

2007-2008 Fellowship Report

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A. Research Accomplishments:

My doctoral research topic is the Barely Off-shell Nucleon Structure (BoNuS) experiment, which ran in Jefferson Lab's Hall B in the Fall and Winter of 2005. The subject of my thesis is the measurement of the tagged F_2^n structure function of the neutron by use of a novel Radial Time Projection Chamber (RTPC) – one of the many interesting results expected from the BoNuS experiment.

The BoNuS collaboration has attempted to explore the structure of the neutron by scattering Jefferson Lab's electron beam off a deuterium target. Backward angle, low-energy recoil protons were measured using gas electron multipliers (GEMs) in a cylindrical geometry around the target. The production detector is a time projection chamber with radial electron drift and its construction and successful implementation marks the first time that GEMs have been used in a curved geometry. This recoil detector was installed in the Hall-B beamline and recorded data in synchronization with the standard CLAS configuration.

In addition to the many small studies and analysis tasks which I performed, I believe that I've completed three major research accomplishments during my JSA Fellowship period. The following sections outline those activities:

1. BoNuS RTPC Drift Velocity Modeling and Calibration

The BoNuS RTPC readout system consists of 3200 charge collection pads, each having 100 possible time bins on which to register a signal. Some of these hits may be eliminated as candidates belonging to a good track because they are outside of the physical area where a particle may travel. The first step towards the goal of clustering the appropriate hits together and identifying proton tracks is to have some knowledge of the paths on which ionization electrons travel before reaching the amplification and readout stages of the RTPC. The fact that the electric and magnetic fields in our configuration are not parallel or even strictly perpendicular throughout the chamber volume gives us a challenging problem in the determination of signal reconstruction. We must have a proper description of the electron drift velocity vectors before

an attempt is even made to describe a particle track. There exists an industry standard program called MAGBOLTZ which takes as inputs the drift gas elements and mixture, the gas temperature and pressure, the magnitudes of the electric and magnetic fields and the angle between the two at a given spatial point. The program then outputs the magnitudes of each component of the drift velocity vector in $\mu m/ns$ with respect to the direction of the electric field. After finding the drift velocity vectors for an adequate number of chamber positions there were two possible directions to take. One choice would have been to use the typical program which handles the simulation of two and three-dimensional drift chambers, known as GARFIELD. However, the approach we have taken is to circumvent the usage of proprietary software by using MAGBOLTZ, together with our own code, to generate approximations to the electron paths.

Using a parameterization of the electric and magnetic fields, and the approximate composition of the gas, MAGBOLTZ predicts the drift velocity vector components at given points in the RTPC. Our own code then reads the resulting spatial grid and simulates the trajectory of an ionization electron through the tracking region that terminates at the center of each pad. In the end, we have a properly curved electron path for each channel which was used to create a function that converts an observed signal into a reconstructed space point P:

$$P_{xyz} = P_{xyz} (I, T_{sig}, V_{cathode}, V_{GEM}, R_{gas})$$

where I is the pad number and T_{sig} is the time (in ALTRO units) at which a signal was recorded. The parameters $V_{cathode}$ and V_{GEM} represent the RTPC operating voltages, and the fraction of helium in the gas mixture is given by R_{gas} . Ideally, the drift paths determined this way would be final. However, the high magnetic field and the imperfect knowledge of the gas mixture led us to include the three parameters and determine effective values for them that provided the best agreement with the data.

Despite our best efforts to simulate and parameterize the paths on which drift electrons travel, a drift velocity calibration was still necessary. The failure of the RTPC's computer controlled gas handling system lead to a large uncertainty in the ratio of Helium to DME in the drift volume. The RTPC expert on shift was tasked with regulating the flow from the bottles manually, keeping the ratio at He/DME = 80/20. The amount of deviation from the nominal values was as much as 10% during each 30 minute increment, depending on the environmental variables of any given day. The calibration constants that we have available to us are the He/DME ratio, the voltage settings on the power supplies that regulate the left and right cathode and gem circuits, the overall ϕ rotation (azimuthal angle measured about the z axis, parallel to the beamline) of the left and right chamber halves, the electronic's start time T_0 , and the (x,y) location of the center of the RTPC. Kirchoff's circuit laws are used to calculate the actual electric fields between the drift, transfer and induction gaps. The potential difference between the inside of the first GEM and ground is dependent on the voltage setting from the power supply which regulates the drift field, as well as it's own power supply. Therefore only the power supply voltage setting on the drift circuit was varied to account for uncertainties in the resistor values during the calibration procedure. The ϕ and time offsets in the data due to the ϕ coverage and the time it takes avalanche electrons travel from the first GEM to the readout pads are accounted for by allowing the electronic's start time and the overall ϕ rotation to be variable during the calibration. The final calibration constant which we consider is the (x,y) coordinate of the center of the RTPC in CLAS coordinates. This position does not affect the drift paths directly but it does have a major impact on the helix fit to the RTPC tracks since the beamline point is included on the track.

The final part of the BoNuS run period consisted of calibration data taken with electrons which only took a single pass around the accelerator. For these calibration runs, the GEM and cathode circuits on both sides of the RTPC had their high voltage increased by 400V so that the chamber would be sensitive to higher momentum and minimally ionizing tracks. The optimal drift velocity parameters are found by matching the trigger electron in CLAS with a track in the RTPC. The 1 GeV beam energy was chosen for this study because it is absolutely crucial that the production vertex and momentum vector of the electron are well measured by CLAS. The uncertainties in momentum and vertex measurement are proportional to beam energy, and the 1 GeV electron data are the easiest to calibrate. The final drift velocity calibration allows us to measure the z , θ , and φ of the RTPC tracks at the vertex within 5.5 mm, 1.5° and 4.5° , respectively.

2. RTPC Channel-by-Channel Gain Calibration

The entire electronics chain was bench-tested prior to installation. No electronic channels were found whose response to a test pulse was more than a few percent away from the mean response. As the tracking analysis matured, however, it became apparent that the overall gain (including both gas gain and electron collection efficiency) varied significantly across the surface of the RTPC. Therefore it was necessary to develop a procedure for determining the relative responses of all 3200 pads before useful dE/dx information could be extracted from the data.

A self-calibration was performed using heavily-ionizing tracks obtained from the RTPC data alone. Making use of the electron drift paths determined earlier, each track was reconstructed and its momentum was determined. Track segments whose ionization electrons should drift onto each individual readout pad were identified. The observed signals were compared with the energy loss predicted by the Bethe-Bloch function for each track segment, yielding a mean sensitivity for each channel when a sufficient number of tracks was analyzed (approximately 10^5 or more tracks). These gain factors were scaled so that the mean value over the entire detector is near unity. They represent a first approximation to the relative gains of all of the readout channels. Although not all of the tracks were created by protons, this mis-assignment causes an error only in the overall scale of the gain estimate, as the mixture of particle species throughout the RTPC appears to be reasonably uniform.

The first-pass gain-normalization factors were used to scale the raw pulse-heights and then the same gain determination process was repeated. However, during the second pass we excluded tracks whose measured dE/dx was inconsistent with that expected for protons. These second-pass gain-normalization factors (which are only slightly different from those obtained in the first pass) are retained and used for the final physics analysis particle identification. Analysis of numerous data sets collected at different times confirms that the relative gains of the channels do not vary significantly. The absolute gains do vary with time, probably as a result of changes in the atmospheric pressure and the gas mixture. One can correct for these effects by normalizing the pulse-heights to the value of the proton dE/dx peak observed in each run.

Once the channel-by-channel gain factors were determined, a particle identification cut was developed based on the visible energy loss. To account for the time dependence of the gas gain, every run's proton peak was fit to a Gaussian form. The mean and sigma of the fit were recorded and time segments during the run period where significant changes in either of these values were identified and split into regions. A simple line fit was then performed on these regions so that short runs with inadequate statistics could be accounted for. If a given particle's dE/dx falls outside of three sigma of the predicted value for that run period, it is removed from the data sample.

3. Quasi-Free Neutron Resonance Structure and Structure Function

One pressing question that exists today in nuclear physics is what happens to the nucleon's structure functions as the Bjorken variable, $x = Q^2/2Mv$, approaches unity ($Q^2 =$ Four momentum transfer squared, $M =$ Nucleon Mass, and $v =$ Energy Transfer). When nearly all of the nucleon's momentum is dominated by the contribution of the u and d valence quarks the different theoretical models predict drastically different behavior. The ratio of proton to neutron unpolarized structure functions is highly sensitive to different symmetry breaking mechanisms in this kinematic region. The proton's unpolarized structure function is well known, but measuring the same quantity for the neutron requires techniques with large uncertainties. The experimental procedure that BoNuS applies extracts the structure function over a significant range in Q^2 (from about 0.5 to 3 GeV²) and W (from the elastic peak to 3 GeV). The kinematic coverage includes the elastic, resonance, and part of the deep inelastic regions. The following procedure allows us to extract neutron resonance excitation strengths and the ratio of nucleon structure functions.

The BoNuS experiment addresses the issue of off-shellness by detecting low momentum (70-200 MeV/c) backward angle protons recoiling off an electron-neutron scattering event. Protons detected in coincidence with the scattered electron can ensure that the electron scattering reaction took place on an almost free neutron, and we can infer its initial four-momentum from the observed spectator-proton. The backward angle reduces the amount of background and such a low recoiling momentum enhances greatly the possibility to estimate reliably the small off-shell effects related to the struck neutron. When viewing low momentum spectators it is necessary to minimize the uncertainty due to deuterium's wave function and on-shell extrapolation.

Figure 1 shows an example of how accounting for the neutron's initial momentum can enhance the resonance structure and drastically sharpen the quasi-elastic peak. The invariant mass of the struck hadron, assuming the initial particle is at rest, can be written,

$$W^2 = M^2 + 2Mv - Q^2.$$

The previously described technique of spectator-proton tagging allows us to use the known Fermi momentum of the struck neutron when calculating the corrected invariant mass,

$$W^{*2} = (p_n + q)^2 \approx M^{*2} + 2Mv(2 - \alpha_s) - Q^2,$$

where the struck neutron's four momentum is given by $p_n^\mu = (M_D - E_s, -\mathbf{p}_s)$, $M^* = p_n^\mu p_{n\mu}$ and the light-cone momentum fraction is defined as $\alpha_s = (E_s - p_s^z)/M$.

Figure 2 depicts the ratio of nucleon structure functions, F_2^n/F_2^p , measured over a large range in W . This quantity was extracted by first dividing the tagged counts by the untagged counts in each bin. Next the data is scaled so that tagged/untagged ratio agrees with a phenomenological model in the range $1.9 < W < 2.1$. Finally, the ratio is multiplied by the known F_2^D/F_2^p . An acceptance correction method is currently being developed and systematic uncertainties are being estimated. The data analysis is nearly complete and will be published in the near future.

B. Presentations:

1. APS Division of Nuclear Physics 2007 meeting – An overview of the BoNuS detector and the spectator tagging technique was given. This talk included presentation of preliminary data.

2. Jefferson Lab User's Group Meeting 2007 – A poster was presented which gave an overview of the BoNuS experiment. This poster won 3rd prize in the poster competition.

3. CLAS Collaboration Deep Processes Working Group Meeting May 2008 – An update on the BoNuS analysis work was given.

4. Gordon Conference on Photonuclear Reactions 2008 – A poster was presented which gave an overview of the BoNuS experiment.

C. Publications based on work:

H. Fenker *et al.* / Nuclear Instruments and Methods in Physics Research A 592 (2008) 273-286

D. Conferences attended:

1. International Workshop on DIS and Related Subjects - 2007
2. APS Division of Nuclear Physics - 2007
3. Gordon Conference on Photonuclear Reactions - 2008

E. Status of Travel Funds:

I have been told by The College of William and Mary's Physics Department's administrative staff that all of the funds from my travel stipend of \$2000 were spent towards my attendance of the aforementioned conferences.

F. Figures:

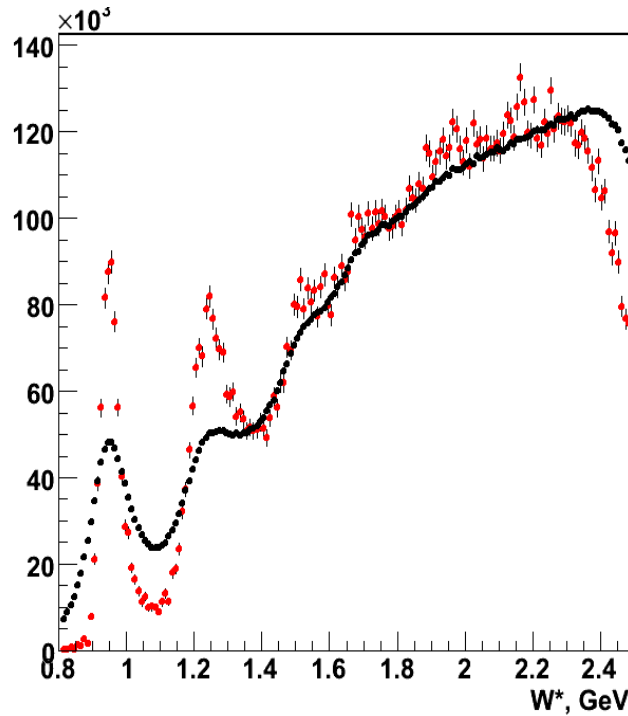


Figure 1: Invariant mass calculated without (black points) and with (red points) accounting for struck nucleon's Fermi momentum

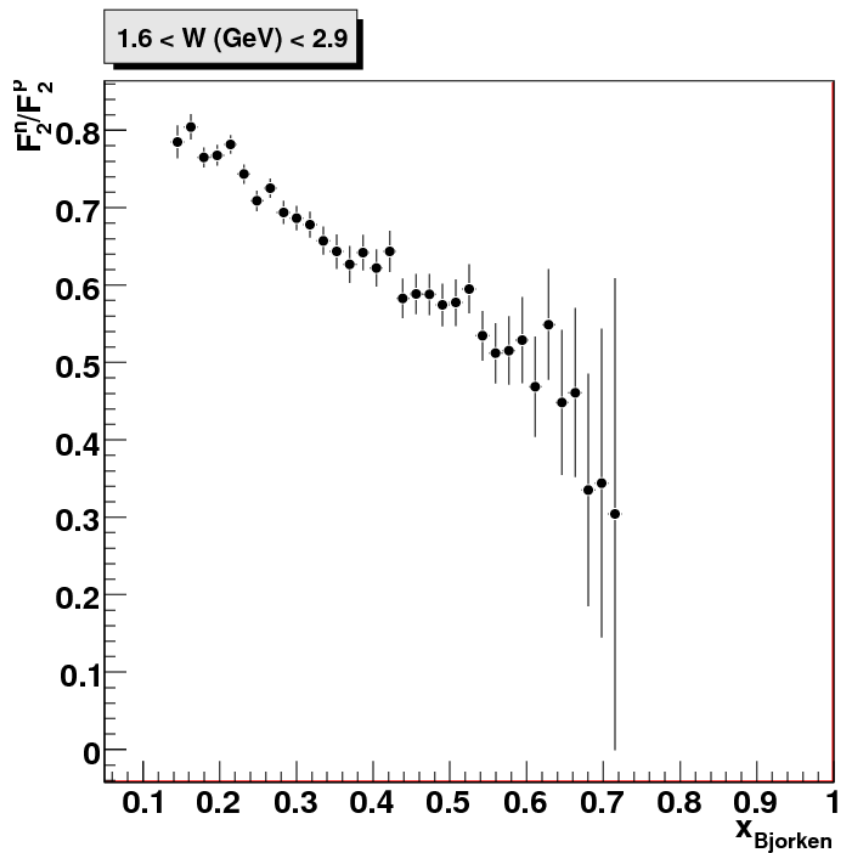


Figure 2: The nucleon structure function ratio F_2^N/F_2^P as a function of x_b . The error bars here are only statistical in nature.