Measurement of the Neutron Structure Function at Large x

PANIC 2011
MIT

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\[ F_2^n / F_2^p: \text{Textbook Physics - d/u at large } x \]

**Quark-Parton Model**

\[
F_2^p (x) = x \sum_q e_q^2 (q(x) + \bar{q}(x)) \approx x \left( \frac{4}{9} u(x) + \frac{1}{9} d(x) \right)
\]

\[
F_2^n (x) \approx x \left( \frac{4}{9} d(x) + \frac{1}{9} u(x) \right)
\]

\[
\frac{F_2^n}{F_2^p} \approx \frac{1 + 4 \frac{d}{u}}{4 + \frac{d}{u}}
\]

(Sea quark dominance, approaches 1)

\[ F_2^n / F_2^p \]

\[ u \text{ quark dominance, } \frac{d}{u} \rightarrow 0 \]

\[ F_2^n / F_2^p \rightarrow 1/4 \]

\[ x \rightarrow 1 \]

**BUT……..**
The deuteron is a nucleus.

Neutron structure typically derived from deuterium target by subtracting proton

*Large* uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function, coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect).
This is a big problem....

Proton and deuterium data from SLAC E139
(L. W. Whitlow, et al.), and E140 (J. Gomez, et al.)

\[ 0.2 < F_2^n/F_2^p < 0.8 \]

Same “textbook” data as previous slide!
Large $x$ - Large Nuclear Effects

- Even simple “Fermi Smearing” leads to significant dependence on D wave function
- Different models for off-shell and “EMC” effects lead to large additional variations
- Contributions from MEC, $\Delta(1232)$ and “exotic” degrees of freedom unknown
- FSI?

Accardi et al, Phys. Rev. D84:014008, 2011 Uncertainties in Determining Parton Distributions at Large $x$ - talk this afternoon
\( F_2^n/F_2^p \) is fundamental to understanding the proton structure

Proton Wavefunction (Spin and Flavor Symmetric)

\[
\left| p \uparrow \right> = \frac{1}{\sqrt{2}} \left| u \uparrow (ud)_{s=0} \right> + \frac{1}{\sqrt{18}} \left| u \uparrow (ud)_{s=1} \right> - \frac{1}{3} \left| u \downarrow (ud)_{s=1} \right> \\
- \frac{1}{3} \left| d \uparrow (uu)_{s=1} \right> - \frac{\sqrt{2}}{3} \left| d \downarrow (uu)_{s=1} \right>
\]

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Predictions for $d/u$ at large $x_{Bj}$

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$$\left| p \uparrow \right\rangle = \frac{1}{\sqrt{2}} \left| u \uparrow (ud)_{s=0} \right\rangle + \frac{1}{\sqrt{18}} \left| u \uparrow (ud)_{s=1} \right\rangle - \frac{1}{3} \left| u \downarrow (ud)_{s=1} \right\rangle - \frac{1}{3} \left| d \uparrow (uu)_{s=1} \right\rangle - \frac{\sqrt{2}}{3} \left| d \downarrow (uu)_{s=1} \right\rangle$$

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$u, d$ same shape $u = 2d$

SU(6) spin-flavor symmetry:
The mass difference between $N$ and $\Delta$ implies symmetry breaking
Predictions for $d/u$ at large $x_{Bj}$

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$$- \frac{1}{3} \left| d \uparrow (uu)_{s=1} \right\rangle - \frac{\sqrt{2}}{3} \left| d \downarrow (uu)_{s=1} \right\rangle$$

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SU(6) symmetry broken - scalar valence diquark, $u$ dominance

$S=0$ diquark dominance

$d/u=(0)/(1/2)=0$

- Hyperfine-perturbed quark model (Isgur at al.) with one-gluon-exchange; MIT bag model with gluon exchange (Close & Thomas);
- Phenomenological quark-diquark (Close) and Regge (Carlitz) arguments
Predictions for d/u at large $x_{Bj}$

Proton Wavefunction (Spin and Flavor Symmetric)

$$ |p \uparrow\rangle = \frac{1}{\sqrt{2}} |u \uparrow (ud)_{S=0}\rangle + \frac{1}{\sqrt{18}} |u \uparrow (ud)_{S=1}\rangle - \frac{1}{3} |d \uparrow (uu)_{S=1}\rangle $$

S_z = 0, di-quark dominance, spin projection is zero
- $d/u = (1/9)/(1/2+1/18) = 1/5$
- pQCD with helicity conservation (Farrar and Jackson); quark counting rules (Brodsky et al.)

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$F_2^n/F_2^p$ (and, hence, $d/u$) is essentially unknown at large $x$: 

- Conflicting fundamental theory pictures
- Data hindered by lack of free neutron target

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Review Articles:

$F_2^n/F_2^p$ (or $d/u$) can be almost anything!
Translates Directly to Large $x$ Valence pdf Uncertainties
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$u(x)$

$\frac{u}{u_{ref}}$

$\frac{d}{d_{ref}}$

max nuclear

min nuclear

$\frac{\delta u}{u}$

$\frac{\delta d}{d}$

CJ2011 - see afternoon talk
Can we reduce model dependence?

Yes! Within the nuclear impulse approximation. The virtual photon interacts with the neutron on a short enough time scale that the proton doesn’t know what happened. The spectator continues on unperturbed with momentum $p_s = -p$

\[
\frac{d\sigma}{dx dW^2 d\alpha d^2 p_T} \approx \frac{2\alpha^2_{em} (1 - \nu/E)}{Q^4} \alpha S(\alpha, p_T) F_2^{n(eff)}(W^2, p^2, Q^2)
\]
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$$\frac{d\sigma}{dx dW^2 d\alpha d^2p_T} \approx \frac{2\alpha_e^2 (1 - \nu / E)}{Q^4} \alpha \ S (\alpha, p_T) \ F_2^{n_{\text{eff}}}(W^2, p^2, Q^2)$$

We focus on VIPs * (Very Important Protons) where $R_n > 99\%$
Detect very important low momentum protons. If the proton is also going backwards in the lab frame it is almost guaranteed to be only a spectator.

Need Low Momentum AND Large Angle

Backward angle
Spectator proton = Neutron target
Choice of Spectator Momentum and Angle

**Target fragmentation**

Negligible

**Bound / free neutron structure**

$O (1\%)$

**Final state interactions**

$O (5\%)$
BONUS is a Standard Inclusive Fixed Deuterium Target Electron Scattering Experiment, with a Tagged Spectator Proton to Ensure the Electron Scattered from the Neutron

**Spectator Proton Detector Features**

- *Low momentum* spectator must escape target
  - Thin deuterium target
  - Low density detector media
  - Minimal insensitive material
- Large acceptance
  - Backward angles important
  - Symmetric about the target
- Detector sensitive to spectators, insensitive to background
BONUS Radial TPC Design using Cylindrical Gas Electron Multipliers

140 μm

φ, z from pads, r from time

dE/dx from charge along track (particle ID)

3 cm He

~50 μm

3 cm Helium/DME at 80/20 ratio

Stagger pads in z to improve theta angle reconstruction
BONUS in CLAS

BoNuS

Solenoid Magnet
**BONUS in CLAS (Hall B at Jefferson Lab)**

- rTPC inside Solenoid inside CEBAF Large Acceptance Spectrometer (CLAS)

- Track scattered $e^-$ in CLAS

- Locate $e^-$ interaction point in target.

- Electron tracked in CLAS provides trigger to BoNuS radial TPC

- Link $p_{\text{spectator}}$ with electron vertex.

CLAS is made of Drift Chambers, Time of Flight Scintillators, Cerenkov counters and Electromagnetic Calorimeters for tracking, momentum determination, and Particle ID.
Spectator Tagging - results

\[ p_n = (M_D - E_S - \bar{p}_S) ; \]
\[ \alpha_n = 2 - \alpha_S \]

\[ p_S = (E_S, \bar{p}_S) ; \quad \alpha_S = \frac{E_S - \bar{p}_S \cdot \bar{q}}{M_D / 2} \]

\[ x = \frac{Q^2}{2p_n^\mu q_\mu} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)} \]

\[ W^2 = M^2 + 2M\nu - Q^2 \]

\[ W^2 = (p_n + q)^2 = p_n^\mu p_{n\mu} + 2((M_D - E_S)\nu - \bar{p}_n \cdot \bar{q}) - Q^2 \]
\[ \approx M^*^2 + 2M\nu(2 - \alpha_S) - Q^2 \]

\( E = 4.223 \text{ GeV} \)
\( \langle Q^2 \rangle = 1.19 (\text{GeV}/c)^2 \)
Angular dependence

\[ Q^2 = 1.66 \text{ GeV}^2 \]
\[ W^* = 1.73 \text{ GeV} \]

- No significant deviations from PWIA (\( p_s < 100 \text{ MeV/c} \)), first 2 panels

- Possible \( \theta \) dependence at higher momenta

\({\text{Ratio}}\ vs. \cos \theta_{pq}\) for different momenta: 78 MeV/c, 93 MeV/c, 110 MeV/c, 135 MeV/c.
Neutron Structure Function - results

BONUS neutron data

Christy-Bosted fit

S.P. Malace et al analysis of deuterium data
Extracted $F_2^n/F_2^p$ (N. Baillie analysis)

- BONUS actually measures $(n/d)*(d/p)$

- RTPC tagged / untagged *
  precision $d/p$ data on ratios at same kinematics (Hall C)

  $P_{\text{spectator}} < 90$ MeV/c

  $\theta_{\text{spectator}} < 90$

- Different $Q^2$ ranges for different $x, W$
Plans for 12 GeV

BONUS
E12-06-113

- Data taking of 35 days on D$_2$ and 5 days on H$_2$
  with $L = 2 \cdot 10^{34}$ cm$^{-2}$ sec$^{-1}$
- **Planned** BoNuS detector
  DAQ and trigger **upgrade**
- DIS region with
  - $Q^2 > 1$ GeV$^2$/c$^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110^\circ$
- Largest value for $x^* = 0.80$
  (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$
Conclusions

• Effective free neutron target technique demonstrated (other experiments now utilizing / proposing)
• Large $x$ n/p results consistent with CJ2011 pdf analysis
• Neutron resonance structure functions to be studied in detail, quark-hadron duality
• Detailed CLAS analysis note final
• Publication draft under review
• BONUS12 proposal approved