1942-16

Sixth International Conference on Perspectives in Hadronic Physics

12 - 16 May 2008

Short-Range Correlations from Hadron-Induced Reactions.

J. Watson
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USA

Study of Short-Range Correlations with 6-9 GeV/c Protons

Adventures Beyond the Shell Model

John Watson
Kent State University

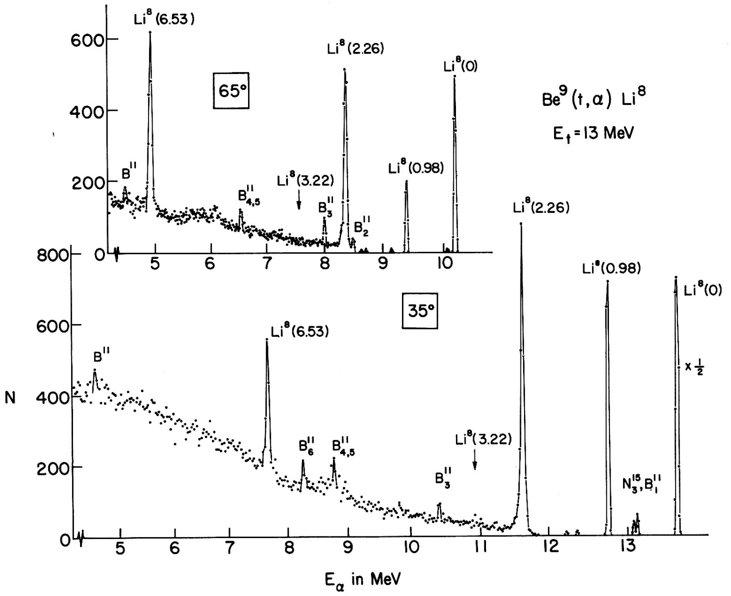
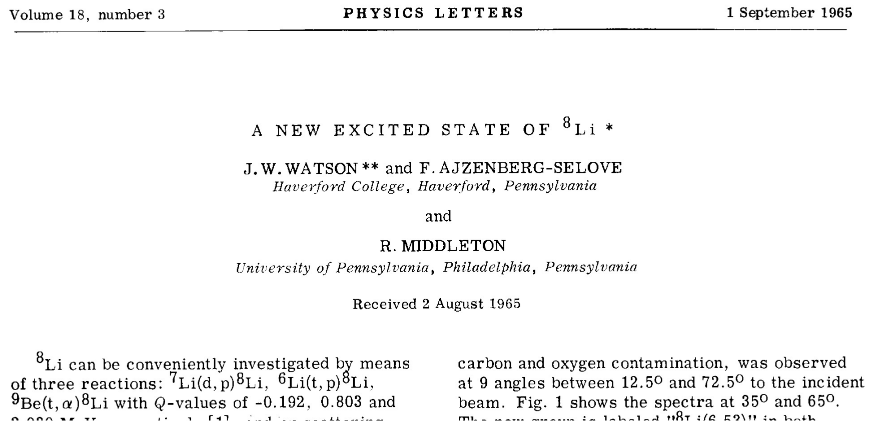


Fig. 1. Spectra of α particles from ^{9}Be(t,α)^{8}Li, ^{12}C(t,α)^{11}B, and ^{16}O (t,α)^{15}N at E_t = 12.87 MeV (θ = 35° and 65°). The ordinate gives the number of α tracks recorded in a 212 μ wide "bin" of the photographic plate detector. ^{8}Li(0), ^{8}Li(0.98) and ^{8}Li(2.26) are alpha groups corresponding to the ground and first two excited states of ^{8}Li. ^{8}Li(6.53) is the new state discussed in the text. The position of α-particles from ^{8}Li(3.22) is indicated. The groups labelled ^{11}B$_x$ (x = 1 to 6) and ^{15}N$_3$ correspond to excited states in ^{11}B and ^{15}N.


Volume 18, number 3 PHYSICS LETTERS 1 September 1965

A NEW EXCITED STATE OF ^{8}Li *

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Received 2 August 1965

^{8}Li can be conveniently investigated by means of three reactions: ^{7}Li(d, p)^{8}Li, ^{6}Li(t, p)^{8}Li, ^{9}Be(t, α)^{8}Li with Q-values of -0.192, 0.803 and

carbon and oxygen contamination, was observed at 9 angles between 12.5° and 72.5° to the incident beam. Fig. 1 shows the spectra at 35° and 65°.

Things I learned from Fay Selove

1. Nuclear Structure can be fascinating.

2. Stay from neutron detection!

PHYSICAL REVIEW C VOLUME 26, NUMBER 3 SEPTEMBER 1982

^{40}Ca$(p,pn)^{39}$Ca and ^{48}Ca$(p,pn)^{47}$Ca neutron knockout reactions at 149.5 MeV

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(Received 11 March 1982)

The reactions ^{40}Ca$(p,pn)^{39}$Ca and ^{48}Ca$(p,pn)^{47}$Ca were studied at 149.5 MeV in coplanar geometries. An overall separation energy resolution of about 1 MeV was achieved. Probable neutron-hole strength is seen for $1d_{5/2}$ and $1p$ shell knockout from both targets. The data are compared with distorted-wave-impulse-approximation calculations and spectroscopic factors are extracted for neutron-hole states.

We identified valance neutron hole states and extracted spectroscopic factors

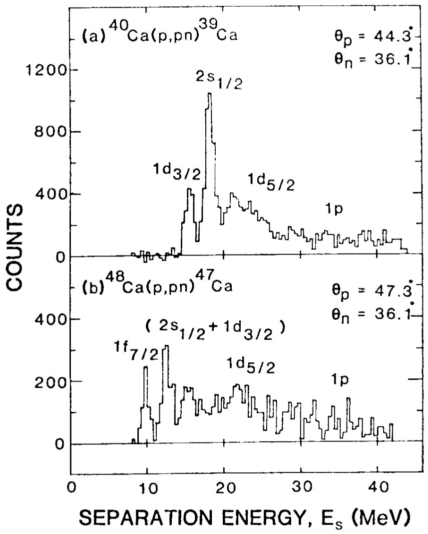
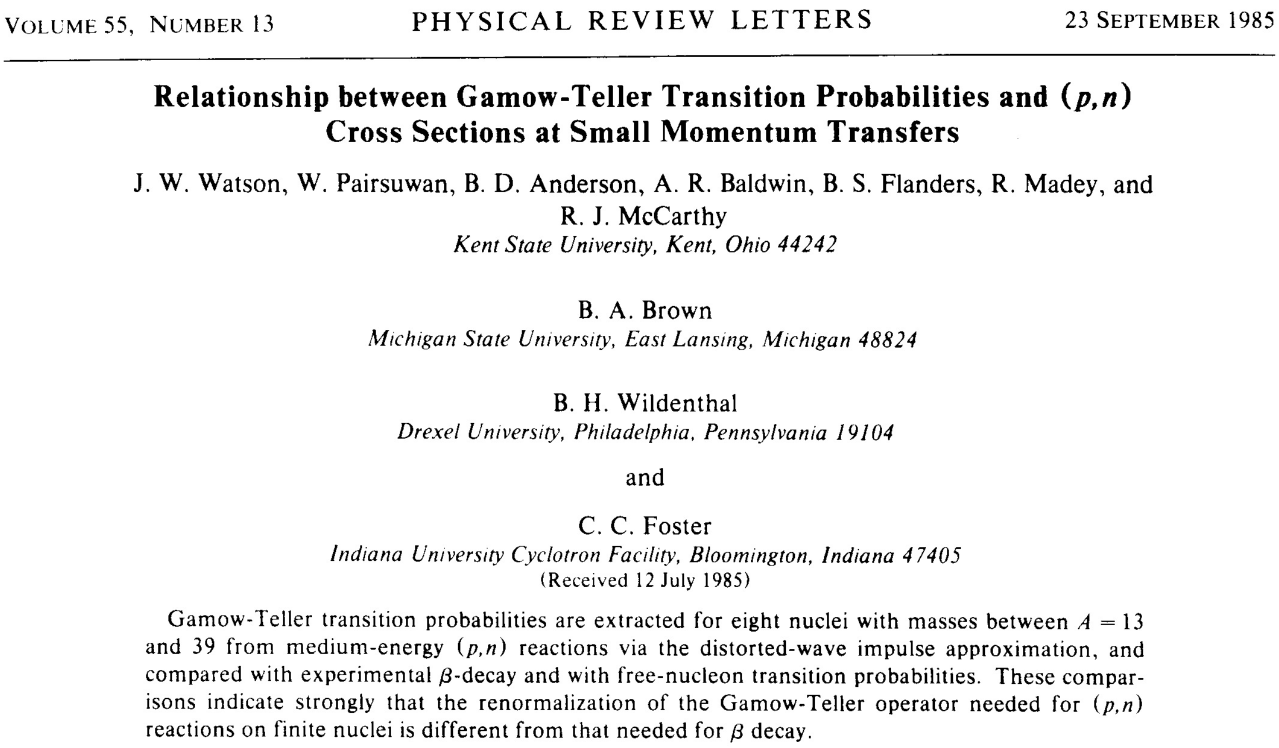


FIG. 1. Neutron separation energy spectra (a) for the ^{40}Ca$(p,pn)^{39}$Ca reaction at 149.5 MeV with (θ_p, θ_n) = (44.3°, 36.1°), and (b) for the ^{48}Ca$(p,pn)^{47}$Ca reaction at 149.5 MeV with (θ_p, θ_n) = (47.3°, 36.1°).



VOLUME 55, NUMBER 13 PHYSICAL REVIEW LETTERS 23 SEPTEMBER 1985

Relationship between Gamow-Teller Transition Probabilities and (p,n) Cross Sections at Small Momentum Transfers

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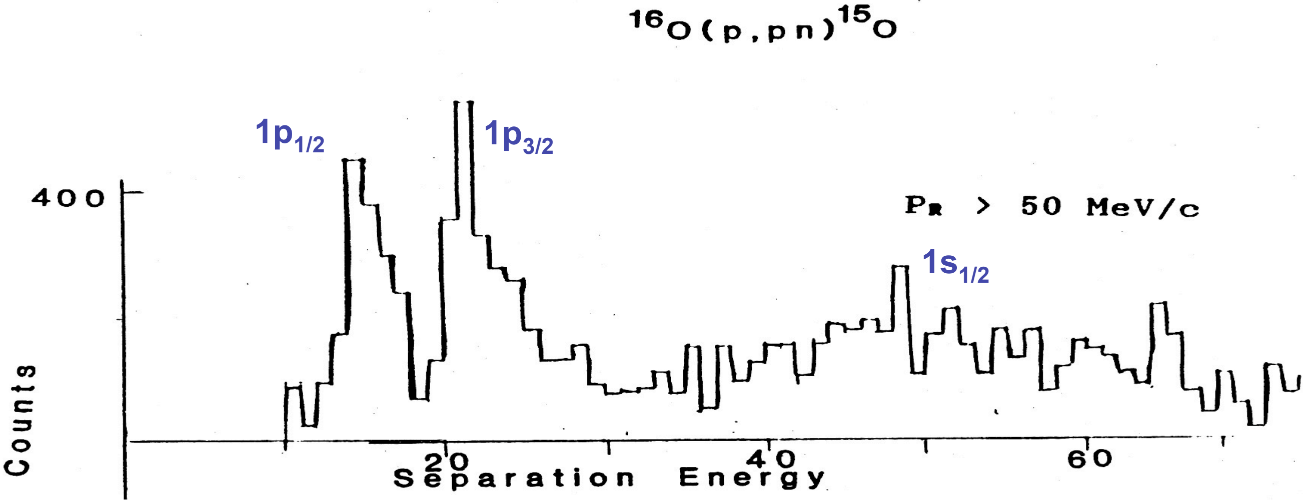
(Received 12 July 1985)

Gamow-Teller transition probabilities are extracted for eight nuclei with masses between $A = 13$ and 39 from medium-energy (p,n) reactions via the distorted-wave impulse approximation, and compared with experimental β-decay and with free-nucleon transition probabilities. These comparisons indicate strongly that the renormalization of the Gamow-Teller operator needed for (p,n) reactions on finite nuclei is different from that needed for β decay.

Here we were converting single proton holes into single neutron holes



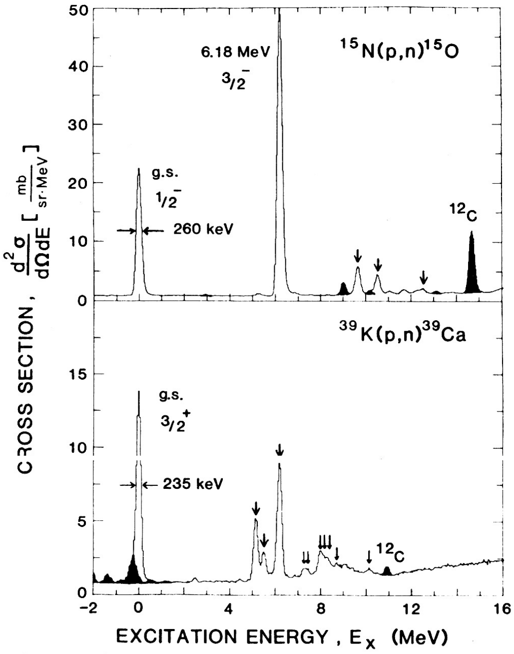


FIG. 1. Excitation-energy spectra for the reactions ^{15}N$(p,n)^{15}$O and ^{39}K$(p,n)^{39}$Ca at 135 MeV and 0°. The arrows indicate the locations of transitions with $\Delta L = 0$ angular distribution which are known or presumed to be $1p_{3/2}$ $(1d_{5/2})$ hole states for ^{15}O (^{39}Ca). Shaded peaks are from contaminants.

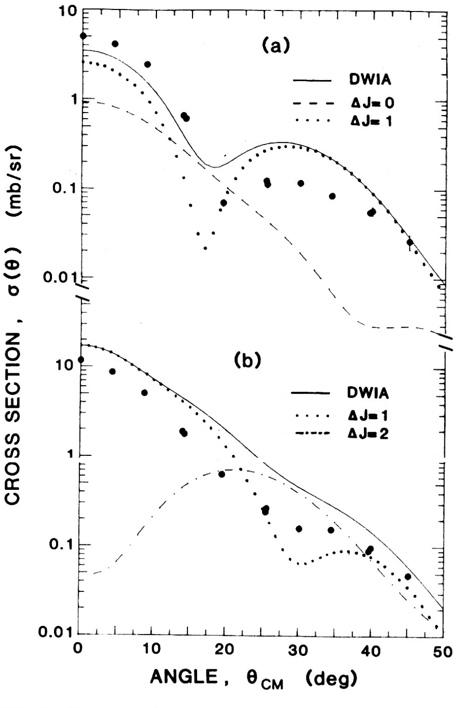
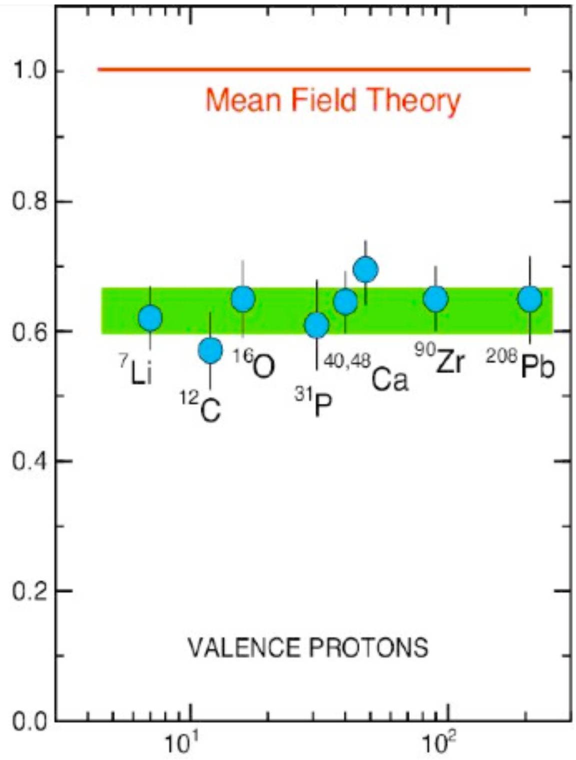


FIG. 2. Cross-section angular distributions for the reaction ^{15}N$(p,n)^{15}$O at 135 MeV, (a) for the ^{15}O g.s. and (b) for the ^{15}O 6.18-MeV state. The curves are DWIA calculations described in the text.

But I knew something was *MISSING!*

Spectroscopic factors for (e,e'p) reactions show only 60-70% of the expected single-particle strength.



There must be more!

Experiment E850

The EVA Collaboration

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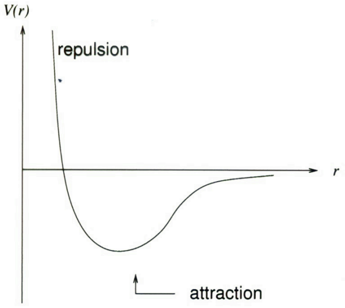
The N-N Interaction, the Shell Model and SRC



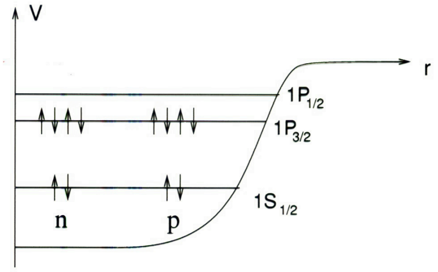
N–N interaction

Nuclear Shell Model (∼ 1950) $\left\{ \begin{array}{l} \text{Maria Mayer} \\ \text{J.H.D. Jensen} \\ \text{Nobel Prize in 1963} \end{array} \right\}$

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.

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Nuclear Fermi Momenta from Quasielastic Electron Scattering

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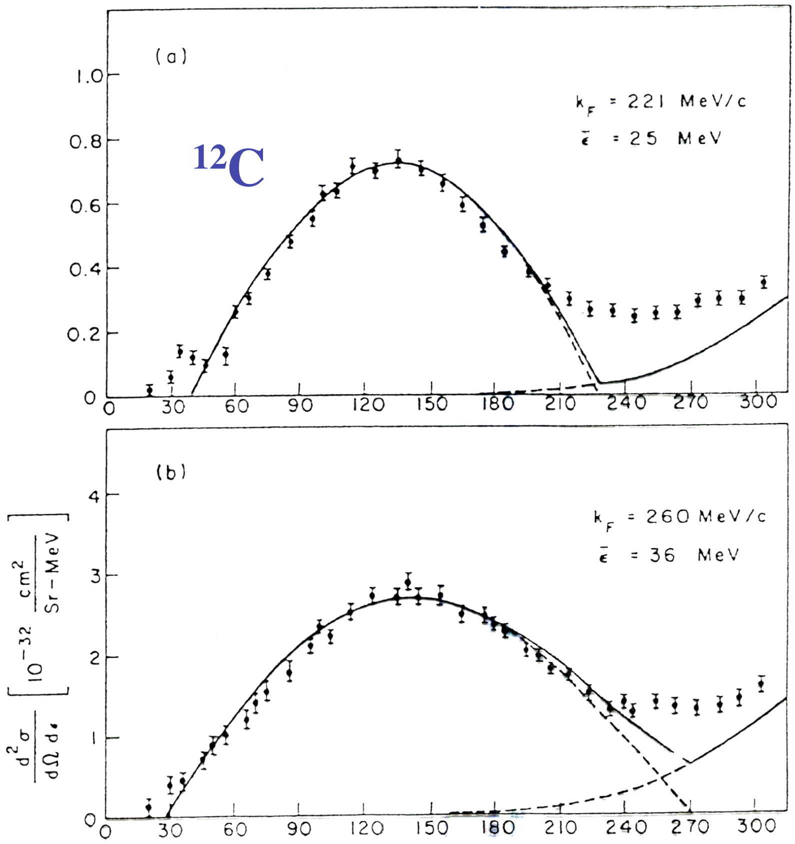
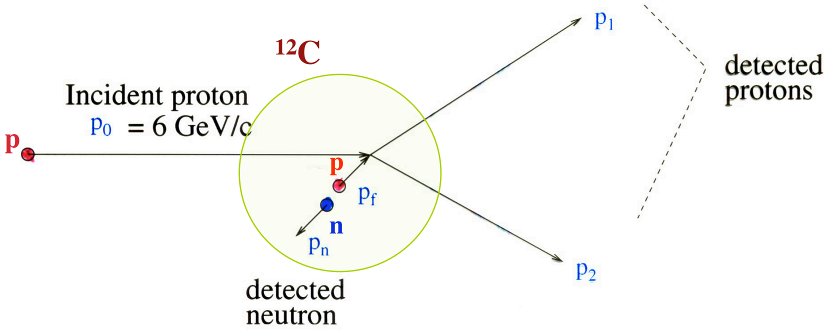


For quasi-elastic scattering, we can apply the impulse approximation (IA) to the interaction of the projectile with a proton in a correlated pair.



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*?

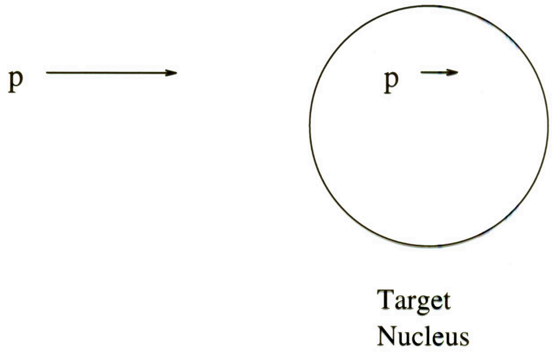
For energies of several GeV and up,
For p-p elastic scattering near 90° c.m.,

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

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

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.



Forward going, high-momentum nuclear protons are preferentially selected, because *this minimizes s.*

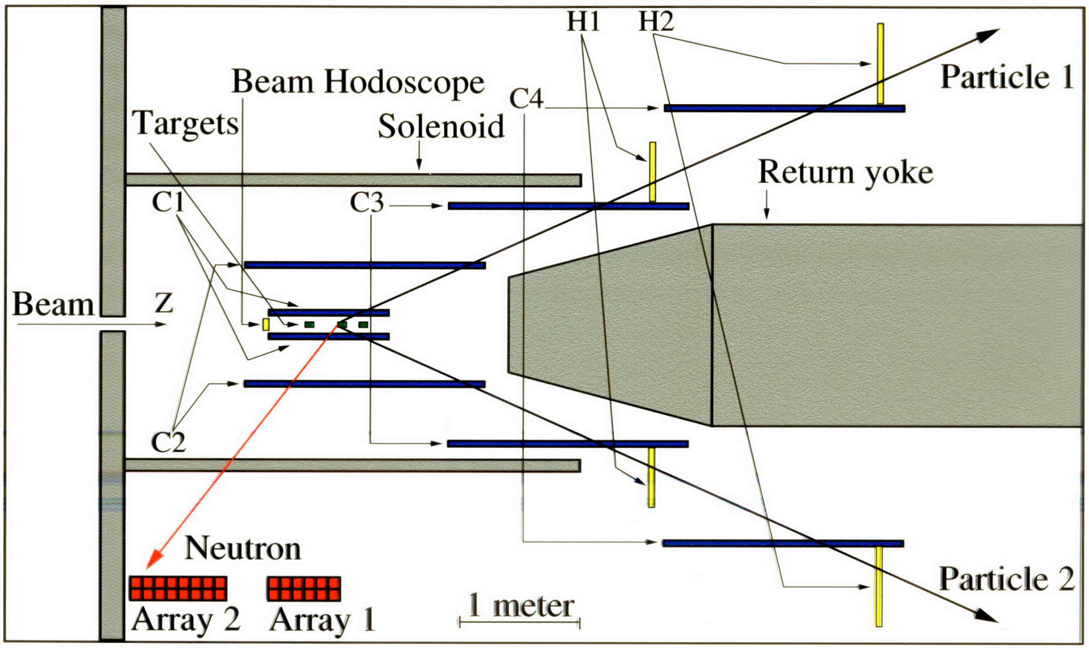
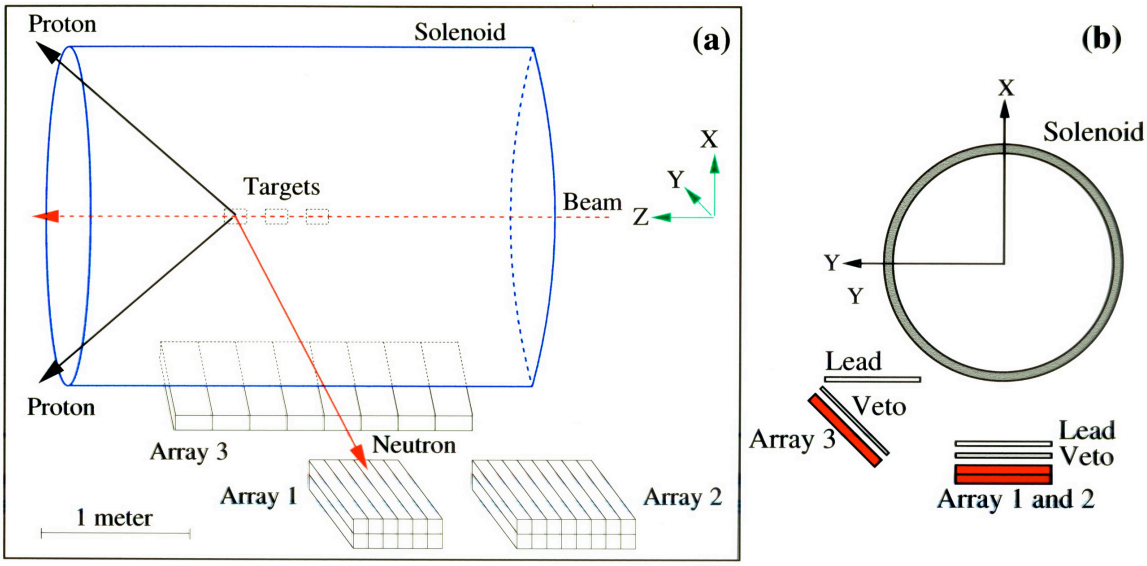


Figure 1: A schematic side view of the EVA spectrometer.

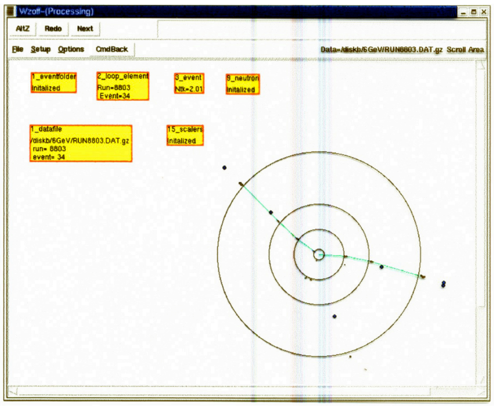


Array 1: total area 0.6×1.0 m^2, 12 counters, 2 layers 0.125 m each.
Array 2: total area 0.8×1.0 m^2, 16 counters, 2 layers 0.125 m each.
Array 3: total area 2×1.0 m^2, 8 counters, 1 layers 0.1 m each.

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

Quasi-elastic analysis:

- Track Reconstruction:



Data=/diskb/6GeV/RUN8803.DAT.gz

1_eventfolder
Initalized

2_loop_element
Run=8803
Event=34

3_event
Ntk=2.01

9_neutron
Initalized

1_datafile
/diskb/6GeV/RUN8803.DAT.gz
run= 8803
event= 34

15_scalers
Initalized

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

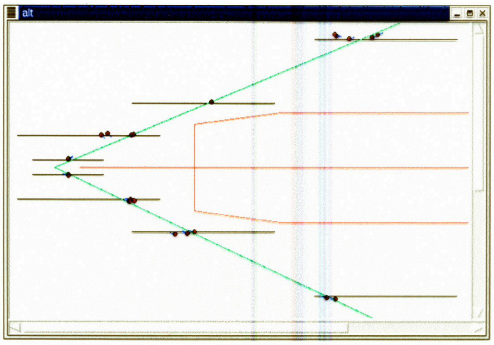


Figure 10: *wzoff* event display in RZ plane.

- Calculation of Kinematic Variables:

z-coordinate of The Vertex:

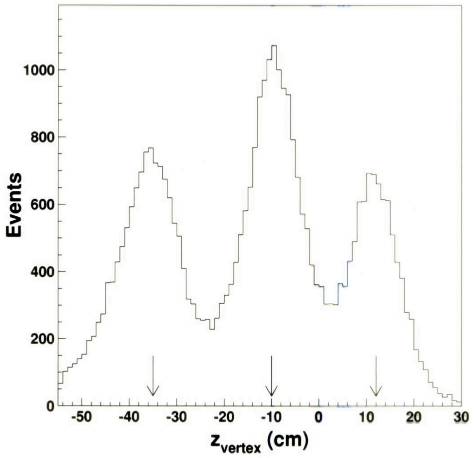


Figure 12: Distribution of z_{vertex} for reconstructed events at 5.9 GeV/c beam momentum. The length of each target is 6 cm and the arrows show the three target central positions.

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.

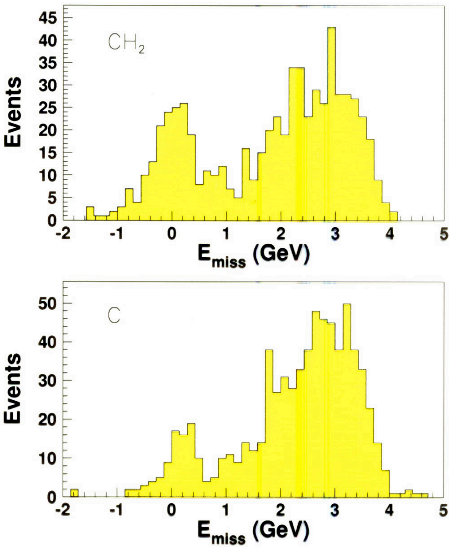
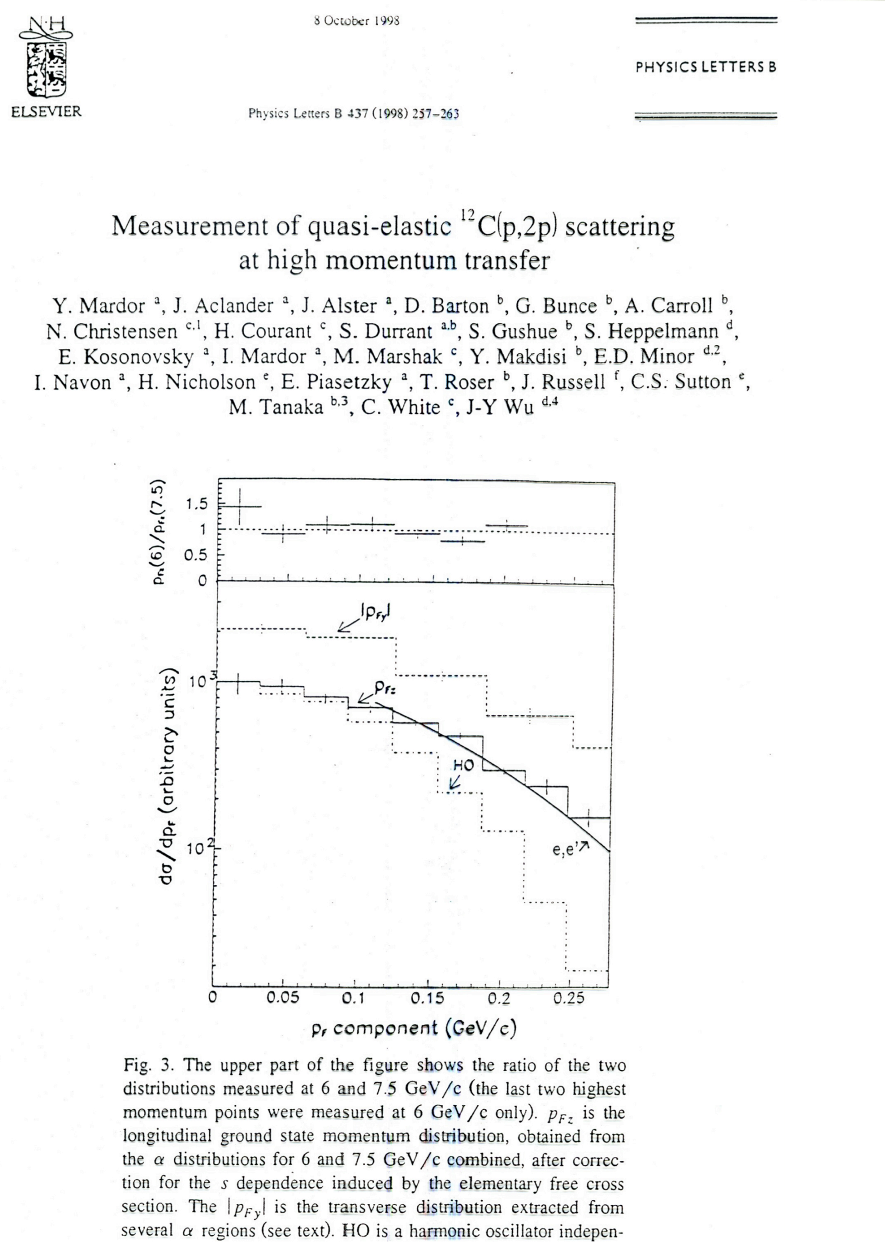


Figure 14: Missing energy spectra for (p,2p) events at 5.9 GeV/c beam momentum on CH$_2$ targets (top panel) and on C targets (bottom panel).



ELSEVIER

8 October 1998

Physics Letters B 437 (1998) 257–263

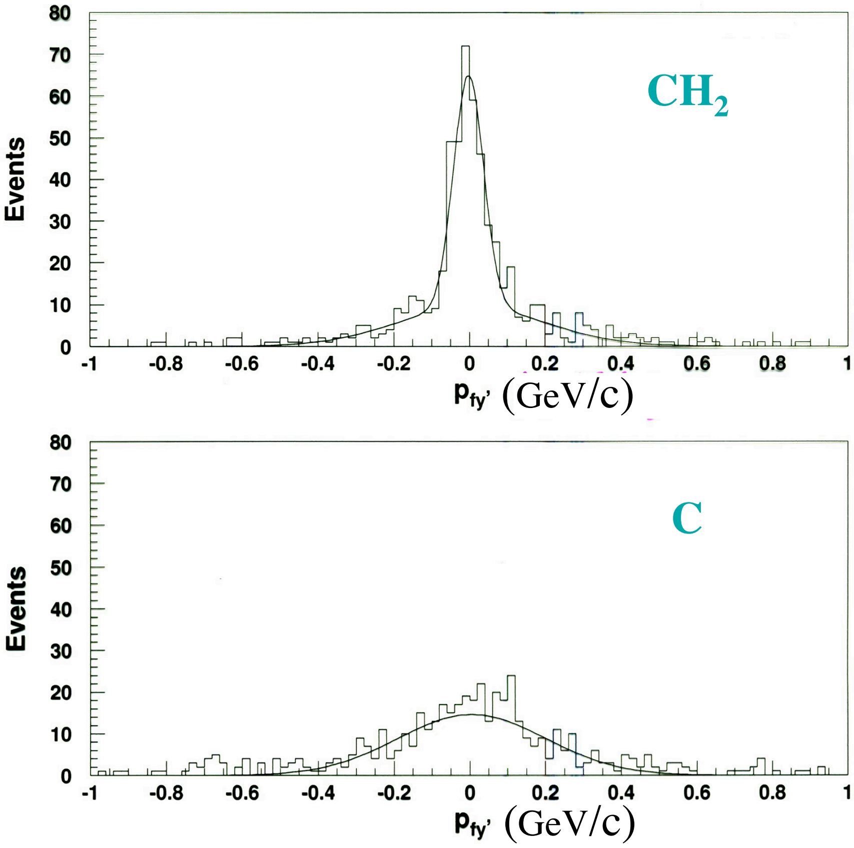
PHYSICS LETTERS B

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-

Transverse component of p_f



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:

$$\begin{aligned} s &= (P_0 + P_F)^2 \\ &= m^2 + m1^2 + 2P_0P_F \\ &= m^2 + m1^2 + (E_0 - P_0)(E_F + p_F^z) + \alpha m(E_0 + P_0) \\ &\sim m^2 + m1^2 + 2\alpha m p_0 \end{aligned}$$

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 component of p_f

From the momentum conservation:

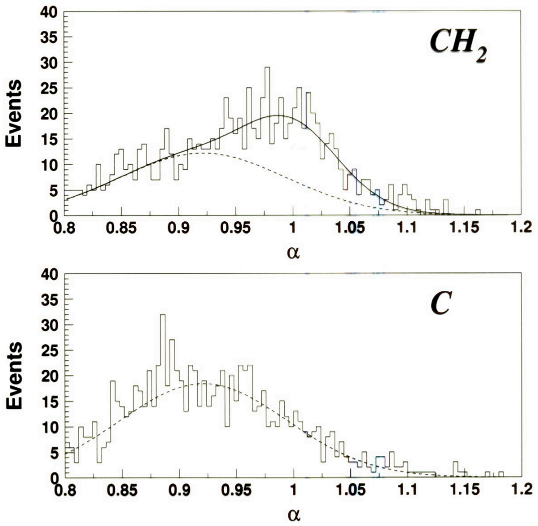
$$p_{fz} = \frac{p_{t1}}{tan\theta_1} + \frac{p_{t2}}{tan\theta_2} - p_0$$

Subtraction
of large numbers

From light cone variable α:

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

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



Light-cone Magic!

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

Neutron Analysis:

- Inverse Velocity:

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

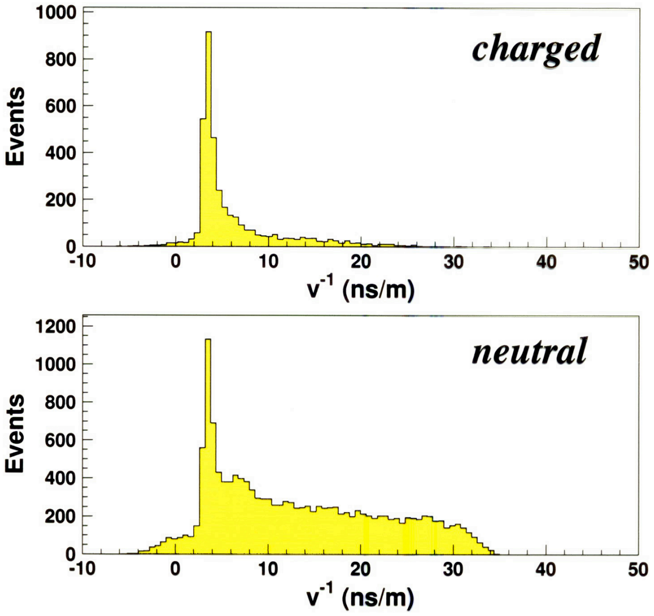


Figure 17: Inverse velocity spectra for charged and neutral particles detected in neutron counter array 3 at 5.9 GeV/c beam momentum.

Software cuts for data replay.

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): $45^\circ < \phi_1 < 135^\circ$, or

$225^\circ < \phi_1 < 315^\circ$

ϕ (for array 3): $0^\circ < \phi_1 < 90^\circ$, or

$180^\circ < \phi_1 < 270^\circ$

Cuts on neutrons:

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

Identification of Correlated Events

One-Dimensional Correlations:

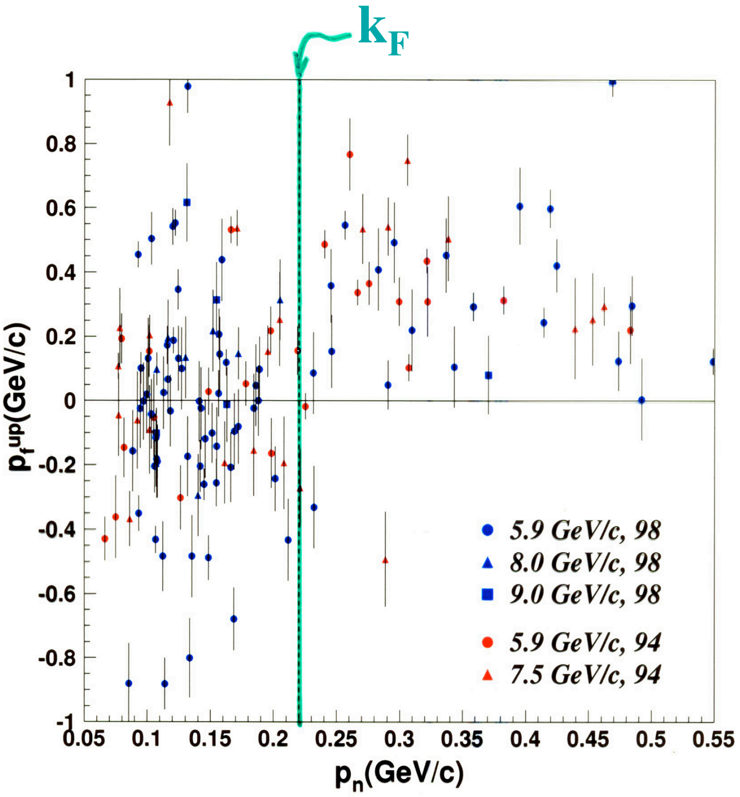
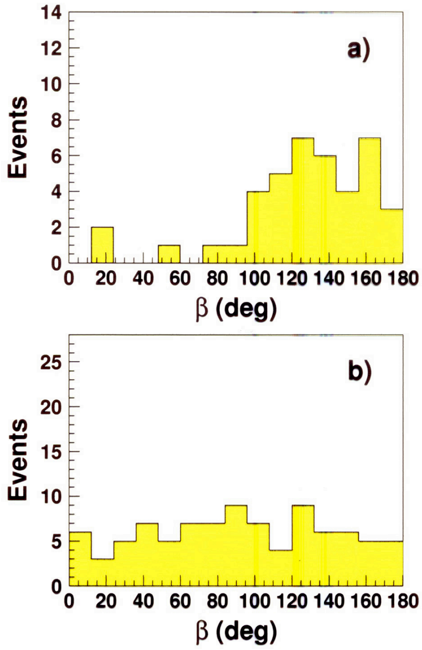


Figure 19: p_f^{up} vs. p_n for ^{12}C(p,2p+n) events. Data labelled “98” (solid symbols) are for 98 runs (this experiment). Data labelled “94” are from Aclander, et al. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

Transverse Correlations:

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

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



$p_n > k_F$

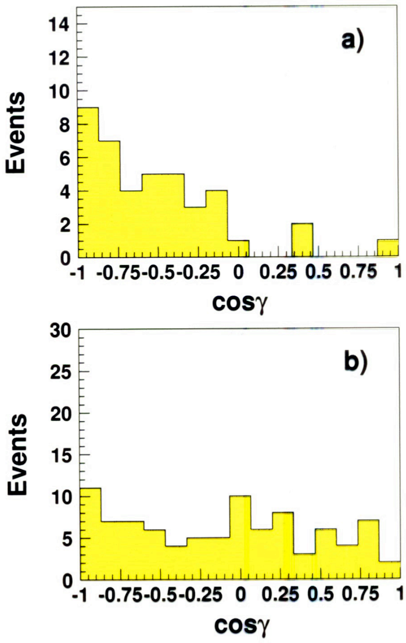
$p_n < k_F$

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

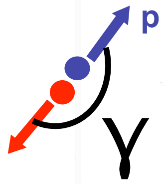
$$cos\gamma = \frac{\vec{p}_f \cdot \vec{p}_n}{|\vec{p}_f||\vec{p}_n|}$$



$p_n > k_F$

$p_n < k_F$

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.



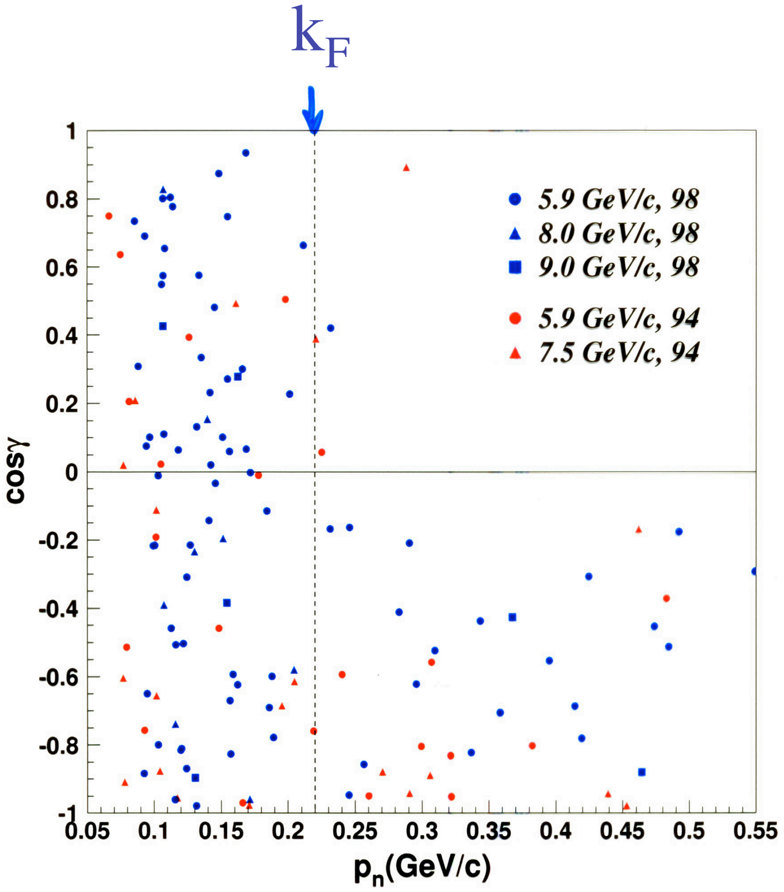


Figure 22: cosγ vs. p_n for ^{12}C(p,2p+n) events. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

So why did this work so well when our count rate was only

* * 1 per week ?

1. The s^{-10} dependence of p-p elastic scattering, which preferentially selects high momentum nuclear protons. (Hadrons ***are*** different from leptons!)

2. The improved resolution from using light cone variables.

3. The small deBroglie wavelength of the incident protons:

$$\lambda = h/p = hc/pc = 2\pi \bullet 0.197 \text{ GeV-fm}/(6 \text{ Gev})$$

$$\approx 0.2 \text{ fm}.$$

This meant that our probe could interact with a single member of a correlated pair!

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:

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

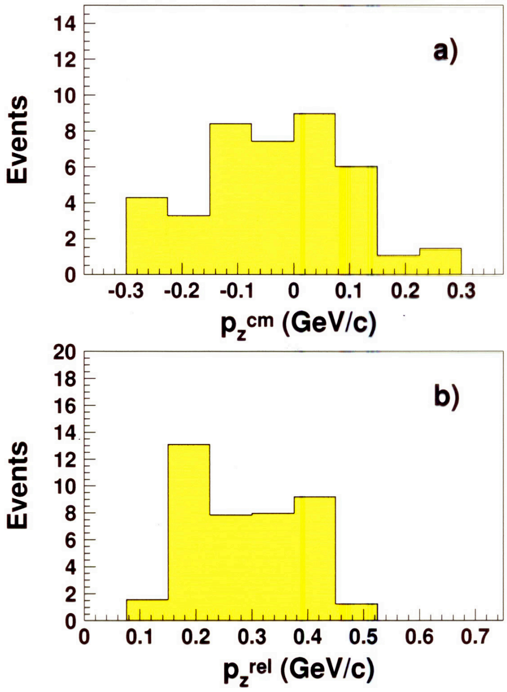
⇨

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

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

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

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



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 $|\vec{p}_n| > k_F = 0.220$ 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 $|\vec{p}_f| > k_F$ had directionally correlated neutrons with $|\vec{p}_n| > k_F$. 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)

Recent 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% NN-SRCs above 275 MeV/c
- Includes the motion of the pair
- Includes absorption of entering and exiting nucleons in the nuclear medium

Conclusion: 92 ± 18% of high-momentum protons have correlated neutrons.

B. JLab Experiment E01-015

Completed in Spring 2005

Spokesmen: Bill Bertozzi, MIT
Eli Piasetzky, Tel Aviv
John Watson, Kent State
Steve Wood, Jlab
And: Shalev Gilad
Doug Higinbotham
Ph.D. Students: Ramesh Subedi, Kent State
Ran Shneor, Tel Aviv
Peter Monaghan, MIT

The Results from E01-015 can be found in:

1) R. Shneor, et al., Phys. Rev. Lett. **99**, 072501 (2007).

2) R. Subedi, et al., **SCIENCE**, in press.

The results of the BNL (p,2p+n) experiment are fully consistent with the results of the JLab (e,e'p+N) experiment:

- Different Laboratories
- Different probes
- Different Graduate Students
- Different millenia
- **Same Results!**
- **We are observing nuclear structure**

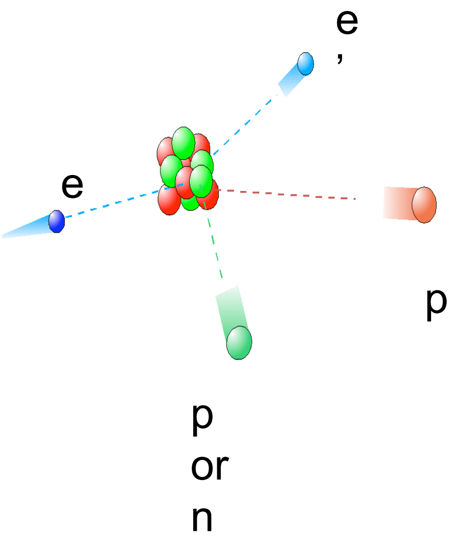
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Studying Short range Correlations in Nuclei at the Repulsive Core Limit via the triple Coincidence (e, e’ p N) Reaction

Hall A / TJNAF

Proposal 07-006

(Next Generation of E01-015)



PAC 31/TJNAF Jan. 2007