Deep-inelastic scattering on the tri-nucleons

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Outline

- **Motivation:** neutron structure at large $x$
  - $d/u$ ratio, duality in the neutron

- **Status of large-$x$ quark distributions**
  - nuclear corrections
  - new global analysis of *inclusive* DIS data (CTEQx)

- **DIS from $A=3$ nuclei**
  - model-independent extraction of neutron $F_2$
  - plans for helium-3/tritium experiments
Quark distributions at large $x$
Parton distributions functions (PDFs)

- provide basic information on structure of hadronic systems

- needed to understand backgrounds in searches for *new physics* beyond the Standard Model in high-energy colliders, neutrino oscillation experiments, ...

→ DGLAP evolution feeds low $x$, high $Q^2$ from high $x$, low $Q^2$

\[
\frac{dq(x, t)}{dt} = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ P_{qq} \left( \frac{x}{y} \right) q(y, t) + P_{qg} \left( \frac{x}{y} \right) g(y, t) \right]
\]

\[
t = \log \frac{Q^2}{\Lambda_{\text{QCD}}^2}
\]
- Ratio of $d$ to $u$ quark distributions at large $x$ particularly sensitive to quark dynamics in nucleon

- \textbf{SU(6) spin-flavor symmetry}

\textit{proton wave function}

$$p^\uparrow = -\frac{1}{3} d^\uparrow (uu)_1 - \frac{\sqrt{2}}{3} d^\downarrow (uu)_1$$

$$+ \frac{\sqrt{2}}{6} u^\uparrow (ud)_1 - \frac{1}{3} u^\downarrow (ud)_1 + \frac{1}{\sqrt{2}} u^\uparrow (ud)_0$$

Interacting quark

Diquark spin

Spectator diquark
Ratio of $d$ to $u$ quark distributions at large $x$ particularly sensitive to quark dynamics in nucleon

**SU(6) spin-flavor symmetry**

**Proton wave function**

\[
p^{\uparrow} = -\frac{1}{3} d^{\uparrow} (uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow} (uu)_1 \\
+ \frac{\sqrt{2}}{6} u^{\uparrow} (ud)_1 - \frac{1}{3} u^{\downarrow} (ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow} (ud)_0
\]

\[\rightarrow u(x) = 2 \ d(x) \ \text{for all } x\]

\[\frac{F_2^n}{F_2^p} = \frac{2}{3}\]
scalar diquark dominance

\[ M_\Delta > M_N \implies (qq)_1 \text{ has larger energy than } (qq)_0 \]

\[ \implies \text{scalar diquark dominant in } x \to 1 \text{ limit} \]

since only \( u \) quarks couple to scalar diquarks

\[
\begin{array}{c}
\frac{d}{u} \to 0 \\
\frac{F_2^u}{F_2^d} \to \frac{1}{4}
\end{array}
\]

hard gluon exchange

at large $x$, helicity of struck quark = helicity of hadron

$\Rightarrow$ helicity-zero diquark dominant in $x \rightarrow 1$ limit

Farrar, Jackson 1975
At large $x$, valence $u$ and $d$ distributions extracted from $p$ and $n$ structure functions

$$F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v$$

$$F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v$$

$u$ quark distribution well determined from $p$ data

$d$ quark distribution requires $n$ structure function

$$\frac{d}{u} \approx \frac{4 - F_2^n / F_2^p}{4F_2^n / F_2^p - 1}$$
Duality in the neutron?
Bloom-Gilman duality well established for the proton

Niculescu et al., PRL 85 (2000) 1182, 1185

Christy et al. (2005)
$F_2^p$ resonance spectrum

how much of this region is *leading twist*?


* JLab Hall C
Higher twists

1/$Q^2$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx \ x^{n-2} \ F_2(x, Q^2) = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

Matrix elements of operators with specific “twist” (= dimension – spin)

\[\text{twist} > 2 \text{ reveals long-range } q-g \text{ correlations}\]

Phenomenologically important at low $Q^2$ and large $x$

\[\text{parametrize } x \text{ dependence by}\]

$$F_2(x, Q^2) = F_2^{LT}(x, Q^2) \left(1 + \frac{C(x)}{Q^2}\right)$$

higher twists $< 10\text{--}15\%$ for $Q^2 > 1 \text{ GeV}^2$
Is duality in the proton a coincidence?

→ consider symmetric nucleon wave function

**cat’s ears diagram** (4-fermion higher twist \( \sim \frac{1}{Q^2} \))

\[
\propto \sum_{i \neq j} e_i e_j \sim \left( \sum_i e_i \right)^2 - \sum_i e_i^2
\]

- **proton**
  \[ \text{HT} \sim 1 - \left( 2 \times \frac{4}{9} + \frac{1}{9} \right) = 0 \]

- **neutron**
  \[ \text{HT} \sim 0 - \left( \frac{4}{9} + 2 \times \frac{1}{9} \right) \neq 0 \]

need to test duality in the neutron!
No **FREE** neutron targets
(neutron half-life ~ 12 mins)

→ use deuteron as “effective” neutron target

**BUT** deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

→ nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

→ need to correct for “nuclear EMC effect”
Nuclear effects in the deuteron
nuclear “impulse approximation”

→ incoherent scattering from individual nucleons in $d$
  (good approx. at $x \gg 0$)

$$F_2^d(x, Q^2) = \int_x d y \ f(y, \gamma) \ F_2^N(x/y, Q^2) + \delta^{(\text{off})} F_2^d$$
nuclear “impulse approximation”

→ incoherent scattering from individual nucleons in \(d\)
  (good approx. at \(x \gg 0\))

\[
F_2^d(x, Q^2) = \int_x dy \ f(y, \gamma) \ F_2^N(x/y, Q^2) + \delta^{(\text{off})} F_2^d
\]

nucleon momentum
distribution in \(d\)
(“smearing function”)

\[
\gamma = |q|/q_0 = \sqrt{1 + 4M^2x^2/Q^2}
\]

→ at finite \(Q^2\), smearing function depends also on parameter

\(N=p+n\)

off-shell correction
(\(\sim 1\%\))
$N$ momentum distributions in $d$

- weak binding approximation (WBA): expand amplitudes to order $\vec{p}^2/M^2$

\[
f(y, \gamma) = \int \frac{d^3p}{(2\pi)^3} |\psi_d(p)|^2 \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right) \\
\times \frac{1}{\gamma^2} \left[1 + \frac{\gamma^2 - 1}{y^2} \left(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\right)\right]
\]


→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy $\varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M}$

→ approaches usual nonrelativistic momentum distribution in $\gamma \to 1$ limit
Off-shell correction

\[ \delta^{(\text{off})} F_2^d \rightarrow \delta^{(\Psi)} F_2^d \]

negative energy components of \( \psi_d \)

\[ \rightarrow \delta^{(p^2)} F_2^d \]

off-shell \( N \) structure function

\[ \leq 1 - 2\% \text{ effect} \]

WM, Schreiber, Thomas
PLB 335 (1994) 11
EMC effect in deuteron

The diagram shows variations in the ratio $F_d^d / F_N^N$ as a function of $x$, with different models contributing to the graph. The larger EMC effect, associated with a smaller $d/N$ ratio, occurs at $x \sim 0.5-0.6$ with binding and off-shell corrections taken into account.

- **Light-cone model** (Frankfurt, Strikman)
- **Relativistic model** (WM, Schreiber, Thomas)
- **Nuclear density model** (Frankfurt, Strikman)

The text highlights the larger EMC effect at $x \sim 0.5-0.6$ with binding and off-shell corrections.
EMC effect in deuteron

EMC ratio depends also on input nucleon SFs; need to iterate when extracting $F_2^n$. 

$\rightarrow$
Symmetry breaking mechanism remains unknown!

Most PDFs assume no nuclear corrections.

Large uncertainty from nuclear effects in deuteron (range of nuclear models*) beyond $x \sim 0.5$

→ Symmetry breaking mechanism remains unknown!

* Most PDFs assume *no* nuclear corrections.
New global analysis ("CTEQx")

[with Accardi, Christy, Keppel, Monaghan, Morfin, Owens]
Global questions

- Can one obtain stable fits including low-$Q^2$, low-$W$ data?
  - how do large-$x$ data affect PDFs?
  - to what extent can uncertainties be reduced?

- Are subleading, $1/Q^2$ corrections under control?
  - how large are higher twists?

- How do nuclear corrections affect $d/u$ ratio?
  - what uncertainties do nuclear effects introduce?

New analysis of proton & deuteron data includes effects of $Q^2/W$ cuts, TMCs, higher twists, nuclear corrections
Kinematic cuts

cut0: \( Q^2 > 4 \text{ GeV}^2, \quad W^2 > 12.25 \text{ GeV}^2 \)
cut1: \( Q^2 > 3 \text{ GeV}^2, \quad W^2 > 8 \text{ GeV}^2 \)
cut2: \( Q^2 > 2 \text{ GeV}^2, \quad W^2 > 4 \text{ GeV}^2 \)
cut3: \( Q^2 > m_c^2, \quad W^2 > 3 \text{ GeV}^2 \)

\[ \sim 2 \text{ times more data for cut3 cf. cut0} \]
Effect of $Q^2$ & $W$ cuts

- Systematically reduce $Q^2$ and $W$ cuts
- Fit includes target mass, higher twist & nuclear corrections (WBA)

\[ d/d_{\text{ref}} \]

$Q^2 = 10$ GeV$^2$

\[ x \]

\[ d \] suppressed by $\sim 50\%$ for $x > 0.5$

\[ \rightarrow \] driven mostly by nuclear corrections
Effect of nuclear corrections

- dramatic effect of nuclear corrections:
  - decrease in $d$ distribution for $x > 0.6$

- modest increase with (additive) off-shell correction (since EMC ratio has deeper “trough”)

* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits
**d/u PDF ratio**

**nuclear smearing**

\[
\frac{d}{u} \rightarrow \frac{d}{u} + c x^\alpha
\]

**density model**

\[Q^2=10 \text{ GeV}^2\]

→ full fits favors *smaller* d/u ratio

→ dominance of nonperturbative physics?

→ critical need for neutron SF at \(x > 0.6\)
How to extract neutron without nuclear uncertainties?
Deep inelastic scattering from $A=3$ nuclei and the neutron structure function

I. R. Afnan,$^1$ F. Bissey,$^2$ J. Gomez,$^3$ A. T. Katramatou,$^4$ S. Liuti,$^5$ W. Melnitchouk,$^3$ G. G. Petrats,$^4$ and A. W. Thomas$^6$

**EMC ratios for $A=3$ mirror nuclei**

\[
R(\text{He}^3) = \frac{F_2^\text{He}}{2F_2^p + F_2^n} \quad \quad \quad R(\text{H}^3) = \frac{F_2^\text{H}}{F_2^p + 2F_2^n}
\]

**Extract $n/p$ ratio from measured $^3\text{He}^3\text{H}$ ratio**

\[
\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^\text{He}/F_2^\text{H}}{2F_2^\text{He}/F_2^\text{H} - \mathcal{R}} \quad \quad \quad \mathcal{R} = \frac{R(\text{He}^3)}{R(\text{H}^3)}
\]

theory input
Nucleon distribution function in $A=3$ nucleus

\[ f_{N/A}(y, \gamma) = \int d^4 p \left( 1 + \frac{p_z}{p_0} \right) S_A(p) \mathcal{F}(p, \gamma) \delta \left( y - \frac{p_0 + p_z}{M} \right) \]

\[ \mathcal{F}(p, \gamma) = \left( 1 + \frac{4 M p_z x^2 \gamma}{y Q^2} \right) - (2 p^2 - p_z^2) \frac{\gamma^2 x^2}{y^2 Q^2} \]

→ nucleon spectral function

\[ S_A(p) = \frac{1}{(2\pi)^3} \sum_f \left| \int d^3 r \ e^{i \vec{p} \cdot \vec{r}} G_{fi}(\vec{r}) \right|^2 \delta(E_3 - E_f - E) \]

\[ S_{3\text{He}} = \frac{2}{3} S_{p/3\text{He}} + \frac{1}{3} S_{n/3\text{He}} , \quad S_{3\text{H}} = \frac{1}{3} S_{p/3\text{H}} + \frac{2}{3} S_{n/3\text{H}} \]

$\text{d + np break-up}$ \quad $\text{pp break-up}$
Nucleon distribution function in $A=3$ nucleus

$\#$ Bissey, Thomas, Afnan, Phys. Rev. C64, 024004 (2001)
$R(^3\text{He}) / R(^3\text{H})$

*PEST* + CSB

*PEST

density

Ernst-Shakin-Thaler separable approx. to Paris potential

→ nuclear effects cancel to < 1% level
*theoretical uncertainty integrated into total error
Tritium Target at JLab

Roy J. Holt

Tritium Target Task Force:

E. J. Beise (Univ. of Maryland), R. J. Holt (ANL),
W. Korsch (Univ. of Kentucky), T. O’Connor (ANL),
G. Petratos (Kent State Univ.), R. Ransome (Rutgers Univ.),
P. Solvignon (ANL), and B. Wojtsekhowski (JLab)

- 12 GeV experiment: E12-06-118, conditionally approved
- d/u ratio
- EMC effect in $^3$H

“... the PAC considers the physics goals of this experiment as highlights of the 12 GeV physics program.”

Condition: “A special JLab Management review of the safety aspects of the tritium target is the condition for approval.”
Summary

- Scientific stage being set at JLab for d/u ratio and EMC measurements
- Totally sealed, passively-cooled target, triple containment, exhaust fan, interlocks
- All tritium gas handling performed at STAR Facility at INL
- Additional independent interlock on beam raster
- Target concept is ready for engineering design

* Safety and Tritium Applications Research (STAR) Facility
Idaho National Laboratory

Conclusion: A safe tritium target is possible at JLab.
Thank you, Iraj, for your critical contributions!