Neutron Structure Function from BoNuS

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for the CLAS Collaboration

- The Structure of the Neutron at Large $x$
- The BoNuS Experiment in 2005
- Results from the BoNuS Experiment
- BoNuS at 12 GeV
- Conclusions

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Structure of the Nucleon

- Deep inelastic electron-proton scattering revealed a substructure of the proton in the late 1960s
- The structure functions of protons, deuterons and nuclei were measured extensively with leptons
- Very high precision measurements for the proton and deuteron $F_2$ structure functions were obtained over a very large kinematic range
  - $Q^2 =$ four-momentum transfer
  - $x =$ Bjorken scaling variable
- Comparable data are still missing for the neutron structure

The European Muon Collaboration made a comparison measurement of the nucleon structure function $F_2$ for heavy nuclei and deuterium

- Nucleons inside nuclei are not free

- Neutron structure function $F_2^n \neq F_2^d - F_2^p$

- Neutron structure function $F_2^n$ is commonly obtained from measurements on bound neutrons, e.g. using deuterium targets

- Extraction of $F_2^n$ at large $x$ introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, ...)

Structure Function Ratio

- The dependence of the structure function ratio $R^{d/N} = \frac{F_{2}^{d}}{F_{2}^{N}}$ on the deuteron wave function model
- Very large variations at high $x$ between the different models
Parton Distribution Functions (PDFs) for the $u$ and $d$ have increasing uncertainty at large $x$, in particular the $d$ distribution being dependent on precise neutron measurements.
Structure Function Ratio $F_{2n}^n / F_{2p}^p$

Structure function ratio $F_{2n}^n / F_{2p}^p$ is related to valence quark ratio $d/u$

$$\frac{F_{2n}^n}{F_{2p}^p} \approx \frac{1 + 4d/u}{4 + d/u}$$

at leading order (and higher orders in DIS scheme) and for $x > 0.4$

$$\Rightarrow \frac{d}{u} \approx \frac{4F_{2n}^n/F_{2p}^p - 11}{4F_{22}^n/F_{22}^p}$$

Extraction of $F_{2n}^n / F_{2p}^p$ or $d/u$ from measurements results at large $x$ in strong dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, ...)

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CTEQ6x / JLab Fits (CJ)

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Spectator Tagging of Barely Off-Shell Neutrons in $d \ (e, \ e' \ p_S) \ X$

Before

Deuteron

Spectator proton

After
Spectator Tagging of Barely Off-Shell Neutrons in \( d \ (e, \ e' \ p_s) \ X \)

Correction of neutron kinematics by measuring the recoiling spectator proton results in improved resolution of invariant mass spectrum.

Measurement from BoNuS

Tagged \( d(e, e' \ p_s)X \)

\[ W^{*2} = (p_n + q)^2 \]
\[ \approx M^{*2} + 2M\nu(2 - \alpha) - Q^2 \]

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

\( \alpha \) = light cone momentum fraction of spectator nucleon

\( W^2 = M^2 + 2M\nu - Q^2 \)

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Final State Interactions

DIS ratio of neutron momentum distributions including FSI to PWIA
Small effect for spectator momenta < 100 MeV/c and backward scattering angles
Measure (map out) FSI over large range in $\theta$ and 70 MeV/c < $p_s$ < 200 MeV/c


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Off-Shell Effects

Modification of the off-shell scattering amplitude


Colour delocalization


PLC suppression


\( \alpha = \text{light cone momentum fraction of spectator nucleon} \)

\( \alpha \)-range for \( \theta > 110^\circ \) (from simulation)

Measure \( \alpha \) up to 1.6
Most events have \( \alpha < 1.1 \)

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Nucleon Off-Shell Correction

- Ratio of bound to free nucleon structure function
- Agreement between calculations for $x < 0.8$ and $p_s < 100$ MeV/c by W. Melnitchouk (updated 2010) and F. Gross and S. Liuti
Effect of Target Fragmentation

Effect of target fragmentation on PWIA calculations of semi-inclusive DIS from the deuteron (updated 2010 by S. Simula)

\[ Q^2 = 4 \text{ (GeV/c)}^2 \]

\[ Q^2 = 1 \text{ (GeV/c)}^2 \]

\[ x = 0.8 \]

\[ p = 0.3 \text{ GeV/c} \]

\[ x = 0.4 \]

\[ x = 0.6 \]

\[ x = 0.8 \]

S. Simula

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The BoNuS Experiment

Inelastic scattering of electrons on a deuteron target \[ \text{d} \left( e, e' \ p_s \right) X \]

- 23 cm long deuterium gas target straw (Ø 6 mm and 7.5 atm pressure)
  - Spectator protons have to leave target
- Large acceptance coverage including backward angles
  - Backward angles: Target fragmentation region and reduced FSI
- Measure momentum by tracking in solenoidal magnetic field of 4 Tesla around target region (spectator momenta > 70 MeV/c (\(E_{\text{kin}} = 2.6 \text{ MeV}\))
  - Small spectator momenta: Reduced on-shell approximation (and fragmentation in conjunction with backward scattering angles)
- Measure energy deposit for particle identification
  - Spectator protons are 20 to 50 times minimum ionizing
- Measurement done at 2.1, 4.2, and 5.3 GeV electron beam energy
- Typical luminosity \(5 \cdot 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}\) (DAQ limitation)
The BoNuS Experiment
Conceptual Design of BoNuS RTPC

H. Fenker

7 atm $D_2$ gas
Thin-wall High Pressure Gas Target

Møller el.
$e^-$ (to CLAS)

Drift Region

Helium/DME at 80/20 ratio

3 GEMs
Readout pads and electronics
Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

Increase RTPC HV to sensitize detector to minimum ionizing electrons

Target

Electron (also seen in CLAS)

Proton

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Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

Data taken end of 2005 run with 1.1 GeV electrons

Scattered electron measured in CLAS and by the RTPC

N. Baillie

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Energy Loss in RTPC

- Energy loss as a function of measured momentum after calibration of RTPC
- Particle identification in RTPC using $^4$He gas target

4He Target, $E=2\text{GeV}$

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BoNuS Analysis Methods

Two analysis methods employed

- **Ratio method**
  - Forming ratio between spectator tagged events to inclusive deuteron scattering events for a given kinematic bin
  - Normalization and CLAS acceptance controlled by ratios

- **Monte Carlo method**
  - Forming ratio between spectator tagged events to MC simulation of CLAS with events generated according to PWIA spectator model

- Both methods are in very good agreement
Monte Carlo Method

- Ratio of tagged event rate and MC simulation from PWIA spectator model
- Backward angles shown $\cos \Theta_{pq} < -0.25$

S. Tkachenko

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**Monte Carlo Method**

- Effective neutron structure function $F^2_n$
- Backward angles shown $\cos \Theta_{pq} > -0.25$
- $F^2_n$ model of Bosted and Christy plotted for comparison
  
  M.E. Christy and P.E. Bosted, PR C77, 065206 (2008)

- Very good agreement between model and data

- Comparison with model dependent extraction from inclusive $F^2_d$ data
  
  S.P. Malace et al., PRL 104, 102001 (2010)

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Monte Carlo Method

- Angular dependence for $Q^2 = 1.66 \text{ (GeV/c)}^2$ and $W^* = 1.73 \text{ GeV}$
- At small spectator momentum, basically no deviations from unity
- At larger spectator momentum, deviation from unity in agreement with model by C. degli Atti, indicating FSI and off-shell effects

S. Tkachenko
Ratio Method

- Extracted neutron structure function $F_2^n$ in resonance region
  - 5.3 GeV beam energy
  - $Q^2 = 1.7 \text{ GeV}^2/c^2$
  - $-0.75 < \cos \theta_{pq} < -0.25$ (backward angles $105^\circ - 140^\circ$)
  - $70 \text{ MeV}/c < p_s < 90 \text{ MeV}/c$
- $F_2^n$ model of Bosted and Christy plotted for comparison
- Open data points are from analysis of inclusive data by S. Malace et al.

![Graph showing $F_2^n$ vs. x with data points and model curves.](image)

N. Baillie

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Structure Function Ratio

- Ratio of neutron to proton $F_2$ structure functions
- Precise measurement on quasi-free neutron up to $x^* \approx 0.6$
- Exploratory analysis up to $x^* \approx 0.8$ with inclusion of the resonance region
- Normalization of the ratio to 0.695 at $x^* = 0.3$

CJ: A. Accardi et al., PRD 84, 014008 (2011)


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New RTPC for BoNuS12

- Basically same design and construction as BoNuS
- Double RTPC and target length to increase luminosity to \(2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) and backward scattering angle acceptance
- Increase active detector region radially from 3 cm to 4 cm to improve momentum resolution, especially for higher momentum protons
- Use Ne/DME drift gas for increased \(dE/dx\) and better PID
- Increase phi coverage by removing central spine (as in EG6)
- Use new GEM foil design for continuous 360° azimuthal coverage
- 6 mm diameter gas cell with 30 µm thin walls
- Potentially change to new readout chip
- Use forward vertex tracker (micromegas) for improved vertex reconstruction
BoNuS12 Expected $F_2^n/F_2^p$ Accuracy

- 35 days of data taking on $D_2$ and 5 days on $H_2$ with $\mathcal{L} = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
- DIS region with
  - $Q^2 > 1 \text{ GeV}^2/c^2$
  - $W^* > 2 \text{ GeV}$
  - $p_s < 100 \text{ MeV}/c$
  - $\theta_{pq} > 110^\circ$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8 \text{ GeV}$ gives max. $x^* = 0.83$
- Overall scale error 5%


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BoNuS12 Projected $d/u$ Accuracy

- Data taking of 35 days on $D_2$ and 5 days on $H_2$ with $\mathcal{L} = 2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
- Open squares represent data points for $W^* > 1.8 \text{ GeV}$

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Conclusions

- Successfully used spectator tagging with BoNuS experiment in 2005
- First measurement of *free* neutron resonance structure
- Two analysis approaches give comparable results
- Analysis notes under review and publications being prepared
- Extend measurement with 11 GeV electron beam energy to reach higher $x$ to be able to distinguish between different models for $d/u$
- Use upgraded CLAS12 spectrometer together with new RTPC recoil detector replacing vertex tracker in new central detector
- Plan to increase luminosity by at least a factor of 40 as compared to the BoNuS experiment of 2005 (factor of 4 compared to EG6)
- **BoNuS creates an effective free neutron target**
- **BoNuS facilitates a broad program of physics, including $F_2^n$ and $F_2^n/F_2^p$ measurements at large $x$**
Inclusive Neutron Resonance Electroproduction

- Cross sections measured at Jefferson Lab Hall C
- Resonance structure well resolved for proton data
- Deuteron data show only $\Delta(1232)$ resonance clearly (not resolved anymore at $Q^2 = 2$ GeV$^2$)
- Extraction of neutron requires modeling of (non-)resonant components, including Fermi motion, nuclear binding effects, etc.

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EMC Effect

- Neutron or proton excess in nuclei leads to an isovector-vector mean field
- Possible isospin dependent EMC Effect
- Calculations can likely be extended to lighter nuclei
- Combination of BoNuS12 and measurement on mirror nuclei could potentially be sensitive to measure this effect

I.C. Cloët, W. Bentz and A.W. Thomas, PRL 102, 252301 (2009)

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The BoNuS Recoil Detector

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