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The BoNuS Detector: A Radial Time Projection Chamber for tracking Spectator Protons

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Abstract

A GEM-based Radial Time Projection Chamber is being developed as a spectator-proton tracker for an experiment at Jefferson Lab. The purpose of the experiment is the study of the structure of nearly free neutrons. Interactions on such neutrons can be identified by the presence of a backward-moving proton in the final state of a beam-deuterium collision. The detector must be of very low mass in order to provide sensitivity to the slowest possible protons. The ionization electron trail left by the protons will drift radially outward to an amplification structure composed of curved GEMs, and the resulting charge will be collected on pads on the outer layer of the detector. Unique design challenges are imposed by the cylindrical geometry and the low mass requirement. The status of the project and results of prototype tests are presented.

1. Introduction

The Jefferson Lab (formerly CEBAF) Program Advisory Committee has approved beam time for Experiment E03-012, a study of neutron structure using the tagged spectator proton technique. The purpose of this experiment is to develop the necessary equipment and inaugurate a broad study of interactions on effectively free neutrons. The experimental program has been dubbed the “BoNuS” experiment[1], for “Barely off shell Nuclear Structure”. This report describes some of the physics of the program and the novel detector we are developing to provide access to that physics.

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2. *Physics Motivation*

Largely because of the relative ease of providing free proton targets for nuclear scattering experiments, there is a wealth of data about proton structure. The proton's isospin partner, the neutron, is equally copious in ordinary matter. However, direct studies of scattering on neutrons are not so common because dense free neutron targets are not available. The most common technique for obtaining neutron scattering data is to collide beam particles with bound nuclear targets and try to infer the behavior of the neutron by applying corrections based on models of the nuclear system.

An example of the sorts of data that can be obtained in this way is given in Fig. 1, which shows the resonance spectra for ep and ed collisions at matched kinematics. It might be hoped that neutron resonance data could be extracted from the ed data by subtracting the measured ep cross sections. While one would expect the neutron resonance spectra to exhibit the same complexity as proton spectra, it is clear from the ed data that any such detail is masked by the effects of the bound nuclear system. The situation only gets worse for more complicated nuclear targets.

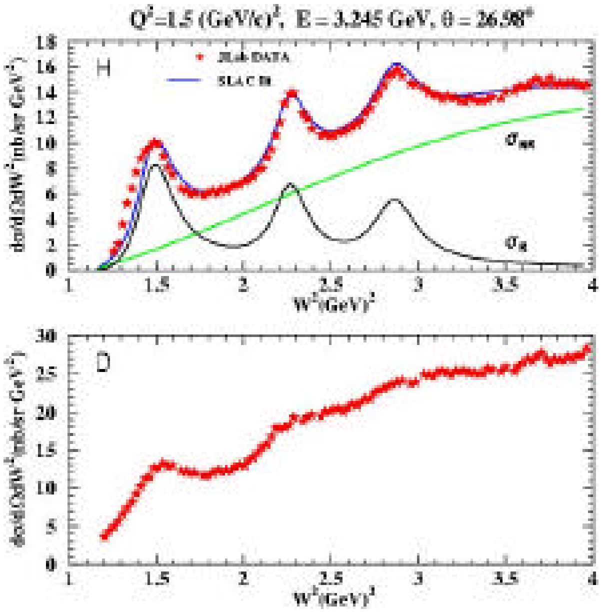


Figure 1: Inclusive resonance electroproduction cross sections from Jefferson lab at Q^2=1.5 (GeV/c)^2. Cross sections are shown as a function of invariant mass squared. The top spectrum is from a hydrogen target and the bottom is from deuterium at matched kinematics. The hydrogen spectra are plotted with total global fit results as well as the resonant and non-resonant fit components.

Similarly, detailed measurements of neutron electric or magnetic form factors and structure functions are limited by our imprecise understanding of the bound system. In the case of form factors it is possible to extract accurate ratios from available data, but not absolute values.

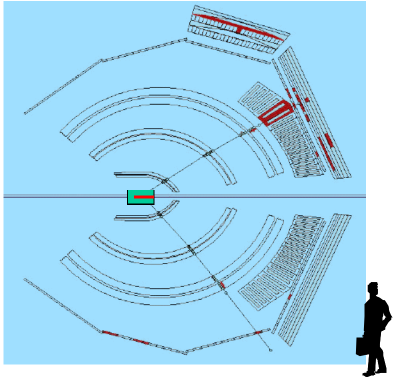
One solution to this problem that has been in use for many years is to use deuterium as a target material and select only those events in which it is apparent that the neutron was the primary participant in the interaction, with the proton being merely a spectator. This is the technique that BoNuS is pursuing and improving upon.

3. Experiment Concept

The goal of the experiment is to develop and use a system of target and detectors that will identify beam-neutron collisions within the background of interactions on the protons and interactions on the combined nuclear system. To do this we will identify events which have a backwards-moving proton (in the lab frame) in the final state. The presence of such a proton is an almost unambiguous signature for a neutron-target event. Measurement of this spectator proton's momentum vector also determines the initial state of the target neutron, so that corrections for target motion can be applied on an event by event basis. Secondary particles from the beam-neutron collision will be tracked and measured in the same way that secondaries from beam-proton interactions are measured in hydrogen-target experiments.

The experiment will be run in Hall-B at Jefferson Lab [2]. This facility provides a continuous beam of electrons with energies up to 6 GeV, as well as a magnetic spectrometer, calorimetry, and particle identification for the secondaries. This CEBAF Large Acceptance Spectrometer (CLAS) is shown in Fig. 2. By linking the production vertex of secondary particles measured in CLAS with a coincident spectator proton vertex, it will be possible to tag individual events as having occurred on a neutron target. With these tools it will be possible to perform measurements on neutrons and protons with similar precision and sensitivity.

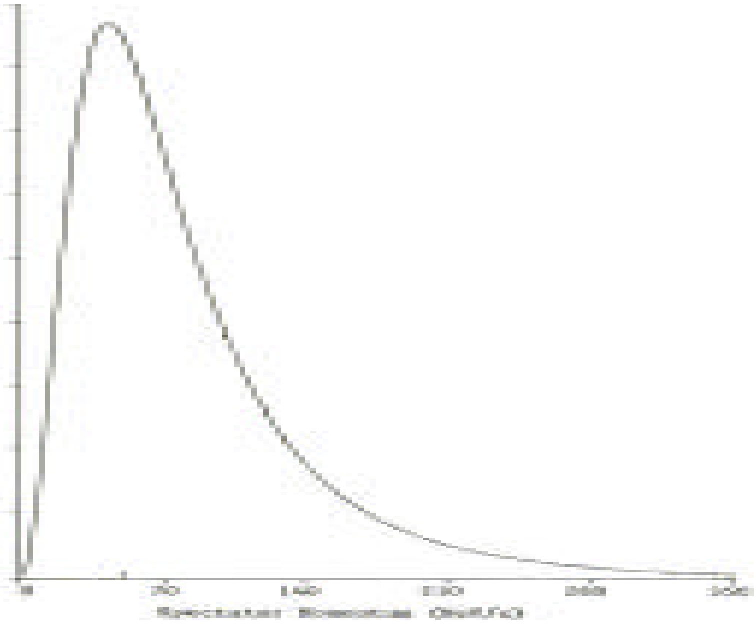
Figure 2. Cross section of the CLAS detector system. Tracks measured in CLAS will be projected back to the target to determine the vertex position. Spectator protons measured in the BoNuS detector surrounding the target will be linked to those vertices.



Spectator Protons

One model of the momentum spectrum of protons suddenly released from deuterons is given by the Hulthen wave function [3] as shown in Fig. 3. This distribution is highly populated at very low end, indicating that an effective spectator proton tagger must be optimized to accept protons with the lowest possible momenta. Such low momentum protons are very heavily ionizing as they pass through matter – some 20 to 50 times minimum-ionizing in the 70 to 100 MeV/c range. This property makes it necessary that the target and detector system be low-mass in order to allow the protons to enter the detector at all. It also means that spectator proton signals in any ionization detector will be very large compared to those arising from lighter particles of the same or higher momentum. Thus it is straightforward to make the system insensitive to even a large background of such particles.

Figure 3*. Momentum Probability Distribution of deuterium nucleons as predicted by the Hulthen wave function.*



The Beam and Target

The CEBAF electron beam has excellent optical properties, with typical beam spot dimensions far less than a millimeter and a very low intensity beam halo. This makes it possible to construct the target with very small lateral size. We plan to use a 7 atm. deuterium gas target cell 10 cm long and 5 mm in diameter. Tests have shown that such a target can be constructed of 25 micron thick kapton. Thus the target material in the path of spectator protons is small. The target cell will be surrounded by helium gas at atmospheric pressure. This keeps the material density low while still allowing a surrounding gas detector to have thin windows. This helium region will also provide an insensitive volume in which Moller electrons can be trapped by a solenoidal magnetic field coaxial with the target.

We have chosen to pursue a time projection chamber (TPC) as the sensor for the spectator protons. It will be of cylindrical shape, with the axis of the cylinder along the beamline and target axis. Because the entire sensitive volume of a TPC contains only gas, it can be made extremely transparent to ionizing particles. As mentioned earlier, the differential pressure across the TPC entrance window (inner cylinder) will be negligible, so that the window can be very thin.

In a conventional TPC electrons drift parallel to the beamline and signals are read out on either or both of the circular endcaps. The BoNuS TPC will use radial drift, making it a radial-TPC (RTPC). This allows a reduction of the mass of the endcaps, through which many secondary particles must pass on their way to the tracking chambers of CLAS. Thus the readout electrodes will be placed on the inner surface of the outside of the cylindrical detector. Use of radial drift also improves the acceptance of the detector as the non-uniform magnetic field that we have to work with would lead many electrons away from the endcaps of a conventional TPC. A sketch of the detector is shown in Fig. 4.

Simulations

Various simulations and studies have been performed to predict the performance and sensitivity of the BoNuS RTPC and target system. The most fundamental study is to determine what is the minimum proton momentum range that can be accessed. We developed a GEANT model incorporating the target and detector materials and geometries. Not surprisingly, the target gas, the target walls, and the entrance window of the RTPC are the most significant absorbers. Protons with initial momenta of about 72 MeV/c and higher are capable of penetrating the RTPC sensitive volume. Both the momentum and production angle impact this result, of course. The gain in acceptance with increasing momentum is rapid, however.

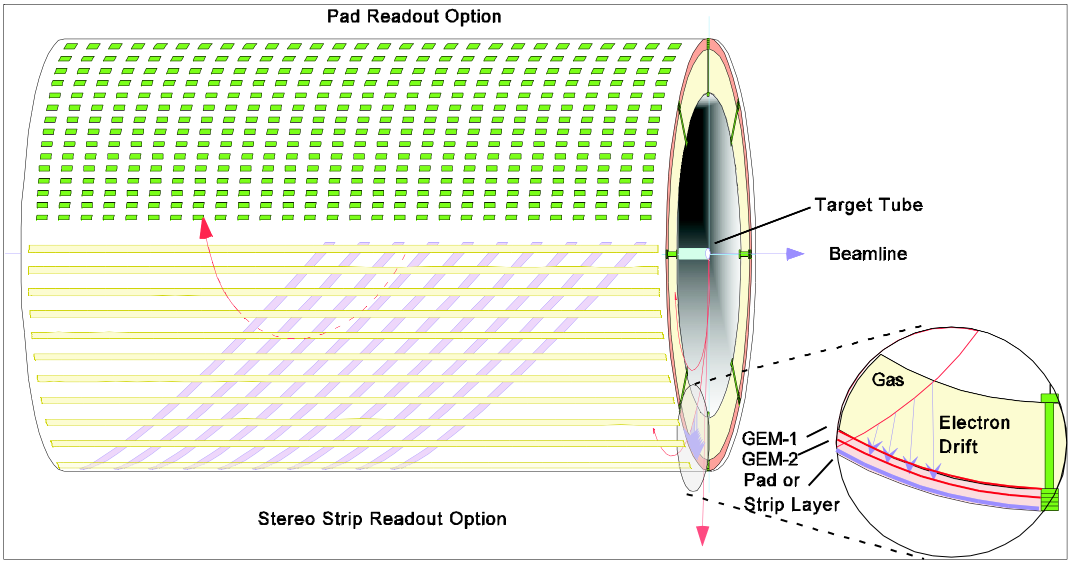


Figure 4. *Conceptual diagram of the BoNuS Radial TPC. The detector is 20cm long with an outer cylindrical diameter of 14cm. The 10cm long target will be placed along the axis at the downstream end of the detector. Sensitive gas will fill the region outside a radius of 4cm. GEMs and readout electrodes comprise the outer ~1cm of radius. The pad readout option, shown on the top of the figure, will be used by BoNuS.*

Because ionization electrons must drift across the magnetic field lines, they are deflected away from the radial electric field through the Lorentz angle which is a property of the gas and fields. The net result of this *ExB* drift is that the electrons take a curved path on their way to the outer cylinder wall. An example is shown in Fig. 5. In the extreme case of a perfectly radial proton track, this Lorentz drift may provide an advantage as the track is effectively viewed and measured from the side instead of on-end. While the non-radial drift will certainly complicate data analysis, the effect is well understood and can be accounted for. To minimize the effect we can choose a gas such as Argon-DME which has a relatively small Lorentz angle.

It was mentioned above that the differing ionization rates of protons and lighter particles of the same momentum allow easy discrimination between protons and lighter particles. In fact, it is anticipated that the RTPC gas gain will be established so low that only protons will register a signal above the threshold of our readout system.

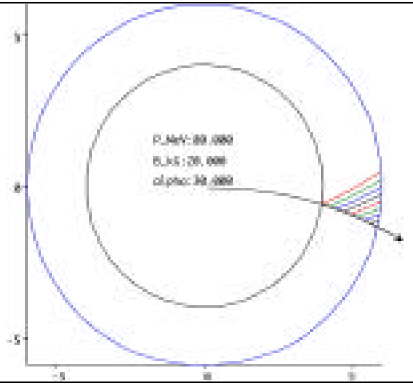


Figure 5. *Simulation of the Lorentz angle effect on electrons in the Radial TPC. In a uniform axial magnetic field, electron drift paths will be curved, making a constant angle with respect to a radius at each point. In the example shown, the proton momentum is 80 MeV/c, the B field is 2 T, and the Lorentz angle is 30°.*

4. Detector Design Details

A sketch of the detector was shown in Fig. 4. The active volume will be 200 mm long, contained between an inner cylinder (the entrance window / cathode) of radius 20 mm and an outer cylinder of radius 69 mm. Pickup electrodes will be on the inner surface of the outermost cylinder.

While the figure shows that we considered both stereo-strip and pad readout options, we have decided to proceed with the pads. There will be roughly 4000 pads, each one being 4mm x 5mm in size. Electrical attachments to the pads will be accomplished by standard printed-circuit vias passing through the cylindrical shell to connectors on the outside. Our initial concern with the expense and complication of reading out so many pads in such a small area has been relieved by the availability of the ALICE TPC (ALTRO) electronics[4]. This system was designed specifically for TPC readout and will work nicely for the BoNuS detector. Pad readout provides the advantage of obtaining maximum information from the detector while avoiding possible confusion that would result should the background track rate be higher than expected.

The outer 9 mm of the detector will contain three Gas Electron Multipliers (GEMs)[5], curved to form coaxial cylindrical surfaces. GEMs were chosen both for their robust nature and to avoid the complications that accompany multiwire proportional chambers. With GEMs there is no need for strong mechanical supports to maintain wire tension and placement, and there is no localization of the avalanche, thus simplifying interpretation of the raw data. By constructing the detector as two half-cylinder shells, edge effects and discontinuities in acceptance are minimized. The only complication is that we must attach the GEMs to frames which are in the shape of the outline of a cylindrical section. We have done this in a straightforward way on a prototype detector and foresee no problems with the technique.

5. *Tests of Prototype Detectors*

We have built and tested a 10cm x10cm flat Gem-based TPC with a 20 mm drift gap. Except for curvature, this flat prototype has the same structure as the BoNuS detector. The GEMs were manufactured by 3M Corporation [6]. Using this detector we have experimented with variation of the GEM internal and external fields, gas mixtures, and various readout electronics, and have begun development of analysis software. Most of our studies have used cosmic rays, but one important test was done using a 10 MeV proton beam at the Triangle Universities Nuclear Lab [7] In this test we scattered the beam protons off of a wire target to produce a spray of protons having energies covering the interesting BoNuS range. These protons were directed onto the flat prototype and produced tracks similar to those shown in Fig. 6. While these low energy protons produced easily identifiable heavy ionization trails, tests performed with cosmic rays at the same gas-gain setting provided no detectable signals in the electronics. This is exactly what BoNuS needs.

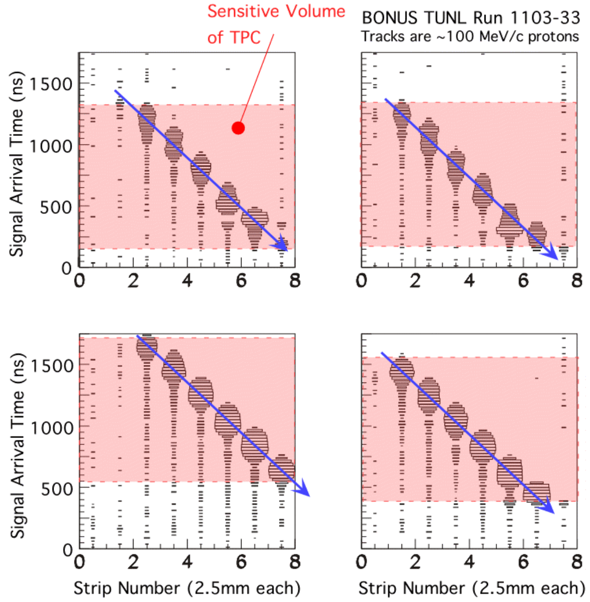


Figure 6*. Tracks observed in the flat prototype TPC when exposed to ~100 MeV/c protons. The vertical axis gives the arrival time of the signals as electrons drift downward to the readout electrodes. The presence of noise 'tails' prior to the arrival of each signal is an artifact of the electronics and analysis procedure.*

At the time of this conference we are assembling a 3-GEM curved prototype RTPC which has the same curvature as the planned BoNuS detector, but only about one-eighth the coverage. (The coverage is dictated by the size of the available standard 10cm x 10cm GEMs, maintaining the proper curvature.) We have attached one GEM to its curved frame with no surprises. While the fixtures required for producing a curved foil are more complicated that those required to lay one flat, there seems to be no trick involved – just care and patience. We look forward to commissioning this, the first detector to use non-planar GEMs, in the coming weeks. We anticipate placing it around a target in CLAS for a test run later this year.

Acknowledgments

We wish to express our gratitude to the many researchers outside our collaboration who have made crucial contributions to this effort. Especially noteworthy have been the support of Dr. L. Musa of CERN with the ALTRO electronics, and the assistance of John Geissinger of 3M Microcircuits Division with the fabrication of GEM foils. The tests at TUNL would not have been possible without the special attention of Dr. D. Dutta.

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