The Neutron Structure Function from BoNuS

Stephen Bültmann

Physics Department, Old Dominion University, Norfolk, VA 23529, USA

Abstract.
The BoNuS experiment at Jefferson Lab’s Hall B measured the structure of the neutron via electron scattering off a deuterium gas target. By augmenting the CLAS detector with a novel radial time projection chamber featuring gas electron multipliers, very low momentum recoiling spectator protons were detected at very backward angles. The selection of these protons provides a tag for scattering on quasi-free neutrons.

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THE NEUTRON STRUCTURE FUNCTION $F_n^2$

The proton structure functions have been measured extensively over the past few decades, however, comparable data on the neutron structure are sparse. Because those measurements are not made on the free neutron, but are inferred from measurements on more complex nuclei, like deuterium or helium, their precision is limited by the theoretical uncertainties of the extraction process. The uncertainties of models describing the interaction of the bound nucleons inside the nucleus are particularly large for the region of large Bjorken-$x$. Besides Fermi motion, models account for nucleon off-shell effects [1, 2] or are assuming a suppression of point-like configurations (PLC) in the bound nucleon [2], for example.

Besides the intrinsic interest in the measurement of the neutron structure function $F_n^2$, the ratio of $d/u$ quarks can be extracted from the structure function ratio $F_n^2/F_p^2$. For the limit of $x \to 1$ different models predict different values for the $d/u$ ratio. A precise measurement of the structure function ratio $F_n^2/F_p^2$ to the highest possible $x$ will therefore enable the discrimination between these predictions. The simplest SU(6) symmetric quark model predicts the ratio of $d$ to $u$ quark distributions in the proton to be $1/2$. However, the breaking of this symmetry in nature should result in a much smaller ratio at large $x$. For example, if the interaction between quarks that are spectators to the deep inelastic collision is dominated by one-gluon exchange, the $d$ quark distribution will be suppressed, and the $d/u$ ratio will tend to zero in the limit $x \to 1$ [3, 4, 5, 6]. This assumption has been built into most global analyses of parton distribution functions, but has never been tested independently [7, 8]. Alternatively, pQCD expectations of hadron helicity conservation lead to a prediction of $d/u \to 0.2$ in the limit $x \to 1$ [9, 10].

1 For the CLAS Collaboration
THE BONUS EXPERIMENT

For the “BoNuS” experiment [11] a novel radial time projection chamber (RTPC) [12] was added to the CEBAF Large Acceptance Spectrometer (CLAS) in Jefferson Lab’s Hall B. The RTPC surrounded thin tubular deuterium gas target to be able to detect very low momentum protons (above $\approx 70 \text{ MeV/c}$) over a large range of scattering angles. The electrons scattering off the deuterium gas target were recorded by the CLAS detector. In case the electron scattered off a neutron, the recoiling “spectator” proton was detected by the RTPC. Selecting very low proton momentum scattering events at backward angles tags events where the neutron and proton are very loosely bound. Estimates of the corrections to the on-shell neutron structure function due to off-shell effects in relativistic spectator-quark di-quark models result in less than 1% for spectator proton momenta below $100 \text{ MeV/c}$ [13, 14] and beyond $100^\circ$ relative to the momentum transfer $\vec{q}$. In this case the final state interactions with the spectator proton are also very small and the measured proton momentum can be used to kinematically correct the electron scattering variables for the initial motion of the neutron [15, 1, 16, 17]. This leads to a significant sharpening of the resonant structures in the rate versus the final state mass $W^*$ as seen in Fig. 1.

The recoil detector and target system are required to have a minimum amount of material in the path of the outgoing low-momentum protons while reliably identifying and measuring the trajectories of these protons and minimizing electromagnetic background. The RTPC was placed inside a longitudinal magnetic field of about 4 T which suppresses Møller electrons entering the CLAS detector and bends the proton trajectories for momentum measurement. It used a mixture of helium and dimethyl ether (DME) as drift
gas in a radially 3 cm thick cylindrical drift region with three layers of gaseous electron multipliers (GEM’s) [18] to amplify the ionization signal. Measuring both the drift time and projection onto the cylindrical shell of each ionization cluster, a three-dimensional reconstruction of the track becomes possible.

ANALYSIS AND RESULTS

The BoNuS experiment took data in the Fall of 2005 at beam energies of 2.1 GeV, 4.2 GeV and 5.3 GeV. The data were analyzed semi-independently using two different techniques. The first (ratio) method sorts events with a spectator proton detected in the RTPC into kinematic bins and normalizes by the inclusive deuteron scattering events for the same kinematics. The absolute normalization and CLAS acceptance were handled naturally this way by using experimental event ratios and world parameterizations of known quantities such as the deuteron and proton cross sections. The second (MC) method makes use only of events with a tagged spectator proton and compares the binned data directly to a Monte-Carlo simulation of the CLAS detector with events generated according to a plane-wave impulse approximation (PWIA) spectator model. The results obtained by either method are in agreement [19].

For the extraction of the free neutron structure functions, momenta $p_s < 0.1$ GeV/$c$ and scattering angles $\theta_{pq} > 100^\circ$ were selected. A sample of the structure function $F_2^n$ for four different ranges in $Q^2$ is shown in Fig. 2 as a function of the invariant mass $W^\star$. Moderately good overall agreement with model-dependent extractions, introduced in the caption, is seen.

The final result for the structure function ratio $F_2^n/F_2^p$ versus $x^\star$ is shown in Fig. 3 for three different $W^\star$ cuts. The CTEQ-Jefferson Lab (CJ) global PDF fit [24], shown by the band, is in good agreement with the data for the $W^\star > 1.8$ GeV cut in the range $0.3 < x^\star < 0.6$. When relaxing the $W^\star$ cut, a structure appears around $x = 0.65$ possibly indicating an enhanced resonance in the neutron as compared to the $F_2^n/F_2^p$ background.

BONUS AT CLAS12

To extend the range of Bjorken-$x$ towards even higher values, an extension of the BoNuS program has been proposed and approved by Jefferson Lab’s PAC 36 (2010) [25] for the 11 GeV era of Jefferson Lab. Recoil protons with momenta down to 70 MeV/$c$ will be detected in coincidence with electrons scattered into CLAS12, measuring $F_2^n$ in the DIS region at high $Q^2$ and $x$ up to $\approx 0.8$, with comparable detail and precision as has been achieved for the proton.

For this “BoNuS12” experiment, a similar RTPC as the one built for the BoNuS experiment will be used. The overall length of the target and detector will be doubled and the drift region extended radially from 3 cm to 4 cm. Together with an increased beam current, this will increase the luminosity to $2 \cdot 10^{34}$ cm$^{-2}$ sec$^{-1}$, improve the momentum resolution for higher momentum spectator protons, and increase the backward scattering acceptance. The CLAS EG6 experiment took data successfully in 2009 with a slightly modified RTPC and a new drift gas mixture, neon-DME. The BoNuS12 experiment will
FIGURE 2. Structure function $F_2^n$ spectra for four different ranges in $Q^2$ as a function of the invariant mass $W^*$ (blue points). For comparison, an extraction [20] of $F_2^n$ from recent $F_2^d$ and $F_2^p$ data using nuclear smearing corrections of [21] are shown (red points). The solid curve is a phenomenological parametrization of $F_2^n$ [22, 23] obtained from inclusive $F_2^d$ and $F_2^p$ data using a model of nuclear effects.

use this drift gas to increase the fractional energy loss for better particle identification. The recoil detector will once again surround a thin deuterium target and “tag” scattering events on a nearly on-shell, loosely bound neutron. The magnetic field needed for momentum measurement of the recoiling protons will be provided by the CLAS12 central detector solenoid magnet.

CONCLUSIONS

The BoNuS experiment successfully demonstrated the feasibility of spectator tagging for the measurement of the nearly free neutron structure function. The measurement will be extended with 11 GeV beam energy to reach values of $x^* \approx 0.8$, improving the constraint on the $d/u$ ratio towards $x^* = 1$ significantly.

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FIGURE 3. The ratio $F_n^2/F_p^2$ versus $x$ for three $W^*$ cuts. Statistical error bars are shown with the total systematic uncertainties indicated by the band above the $x$-axis. For comparison the CTEQ-Jefferson Lab (CJ) global PDF fit [24] is shown by the band.

REFERENCES