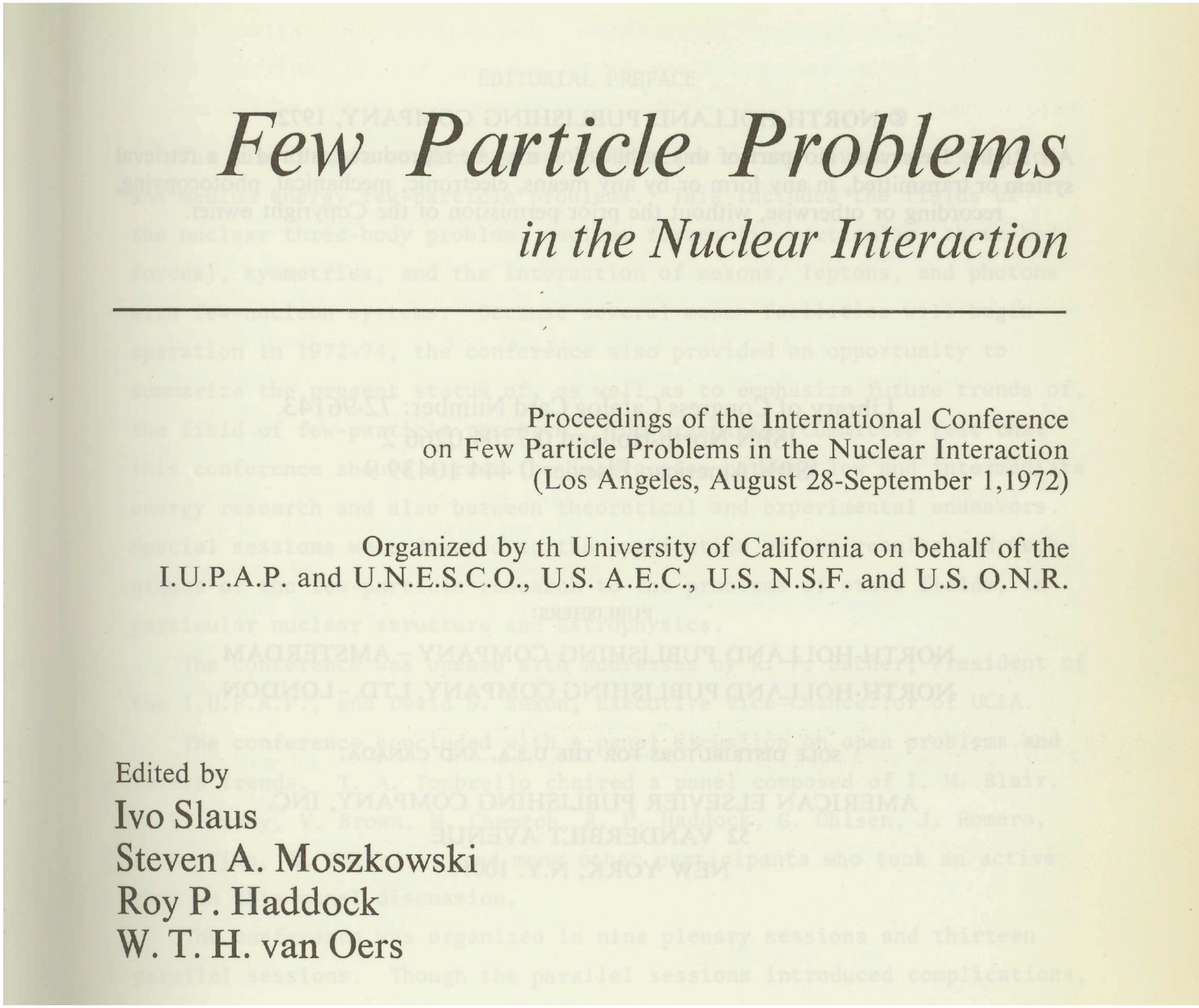
Heavy-Ion Elastic Scattering
and
Other Fortuitous Collaborations
(for me)

John Watson: Kent State University



Few Particle Problems
in the Nuclear Interaction

Proceedings of the International Conference
on Few Particle Problems in the Nuclear Interaction
(Los Angeles, August 28-September 1,1972)

Organized by th University of California on behalf of the
I.U.P.A.P. and U.N.E.S.C.O., U.S. A.E.C., U.S. N.S.F. and U.S. O.N.R.

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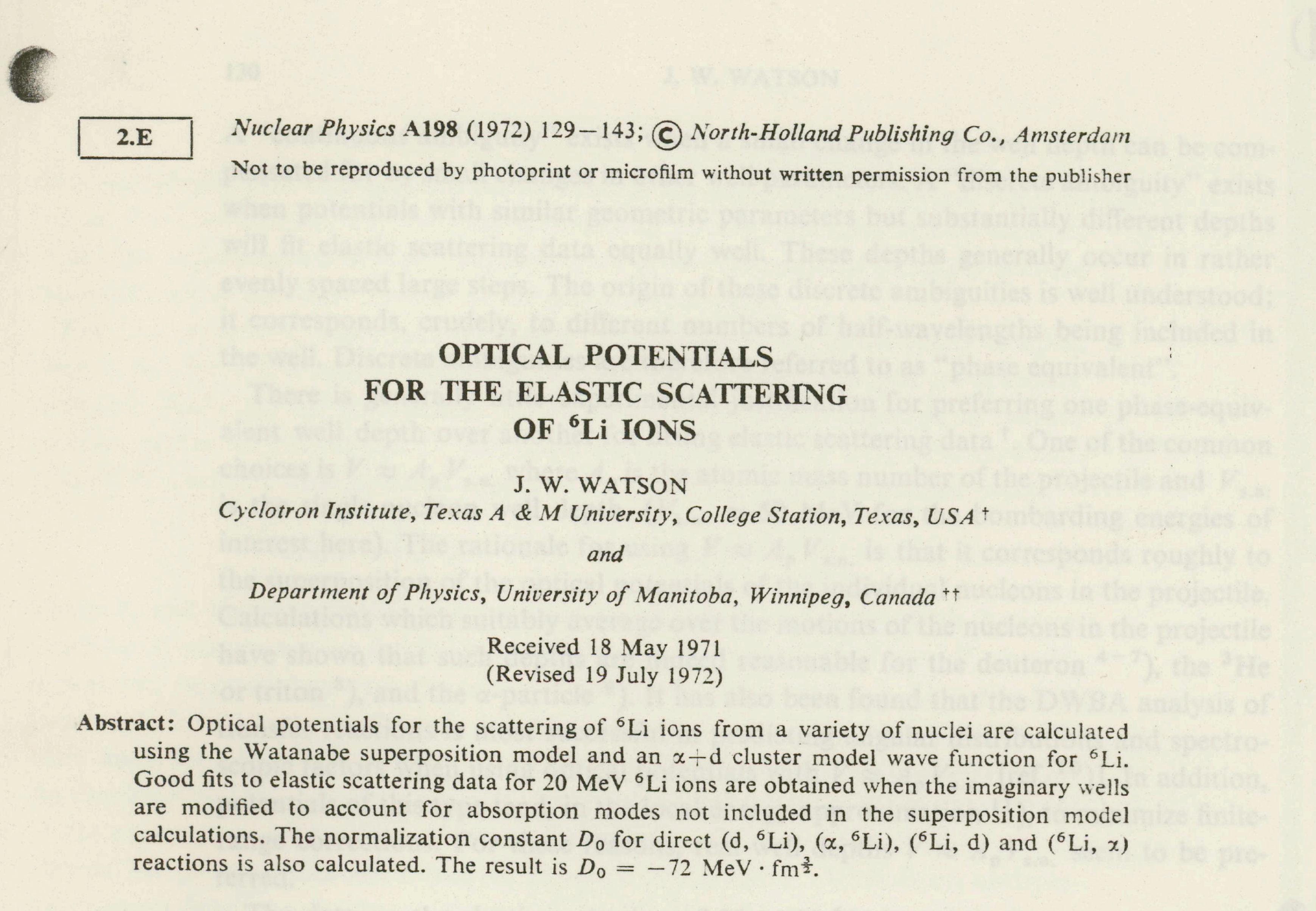

2.E

Nuclear Physics **A198** (1972) 129–143;

OPTICAL POTENTIALS FOR THE ELASTIC SCATTERING OF ^{6}Li IONS

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Received 18 May 1971
(Revised 19 July 1972)

Abstract: Optical potentials for the scattering of ^{6}Li ions from a variety of nuclei are calculated using the Watanabe superposition model and an $\alpha+d$ cluster model wave function for ^{6}Li. Good fits to elastic scattering data for 20 MeV ^{6}Li ions are obtained when the imaginary wells are modified to account for absorption modes not included in the superposition model calculations. The normalization constant D_0 for direct (d, ^{6}Li), (α, ^{6}Li), (^{6}Li, d) and (^{6}Li, α) reactions is also calculated. The result is $D_0 = -72$ MeV $\cdot$ fm$^{\frac{3}{2}}$.

$$V_{^6\mathrm{Li}}(r) = \int \{V_\alpha(r-\tfrac{1}{3}R)+V_\mathrm{d}(r+\tfrac{2}{3}R)\}|\psi(R)|^2\,\mathrm{d}R,$$

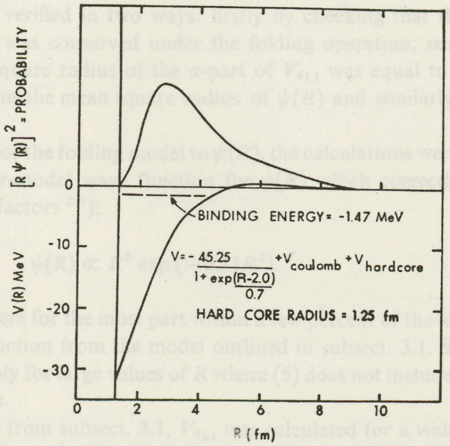


Fig. 1. The potential $V(R)$ for the α-d interaction and the resulting probability distribution for $\psi(R)$, the $\alpha+$d cluster model relative motion wave function for ^{6}Li.

3.1. THE CLUSTER-MODEL WAVE FUNCTION

The model of ^{6}Li used for these calculations has been discussed in considerable detail elsewhere [16,17]), and only a brief description will be presented here. The model may be summarized as follows:

(i) the ^{6}Li ground state consists of an α-particle and a deuteron in a relative $^3S_1$ state;

(ii) the α-particle and deuteron are unpolarized and are in their ground states;

(iii) the α-particle and deuteron interact through a potential $V(R)$ where R is the separation of their c.m.;

(iv) the potential $V(R)$ is a real, static, local potential which includes the Coulomb interaction, and

(v) the potential $V(R)$ has a repulsive core to allow for the effects of the exclusion principle.

The parameters of this model were adjusted to fit the most relevant facts about the ^{6}Li ground state. The model was required to predict correctly:

(a) the binding energy (1.47 MeV) of ^{6}Li with respect to break-up into $\alpha+$d;

(b) the low-energy $^3S_1$ α-d scattering phase shifts;

(c) the rms charge radius and the charge form factor for the ^{6}Li ground state (as determined from electron scattering).

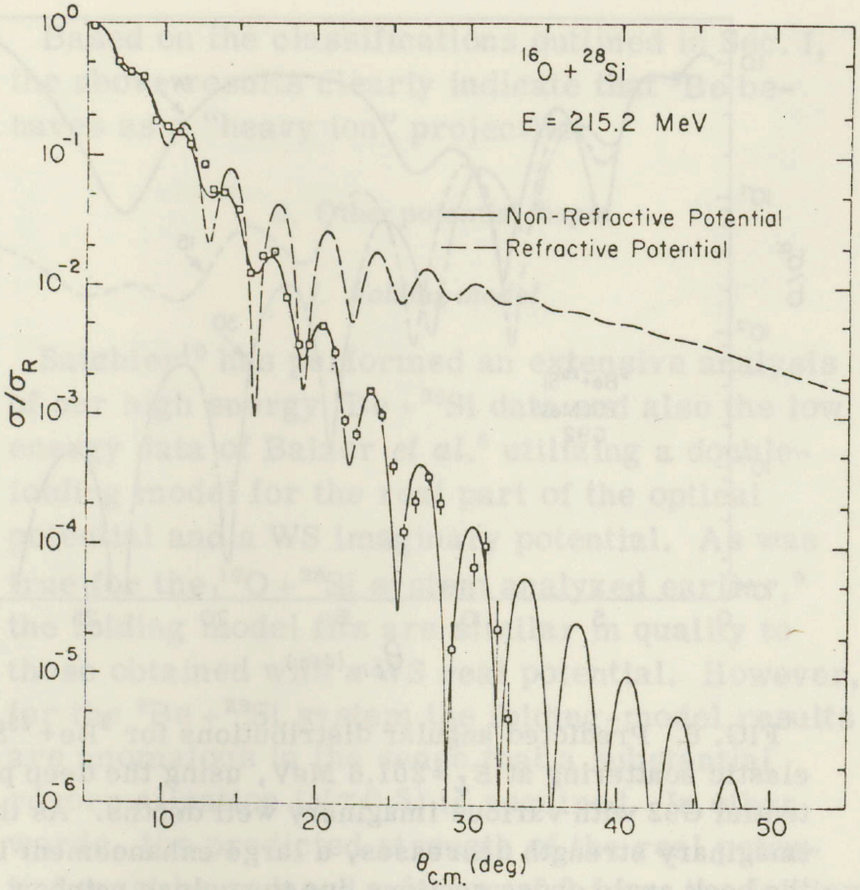
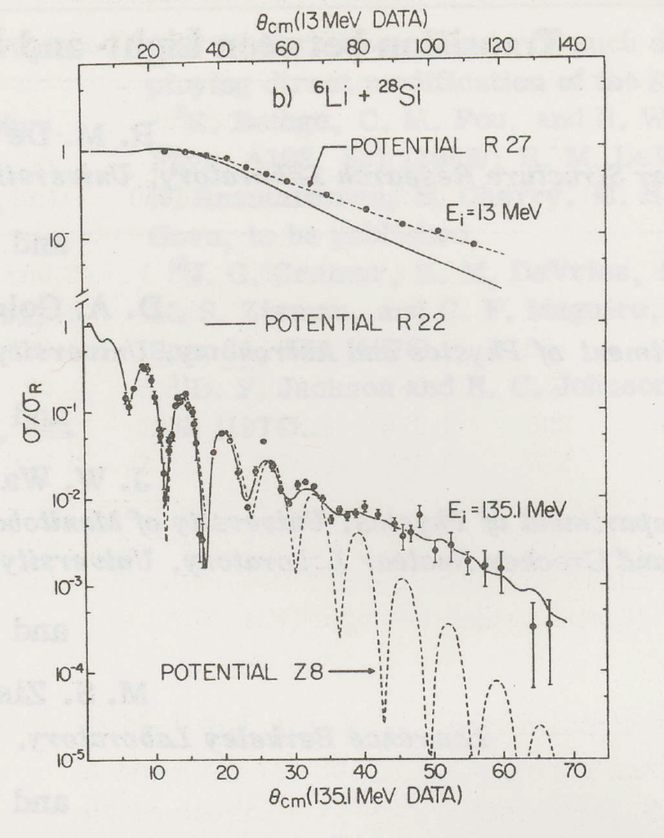


FIG. 2. ^{16}O+^{28}Si elastic scattering angular distribution at $E_L = 215.2$ MeV (taken from Ref. 1). The solid curve is a fit with a shallow WS potential, E18, and the dashed curve is a prediction using the deeper potential S75 of Table II. Although the deep potential predicts a substantial enhancement of the back angle cross sections due to the existence of nuclear rainbow scattering, the data show no such effect.



^{6}Li + ^{28}Si

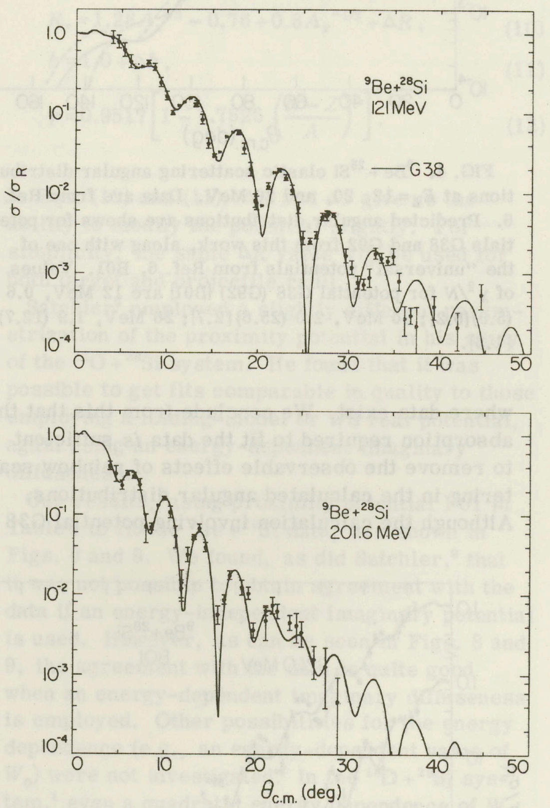
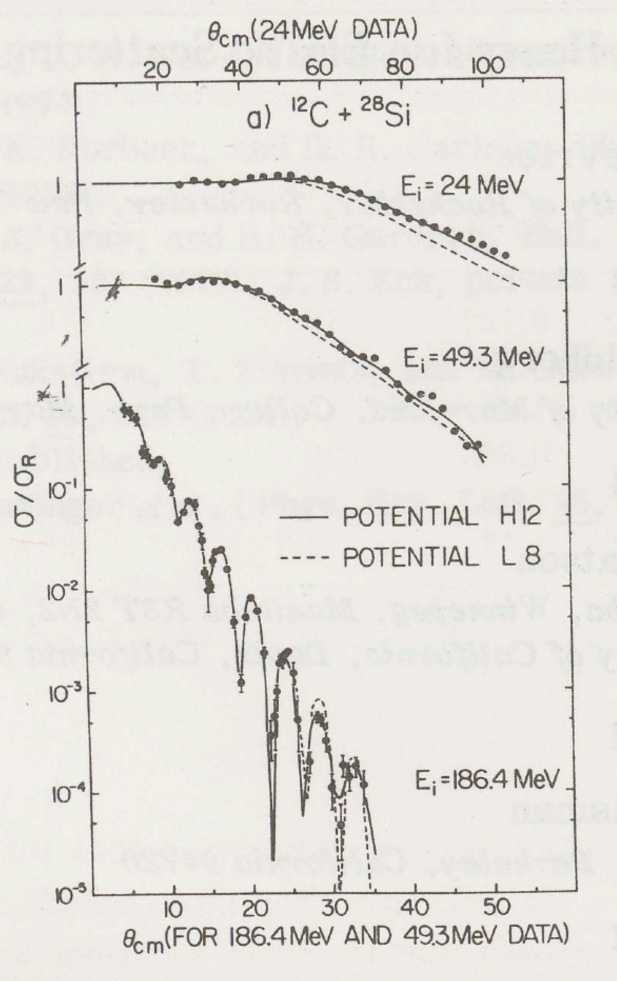


FIG. 3. ^{9}Be+^{28}Si elastic scattering angular distributions at $E_L = 13$, 121.0, and 201.6 MeV. The solid curve is a fit to all three energies using potential G38. Values of χ^2/N for potential G38 are 13 MeV, 1.2; 121.0 MeV, 10.2; 201.6 MeV, 1.8.

^{9}Be + ^{28}Si



^{12}C + ^{28}Si

Phys. Rev. Lett. 39, 1104 - 1107 (1977)

Distinguishing between Stars and Galaxies Composed of Matter and Antimatter Using Photon Helicity Detection

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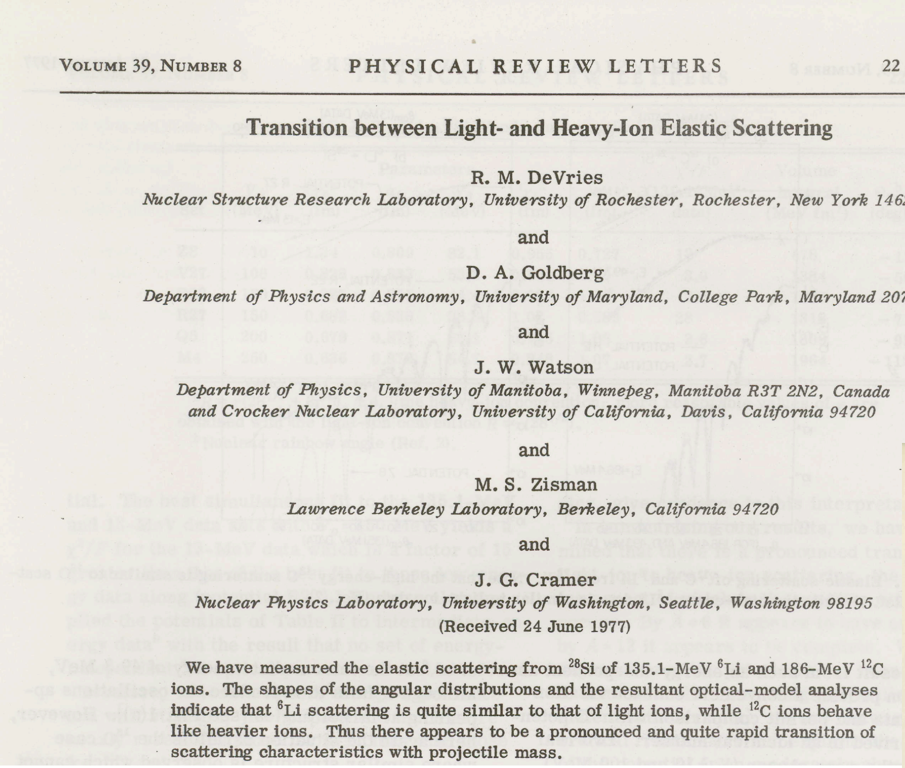
Received 14 February 1977; revised 12 July 1977

The positrons produced in fusion processes in matter stars will have predominantly a "right" helicity due to the nonconversation of parity in weak interactions. This helicity is transferred to bremsstahlung and forward in-flight annilation radiation, which will be right-circularly polarized. In antimatter stars, CP symmetry will make the equivalent radiation left-circularly polarized. The helicity of such radiation can be used to distinguish between astronomical objects composed of matter and antimatter.



VOLUME 39, NUMBER 8 PHYSICAL REVIEW LETTERS 22 AUGUST 1977

Transition between Light- and Heavy-Ion Elastic Scattering

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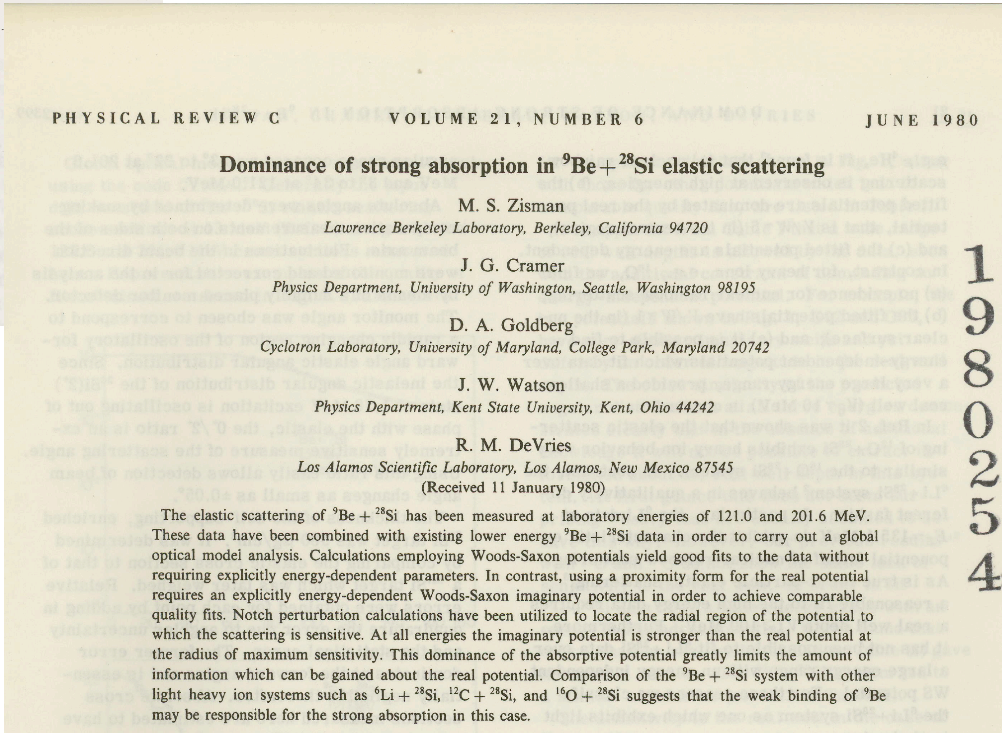
(Received 24 June 1977)

We have measured the elastic scattering from ^{28}Si of 135.1-MeV ^{6}Li and 186-MeV ^{12}C ions. The shapes of the angular distributions and the resultant optical-model analyses indicate that ^{6}Li scattering is quite similar to that of light ions, while ^{12}C ions behave like heavier ions. Thus there appears to be a pronounced and quite rapid transition of scattering characteristics with projectile mass.



PHYSICAL REVIEW C VOLUME 21, NUMBER 6 JUNE 1980

Dominance of strong absorption in ^{9}Be + ^{28}Si elastic scattering

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(Received 11 January 1980)

The elastic scattering of ^{9}Be + ^{28}Si has been measured at laboratory energies of 121.0 and 201.6 MeV. These data have been combined with existing lower energy ^{9}Be + ^{28}Si data in order to carry out a global optical model analysis. Calculations employing Woods-Saxon potentials yield good fits to the data without requiring explicitly energy-dependent parameters. In contrast, using a proximity form for the real potential requires an explicitly energy-dependent Woods-Saxon imaginary potential in order to achieve comparable quality fits. Notch perturbation calculations have been utilized to locate the radial region of the potential to which the scattering is sensitive. At all energies the imaginary potential is stronger than the real potential at the radius of maximum sensitivity. This dominance of the absorptive potential greatly limits the amount of information which can be gained about the real potential. Comparison of the ^{9}Be + ^{28}Si system with other light heavy ion systems such as ^{6}Li + ^{28}Si, ^{12}C + ^{28}Si, and ^{16}O + ^{28}Si suggests that the weak binding of ^{9}Be may be responsible for the strong absorption in this case.

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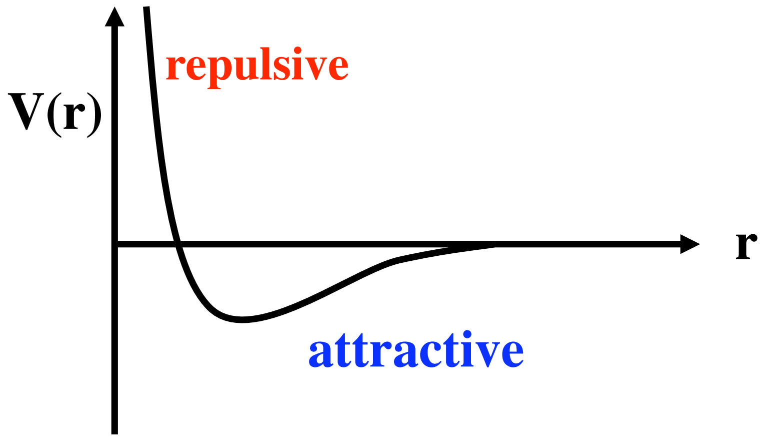
Short-Range Correlations

“The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory”

(Nuclear Science: A Long Range Plan, The DOE/NSF Nuclear Science Advisory Committee, Feb. 1996 [1].)

The N-N Interaction and the Shell Model

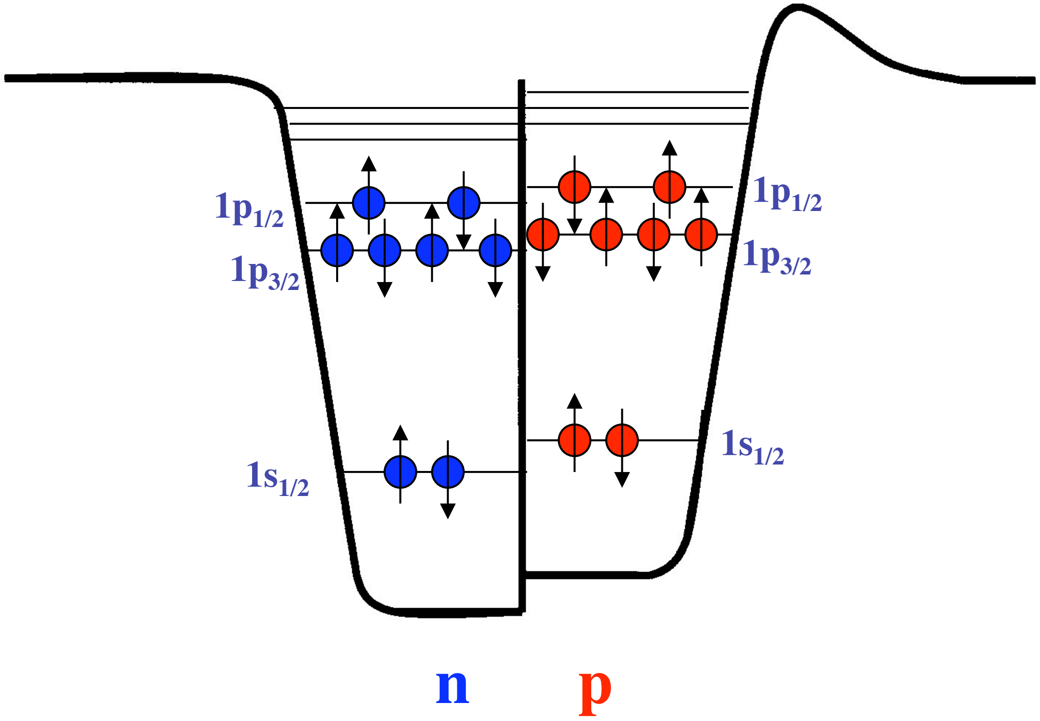
The N-N interaction is attractive at a typical distance of 2 fm, but highly repulsive at distances < 0.5 fm.



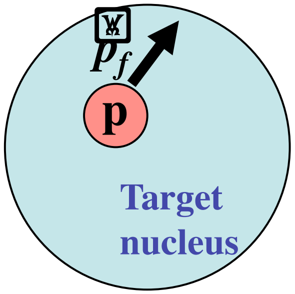
The attractive part of this interaction between all of the pairs of nucleons in a nucleus, in combination with the Pauli principle, produces a mean field in which the neutrons and protons move like independent particles in well-defined quantum states.

Maria Mayer and J.H.D. Jensen received the Nobel Prize in 1963 for developing the shell model.

Simple, schematic, shell-model picture of ^{16}O (8n,8p)



One of the best ways to study the shell model is with “knockout” reactions (also called “quasi-elastic scattering”).



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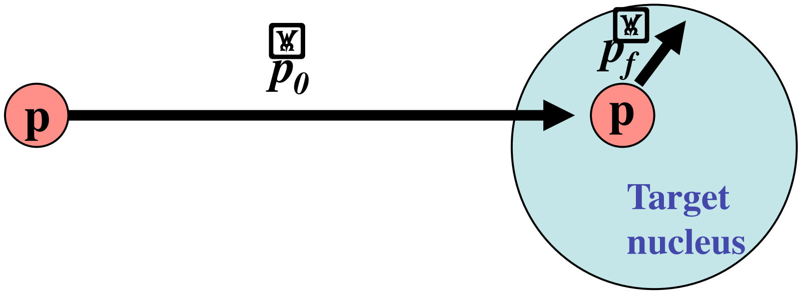
Let’s consider a “(p,2p)” reaction.



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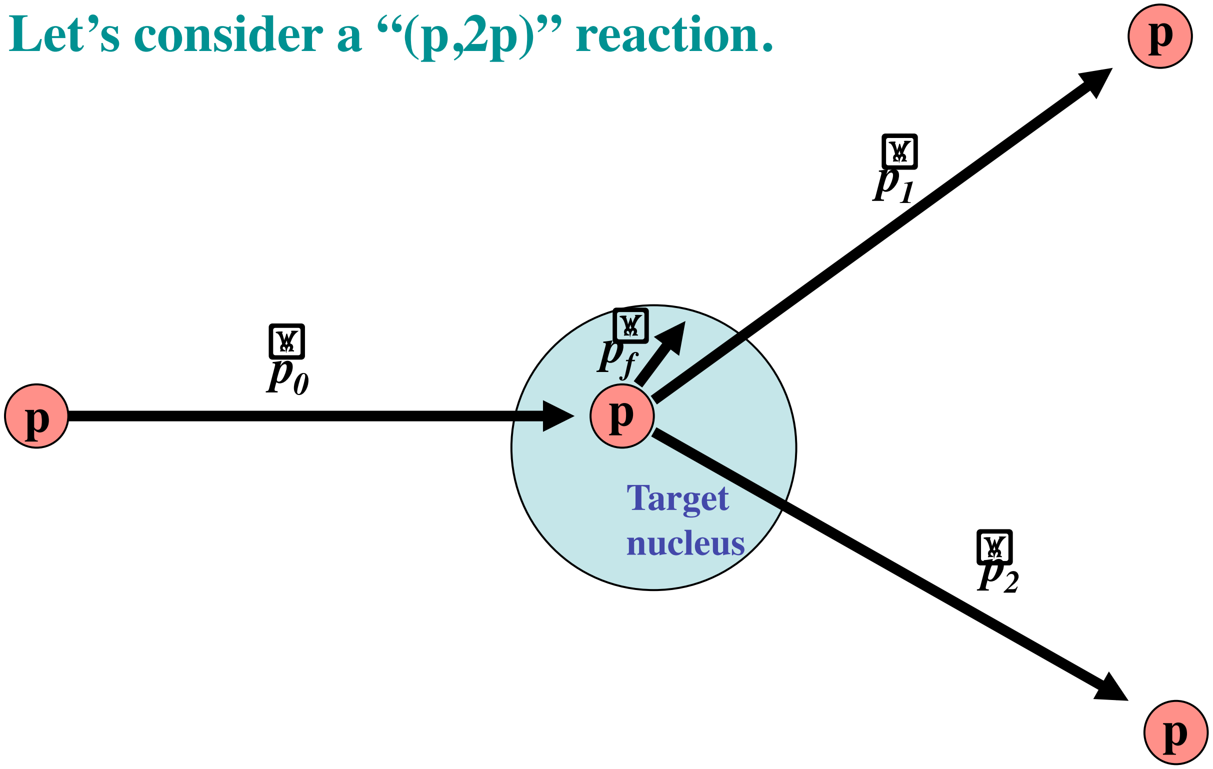

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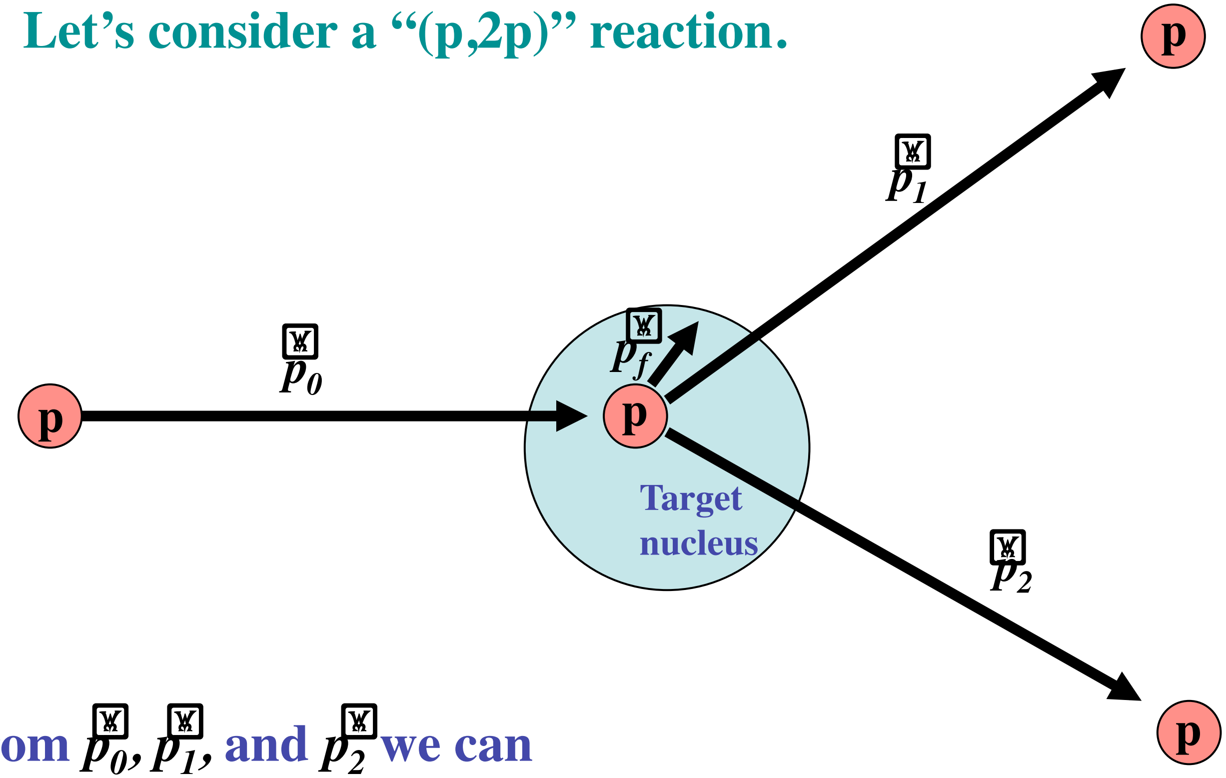
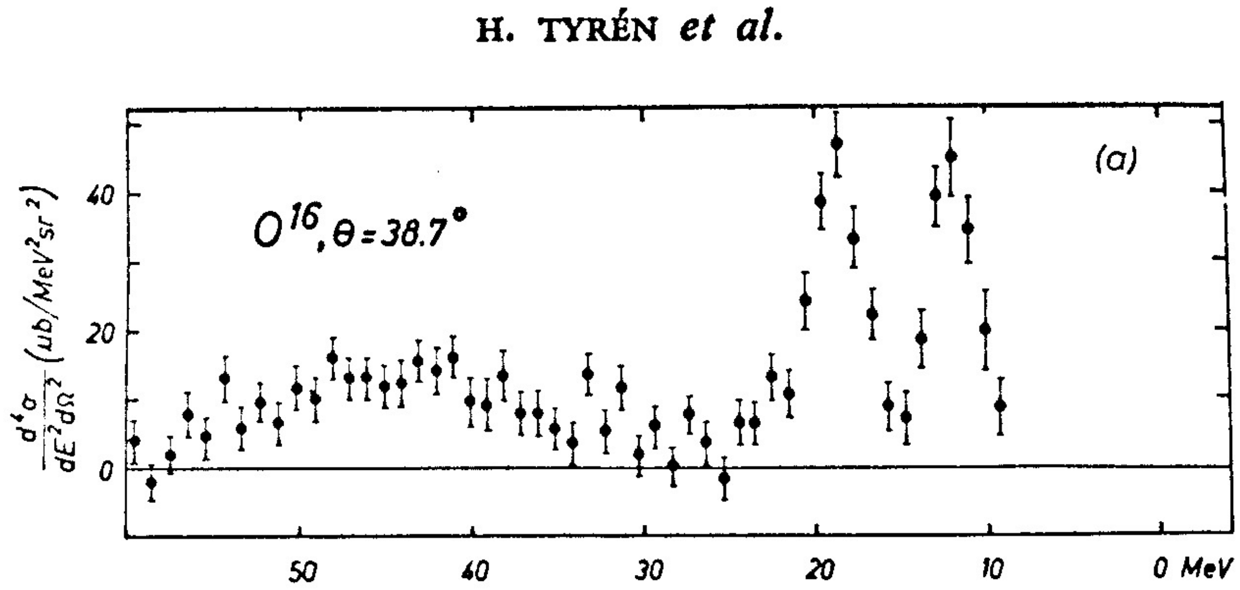


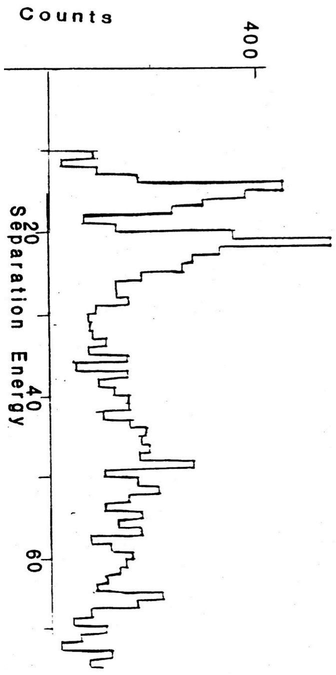
From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the *separation energy* of each knocked-out proton is.

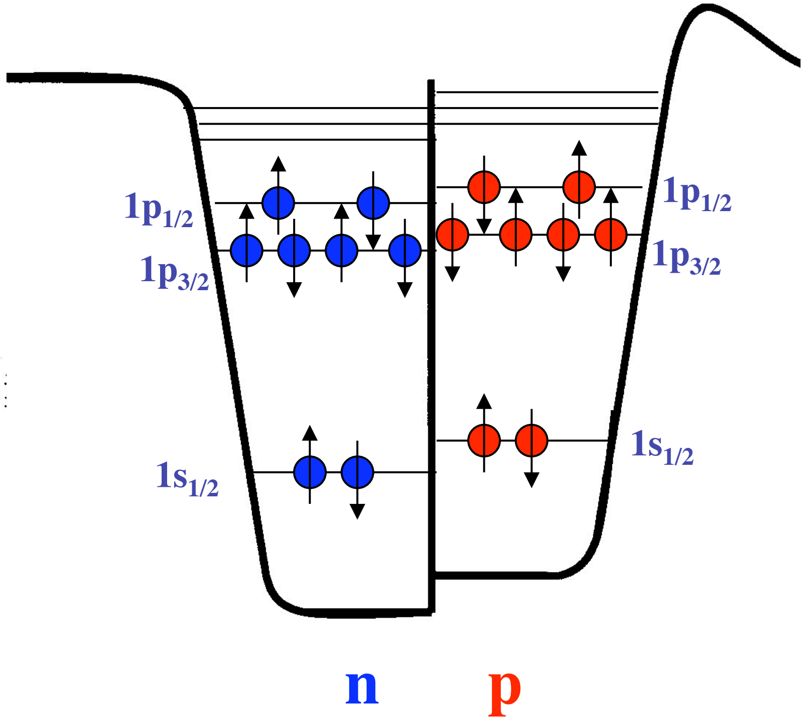
^{16}O(p,2p) at 460 MeV from the Enrico Fermi Institute University of Chicago: Nucl. Phys. **79,** 321 (1966).

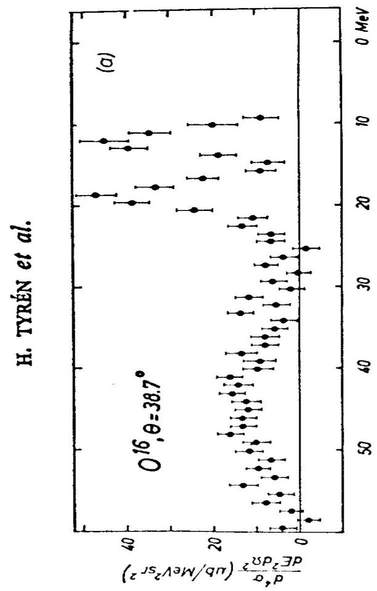


Separtion Energy (MeV)

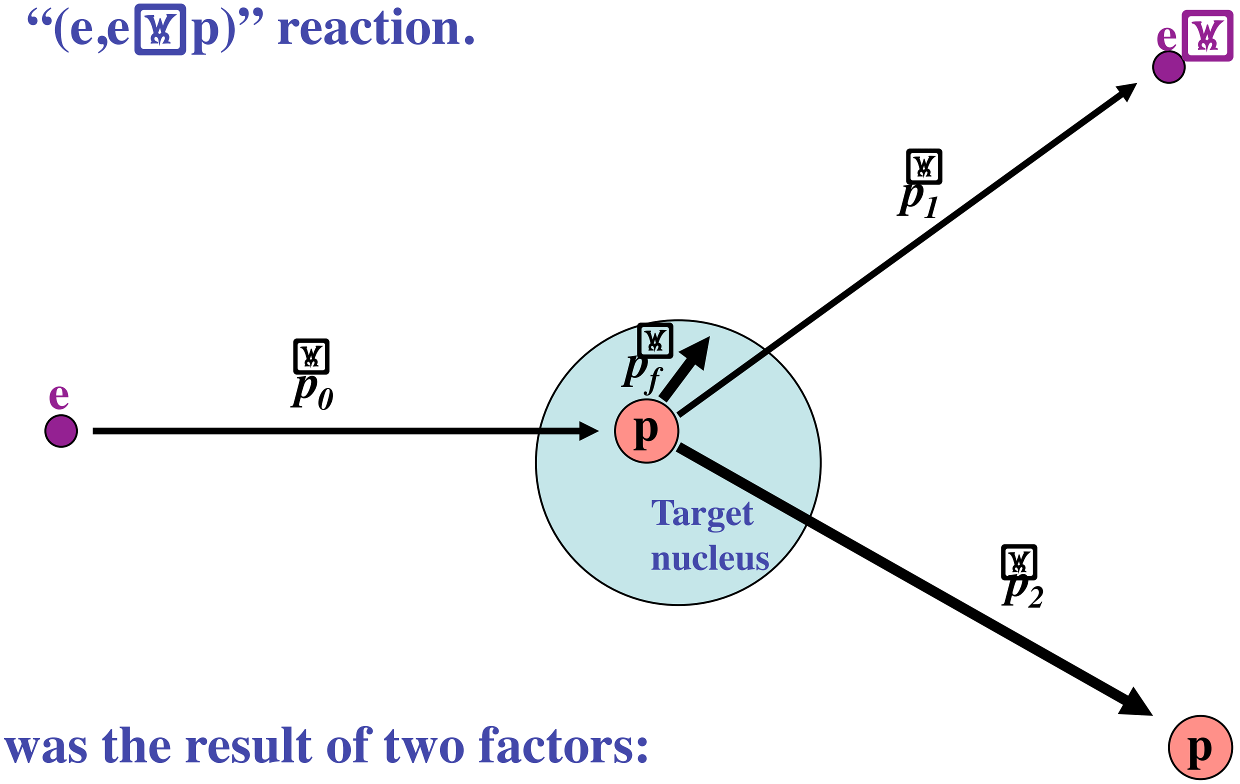
Simple, schematic, shell-model picture of ^{16}O (8n,8p)







During the ‘80s and ‘90s the premier tool for knockout-reaction spectroscopy became the “(e,e′p)” reaction.

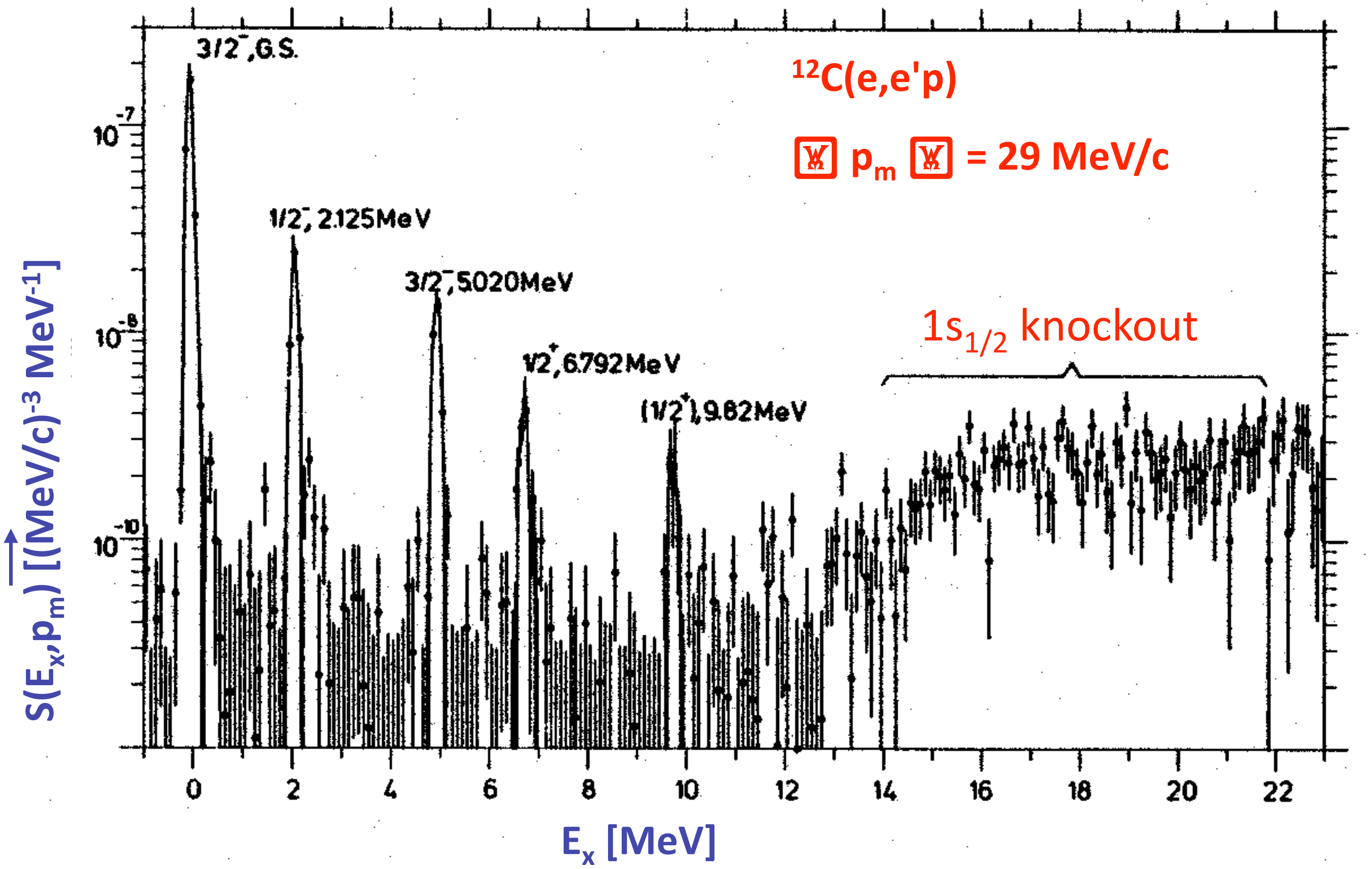


This was the result of two factors:

1) Improvements in electron accelerators.

2) The ability to do “exact” reaction calculations because the e-p interaction is electromagnetic.

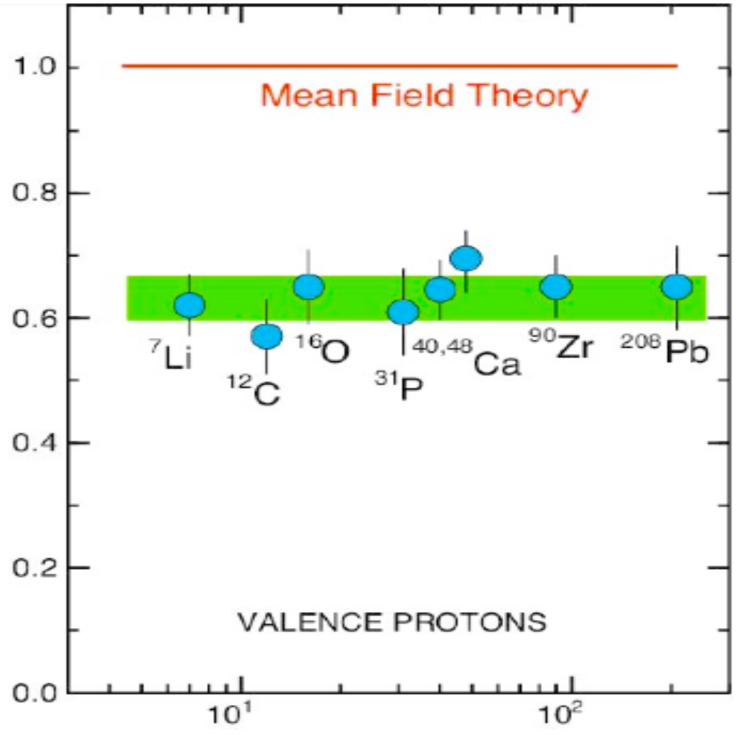
1988: NIKHEF



G. van der Steenhoven *et al.*, Nucl. Phys. **A484**, 445 (1988).

Something is *MISSING!*

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



L. Lapikas, Nucl. Phys. A553, 297c (1993)

There must be more!

The N-N Interaction and Correl

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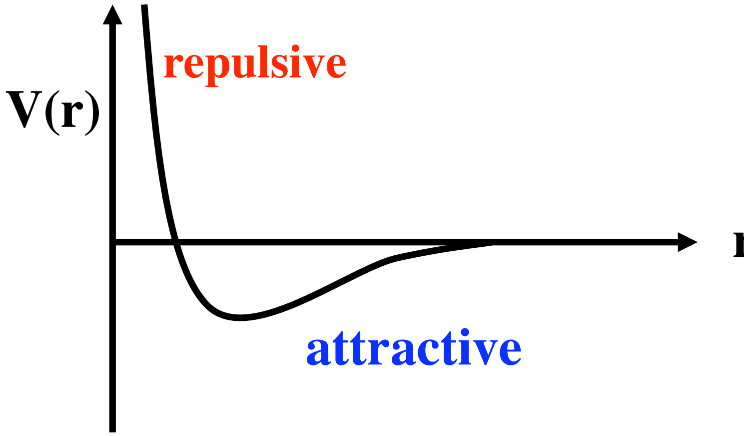
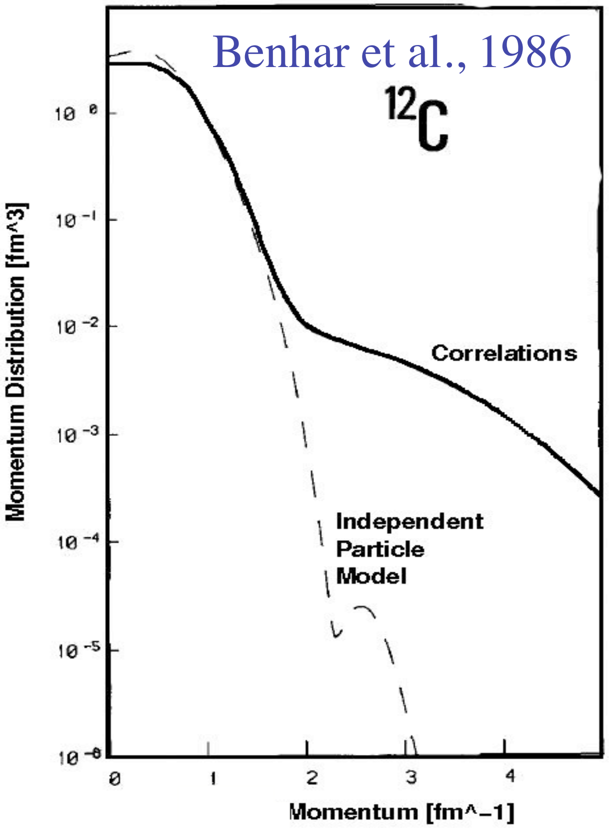
but highly repulsive at distances < 0.5 fm.





The short-range repulsion leads to phenomena such as the saturation of central nuclear densities. But it also must manifest itself in the wave functions of the nucleons in the nucleus. Because it is short range, high-momentum components should be affected. Typically we might expect N-N interactions at short range to produce pairs of nucleons with large, roughly equal, and opposite momenta.

Experiment E850

The EVA Collaboration

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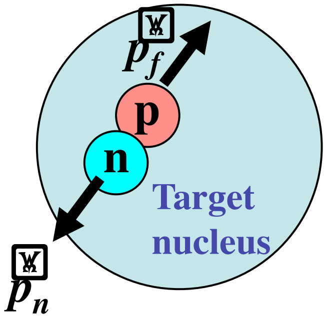
Kyoto Univ.

Instead of considering a single proton in a nucleus, let’s consider a short-range correlated neutron-proton pair.

Let’s start with a (p,2p) reaction.



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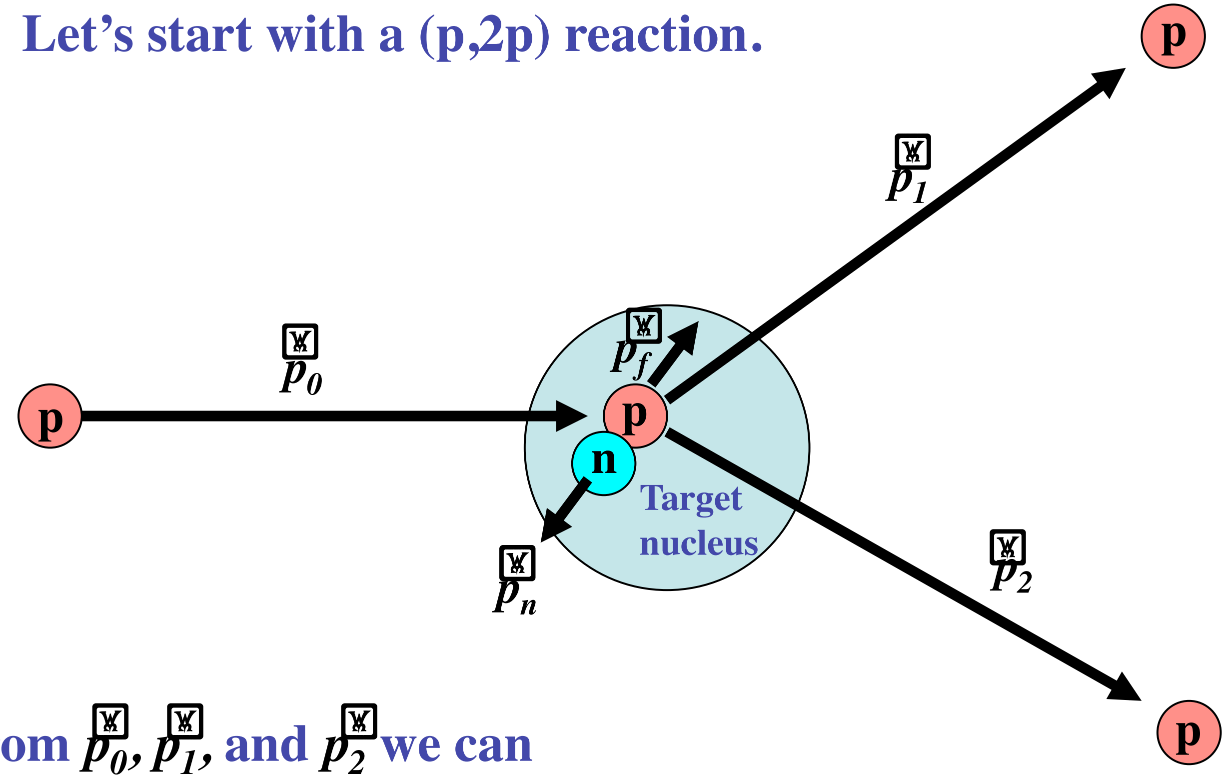

From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

Instead of considering a single proton in a nucleus, let’s consider a **short-range correlated** neutron-proton pair.

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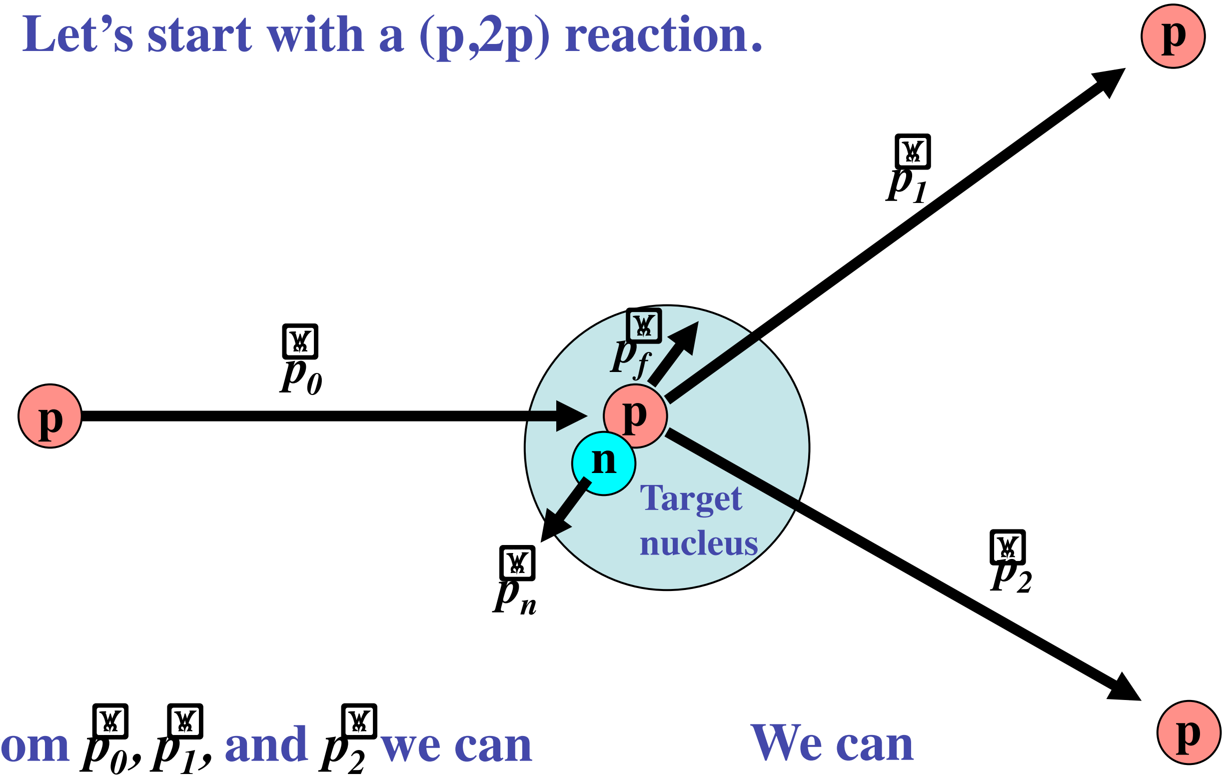
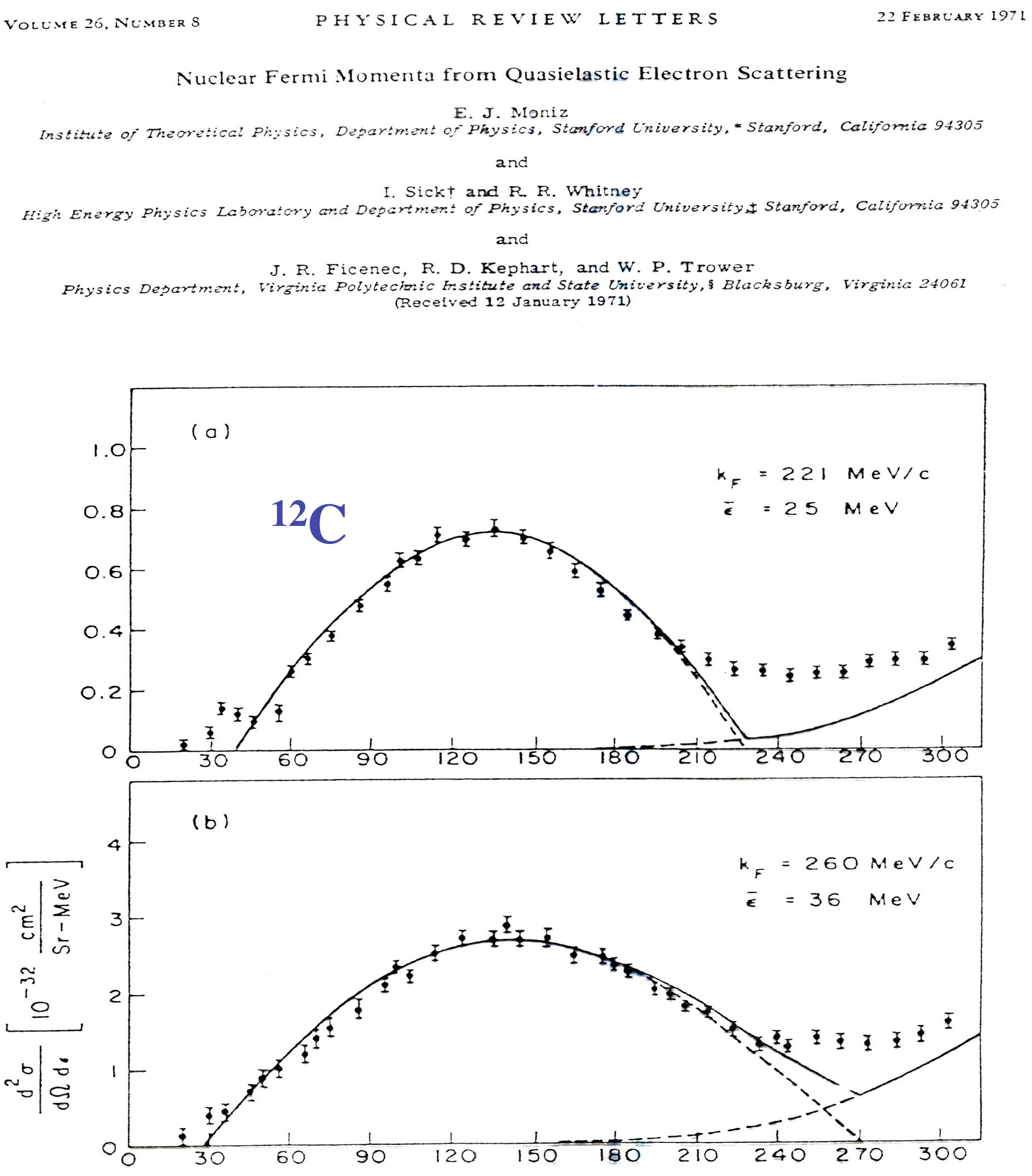


From $\vec{p}_0$, $\vec{p}_1$, and $\vec{p}_2$ we can deduce, event-by-event what $\vec{p}_f$ and the binding energy of each knocked-out proton is.

We can then compare $\vec{p}_n$ with $\vec{p}_f$ and see if they are roughly “back to back.”



Volume 26, Number 8 PHYSICAL REVIEW LETTERS 22 February 1971

Nuclear Fermi Momenta from Quasielastic Electron Scattering

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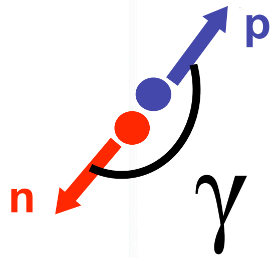
(Received 12 January 1971)

k_F = 221 MeV/c



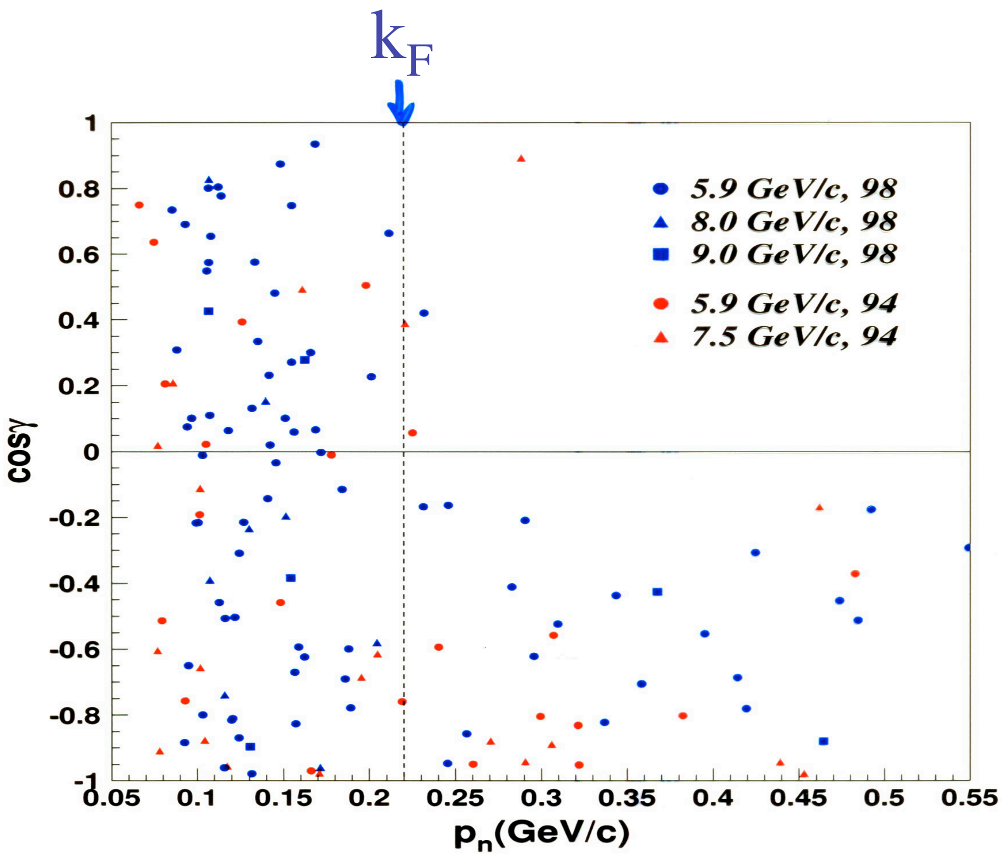


Figure 22: cosγ vs. p_n for ^{12}C(p,2p+n) events. The vertical line at 0.22 GeV/c corresponds to k_F, the Fermi momentum for ^{12}C.

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.

2. The improved resolution from using light cone variables.

3. The small deBroglie wavelength of the incident protons:

   □ = h/p = hc/pc = 2□ □ 0.197 GeV-fm/(6 Gev)

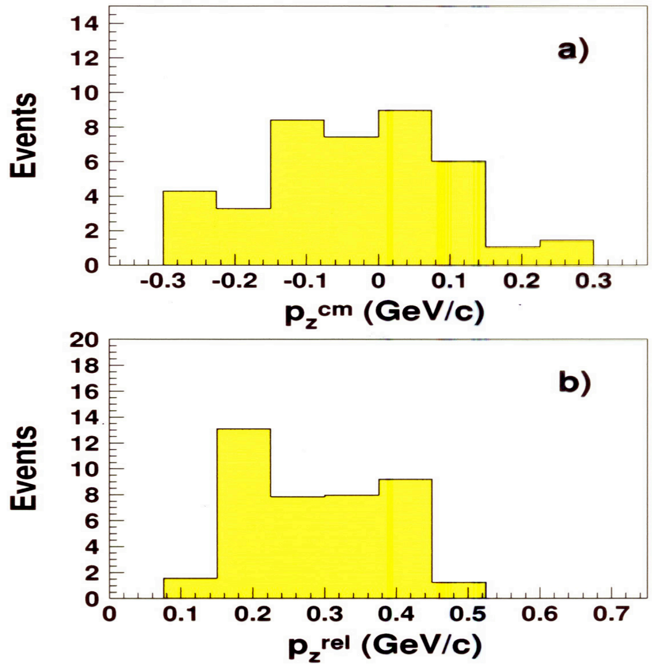
   □ 0.2 fm.

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

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
⊠ = 0.143 ⊠ 0.017 GeV/c

Remember this one

Centroid = 0.289 ⊠ 0.017 GeV/c
⊠ = 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".

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

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

Recent Development

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

by

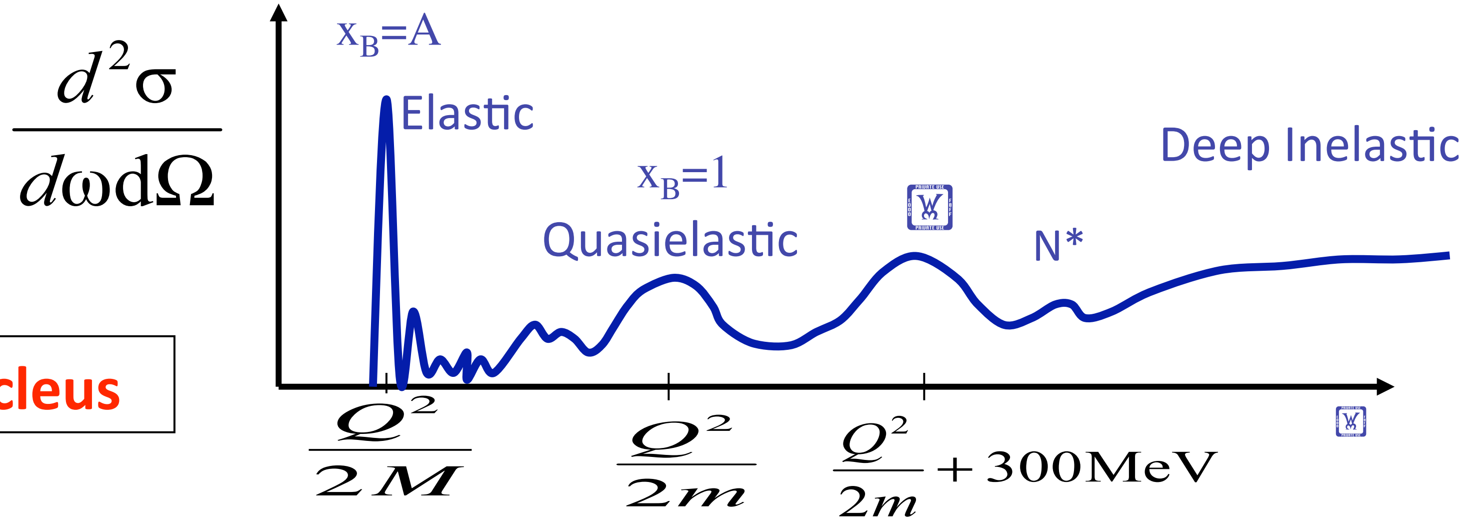
E. Piasetzky, M Sargsian, L. Frankfurt, M Strikman
and J. W. Watson
Phys. Rev. Lett., 20 October 2006

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

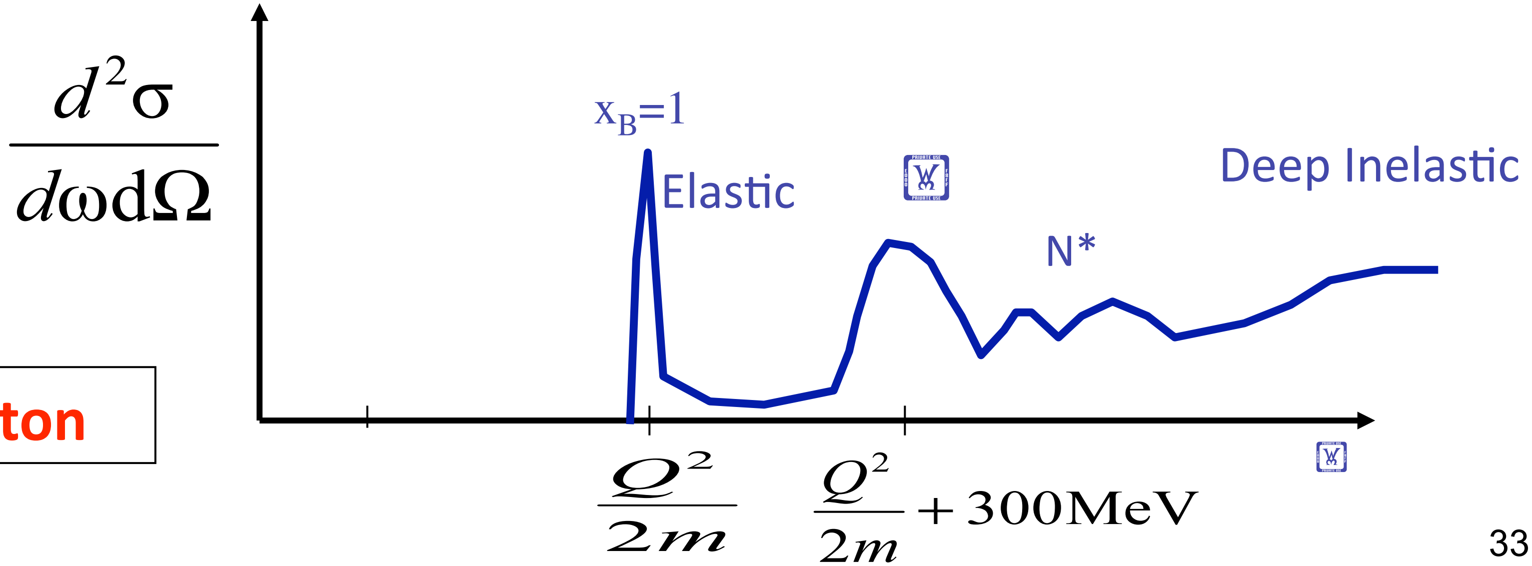
Conclusion: 92 ± 18% of high-momentum protons have correlated neutrons.

A. A. Tang et al., Phys. Rev. Lett. <u>90</u>, 042301 (2003)

Electron Scattering at Fixed Q^2



Nucleus



Proton

CLAS A(e,e') Data

K. Sh. Egiyan *et al*., Phys. Rev. C **68** (2003) 014313.

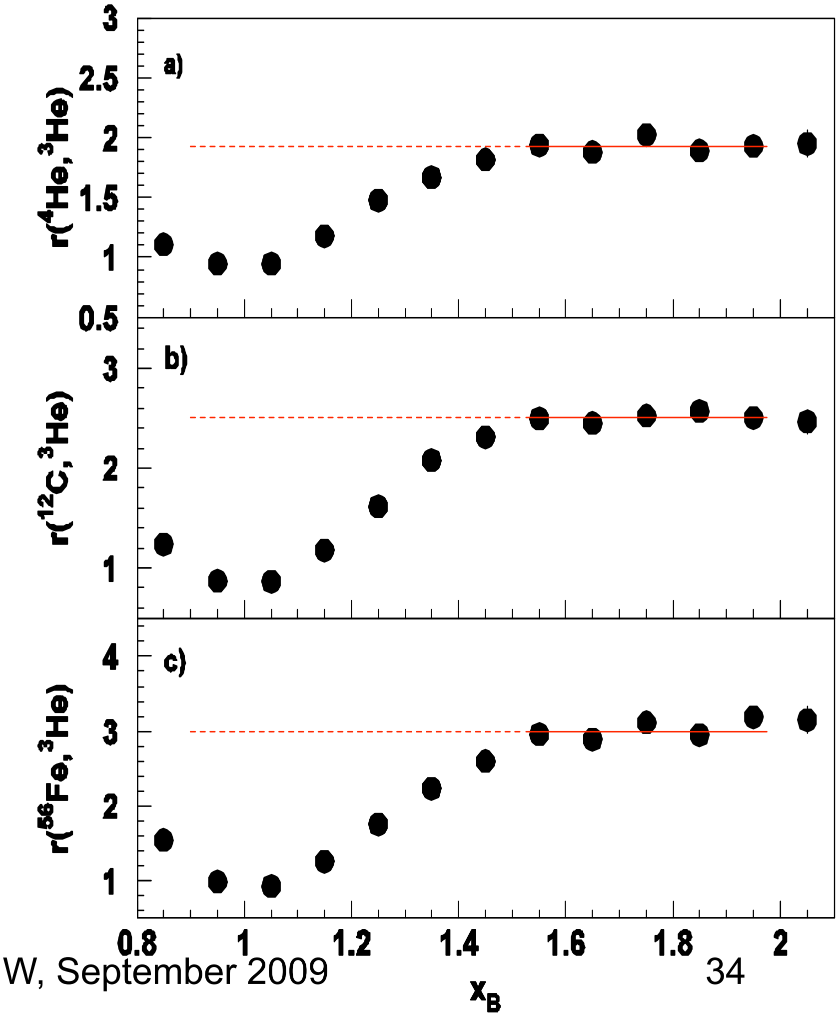
Originally done with SLAC data by D.B. Day *et al*., Phys. Rev. Lett. 59 (1987) 427.

$$x = \frac{Q^2}{2M\omega} > 1.5 \quad \text{and} \quad Q^2 > 1.4\ [\mathrm{GeV/c}]^2$$

then

r(A,3He) = a2n(A)/a2n(3He)

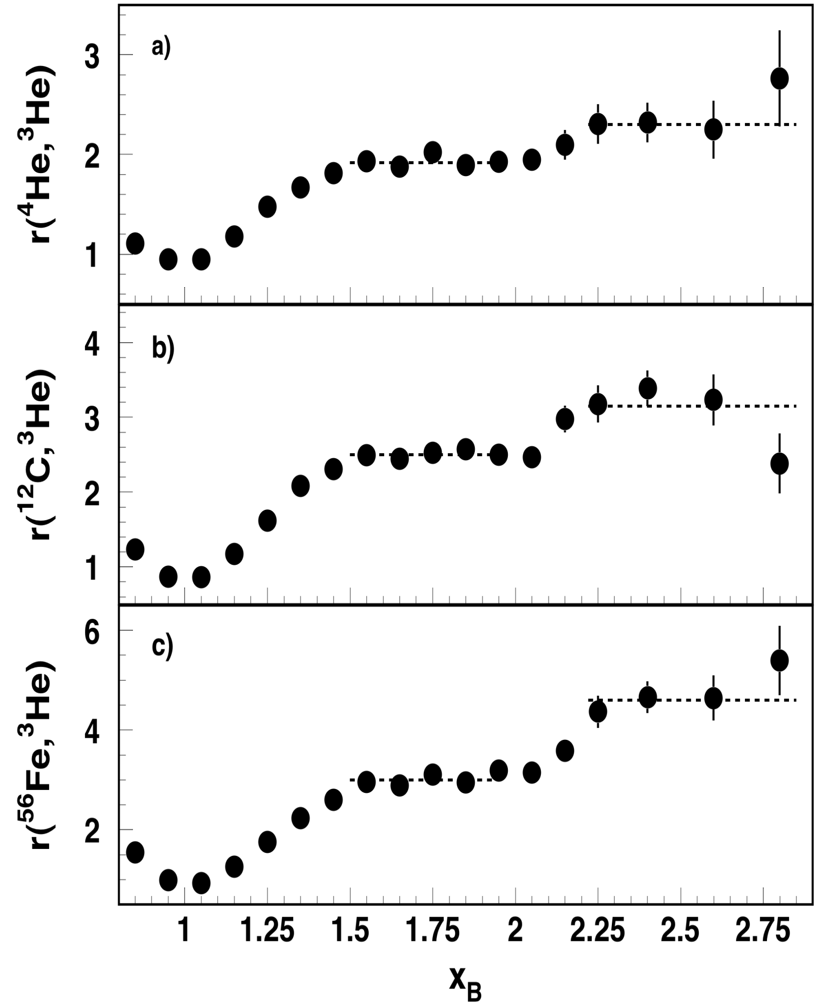
The observed *scaling* means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with A>3 relative to 3He



Estimate of ^{12}C Two and Three Nucleon SRC

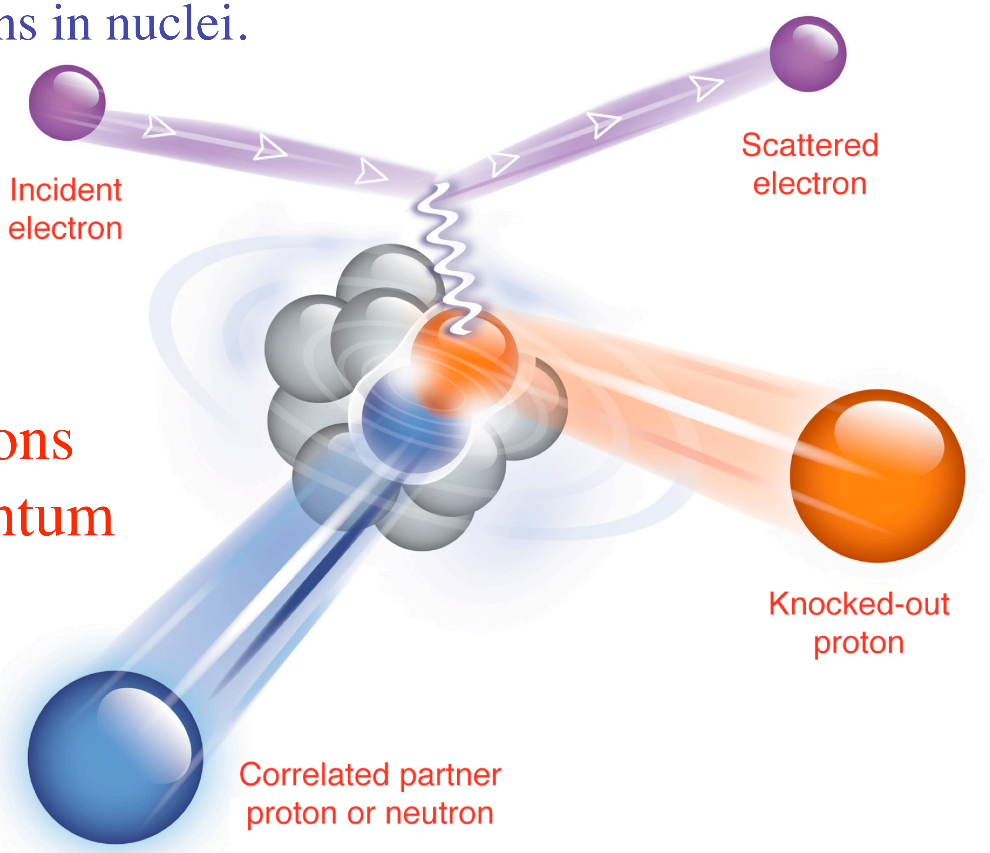
K. Sh. Egiyan *et al*., Phys. Rev. Lett. **96** (2006) 082501.

- K. Egiyan *et al*. related the known correlations in deuterium and previous r(^{3}He,D) results to find:
- ^{12}C 20% two nucleon SRC
- ^{12}C <1% three nucleon SRC



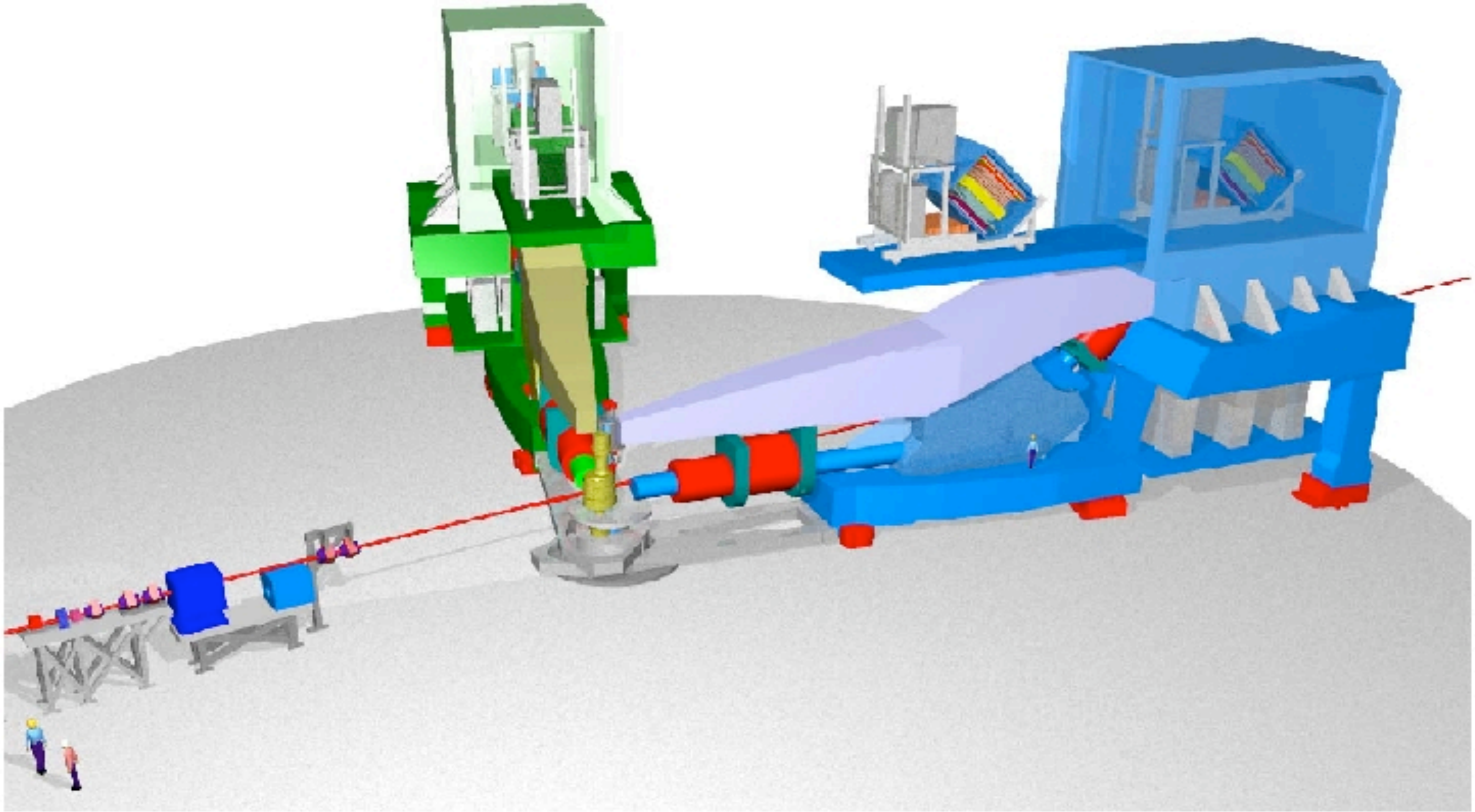
E01-105: A customized (e,e'pN) Measurement

To study nucleon pairs at close proximity and their contributions to the large momentum tail of nucleons in nuclei.

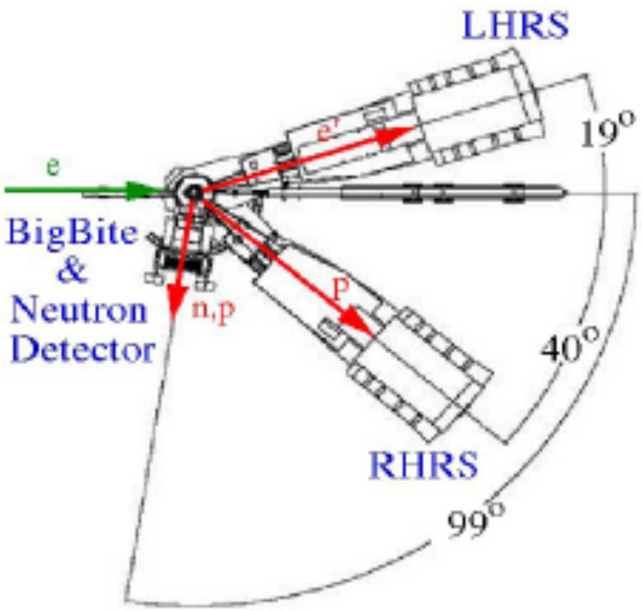


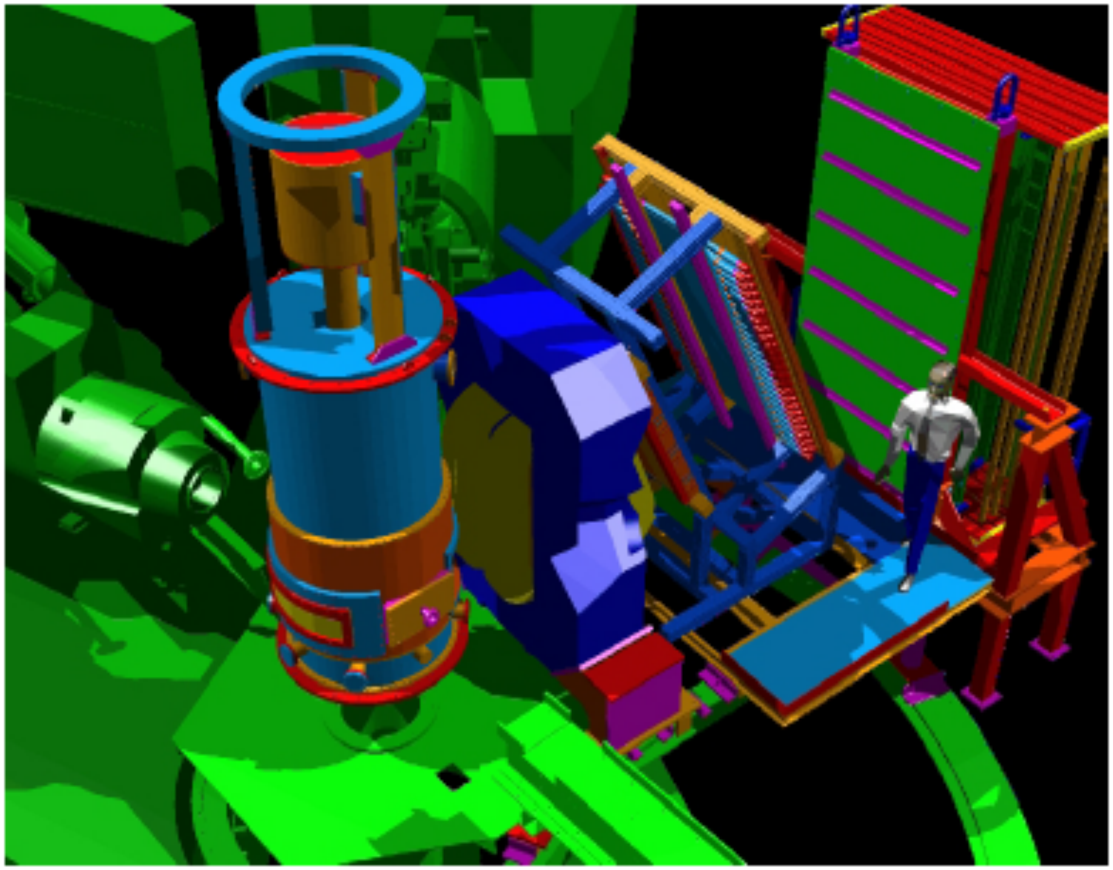
A pair with "large" relative momentum between the nucleons and small center of mass momentum

- high Q2 to minimize MEC
- x>1 to suppress isobar contributions
- anti-parallel kinematics to suppress FSI



New Equipment for the Experimental Setup

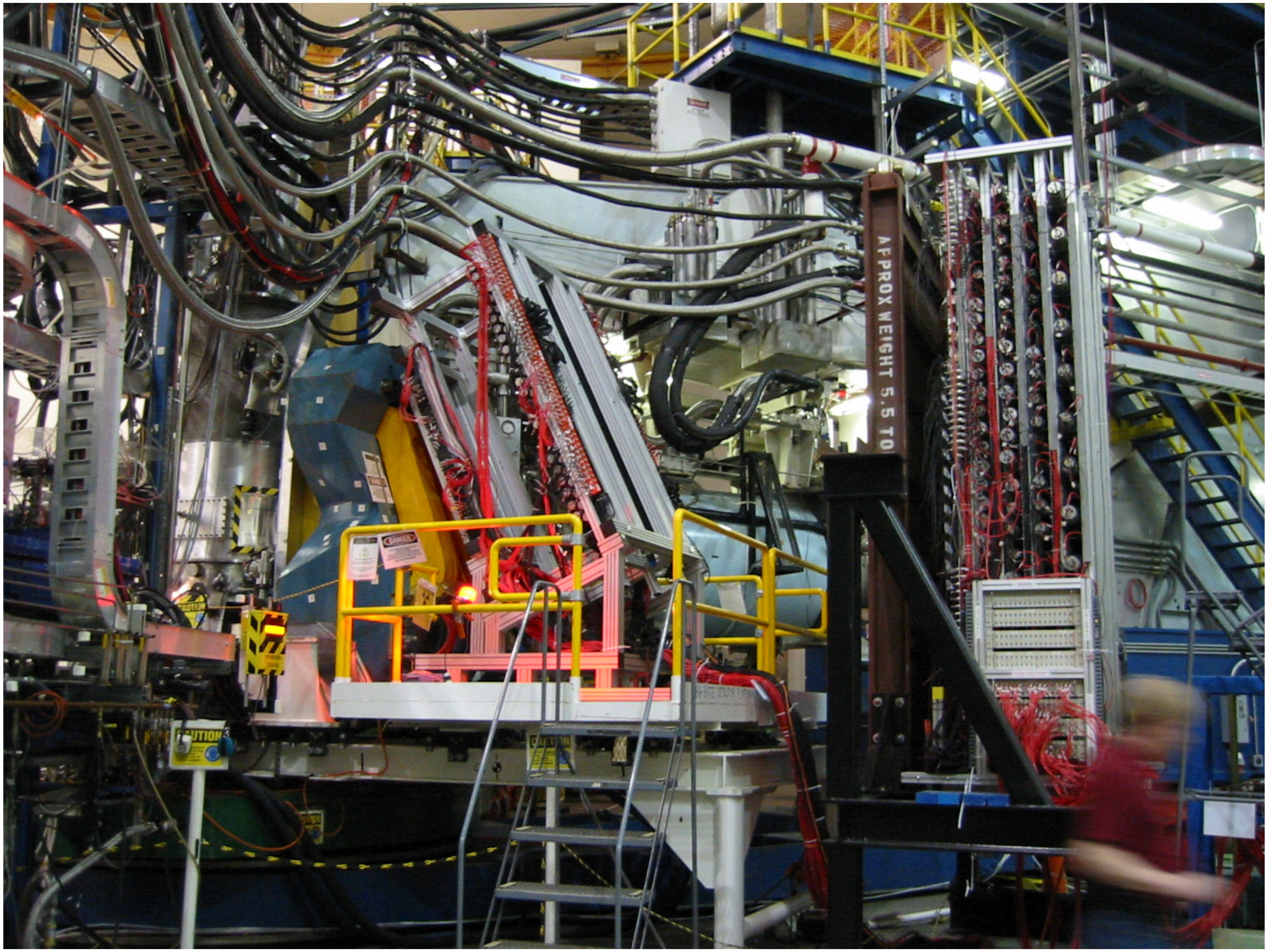


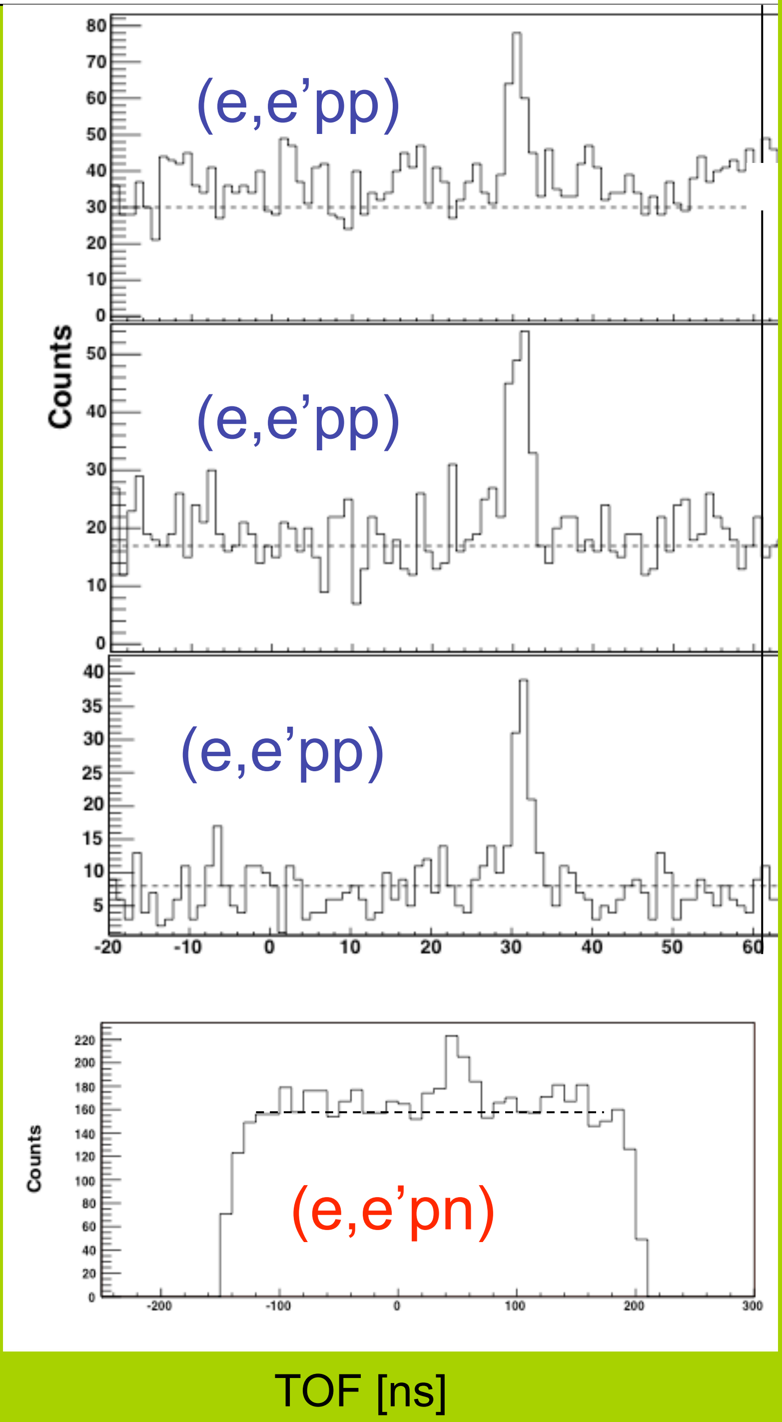


- New Scattering Chamber
- New BigBite Hadron Spectrometer (100 msr)
- New Low Energy Neutron Detector

The neutron detector array consisted of 88 bars of plastic scintillator, with a PMT on each end of each bar, for "mean timing."

These were gathered from around the world.


APPROX WEIGHT 5.5 TO



P_{mis}="300" MeV/c

(Signal : BG= 1.5:1)

P_{mis}="400" MeV/c

(Signal : BG= 2.3:1)

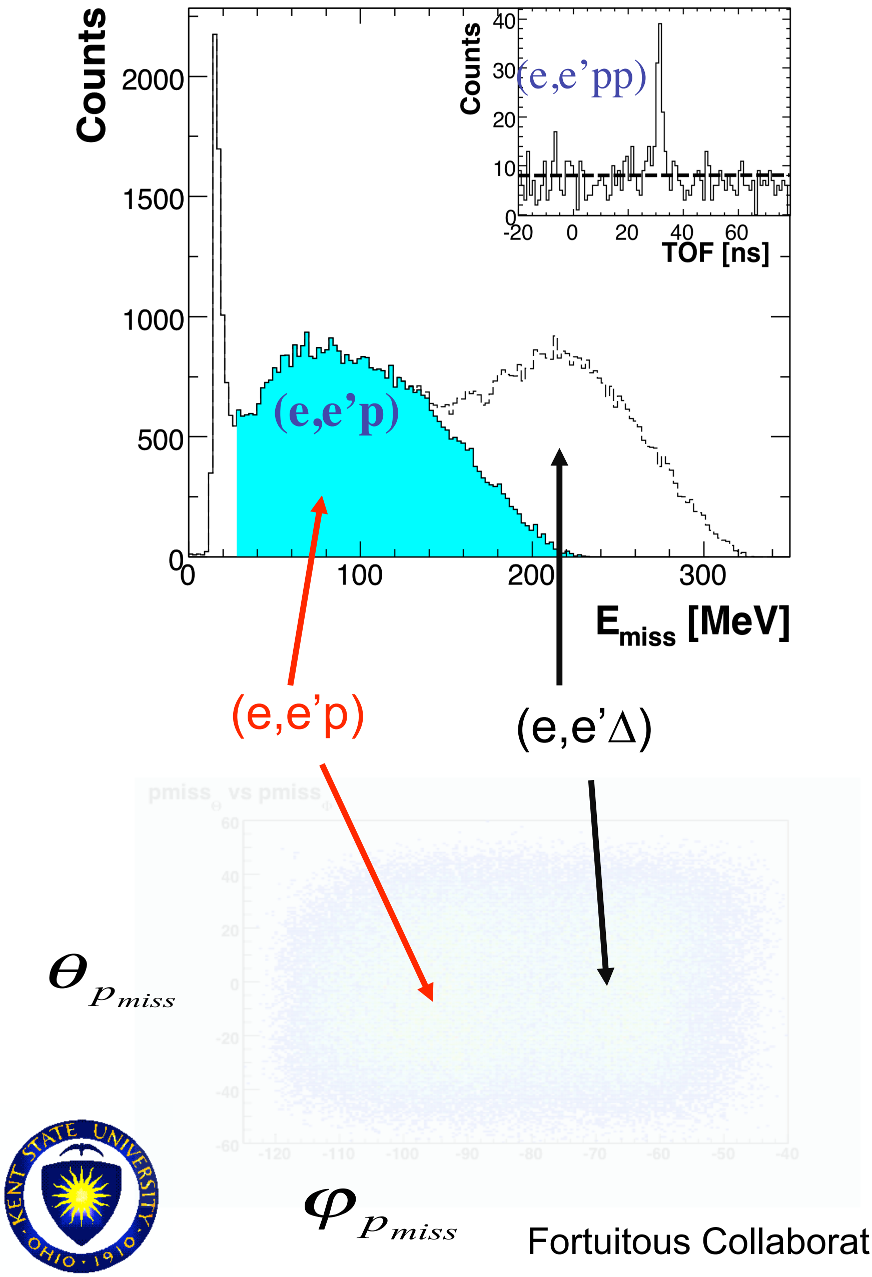
P_{mis}="500" MeV/c

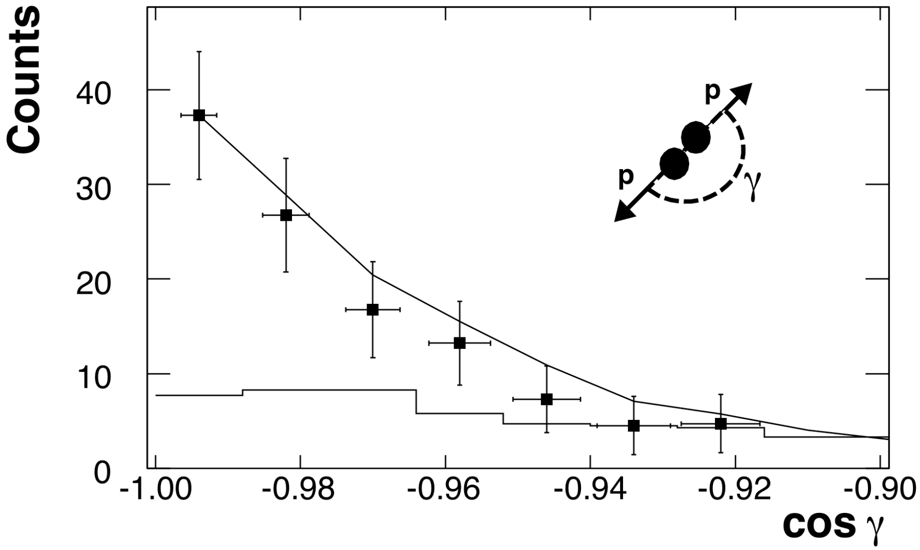
(Signal : BG= 4:1)

P_{mis}="500" MeV/c

(Signal : BG= 1:7)

(e,e'p) & (e,e'pp) Data



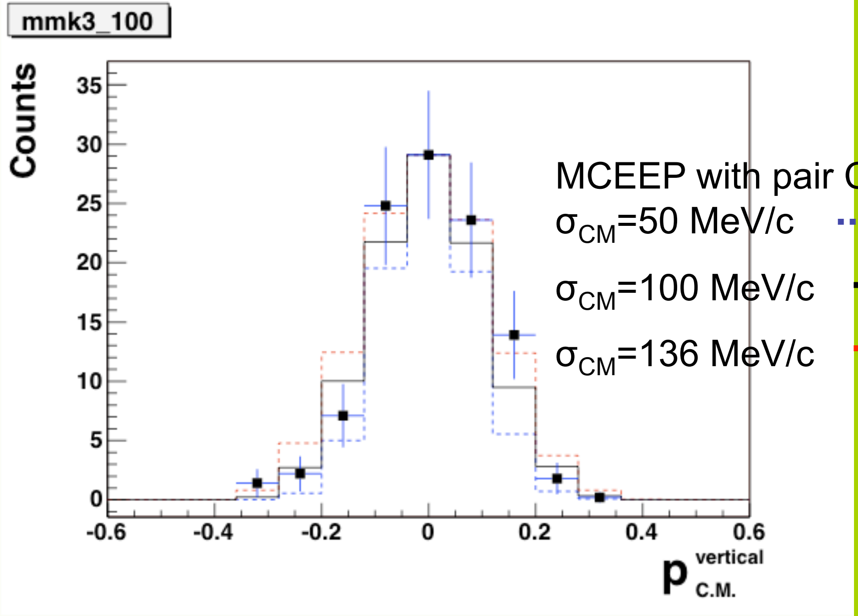


Strong back-to-back correlation!

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

CM motion of the pair:

$P_{c.m}^{vertical}$, "500 MeV/c " setup

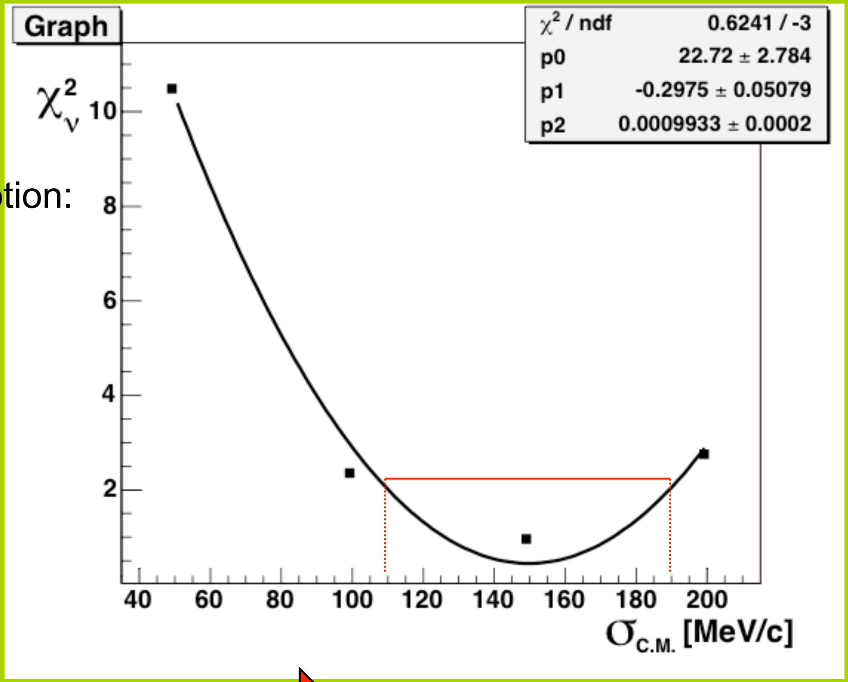


MCEEP with pair CM motion:

σ_{CM}=50 MeV/c ┅┅┅

σ_{CM}=100 MeV/c ━━━

σ_{CM}=136 MeV/c ┅┅┅



2 components of $\vec{p}_{c.m}$ and 3 kinematical setups

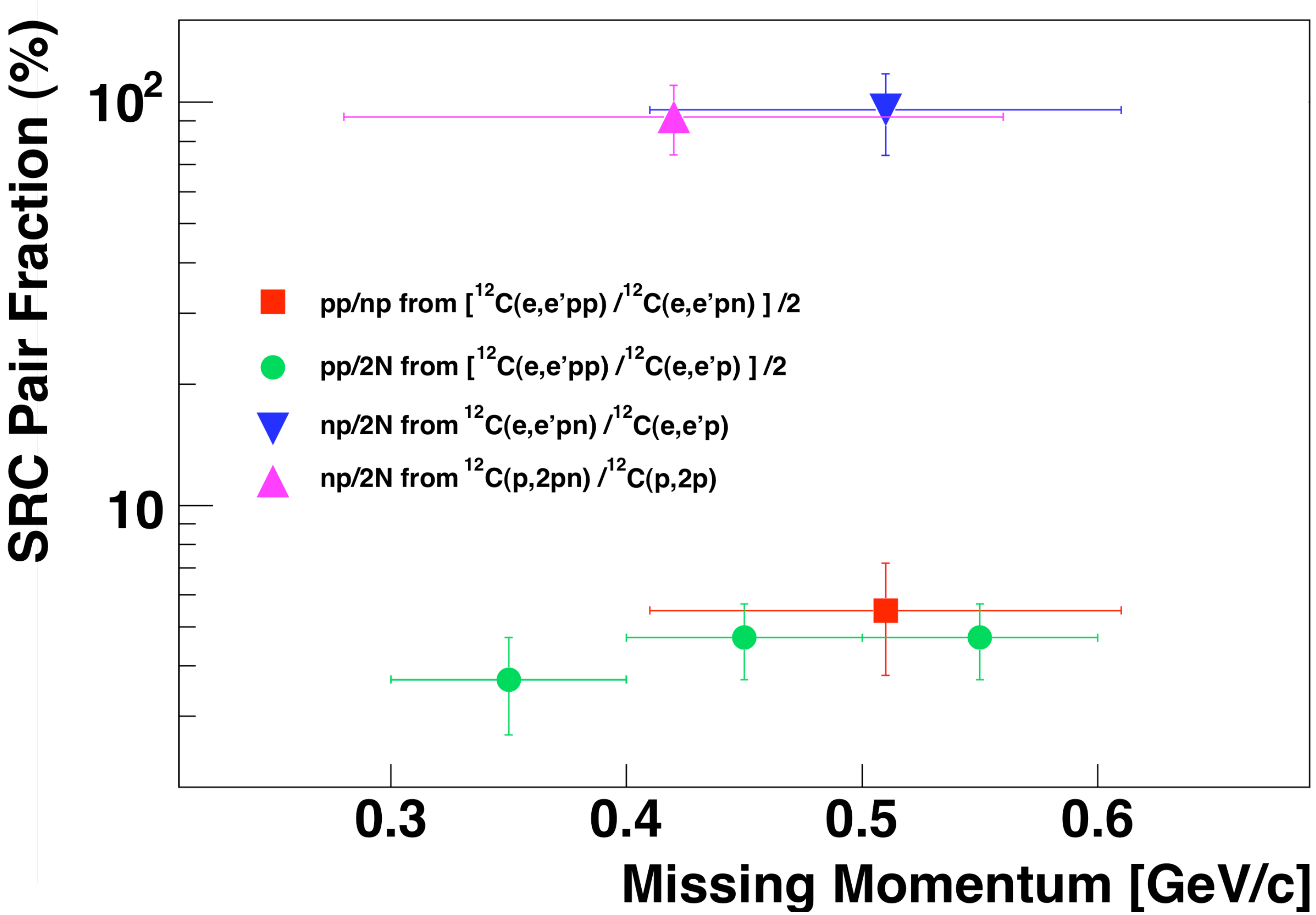
This experiment : σ_{CM}=0.136 ± 0.020 GeV/c

(p,2pn) experiment at BNL : σ_{CM}=0.143±0.017 GeV/c

Theoretical prediction (Ciofi and Simula) : σ_{CM}=0.139 GeV/c

Short-Range Correlation Pair Factions

R. Subedi *et al*., Science **320** (2008) 1476).



The Results from E01-015 can be found in:

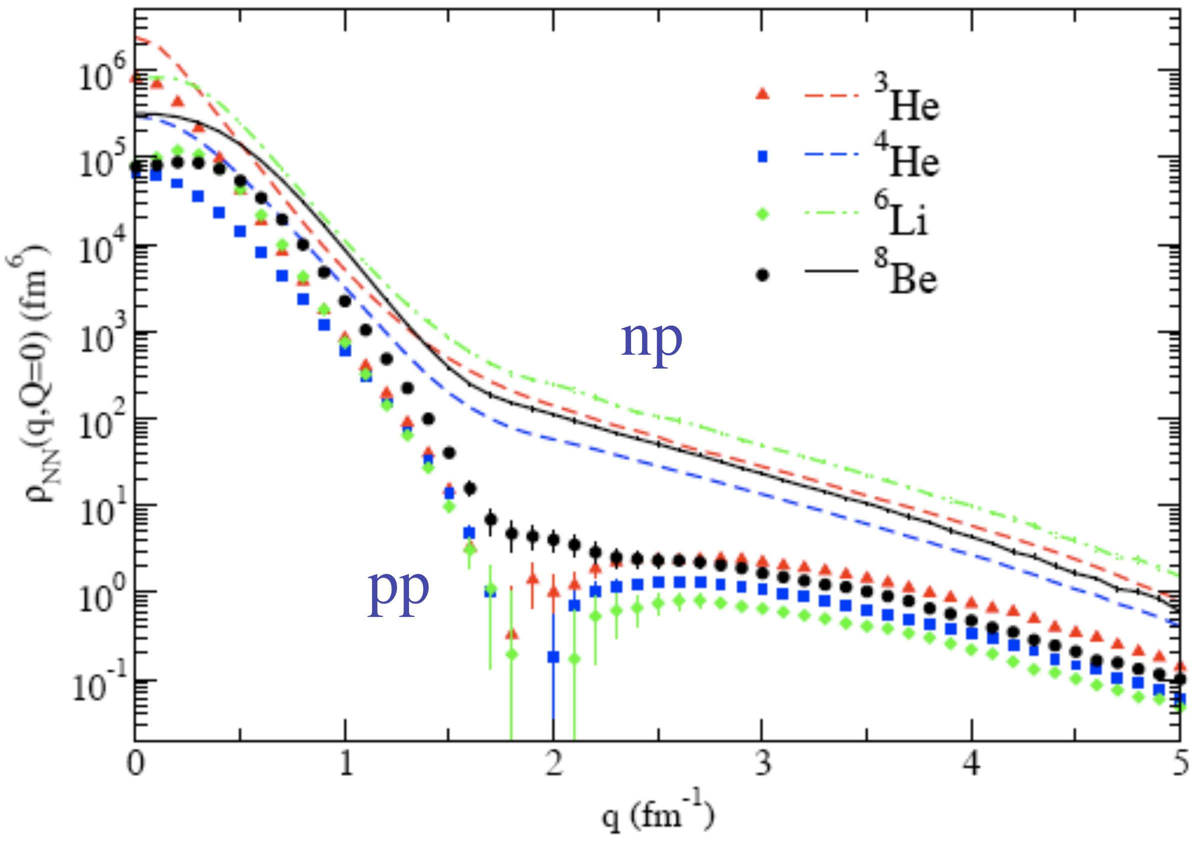
1) R. Shneor, et al., Phys. Rev. Lett. **99**, 072501 (2007).

2) R. Subedi, et al., **SCIENCE 320**, 1476 (2008).

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**

Importance of Tensor Correlations



- M. Sargsian et al., Phys. Rev. C (2005) 044615.
- R. Schiavilla et al., Phys. Rev. Lett. 98 (2007) 132501. [shown above]
- M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. Lett. 100 (2008) 162503.

Acknowledgment

Exp 01 – 015 collaboration **Hall A /JLab**

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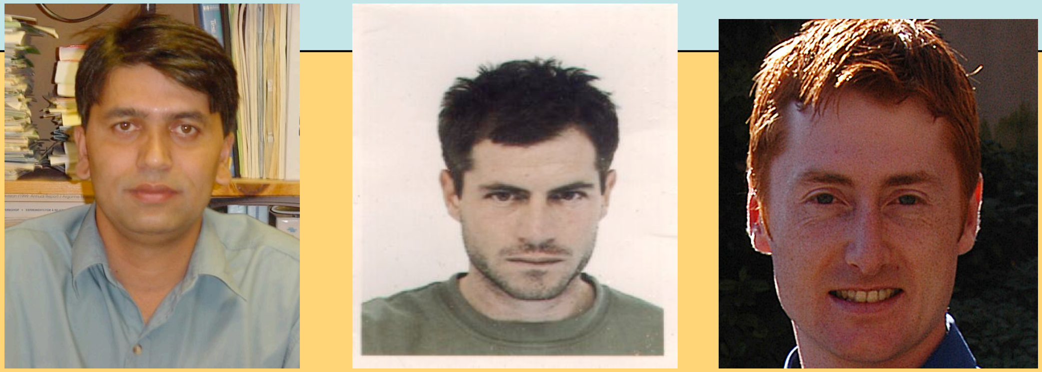

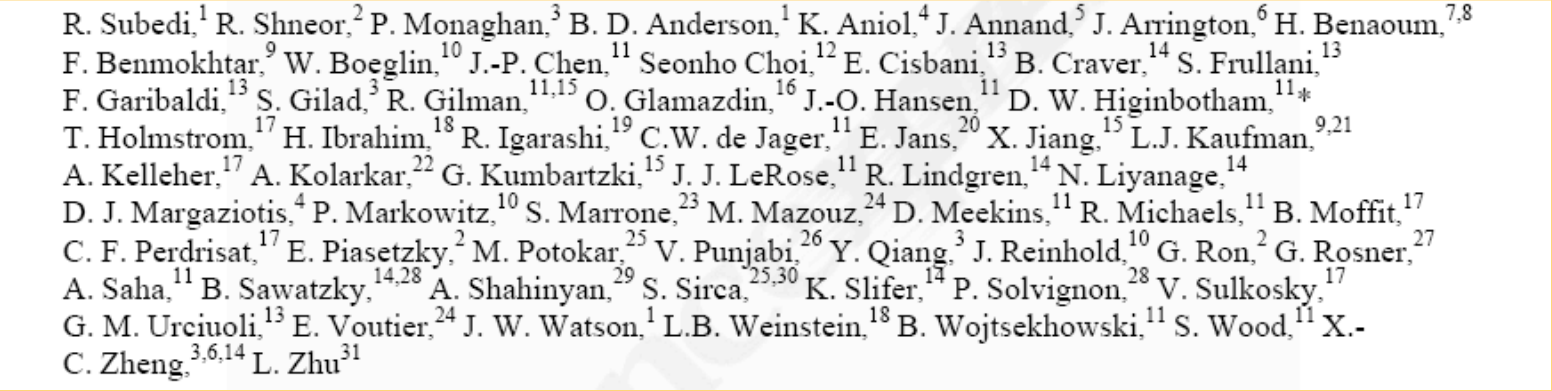

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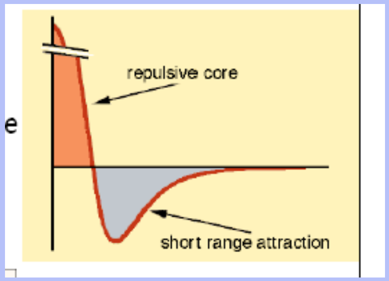
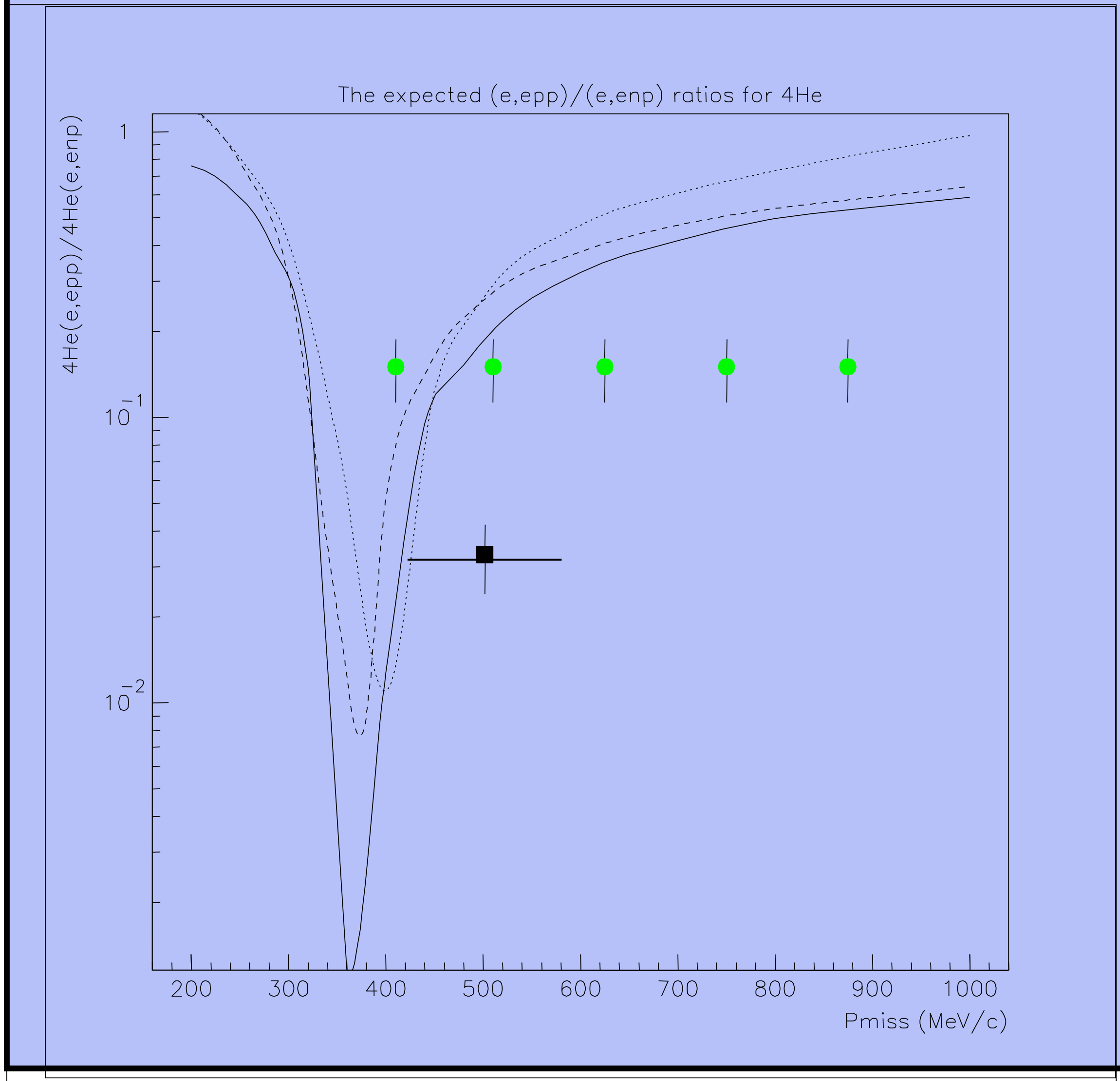
PRL 99, 072501 (2007)

Science 320,1476 (2008)

A new approved experiment at Jlab E07-006

Measurement of the ^{4}He(e,e’pp) and ^{4}He(e,e’pn) reactions over the ^{4}He(e,e’p) missing momentum range from 400 to 875 MeV/c.





■ E01-105 ^{12}C (scaled to ^{4}He)

● This proposal - ^{4}He

Density distributions:

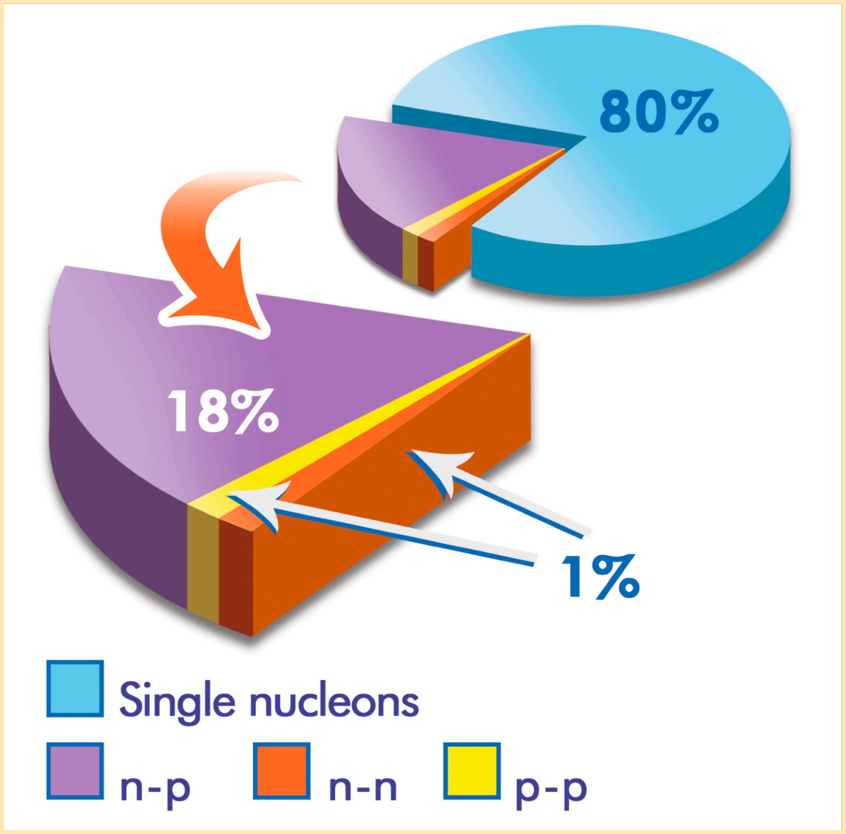
┈┈┈┈ / - - - - Sargsian et al.

———— Schiavilla et al.

(e,e’pN) calculations are needed

Summary of Results

- Almost all nucleons above the Fermi sea are part of 2N-SRCs.
- These SRC pairs move inside the nucleus with c.m. motion of $\sigma \sim 140$ MeV/c.
- The 2N-SRC consists of –
  n-p pairs (90%)
  p-p pairs(5%)
  n-n pairs(5%).
- A new experiment has been approved at Jlab, continuing this work with the target ^{4}He.



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Jefferson Lab 2009 Tshirt

FRONT **BACK**