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

$$F_{2n} \neq F_{2d} - F_{2p}$$

Neutron structure function $F_{2n}$ is commonly obtained from measurements on bound neutrons, e.g. using deuterium targets.

Extraction of $F_{2n}$ at large $x$ introduces theoretical model dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, ...)

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 $u_\nu$ and $d_\nu$ have increasing uncertainty at large $x$, in particular the $d_\nu$ distribution being dependent on precise neutron measurements.
Structure function ratio $F_2^n / F_2^p$ is related to valence quark ratio $d/u$

$$\frac{F_2^n}{F_2^p} \approx \frac{1 + 4d/u}{4 + d/u}$$

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

$$\implies \frac{d}{u} \approx \frac{4F_2^n/F_2^p - 11}{4 - F_2^n/F_2^p}$$

Extraction of $F_2^n / F_2^p$ or $d/u$ from measurements results at large $x$ in strong dependence on nuclear corrections (Fermi motion, nucleon off-shell corrections, FSI, ...)

CTEQ6x / JLab Fits (CJ)
Spectator Tagging of Barely Off-Shell Neutrons in d (e, e’ p_s) X

Before

Deuteron

After

Spectator proton

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

\[
W'^2 = (p_n + q)^2 
\approx M'^2 + 2M_N(2 - \alpha) - Q^2
\]

\[
\alpha = \text{light cone momentum fraction of spectator nucleon}
\]

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**Inclusive $d(e,\ e')$**

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

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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

by C. Ciofi degli Atti and L.P. Kaptari

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**Off-Shell Effects**

Modification of the off-shell scattering amplitude


Colour delocalization


PLC suppression


Measure $\alpha$ up to 1.6

Most events have $\alpha < 1.1$

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

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Nucleon Off-Shell Correction

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

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Effect of Target Fragmentation

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

\[ Q^2 = 4 \text{ (GeV/c)}^2 \]
\[ x = 0.8 \]

\[ Q^2 = 1 \text{ (GeV/c)}^2 \]
\[ p = 0.3 \text{ GeV/c} \]
The BoNuS Experiment

Inelastic scattering of electrons on a deuteron target \( \textbf{d (e, e' p_s) X} \)

- 23 cm long deuterium gas target straw (\( \varnothing \) 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 \( (E_{kin} = 2.6 \text{ MeV}) \))
  *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

Thin Al-Mylar Window

Thin Al-Mylar Cathode

Helium/ DME at 80/20 ratio

3 GEMs

Drift Region

Readout pads and electronics

7 atm D₂ gas

Thin-wall High Pressure Gas Target

Møller el.

e⁻ (to CLAS)
Calibration by Elastic Electron-Proton Scattering at 1.1 GeV

Increase RTPC HV to sensitize detector to minimum ionizing electrons

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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

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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, $E=2$GeV

- proton
- triton
- helium 3
- helium 4
- deuteron

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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
- Published results are based on the Ratio Method
Ratio Method

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

\[ R_{\text{exp}} = \frac{N_{\text{tagged}}(\Delta Q^2, \Delta W^*, \Delta p_s)}{N_{\text{incl}}(\Delta Q^2, \Delta W)} / \frac{A_e(Q^2, W^*)}{A_e(Q^2, W)} \]

\[ R_{\text{exp}} = \frac{F_2^n(Q^2, W^*)}{F_2^d(Q^2, W)} \frac{I_{\text{VIP}}}{I_{\text{VIP}}} \]

\[ \frac{F_2^n}{F_2^p} = R_{\text{exp}} \frac{F_2^d}{F_2^p} / I_{\text{VIP}} \]

\[ I_{\text{VIP}} = \text{integrated spectral function over proton acceptance within RTPC VIP cuts} \]

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Ratio 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)
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
  - $Q^2 = 1.7$ GeV$^2/c^2$
  - $-0.75 < \cos\theta_{pq} < -0.25$ (backward angles $105^\circ - 140^\circ$)
  - $70$ MeV/$c$ < $p_s$ < $90$ 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.
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)

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 $360^\circ$ azimuthal coverage
- 6 mm diameter gas cell with 30 $\mu$m 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 $\mathcal{L} = 2 \cdot 10^{34}$ cm$^{-2}$ sec$^{-1}$
- 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. $x^* = 0.83$
- Overall scale error 5%

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 $W^* > 1.8 \text{ GeV}$
Conclusions

- Successfully used spectator tagging with BoNuS experiment in 2005
- First measurement of free neutron resonance structure
- Two analysis approaches give comparable results
- 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 $F_{2n}$ and $F_{2n}/F_{2p}$ measurements at large $x$
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.
The BoNuS Recoil Detector

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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)
Monte Carlo Method

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

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