Short range nucleon correlations studied with electron and photon probes

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Short range nucleon correlations studied with electron and photon probes

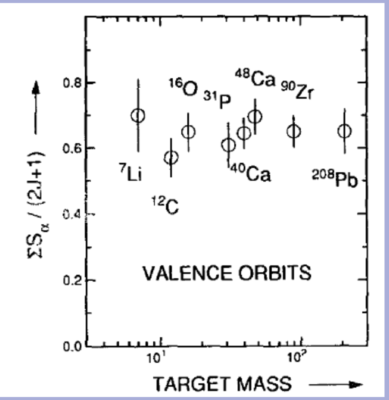
- Introduction: Why short range correlations are important
- Low energy (γ,pN) experiments at Mainz
- High energy (e,e') experiments at Jefferson Lab
- Exclusive 3-nucleon knockout experiments
- Summary and conclusions

This talk will give a selective overview of investigations of few-body nucleon interactions using electromagnetic probes, with an emphasis on experiments carried out at Mainz and Jefferson Lab in the A2, CLAS and CLAS12 collaborations.

SRC and electromagnetic interactions

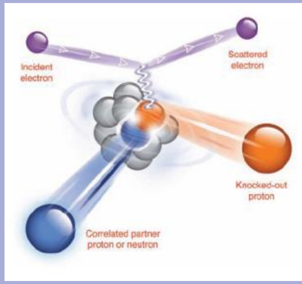
- 1N knockout reactions

⇒ missing single particle strength observed in (e,e'p) reactions
⇒ Attributed to 2N correlations



Missing Spectroscopic Strength, Lapikas, NPA 553 (1993) 297c)

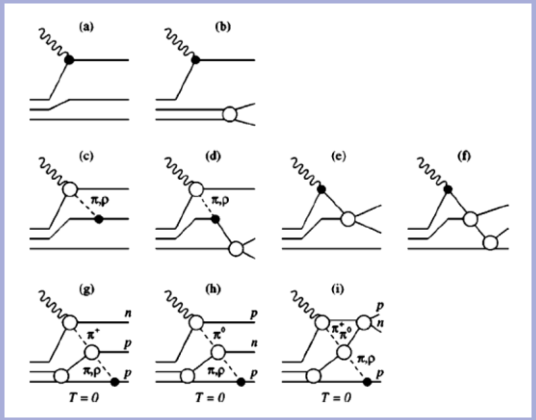
⇒ Investigate with 2N knockout reactions
⇒ Residual nucleus is spectator
⇒ Look for strength at high p_m, corresponding to short NN separations



2N knockout reactions, Subedi et al, Science 1476 (2008) 8

⇒ 3N correlations take this a stage further.
⇒ Energy and momentum given to three nucleons.
⇒ Expect effects at even higher p_m, higher excitation energies and even shorter distances
⇒ Expect magnitude of 3Neffects to be small (~10% 2N strength)
⇒ Enhance with kinematic selection
⇒ Information on nuclear physics at high nucleon densities (cold dense nuclear matter).

1N
2N
3N

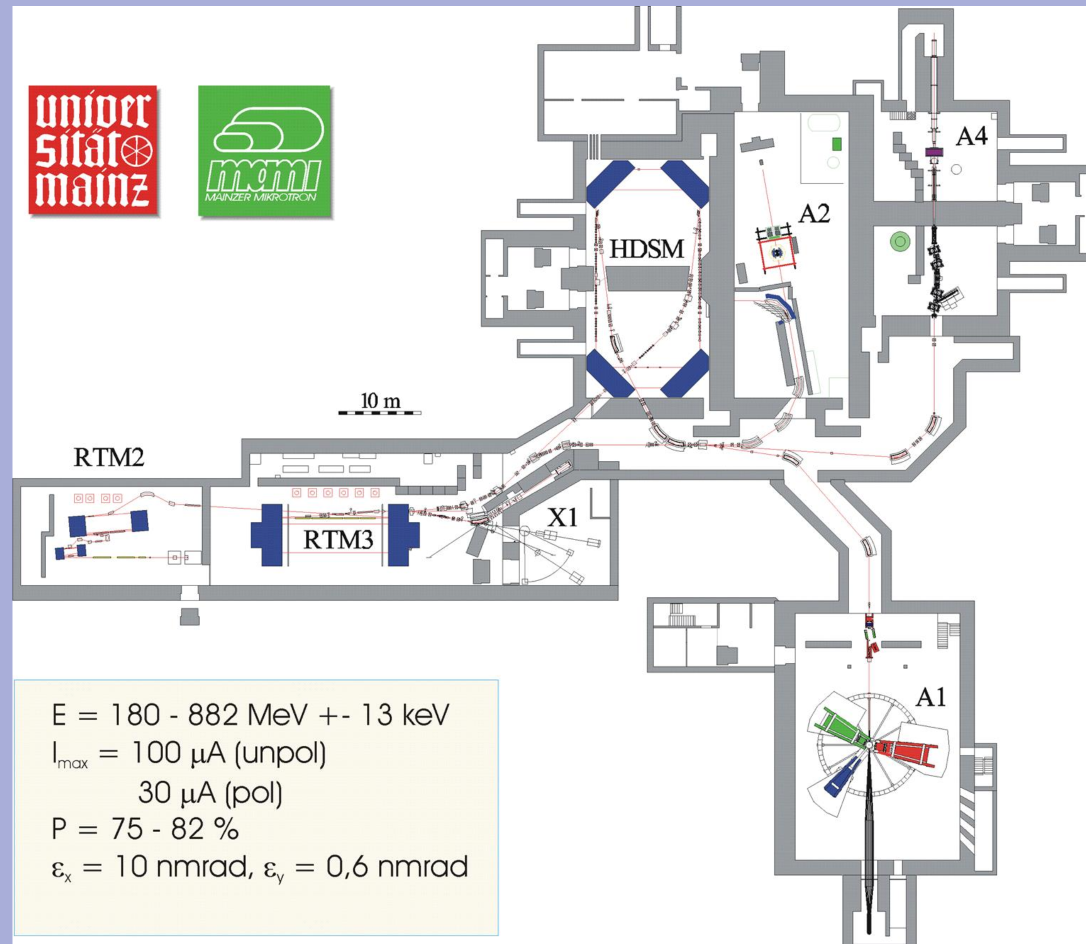


Laget calculations of 1N, 2N and 3N mechanisms, Niccolai et al, PRC 70 (2004) 064003

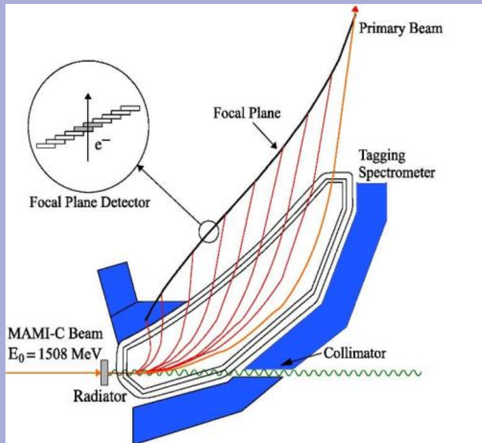
The MAMI Racetrack Microtron Facility at Mainz

A2 (Real Photon) Collaboration

RTM3



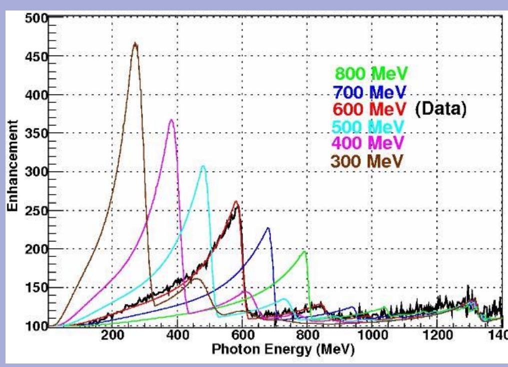
Glasgow Tagged Photon Spectrometer

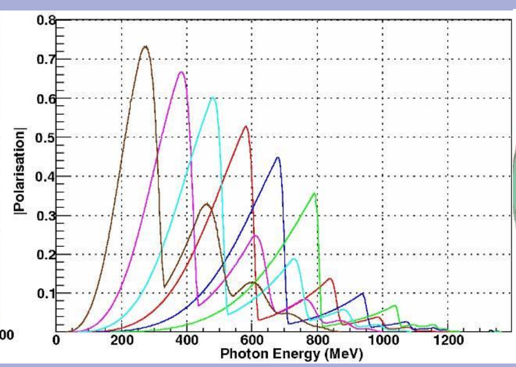


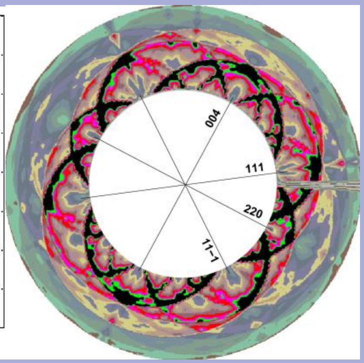
Glasgow Tagged Photon Spectrometer
I Anthony et al, NIM 301 (1991) 230

- Photon Energy: $E_\gamma = E_e - E_{e'}$
- Resolution: 2-4 MeV
- Circ. pol. γ from long. pol. e^- (up to 85%)
- Lin. pol. γ from diamond radiator (up to 70%)

Linear Photon Polarisation from Coherent Bremsstrahlung







Stonehenge crystal alignment technique, K Livingston, NIM A 603 (2009) 205

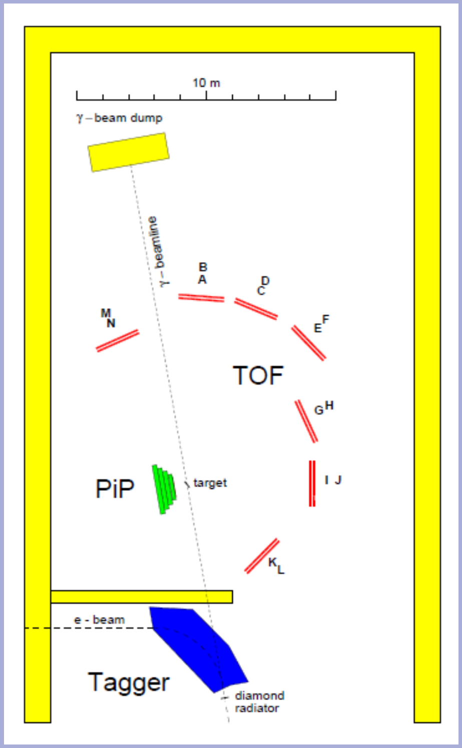
Yield Enhancement

Polarisation

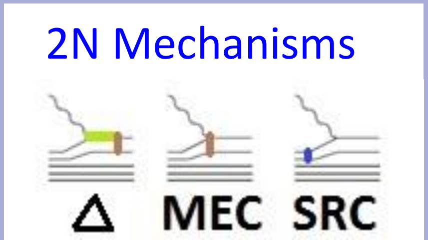
Photon-induced 2N-knockout reactions

At low E_m only 2 nucleons participate, but at higher missing energies contributions from 3N forces are possible.

$^{12}C(\gamma,pN)$ Reactions at Mainz



- There are many possible contributions to two nucleon knockout e.g. Δ excitation, MEC, 2N SRC, 3N SRC, FSI etc.



- Experimentally separate processes can't be distinguished.

Rather, selection of kinematics is used to enhance contribution of particular processes, prior to comparison with models.

- $^{12}C(\gamma,pN)$ **cross sections measured and compared** with predictions of the Valencia Model (VM) Carrasco et al, NPA 570 (1994) 701

- The VM 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.

Missing Energy spectra

Lamparter et al, ZPA 355 (1996) 1

- ◆At low E_γ $^{12}C(\gamma,pn)$ 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 $^{12}C(\gamma,pp)$ reaction is a factor of ~30 weaker than $^{12}C(\gamma,pn)$ at low E_m
- ◆It has no discernible peak at low E_m, but has a broader distribution, indicating stronger FSI

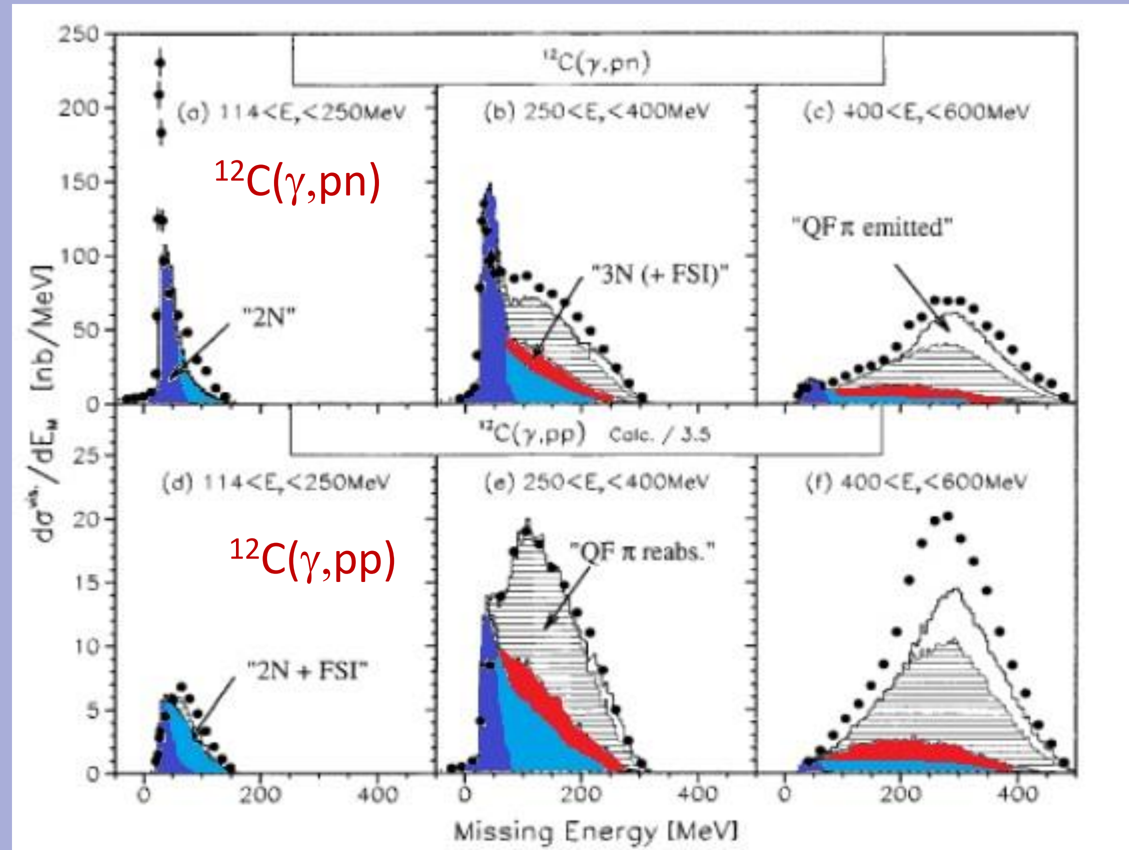
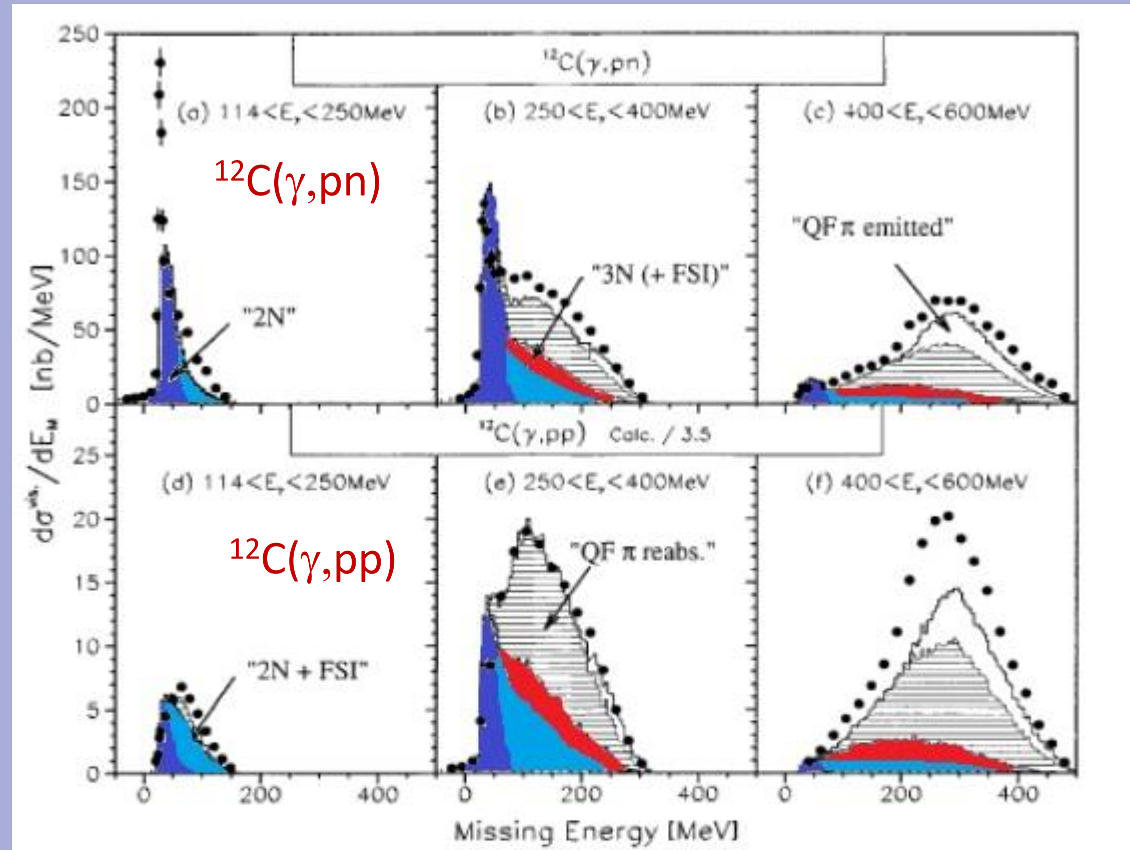


Table 1. Calculated mean multiplicities of nucleons emitted in pn/pp events

E_m/MeV	2N	2N + FSI	3N(+ FSI)	QFπ reabs.	QFπ emitted	Total
27 - 80	2.0/2.0	2.9/3.0	3.1/3.1	3.2/3.1	- / -	2.2/2.5
100 - 200	- / -	3.6/3.7	3.8/3.9	4.0/4.0	2.1/2.2	3.9/3.9
300 - 500	- / -	4.9/5.0	5.3/5.4	5.8/5.9	3.6/3.8	5.3/5.5
27 - 500	2.0/2.0	3.5/3.6	4.1/4.2	4.8/4.7	3.1/3.3	3.8/4.2

Interpretation

- ◆The $^{12}C(\gamma,pn)$ E_m spectra agree reasonably in shape and magnitude with the VM predictions
- ◆The VM calculations give the correct shape for the $^{12}C(\gamma,pp)$ E_m spectra but over-predict the strength by a factor 3.5
- ◆ 2N and 2N+FSI processes occur at low E_m
- ◆ 3N and 3N +FSI processes contribute to both channels at E_m>60 MeV and E_γ>250 MeV
- ◆ Relative contribution of 3N and 3N + FSI is similar in both channels



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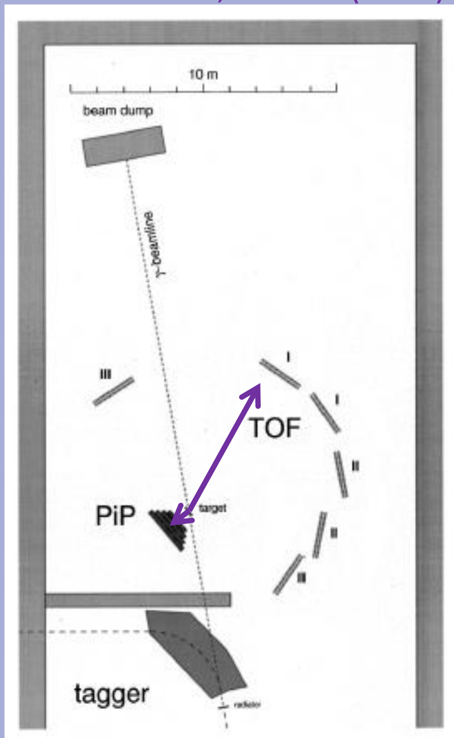
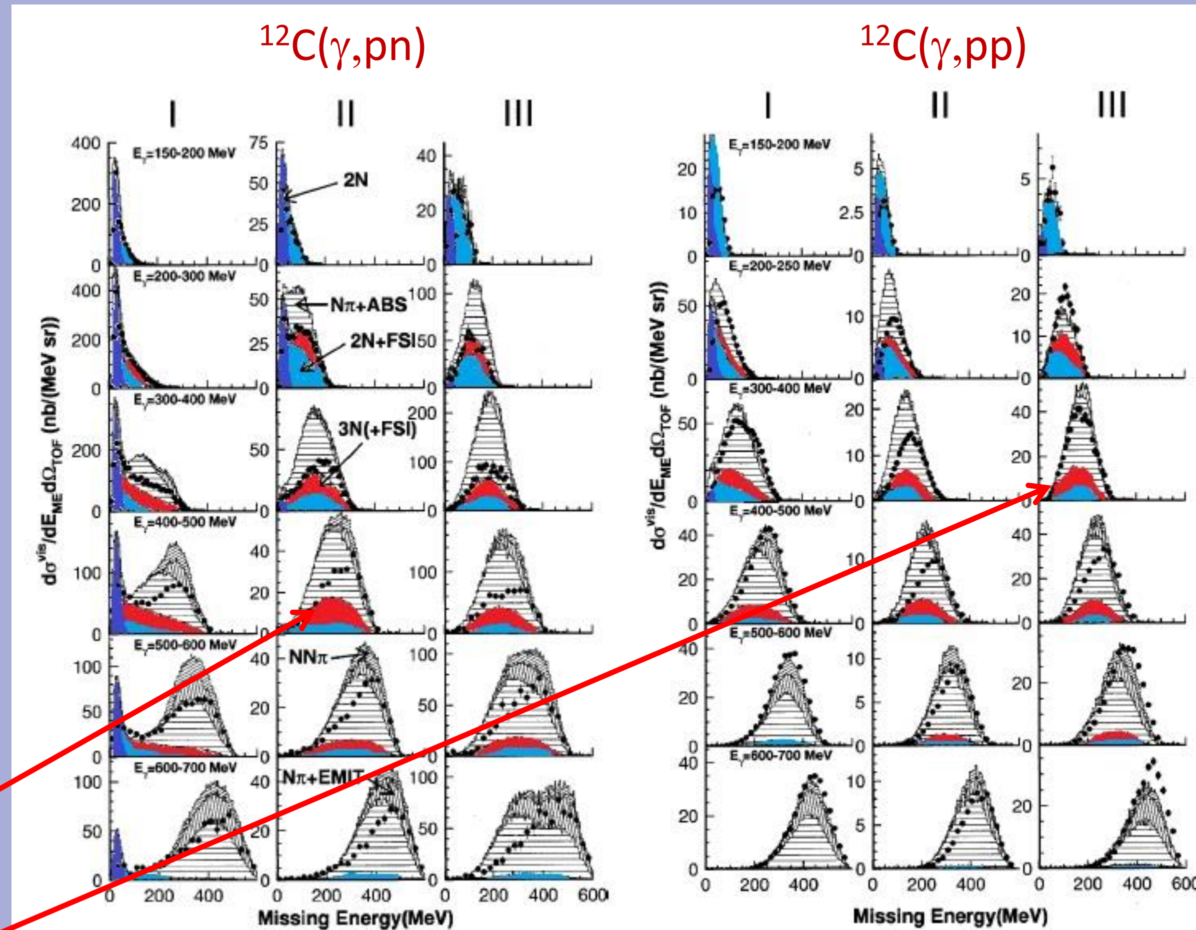
100 - 200	- / -	3.6/3.7	3.8/3.9	4.0/4.0	2.1/2.2	3.9/3.9
300 - 500	- / -	4.9/5.0	5.3/5.4	5.8/5.9	3.6/3.8	5.3/5.5
27 - 500	2.0/2.0	3.5/3.6	4.1/4.2	4.8/4.7	3.1/3.3	3.8/4.2

Variation of kinematics to enhance 3N contributions

Watts et al, PRC 62 (2000) 014616





Region I: back-to back, suppresses 2N FSI

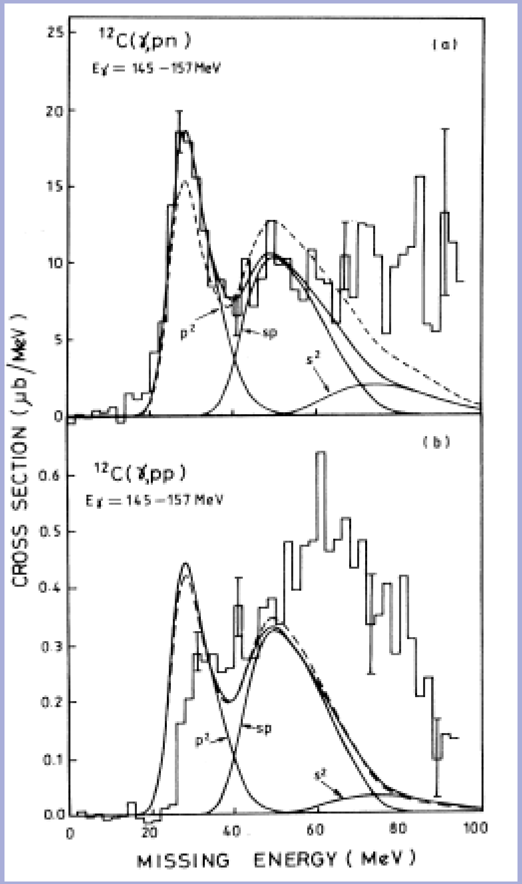
Region II: large opening angles, enhances 3N

Region III: extreme kinematics, both nucleons on same side of photon beam line, enhances 3N

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

McGeorge et al, PRC 51 (1995) 1967

- E_m spectra modelled by folding together two (e,e'p) spectra, together with 7 MeV detector resolution
- Gives a good account of shape of E_m spectra for $^{12}C(\gamma,pn)$
- Strength of $(1p)^2$ and (1p)(1s) emission determined from number of $(1p)^2$ and (1p)(1s) pairs
- $^{12}C(\gamma,pp)$ shape not so well reproduced, perhaps suggesting other processes, such as 2N+FSI are important
- For E_m < 40 MeV the $^{12}C(\gamma,pp)$ strength is <2% of the $^{12}C(\gamma,pn)$ cross section



Missing Momenta

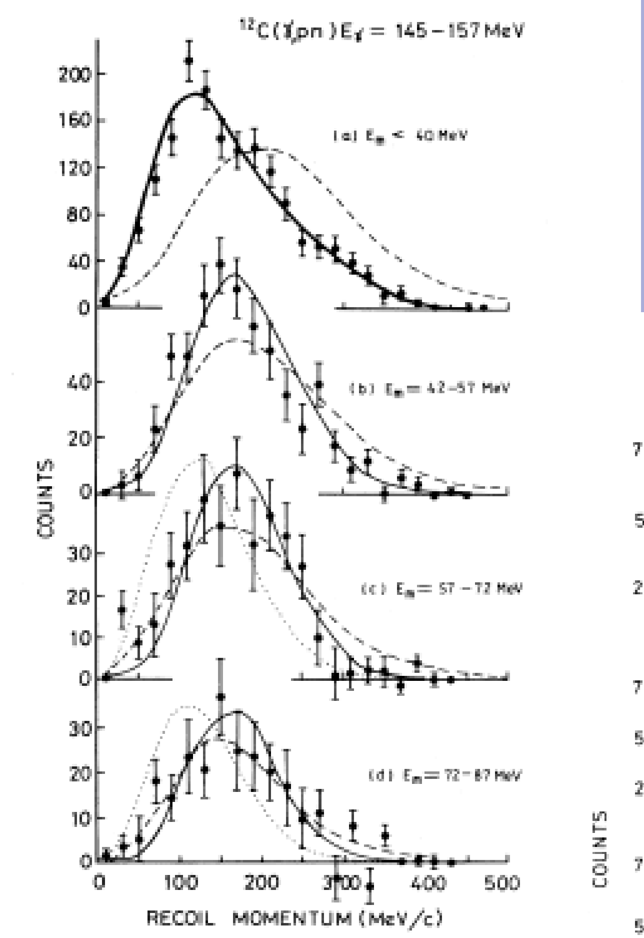
◆ The initial pair momentum:

$P_{pair} = -P_{\gamma} + P_{N1} + P_{N2}$

◆ For $^{12}C(\gamma,pn)$ spectrum shape agrees well with simple model folding momentum wavefunctions of two nucleons, for a range of E_m

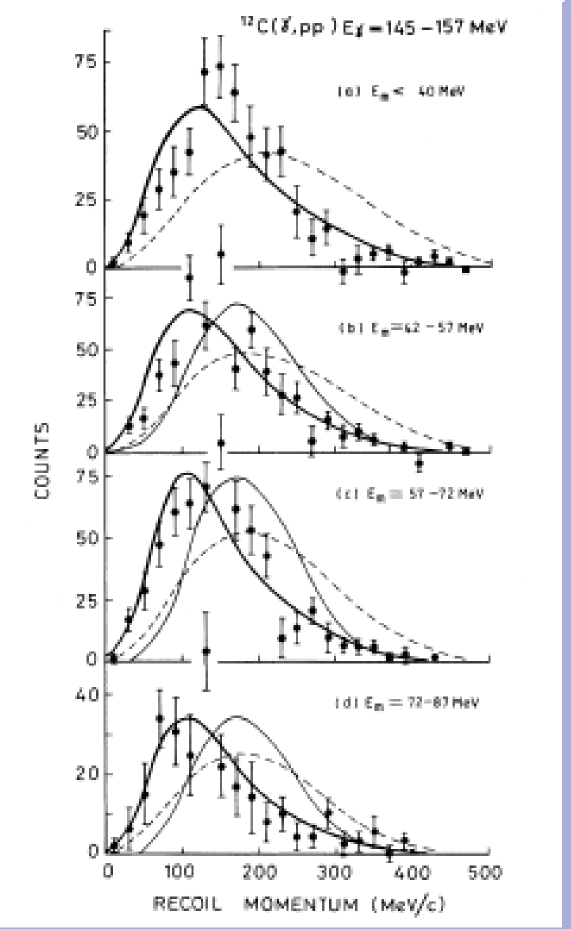
◆ For $^{12}C(\gamma,pp)$ shapes also agree

◆ Confirms both 2-nucleon knockout reactions are described by 2N and 2N+FSI processes



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

$^{12}C(\gamma,pp)$



Polarised Photons I

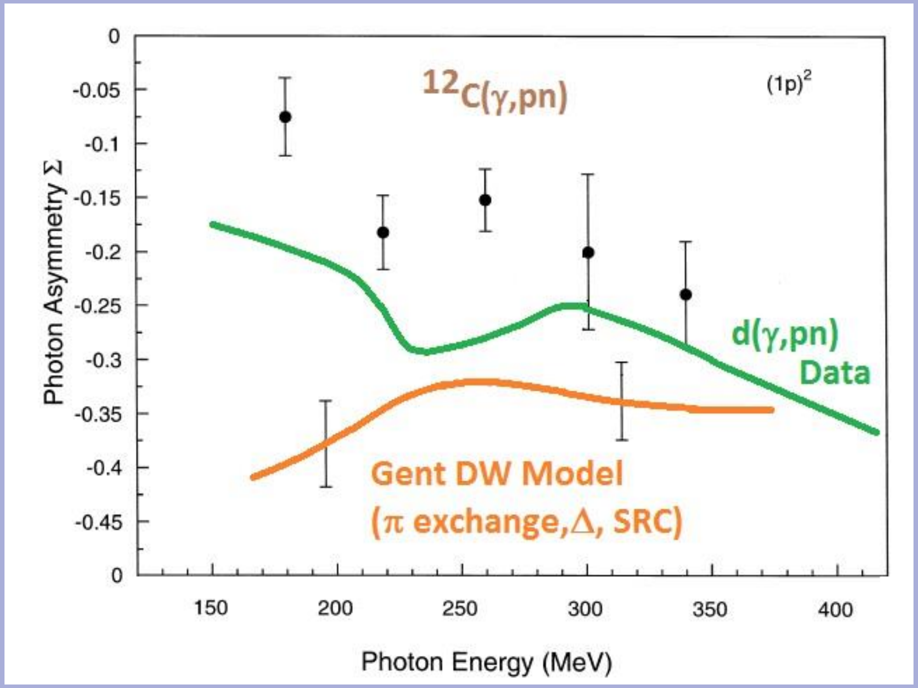
Franczuk et al, PLB 450 (1999) 332

- The photon asymmetry is defined by

$$\Sigma = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

where $\sigma_{\parallel}$ is the cross section parallel to the linearly polarised photon and $\sigma_{\perp}$ is the perpendicular cross section

- For $^{12}C(\gamma,pn)$ Σ for $E_m < 40$ MeV is negative, but not as strong as $d(\gamma,pn)$



- Comparison with a detailed Gent model, including π-meson in flight, π-seagull, Δ terms and SRC, averaged over our detector acceptance, is a poor fit to the data.

- Theoretical approximations limit these calculations to photon energies of a few hundred MeV

- There is a need for improved calculations, before detailed information on the strength of each contributing mechanism can be extracted.

Polarised Photons II

Powrie et al, PRC 64 (2001) 034602

- The photon asymmetry is defined by

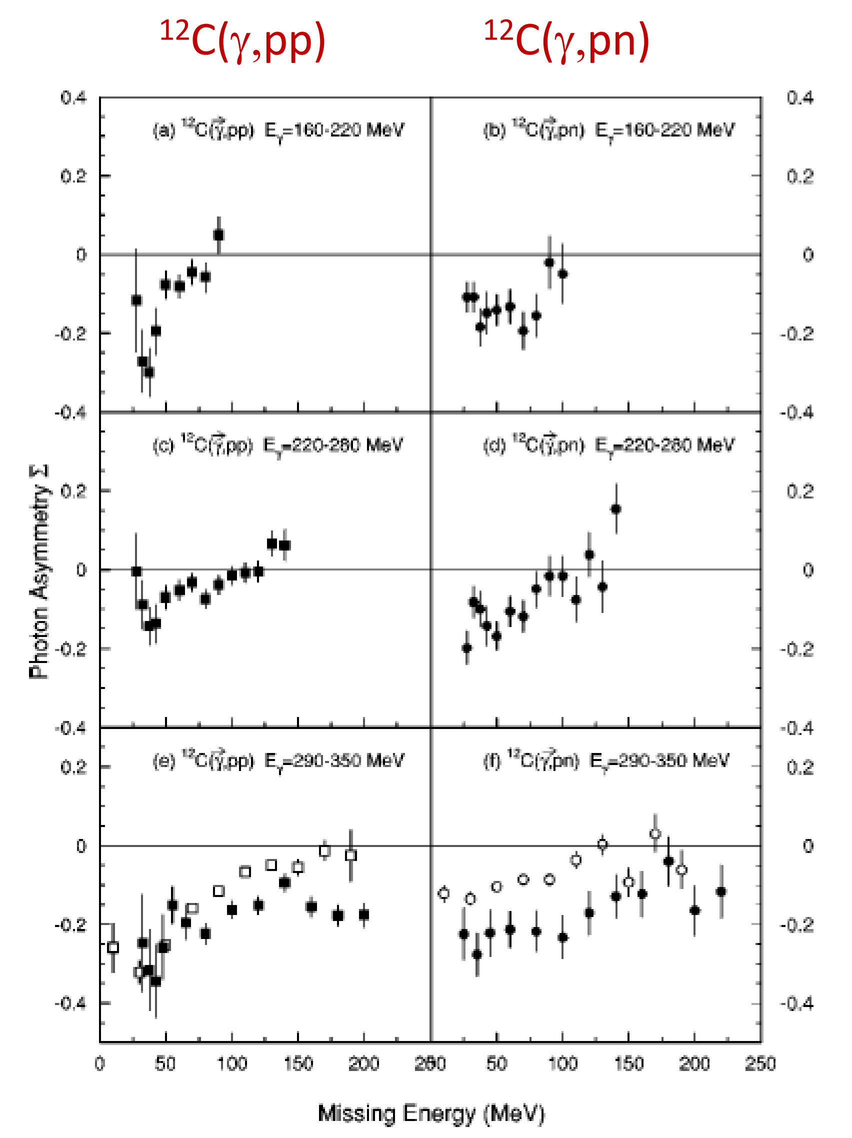
$$\Sigma = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

where $\sigma_{\parallel}$ is the cross section parallel to the linearly polarised photon and $\sigma_{\perp}$ is the perpendicular cross section

- For $^{12}C(\gamma,pp)$ Σ shows a strong signal at low E_m

- This is stronger than for $^{12}C(\gamma,pn)$ indicating a distinct 2N process (FSI will reduce $|\Sigma|$)

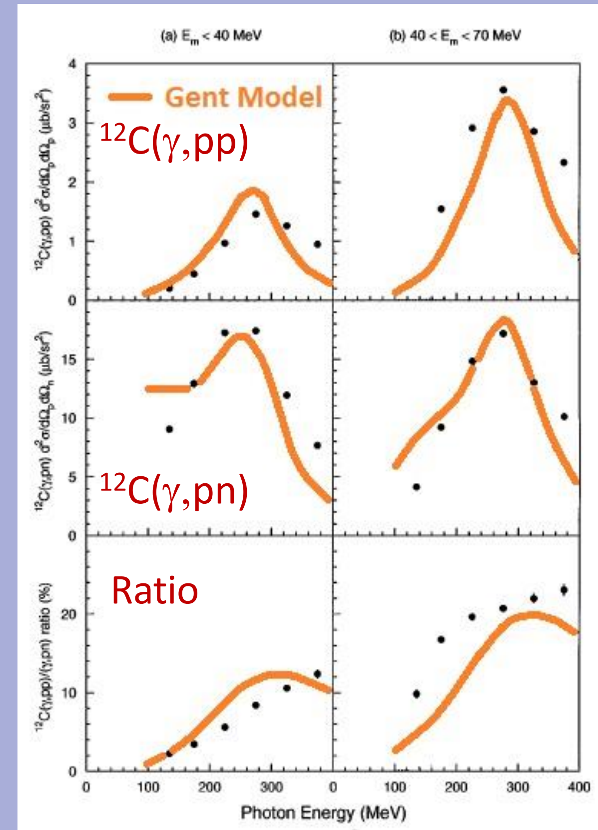
- Confirms both 2-nucleon knockout reactions are described by 2N and 2N+FSI processes

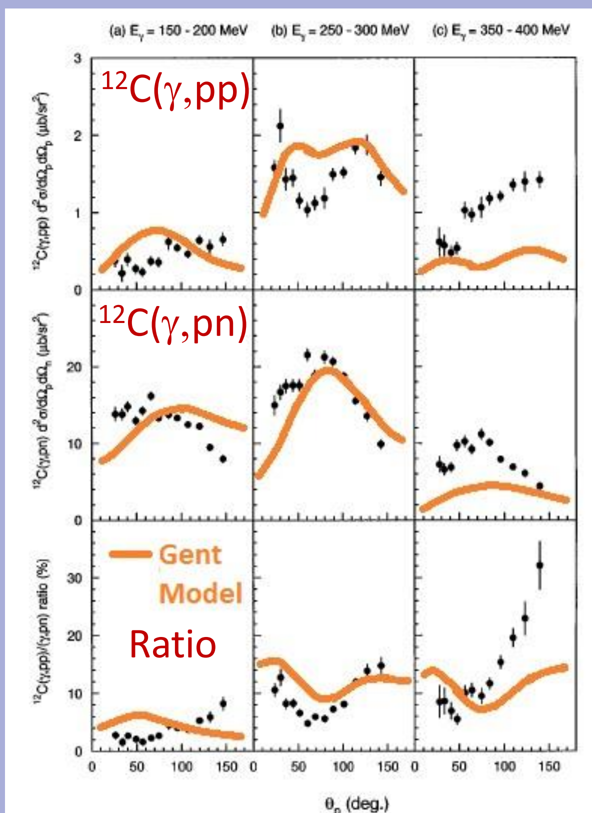


Further studies of 2-nucleon knockout

MacGregor et al, PRL 80 (1998) 245

- Further studies of
  - i) the E_γ dependence of the 2N cross section
  - ii) The $^{12}C(\gamma,pp)$ to $^{12}C(\gamma,pn)$ ratio
  - iii) The differential cross section





- Both $^{12}C(\gamma,pp)$ to $^{12}C(\gamma,pn)$ cross sections peak in the Δ-resonance region
- The $^{12}C(\gamma,pp)$ / $^{12}C(\gamma,pn)$ ratio increases strongly with photon energy
- The angular distributions of both channels are very different and do not agree with Gent Model

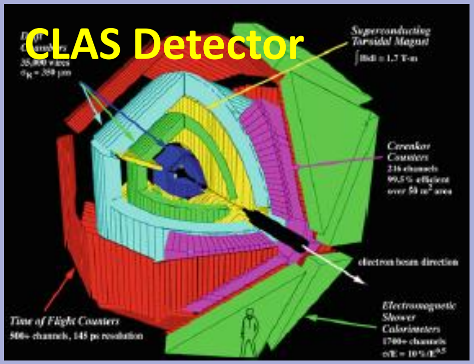
Summary of low energy (γ,pN) reactions

- Both $^{12}C(\gamma,pn)$ and (γ,pp) reactions show clear evidence of 2N and 2N +FSI photon absorption at low E_m. (Similar results seen in other light nuclei: ^{4}He, ^{6}Li, ^{16}O)
- Clean reaction with the rest of the nucleus acting as a spectator
- There is evidence of a strong Δ-excitation mechanism
- Comparison of angular distributions with models indicates significant MEC in (γ,pn)
- The strength of the (γ,pp) reaction is very much less than (γ,pn) and varies with photon energy, emission angle and missing energy
- Note that (γ,pp) has fewer MEC channels available and has no Tensor contribution
- The mechanisms have a strong angular variation, which differs between (γ,pn) and (γ,pp)
- The reactions have a strong photon asymmetry Σ ,which is stronger for (γ,pp) than (γ,pn)
- Exclusive (γ,pN) measurements require comparison with detailed calculations to identify specific contributions from SRC – Current comparisons are not sufficiently good enough for this

- 3N and other absorption processes occur at higher E_m

Inclusive (e,e') measurements (CLAS)

Egiyan et al, PRL 96 (2006) 082501



◆ Inclusive electron scattering at **high Q^2** and **high x_B** is able to transfer very high energies and momenta to the nucleus

◆ The cross section is sensitive to not just 2N but also 3N and higher correlations:

$$\sigma_A = A\,(a_1\sigma_1 + a_2\sigma_2/2 + a_3\sigma_3/3 + \dots)$$

◆ σ_j is the cross section for electron interaction with a j-nucleon correlation and a_j is the ratio of the probabilities for a given nucleon to belong to correlation j in nucleus A to correlation j in a nucleus of j nucleons

◆ It is expected that interaction with 2N SRC will dominate for $1< x_B <2$ and 3N SRC for $2< x_B <3$

◆ As cross sections drop rapidly with x_B, the **key** is *not* to look at the absolute cross sections, but to look at ratios for different nuclei, incorporating the elementary cross sections.

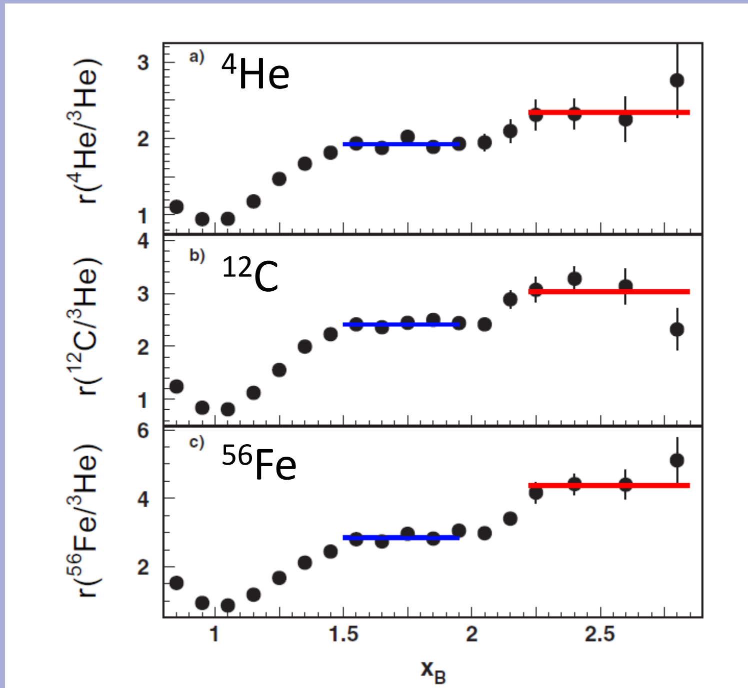


TABLE I. $a_j(A/^3\text{He})$ and $a_{jN}(A)$ ($j = 2, 3$) are the per nucleon relative (to ^{3}He) and absolute probabilities of (jN) SRC, respectively. Errors shown are statistical and systematic for a_j and are combined (but systematic dominated) for a_{jN}. The systematic uncertainties due to the Coulomb interaction and SRC c.m. motion are not included. For the ^{56}Fe/^{3}He ratio they are expected to be <2%–6% and <20%, respectively, and are somewhat smaller for ^{12}C/^{3}He and smaller still for ^{4}He/^{3}He ratios.

	$a_2(A/^3\text{He})$	$a_{2N}(A)$ (%)	$a_3(A/^3\text{He})$	$a_{3N}(A)$ (%)
^{3}He	1	8.0 ± 1.6	1	0.18 ± 0.06
^{4}He	1.93 ± 0.02 ± 0.14	15.4 ± 3.3	2.33 ± 0.12 ± 0.19	0.42 ± 0.14
^{12}C	2.41 ± 0.02 ± 0.17	19.3 ± 4.1	3.05 ± 0.14 ± 0.21	0.55 ± 0.17
^{56}Fe	2.83 ± 0.03 ± 0.18	22.7 ± 4.7	4.38 ± 0.19 ± 0.33	0.79 ± 0.25

Observed ratios

Per nucleon probabilities

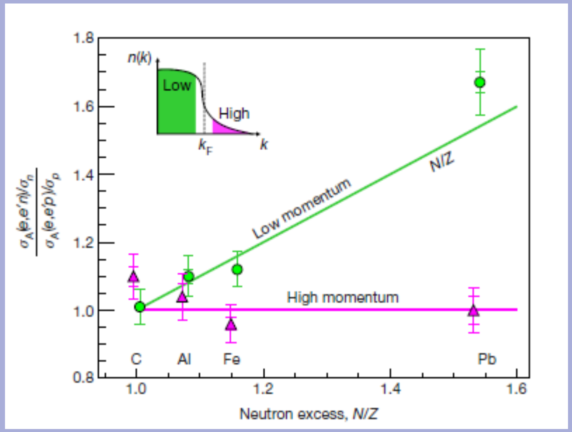
- Ratios of cross sections plotted for ^{4}He/^{3}He, ^{12}C/^{3}He and ^{56}Fe/^{3}He
- In each cases plateaus are seen for $1.5 < x_B < 2.0$ and $2.3 < x_B < 2.6$, although statistics become poorer at high x_B
- The lower x_B region is an indication of the universality of 2N correlations and the higher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

High Momentum Protons and Neutrons

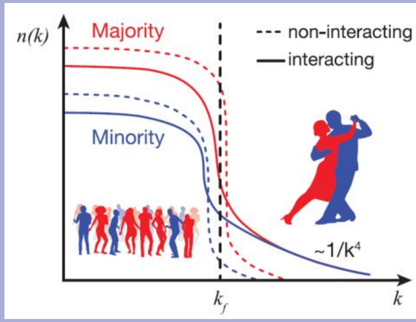
Hen et al, Science 436 (2014) 614, CLAS

Duer et al, Nature 560 (2018) 617, CLAS

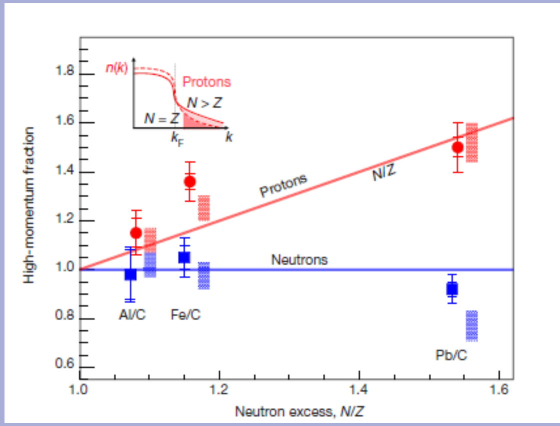
- SRC produce high momentum nucleons and the interaction between np pairs is stronger than between pp or nn pairs.
- How does this affect momentum distribution of protons and neutrons in heavy nuclei, such as Pb?
- Due to the neutron excess, on average each proton undegoes more SRC than the average neutron



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



- In a dancing 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 measured in CLAS data mining experiments



- In Pb there are fewer high momentum neutrons than high momentum protons

SRC possible connection to EMC?

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 larger in heavy nuclei than in light nuclei
- i.e. The distributions of quark properties is affected by the nuclear environment (EMC effect)

- SRC enhance the high momentum components of nucleons
- In particular, proton high momentum fraction is increased in in heavy nuclei
- Could SRC affect the internal structure of nucleons?

- Measure DIS and quasi-elastic cross sections simultaneously at CLAS

SRC possible connection to EMC?

Smookler et al, Nature 566 (2019) 354

- EMC effect is measured by slope of ratio of per nucleon F_2 structure function in nucleus A to F_2 in deuterium
- Write F_2^A in terms of interaction with uncorrelated protons and neutrons and with SRC pairs

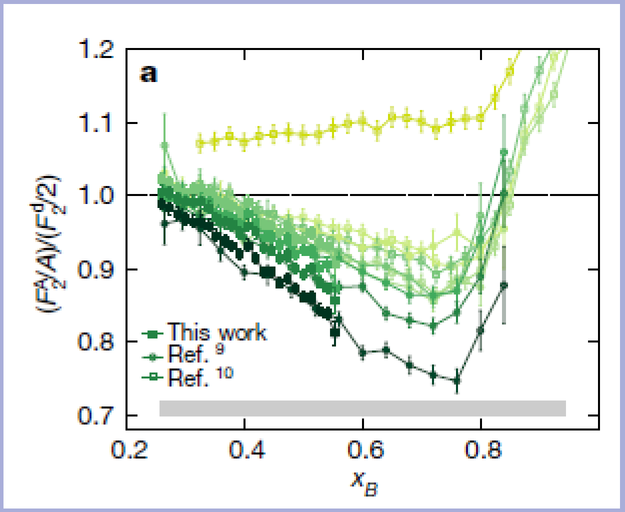
$$F_2^A = (Z - n_{SRC}^A) F_2^p + (N - n_{SRC}^A) F_2^n + n_{SRC}^A (F_2^{p*} + F_2^{n*})$$

- F_2^n is obtained from deuterium $F_2^d - F_2^p - n_{SRC}^d (\Delta F_2^p + \Delta F_2^n)$

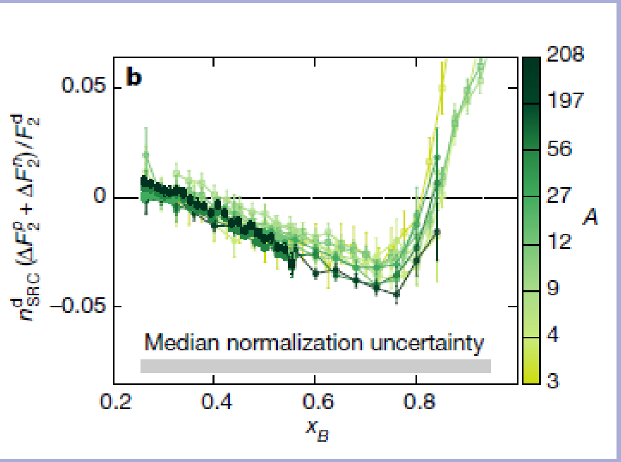
- This allows a nucleus-independent ratio to be extracted

$$\frac{n_{SRC}^d (\Delta F_2^p + \Delta F_2^n)}{F_2^d} = \frac{\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N}{(A/2)a_2 - N}$$

- The universality of the response strongly suggests a connection between SRC and the EMC effect in nuclei



EMC Effect: Uncorrected slope of $(F_2^A/A) / (F_2^D/2)$ for range of nuclei



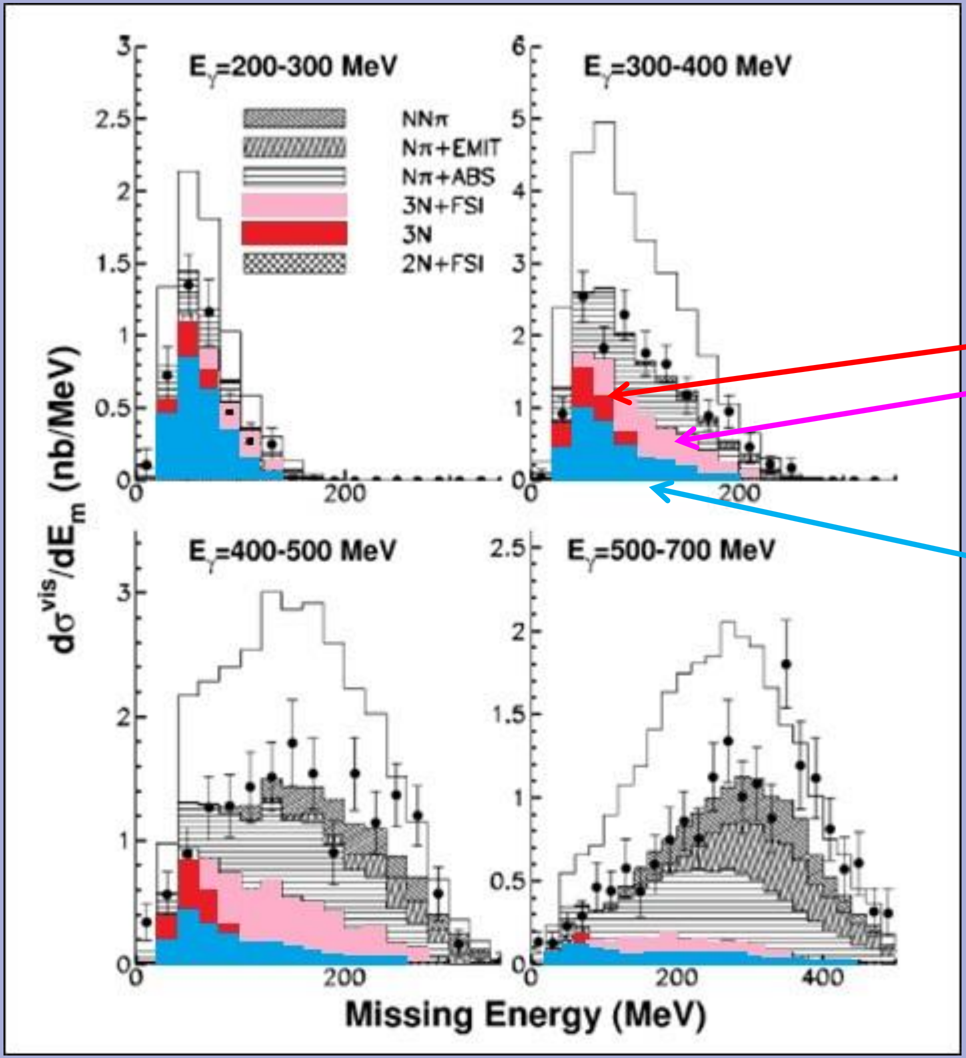
Universal ratio $n_{SRC}^d (\Delta F_2^p + \Delta F_2^n) / F_2^d$ for same range of nuclei

Summary of high energy (e,e') measurements

- Inclusive (e,e') experiments at high Q and high x_B transfer large quantities of energy and momentum to the nucleus
- Virtual photons are absorbed on single nucleons as well as correlated 2N pairs and 3N triples
- JLab data show strong evidence of 2N SRC and 3N SRC in both light and heavy nuclei
- Studies of the isospin dependence show that the neutron excess in heavy nuclei results in the protons having a larger high-momentum fraction than the neutrons
- Recent work has suggested a connection between SRC and the EMC effect

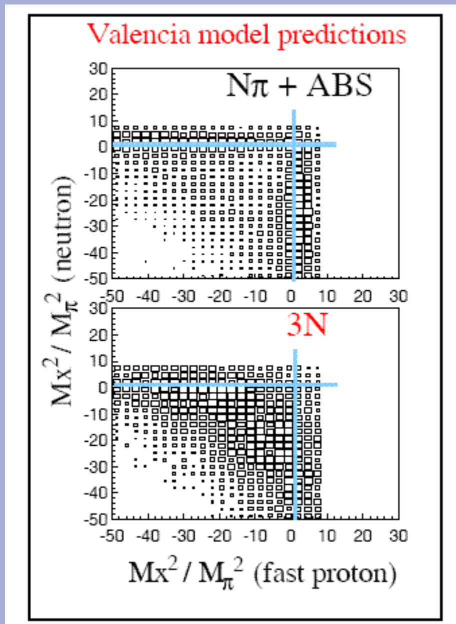
$^{12}C(\gamma,ppn)$ experiments at Mainz

Watts *et al.* PLB 553 (2003) 25

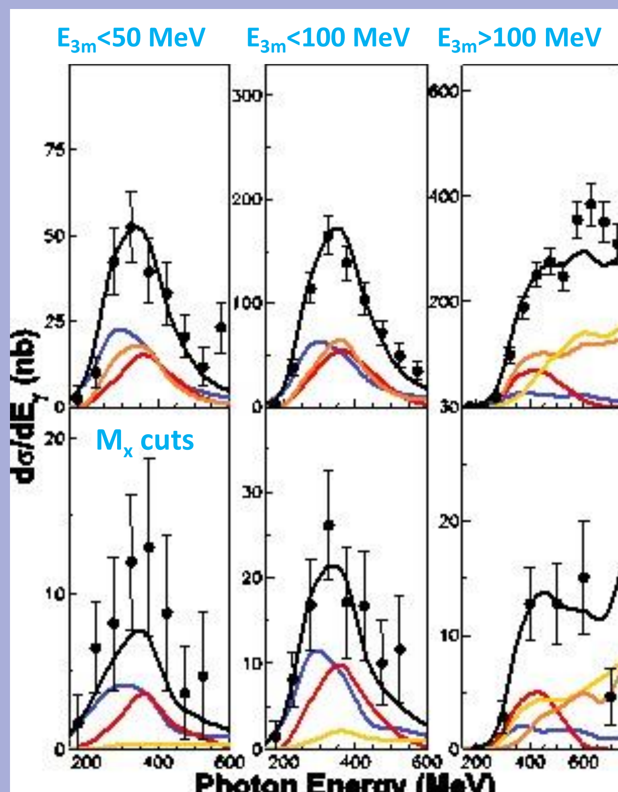


- ◆ 3-nucleon knockout is a natural reaction to investigate 3N forces
- ◆Use VM to identify the processes
- ◆ 3N and 3N+FSI are small part of cross section
- ◆There are also contributions from 2N+FSI, Nπ + πABS, etc
- ◆ 3N strength concentrated at low missing energy E_{3m} < 100 MeV
- ◆ 3N+FSI extends to higher E_{3m}

$^{12}C(\gamma,ppn)$ Kinematic selection to enhance 3N contribution



- Cut E_{3m} < 100 MeV enhances 3N (+FSI) contribution
- For γ+N -> N+X process, followed by absorption of X on two more nucleons, $M^2_X = (E_\gamma + m_N - E_N)^2 - (\mathbf{p}_\gamma - \mathbf{p}_N)^2$
- Cut on invariant mass $(M_x / M_\pi)^2 < -1.5$ to suppress Nπ + πABS
- Can find regions where 3N (+FSI) contributes ~40% of total strength.



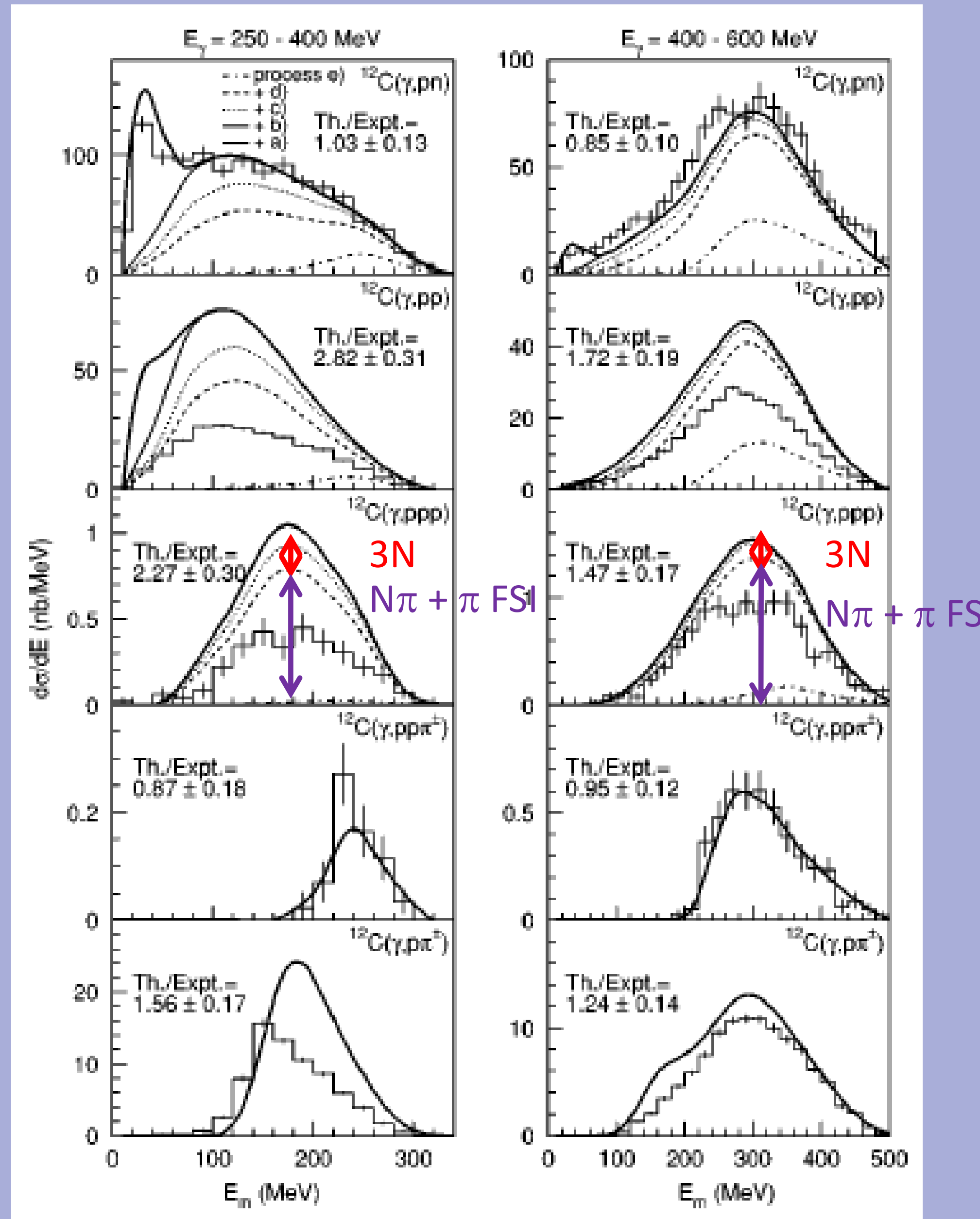
VM total
3N (+FSI)
2N (+FSI)
Nπ + π ABS (reduced)
Nπ = π EMIT

$^{12}C(\gamma,ppp)$ reaction

Harty et al, PRC 57 (1998) 123

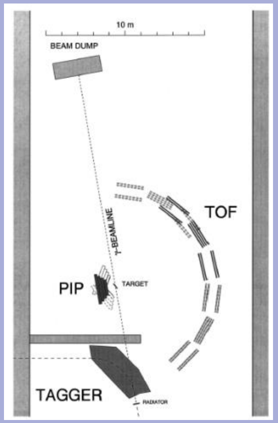
- Study of 3-nucleon final states in $^{12}C(\gamma,ppp)$ reaction
- E_m spectra to VM
- VM gets shapes right but not absolute magnitude
- 3N contribution is significant, but not the dominant process
- Pion production + reabsorption

$N\pi + \pi$ FSI is much larger



$^{12}C(\gamma,pd)$ Reaction at Mainz

McAllister et al, PRC 60 (1999) 0044610
Watts et al, PLB 647 (2007) 88



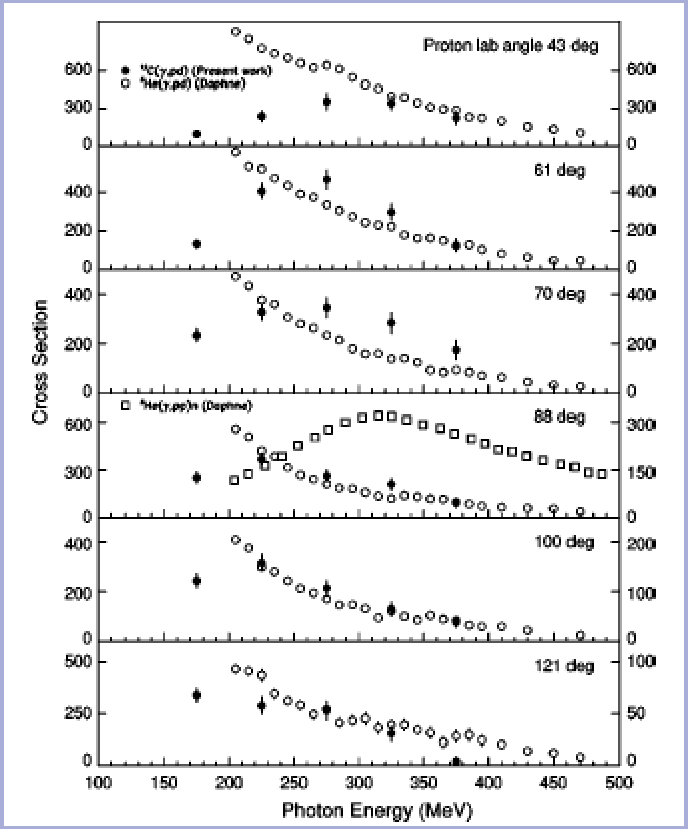
Reaction measured in back-to back kinematics in three settings covering forward, central and backward proton angles

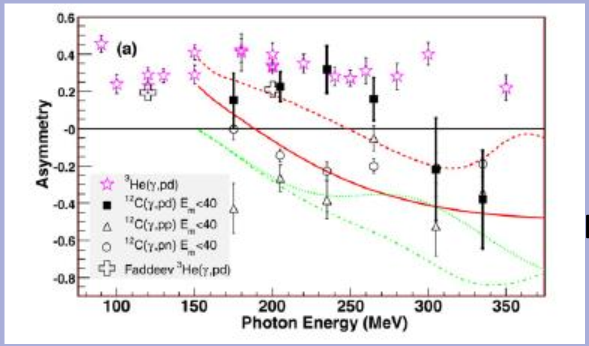
Comparison of $^{12}C(\gamma,pd)$ and $^{3}He(\gamma,pd)$

The photon energy dependence of the $^{12}C(\gamma,pd)$ cross section For $E_m < 44$ MeV is compared to that from $^{3}He(\gamma,pd)$

Above 300 MeV both have a similar shape with no influence from the Δ–resonance.

There are further similarities between both reactions when the photon asymmetry is considered.





Black squares: $^{12}C(\gamma,pd)$ for E_m<40 MeV
Pink stars: $^{3}He(\gamma,pd)$
Belyaev et al, JETP Lett. 40 (1984) 1275

Recoil momentum distributions

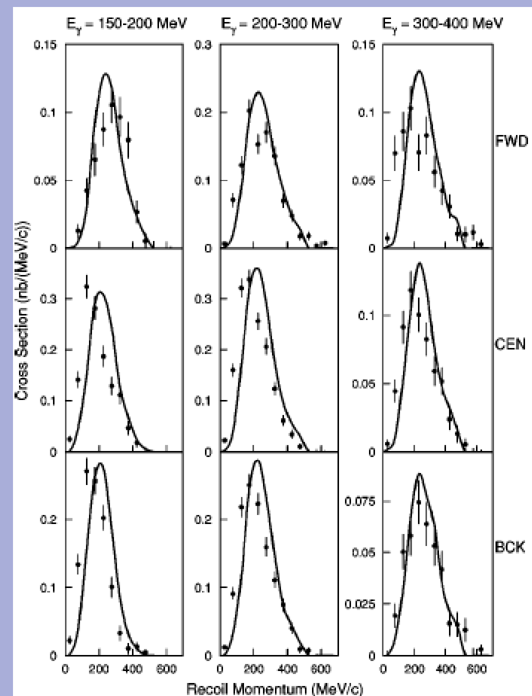
◆ Data are split into two E_m regions E_m<44 MeV and 44<E_m<70 MeV

◆ Distributions are compared with a 3 nucleon plus spectator model folding together 3 Elton-Swift nucleon wavefunctions in a relative S state.

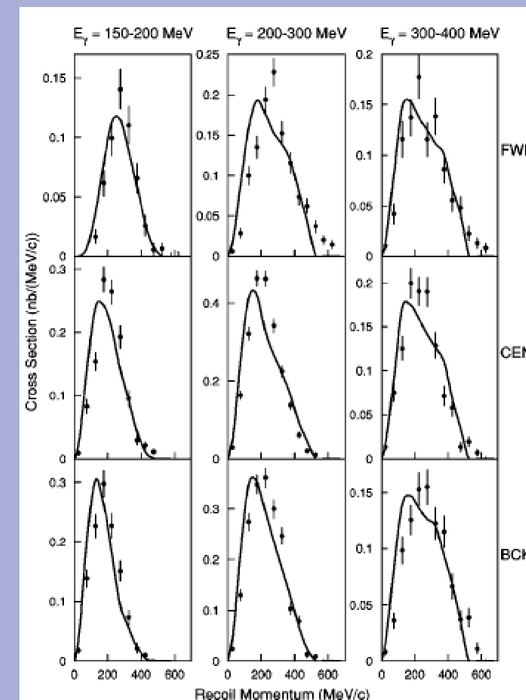
◆ Data agree surprisingly well with calculations and support interpretation of 3 active nucleons.

◆ However, this is <u>not</u> a theoretical calculation of 3N processes

E_m<44 MeV



44<E_m<70 MeV



Summary and Conclusions I

- Electromagnetically induced 2- and 3-nucleon knockout reactions have contributions from many processes, including 2N, 2N+FSI, 3N, and 3N+FSI
- 2N mechanisms occur at low E_m in both (γ,pn) and (γ,pp) reactions, with FSI extending strength to higher E_m
- 2N mechanisms include Δ-excitation, MEC as well as SRC
- Kinematic selection can enhance the 2N contribution, but cannot experimentally separate SRC from Δ-excitation and MEC
- Strength of each component can only be deduced by comparison with theoretical models
- State-of-the-art calculations are needed to compare with each experiment, but have to be filtered through the detector acceptances

Summary and Conclusions II

- ◆ 3N interactions tend to take place at somewhat shorter ranges than 2N processes due to the involvement of an additional nucleon
- ◆ 3N and 3N+FSI occur in (γ,pn) and (γ,pp) reactions at high E_m
- ◆ 3N processes also occur at low E_m in 3-nucleon knockout reactions
- ◆ Kinematic selection can be used in each reaction to enhance the relative 3N contribution
- ◆ However, 3N and 3N+FSI processes generally remain a small part of the cross section
- ◆ Estimating the strength of each component requires comparison with detailed theoretical models

Summary and Conclusions III

- Inclusive (e,e') experiments at high Q and high x_B transfer large quantities of energy and momentum to the nucleus
- Virtual photons are absorbed on single nucleons as well as correlated 2N pairs and 3N triples
- JLab data show strong evidence of 2N SRC and 3N SRC in a range of light and heavy nuclei
- Studies of the isospin dependence show that the neutron excess in heavy nuclei results in the protons having a larger high-momentum fraction than the neutrons
- Recent work has also suggested a connection between SRC and the EMC effect

Acknowledgements

◆ The work reported in this talk is the output of efforts made by many colleagues, past and present, over a large number of years

◆ I would particularly like to thank those physicists working in the

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