SHORT-RANGE CORRELATIONS

from

$^{12}C(p,2p + n)$ at BNL

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and the
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Memorial Workshop Oct. 2006

Experiment E850

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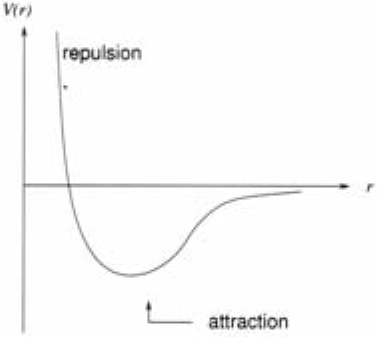
The N-N Interaction, the Shell Model and SRC



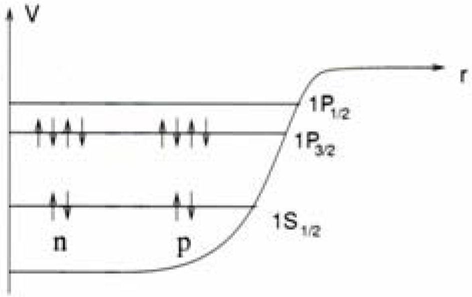
N–N interaction

Nuclear Shell Model (∼ 1950) { Maria Mayer, J.H.D. Jensen, Nobel Prize in 1963 }

The attractive part of the N-N interaction in combination with Pauli principle produces an average attractive potential with well defined quantum states.

^{12}C

(shell model picture)



Short-range repulsion → saturation of nuclear densities, etc.

However, the short-range repulsive part must also manifest itself in the wavefunctions of nucleons in the nucleus. Because it is short range, high-momentum components will be affected. Typically we might expect N-N interactions of short range to produce pairs of nucleons with large, ∼ equal, and opposite momenta.

Nuclear Fermi Momenta from Quasielastic Electron Scattering

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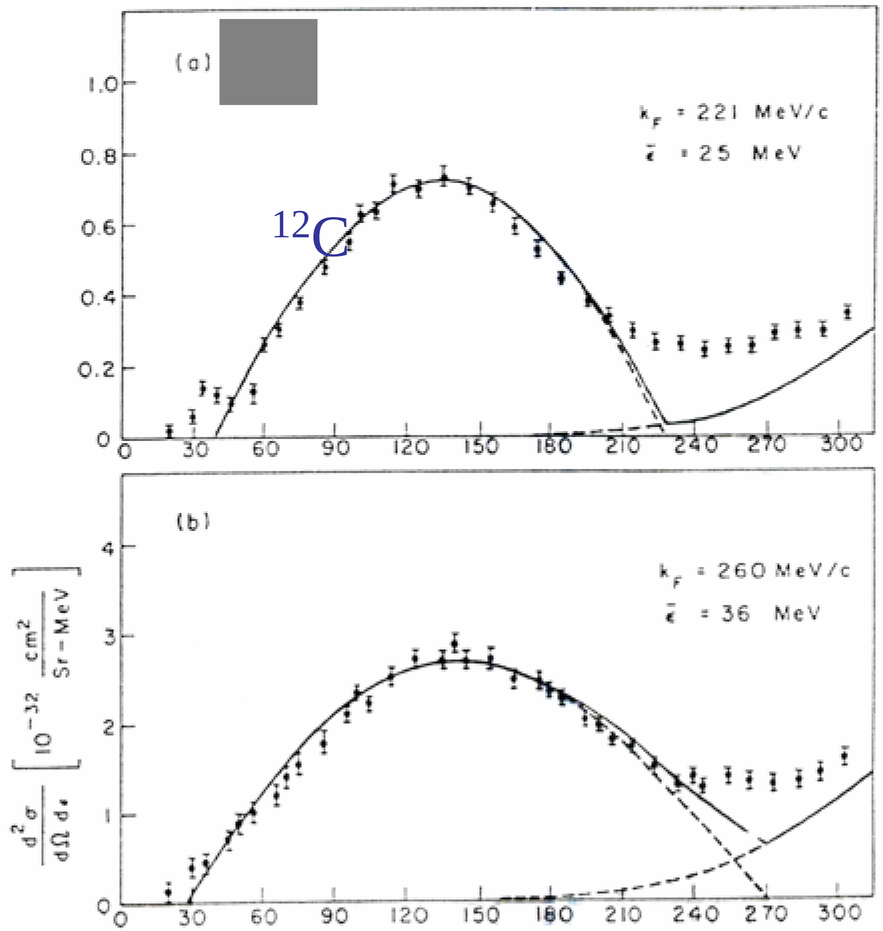
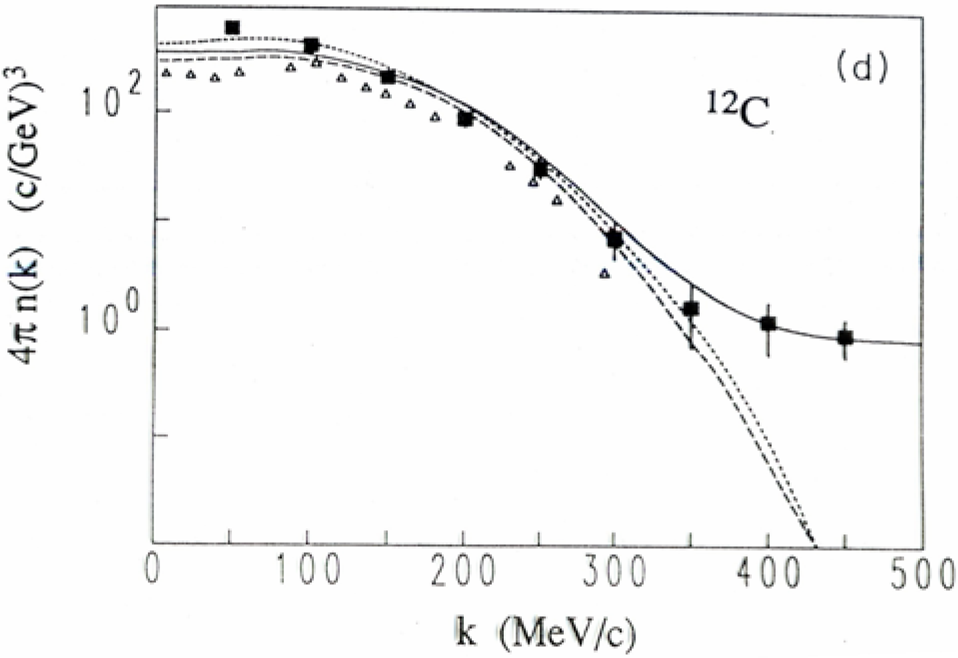


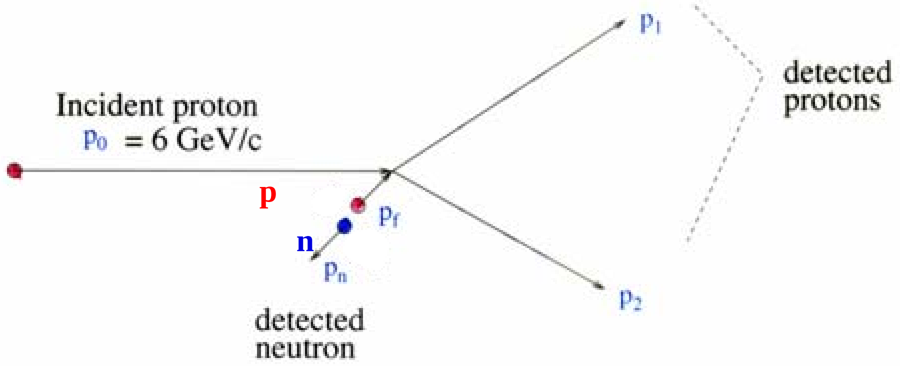
PHYSICAL REVIEW C VOLUME 43, NUMBER 3 MARCH 1991

y-scaling analysis of quasielastic electron scattering and nucleon momentum distributions in few-body systems, complex nuclei, and nuclear matter

C. Ciofi degli Atti,[1,2] E. Pace,[1,3] and G. Salmè[1]



For quasi-elastic scattering, we can apply the impulse approximation (IA) to the interaction of the projectile with a proton in a correlated pair.



We reconstruct the momentum $\vec{p}_f$ of the struck proton:

$$\vec{p}_f = \vec{p}_1 + \vec{p}_2 - \vec{p}_0$$

We then ask is there a neutron in coincidence, and are $\vec{p}_n$ and $\vec{p}_f$ "Correlated"

i.e. roughly *equal* and *opposite*?

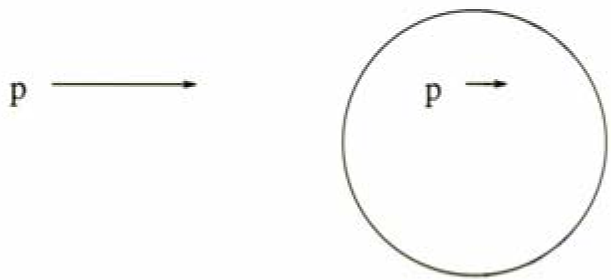
For energies of several GeV and up,
For p-p elastic scattering near 90° c.m.,

$$\frac{d\sigma}{dt} \sim s^{-(n_1+n_2+n_3+n_4-2)}$$

$$\sim s^{-10}$$

where the Mandelstam variable $s = (P_0 + P_F)^2$ is the square of the total c.m. energy.

So for quasi-elastic p-p scattering near 90° c.m., we have a very strong preference for reacting with nuclear protons with their Fermi motion in the beam direction.



Target
Nucleus

This minimizes s

Preferentially selects **high momentum components**

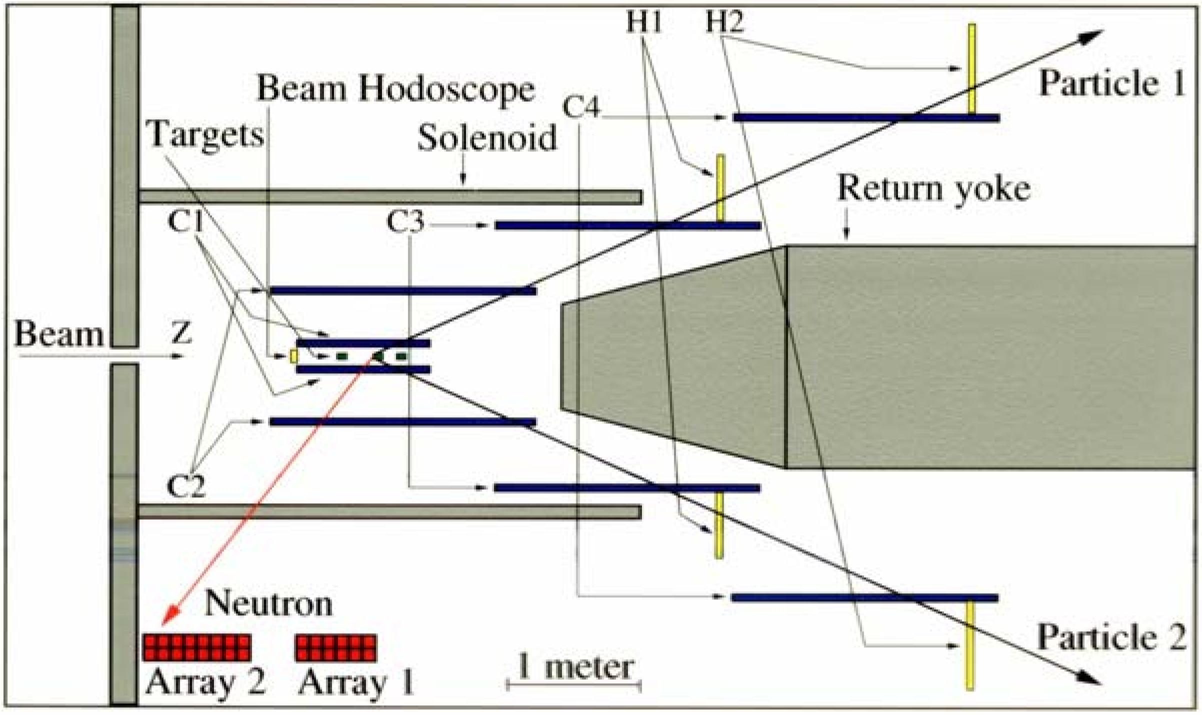
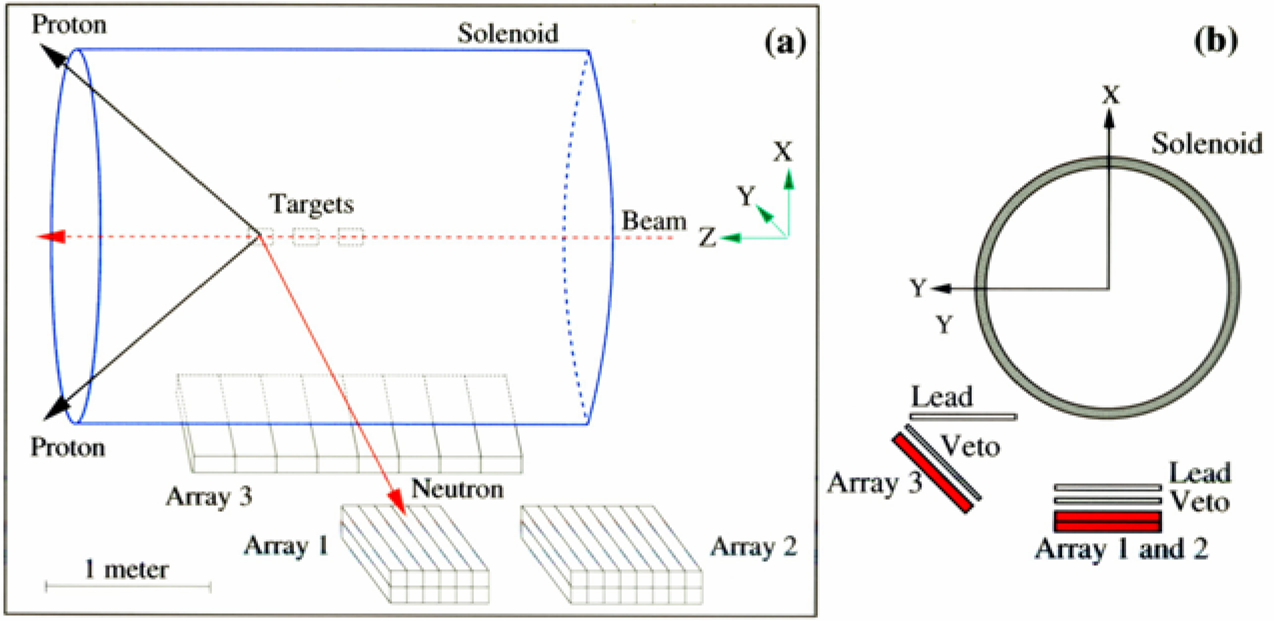


Figure 1: A schematic side view of the EVA spectrometer.



Array 1: total area 0.6×1.0 m^2, 12 counters, 2 layers 0.125 m each.
Array 2: total area 0.8×1.0 m^2, 16 counters, 2 layers 0.125 m each.
Array 3: total area 2×1.0 m^2, 8 counters, 1 layers 0.1 m each.

Figure 5: A schematic side view (a) and a head-on view (b) of the EVA spectrometer and the neutron counter arrays.

Bunch Formation:

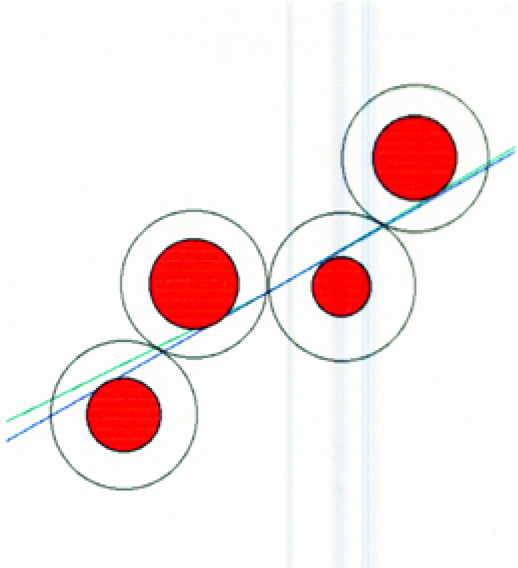


Figure 11: An example of a straw-tube bunch. The outer circles represent the walls of the tube. The radius of the inner red circles is the drift distance. The blue line is the local derivative to a trajectory and the green line is the global particle track.

Track Fit:

$$y(x) = bx + cx^2$$

Quasi-elastic analysis:

➥ Track Reconstruction:

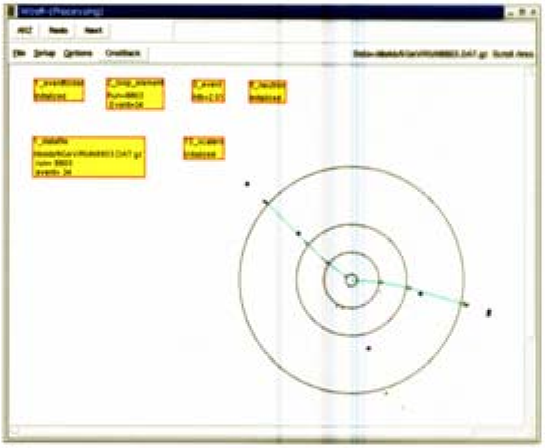


Figure 9: *wzoff* event display in transverse plane.

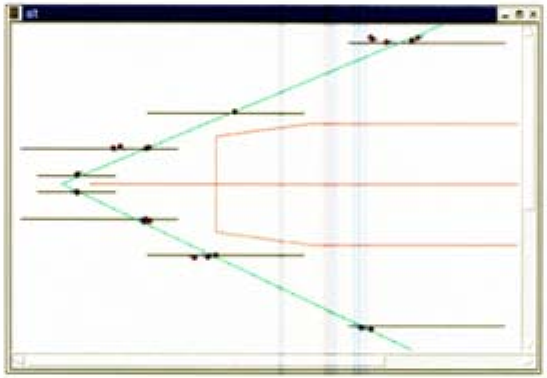


Figure 10: *wzoff* event display in RZ plane.

➥ Calculation of Kinematic Variables:

z-coordinate of The Vertex:

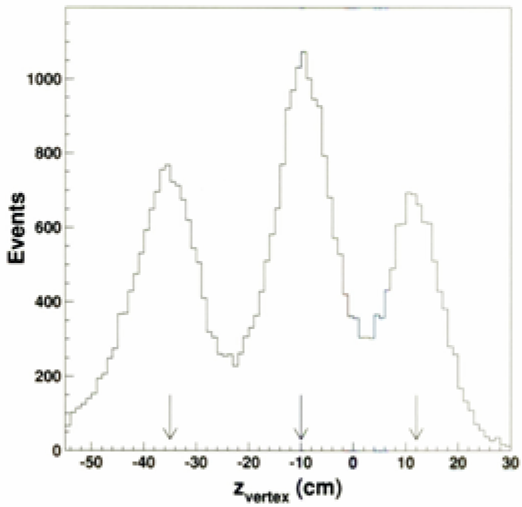


Figure 12: Distribution of z_{vertex} for reconstructed events at 5.9 GeV/c beam momentum. The length of each target is 6 cm and the arrows show the three target central positions.

Cuts to identifying the targets:

$$dz < 15 \text{ cm}$$

$$-45 < z_{vertex} < -25 \longrightarrow \text{target at -35 cm}$$

$$-20 < z_{vertex} < 0 \longrightarrow \text{target at -10 cm}$$

$$0 < z_{vertex} < 25 \longrightarrow \text{target at 12 cm}$$

➥ Calculation of Physical Quantities:

Missing Energy:

$$E_{miss} = E_0 + m - E_1 - E_2$$

where E_0 is the beam energy, m is the mass of proton, E_1 and E_2 are the energies of the two outgoing protons.

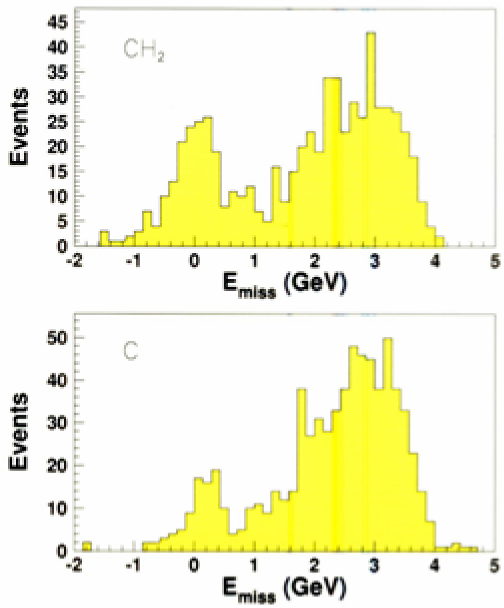


Figure 14: Missing energy spectra for (p,2p) events at 5.9 GeV/c beam momentum on CH_2 targets (top panel) and on C targets (bottom panel).

ELSEVIER

8 October 1998

PHYSICS LETTERS B

Physics Letters B 437 (1998) 257–263

Measurement of quasi-elastic $^{12}C(p,2p)$ scattering at high momentum transfer

Y. Mardor [a], J. Aclander [a], J. Alster [a], D. Barton [b], G. Bunce [b], A. Carroll [b], N. Christensen [c,1], H. Courant [c], S. Durrant [a,b], S. Gushue [b], S. Heppelmann [d], E. Kosonovsky [a], I. Mardor [a], M. Marshak [c], Y. Makdisi [b], E.D. Minor [d,2], I. Navon [a], H. Nicholson [e], E. Piasetzky [a], T. Roser [b], J. Russell [f], C.S. Sutton [e], M. Tanaka [b,3], C. White [c], J-Y Wu [d,4]

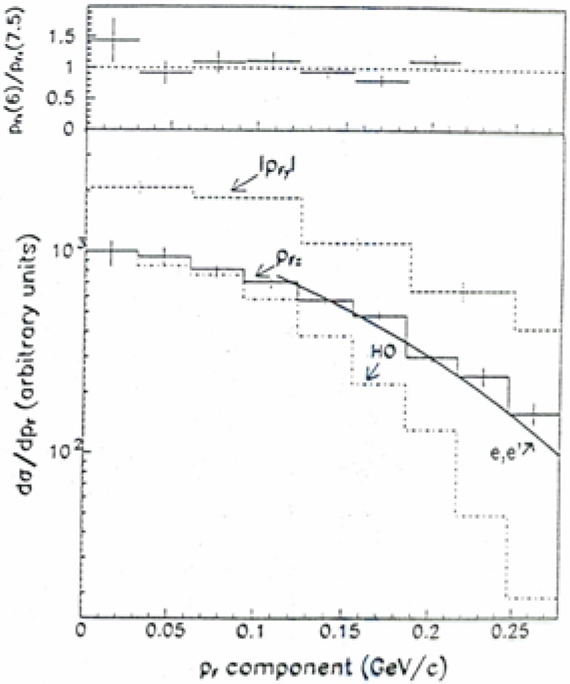
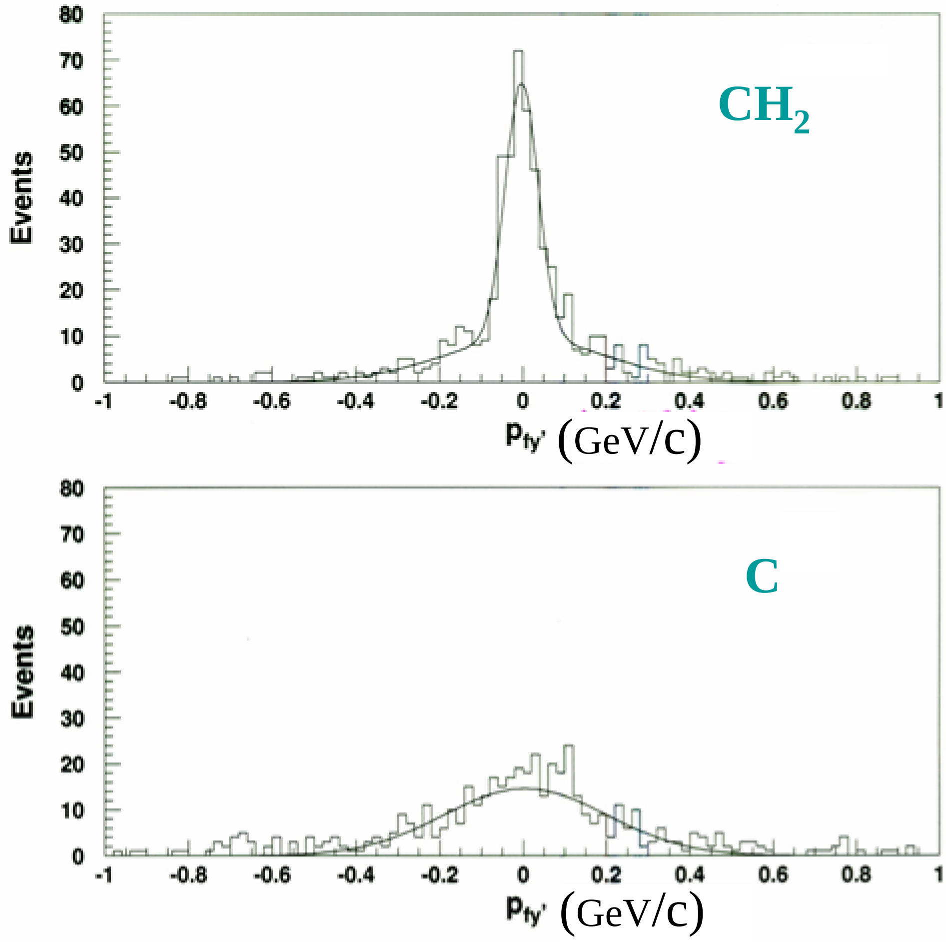


Fig. 3. The upper part of the figure shows the ratio of the two distributions measured at 6 and 7.5 GeV/c (the last two highest momentum points were measured at 6 GeV/c only). p_{Fz} is the longitudinal ground state momentum distribution, obtained from the α distributions for 6 and 7.5 GeV/c combined, after correction for the s dependence induced by the elementary free cross section. The $|p_{Fy}|$ is the transverse distribution extracted from several α regions (see text). HO is a harmonic oscillator indepen-


CH2
Events
pfy' (GeV/c)
C
Events
pfy' (GeV/c)

Light Cone Description of the (p,2p+n) Reaction:

The momentum of a nucleon is described in light-cone space by (p_t, α), where p_t is the transverse momentum and α defined as:

$$\alpha = \frac{E - p_z}{m}$$

represents the fraction of the nuclear momentum carried by the target nucleon in the light-cone reference frame.

- Mandelstam variable s:

$$\begin{aligned} s &= (P_0 + P_F)^2 \\ &= m^2 + m1^2 + 2P_0 P_F \\ &= m^2 + m1^2 + (E_0 - P_0)(E_F + p_F^z) + \alpha m(E_0 + P_0) \\ &\sim m^2 + m1^2 + 2\alpha m p_0 \end{aligned}$$

where $\alpha = \frac{E_F - p_F^z}{m}$ is the light cone variable for target nucleon and for large incident momenta, the approximation: $E_0 - p_0 \approx 0$ and $E_0 + p_0 \approx 2p_0$ was used.

Longitudinal Fermi Momentum and α:

From the momentum conservation:

$$p_{fz} = \frac{p_{t1}}{tan\theta_1} + \frac{p_{t2}}{tan\theta_2} - p_0$$

From light cone variable α:

$$\alpha = \frac{E_f - p_{fz}}{m} \sim 1 - \frac{p_{fz}}{m}$$

$$p_{fz} = m \cdot (1 - \alpha).$$

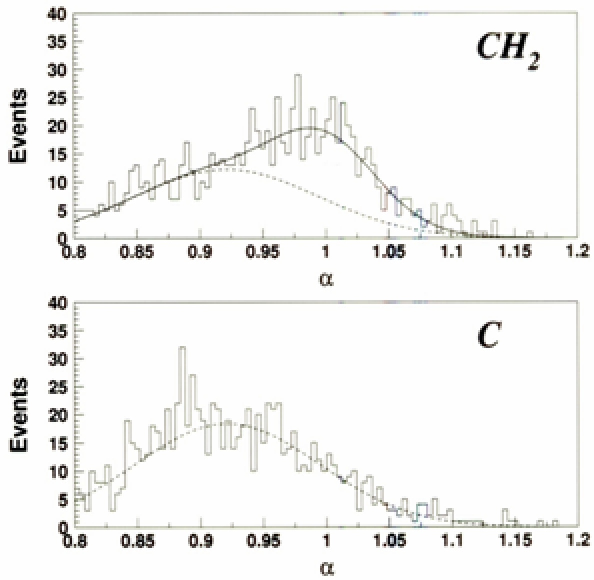


Figure 16: Light-cone variable α distribution for CH_2 and C targets at 5.9 GeV/c beam momentum.

Neutron Analysis:

- Inverse Velocity:

$$v^{-1} = \frac{TOF}{l} = \frac{TOF}{\sqrt{x_{hit}^2 + y_{hit}^2 + (z_{hit} - z_{target})^2}}$$

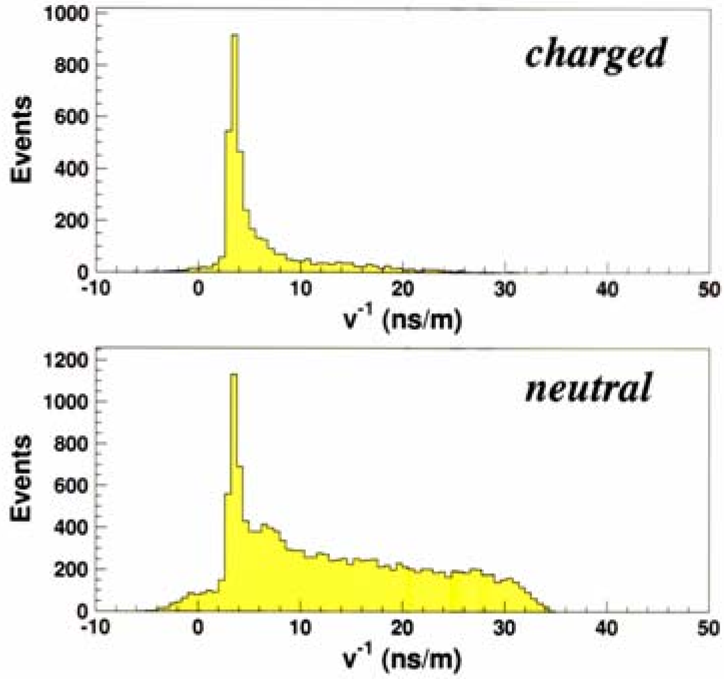


Figure 17: Inverse velocity spectra for charged and neutral particles detected in neutron counter array 3 at 5.9 GeV/c beam momentum.

Results and Conclusions

List of Cuts Applied For Triple Coincident Events

Cuts on protons:

Čerenkov cut:	select protons
Number of tracks:	2 tracks
Target Positions:	$\|z_{target} + 10\| < 10$
	$\|z_{target} + 35\| < 10$
	$\|z_1 - z_2\| < 12$
Missing Energy:	$\|E_{miss} - 0.32\| < 0.5$ GeV
ϕ (for arrays 1 and 2):	$45° < \phi_1 < 135°$, or
	$225° < \phi_1 < 315°$
ϕ (for array 3):	$0° < \phi_1 < 90°$, or
	$180° < \phi_1 < 270°$

Cuts on neutrons:

Neutron Momentum: $0.05 < p_n < 0.55$ GeV/c

Identification of Correlated Events

One-Dimensional Correlations:

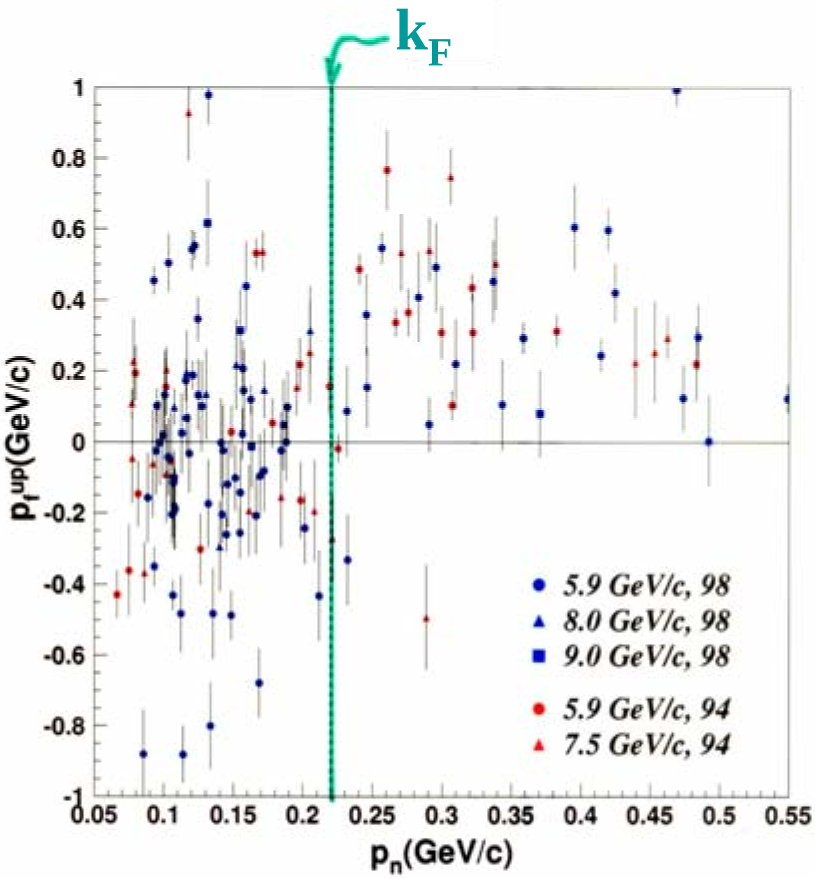
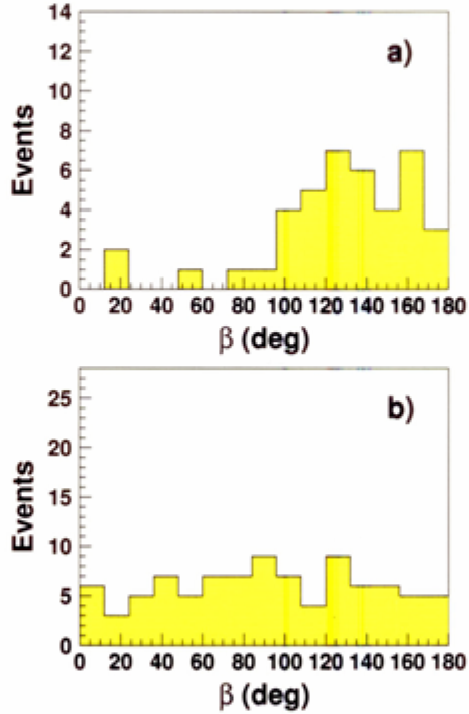


Figure 19: p_f^{up} vs. p_n for $^{12}C(p,2p+n)$ events. Data labelled "98" (solid symbols) are for 98 runs (this experiment). Data labelled "94" are from Aclander, et al. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

Transverse Correlations:

The angle between the transverse momenta of proton and neutron is defined as:

$$\beta = \cos^{-1}\left(\frac{\vec{p}_{nt} \cdot \vec{p}_{ft}}{|\vec{p}_{nt}||\vec{p}_{ft}|}\right).$$



$p_n > k_F$

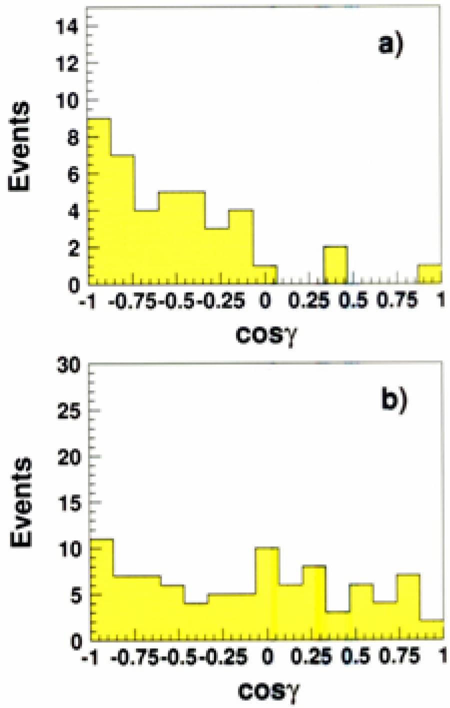
$p_n < k_F$

Figure 20: Plots of β, the angle in the transverse plane between $\vec{p}_f$ and $\vec{p}_n$. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c, where 0.22 GeV/c = k_F, the Fermi momentum for ^{12}C.

Full Correlations:

We then construct the directional correlation between $\vec{p}_f$ and $\vec{p}_n$ as

$$cos\gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{|\vec{p}_f||\vec{p}_n|}$$



$p_n > k_F$

$p_n < k_F$

Figure 21: Plots of cosγ, where γ is the angle between $\vec{p}_n$ and $\vec{p}_f$. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c; 0.22 GeV/c = k_F, the Fermi momentum for ^{12}C.

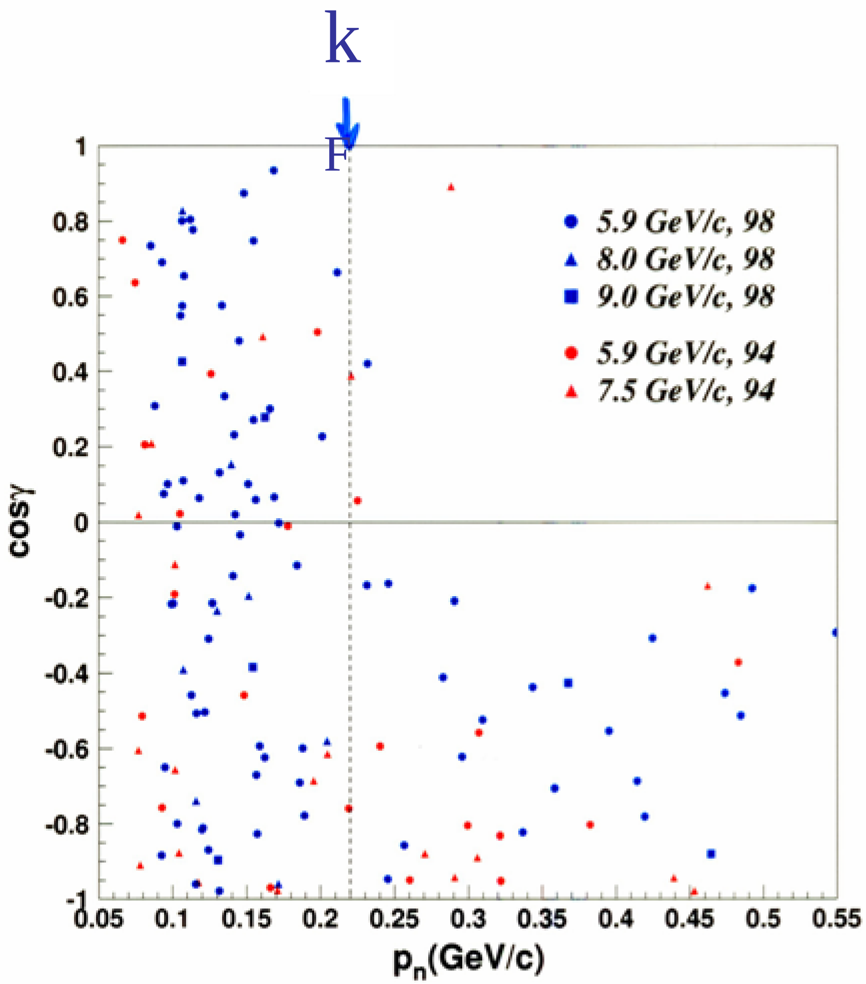


Figure 22: cosγ vs. p_n for ^{12}C(p,2p+n) events. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

The Correlated Fraction of (p,2p) Events:

For the 6 GeV 1998 data set we estimated the fraction of (p,2p) events with $p_f > 0.22$ GeV/c, which have a correlated backwards neutrons with $p_n > 0.22$ GeV/c.

$$F = \frac{corrected\ \#\ of\ (p,2p+n)\ events}{\#\ of\ (p,2p)\ events} = \frac{A}{B}$$

The quantity A was obtained from the sample of all 18 (p,2p+n) events with $p_n \geq k_F = 0.22$ GeV/c, where a correction for flux attenuation and detection efficiency was applied event-by-event, and then corrected for the solid-angle coverage:

$$A = \frac{2\pi}{\Delta\Omega} \sum_{i=1}^{18} \frac{1}{\epsilon_i} \cdot \frac{1}{t_i} = 1090.$$

The average value of $(1/e_i t_i)$ was 8.2 ± 0.82 and $2\pi/\Delta\Omega = 7.42$. We can then calculate

$$F = \frac{A}{B} = \frac{1090}{2205} = 0.49 \pm 0.13.$$

- The Center of Mass Motion of the $n-p$ Pair:

$$p_z^{cm} = p_{nz} + p_{fz}$$

We can express this in terms of α as

$$\begin{aligned}\alpha_p + \alpha_n &= \frac{E_f - p_p^z}{m} + \frac{E_f - p_n^z}{m} \\ &= (1 - \frac{p_{fz}}{m}) + (1 - \frac{p_{nz}}{m})\end{aligned}$$

⇨

$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2})$$

- The Relative Motion of the Correlated Nucleons:

$$\begin{aligned}\alpha_p - \alpha_n &= (1 - \frac{p_{fz}}{m}) - (1 - \frac{p_{nz}}{m}) \\ &= (\frac{p_{nz} - p_{fz}}{m})\end{aligned}$$

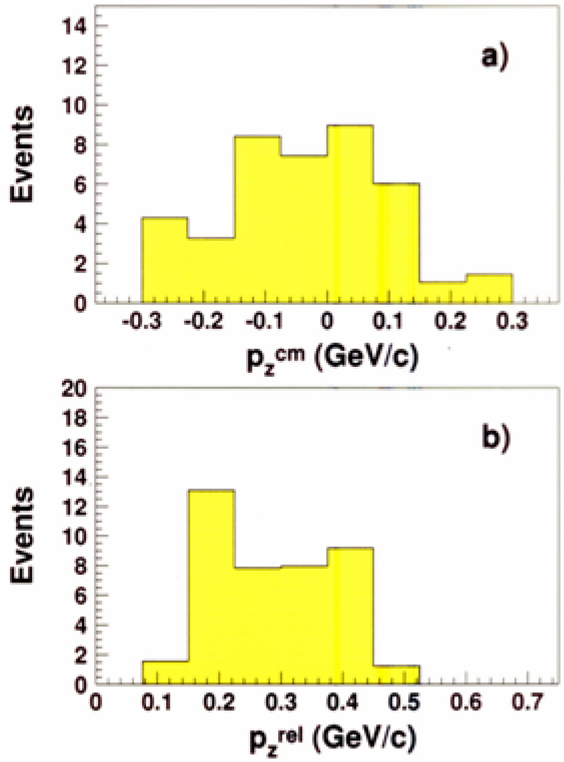
⇨

$$\begin{aligned}p_z^{rel} &= |p_{fz} - p_{nz}| \\ &= m|\alpha_p - \alpha_n|\end{aligned}$$

The Relative and c.m. Motion of Correlated n-p Pairs:

$$p_z^{cm} = 2m(1 - \frac{\alpha_p + \alpha_n}{2}),$$

$$p_z^{rel} = m|\alpha_p - \alpha_n|.$$



Centroid = -0.013 ± 0.027 GeV/c
σ = 0.143 ± 0.017 GeV/c

Centroid = 0.289 ± 0.017 GeV/c
σ = 0.097 ± 0.007 GeV/c

Figure 23: Plots of (a) p_z^{cm} and (b) p_z^{rel} for correlated n-p pairs in ^{12}C, for $^{12}C(p,2p+n)$ events. Each event has been "*s*-weighted".

Summary

1. For quasielastic (p,2p) events we reconstructed $\vec{p}_f$ the momentum of the knocked-out proton before the reaction; $\vec{p}_f$ was then compared with $\vec{p}_n$, the measured, coincident neutron momentum. For $|\vec{p}_n| > \mathrm{k}_F = 0.220$ GeV/c (the Fermi momentum) a strong back-to-back directional correlation between $\vec{p}_f$ and $\vec{p}_n$ was observed, indicative of short-range n-p correlations.

2. We determined that 49 ± 13 % of events with $|\vec{p}_f| > \mathrm{k}_F$ had directionally correlated neutrons with $|\vec{p}_n| > \mathrm{k}_F$. Thus 2N SRCs are a major source of high-momentum nucleons in nuclei.

3. We also measured the c.m. and relative momenta of correlated n-p pairs in the longitudinal direction.

4. And . . .

A. A. Tang et al.,
Phys. Rev. Lett. 90, 042301 (2003)

B. JLab Experiment E01-015
Completed in Spring 2005

Spokesmen: Bill Bertozzi, MIT
Eli Piasetzky, Tel Aviv
John Watson, Kent State
Steve Wood, JLab

Latest Development

Evidence for the Strong Dominance of Proton-Neutron Correlations in Nuclei

by

E. Piasetzky, M Sargsian, L. Frankfurt, M Strikman and J. W. Watson

Phys. Rev. Lett., 20 October 2006

- Analysis of the EVA Data
- Assumes 100% SRC above 275 MeV/c
- Includes the motion of the pair
- Includes absorption of entering and exiting nucleons in the nuclear medium

Conclusion: "Within the NN-SRC dominance assumption the data indicate that the probabilities of pp or nn SRCs in the nucleus are at least a factor of six smaller than that of pn SRCs. Our result is the first estimate of the isospin structure of NN-SRCs in nuclei."