THE G0 PARITY VIOLATION EXPERIMENT:

OVERVIEW
AND
STATUS AFTER THE FIRST COMMISSIONING RUN.

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Abstract: The basis of the G0 experiment is a parity-violating process giving access to the strange form factors of the proton. It requires the measurement of a set of asymmetries, in elastic electron scattering from hydrogen and quasi-elastic scattering from deuterium, at different Q^2 and at different angles. The experimental site is the Thomas Jefferson National Accelerator Facility (JLab.), Newport News, VA (USA). The formalism that connects asymmetries with the proton properties at the quark level, the experimental set-up and the present status are described. A section is devoted to a special electronic module, built at the IPN-Orsay, using Digital Signal Processors (DSPs).

Keywords: *Experiment, asymmetry, parity violation, strange form factors*

Introduction

The amplitude of the strange quark component in the description of the proton still has to be established. It cannot be evaluated from the electromagnetic interaction alone, but it can be accessed through electro-weak processes. The electro-weak interaction is smaller than the former one by orders of magnitude and requires special techniques to be observed and isolated. Parity violation is specific to the electro-weak interaction and forms the basics of the G0 experiment.

The observables, the strange form factors of the proton, will be extracted from asymmetry measurements for which many cancellations of experimental parameters

[1] (see http://www.npl.uiuc.edu/exp/G0/)

permit access to a signal at the 10^{-5} level. The first proposal was made in 1991[**1**]. The French teams joined the collaboration in 1998.

Since the first proposal there have been other similar experiments running or proposed, based on parity violation, to determine the strange component of the nucleon, HAPPEX [**2,3**], He TARGET (EXP 00-117) [**4**], PVA4 [**5**] and SAMPLE [**6**], but G0 will be the largest investigation when both forward and backward angle measurements have been achieved, providing values of three form factors at three different Q^2.

1. - Physics

Parity violation in elastic electron scattering arises at leading order from the interference of the g or Z^0 exchange processes shown in Fig. 1.

Figure 1. *Diagrams for electromagnetic and electro-weak interactions.*

The asymmetry of the reaction for the two helicity states of the beam can be expressed as:

$$A = -\frac{G_F Q^2}{4pa\sqrt{2}} \left\{ \frac{e G_E^g G_E^Z + t G_M^g G_M^Z - (1 - 4\sin^2 q_w)\, e' G_M^g G_A^e}{e (G_E^g)^2 + t (G_M^g)^2} \right\}$$

where: G^{γ}_E and G^{γ}_M are the electromagnetic form-factors, G^{Z}_E and G^{Z}_M are the electroweak form-factors and G^{e}_A is the effective axial form-factor of the proton seen in parity-violating electron scattering. From the measurements of G^{Z}_E, G^{Z}_M and G^{e}_A and the knowledge of the electromagnetic form-factors of the proton and the neutron, it is possible to extract the ***s*** quark contribution (G^{s}_E and G^{s}_M) to the nucleon structure. This decomposition only relies on charge symmetry of the nucleon and on the assumption that only the light quark flavours contribute to these form factors. Finally the measured asymmetry can be expressed in terms of strange form factors:

$$A = h + x\, G^{s}_E + c\, G^{s}_M + f\, G^{e}_A$$

where h is the asymmetry known from neutron and proton form factors (for the G0 experiment h varies between -1 and -35 $\times 10^{-6}$).

Three asymmetry measurements are necessary to extract G^{Z}_E, G^{Z}_M and G^{e}_A - from which the strange form-factors can be deduced [**7**].

Table 1 shows the kinematics used in different experiments. Two of them, SAMPLE [**6**] and HAPPEX [**2,3**] measure asymmetries at a given angle and take advantage of the kinematical suppression of one of the observables (respectively G^s_E and G^e_A). On the contrary, the G0 program [**1**] will give separate values of G^z_E, G^z_M and G^e_A by measuring asymmetries, at the forward electron angle (7°) for one incident energy (3 GeV) on a hydrogen target [protons will be detected] and three different energies on hydrogen and deuterium targets at backward electron angles (110°) [electrons being detected].

Table 1. *Comparison of experiments measuring the strange form factors.*

Observables	Target	θ_e (deg.)	Q^2 ((GeV/c)^2)	Observables
SAMPLE [**6**]	*p*	146	0.1	$G^s_M = 0.14 \pm 0.35 \pm 0.40$
(*MIT – Bates*)	*d*	146	0.1	$G^e_A = 0.22 \pm 0.45 \pm 0.39$
	d	146	0.04	$G^s_M + 0.38\, G^e_A$
HAPPEX [**2**]	*p*	12.3	0.48	$G^s_E + 0.392\, G^s_M = 0.025 \pm 0.020 \pm 0.014$
HAPPEX II [**3**]	*p*	6	0.1	$G^s_E + 0.1\, G^s_M$
EXP 00-114 [**4**]	*He*	6	0.1	G^s_E
(*JLab*)				
PV–A4 [**5**]	*p*	35	0.235	$G^s_E + 0.218\, G^s_M$ $*A_{PV} = 5.58 \pm 0.57 \pm 0.17 \pm 0.06$
(*MAMI*)	*p*	35	0.110	$G^s_E + 0.1\, G^s_M$
G0 [**1**]	*p*	7	0.1 ... 1.0	G^s_E , G^s_M , G^e_A
(*JLab*)	*p*	110	0.3, 0.5, 0.8	
	d	110	0.3, 0.5, 0.8	

*A_{PV} is the asymmetry for parity violation. The quoted uncertainties come successively from statistics, systematic errors and beam polarization uncertainty.

The G0 experiment will therefore measure the evolution of these three form-factors for different momentum transfers Q^2 between 0.1 and 1.0 (GeV/c)^2. Figure 2 shows the expected total errors bars of the G0 and Happex-II combined with He target measurements compared to the predictions of different models: dipersive approach [**8**], Heavy Baryon Chiral Perturbation Theory [**9**] and Lattice QCD [**10**] for the strange form-factors and an estimate of $G^e_A(Q^2)$ from electroweak radiative correction calculations [**11**] for which the calculation at $Q^2 = 0$ has been extended using the standard dipole form of G_A measured in neutrino scattering.

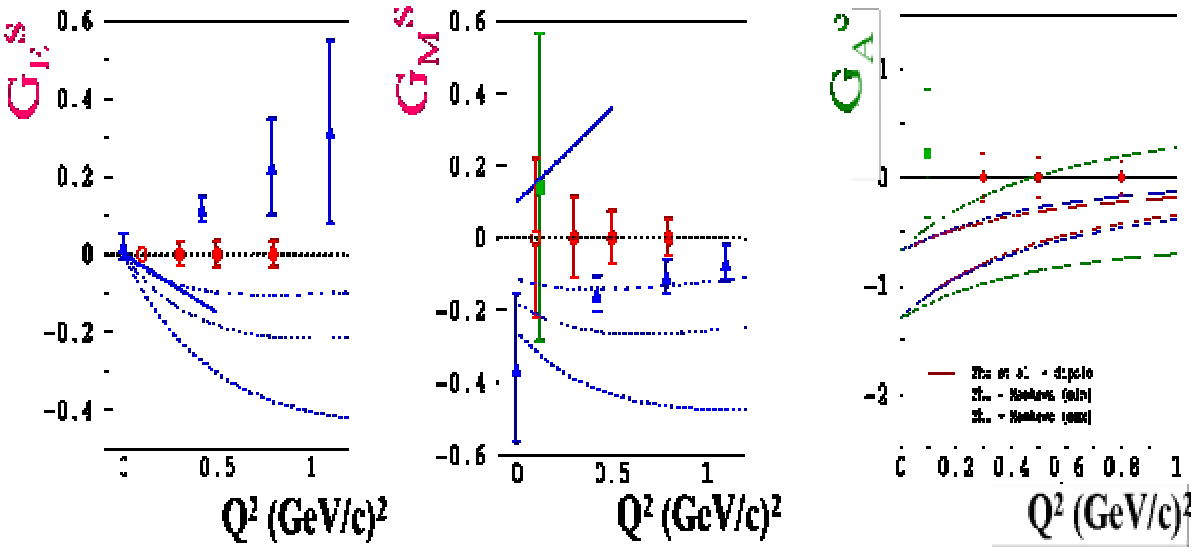

Figure 2. *Expected errors for G0 and comparison with other experiments and theory.* The three full circles with error bars correspond to G0 expectations [**1**], the open circle to a proposed measurement HAPPEX-II combined with a study on a He target [**3,4**]. The full squares represent the SAMPLE results [**6**]. The full triangles are for Lattice QCD calculations [**10**]. The full lines are calculations within the heavy baryon chiral perturbation theory for G^s_E and G^s_M [9]. The intermittent lines for G^s_E and G^s_M are calculations made with a dispersive approach [**8**]. The curves for G^e_A are estimations made within the heavy baryon chiral perturbation theory and electro-weak radiative corrections [**11**].

For the strange form-factors both models agree with the zero-compatible published results of the SAMPLE and HAPPEX experiments[2] but they predict non-zero values for $G^s_E(Q^2)$ and $G^s_M(Q^2)$ and their evolution with Q^2 which will be investigated with the given accuracy of the experiment. The projected errors include here the statistical uncertainty ($\Delta A/A$ = 5%) of the measurements for 700 hours of data taking, the systematic accuracy and the possible errors from the knowledge of the electromagnetic form-factors of the proton and the neutron. Despite the specific design of the experimental apparatus, the G0 measurements overall errors will be dominated by statistics.

Additional physics information will be obtained from backward angle measurements. Concurrently with $\vec{e} + p$ elastic scattering, events corresponding to scattering in the $N \rightarrow \Delta$ region can be isolated and will give access to the $N \rightarrow \Delta$ axial transition form-factor $G^{ND}_A(Q^2)$, a first measurement in this neutral current process [**12**].

[2] In fact, the Heavy Baryon Chiral model actually uses the SAMPLE and HAPPEX results to fix two of its perturbative constants.

2. - Set-up

To undertake the experiment, special apparatus have been set up in Hall C of Jefferson Laboratory, Newport News, Virginia, USA. The full measurement asks for at least four periods of 700 hours of data taking to complete the experiment and will therefore last several years. The detection system has to be removable to allow other experiments in the same hall and that has fixed the location as shown in Figure3.

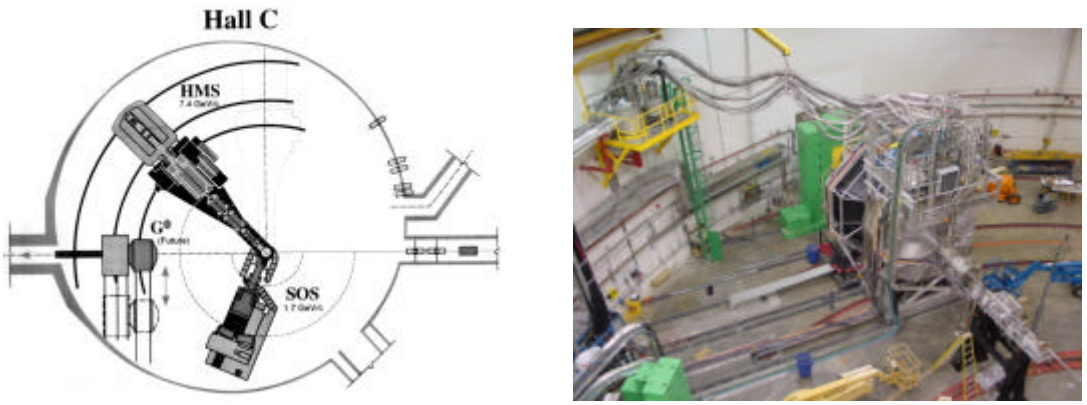

Figure 3. *Position and general view of the G0 set-up in Hall C.*

Requirements

The experiment is only possible if the following characteristics of beam and instrumentation are under control:

- stable intensity of 40 µA of longitudinally polarized electrons, with beam pulses delivered every 32 nsec, with 33 msec, between helicity changes.
- helicity sequence by quartets like (+ - - +) or (- + + -) to minimize slow time dependent and periodic effects, the first helicity state of each quartet being chosen pseudo randomly.
- helicity correlated beam fluctuations, within a quartet, limited in current to $\Delta I/I < 2000$ ppm and in position to Δx and $\Delta y < 20$ µm .
- liquid hydrogen target, 20 cm long and supporting 250 W heat load from the 40 µA beam.
- superconducting toroidal magnet working at 5000 A to fit the detector geometry and the Q^2 separation.
- background minimizing and shielding to keep total counting rates within the limit compatible with the characteristics of the detectors and of the DAQ system (described later).
- dead time determinations and corrections to compensate for possible beam charge asymmetry .

Here are the choices made for the final realization of the experiment.

Subsystems

- **Polarized source**

The experiment requires an unusual time structure of 31.2 MHz, instead of the standard 499 MHz of the regular CEBAF operating mode. The pulse separation of 32 nsec makes the time-of-flight separation of protons possible, a mandatory condition for the forward angle measurements. To achieve this goal it has been necessary to buy and install a specific Ti/Sapphire laser for the polarized electron gun and to solve complicated beam transport problems due to much higher space charge effects as the intensity needs to be kept at the 40 µA level.

- **Beam-line**

The beam is focused on the target at a specific point. New optics, new controls systems and a special raster have been developed and set up for the G0 experiment. For the forward angle part an energy of 3 GeV and an intensity of 40 µA are used. The helicity correlated variations in 30 days of data taking must be kept less than 2.5×10^{-8} for the energy, 1 ppm for the intensity, 20 nm for the position and 2 nrad for the angle[3].

- **Target**

Figure 4 presents a drawing and a picture of the cryogenic target built for the experiment. The cell is 20cm long. A high cooling power is provided by the

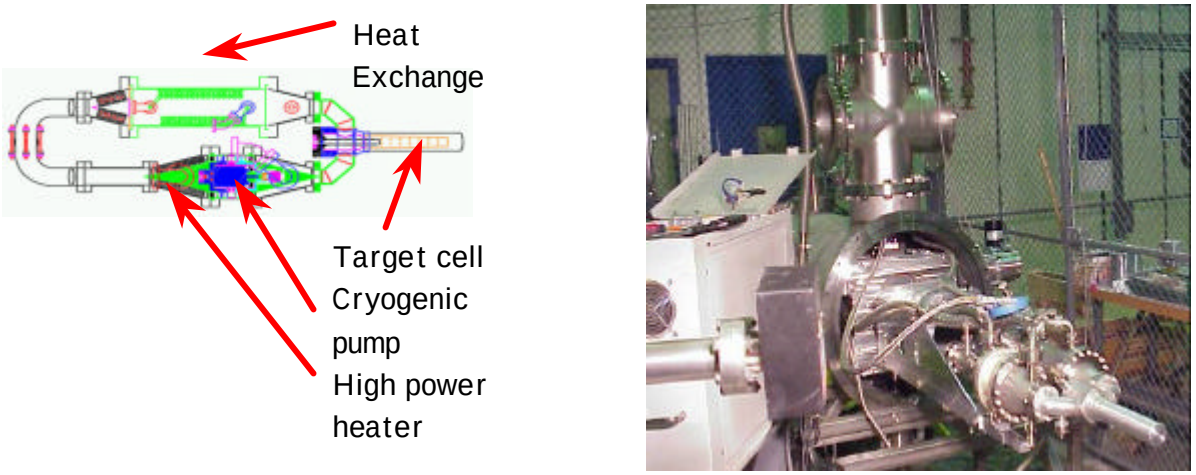

Figure 4. *Schematic drawing and photo of the G0 LH_2 cryo-target.*

high flow from the cryogenic pump to remove up to 320 watts deposited by the electron beam. A special heater is used to compensate intensity variations and insure a stable status of the cooling system. However the use of a raster is mandatory to spread the heating by the beam and avoid local boiling.

[3] This was achieved in 1999 for HAPPEX with the strained GaAs source.

➢ **Magnet**

A special superconducting magnet system (SMS) has been built. It is a toroidal magnet with 8 sectors and an azimuthally symmetrical angular acceptance. The higher current for data taking is 5000 A. The zero-magnification optics of the magnet makes all the protons emitted in elastic scattering with the same Q^2 to focus on the same detector. Line-of-sight shielding is possible because the bending angle is larger than 35°. The angle of detection is 70°, for recoiling protons for the forward angle measurements and 110° for electrons at backward angles. The angular aperture is 20° in both directions. Figure 5 illustrates the magnet system.

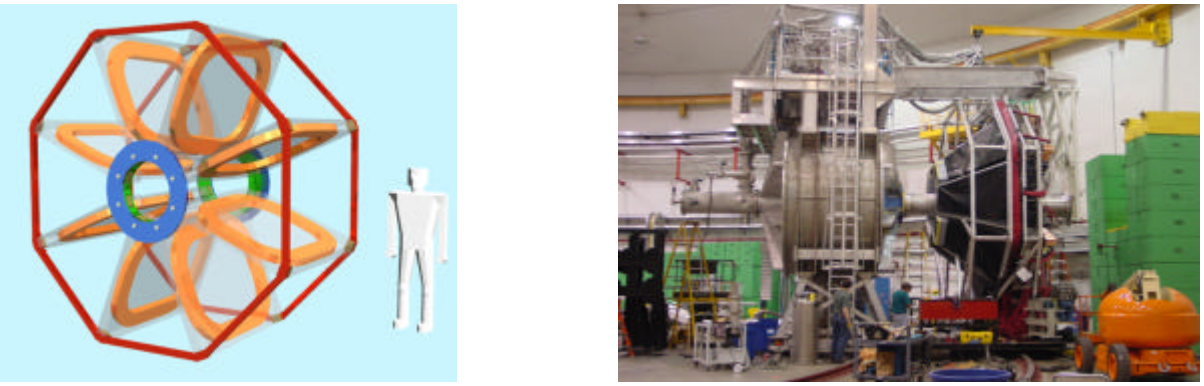

Figure 5. *Schematic drawing and photo of the SMS.*

➢ **Detectors**

Figures 6 and 7 show respectively sketches of the setups for the forward and backward angles. The shapes of the scintillators for the FPDs (focal plane detectors) have been adapted to the results of simulations, made with the magnet model, optimizing counting rates and backgrounds. There are 16 detectors of different sizes and locations. Each detector is made of 2 scintillators, placed one behind the other, spaced by aluminium (French option) or plastic (North American option) and put in coincidence to reduce the background.

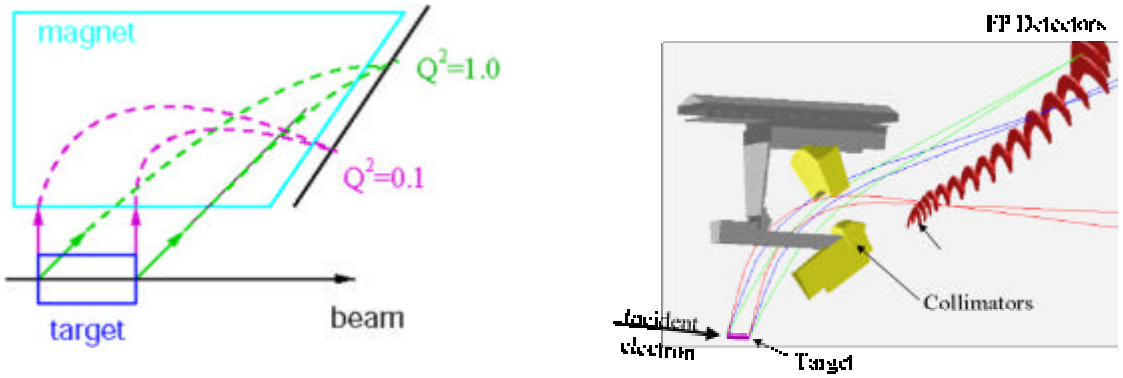

Figure 6. *Schematic drawings of the forward angle set-up.*

Each scintillator is read at both ends. The bases for the PMTs include an amplifier (French option) or are followed by an amplifier (NA option) to work at

lower voltage and with-stand for higher counting rates and have a longer lifetime.

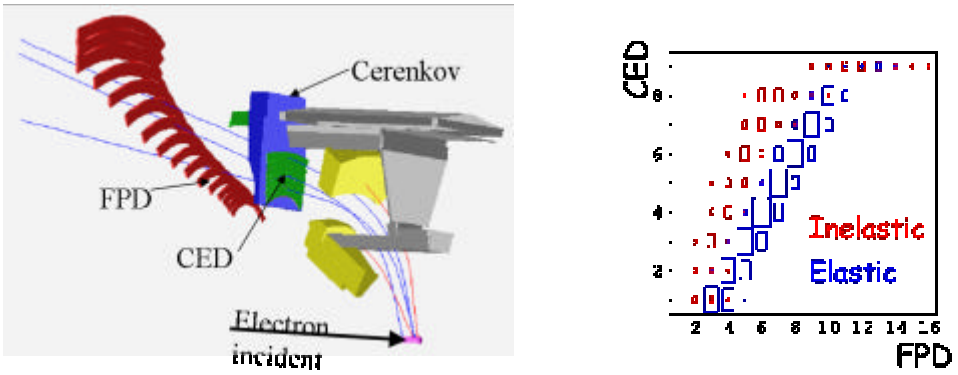

Figure 7. *Sketch of the backward angle set-up and zones of expected counts.*

For the backward angle measurements, electrons are detected. There is a contamination by pions that must be resolved using Cerenkov detectors. The time- of-flight identification of protons cannot be used. Additional detectors will be put at the cryostat exit (CEDs) to work with the FPDs to give a coincidence pattern as shown on Figure 7. The separation of elastic and inelastic events is good and will make the study of the $N \rightarrow \Delta$ region possible.

➢ Electronics

The electronics for NA and French detectors are similar [**13**]. The direct time-of-flight histogramming principle is represented in Figure 8. The NA electronics are using latching time digitizers (LTD) and scalers, covering 24 nsec with 1 nsec of resolution, whereas the French system is based on flash time to digital converters (TDC) of 250 psec resolution leading to a 128 channels histogram covering the full 32 nsec period between pulses.

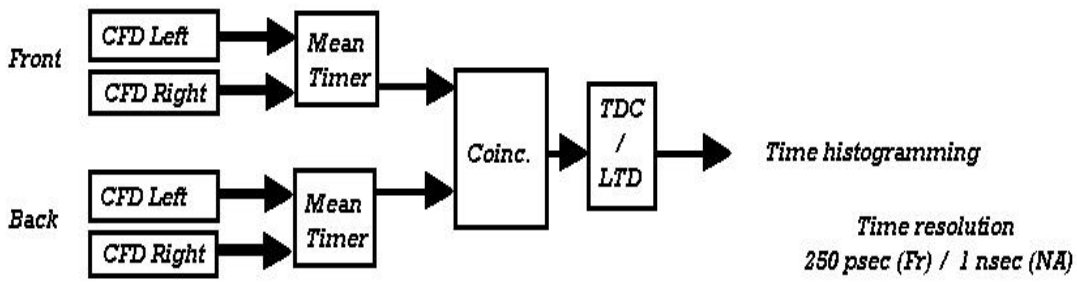

Figure 8. *TOF measurement principle in the forward angle mode.*
CFD is used for Constant Fraction Discriminator, TDC for Time to Digital Converter and LTD for Latching Time Digitizer.

In Figure 9 one can see samples of these modules. On the right side is one of the 8 DMCH necessary for the full encoding of the French part of the detector, and, on the left side, four crates containing the NA time encoding part. In parallel to this high speed histogramming part of the acquisition, after splitting the

incoming signals from the detectors a slow - event by event – acquisition will be processed to allow a survey of the correctness and the stability of the detector response. This slow electronics is using fastbus ADCs and TDCs giving individual amplitude and timing of all different signals (see Figure 10).

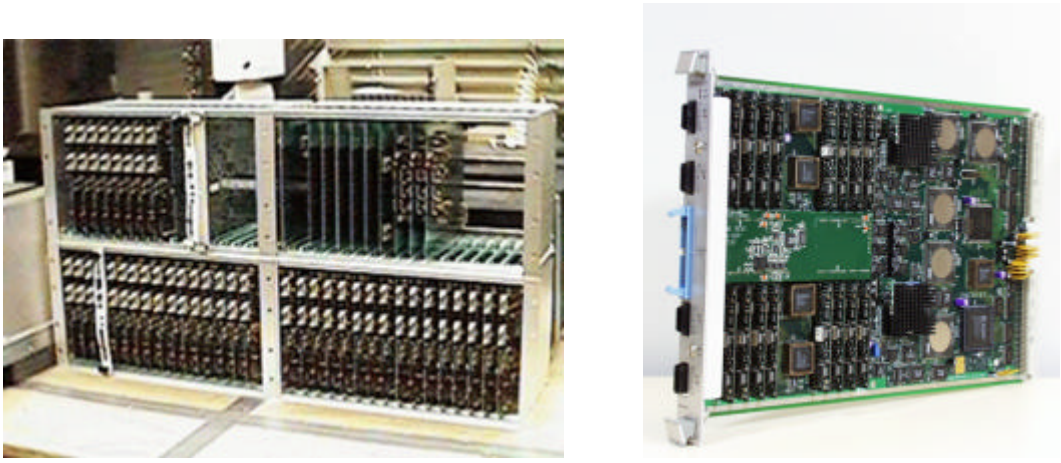

Figure 9. *LTD (latching time digitizer) modules for time encoding of NA electronics and DMCH module of the French system.*

- **Data acquisition (DAQ)**

  The North American and French systems are considered as independent subsystems, read subsequently as directed by a trigger supervisor module. The NA system delivers numbers from individual scalers and the French system provides histograms and scalers for individual counting at CFD (Constant Fraction Discriminator) and MT (Mean Timer) levels before histogramming. As mentioned above, some events from the fastbus system are also recorded in parallel.

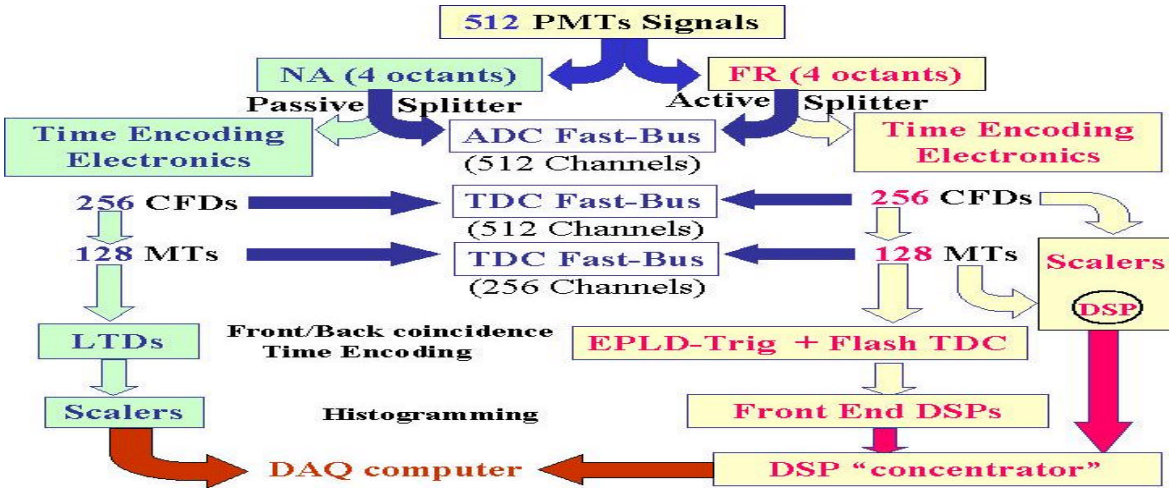

Figure 10. *General view of signal processing.*

3. - DMCH-16X module

Special electronics modules have been built in the Institute of Nuclear Physics of Orsay (IPNO) to satisfy specifically the requirements of the G0 experiment [**14**]. Active splitters are used first, to provide identical signals for time encoding lines and slow control lines, with the full amplitude from the PMT's bases.
Then, for time encoding and histogramming, 8 integrated and sophisticated DMCH-16X modules (**DMCH-16X** standing for **D**iscriminator, **M**eantimer, time to digital **C**onverter and **H**istogramming, processing **16** MT channels in each module, and plugged in a C size V**X**I crate). Figure 11 summarizes, on the left, the functions of one channel and presents, on the right, a photo of the module.

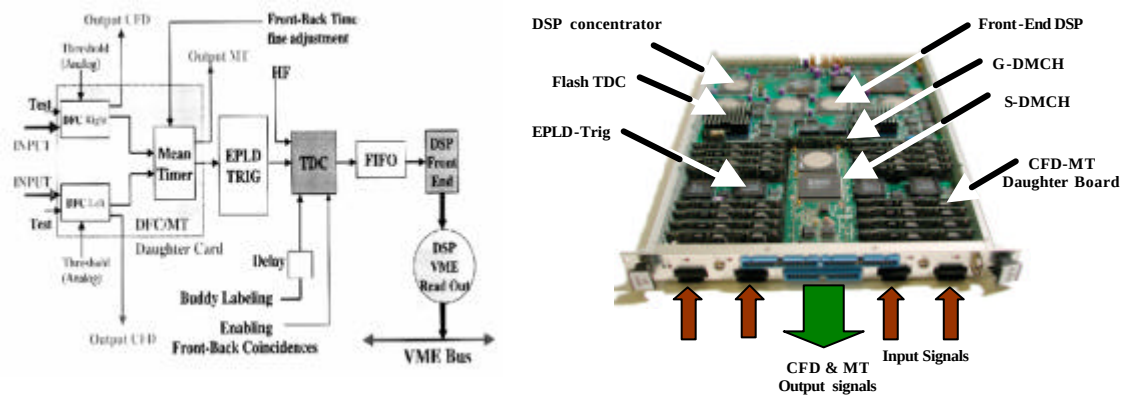

Figure 11. *Architecture of one DMCH channel and view of one open module.*

Each DMCH mother board receives 32 PMT analog signals and builds 16 TOF(Time-of-flight) histograms, 8 for the front detectors if a signal from the back detector is in coincidence, and, 8 for the 'Buddies', if working in the buddy mode (described below). Each board, connected through the VXI back plane to a CPU (MVME 2401), supports: 3 types of daughter boards, 4 programmable logical devices (EPLD-trig) to enable different operating modes, 2 ASICs (9 channel flash TDCs) 4 FiFo buffers (for high rate performance) and 5 DSP (digital signal processors) for histogramming and data transfer.

There are 16 *CFD-MT* daughter boards for discrimination, in a constant fraction mode, of the signals from both ends of one scintillator. The meantimer system (MT) is used to have a time reference independent of the location of the hit (with a compensation time of about 17 nsec to fit the experimental conditions). These boards connect to the logical device (EPLD-Trig) which generates signals for the different operating modes as Front or Back, Front if Back, Front if Back Buddy, etc…

The TDC is an integrated circuit, processing 8 channels in the implicit start mode, plus one that can be used as explicit start in case of need, as for laser calibration of PMT gains. The time resolution is 250 psec. The differential non linearity can be optimized, and corrected, off line if necessary, for the remaining non linearity. Gates and readable flags on the ASIC allow to work with Front/Back coincidence and to use the Buddy option, which is explained later. The outputs of the 2 TDCs are read through a buffer by 4 DSPs, at a maximum rate of 8 MHz per DSP. Histograms are built directly by these 4 frontend DSPs and then transferred to the DSP concentrator that sends the final information to the recording unit through the CPU, running the VxWorks real-time operating system.

A second kind of daughter board is called *Sdmch* (*S* for scalers). It carries 104 independent counters used to monitor rates at different levels: CFD, MT, etc…and transfers the data from its own DSP to the DSP concentrator.

The last daughter board is called *Gdmch* (*G* for generator). It carries an internal generator, remotely control by computer, and very useful for tuning and checking the full module.

The electronics must receive signals from the accelerator. The most important ones are the one called YO, which serves as a start signal indicating the arrival time of the electron beam on target, and the one called MPS (Macro Pulse Signal) corresponding to the helicity change every 33 msec. There are other signals which need to be seen by the DMCH, as, for example, a laser pickoff signal when doing laser calibration. An Interface Box (**IB**) has been built that transmits the external signals from the accelerator or provides its own internal signals for calibrations and tuning purposes.

This electronics is very convenient as changes and checks are made through a computer. One can set and check the CFD thresholds, adjust delay between Front and Back signals to insure safe coincidence, adjust parameters for good DNL (differential non linearity) and for the Buddy option, which will now be explained.

Buddy: principle and operating mode

The experiment is possible if beam qualities and properties can be kept stable enough to make the asymmetry signal measurable at the ppm (part per million) level with reversal of the helicity of the electron beam. The cancellation, in the expression of measured asymmetry, of some experimental characteristics such as beam intensity, beam energy, detector efficiencies, etc… that can be neither controlled nor kept at this level of accuracy, makes this observable very attractive. Feedback and regression procedures are used to improve the quality of measurements and the interpretation of the data. Particular attention should also be given to the acquisition dead time that has to be monitored for both helicity states. To have a better control of this dead time, it has been decided, for both NA and

French electronics, to work in a mode with next pulse neutralization (NPN), using specific signals that inhibit the time encoding during the duration of the next pulse when a Front/Back coincidence is detected. Doing so, the dead time, different for events with different TOFs, is precisely known.

The idea underlying the *buddy mode* is an attempt to experimentally measure the loss of events resulting from this dead time. The direct counting of these events is impossible because they occur when the electronics is busy from a preceding event, however a perfect image can be obtained by checking, for each event if an associated detector, supposed to count similar events, is busy or not. This is now possible because it involves two different channels. As one needs time to process the signals the comparison is made after a delay in time corresponding to exactly one pulse duration. In summary, they are two basic assumptions: that counting is identical, not only in an appropriate spatial shift (rotation of 180° for G0), but also in an appropriate time shift (32 nsec for G0).

The GLOBAL BUDDY

The time encoding is continuous and the histogram is made for every 32 nsec in 128 channels of 250 psec each between YO signals, the clock for coding. When an event (Front if Back) is encoded for one detector, it creates a flag on the corresponding buddy channel and if a count appears in this channel during the 32 nsec period of the clock, the scale is incremented by one, meaning a probability of loss in the detector. This indication is interesting for beam stability control but does not reflect the next pulse neutralization dead time and does not give a quantitative measurement. The first controls with beam have shown that the counting follows the $\mathbf{I}^2$ law (**I** being the beam intensity).

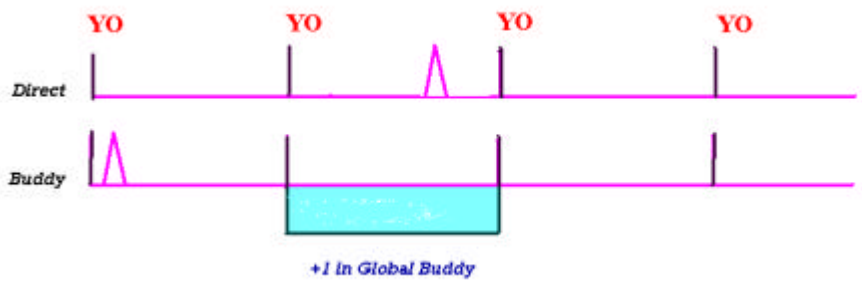

Figure 12. *Schematic principle of Global buddy counting.*

The DIFFERENTIAL BUDDY

For a more precise and detailed study of the dead time it is possible to make time distribution histograms of estimated losses in counting resulting from busy electronics. The idea is the same as for the global buddy . A signal associated with the dead time, or busy time, of one detector (of about 45 to 65 nsec - depending on

the channel - when including the next pulse neutralization) is shifted by 32 nsec and used as a flag to build a specific histogram of events that would have encountered a busy buddy detector if they had occurred 32 nsec earlier.

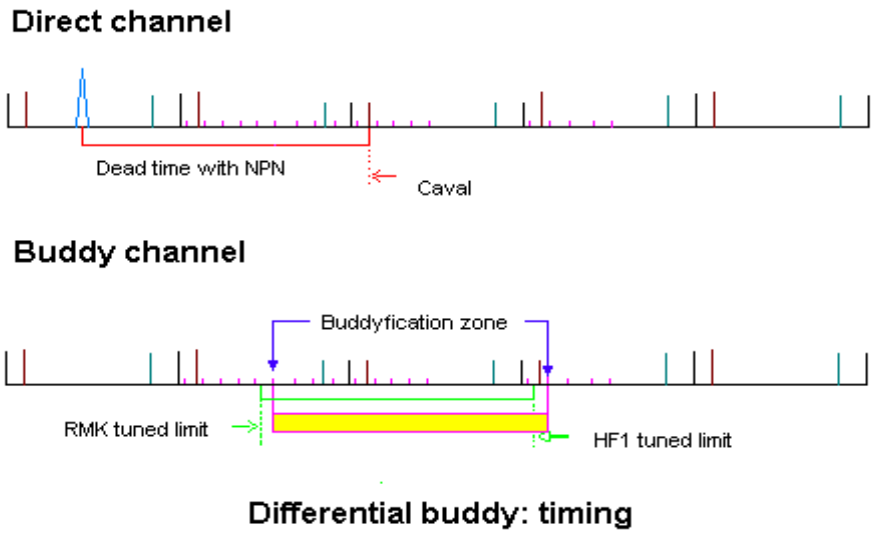

Figure 13. *Schematic principle of Differential buddy histogramming.* RMK and HF1 are two adjustable delays that one must use to shift by 32 nsec the dead time zone after one event and keep a flag on the buddy channel for the same duration. The "Buddyfication zone" is the period of time during which any event of the buddy channel is put in the buddy histogram to reflect a loss that would have happened in the direct channel, with the effect of reading the flag only every 4 nsec being taken into account.

The concept is good and the technology makes implementation possible, but a characteristic of the ASIC used for the coding make the interpretation uncertain because the flag status is only read every 4 nsec whereas the time resolution is 250 psec. The tuning and the measurements are more delicate, and this will probably restrict the usefulness of the method to a stability check. Independently of the buddy option, the final dead time corrections can be obtained, off line, from an algorithm reflecting the DMCH properties [**15**].

4. – Commissioning

The G0 experimental setup is new. The installation, controls and tuning were very demanding. First beam was delivered from September 2002 to the end of January 2003. All parts: source, beam line, target, magnet, detectors, electronics, data acquisition and analysis codes had to be tested, the background had to be measured and reduced and finally everything was tuned into an operational state. The status of the G0 experiment has been presented at some conferences [**16**]. Let us summarize here the crucial milestones that were passed.

SMS

A major concern was the magnet. Manufacturing defects had been repaired in early 2002. For safety reasons it ran at 4500 A initially from August to December 2002 and was successfully operated at 5000 A on December 18th and during the January 2003 running.

Polarized source and beam properties

The new laser installed for this specific experiment worked successfully and from January 2003 it was possible to have the 40 µA G0 beam on target with most of the required properties of size, alignment, stability. However, some of the feedback systems needed adjustments.

Liquid Hydrogen target

The target system worked ideally during the commissioning. With the raster on and a fan speed of 40 Hz, it has not shown any signs of significant boiling (see Figure 14). The target cell can be filled with liquid hydrogen or cold gas (hydrogen or helium) and in addition a ^{12}C target and 2 "halo" targets (circular holes of different diameter in an aluminium plate) can be placed in the beam and proved very useful for commissioning.

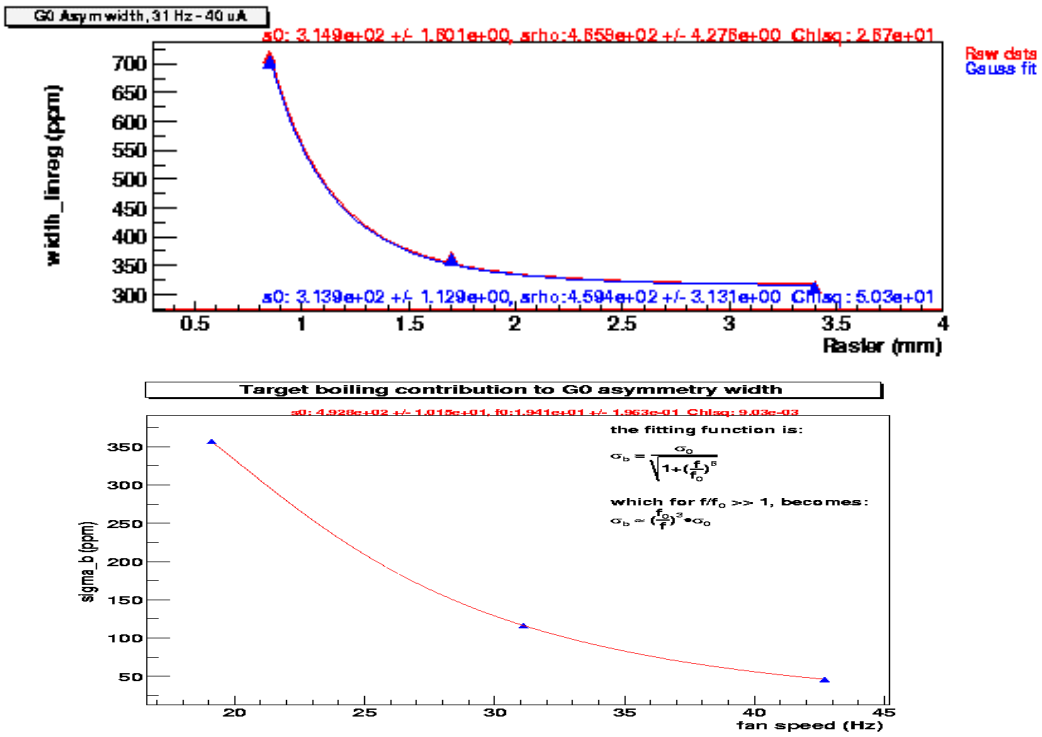

Figure 14. *Results from boiling tests of the liquid hydrogen target.*

However, it was observed that events from the aluminium windows introduce a dilution factor into the signal and consequently their thickness will be reduced to minimize this effect in the next run.

Detectors

Detailed studies have been made of detector gains, symmetry and centering, with beam manipulations to measure the detector response sensitivity.

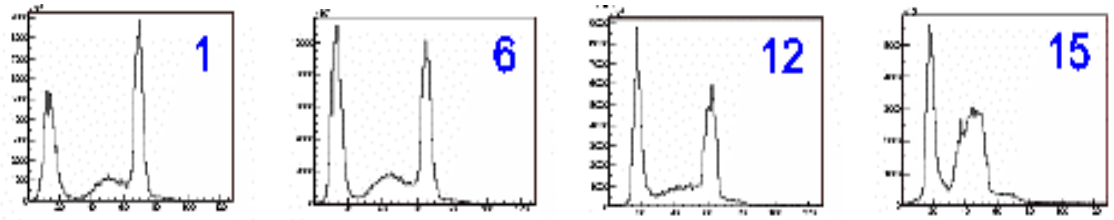

Figure 15. *Samples of TOF histograms.*

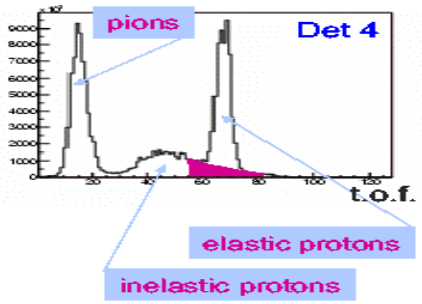

Figure 16. *Detector response.*

The photon background, initially high, was reduced by a factor of 2 with extra shielding. Some further efforts are still necessary. Figures 15 and 16 show typical responses of the detectors, from a DMCH module. The separation of protons and pions is excellent but some inelastic protons contaminate the elastic peak. A new investigation is necessary to reduce this effect, which has been partially attributed to the aluminium windows of the target.

Alignment effects are also under study.

Analysis

Electronics and DAQ have been working well. With the magnet operating at 5000 A and beam qualities sufficiently good, measurements were done at different intensities to check that dead time corrections were properly applied. Finally a few days were devoted to data taking, with alternate insertions of a half wave plate in the beam to reverse the sign of the expected asymmetry. The very encouraging results are presented in Figure 17.

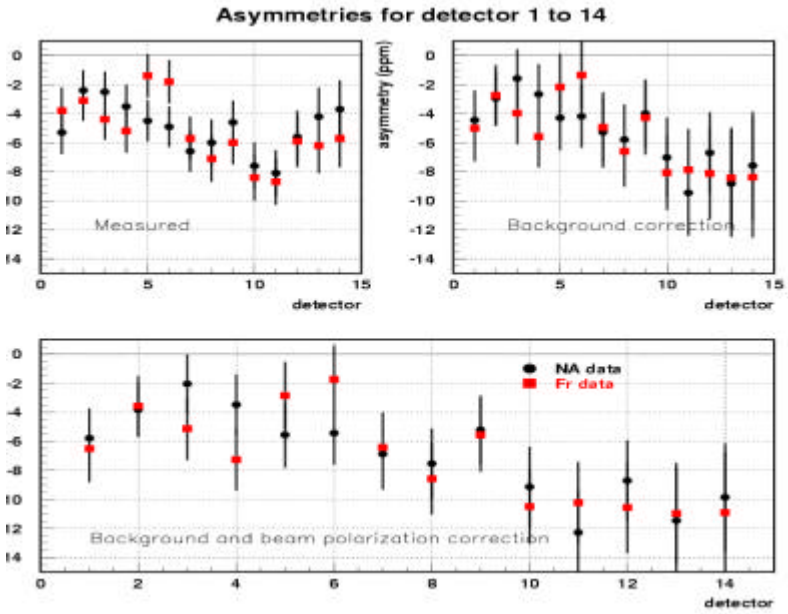

Figure 17. *Preliminary asymmetry results from the January 2003 running.*

The measurements, corrected only for dead time and false asymmetry (and the sign due to the half wave plate setting), are shown in the top left plot. The top right includes additional corrections for background and the final bottom graph has both background and beam polarization corrections included. North American and French apparatus results overlap correctly within the error bars based on 51 hours of data taken with 40 µA.

Summary and future

The G0 experimental setup is now installed in the Hall-C at JLab. The first commissioning run has successfully established that operational conditions can be obtained for all the subsystems and that, in a limited period of time, when working as a whole they give results in qualitative agreement with simulations and with the expected error bars. The second commissioning run is planned for the fall of 2003, from mid October to the beginning of December. If all systems continue to operate properly the forward angle data taking will begin in early 2004.

The second part of the experiment will start right after, with modifications and commissioning for the backward angle measurements. The positions of the magnet, the detectors and the target will be changed. CED and Cerenkov detectors must be installed, tested and calibrated, and electronics and DAQ modified. The beam has to be tuned at much lower energy to measure at the correct Q^2 values. Only the first back angle measurement is presently given beam time by the PAC of Jlab, the other ones depend on the results of the first one and will probably be obtained by the end of 2005.

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