MEASUREMENTS OF THE ELECTROMAGNETIC AND SPIN STRUCTURE OF NUCLEONS AND NUCLEI WITH THE BATES LARGE ACCEPTANCE SPECTROMETER TOROID (BLAST)

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The Bates Large Acceptance Spectrometer Toroid (BLAST) is presently nearing completion and undergoing commissioning. In this presentation I describe the detector, its operational parameters, and an overview of the scientific program including expected results on key experiments.

1. Introduction

The BLAST Collaboration is preparing to embark on a program of measurements of the electromagnetic and spin structure of nucleons and nuclei. A new detector is presently nearing completion and undergoing commissioning at the MIT-Bates Accelerator Laboratory. The requirements for completing this program have driven the design of the detector.

Specifically, regarding the structure of the nucleon, the program includes accurate measurements of the electromagnetic form factors of both the proton (G_E^p, G_M^p) and the neutron (G_E^n, G_M^n). The proton rms charge radius will be measured with unprecedented accuracy.

The structure of the deuteron will be studied by measuring and separating the elastic form factors G_C, G_Q, and G_M using both tensor and vector polarized targets. The spin dependent momentum distributions will be investigated using quasielastic scattering on the constituent nucleons. These are sensitive to details of the $N-N$ interaction. Using polarized ^{3}He, the S, S', and $D-$wave components will be extracted from studies of the 2-body electrodisintegration.

The ability to carry out such an ambitious program requires complete control of the spin variables of both beam and target and, simultaneously, the ability to study fully exclusive electron scattering. The general ex-

pression for the cross section for the scattering of longitudinally polarized electrons from a polarized target, the cross section can be written as:

$$\frac{d\sigma}{d\Omega} = \Sigma + h\Delta$$

where h is the electron helicity. For spin 1/2 targets, such as the proton and ^{3}He, Σ is the usual unpolarized differential cross section depending on the squared form factors. The helicity dependent term Δ contains terms which also depend on the polarization of the target and are interference products of the form factors. This allows one to separate the form factors using double polarization asymmetries:

$$A_{exp} = P_e P_t \frac{\Delta}{\Sigma}$$

where we have included the actual beam and target polarizations P_e and P_t.

2. BLAST

Target polarization technology has made great advances during recent years. ^{3}He targets have been used in several laboratories around the world with reasonably high polarization and with sufficient density to support exclusive studies with beams of a few microamps. However, the story with polarized ^{1}H or ^{2}H is still that pure polarized gaseous targets are far too thin to allow exclusive studies with such beams. Thicker targets exist using compounds such as NH_3, but the signal to background suffers due to the contaminant, and such targets have not attained as high a degree of polarization as gaseous targets. In order to exploit gaseous targets, a much higher beam current is needed, on the order of hundreds of milliamperes. The Bates South Hall Ring can routinely provide a circulating current of 100 mA.

The use of gaseous ^{1}H and ^{2}H targets in conjunction with a storage ring such as the Bates SHR provides a number of advantages. The target is isotopically pure. There can be no entrance or exit windows on the containment cell. Thus there is no background from target contaminants. The polarization that can be achieved is typically around 80%. The required holding field is low, allowing the target spin to be oriented at an arbitrary angle to the beam (and hence to the momentum transfer). Because the gas is at such a low density and pressure, the target is thin and the containment

cell also can have extremely thin walls, allowing detection oflow energy recoils. Thus fully exclusive reactions can be pursued to low momentum transfer Q^2.

The low target thickness provides an obvious disadvantage: even with 100 mA of beam the luminosity is low, of the order of 10^{31} to 10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Thus the study of fully exclusive processes can only be accomplished by compensating for the low luminosity using a large acceptance detector. This has led to the design and construction of BLAST.

BLAST consists of a toroidal magnetic field generated by eight coils equispaced azimuthally about the internal target area of the South Hall Ring at the MIT Bates Accelerator Laboratory. By providing highly polarized ($\sim 80\%$) electron beam on highly polarized (again $\sim 80\%$) targets of hydrogen and deuterium, with sufficient luminosity and acceptance to permit exclusive coincidence measurements, BLAST provides a unique facility for the study of the structure of the nucleon and the deuteron. Since the target polarization can be oriented at arbitrary polar and azimuthal angles relative to the beam as opposed to being constrained to be along the beam direction, the large acceptance allows measurements to be made simultaneously at many angles of the target polarization relative to the momentum transfer.

In its present configuration, two of the eight sectors are fully instrumented with each having three drift chambers (MIT) backed up by an array of Cerenkov detectors (ASU), timing scintillators (UNH), neutron detector bars (OU), and a Pb-glass calorimeter (BU). This provides coverage from 20° to 80° relative to the beam and approximately $\pm 20^\circ$ relative to the plane of the floor. A CAD drawing of BLAST is shown in Fig. 1. Additional detectors are being considered by various collaborators. Another array of neutron detectors has arrived from LADS but are not yet installed. We will be adding a set of silicon strip detectors (UNH/Bates) in order to take advantage of the ability to look at low momentum recoil particles.

This array of detectors will provide momentum resolution of 1%, vertex reconstruction along the target length to 3 mm out of a total containment cell length of 40 mm, and angular resolution of 2 mr. The various detectors allow good particle identification for electrons, pions (both positive and negative), protons, neutrons, and deuterons. Thus it satisfies the criteria for being able to carry out the program outlined earlier. Following is a sample of some detailed expectations.

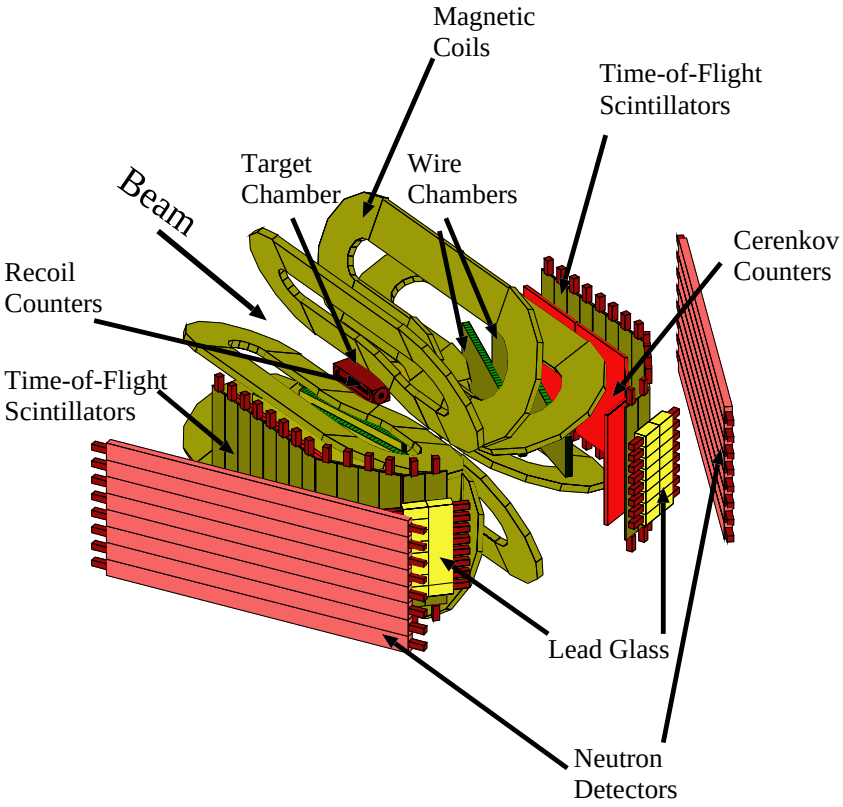

Figure 1. CAD representation of the BLAST detector.

3. Some Specific Experiments

Nucleons (protons and neutrons) are fundamental building blocks of nuclei. Knowledge of the internal structure of protons and neutrons in terms of quark and gluon degrees of freedom of Quantum Chromodynamics (QCD) is not only essential for testing QCD, it also provides a basis for understanding more complex, strongly interacting matter at the level of quarks and gluons.

3.1. *Proton Form Factors*

The recent experiments at Jefferson Lab[1,2,3] on the ratio of the electric and magnetic form factors of the proton $\mu_p G_E^p/G_M^p$ up to $-Q^2$ of 5.6 (GeV/c)^2. have stirred up quite a controversy in the field because they show a very significant deviation of $\mu_p G_E^p/G_M^p$ below the heretofore accepted value of ≈ 1, dropping to near 0.2 at 5.6 (GeV/c)^2.

That the ratio $\mu_p G_E^p/G_M^p$ deviates significantly from 1 and in the direction observed is of no surprise to theorists. Many show at least qualitative agreement with the trend of the JLab results, using approaches that vary from dispersion theory[5] to different constituent quark models[4,6]. Some of these show a less dramatic departure, some even more dramatic, but most predict that G_E^p will cross zero at some more or less accessible value of Q^2 while G_M^p does not.

Near the other end of the Jefferson Lab range, at a Q^2 of slightly less than 1 (GeV/c)^2, several of the calculations are consistent with the results but clearly are approaching the canonical value of $\mu_p G_E^p/G_M^p = 1$ at $Q^2 = 0$ in very different fashion. In spite of the improved precision of the Jefferson Lab data, they are unable to discriminate between these several models. BLAST will make accurate measurements of $\mu_p G_E^p/G_M^p$ in the Q^2 range of 0.08 to 1.0 (GeV/c)^2 which will overlap the lowest two Jefferson Lab data points but with error bars that are smaller by a factor of about 2. For lower Q^2 the expected errors are even smaller. This will both check the JLab results, using still another experimental technique, and extend them to lower Q^2 with unprecedented accuracy. Expected results are shown in Fig. 2, including the JLab points and some of the many calculations.

The technique that will be used at BLAST is based on the ability to arbitrarily orient the target spin relative to the beam and the symmetry of the detector relative to the beam. By orienting the target spin not parallel to the beam, one sector of BLAST sees events for a set of spin angles ϑ_1^* and φ_1^* while the mirror detector in the opposite sector of BLAST looks at events with the same Q^2 but with ϑ_2^* and φ_2^* (where ϑ^* and φ^* are the polar and azimuthal angles of the proton spin vector with respect to $\vec{q}$ and the scattering plane). The experimental spin-dependent asymmetries A_1 and A_2 are then measured simultaneously in the two BLAST sectors and $\mu_p G_E^p/G_M^p$ is determined from the super-ratio $R = A_1/A_2$. This method is quite robust, requiring neither the absolute cross section nor the experimental beam and target polarizations to be known with precision. (See the next presentation.)

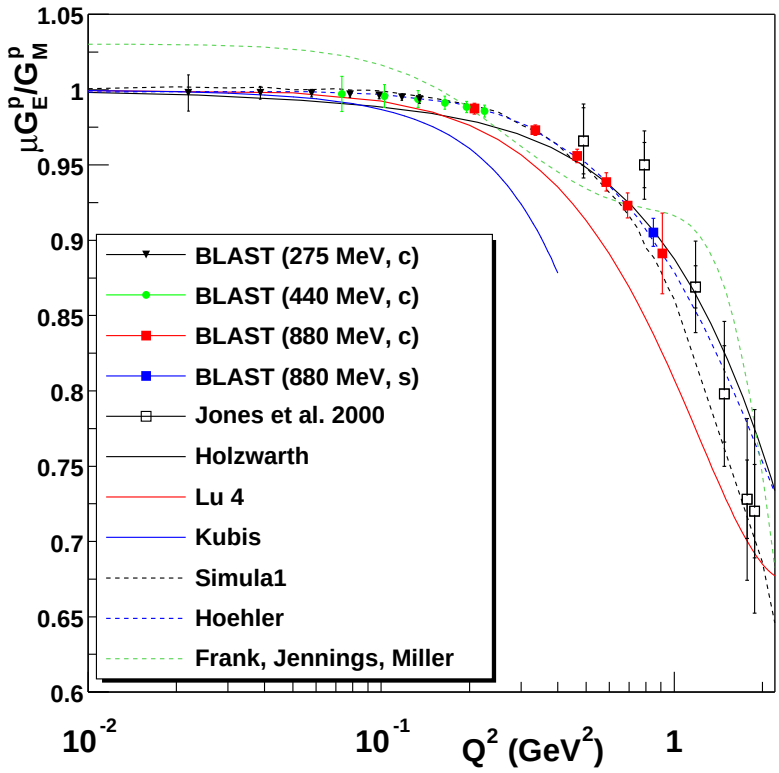

Figure 2. Expected error bars from experiment 01-01 with BLAST compared with the lower Q^2 Jefferson Lab data [1] and a sample of the many theoretical calculations available [10,9,8,7,11,6]

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3.2. *Neutron Form Factors*

Using vector polarized deuterium as the target, BLAST will make similar measurements of the form factors of the neutron. Since, in a vector polarized deuteron, both the proton and the neutron spins are aligned along the holding field, quasifree electron scattering from this polarized neutron provides a similar separation of G_E^n and G_M^n as for the free proton. There are corrections for the fact that the neutron is not free but embedded in the deuteron wave function. BLAST provides a unique opportunity to check these corrections because data will be accumulated simultaneously on the quasifree scattering from the proton which can be compared to the results from the free proton.

The statistical precision of the expected results from quasifree scattering off the neutron in vector polarized deuterium is shown in Fig. 3 compared with previous data from around the world. The large acceptance and high neutron detection efficiency provided by the walls of neutron bars, enhanced by the recent acquisition of the LADS neutron detectors, results in statistical uncertainties which are very small compared to all previous measurements.

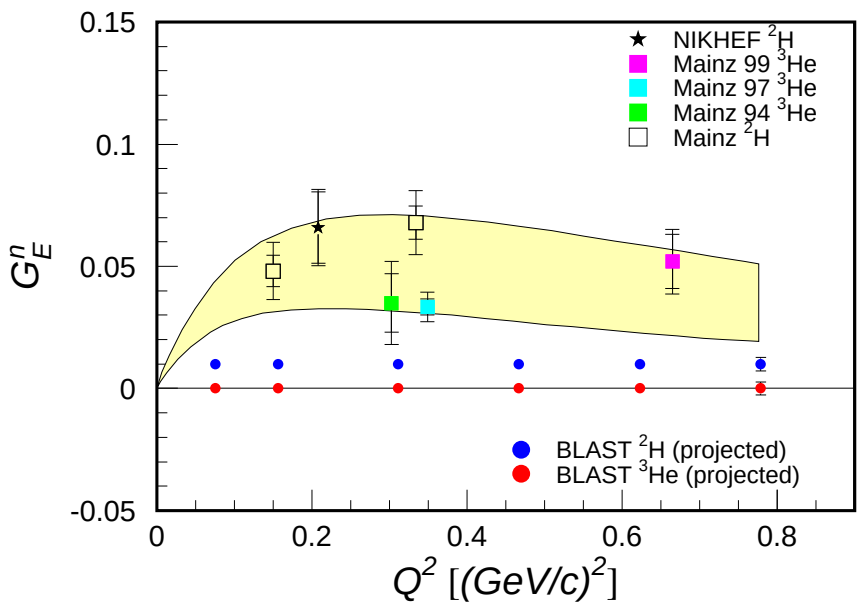

Figure 3. This figure displays the expected error on our proposed measurements of the neutron electric form factor G_E^n, compared with previous results. The errors are statistical only.

A polarized ^{3}He target is being built for BLAST. In addition to experiments to probe the spin structure of ^{3}He, BLAST will also use this target as a similar quasifree neutron target and extract G_E^n from these data. Fig. 3 shows the expected statistical errors from these measurements as well. The availability of quasifree neutron scattering from both ^{3}He and deuterium in conjunction with both the quasifree proton data from deuterium and the

free proton results, all collected in a common detector system, will provide unique constraints on the results and the theoretical corrections.

3.3. *Proton Charge Radius*

Recent results from lattice QCD calculations suggest that the proton root-mean-square (rms) charge radius can be calculated from first principles with an uncertainty of only a few percent, and this field is rapidly evolving due to both improvements in computer architecture and new algorithms. Thus, precise information on this fundamental quantity is essential in terms of testing QCD.

The two most precise and widely cited determinations of the proton charge radius give $r_p = 0.805(11)$ fm [12] and $r_p = 0.862(12)$ fm [13], respectively, differing from each other by more than 7%. While the recent precision hydrogen Lamb shift measurements [14,15,16,17,18] are in better agreement with the QED predictions using the smaller value of the proton charge radius without the two-loop binding effects, they are consistent with the larger value of the proton charge radius when two-loop binding effects are included in the QED calculations. Before accurate comparisons between theory and experiment can be made, both in QCD and QED, a precise measurement of the charge radius is needed.

This experiment is based on measuring the slope of the cross section for elastic electron scattering from the proton in the limit of low Q^2. On very general grounds, an expansion of the proton charge form factor leads to :

$$lim|_{Q^2 \to 0} \left\{ 6 \frac{dG_E^p}{dQ^2} \right\} = - < r^2 >$$

with the boundary condition $G_E^p(Q^2 = 0) = 1$.

Thus, to adequately determine the rms radius of the proton, high precision data of the proton form factors in the $Q^2 \to 0$ region are needed. However, because of the boundary condition at $Q^2 = 0$, only accurate relative cross sections are required. Thus the detection efficiency of each BLAST detector relative to its nearest neighbors on either side must be accurately measured. This can be done in a number of ways.

The usual assumption in all previous measurements has been that $\mu_p G_E^p / G_M^p$ is equal to 1. While this is certainly true in the limit as $Q^2 \to 0$, we know that the JLab data have already shown that this does not hold as Q^2 increases. Since we are planning to measure the slope of G_E^p to better accuracy than ever before, we need to know the contribution of G_M^p

more accurately as well. To this end we will extend the measurements of $\mu_p G_E^p/G_M^p$ down to the lowest Q^2 needed for the rms radius extraction, $Q^2 = 0.005$ (GeV/c)^2. When combined with the measurements of this ratio described earlier, these data will provide an accurate determination of $\mu_p G_E^p/G_M^p$ for Q^2 of $0.005 - 1.2$ (GeV/c)^2. Some of the expected results on $\mu_p G_E^p/G_M^p$ were shown in Fig. 2. The expected result for the rms radius is shown in Fig. 4, compared to previous measurements.

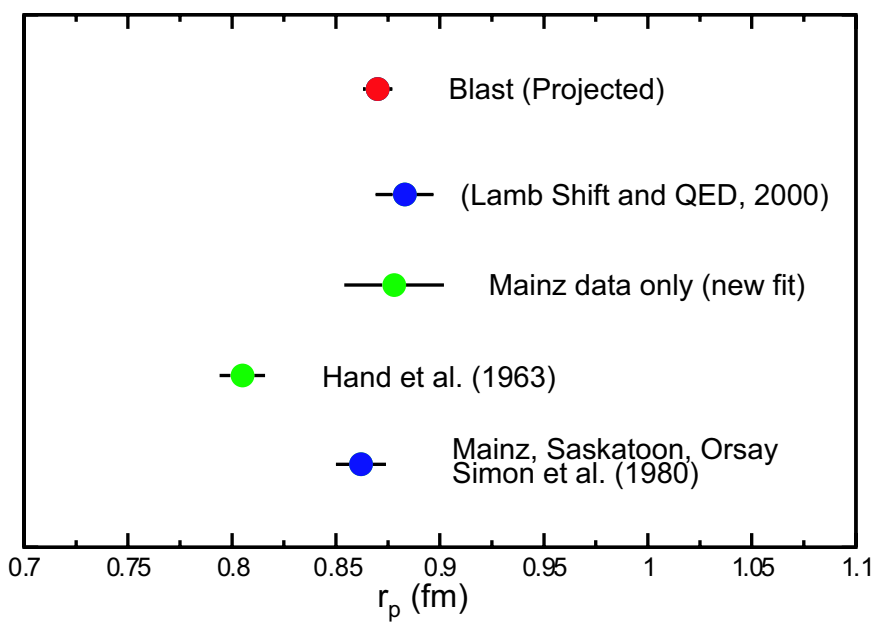

Figure 4. This figure displays the expected error on our proposed measurement of the proton charge radius with previous results.

3.4. *Deuterium Elastic Form Factors*

Elastic electron scattering from the deuteron is completely described by three form factors, the charge monopole (G_C), charge quadrupole (G_Q) and magnetic dipole (G_M) form factors. Cross section measurements yield the structure functions A(G_C,G_Q,G_M) and B(G_M), which with T_{20}(G_C,G_Q,G_M) allow the determination of these form factors [19]. The present data set for elastic e-^{2}H scattering and the isoscalar charge form factor of the 3-body system pose an interesting puzzle [20] for few-body theory:

there exists no theoretical model capable of describing all measurements simultaneously.

Not only are there theoretical discrepancies among various models, but also inconsistencies between the available data sets. A precise and consistent measurement is important in order to resolve the situation. BLAST will measure T_{20} (as well as T_{22}) over a broad Q-range from $Q = 1.5 — 5$ fm^{-1}, which provides an overlap with both the Bates and JLab recoil polarization measurements. The expected high statistical accuracy is shown compared to the present world data and various calculation in Fig. 5.

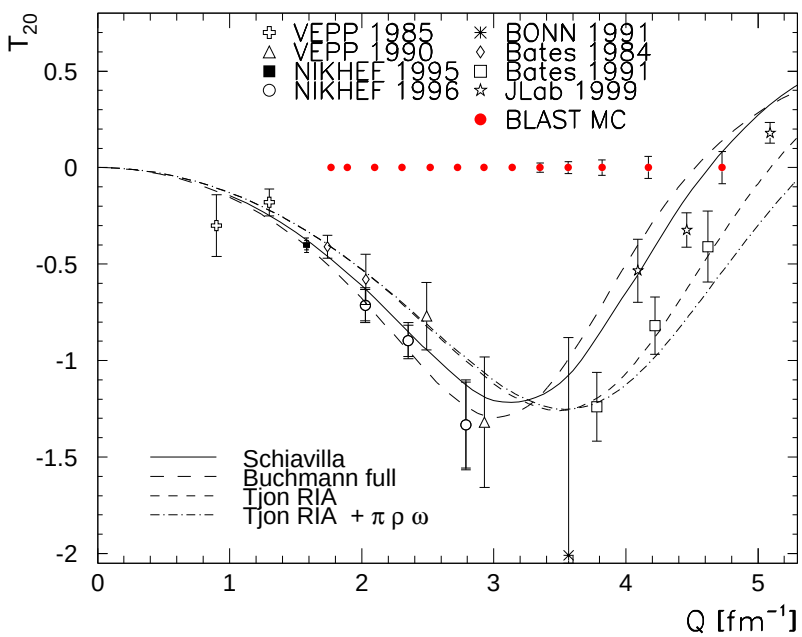

Figure 5. This figure displays the expected error on our proposed measurement of the polarization asymmetry T_{20} in elastic electron scattering on deuterium, compared with previous results.

Because BLAST will also have polarized electrons and because the ABS will provide vector polarized deuterons simultaneously with tensor polarized deuterons, there will be an independent measurement of the elastic form factors. The double spin asymmetries T_{11} and T_{10} are independent

functions of G_C, G_Q, and G_M. The combination of asymmetries provides a powerful constraint on both the form factors and theoretical calculations.

4. Conclusion

This concludes a sample of the expected results from the BLAST spin physics program. It is clear that BLAST will make a major impact on our knowledge of the structure of the nucleons and light nuclei. Of course, as a large acceptance detector, BLAST will simultaneously provide data on many other reaction channels. The $N \to \Delta$ transition will be studied on the free proton and on the quasifree nucleons in the deuteron. The quasireal photodisintegration of the deuteron is expected to provide a significant fraction of the events from deuterium. In addition to using the quasifree electron scattering processes at low missing momentum to extract the nucleon form factors, the same processes will be studied at high p_m to study the nuclear spin structure.

BLAST has been constructed. The coils, timing scintillators, and Cerenkov detectors have been installed and are currently undergoing commissioning with beam on unpolarized hydrogen gas. The neutron bars and Pb-glass calorimeter have been mounted and are ready to be installed. A prototype silicon strip wafer has been purchased and will be installed for tests later this year. The ABS is presently being installed and tested. The detector and the collaboration plus Bates staff are shown in Fig. 6.

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Figure 6. The BLAST detector with the collaboration and Bates support staff.

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