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The G0 experiment: Parity violation in e-N elastic scattering

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Abstract. The G^0 experiment will measure the parity-violating asymmetries in elastic electron-nucleon scattering. The experiment is being performed in Hall C at the Jefferson Laboratory using a polarized electron beam and a dedicated experimental setup. Measurements of the electron-proton asymmetries will be made at both forward and backward angles, and electron-deuteron asymmetries at the backward angles. These measurements will cover a momentum transfer range of $0.1 - 1.0$ GeV^2/c^2. ¿From these data the vector neutral weak form factors, G_E^Z and G_M^Z, and the effective axial current of the nucleon, G_A^e, may be extracted. When combined with the known electromagnetic form factors, one will be able to extract the contributions of u, d, and s quarks to the proton's charge and magnetization distributions. The first measurements at forward angles for the full momentum transfer range have very recently been successfully completed and preliminary results are presented here.

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1 Introduction

A crucial aspect to our knowledge of the structure of the nucleon is the understanding of the role of the quark-antiquark sea in contributing to the various properties of the nucleon - charge, magnetism, spin, etc. To this end, over the past decade several parity-violating electron scattering experiments have been carried out in an effort to identify and quantify the strange quark contribution to the nucleon sea. Experiments for which data have already been published are the SAMPLE experiment at MIT-Bates [1, 2,3,4], the HAPPEX experiment in Hall A at Jefferson Lab [5], and the PVA4 experiment at Mainz [6,7]. Each of these experiments has been discussed at this meeting, and the contributions are included in these proceedings. In each of these experiments a measurement is made for a single Q^2 value.

A new parity-violating electron scattering experiment currently being carried out in Hall C at Jefferson Lab is the G0 experiment [8]. The G0 collaboration consists of approximately 100 Ph.D. scientists from 20 institutions in the United States, Canada, France, and Armenia. The G0 experiment will measure parity violation (PV) in the scattering of polarized electrons from nucleons at both forward and backward angles using hydrogen and deuterium targets. The ultimate goal of G0 is to use the measurements of the parity-violating asymmetries in elastic electron scattering from the nucleon to provide a comprehensive and precise map of the neutral weak form factors of the proton over the range of momentum transfers 0.1-1.0 (GeV/c)^2,

The interaction between electrons and nucleons involves interference between the dominant electromagnetic interaction (γ exchange) and the parity-violating weak interaction (Z^0 exchange). This interference leads to a helicity dependence in the cross section for elastic scattering of polarized electrons from the nucleon, the observable measured by the G0 experiment, as well as the other experiments mentioned above. The asymmetry has three contributing terms that reflect this interference. Specifically, the parity-violating asymmetry for elastic electron scattering from the proton can be written as a sum of three terms:

$$A = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \times \frac{\left[\varepsilon G_E^p G_E^Z + \tau G_M^p G_M^Z - \left(1 - 4\sin^2\theta_W\right)\varepsilon' G_M^p G_A^e\right]}{\varepsilon\left(G_E^p\right)^2 + \tau\left(G_M^p\right)^2} \quad (1)$$

where $\tau = Q^2/4M_p^2$, $\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$ and $\varepsilon' = \sqrt{(1-\varepsilon^2)\,\tau\,(1+\tau)}$. When combined with known information on the nucleon electromagnetic form factors and assuming isospin conservation, it is possible to extract explicit contributions of $s\bar{s}$ pairs to the nucleon form factors. Away from the static limit, this information is characterized by the strange quark form factors, G_M^s and G_E^s, which contribute to the nucleon electric and magnetic form factors, defined by

$$G_{E,M}^Z = (1 - 4\sin^2\theta_W)(1 + R_V^p)G_{E,M}^p - (1 + R_V^n)G_{E,M}^n - G_{E,M}^s \quad (2)$$

[a] Jefferson Lab Experiment E-00-006. A list of collaborators and information about the experiment can be found at http://www.npl.uiuc.edu/exp/G0/

The strange form factors are of particular interest because they are a direct probe of the quark sea contribution to ground state properties of the nucleon. A complication arises from the third term in 1, the axial form factor G_A^e which has contributions both from the first-order exchange of a Z-boson, but also from higher order processes that produce a parity violating electromagnetic, or "anapole" interaction. For example, there can be a Z-exchange between two quarks in the proton and a photon exchange between the electron and proton. Theoretical estimates of these axial radiative corrections have been made for the SAMPLE experiment [9,10], but not for higher Q^2 values. In order to measure G_A^e and thus address the uncertainty in these corrections, a third measurement is needed. To obtain a third measurement the G0 experiment will adopt the method used by the SAMPLE collaboration; specifically, we will carry out measurements of parity-violating quasielastic scattering from deuterium at back angles. The different sensitivities to the axial form factor between the proton and the deuteron permit one to extract all three terms G_M^s, G_E^s, and G_A^e. The sensitivities of the three measurements of the G0 experiment to the various form factors are indicated for one value of Q^2 in the following.

G0 elastic scattering program

A_F: one measurement for all $Q^2 \rightarrow$ detect recoil protons
A_B: three measurements for three Q^2 values
$\rightarrow$ detect electrons at 108°
A_d: Quasielastic scattering from deuterium
$\rightarrow$ detect electrons at 108°

$$\begin{pmatrix} A_F \\ A_B \\ A_d \end{pmatrix} = \begin{pmatrix} \xi_F & \chi_F & \psi_F \\ \xi_B & \chi_B & \psi_B \\ \xi_d & \chi_d & \psi_d \end{pmatrix} \begin{pmatrix} G_E^s \\ G_M^s \\ G_A^e \end{pmatrix} + \begin{pmatrix} \eta_F \\ \eta_B \\ \eta_d \end{pmatrix}$$

at $Q^2 = 0.44$ (GeV/c)^2.

	η(ppm)	ξ(ppm)	χ(ppm)	ψ(ppm)
A_F	-13.77	51.80	18.63	1.01
A_B	-25.01	16.10	31.41	6.96
A_d	-34.00	13.13	7.07	8.41

2 G0: Forward angle scattering

To carry out the G0 measurement program on a reasonable time scale, it was necessary to meet certain specifications. Because the asymmetries were expected to be as small as a few ppm, it is necessary to achieve counting statistics of the order of 10^{13} to 10^{14} counts. This necessitated the design of a large acceptance device with high count rate detectors and electronics, and the capability of isolating elastic scattering from inelastic processes. In addition an electron beam with high intensity, high polarization and small helicity-correlated beam properties is highly desirable, if not absolutely essential. These requirements led to the design and construction of specialized equipment by the G0 collaboration, as detailed next.

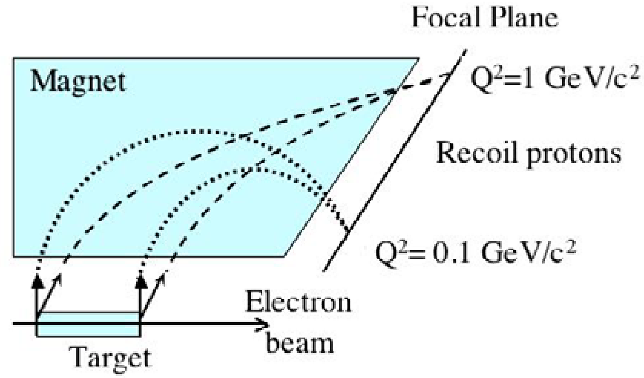

Fig. 1. A schematic diagram of the G0 magnet and detection scheme for the "forward" angle mode

The heart of the G0 apparatus is a superconducting toroidal magnet that focuses scattered particles through collimators onto a focal plane array of scintillators. The magnet contains eight superconducting coils splitting the magnet and detector system into octants. Each octant, as defined by collimators near the cryogenic target, accepted 20° in azimuthal angle. Combined with the polar angle acceptance, defined by the momentum defining collimators, the device had a total solid angle of about 0.9 sr. Figure 1 shows a schematic representation of the principle of operation for the forward angle scattering mode ("forward" mode). In its "forward" mode, the apparatus detects and counts recoiling protons from forward angle electron scattering (the protons are ejected at angles between approximately 60° and 75°). In this mode a simultaneous measurement for all Q^2 values (0.1-1.0 (GeV/c)^2) is made. Note that for a given Q^2 the magnet focuses protons from any point along the target length, at least at the center of each octant. After delays in delivery of the magnet and the necessity for significant modifications, in the end the magnet operated very reliably at the design current of 5000 A.

The Focal Plane Detectors (FPD) for each octant consisted of 16 pairs of scintillation detectors (Bicron BC400) which were shaped and segmented to detect protons corresponding to a limited band of Q^2 and to limit the e-p elastic count rate to less than approximately 750 kHz. These were placed at, or near, the focal plane of the magnet. FPD1-14 accepted relatively narrow bands of Q^2, whereas FPD15 accepted a broad band of Q^2 at the end of the range of acceptance. No elastic scattering events were recorded by FPD16, and it was used as a monitor of background and magnet current. Pairs of scintillators were used to suppress background from neutral particles. Light from both ends of each scintillator was transmitted through light guides to photomultiplier tubes which were mounted in a region of very low magnetic field. A picture of one of the detector octants is shown in Fig. 2.

The signals from the FPD photomultiplier tubes were sent to constant fraction discriminators, mean timing was done between the two ends of the scintillators, and a coincidence was done between the front and back scintillator.

Fig. 2. Forward proton detector octant

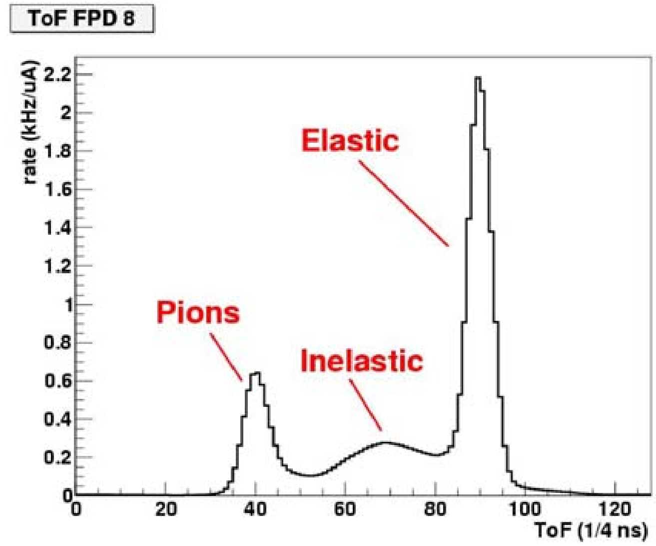

Fig. 3. Typical time spectra for the G0 experiment

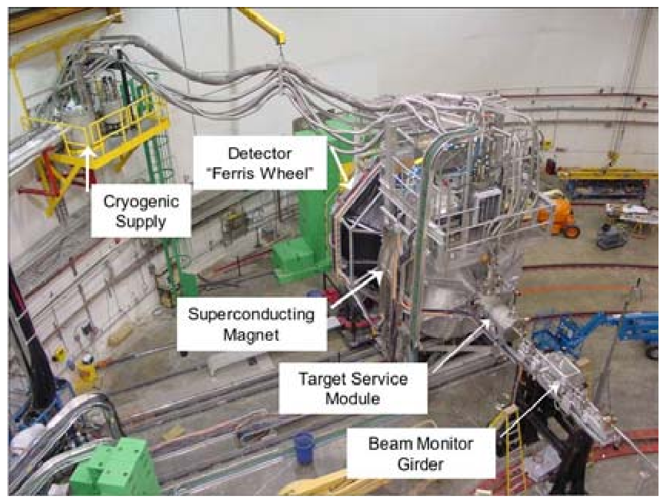

Fig. 4. G0 experiment installed in Hall C at Jefferson Lab

The resultant signal was sent to custom time-encoding electronics which measured the flight time of the particle using a signal associated with the beam arrival on target. This time measurement is the primary method used to separate elastic protons from inelastic protons and pions. Two different sets of time-encoding electronics were used. Four of the octants used latching time digitizers to extract the flight time with a resolution of 1 ns. This information was recorded by fast scalers, so that rates of several MHz could be handled. The other four octants utilized electronics designed and built in France that were based on flash TDCs. This system had a time resolution of 0.25 ns, and could operate up to about 4 MHz. The basic data transfered to the computer consisted of 128 bit timing histograms. The time histograms were read out every 33 msec, corresponding to the helicity reversal period. A typical time spectrum is shown in Fig. 3.

The cryogenic target is 20 cm long and was designed to have high flow rate to minimize target density fluctuations. At the 40 μA current and 3 GeV electron energy for the forward angle mode, the heat load on the target was 250 W. In tests during G0 running the observed target density fluctuations were negligible at 40 μA, and we believe that we can run at currents up to 80 μA for the back angle mode.

The final requirement for the forward angle G0 run is the time structure of the beam. Since we require a measurement of the time-of-flight of the particles, we requested a time structure of 32 MHz. Producing a 40 μA beam with this time structure, and hence very high charge density, required extensive development work on the part of the JLab accelerator group, and I would like to acknowledge their crucial contributions to the G0 experiment. After lengthy development time, the accelerator was ultimately able to provide parity quality beam with the required time structure.

After two commissioning/engineering runs in 2002 and 2003, followed by a production run, the forward angle measurement of the G0 experiment has now been completed, and analysis is proceeding. The desired statistical uncertainties were achieved, and most subsystems of the apparatus performed at or above their design goals. Figure 4 shows the G0 experiment as installed for the forward angle mode. The success of this run was due in large part to the heroic efforts of the postdocs and graduate students associated with G0.

Two problems that could potentially impact the error in the final results were encountered during the production running. Both were due to small background yields which had an unexpectedly large asymmetry. The first was due to leakage current from the other two halls at JLab.

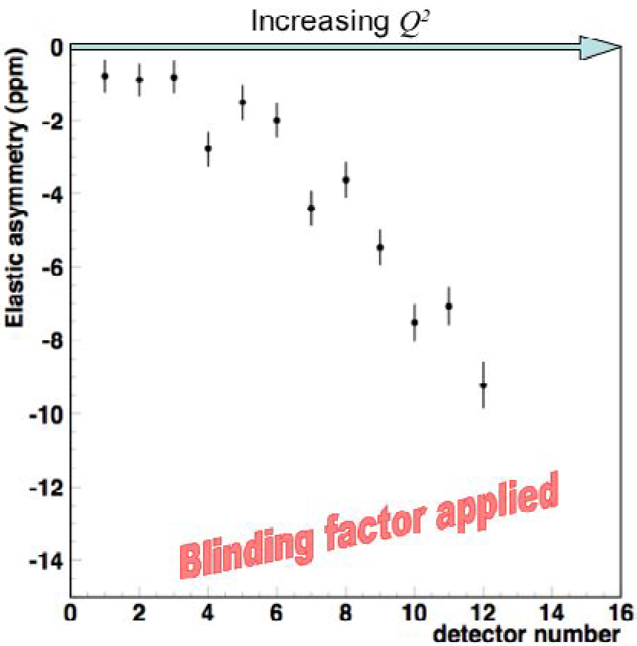

Fig. 5. Preliminary G0 forward angle data. The data are blinded by an overall multiplicative factor

These leakage beams, although small, had the standard 499 MHz time structure and a helicity dependent charge asymmetry not under our control. With some dedicated running under various conditions, we are able to correct for this contribution to the measured asymmetry to a precision of approximately 0.1 ppm, insignificant compared to our statistical error.

The second problem encountered is due to an unexpected background lying under the elastic peak in the time spectra. This background has a significant asymmetry which changes over the time spectrum. A great deal of effort has gone into attempting to understand this background, and to devise methods of subtracting it from the elastic scattering. In addition to expected background from inelastic protons and target windows, we believe that the large asymmetry in the background arises from hyperon decay, and a large simulation effort is underway.

Overall we believe that we have achieved the goals of the G0 proposal for the forward angle measurement with the caveat that our understanding, or lack thereof, of the background may increase the overall error bar somewhat, particularly for the higher Q^2 values. Shown in Fig. 5 are preliminary results for the first 12 FPDs for which the background is less severe. These results are blinded by an overall multiplicative factor to reduce possible analysis biases, and should not be interpreted as anything other than an indication of the overall quality and rough magnitude of the asymmetry.

3 G0: Backward angle scattering

The second phase of the G0 experiment is a measurement of the parity-violating asymmetry for backward angle elastic scattering. For these measurements the magnet-detector system is rotated by 180° – a process which has already been completed. In the "backward" mode (first run tentatively scheduled to begin in late 2005), there are a number of differences compared to the forward angle mode. Firstly, elastically scattered electrons are detected rather than recoil protons. The optics of the magnet are such that the scattered electrons are at an average angle of $108°(\pm 10°)$, corresponding to a single value of Q^2 for each beam energy. Therefore, to cover the full range of Q^2, measurements will be required at a variety of incident energies. The G0 collaboration has proposed measurements at three values of Q^2: 0.3, 0.5 and 0.8 $(\mathrm{GeV/c})^2$, corresponding to incident electron energies of 0.434, 0.585 and 0.799 GeV, respectively.

Another major difference is that the elastically scattered electrons are not focused on specific focal plane detectors (FPD), but rather on each focal plane detector there are both elastic and inelastic events. To separate these, a second scintillator array (labeled the Cryostat Exit Detectors or CEDs) will be mounted near the magnet cryostat exit window for each octant. The CED array consists of 9 arch shaped scintillators, similar in shape to the FPDs but smaller, since they lie closer to the target. By recording all possible combinations of coincidences between the 9 CEDs and 14 FPDs, we will be able to separate the elastic and inelastic events. In the worst case the contamination of the elastic events due to inelastic electrons will be less than a few percent. While elastic and inelastic electrons can be separated this way, the FPD/CED combination does not provide any discrimination between electrons and negative pions, both of which have velocities close to that of the speed of light. This is not a serious issue for the hydrogen run, since at the G0 energies the 2-pion production rate is very low, resulting in a contamination of less than a percent even at the highest proposed energy. However, there will be a small π^- rate from the target windows. More importantly the π^- rate from the neutron in the deuterium target will be similar to or greater than that of the electrons. For this reason 8 aerogel Čerenkov detectors have been added to the design to separate electrons and pions. The CED scintillators and light guides have been fabricated at TRIUMF and are currently being assembled on the support structure at JLab. The Čerenkov detectors, provided by the Canadian and Grenoble collaborators, are complete and at JLab awaiting mounting. A cartoon of the backangle setup and its operation are shown in Fig. 6. The diagram on the bottom shows the combinations of CEDs and FPDs and the relative contributions from elastic and inelastic electrons.

Rather than use time-of-flight to identify the particles of interest, we will now simply count the particles detected in every possible FPD/CED combination that did not also fire the Čerenkov. Custom electronics modules which record and sort all possible coincidences between the 9 CEDs and 14 FPDs were designed in Grenoble and Louisiana Tech. Prototypes have been fabricated and tested, and production of the final modules is nearing completion with delivery expected by Spring 2005.

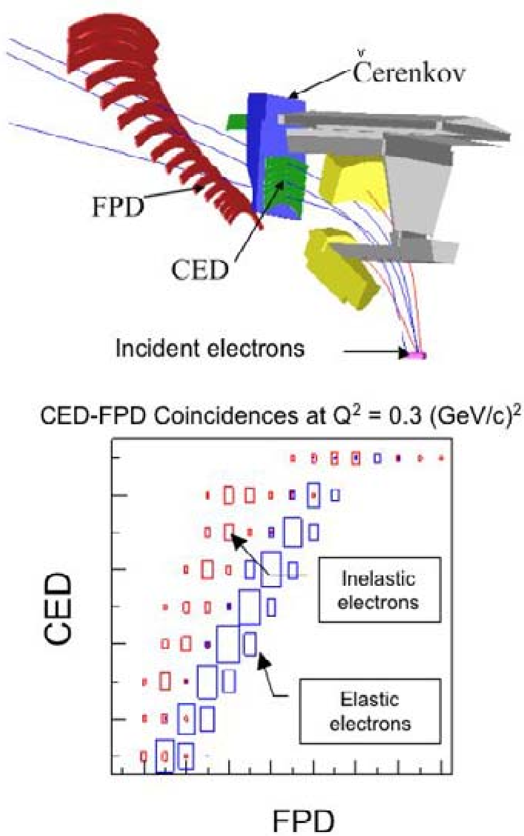

Fig. 6. G0 setup for backangle e-N scattering

With the above differences some distinct benefits have come. Since we no longer will be taking time-of-flight information, we do not require the special 32 MHz time structure needed for the forward angle measurements for which the beam current limit was 40 μA. We therefore plan to make use of the excellent performance of the cryotarget to run with 80 μA of beam current with the standard JLab 2 ns beam structure. This will improve our expected statistics by a factor of two, thereby reducing the statistical error, the largest contributor to the uncertainties at the backward angle.

The inelastically scattered electrons in the G0 backward mode are primarily due to excitation of the Δ resonance. As stated above these events are separated from the elastic events in the space mapped out by different combinations of FPD/CED pairs. As a result, it will be possible to simultaneously measure the parity violation asymmetry in the N-Δ transition [11]. The dominant contribution to the inelastic asymmetry is expected to be from the one-body, axial transition form factor, $G^A_{N\Delta}$. This transition form factor has been measured in charged current reactions, but the G0 measurement would be the first determination of this form factor in the neutral current sector. Since we can tag the pions, the collaboration is also considering a simultaneous measurement of the parity violating asymmetry in pion production.

4 Conclusion

After many years and a great deal of effort on the part of many G0 collaborators, we are seeing the payoff from this work. We have successfully completed the forward angle measurements, as described above, and are embarking on measurements at back angle. With the completion of G0 and the other measurements by the HAPPEX and PVA4 collaborations, we will have a new view into the underlying quark makeup of the nucleon. It promises to be an exciting next few years.

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