Studying the Nucleon Structure with Spin

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Abstract. The BLAST (Bates Large Acceptance Spectrometer Toroid) collaboration is finalizing the analysis of a systematic study of the spin-dependent, electromagnetic interaction on hydrogen and deuterium. The experiment utilized: the highly polarized electron beam of the MIT-Bates Linear Accelerator Center stored in the South Hall Ring; an internal gas target of isotopically pure and highly polarized hydrogen or deuterium provided by an atomic beam source; and the symmetric, general purpose BLAST spectrometer. By making simultaneous measurements of many reaction channels for different combinations of beam helicity and target polarization BLAST is providing new, precise measurements for the nucleon and deuteron elastic form factors as well as studying the structure of deuterium and pion production from hydrogen and deuterium. A brief overview of the experiment will be presented together with a selection results.

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INTRODUCTION

Nucleon elastic form factors are fundamental to our understanding of nucleon structure at the confinement level. The form factors parameterize coherent scattering without exciting internal degrees of freedom assuming single photon exchange. Unlike the scattering of point-like, spin $\frac{1}{2}$ particles where the scattering cross section is given simply by:

$$\sigma_{Dirac} = \sigma_{Mott}\left(1 + 2\tau\tan^2\frac{\theta}{2}\right) \tag{1}$$

the cross section for elastic scattering of electrons from extended objects, like nucleons, requires form factors:

$$\sigma = \sigma_{Mott}\left[\left(\frac{G_E^2 + \tau G_M^2}{1+\tau}\right) + 2\tau G_M^2\tan^2\frac{\theta}{2}\right] \tag{2}$$

where the charge and magnetic form factors, G_E and G_M (Sachs formalism), are functions of the momentum transfer, Q^2. These form factors are the first moments of generalized parton distributions and together with data from deep inelastic scattering, exclusive processes, and spin observables; will help complete our knowledge of nucleon structure.

Traditionally the elastic form factors have been parameterized by a dipole form corresponding to an exponential charge distribution. Remarkably a single dipole parameterization provides a reasonable description for the charge and magnetic form factors for the

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proton, G_E^p and G_M^p, and for the magnetic form factor of the neutron, G_M^n. However, the electric form factor for the neutron, G_E^n, is roughly an order of magnitude smaller. Also the simple dipole parameterization fails to reproduce the detailed structure observed. A new parameterization comprising of a "smooth" part formed by the sum of two dipoles and a "bump" term given by the sum of two gaussians has been proposed by Friedrich and Wallcher [1] and used to fit available elastic form factor data. This parameterization reproduces the detailed structure but at the cost of significantly more parameters and a more complicated interpretation.

Another interesting development in the area of nucleon form factors was discovered at JLAB [2, 3, 4]. The ratio of electric to magnetic elastic form factors for the proton, $\mu_p G_E^p / G_M^p$, measured using the standard Rosenbluth technique, has generally yielded a value close to unity and constant with Q^2; consistent with the observation that both electric and magnetic form factors for the proton can be reasonably described by the same parameterization. However, the JLAB measurements, using a polarization transfer technique, show the ratio deceasing rapidly with Q^2. The proposed explanation for this discrepancy is that two photon contributions are significant and not accounted for properly in the Rosenbluth analyses. If this is true it would require a reanalysis of existing data on nucleon form factors with corresponding implications for our knowledge of nucleon structure.

THE BLAST EXPERIMENT

The MIT-Bates linear accelerator is a 500 MeV linac with recirculator capable of producing electron beams with energies up to 1 GeV. Polarized electrons were generated by shining circularly polarized laser light on a strained GaAs crystal producing electrons with 70% polarization (typical) which were accelerated and injected into the South Hall storage ring. Typically currents in the ring were over 200 mA with a 25 minute lifetime. A Siberian snake maintained the longitudinal polarization of the electron beam at the BLAST target. A Compton polarimeter situated just upstream of the BLAST detector monitored the beam polarization in the storage ring (typically $\sim$ 65%).

An atomic beam source produced highly polarized targets of pure hydrogen or deuterium. Combinations of magnets and RF transition units populated and transported the desired spin states into the target cell (a open-ended, thin-walled aluminum cylinder 1.5 cm in diameter and 60 cm long, aligned with the electron beam). Typical target density was 6×10^{13} atoms/cm^2 with polarizations of 80% vector or 68% tensor (deuterium). A magnetic holding field defined the target spin angle to be 32° (2004) or 45° (2005) horizontally into the left sector of the experiment. This simplified some kinematics as an electron scattering to the left (right) sector corresponds to a momentum transfer roughly perpendicular (parallel) to the spin angle.

The BLAST detector (Figure 1) was based on an eight sector, toroidal magnet with a maximum field of $\sim$ 3800 G. The detectors in the left and right horizontal sectors nominally subtended 20°–80° polar and $\pm 15^\circ$ azimuthal. The detector was left/right symmetric with each sector containing: wire chambers for charged particle tracking, Čerenkov detectors for electron/pion separation, and time of flight scintillators to measure the relative timing of scattered particles. The neutron detectors were somewhat

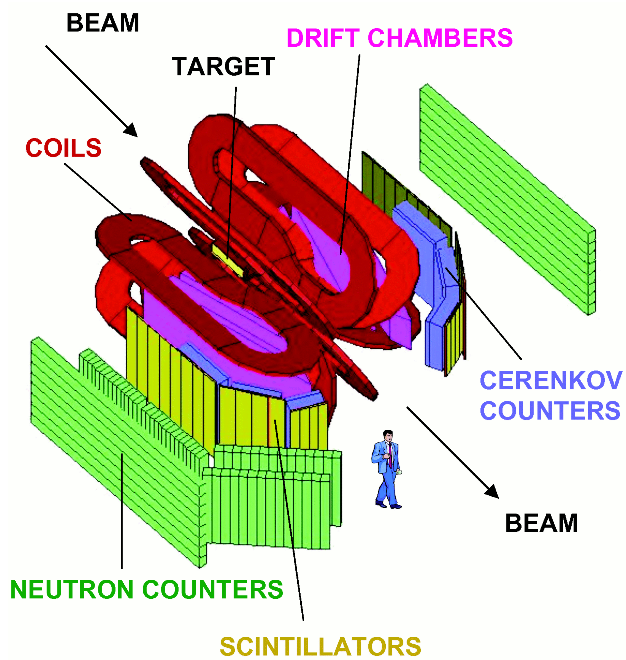

FIGURE 1. Schematic of the BLAST detector showing the main detector elements.

asymmetric with the right sector having a greater thickness.

In each sector three wire chambers were combined into a single gas volume. Each chamber had two super-layers of drift cells, inclined $\pm5^\circ$ to vertical, with three planes of sense wires (18 planes of sense wires per sector). Momentum resolutions around 3%, angular resolutions of 0.5°, and vertex resolutions of 1 cm have been obtained.

The Čerenkov detectors [5] had 5–7 cm of Aerogel tiles (n $\sim$ 1.023) inside aluminum boxes painted with a white reflective paint. Readout used several 5″ diameter PMT's top and bottom of each box. An electron/pion separation efficiency greater than 85% was achieved.

The time of flight (TOF) detectors consisted of sixteen vertical scintillator bars in each sector. The scintillator was 1″ thick and 8″ wide with PMT's at top and bottom. Timing resolutions of 300 ps were typical. The TOF detectors measured the relative timing between scattered particles and provided the trigger timing for the data acquisition system.

The neutron detectors consisted of two types. Each sector had eight horizontal, 15 cm thick, 22.5 cm high, and 400 cm long scintillator bars. Additionally, the right sector had two walls (15 cm and 20 cm thick) of vertical scintillators to improve detection efficiency. All bars were read out by PMT's at both ends.

The data acquisition was based on the CODA and trigger supervisor systems from JLAB. This allowed multiple triggers to be defined for a variety of simultaneous reactions. A two level trigger system was used and the data buffered to minimize deadtime and maximize the allowable event rate. An EPICS control system monitored and recorded all slow control systems and also interfaced the experiment with the accelerator, target, and Compton polarimeter systems. Data was collected reversing the beam helicity each fill and randomly cycling through target spin states every 5 minutes to minimize systematic uncertainties.

SOME RESULTS FROM BLAST

With a polarized electron beam and a polarized hydrogen target one can measure a beam-target asymmetry:

$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_l {G_E^p}^2 + 2\tau v_T {G_M^p}^2} \tag{3}$$

With BLAST we can measure this asymmetry simultaneously in the left and right sectors and form the super-ratio:

$$R_A = \frac{A_L}{A_R} = \frac{z_L^* - x_L^* G_E^p / G_M^P}{z_R^* - x_R^* G_E^p / G_M^P} \tag{4}$$

which is independent of beam and target polarizations as well as luminosity and just depends on some kinematic factors. This super-ratio gives a direct measure of the charge to magnetic form factor ratio for the proton [6, 7, 8]. Results are shown in Figure 2. The

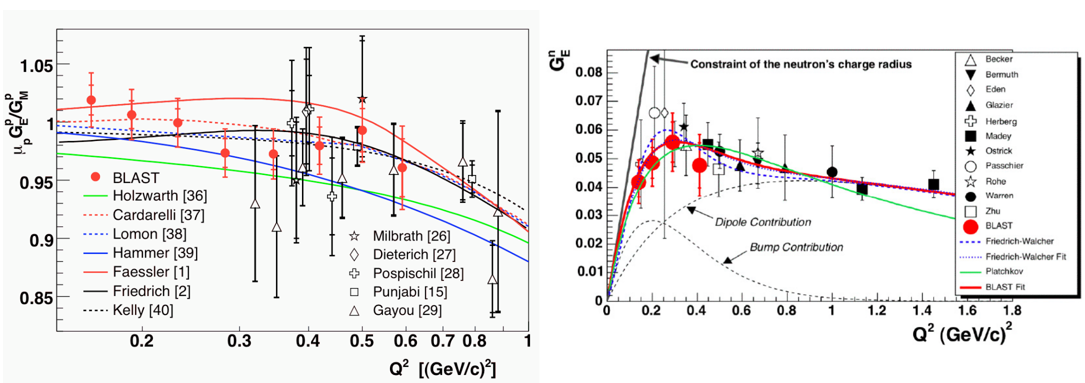

FIGURE 2. The ratio $\mu_p G_E^p / G_M^p$ (left plot) showing BLAST results and existing world data with several theoretical predictions. BLAST and some world data for G_E^n (right plot) with some fits to the data.

impact of these measurements on our knowledge of the proton form factors is to reduce the uncertainties by approximately a factor of two.

One of the primary motivations for the BLAST experiment was to measure G_E^n. This has generally been poorly measured because of its small amplitude and because nature does not provide a convenient neutron target for experiments. Using a vector polarised deuterium target and studying the beam-target asymmetry for quasi-elastic scattering:

$$A_{ed}^V = \frac{a {G_M^n}^2 \cos\theta^* + b G_E^n G_M^n \sin\theta^* \cos\phi^*}{c {G_E^n}^2 + {G_M^n}^2} \approx a\cos\theta^* + b\frac{G_E^n}{G_M^n} \sin\theta^* \cos\phi^* \tag{5}$$

the BLAST experiment was able to measure the neutron charge form factor [9, 10] assuming the magnetic form factor to be well known. The results of the BLAST measurements together with some other data are shown in Figure 2. The Platchov curve is similar to the traditional Galster curve used to describe G_E^n but with the additional constraint that the slope as $Q^2 \to 0$ yields the slope required by the measurements of the neutron charge radius. The Fiedrich and Walcher, FW, curves (described above) are also shown for comparison. The BLAST fit (very similar to re-fit FW) has the same parameterization as FW with the additional constraint of the neutron charge radius imposed. Note that the slope is determined primarily by the "bump" term.

The deuteron has three elastic form factors: G_C, G_M, and G_Q where the quadrupole form factor, G_Q, arises from the tensor force. Unpolarised experiments are unable to unfold the three form factors or have to perform difficult double scattering experiments to measure the polarization of the scattered deuteron. With a polarized deuterium target and both vector and tensor polarizations BLAST can resolve all terms. The BLAST results for the tensor asymmetry T_{20} [11] are shown in Figure 3. The BLAST results,

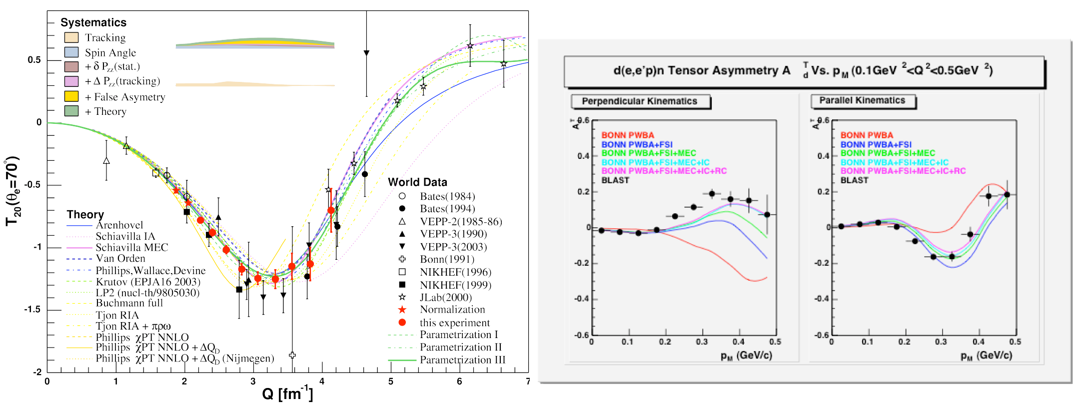

FIGURE 3. Preliminary results (left plot) from BLAST for T_{20} from *ed* elastic scattering compared to existing data and calculations from theory. Tensor asymmetry versus missing momentum (right plot) for quasi-elastic electron scattering from deuterium.

normalized to theory at the lowest two points, span a large range with very precise measurements. Other spin observables, such as: T_{21} and the first measurements of T_{11}, and T_{10} [12], have also been made and will be used to unfold G_C, G_M, and G_Q in a global fit.

By studying quasi-elastic *ep* scattering from deuterium the D-state contribution and hence the tensor force can be studied. The deuteron is an admixture of $L = 0$ and $L = 2$ wave functions. The S-state or $L = 0$ is generally dominant but at relative nucleon momenta greater than approximately 0.3 GeV/c the D-state is dominant and thus provides a regime where it can be studied. In the Born approximation the tensor asymmetry for quasi-elastic scattering should be zero in the absence of D-state contributions. As seen in Figure 3 for both perpendicular and parallel kinematics a significant tensor asymmetry [13] is seen to develop as the missing momenta (relative nucleon momentum) increases indicating the onset of D-state contributions. The theoretical calculations [14] show that all corrections (final state, relativistic, isobaric, and meson exchange) are necessary to approach agreement with the data. However, there is some indication perhaps that the D-state effects develop faster than expected by the current theoretical model. Similar observations can be made for the beam-vector asymmetry for quasi-elastic *ep* scattering from deuterium.

Not shown in this paper are data on: a direct measurement of G_M^n by studying inclusive electron scattering from deuterium [15] or results on pion production from hydrogen and deuterium which will provide information on the nucleon resonance [16].

CONCLUSION

The BLAST experiment has collected a wealth of data. Since all data was taken with a single experiment it can be analysed together in a self consistent manner to minimize systematic uncertainties and provide precise data to constrain theoretical models.

In addition, proposals are being investigated to use the BLAST detector system at the DORIS storage ring at DESY, Hamburg to definitively determine the role of two photon contributions in elastic electron scattering from nucleons by measuring the ratio of electron-proton and positron-proton elastic scattering. Models which explain the discrepancy observed at JLAB predict a deviation from unity on the order of 4-5%. This would be a further important measurement that BLAST could make towards understanding the structure of the nucleons and deuterium.

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