Nucleon-nucleon correlations inside atomic nuclei: (brief)review of experimental observations

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Work* carried out in collaboration with

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Presentation in
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*Ranjeet Dalal, I.J. Douglas MacGregor, Nucleon-nucleon correlations inside atomic nuclei: synergies, observations and theoretical models, https://arxiv.org/abs/2210.06114

Independent Particle Shell Mode

Nuclei are understood in terms of IPSM

- Neutron (n) and Protons (p) moving in a mean field
- Mean field is generated by cumulative effect of all nucleon
- n's and p's are filled independently
- Mean nuclear separation of ~1.5fm with Fermi momentum of ~250MeV
- Apart from pairing or long-range correlations between like nucleon, no significant correlation is expected

However,

- Considering size of n & p ~ 0.8fm or so => Nuclei are very crowded system
- n's and p's are occupying similar orbits
  - Interaction between n's & p's is not restricted by Pauli's Principle
- The proton and neutron are having opposite surface charge densities*

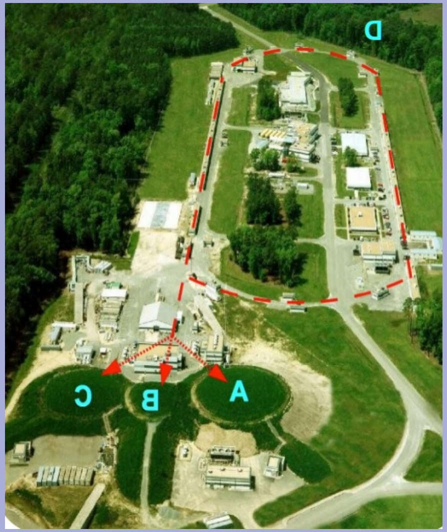
There could be significant short-ranged NN correlations inside nuclei!

*C. Lorce, Phys. Rev. Lett. 125, 232002 (2020)

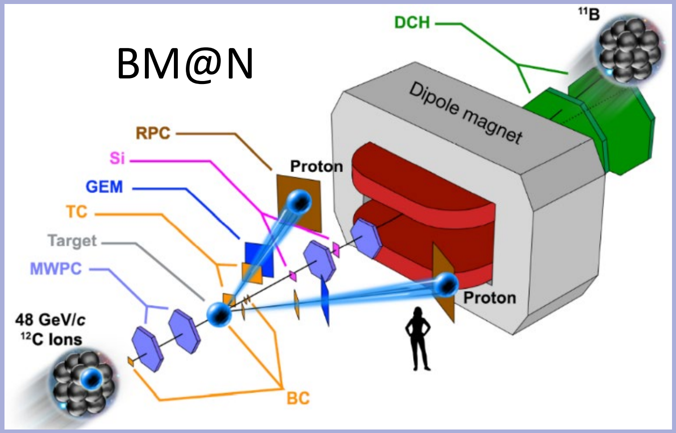
Golden Era for short-range NN correlation (2001 onward)

Hard Interaction (high energy and large momentum transfer > 500MeV/c) of p/e-/pion beam => Study coincidence events of outgoing nucleon

- Triple coincidence experiments
- Using multi GeV p/pion beam at BNL => quasi-elastic (p, p,NN)
- Using multi-GeV e^- beam at Jefferson lab => (e, e,NN)
- Inverse Kinematics e.g. BM@N at JINR
- Upcoming EIC



Jefferson lab



It started with….

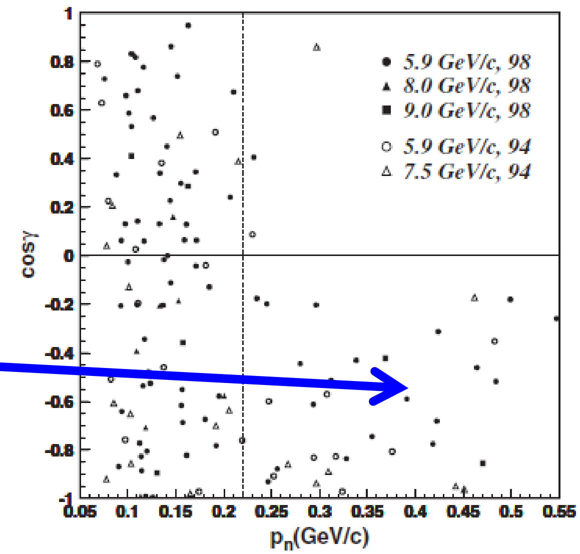
2001 PRC paper by Malki*et al*.

- 5.9 MeV/c proton & pion beams on C target in EVA spectrometer in BNL
- For high p_t outgoing protons (>0.6GeV/c) from nucleus in forward hemisphere are followed with at least one backward emitted neutron with momentum >0.32 GeV/c.
- Similar results were reported for pion beam

- Detailed analysis of high energy (p,p’pn) data by Piasetzky *et al. (2006)* showed strong back-to-back correlations for neutrons energies above Fermi momentum.

- At least 74% of the time, the ejection of fast protons results in the emission of a fast neutron

- pn correlations were a factor of 6 stronger than pp and nn correlations

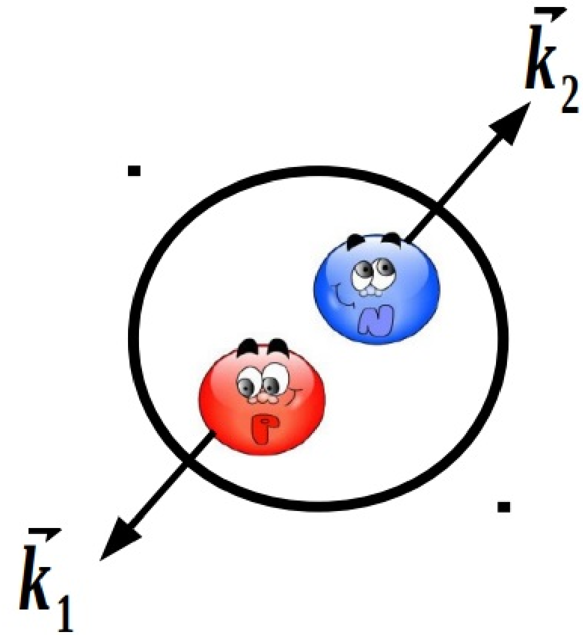


Neutron momentum vs angle between neutron and struck proton for ^{12}C(p,p’pn) reactions [Piasetsky *et al* PRL 97, (2006) 162504]

2N - Short Range Correlations (SRC)

A pair with:

* Large relative momentum $(k_{rel} > k_F)$
* Small C.M. momentum $(k_{CM} < k_F)$



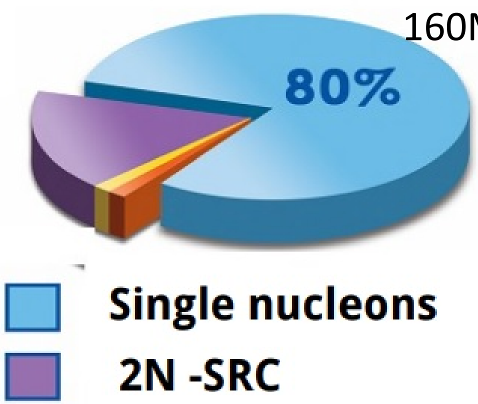
◆~20% of nucleons have momentum > Fermi momemta (~250MeV/c)

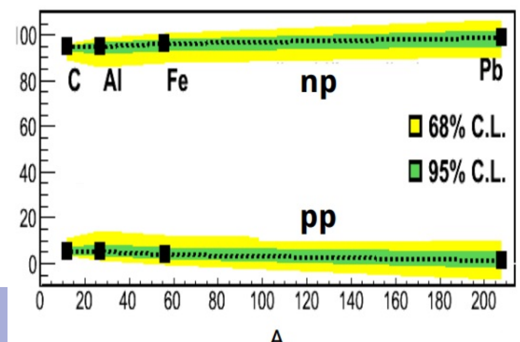
◆Low C.M. momenta for NN SRC (~100 to 160MeV/c)

◆ ~94% of SRCs are n-p pairs

$$k_1 > k_F \qquad k_2 > k_F$$

$$k_1 \simeq k_2$$





Hen et al., Science 346 (2014)

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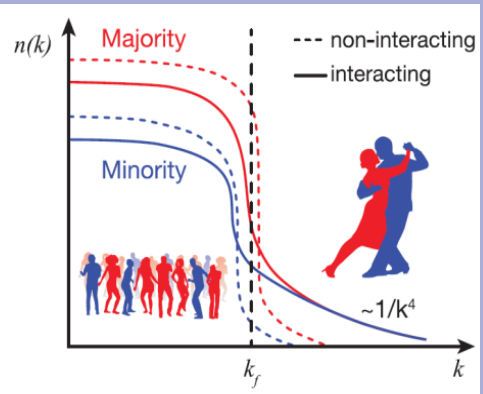
High Momentum Protons and Neutrons

◆How does this affect momentum distribution of protons and neutrons in heavy nuclei, such as Pb?

- ◆ Due to the neutron excess, on average each proton undergoes more SRC than the average neutron

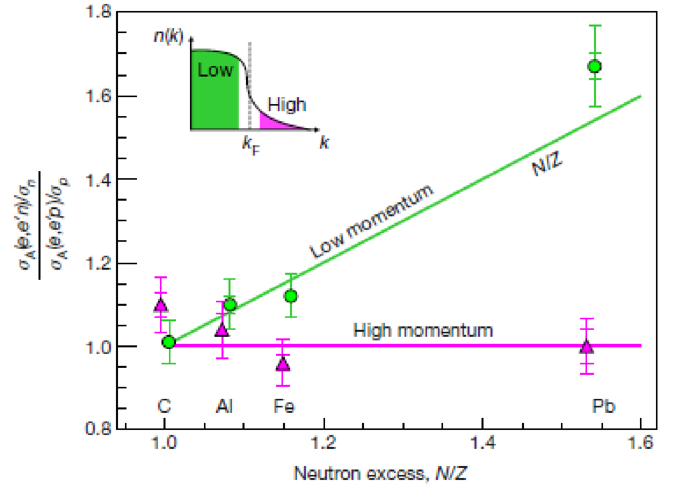
◆ In an old-fashioned analogy, the protons get more dances, and a greater fraction end up with high momenta



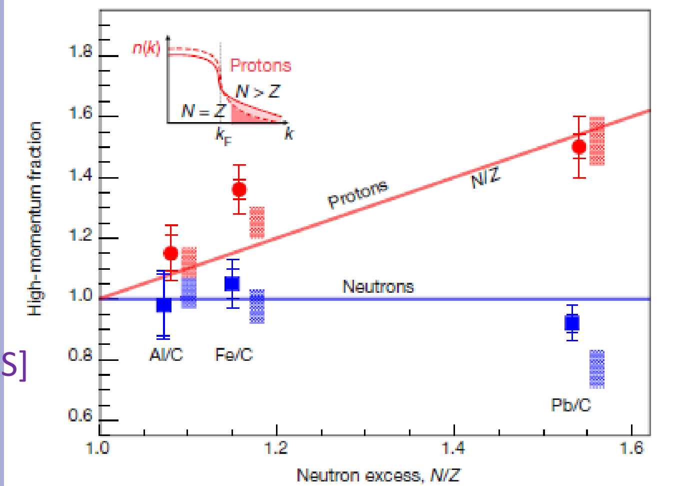
◆ Confirmed by (e,e'p) and (e,e'n) cross section measurements from the CLAS data-mining programme

[Hen *et al* Science 436 (2014) 614, CLAS, Duer *et al* Nature 560 (2018) 617, CLAS]

Huge enthusiasm in nuclear community about SRC discovery!
- About 20 papers in Nature, Science and PRL in last 3 years or so..



In Pb there are fewer high momentum neutrons than low momentum neutrons.



The fraction of high momentum protons increases with neutron excess, but not for neutrons

If SRCs inside nuclei is fact of nature, they must be revealed in other type of reactions too?

And it is true...
You just have to look for suitable probe and energy scale

- Photons... look for photo-nuclear reaction above GDR- region
- Pion absorption mechanism
- Scattering experiments with nuclei using multi-hundred MeV nucleons
- Production of unstable particles in hadron-nuclei, nucleus-nucleus collisions

  =>Anti-proton, koan, pion production much below the particle production threshold for free N – free N collisions

- If there are quasi-deuterons type of structures inside nuclei,

=> they would be ejected in one-step quasi-elastically by struck particles (say nucleons)

- Interaction of neutrino with nuclei (already known contribution from 2p-2h events)

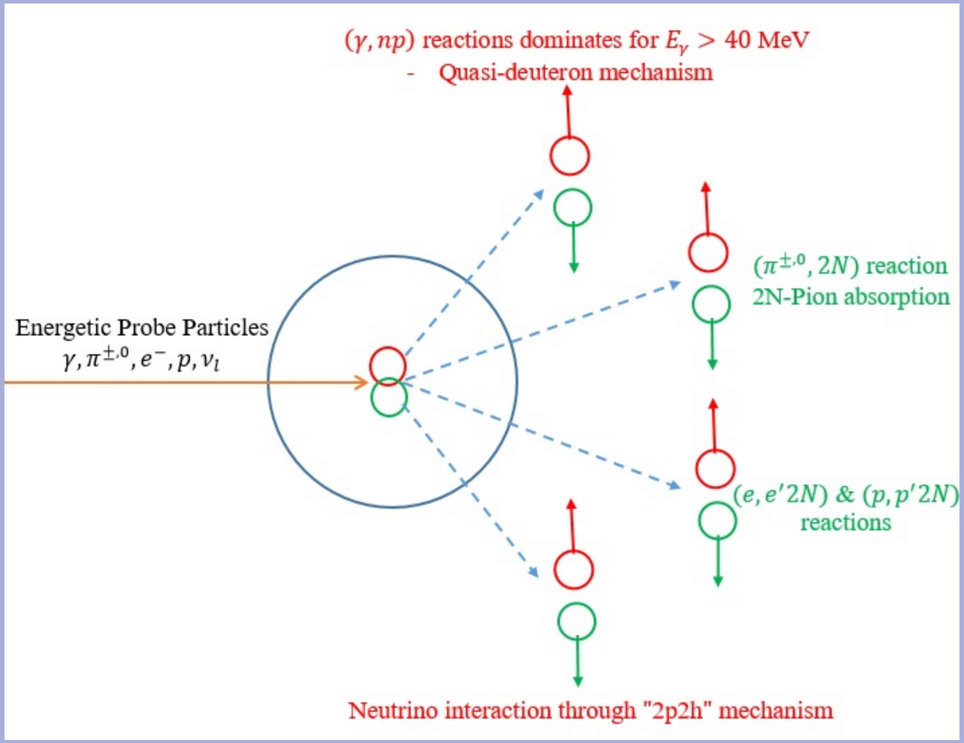
and if size of nucleus is ~0.8fm, inter-nucleon separation is ~1fm in SRCs,

⇒Nucleon overlapping would disturb the parton distribution inside nuclei

- EMC effect (already figured out!)

Direct emission of correlated hadron pairs

- Photon absorption reactions
- Pion absorption reactions
- High energy (e,e'NN) and (p,p'NN) reactions and the EMC effect (already discussed)
- Interaction of neutrinos with nuclei



Interaction of energetic photons with nuclei

- Photo-emission reactions were expected to occur either by absorption on a single proton, or through statistical "boil off" of nucleons from an excited compound system

- Below pion threshold, (γ,p) was expected to be stronger than (γ,n) due to its electric dipole interaction, absent in neutron interactions (Courant paper-1950)

- No strong angular correlations between emitted nucleons were expected

- Despite a scarcity of good (γ,n) data, it became apparent early on that (γ,n) and (γ,p) cross sections, and their ratio, could not be accounted for by either of these reaction models

- To explain these findings, Levinger proposed a quasi-deuteron model (QDM) [PR 84 (1951) 43] in which p and n form deuteron-like sub-structures inside nuclei

$$\sigma_{X(\gamma,np)} = L\,\frac{NZ}{A}\,\sigma_{d(\gamma,np)}$$

- Strong contributions from initial QD absorption explained photo-emission cross section data

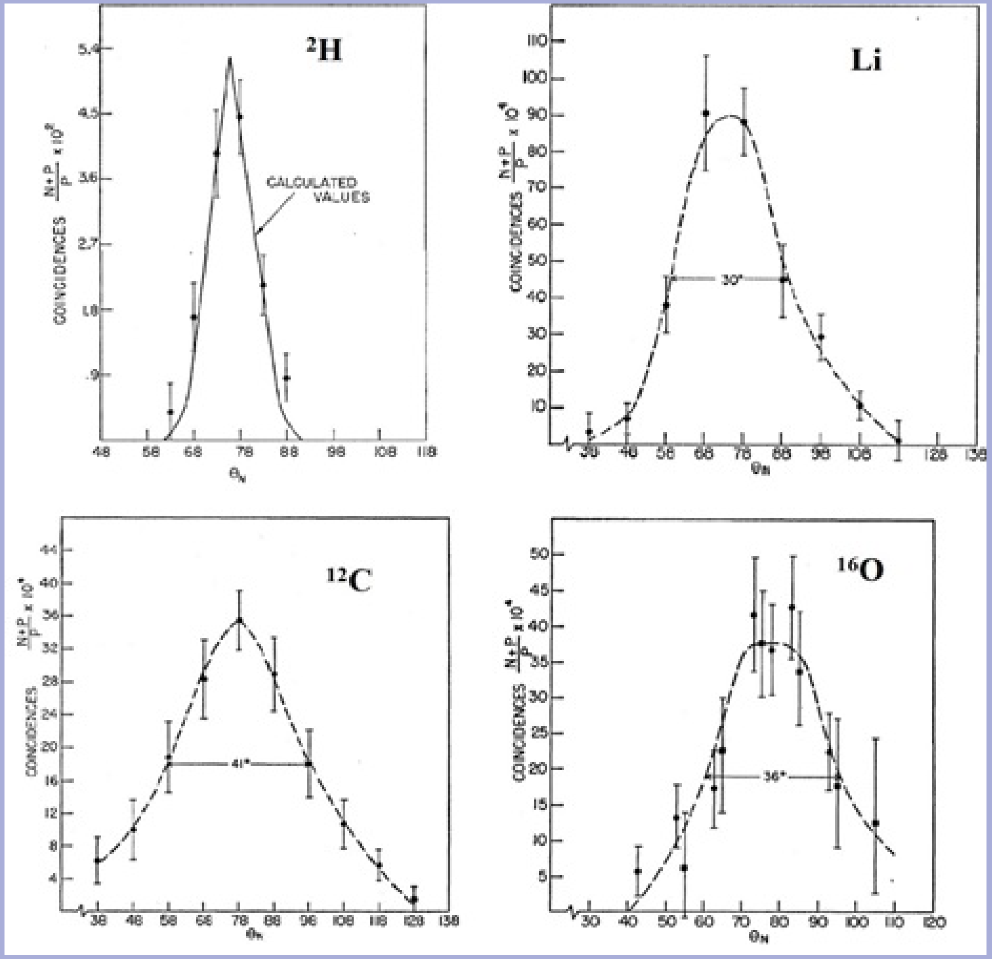
Levinger's hypothesis

- Verified by large no of experiments

MIT Synchrotron experiment with 340 MeV Bremsstrahlung beam

Fixed proton telescope at 76° (corresponding to 90°CM) while n-detector arm angle varied

- n-distribution in Li, C, O, Al, Cu are very similar to that of ^{2}H
- n-p High relative momenta and low CM momenta (~100 MeV/c)



Wattenberg A. *et al.,* Momentum of Nucleons in Various Nuclei from the High-Energy Photoeffect, Phys. Rev.104, 1710 (1956).

$^{12}C(\gamma,pn)$ Missing Energy Spectra

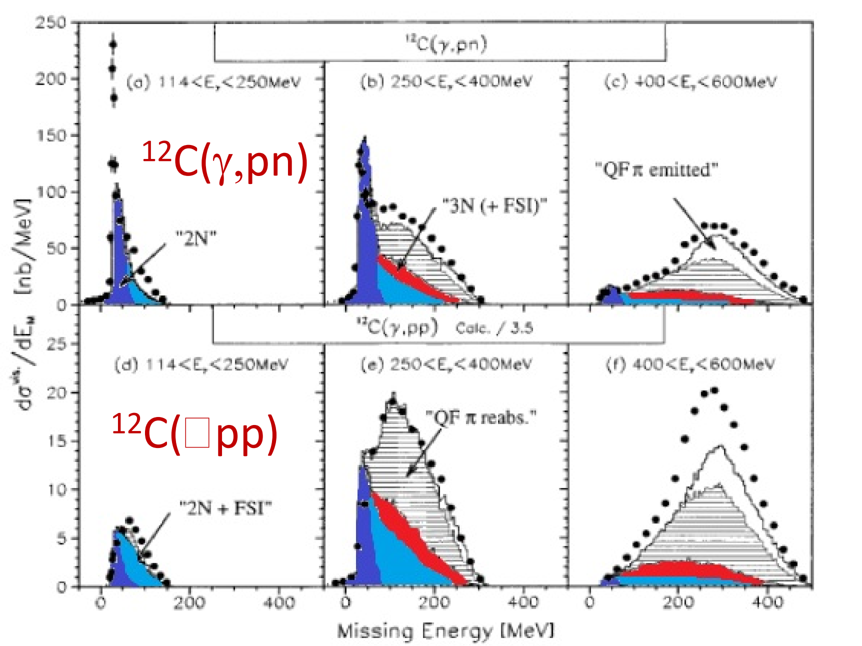
[Lamparter et al, ZPA 355 (1996) 1]

- At low E_γ ^{12}C(□pn) has sharp peak at low $E_{m,}$ indicating only two nucleons involved

- At higher E_γ more complex processes involving more nucleons occur at higher E_m

- The ^{12}C(□pp) reaction is a factor of ~30 weaker than ^{12}C(□pn) at low E_m

- It has no discernible peak at low E_m, but has a broader distribution, indicating stronger FSI



[Lamparter et al, ZPA 355 (1996) 1]

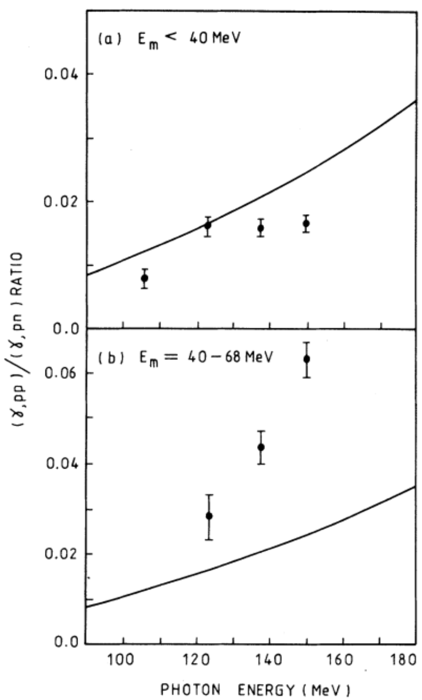
2N, 2N + FSI, 3N, 3N+FSI

$^{12}C(\gamma,pn)$ and (γ,pp) reactions

[McGeorge et al PRC 51 (1995) 1967]

◆ P_{pn} =-P_{recoil}

◆ P_{recoil} distributions for both $^{12}C(\gamma,pn)$ and $^{12}C(\gamma,pp)$, for low missing energies, E_m< 40 MeV, fit QDM well but disagree with phase space distribution



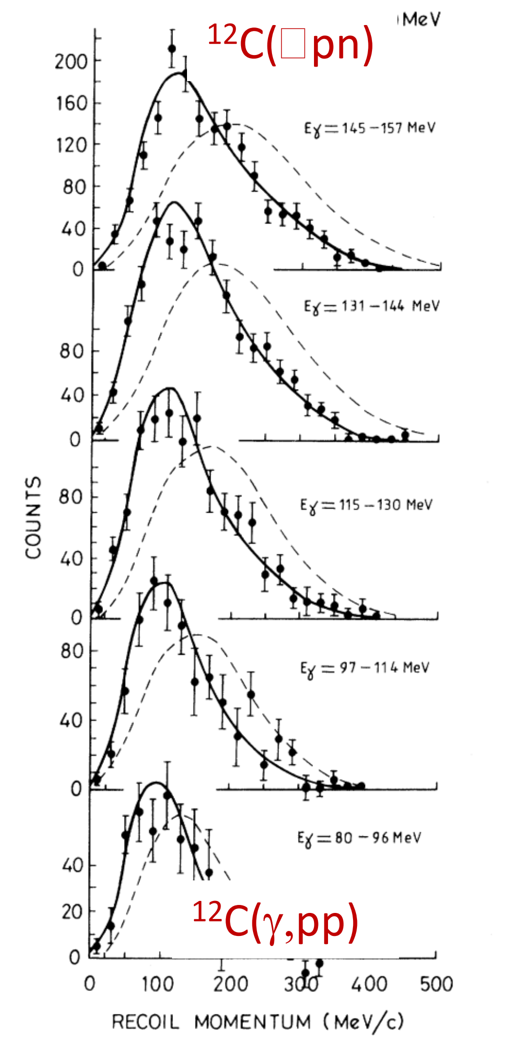
[McGeorge *et al* PRC 51 (1995) 1967]

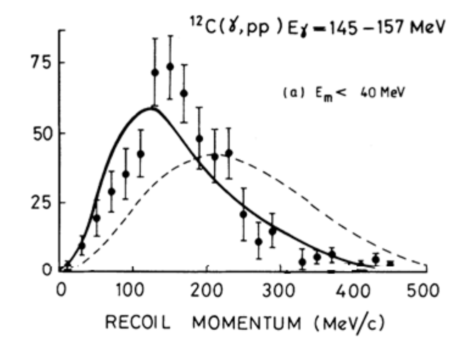
◆For 100 MeV photons, about 90% interactions are through QD mechnism

◆ *The (g,pp)/(g,pn) ratio is only a few percent*

=> pp are just few % of np

◆ It increases both with photon energy and with missing energy



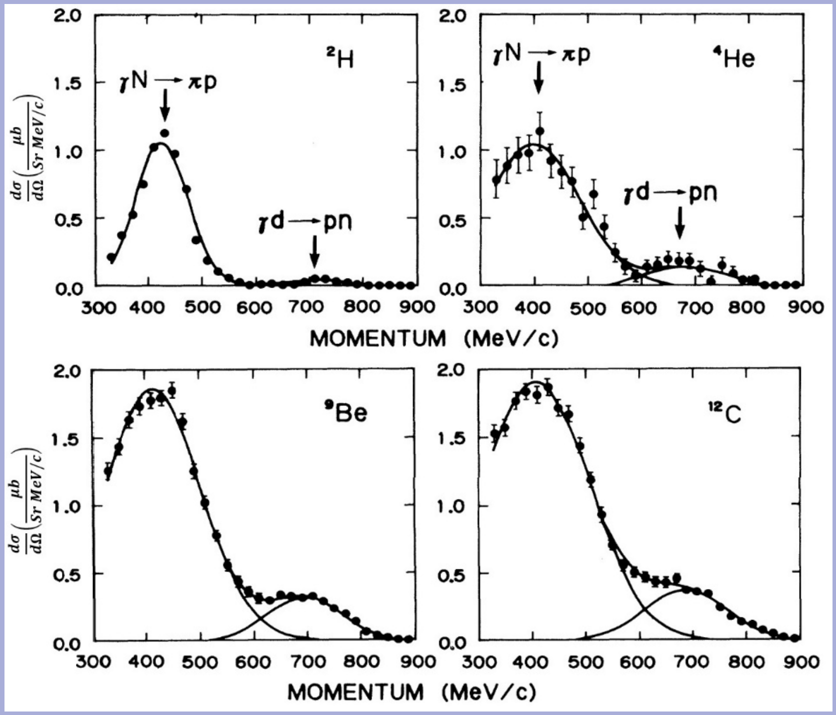


[McGeorge *et al* PRC 51 (1995) 1967]

For E_γ>140 MeV, energetic nucleons are emitted by two main mechanisms*
(a) γ+ N →N + π pion photo-production
$(b)\gamma$+ NN →N + N photodisintegration of quasi-free NN system

Kinematic separation of these channels is possible

- Verified by coincidence measurements
- For most of NN-photodisintegration events protons are accompanied with kinematically correlated neutron
- Confirmed Levinger model for E_γ up to 620 MeV**



*Homma S. et al. (γ, p) reaction on light nuclei in the Delta(1232) resonance region, Phys. Rev. Lett. 53, 2536 (1984).
** Baba K. et al., Proton momentum spectra in high-energy reactions of 9Be and 12C with quasimonochromatic photons, Nucl. Phys. A 415, 462 (1984).

Pion Absorption on Nuclei

◆ Pion absorption is essentially a 2- or multi-nucleon process due to energy-momentum conservation

◆ More complex than photon absorption due to additional initial state interactions (ISI)

◆ Process described by Brueckner *et al* [PR 84 (1951) 258] using a quasi-free 2N absorption model, similar to the Levinger QDM

◆ In a stopped π^- absorption experiment on ^{12}C [Ozaki *et al* PRL 4 (1960) 533], a ratio of ~5 was obtained for π^- absorption on np (leading to nn emission) compared to absorption on pp (leading to pn emission)

◆ Similarly Steinacher *et al.* [Nuc Phys A 517 (1990) 413] confirmed a quasi-free 2N absorption mechanism in ^4He and reported a cross section ratio for 120 MeV pions of

$$\sigma(^4He(\pi^+,pp)nn) \,/\, \square\ ^4He(\pi-,pn)pn)$$

of 20 ± 5, confirming the dominance of pion absorption by pn pairs.

Interaction of neutrinos with nuclei

◆ Neutrino oscillations studied at T2K, DUNE, MiniBoone, mainly through charged current quasi-elastic (CCQE) interactions

$$\nu_l + n \rightarrow l^- + p; \qquad \bar{\nu}_l + p \rightarrow l^+ + n$$

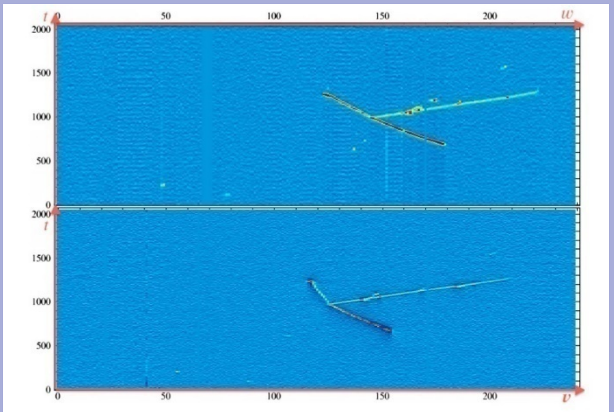
◆ In nuclei, events leading to pion production at interaction vertex and interaction with NN pair can also mimic the genuine CCQE outcome. These limitations persist in most of the present and future neutrino detectors

◆ Recently, the neutrino interactions event with correlated np pairs are reported

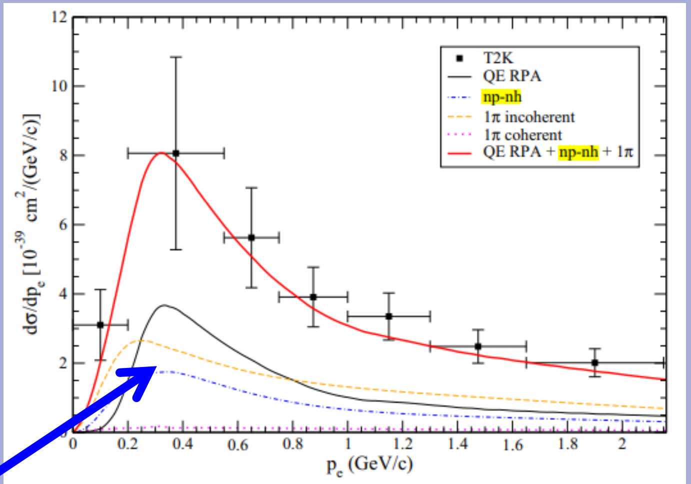
$$\nu_\mu + np \rightarrow \mu^- + 2p$$

- Acciarri *et al* at ArgoNeuT detector in the NuMI (Neutrinos at the Main Injector) low energy beam line of Fermi Lab, with 4 events having characteristic proton back-to-back "hammer" signature.

◆ Martini *et al* showed multi-nucleon inter-actions are required to fit measured T2K ν_e differential cross sections



"Hammer event" with back-to-back protons and forward moving μ^-. [Acciarri *et al* PRD 90 (2014) 012008]



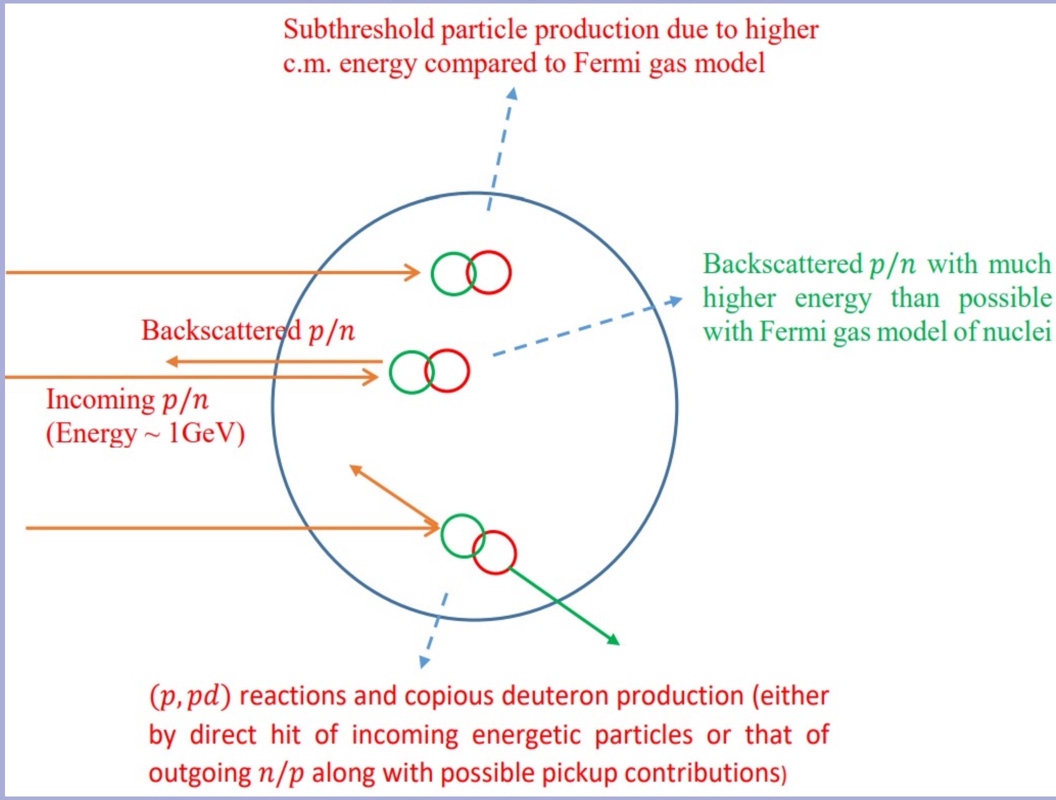
Calculated T2K cross section contributions [Martini *et al* PRC 94 (2016) 015501]

Indirect evidence of role of correlated hadrons

◆ Backscattering of hadrons of several hundred MeV energy from nuclei

◆ Sub-threshold production of energetic particles

◆ Direct quasi-elastic knockout of deuterons at forward angles using nucleons of a few hundred MeV energy

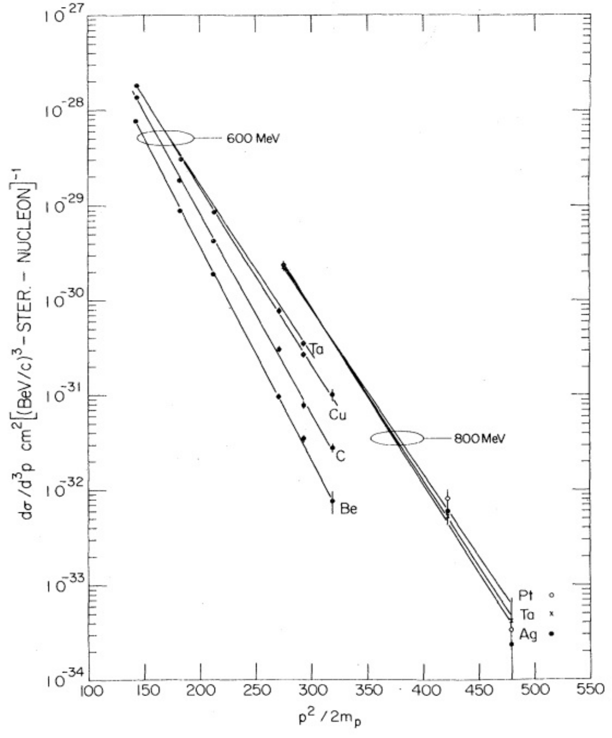


Back-scattering of hadrons from nuclei

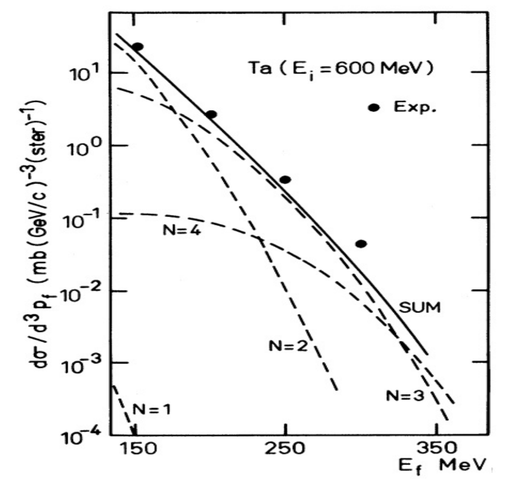
◆ 600 MeV proton has wavelength ~0.16 fm and momentum ~1220 MeV/c (cf Fermi momentum ~250 MeV/c)

◆ At energies up to ~1 GeV protons scattered from nuclei are expected to be due to interactions with a single nucleon and to be at forward angles

◆ Unexpectedly, protons with energies up to half the incident energy are observed at θ=180° from a range of nuclei (with exponential energy dependence)



Energy dependence of θ=180° proton back-scattering from nuclei [Frankel *et al* PRL 36 (1976) 642]



◆ Observations cannot be explained by IPSM

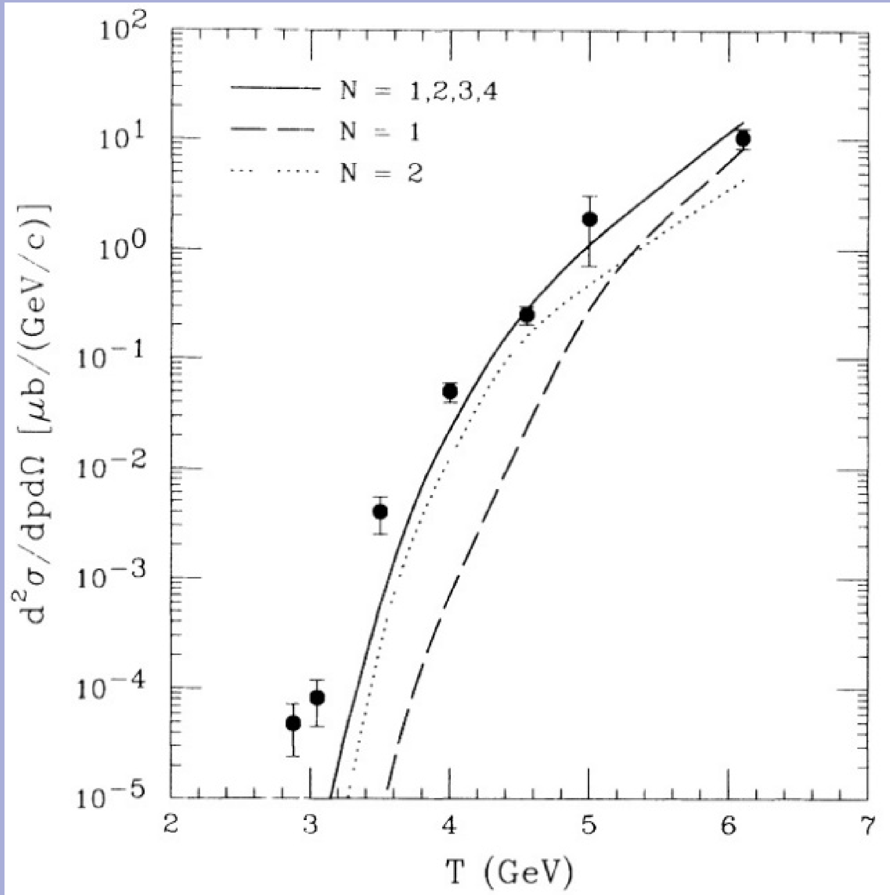
◆ Correlated Cluster model of Fujita fits data

◆ Note strong contribution from N=2 clusters at lowest energies

[Fujita PRL 39 (1977) 174]

Sub-threshold production of anti-protons

- Sub-threshold particle production, at CM energies below that allowed for free NN collisions, has been studied since the 1950s.
- Internal nuclear momentum cannot contribute (much) additional energy to the collisions.
- However, momentum of stuck nucleon or cluster can counteract momentum of incident projectile, so more energy goes into particle production and less into recoil energy.
- Key question is whether struck particle is a single nucleon or a short-range nucleon cluster posing as single unit?
- Cross section calculations in the threshold region indicate largest contribution from N=2 clusters at lowest observed energies.



^{63}Cu(p,p̄)X cross section data [Dorfan *et al* PRL 14 (1965) 995] c.f. multi-particle calculations [Danielewicz PRC 42 (1990) 1564]

Knockout of deuterons at forward angles

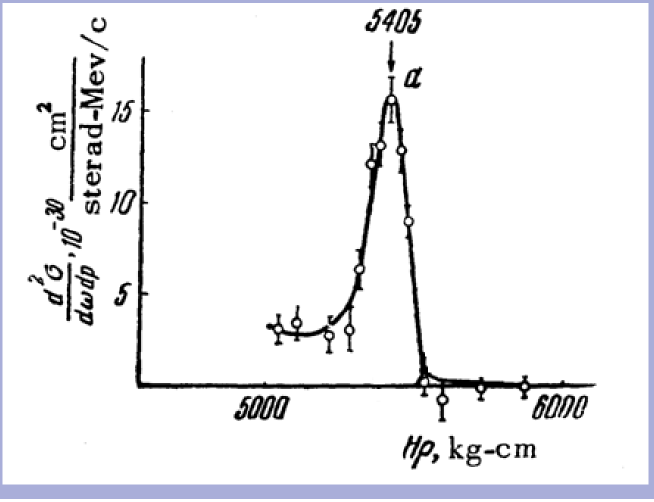
- The quasi-elastic deuteron knockout in forward angles measured in D, Li, Be, C and O targets by Azhgirei *et al.*

- Deuterons observed at forward angles with energies only slightly less than the energy of free deuteron case.

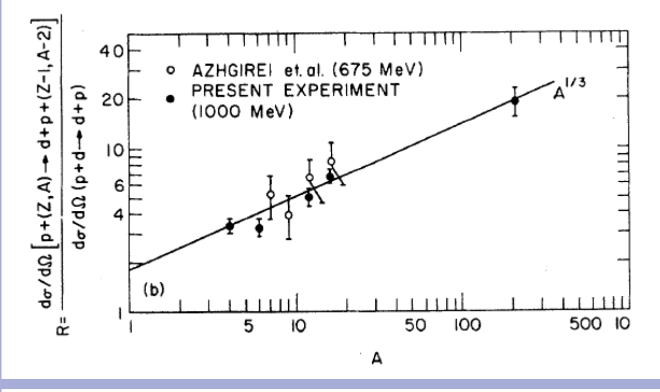
- Width of the peaks provides information about the CM momentum distribution of interacting neutron-proton pair, inside nuclei.

- Confirmed by later, more detailed, measurements of Sutter *et al.*

- Differential cross sections proportional to $A^{1/3}$ indicated only deuterons from the nuclear surface are observed.



Deuteron momentum distribution
[Azhgirei *et al* JETP 6 (1958) 911]



Mass dependence of A(p,d) differential cross section
[Sutter *et al* [PRL 19 (1967)1189]

$^{16}O(p,pd)^{14}N$ reactions at RCNP using 392MeV proton beam
-See details in Phys. Rev. Lett. **121**, 242501 (2018)
- Explicit identification of spin and isospin of NN correlated system

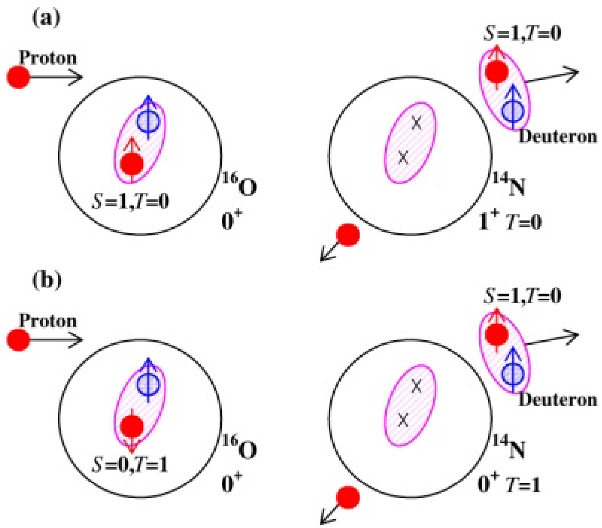


Fig from RCNP group

Figure: The pickup mechanism of a neutron dominates when a scattered deuteron is observed at small angles

- 2 channels: $S, T = 1, 0$ and $S, T = 0, 1$
- the reaction occurs with a $S, T = 1, 0$ pair $\rightarrow$ the final state of the residue: $T = 0$

Hadron Correlations and the EMC Effect

[Smookler *et al* Nature 566 (2019) 354, CLAS]

- ◆ Neutrons and protons are composite objects
- ◆ Deep Inelastic Scattering (DIS) probes internal quark structure
- ◆ DIS cross sections are significantly altered in heavy nuclei than in light nuclei
- ◆ The quark distributions are affected by the nuclear environment (EMC effect)

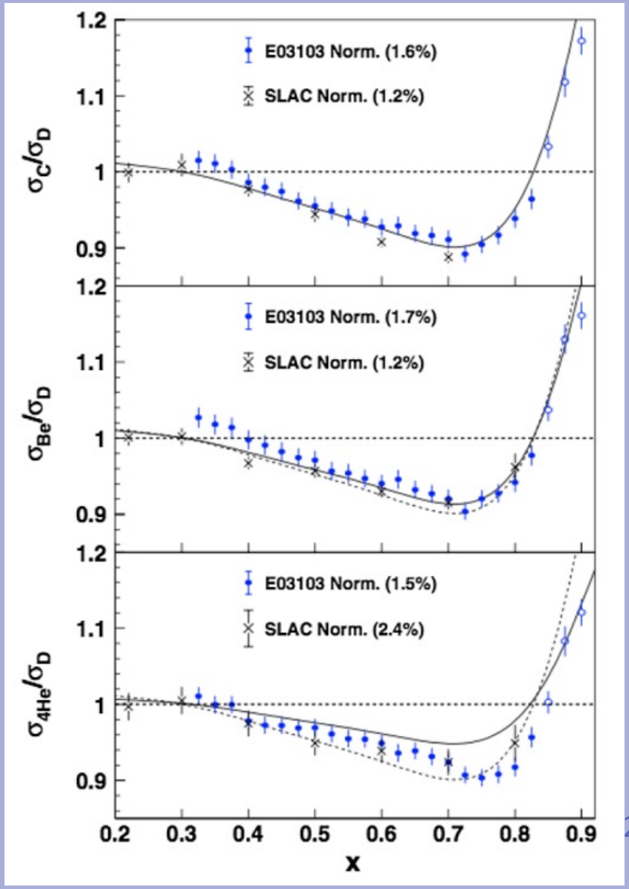
◆ SRC formation inside nuclei would result into

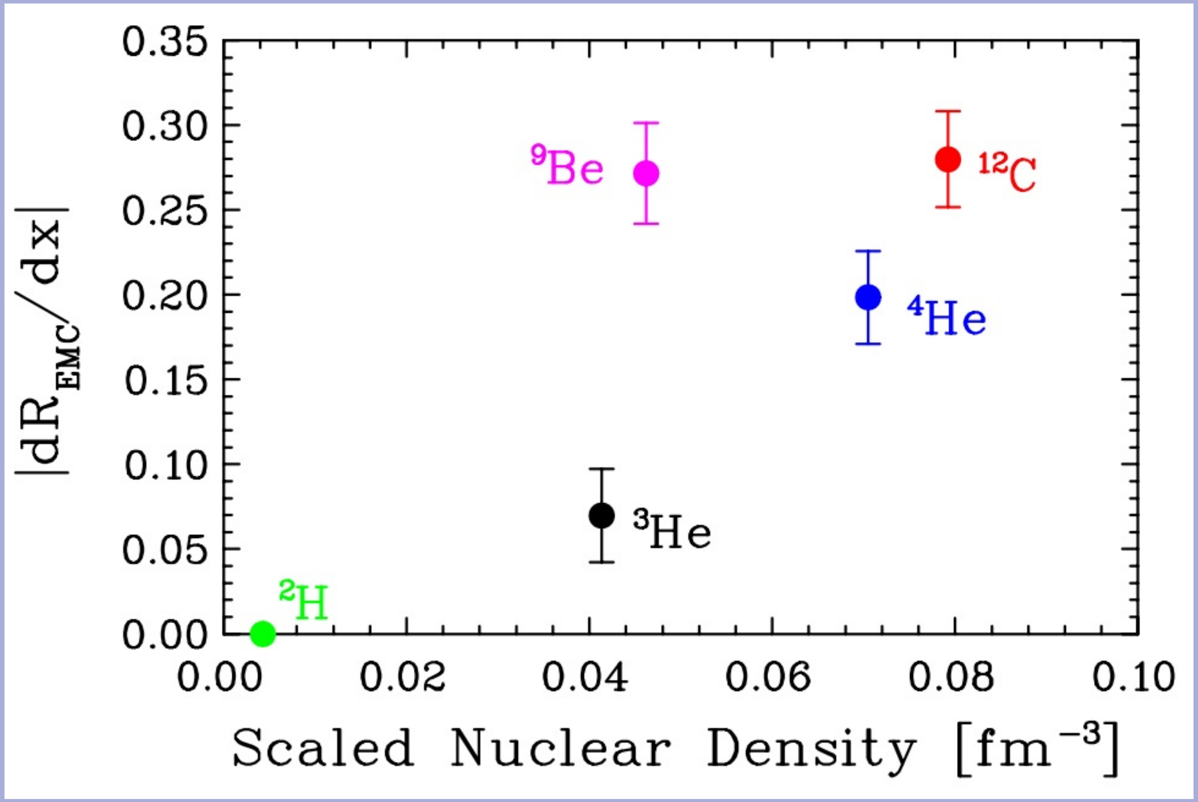
◆ Enhanced high momentum components of nucleons

◆ Significant overlap of nucleonic wavefunction => additional quark interaction of participating nucleons

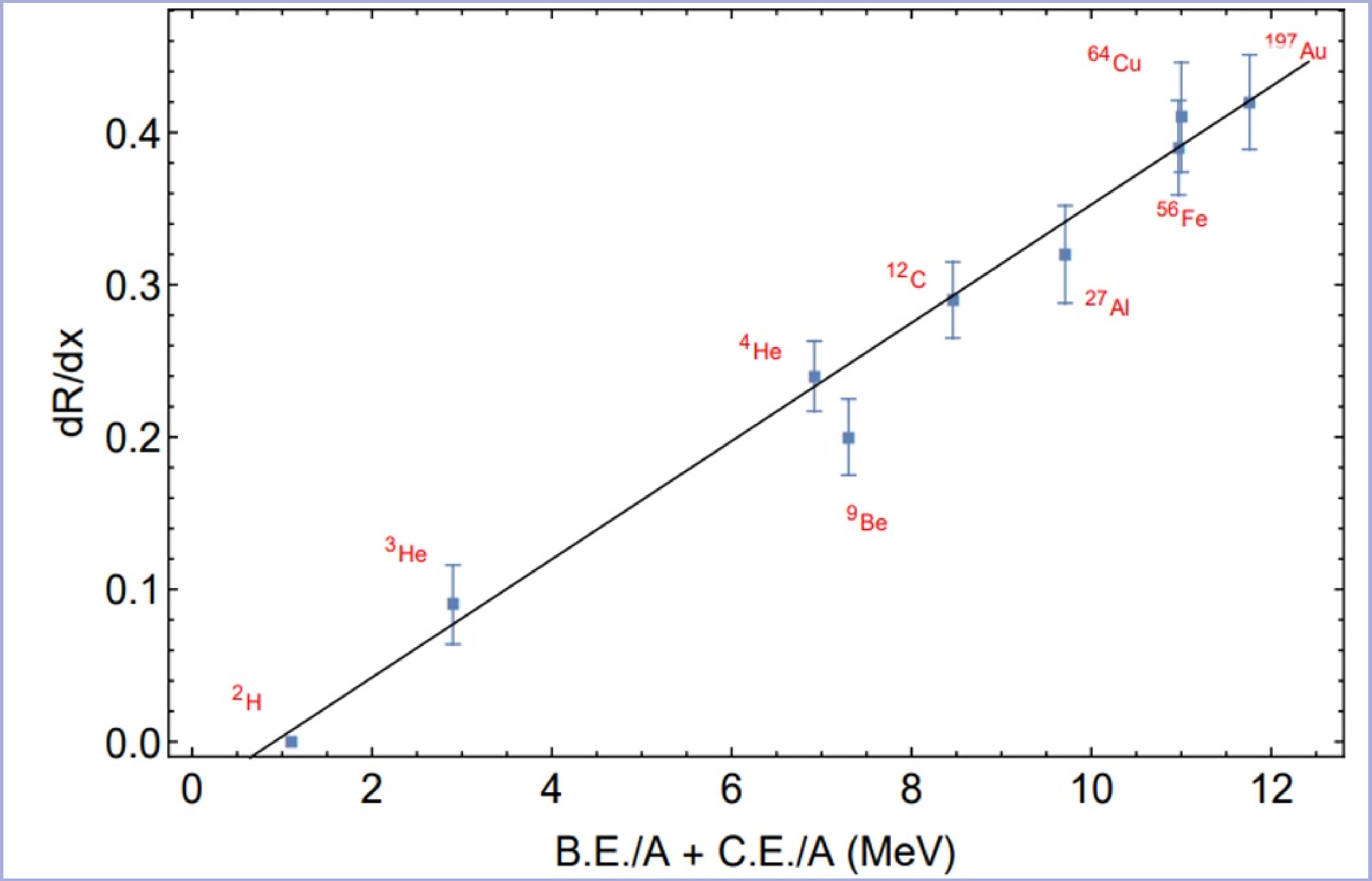
◆Could SRC affect the internal structure of nucleons?

Measure DIS and quasi-elastic cross sections simultaneously at EIC





Initially, EMC effect was expected to scale with nuclear density
- ^{9}Be measurement did not fit the scaling



More Interaction => More Nuclear B.E. (BE + Coulomb Energy)
More NN interaction => Higher EMC effect

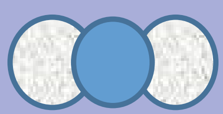
3N Correlations

Plenty of literature and expectations for 3N SRCs but no tangible experimental detection

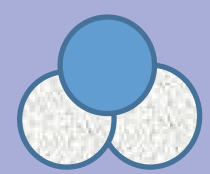
- Recent review by Donal B. Day , Leonid L. Frankfurt , Misak M. Sargsian and Mark I. Strikman, Towards observation of three-nucleon short-range correlations in high Q2 A(e, e0)X reactions, arXiv:1803.07629v2)

We need fresh ideas!

There are two distinct possibilities for 3N (npn or pnp) Structures



or



Collinearly or near collinear

Triangle shaped 3N Structures

Collinear shaped 3N structures would be preferred compared to Triangle shaped 3N structures sin

- n-p SRCs are much more prominent compared to pp and nn SRC
- Stronger interaction between opposite kind of nucleons, possibly, role of opposite surface charge densities on n & p, Pauli’s principle
    - In triangle shaped (or near triangle shaped) npn (or pnp) SRC, we would have significant overlap of 2n (2p) wavefunctions

Simplest 3N Structures

^{3}H and ^{3}He systems can pose as simplest 3N structures.
^{3}H and ^{3}He do not have any excited states! (just like deuteron!)

For ^{3}H, assuming simplest case of all 3-nucleons in s-state, we have equal probability for singlet a
between n and p.

Almost equal probability for break up of singlet and triplet n-p bond through photonic interactio

- Singlet bond break up would lead to n + np (np in triplet state, or deuteron) final state
  => (⍰, nd) reactions – two body disintegration
- Triplet bond break up would lead to n + np (np in singlet state which is unbound)
  => (⍰, npn) reaction or three body disintegration

Hence, we expect almost equal probability for (⍰, nd) &(⍰, npn) reactions for ^{3}H target
- Confirmed by measurements too.

In fact, the deuteron photodisintegration relations can be used to calculate the $\sigma(\gamma, nd)$&$\sigma(\gamma, n$
appropriate separation energy, reduced mass and effective range to reproduce experimental cro

- Similar is the case for ^{3}He (ignoring small Coulomb effect in ^{3}He)

Where to Look for 3N Structure?

Do not look 3N structure inside N=Z nuclei

- In N=Z nuclei, neutrons and protons are in similar states, leading to strong interaction between n & p
- 3N structure formation would be highly supressed

Look in N>Z nuclei for npn 3N structure

- Extra neutrons would interact with pre-existing np structures resulting into quasi-tritium structures

Look in Z>N nuclei for pnp 3N structure

- Extra protons would interact with pre-existing np structures resulting into quasi-^{3}He structures

There could be several possible ways for detecting/confirming the presence of 3N structures inside nuclei!

Summary and Conclusions

◆ NN correlations are an essential ingredient in our understanding of the structure of nuclei

◆ A huge variety of different nuclear reactions provide remarkably consistent evidence of their role and features (kindly, look into https://arxiv.org/abs/2210.06114 for details) => Very diverse implications

◆ np correlations are observed to be much stronger than pp or nn correlations

◆ Detailed nature of correlations at short range is complex and difficult to model, but of vital importance to fully understanding nuclear structure

◆ Two body breakup of 3N structures should be used to explore the 3N correlated structures inside nuclei

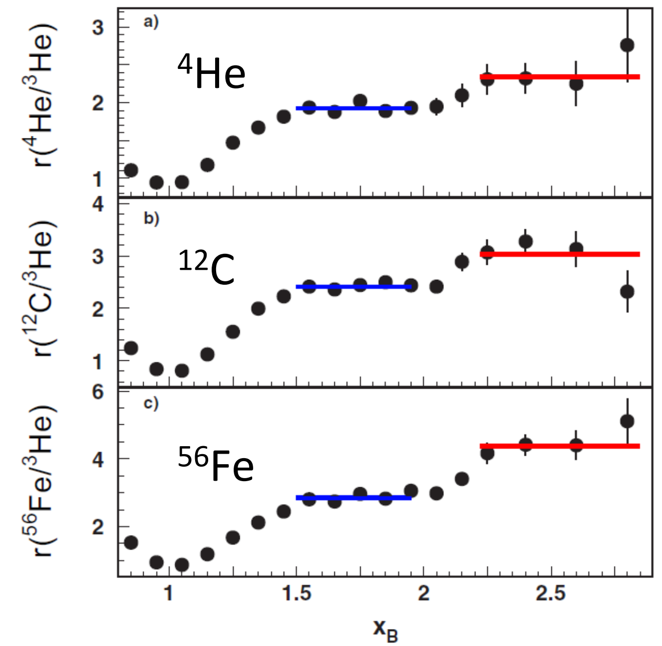
◆ There is huge scope for further detailed study of this subject

Acknowledgements

This review arose out of ongoing discussions between Prof. Douglas Macgregor and myself regarding synergies and similarities in studies of hadron correlations, using a wide variety of very different nuclear probes.


Thank you!!

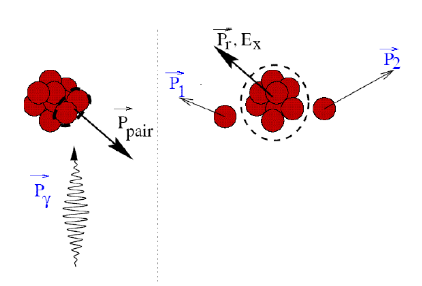
Inclusive (e,e') measurements (CLAS)



[Egiyan *et al* PRL 96 (2006) 082501]

- Ratios of cross sections plotted for $^4He/^3He$, $^{12}C/^3He$ and $^{56}Fe/^3He$
- In each cases plateaus are seen for $1.5 < x_B < 2.0$ and $2.3 < x_B < 2.6$, although statistics become poorer at high x_B
- The lower x_B region is an indication of the universality of 2N correlations and the higher x_B region is a signal of 3N correlations

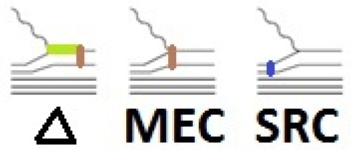
Photon-induced 2N-knockout reactions



◆ Direct emission occurs at low missing energy where the photon interacts with a pair of nucleons and the remainder of nucleus is a spectator.

◆ At higher missing energies contributions from additional nucleons are possible through 2N+FSI and 3N forces

◆ The direct emission process includes several mechanisms e.g. Δ-excitation, MEC, SRC, etc.



2N Mechanisms

◆ Experimentally these processes can't be distinguished. Rather, selection of kinematics is used to enhance contribution of particular processes, which are then compared with models.

◆ One simple model is the Valencia Model (VM) [Carrasco *et al.* NPA 570 (1994) 701]. This simplifies the nuclear many-body problem using a Fermi-gas model and a local density approximation. It incorporates all of the expected major mechanisms and calculates FSI, treating propagation of produced particles semi-classically.