BoNuS Program at CLAS and CLAS12:

**BoNuS** = **Barely off-shell Nuclear Structure**

Measurement of the free neutron structure function at large $x$ in deuterium via spectator tagging

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Structure Functions and Moments

\[ \frac{d^2 \sigma}{d\Omega dE'} = \sigma_{Mott} \left( 2 \tan^2 \frac{\theta}{2} \frac{F_1(x)}{M} + \frac{F_2(x)}{\nu} \right) \]

\[ F_2(x, Q^2) = x \sum_{f=\text{up}, \text{down}, \ldots} z_f^2 (q_f(x, Q^2) + \bar{q}_f(x, Q^2)) \]

- Precise PDFs at large \( x \) needed as input for LHC
  - Large \( x \), medium \( Q^2 \) evolves to medium \( x \), large \( Q^2 \)
- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large \( x \)
Nucleon Structure Functions

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

SU(6) symmetry \( u_\nu(x) = 2d_\nu(x) \)

\[ \frac{F_2^n}{F_2^P} = \frac{2}{3}, \quad \frac{d}{u} = \frac{1}{2} \]

S\(_z = 0\) dominant, helicity conservation

\[ \frac{F_2^n}{F_2^P} \to \frac{3}{7}, \quad \frac{d}{u} \to \frac{1}{5} \]

S\(_z = 0\) dominant, one-gluon exchange

SLAC E139 (L. W. Whitlow, et al.), and E140 (J. Gomez, et al.)
Inclusive Cross Section

- Data on the Proton: Clear resonant structure, separation from the non-resonant background is possible

- Data on the deuteron: Kinematically smeared due to binding, off-shell, final state interactions (FSI), etc.

Off-Shell and FSI for D(e,e'p_s)X

Select low P_s (<120 MeV/c) and large backward θ_pq (>100°), angle between P_s and virtual photon, to minimize FIS.

Off-shell effects are negligible for small P_s. Choose P_s < 120 MeV/c as Very Important Spectator Protons (VIP)

Electron beam energies: 2.1, 4.2, 5.3 GeV
Spectator protons were detected by the newly built Radial Time Projection Chamber (RTPC)
Scattered electrons and other final state particles were detected by CEBAF Large Acceptance Spectrometer (CLAS)
Target: 7 atm $\text{D}_2$ gas, 20 cm long
Data were taken from Sep. to Dec. in 2005
Jefferson Lab

Continuous Electron Beam Accelerator Facility

- $E$: 0.75 – 6 GeV
- $I_{\text{max}}$: 200 $\mu$A
- RF: 1499 MHz
- Duty Cycle: $\sim$ 100%
- $\sigma(E)/E$: $\sim 10^{-4}$
- Polarization: 85%
- Simultaneous distribution to 3 experimental Halls
CLAS in Jefferson Lab, Hall B

CEBAF
Large Acceptance Spectrometer

DC: Drift Chamber
CC: Cerenkov Counter
SC: Scintillation Counter
EC: Electromagnetic Calorimeter
RTPC Sits in the Center of CLAS
Radial Time Projection Chamber (RTPC)
Radial Time Projection Chamber (RTPC)

Sensitive to protons with momenta of 67-250 Mev/c
3 layers of GEM
3200 pads (channels)
5 Tesla B field
Particles ID by dE/dx
3-D tracking: time of drift -> r, pad position -> φ, z

7 Atm. D2 gas target, 20 cm in length
Thin-wall High Pressure Gas Target
Thin Al-Mylar Window
Thin Al-Mylar Cathode
Track Ionization / Drift Gas
GEM (Gas Electron Multiplier) Gain Stage
Readout Electrodes (pads)
Readout Connections

100 µm

Beam
Möller Electrons
Trigger Electron

dE/dX
Channel by Channel gain multipliers can be determined for each run by comparing the track's expected energy loss to the measured value. After applying these gain corrections, a clear separation of protons and heavier particles through $dE/dx$ has been achieved.

Gain constants (vs phi and z) determined independently for two different runs.
RTPC Resolution

Trigger electrons measured by CLAS are compared to the same electrons measured in BoNuS during High Gain Calibration runs.

\[ \Delta Z = 8 \text{mm} \]

\[ \Delta \theta = 1.4^\circ \]

\[ \Delta \phi = 4^\circ \]

Proton momentum measured in RTPC and inferred from CLAS

Simulation Overview

RTPC(Geant4) \rightarrow CLAS(geant3) \rightarrow Reconstruction \rightarrow Analysis

What have been done with simulation?
- Debug/optimize RTPC reconstruction packages
- Generate energy loss correction tables, radiation length tables
- Study Detector’s acceptance for various reactions
- Study particle detection efficiency
- Model the background…
BoNuS6 Data Volume and Kinematic Coverage

- 5.262 GeV: 456 M (D$_2$) and 64 M (H$_2$)
- 4.223 GeV: 306 M (D$_2$) and 11 M (H$_2$)
- 2.140 GeV: 91 M (D$_2$) and 15 M (H$_2$)
- Overall tagged count on D$_2$ is ~ 2%
- $I = 35$ nA, target = D$_2$: $L = 4.3 \times 10^{33}$ g s$^{-1}$ cm$^{-3}$
E_{beam} = 4.223 \text{ GeV} \\
\langle Q^2 \rangle = 1.19 \ (\text{GeV/c})^2 \\

\begin{align*}
p_S &= (E_S, \vec{p}_S) \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \vec{q}}{M_D/2} \\
p_n &= (M_D - E_S, -\vec{p}_S) \quad \alpha_n = 2 - \alpha_S \\
W^*^2 &= (p_n + q)^2 \\
&\approx M^*^2 + 2Mv(2 - \alpha_S) - Q^2 \\
W^2 &= M^2 + 2Mv - Q^2 \\
\end{align*}
BoNuS Extracted $F_2^n/F_2^p$
"Free" neutron structure function compared with a model by P. Bosted, Phys. Rev. C77 (2008) 065206
What else we can do?  
**Exclusive $\pi^-$ electro-production**

Detect $e'$, $\pi^-$ and at least ONE of the two final state protons in $D(e,e'\pi^-p)p$ to ensure exclusivity and select events where the “spectator” proton has low, backwards momentum. Conservation of energy and momentum allows to determine the initial state of the neutron.

Novel approach by the BoNuS collaboration: detect the spectator proton directly.
Cross Section: BoNuS Vs MAID and SAID

$Q^2 = 0.93, 1.33, 2.11, 3.59$

$\cos \theta^*$

$4 \text{ GeV}, W = 1.23$

MAID 07, SAID 08

$D(e,e^{'\pi^-}p_{\text{RTPC}})p$

$D(e,e^{'\pi^-}p_{\text{CLAS}})p$

preliminary
Cross Section Fitting

\[ D(e,e'p_{\text{CLAS}})p \]

- Yield
- \( \sigma_T + \epsilon \sigma_L \)
- \( \sqrt{2\epsilon(1+\epsilon)} \sigma_{LT}\cos\phi^* \)
- \( \epsilon \sigma_{TT}\cos2\phi^* \)
- Global Fit

\[ \begin{align*}
A0 &= 2.146 \\
A1 &= -0.2745 \\
A2 &= -0.5254
\end{align*} \]

\[ D(e,e'p_{\text{RTPC}})p \]

- Yield
- \( \sigma_T + \epsilon \sigma_L \)
- \( \sqrt{2\epsilon(1+\epsilon)} \sigma_{LT}\cos\phi^* \)
- \( \epsilon \sigma_{TT}\cos2\phi^* \)
- Global Fit

\[ \begin{align*}
A0 &= 3.235 \\
A1 &= -0.6793 \\
A2 &= -0.9862
\end{align*} \]

\[ \frac{\partial^2 \sigma}{\partial \Omega_{\pi}^*} = \sigma_T + \epsilon \sigma_L + \sqrt{2\epsilon(1+\epsilon)} \sigma_{LT}\cos\phi^* + \epsilon \sigma_{TT}\cos2\phi^* \]

\[ = A0 + A1 \cos\phi^* + A2 \cos2\phi^* \]
$A_0$: BoNuS VIP Vs MAID, 4 GeV
$A_0$: BoNuS VIP Vs MAID, 5 GeV

$Q^2 = 0.93, 1.33, 2.11, 3.59$
A₀: BoNuS VIP Vs MAID, 2 GeV

\( Q^2 = 0.30 \)

\( Q^2 = 0.57 \)

\( Q^2 = 0.93 \)

\( Q^2 = 1.33 \)
12 GeV CEBAF

- Upgrade of the arc magnets
- Construction of the new Hall D
- Upgrade of the instrumentation of the existing Halls

Beam Power: 1MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV
CLAS12

Forward Detector:
- TORUS magnet
- Forward SVT tracker
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Preshower calorimeter
- E.M. calorimeter (EC)

Central Detector:
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

Proposed upgrades:
- Micromegas (CD)
- Neutron detector (CD)
- RICH detector (FD)
- Forward Tagger (FD)
RTPC 12

- Remove support spikes
- Expand the drift region by 1 cm in radius
- Double the length
- More channels
- Read out hardware upgrade
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. $x^* = 0.83$
Summary and Outlook

• Neutron structure is of high interest, but hard to access reliably at high $x$ and in the resonance region.

• BoNuS RTPC detector works well. Another RTPC has also been successfully used in a second experiment already - EG6.

• Spectator tagging technique works. BoNuS provides nearly model-independent results (Will settle d/u question at 12 GeV).

• Neutron structure function extracted and under review. Analysis note and paper are underway.

• Measured absolute cross sections for $D(e,e'\pi^-p)p$ reaction over a wide kinematic range. Huge increase in available data for neutron channel. These data will be used to improve our understanding of neutron structure, as part of fits to world data (SAID, MAID…)

• BoNuS12 proposal re-submission in preparation.
Thank you!
Outline

• Motivation
• Experiment setup
• Data Analysis
• BoNuS6 Result
• BoNuS12
• Summary
d(x) and u(x) as $x \to 1$

- Valence structure of the nucleon - sea quarks and gluons don’t contribute
- SU(6)-symmetric wave function of the proton in the quark model:
  \[
  \frac{1}{\sqrt{18}} \left( 3\bar{u}[ud]_{s=0} + \bar{u}[ud]_{s=1} - \sqrt{2}\bar{u}[ud]_{s=1} - \sqrt{2}\bar{d}[uu]_{s=1} - 2\bar{d}[uu]_{s=1} \right)
  \]
  - In this model: $d/u = 1/2$, $\Delta u/u^*) = 2/3$, $\Delta d/d = -1/3$ for all $x$
- Hyperfine structure effect (1-gluon exchange): $S=1$ suppressed $\Rightarrow$
  $d/u = 0$, $\Delta u/u = 1$, $\Delta d/d = -1/3$ for $x \to 1$
- pQCD: helicity conservation ($q^{\uparrow\uparrow}p$) $\Rightarrow$
  $d/u = 1/5$, $\Delta u/u = 1$, $\Delta d/d = 1$ for $x \to 1$
- Wave function of the neutron via isospin rotation:
  replace $u \to d$ and $d \to u$ $\Rightarrow$ using experiments with protons and neutrons one can extract information on $u$, $d$, $\Delta u$ and $\Delta d$ in the valence quark region.

*) helicity $\Delta q = (q^{\uparrow} - q^{\downarrow})$ for Nucleon $N^{\uparrow}$
Why nuclear structure from DIS on a neutron target

✓ Need proton and neutron targets to pin down u/d PDFs from DIS

At leading order

At large $x$ proton dominated by $u(x)$ and neutron by $d(x)$ due to charge weighting.

✓ Proton minus neutron can determine non-singlet (valence) contributions to structure functions at all $x$
Fit Helix to the Chains

Momentum from Curvature

Pitch and z-vertex position
Reconstructed Points (x-y plane)
Extraction of Structure Function Ratios

Now that we’ve identified spectator proton candidates we can take the ratio of tagged events (contain a spectator) to untagged (inclusive scattering on deuteron), apply a few standard corrections, and have a measurement of the structure function ratios.

\[
\frac{F_2^n}{F_2^d} = (R_{corr})(C_{e^+})(C_{\pi})(r_{rc})(n)
\]

tagged/untagged counts, corrected for accidental backgrounds and CLAS acceptance

corrections to the ratio from pion background and electrons from pair production

radiative correction

overall normalization to the world’s data at low x. Accounts for overall RTPC efficiency

\[
\frac{F_2^n}{F_2^p} = \left(\frac{F_2^n}{F_2^d}\right)\left(\frac{F_2^d}{F_2^p}\right)_{\text{model}}
\]
Data normalized so that tagged/untagged ratio agrees with the world’s data below $x = 0.5$.

Cut $Q^2 > 1.0 \text{ (GeV/c)}^2$, $W > 1.6 \text{ GeV}$ but with the further requirement that $Q^2 > 2.0 \text{ (GeV/c)}^2$ if $W = 1.6 - 2.0 \text{ GeV}$ to extend our coverage into the resonance region.
The Drift Path of An Ionized Electron

A MAGBOLTZ simulation of the crossed E and B fields, together with the drift gas mixture, determines the drift path and the drift velocity of the electrons.

• The red lines show the drift path of each ionization electron that would appear on a given channel.

• In green is the spatial reconstruction of where the ionization took place.

• In reconstruction, hits which are close to each other in space are linked together and fit to a helical trajectory.

• This resulting helix tells us the vertex position and the initial three momentum of the particle.
RTPC Proton Identification

\[ \frac{dQ}{dx} \]

- **proton**
- **Deuteron Helium**

Real data
Channel by Channel gain multipliers can be determined for each run by comparing the track’s expected energy loss to the measured value.

After applying the gain corrections, a clear separation of protons and heavier particles through dE/dx has been achieved.

Before and After Gain Calibration

Gain constants (vs phi and z) determined independently for two different runs.