV

Possible three processes



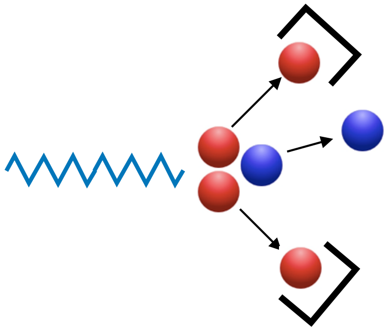
$^3\mathrm{He}(\gamma, \mathrm{np})\mathrm{p}_{\mathrm{spectator}}$

Photodisintegration of "np"



$^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}_{\mathrm{spectator}}$

Photodisintegration of "pp"

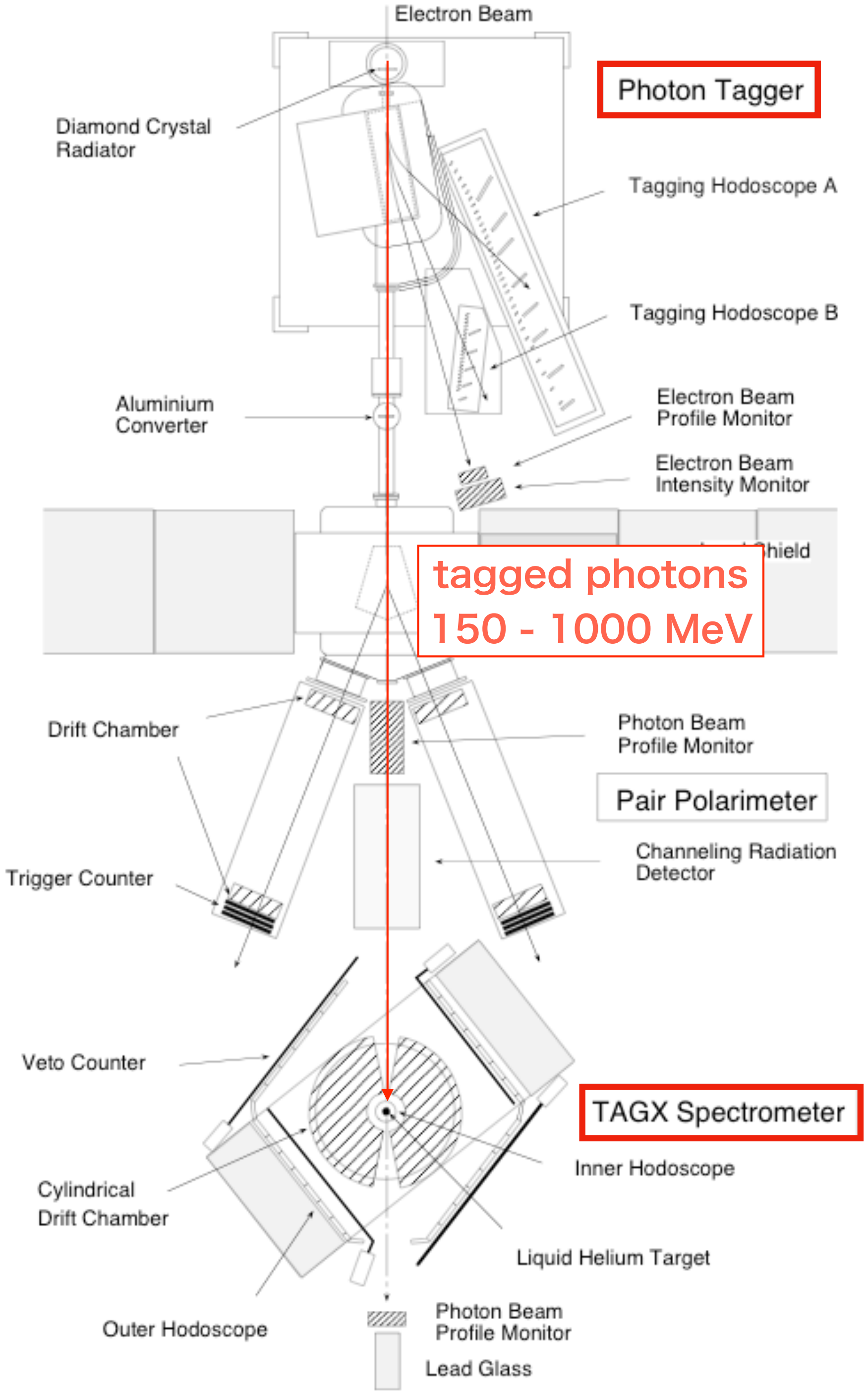


$^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$

no spectator

three-body process?????
(three-body force)

Photodisintegration of ^{3}He (1990-1994)



Ee = 1.3 GeV

Eγ = 150 - 600 MeV

tagged photons (up to 1 GeV)
~10^6 /sec

TAGX spectrometer (NIM 376 ('96) 335)

ΔΩ~π (3.1) str (largest)
SAPHIRE@Bonn followed

Liq. ^{3}He target (NIM 307 ('91) 213)

first large-volume liq. 3He target in Japan

three-body photodisintegration

γ + ^{3}He -> p p n

^{3}He(γ,np)p
^{3}He(γ,pp)n

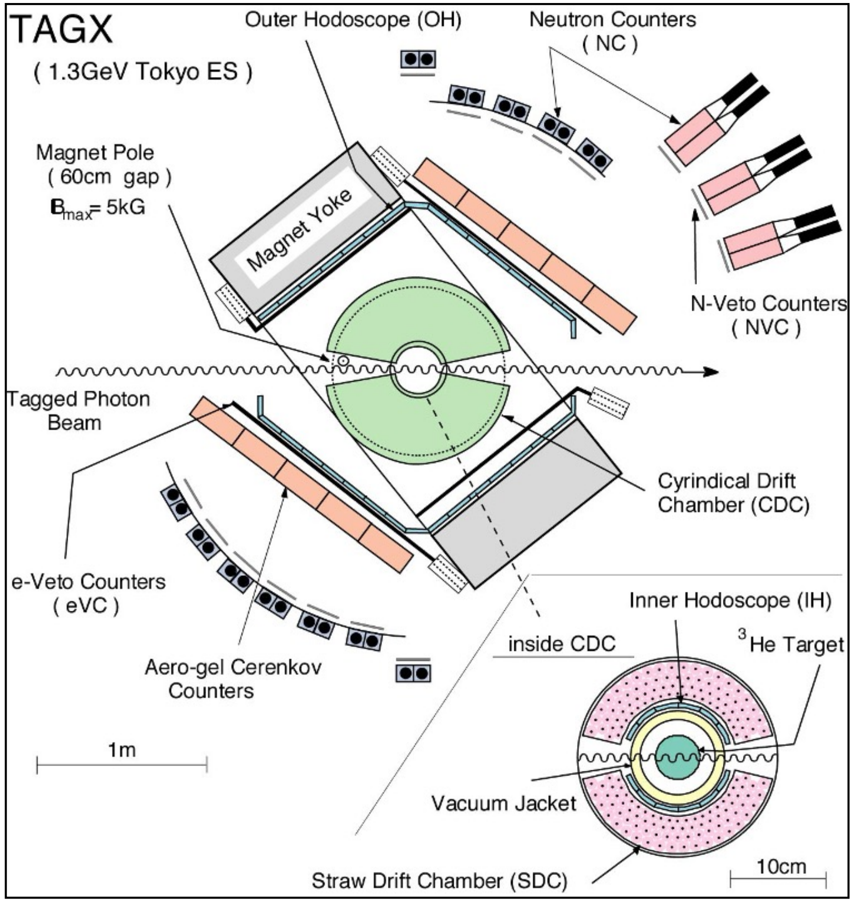
kinematically overdetermined

PRL 73(94)404.
PRC49(94)R597.
PRL 74 (95) 1034.
物理学会誌 52 (97) 103-110

NIM A307 (1991) 213-219
NIM A376 (1996) 335.

TAGX spectrometer

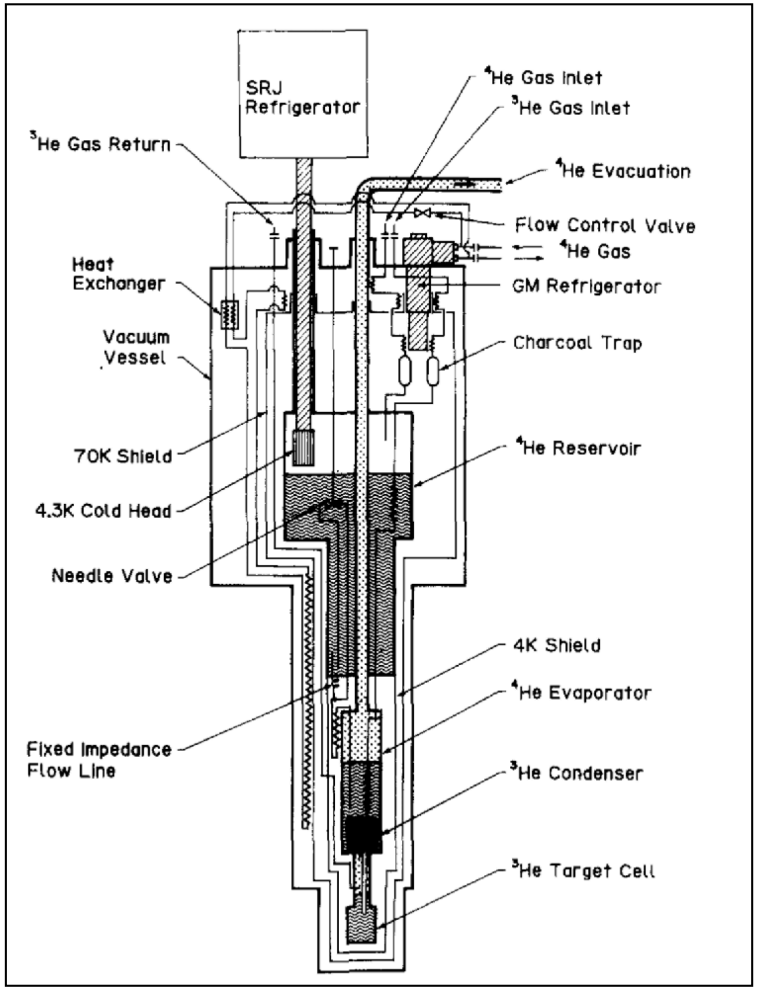
- 1987 (K. Maruyama, Y. Sumi) - 1998
- tagged photons : 100 ≤ Eγ ≤ 1000 MeV
- photodisintegration of d, ^{3}He, ^{4}He
- tagged polarized photon with a diamond crystal
- ΔΔ in deuteron (Y. Wada)
- ^{12}C(γ,K$^+$) (γ,η) (K. Maeda)
- ^{3}He(γ,ρ) : ρ ->π$^+$π$^-$ (Y. Yamashita)



NIM A376 (1996) 335.

Liquid ^{3}He target

- 180 ml @ 2.0 K
- 1000 h maintenance-free operation
- 5.0ϕ x 8.0 (cm^3)
- maintenance free for ≥ 1000 hours



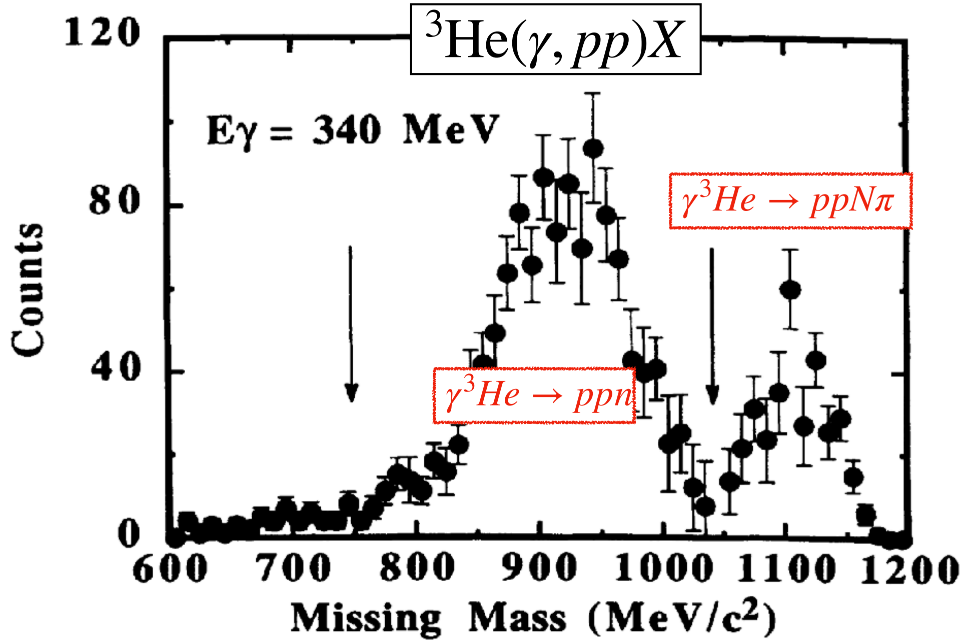
NIM A307 (1991) 213-219.

Photodisintegration of ^{3}He (1990-1994)

$$^3\mathrm{He}(\gamma, np)X_1 \qquad X_1 = p \text{ or } N\pi$$

$$^3\mathrm{He}(\gamma, pp)X_2 \qquad X_2 = n \text{ or } N\pi$$

kinematically over-determined
for photo disintegration



identification of photodisintegration
by missing mass of ^{3}He(γ, pp)

◆◆◆ 解説 ◆◆◆

γ線で見る原子核内の中間子交換相互作用

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須 田 利 美 〈東北大学大学院理学研究科 980-77 仙台市青葉区川内 suda@susy.kaws.coge.tohoku.ac.jp〉

核子間には短距離でのみ強い力を及ぼす2体核力が作用する．核子の集合体は，核力により物質の基本的階層の一つである原子核を形成する．原子核内の核子同士は仮想的状態にあるπ中間子を絶えず交換し，核子は衝突を繰り返していると言える．これまで，核内で中間子交換相互作用している核子対を直接観測して核子対の性質を決定した例はなかった．荷電π中間子の交換もあるのだから，それに起因する電流が存在するはずである．我々はこの核内電流と短波長の光（数百 MeVγ線）の電磁相互作用を利用した新たな実験手法を開発し，^{3}He 原子核内の陽子–中性子対及び陽子–陽子対を捉えた．核子間に作用する核力は，γ線で“見える”のである．

§1. 初めに—中間子交換相互作用による核力—

物質の基本的な階層の一つに原子核がある．原子核は核子（陽子と中性子の総称）の集合体である．2核子が近接する場合，核子間には核力が働く．この核力は到達距離が電磁力や重力に比べて短く，核子の大きさ（$\sim 1\ \mathrm{fm} = 10^{-15}\ \mathrm{m}$）程度以下の距離でのみ強い力を及ぼす．その力の向きは，比較的長距離（>1 fm）では引力であり，極く短距離（≤ 0.4 fm）では強い斥力（斥力芯）もあることが，核子–核子散乱実験で明らかにされた．[1] また核力は中心力の他に非中心力のテンソル成分を合わせ持っている．以上定性的に述べた核力の性質は，核子が多様な原子核を形成するために必要な条件になっている．核子は引力により凝集して原子核を作ることができ，かつ短距離では斥力やテンソル力が働くので原子核は潰れない．

湯川秀樹はこの2体核力の性質を，核子間のπ中間子交換という模型で説明した．この中間子交換相互作用は場の理論の枠組みで核子と中間子との間に働く力を表わし，その擬スカラー型相互作用ラグランジアン密度は

$$L = g(\overline{\Phi} i \gamma_5 \tau \Phi) \cdot \phi \qquad (1)$$

で与えられる．ここにΦは荷電スピン* 1/2の核子場，γ_5はDiracのγ行列，τは核子の荷電スピンに関するPauli行列，ϕは荷電スピン1の擬スカラー中間子場で，gは核子場と中間子場との結合定数である．

(1)式のラグランジアンから，核子1と核子2の間の1π中間子交換による次の核力ポテンシャルが生成される．

$$V_{12} = V_S(r)(\sigma_1 \cdot \sigma_2) + V_T(r) S_{12}. \qquad (2)$$

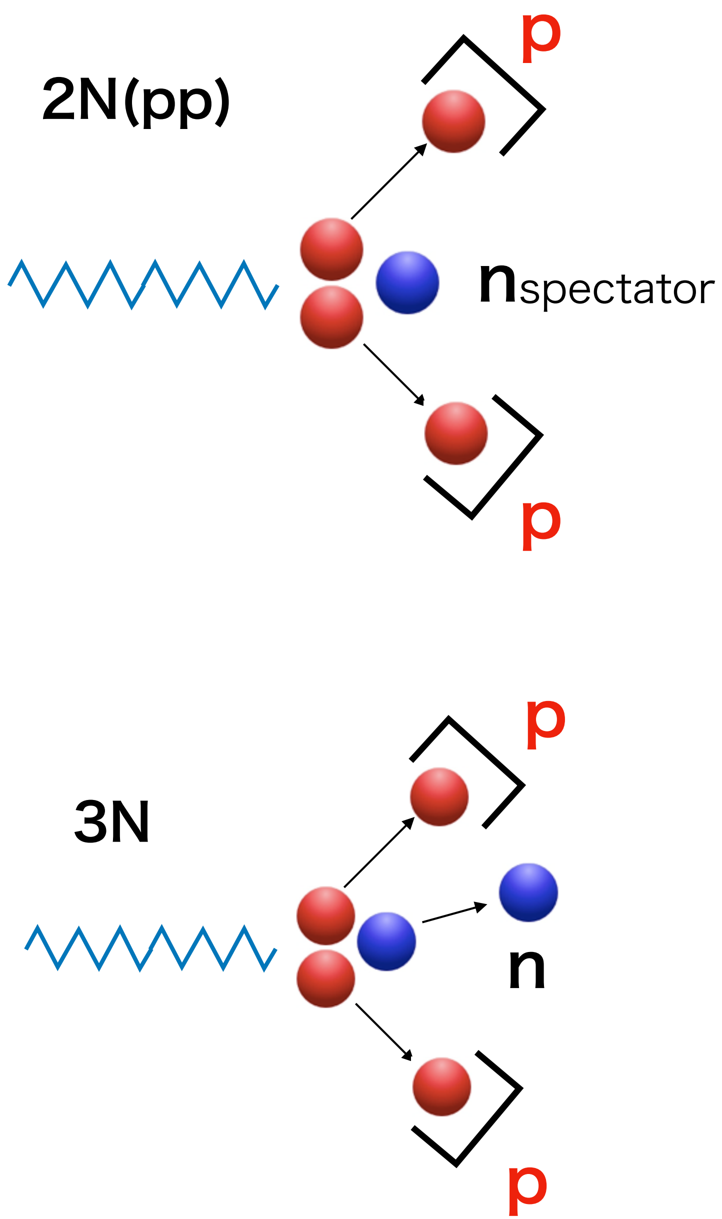
ここにV_S, V_Tは核子間距離rのスカラー関数，σは核子スピン，S_{12}はテンソル演算子である．[1] 第1項は中心力，第2項がテンソル力である．この核子–核子間の相互作用を図1に示す．核力のこの描像は自由空間においては確立している．核子が原子核を形成したとき，この2体核力からできあがった平均ポテンシャル中を，それぞれの核子が独立運動すると仮定するのが原子核の独立粒子模型である．最も大きな成功を収めた原子核理論は，中心力ポテンシャルに核子のスピンと軌道角運動量に依存したスピン–軌道結合ポテンシャルを加えた殻模型である．

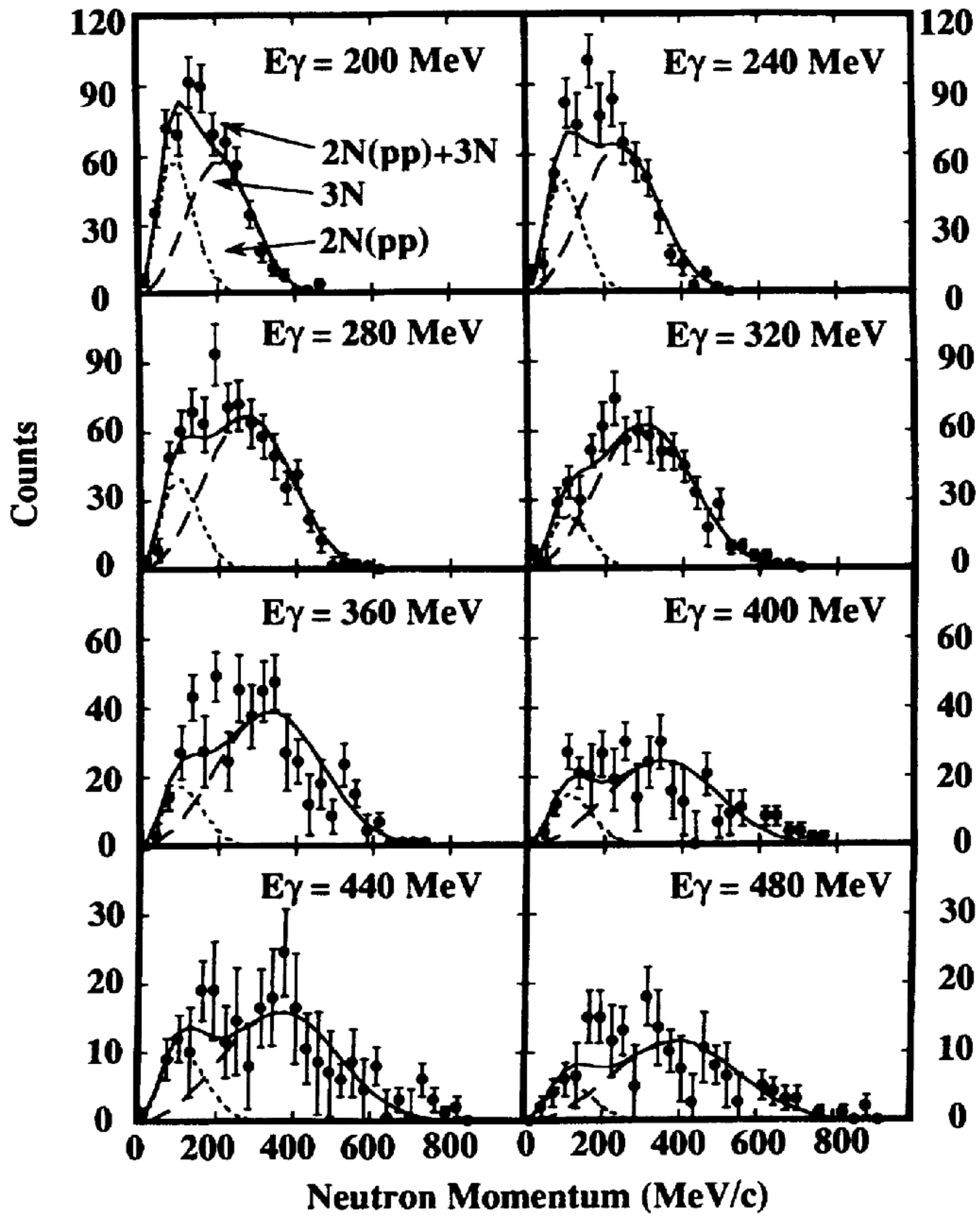
原子核内に存在する任意の2核子は，仮想的状態にあるπ中間子を絶えず交換し衝突を繰り返している．原子核内部でのこの相互作用が自由空間での核力と同じであるという保証はない．事実，核内では核力，さらには核子や中間子そのものの性質が変化するという多くの理論的予測がある．[2,3] 唯一の2核子束縛状態である重陽子についての研究は，自由空間での核力を理解するうえで重要な役割を果たした．それにならって，核内で中間子交換相互作用をしている2核子系を直接調べることは，核内での核力を理解するための良い方法であろう．核内2核子系の波動関数は重陽子とどのように違うのであろうか．重い核の半径の値から評価すると，核内2核子系の大きさは重陽子に比べて

* 荷電スピン：陽子と中性子は核子の荷電スピン$I=1/2$の2重項．π中間子の荷電スピンは$I=1$．

物理学会誌「解説」 丸山浩一、須田利美 52号 1997 103-110

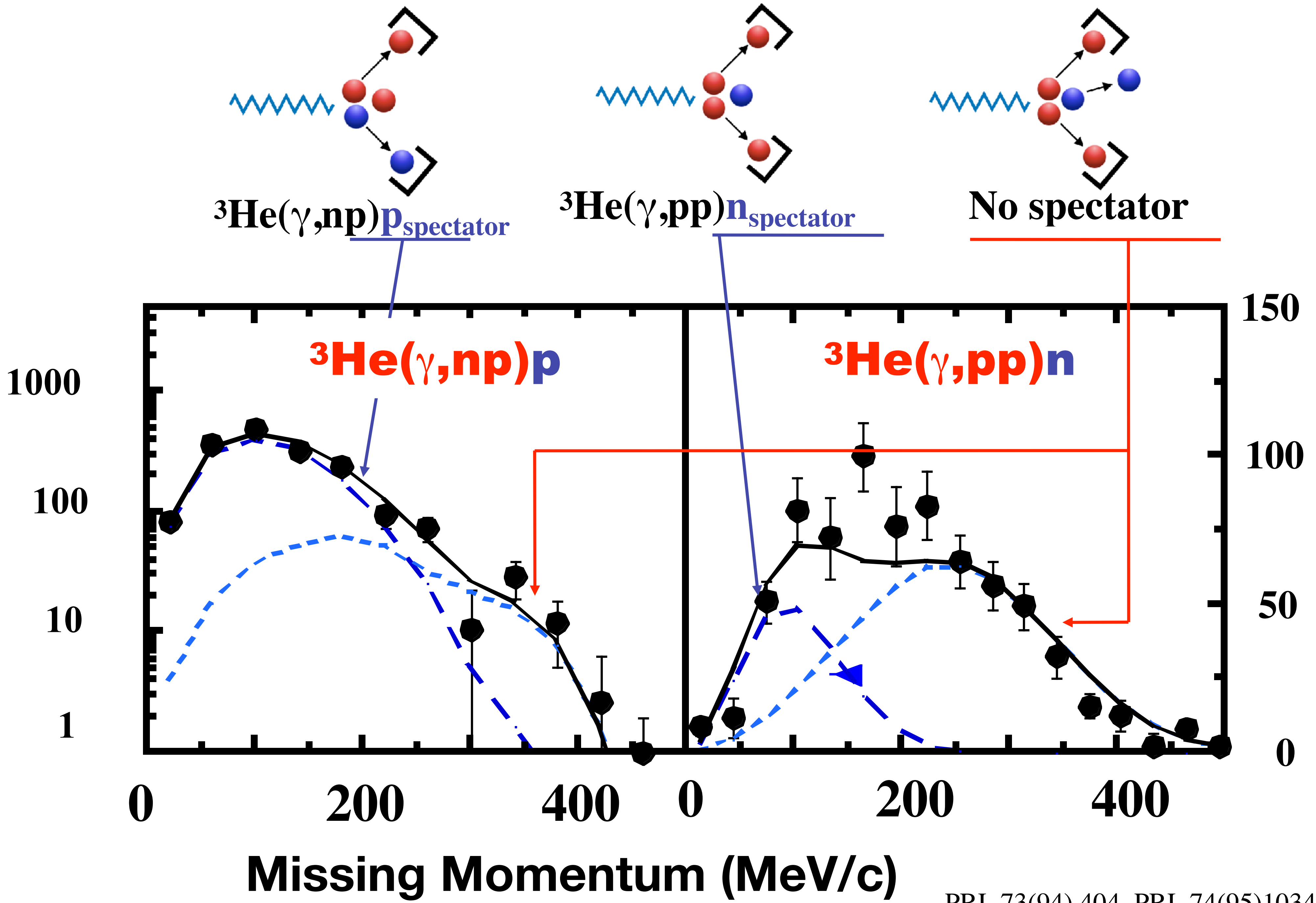
neutron-momentum spectra of $^3He(\gamma,pp)n$





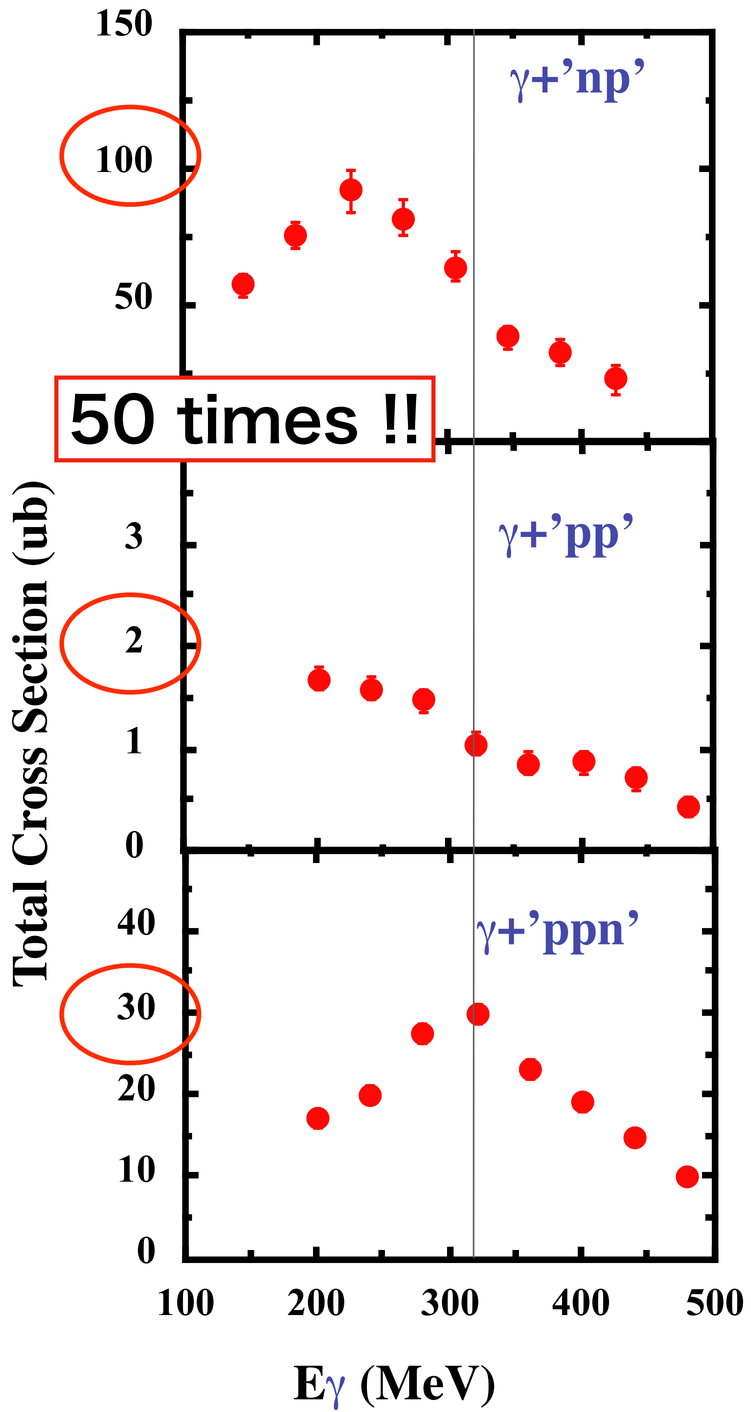
PRL 73(94) 404, PRL 74(95)1034

$^3He(\gamma,np)p$, $^3He(\gamma,pp)n$ at TAGX

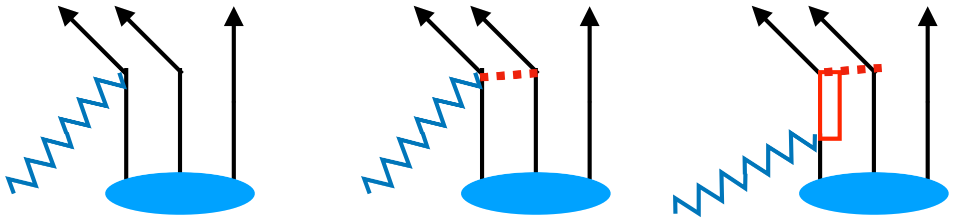


PRL 73(94) 404, PRL 74(95)1034

Total Cross Section of $\gamma+^3He$ -> ppn

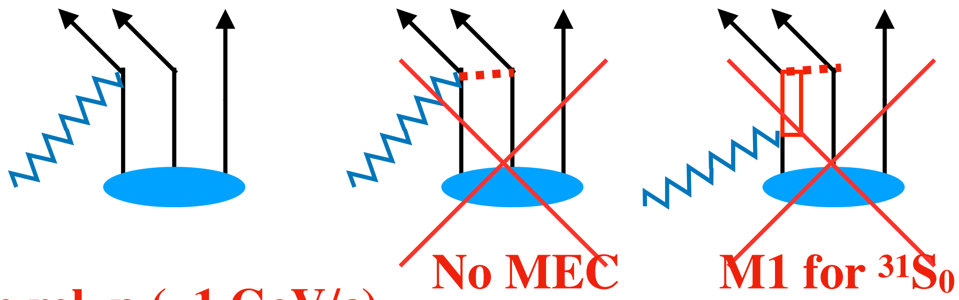


$^3\mathrm{He}(\gamma, \mathrm{np})\mathrm{p}_{\mathrm{spectator}}$



***no need** to be high. rel. mom.*

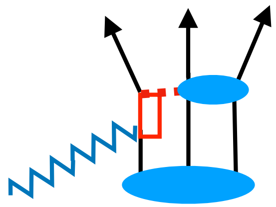
$^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}_{\mathrm{spectator}}$



need high rel. p (~1 GeV/c)

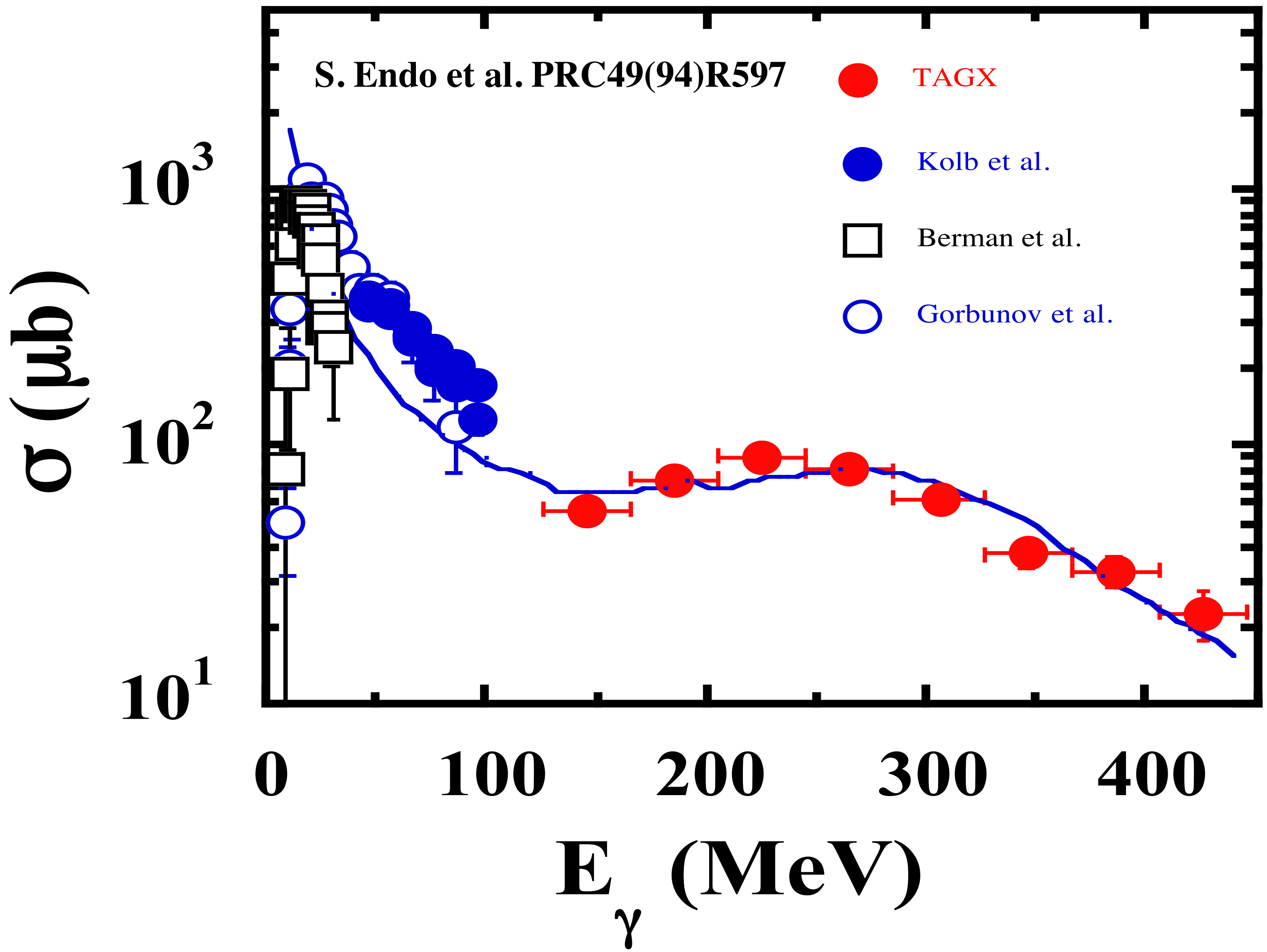
low c.m. momentum

$^3\mathrm{He}(\gamma, \mathrm{pp})\mathrm{n}$



Δ production +
π absorption

Photodisintegration of ‘np’ pair in a nucleus

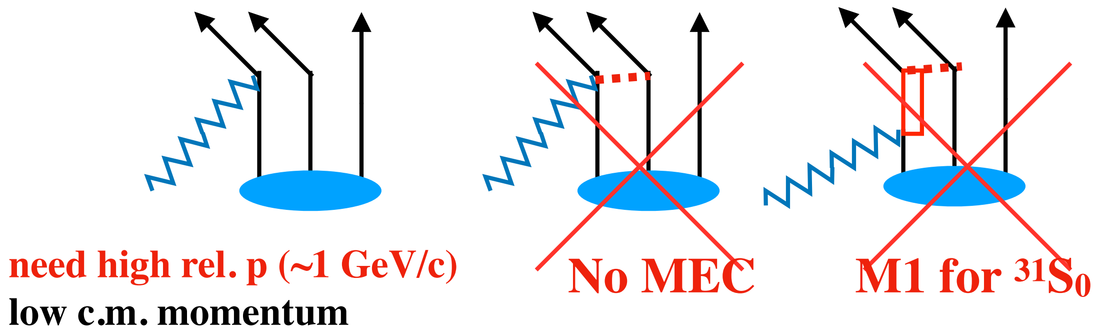


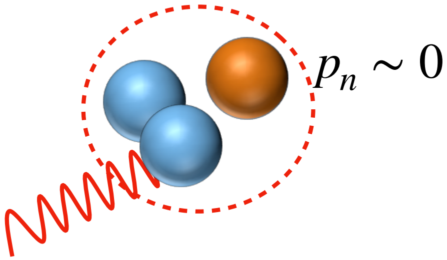
$$\sigma_{\gamma+'pn'}(E_\gamma) \sim 1.5 \;\; \sigma_{\gamma+d}(E_\gamma)$$

First clear indication of “Quasi-Deuteron” picture

Photodisintegration of ‘pp’ pair in a nucleus

- first identification of γ+’pp’ reaction
- no MECs contribute
- only one-body current operator that photon can couple



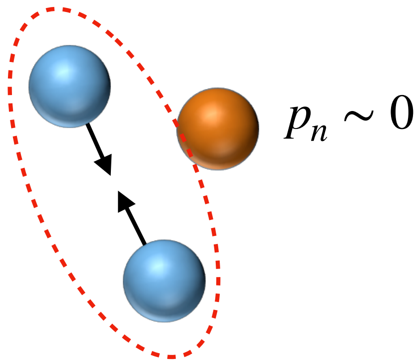


$$\overrightarrow{k_\gamma} + \overrightarrow{p_{p_1}} \rightarrow \overrightarrow{p'_{p_1}}$$

$E'_{p_1} \sim 150$ MeV

$300 + \overrightarrow{p_{p_1}} = \sim 600$ MeV/c

$p_{p_1} \sim 300$ MeV/c

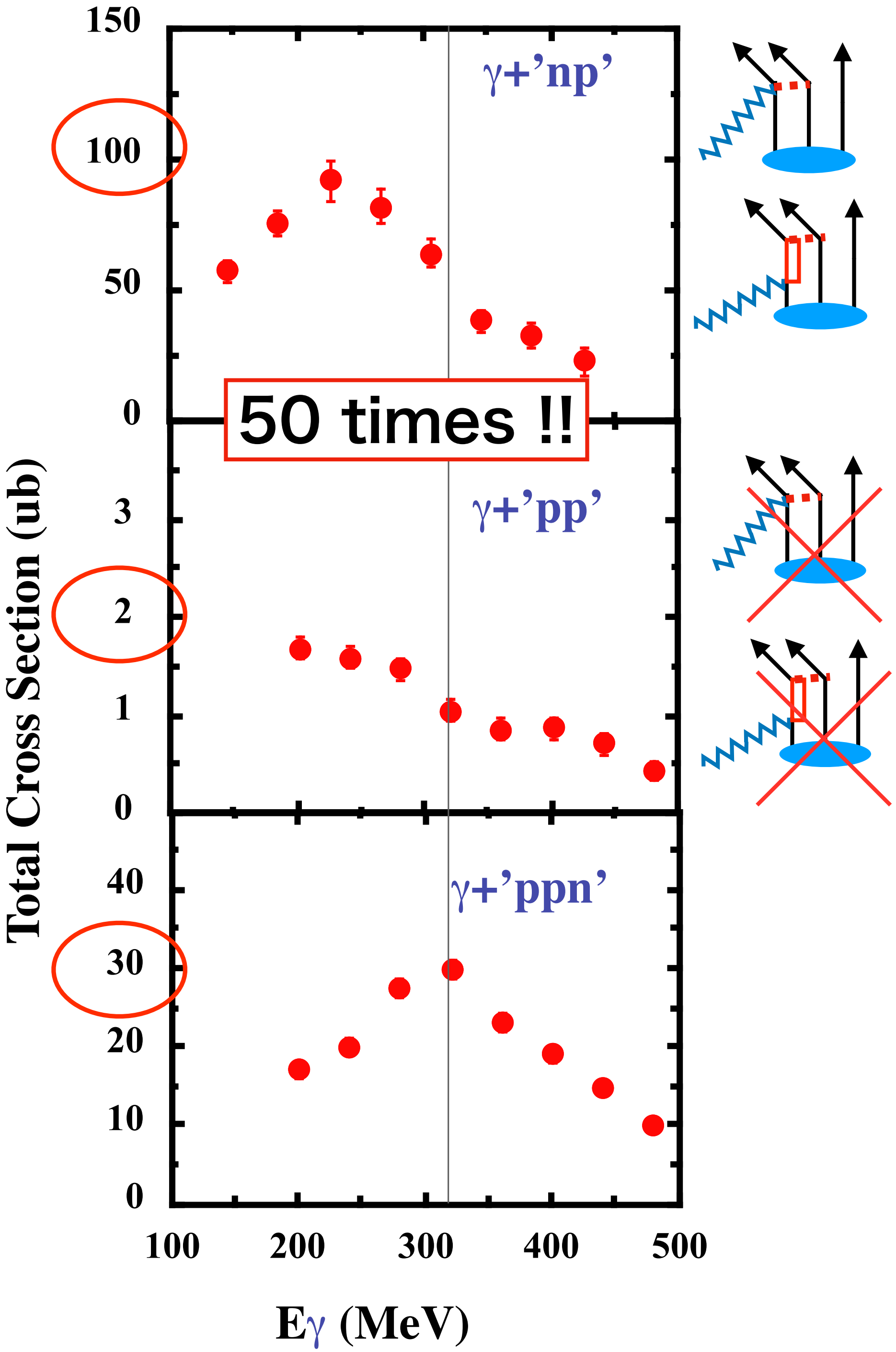


$p_{relative} \sim 500 - 1000$ MeV/c

T. Suda et al., PRL 73(94) 404, PRL 74(95)1034

TAGX

PRL 73(94) 404,
PRL 74(95)1034
PRC49(94)R597



Science 320, 2008, 1476.

$^{12}C(e,e'pp)/^{12}C(e,e'p)$

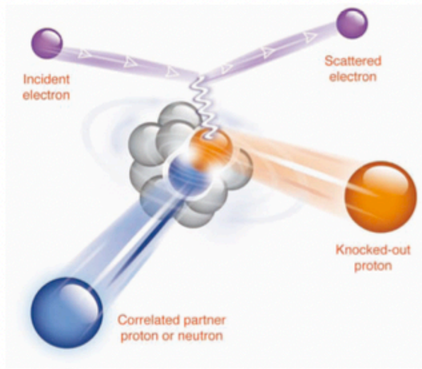


Fig. 1. Illustration of the $^{12}C(e,e'pN)$ reaction. The incident electron beam couples to a nucleon-nucleon pair via a virtual photon. In the final state, the scattered electron is detected along with the two nucleons that are ejected from the nucleus. Typical nuclear density is about 0.16 nucleons/fm^3, whereas for pairs the local density is approximately five times larger.

Science 320, 2008, 1476.

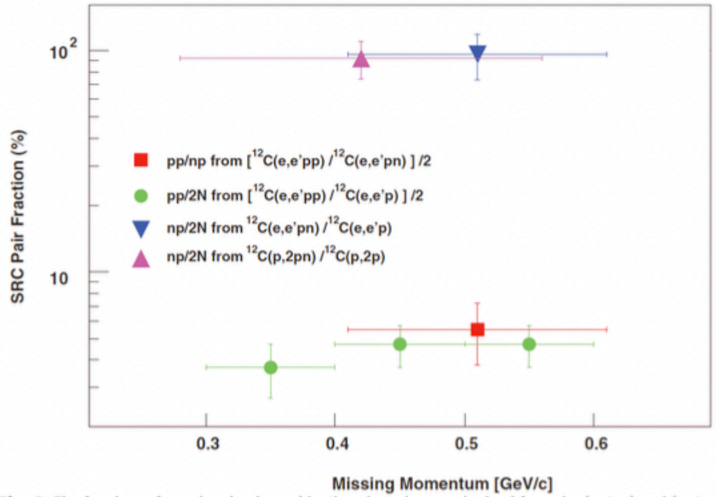


Fig. 2. The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in table S1.

$$\frac{\sigma(e,e'pp)}{\sigma(e,e'pn)} \sim 1/100$$

Final-state interaction in heavy nuclei???????

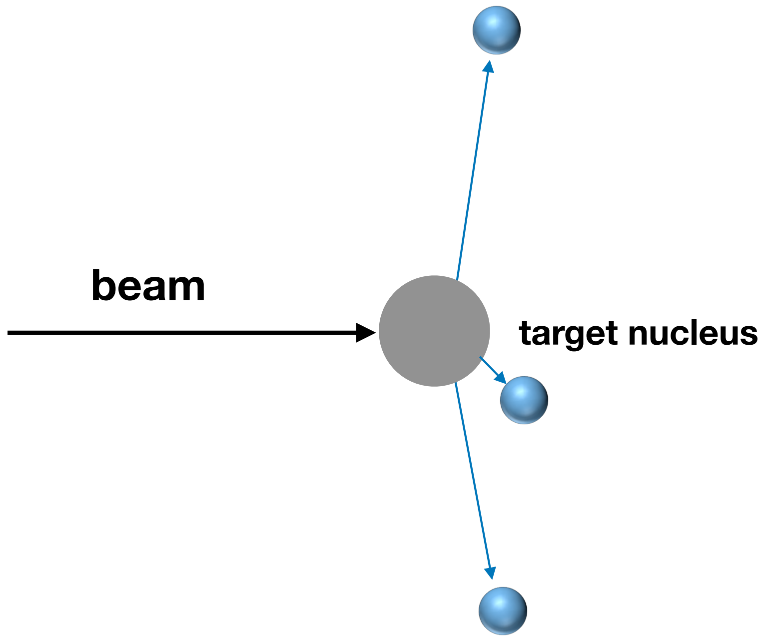
charge exchange after γ*+'np' : (e,e'pp) events

Notes for experimental SRC study from our previous studies

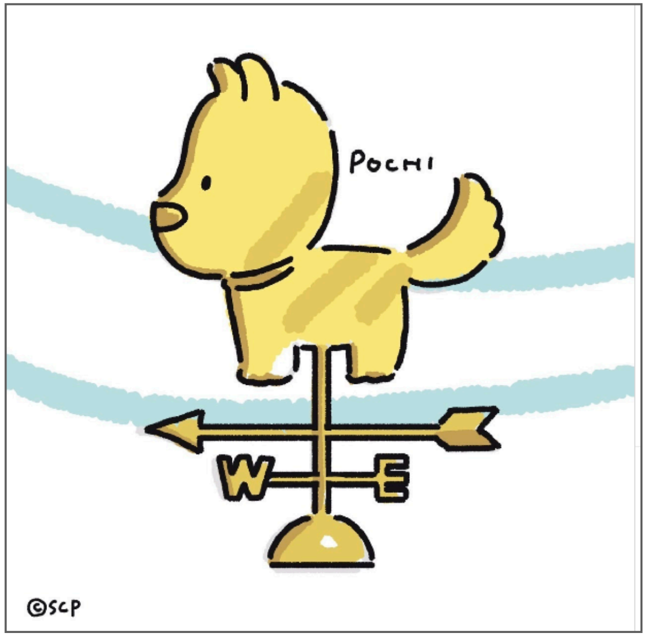
1) Keep in mind the el.mag. probe views the 2N(np,pp,nn) system in a nucleus in a complete different way (due to MEC (two-body current))

2) kinematically complete measurement is essential to identify a process where ONLY 2N are involved.

3) detecting ONLY 2N in the final state is not sufficient to identify the 2N process, where SRC may play a role.



“back-to-back correlation”
=> means “momentum” conservation only



「犬が西むきゃ尾は東」

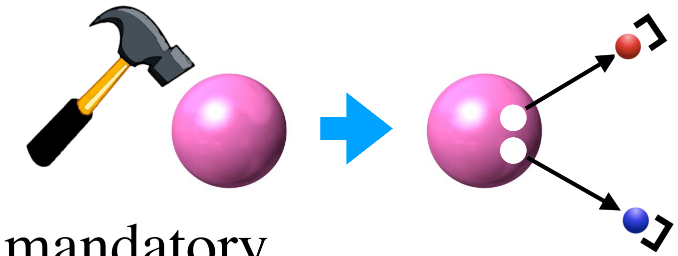
“when a dog faces west, its tail turn to the east” (of course!!)

Notes for experimental SRC study from our previous studies

- no firm definition theoretically SRC, to my knowledge
- el.mag. probe may be only a way for quantitative study of SRC
- experimental ways for the SRC study

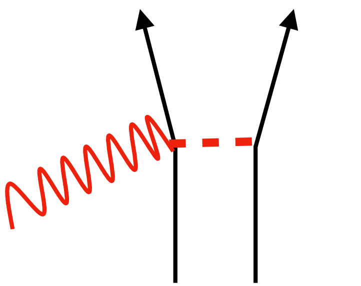
  1) high-momentum component of single nucleon

  - does not necessarily suggest SRC <= tensor
  - MEC may play a role



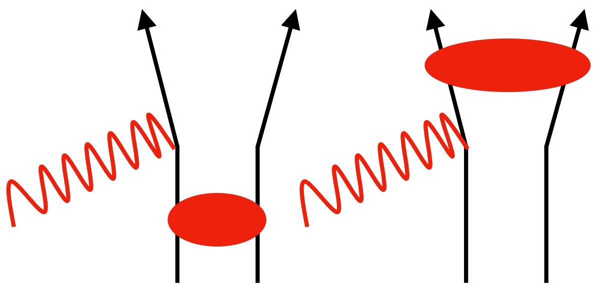
  2) two-nucleon knockout

  - kinematically complete measurement is mandatory
  - two-body current contribution is no connection to SRC
  - one needs to confirm that one-body operator works



$< N_1' N_2' \,|\, j_2 \,|\, N_1 N_2 >$

2 body operator



$< N_1' N_2' \,|\, j_1 \,|\, N_1 N_2 >$

1 body operator

the "best" way to study SRC based on my personal view

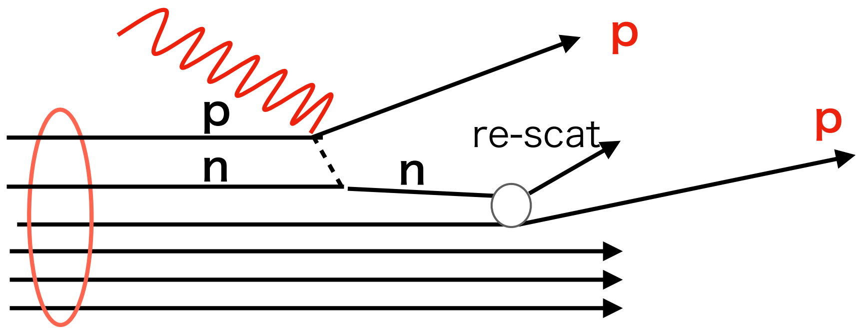
- utilizing the charge coupling (one-body operator) of (virtual) photons

  => electron scattering (not real photons)

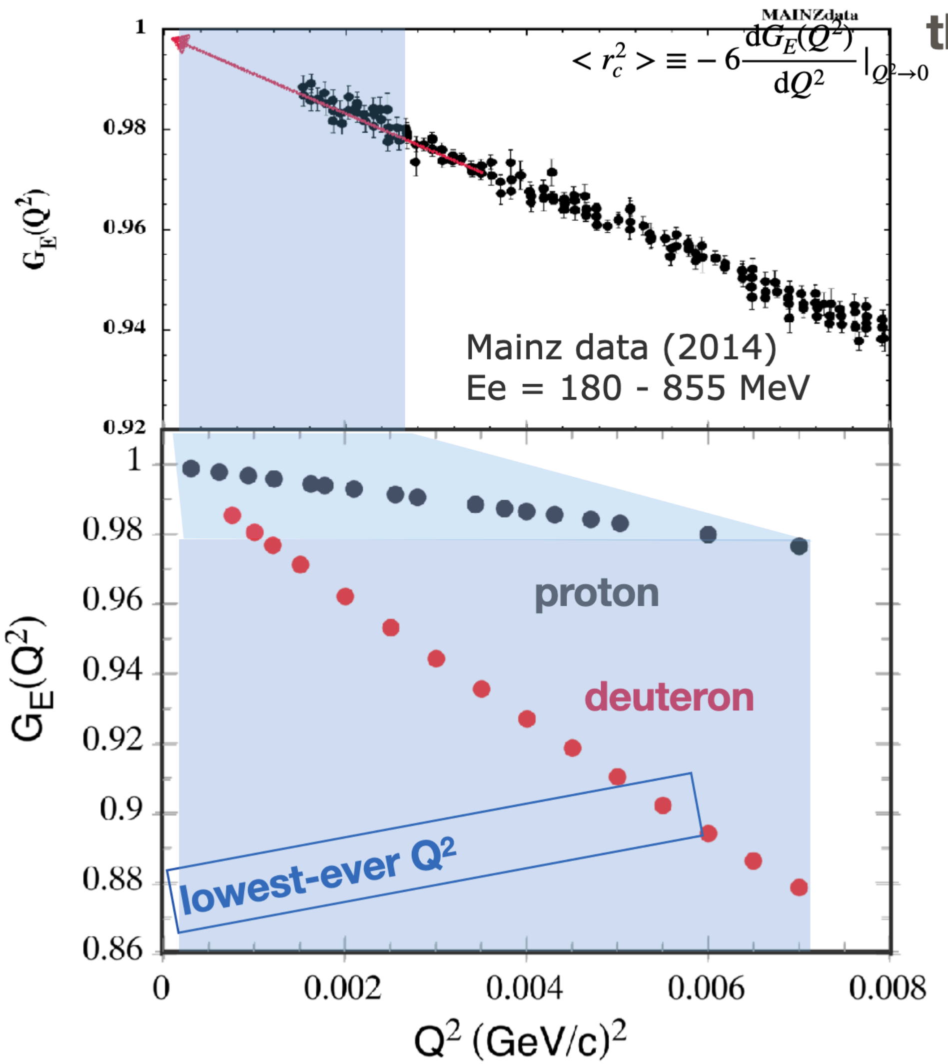
- A(e,e'pN) kinematically complete measurements
- Longitudinal response of A(e,e'pN) reaction (Rosenbluth separation)

  longitudinal (e,e'pn) vs (e,e'pp) responses are free from two-body current
  difference would be due to the tensor contribution ($^{13}S_1 + ^{13}D_1$ vs $^{31}S_0$)

- should start from A=3, 4,,,,
- Final state interaction for larger A??? σ(e,e'pn) >> σ(e,e'pp)



ULQ2 measurements for e+p and e+d



three-year data-collection completed (2024, October)

Yuki Honda
Ph.D. student
(C. Legris, T. Goke)

1) proton
- charge radius
- magnetic radius (next step)

2) deuteron
- deuteron charge radius
  => neutron charge radius