Update of Experiment 91-015 Submitted to PAC20, 31 May 2001

Helicity Structure of Pion Photoproduction

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ABSTRACT

The physics case for an experimental measurement of the helicity asymmetry in the two single-pion photoproduction processes $\gamma p \rightarrow \pi^+ n$ and $\gamma p \rightarrow \pi^0 p$ at energies up to 2.3 GeV is just as valid today as it was when Proposal 91-015 was originally submitted. Although an extensive set of measurements on these reactions has been completed at Mainz at energies up to 800 MeV, no helicity-separated exclusive data exist above 800 MeV, and none are anticipated at other laboratories in the near future. The data are an important input to the partial-wave analyses of pion photoproduction, and the helicity-separated angular distributions will be important in making acceptance corrections to the ongoing program of measurements of the GDH sum rule by the total cross section method at Bonn and other laboratories. We request that the approval of the experiment be reaffirmed for the next 3 years, during which time we are confident that a suitable polarized target can be obtained and the experiment can be completed.

1. Desire for the experiment to remain approved

The proposers of this experiment hereby express their unqualified desire for this experiment to remain approved. The Real Photon Working Group of the CLAS Collaboration endorsed the continuation of this experiment at its meeting of 18-19 May 2001, both on its own merits and as part of an anticipated program of double-polarization measurements of other processes which also require a frozen-spin target.

2. Updated scientific case for the experiment

2A. Summary

Proposal 91-015 was originally submitted with the following scientific goals:

(1) to test the hitherto untested predictions of the helicity asymmetry by partial wave analyses.
(2) to evaluate accurately the single-pion photoproduction contribution to the Drell-Hearn-Gerasimov (DHG) sum rule.
(3) to use the helicity asymmetry as a new diagnostic tool in searching for evidence of poorly determined baryon resonances.
(4) to perform a preliminary evaluation of the contributions of other significant processes (particularly $\gamma p \rightarrow \pi^+\pi^- p$) to the DHG sum rule

Of these, goals (1) and (2) require some modest updating in the light of completed and ongoing measurements at Mainz and Bonn, while goals (3) and (4) remain essentially unchanged.

2B. Scientific background for the proposal

The important points motivating this proposal are as follows: (references can be found in the original proposal for Experiment 91-015.)

1) The Gerasimov-Drell-Hearn (GDH) sum rule is the relation

$$\int_{thr}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{k} dk = -\frac{2\pi^2 \alpha \kappa_p^2}{m_p^2} = -204.8\,\mu\mathrm{b}\ ,$$

where $\sigma_{1/2}$ and $\sigma_{3/2}$ are the total cross sections for hadron photoproduction on the proton in the helicity-1/2 and helicity-3/2 states, k is the laboratory photon energy, α is the fine structure constant, κ_p the proton's anomalous magnetic moment, and m_p the proton mass. The sum rule follows from very general principles (Lorentz and gauge invariance, crossing symmetry, causality and unitarity) applied to the forward Compton scattering amplitude, and from the earliest days there has been at least as much interest in **how** the sum rule is satisfied (i.e. rate of convergence, signs of contributions of indivdual processes, etc.) as in **whether** it is satisfied.

2) Measurements of $\sigma_{1/2}$ or $\sigma_{3/2}$ require the use of circularly polarized photons incident on longitudinally polarized protons. At the time of the original proposal, there were **no** direct measurements of $\sigma_{1/2}$ or $\sigma_{3/2}$ (or their equivalent representations), in either differential or total

cross section form, for any photoproduction reaction.

3) Predictions of $d\sigma_{1/2}$ and $d\sigma_{3/2}$ can be made from partial wave analyses of $\gamma p \to \pi^+ n$ and $\gamma p \to \pi^0 p$ using existing unpolarized and transversely polarized data. (We will use the symbol $d\sigma$ to stand for $d\sigma/d\Omega$). These analyses predicted that a very large fraction of the GDH sum rule should be exhausted by the two single-pion reactions at energies below about 1.2 GeV.

4) Polarized deep inelastic muon and electron scattering experiments measure the spin structure function $g_1(x,Q^2)$, which is the analog of the quantity $d\sigma_{1/2} - d\sigma_{3/2}$ in photoproduction. The earliest experiments of this type led to the interesting result that a Q^2 extrapolation of the integral $I_1(Q^2) = \frac{2m_p^2}{Q^2}\int_0^1 g_1(x,Q^2)\,dx$, which is a generalization of the GDH integral for $Q^2 \neq 0$, would require an extraordinarily rapid change of magnitude and sign in order to evolve smoothly toward the GDH sum rule value at $Q^2 = 0$.

While the angular coverage of the CLAS detector system is not sufficiently complete to make it a good device for measuring total cross sections in photoproduction experiments (and hence for a direct measurement of the GDH sum rule), it was judged that we could make a valuable contribution to the GDH effort by measuring the differential cross sections $d\sigma_{1/2}$ and $d\sigma_{3/2}$ for the single-pion and 2-pion photoproduction processes within the combined acceptance of the CLAS and the high-field polarized target which was then under design. Such data would be important inputs to the partial wave analyses, which could then predict much more reliable total cross section values.

We note in passing that the helicity decomposition of the cross section can be expressed in three equivalent ways: (1) the individual cross sections $d\sigma_{1/2}$ and $d\sigma_{3/2}$, (2) the unpolarized cross section $d\sigma = (d\sigma_{1/2} + d\sigma_{3/2})/2$ and cross section difference $\Delta(d\sigma) \equiv d\sigma_{1/2} - d\sigma_{3/2}$, or (3) the unpolarized cross section $d\sigma$ and the helicity asymmetry $E \equiv (d\sigma_{1/2} - d\sigma_{3/2})/(2\,d\sigma)$. Experimentally it is always advantageous to extract either $\Delta(d\sigma)$ or E from the polarized-target data, and use measurements on an unpolarized target for $d\sigma$.

2C. Update of the scientific justification

Since the submission of the proposal, additional predictions from partial-wave analyses of single-pion photoproduction have appeared[1,2,3], without altering the fundamental conclusions of the earlier works. State-of-the-art partial wave analyses of photoproduction at Mainz (MAID)[4] and GWU (SAID)[5] are available on-line, making it possible to evaluate GDH contributions at energies up to 1 GeV and 2 GeV, respectively.

More recent measurements of polarized deep inelastic lepton scattering have been performed at SLAC, CERN (SMC collaboration) and DESY (HERMES collaboration).[6] In particular, the HERMES experiment[7] shows that the generalized GDH integral continues to rise with decreasing Q^2 down to Q^2= 1.28 GeV^2, making the rapid turnover required to reach the real-photon value even more remarkable.[8]

Most important, measurements of the contributions to the GDH sum rule on the proton between 200 and 800 MeV have been performed at Mainz, using tagged photons and a frozen spin target inside the DAPHNE large-acceptance detector. Measurements of the total γp cross section difference $\Delta\sigma$ ($\equiv\sigma_{1/2}-\sigma_{3/2}$) from 200 to 400 MeV , and the resulting contribution to the GDH sum rule, have been published.[9] Data for the differential cross sections for all exclusive 1- and 2-pion photoproduction processes up to 800 MeV have been taken and reported in conference talks.[10,11] In addition, measurements of $\Delta\sigma$ at energies from 680 to 3100 MeV have begun at Bonn, using a total-cross-section detection system and the same polarized target system used at Mainz.

Re-evaluations of the GDH sum rule using preliminary results from the Mainz measurements have appeared in conference proceedings. The integral from 200 to 800 MeV has been quoted as 216±6±13 μb,[10] compared to the sum rule value of +205 μb. (The Mainz-Bonn GDH collaboration prefers to define $\Delta\sigma$ and the GDH integral with sign opposite to that of Section 2.) For this measured energy region, the sum rule is dominated by the single-pion contribution of the $\Delta(1232)$ resonance, and the existing partial-wave analyses account for this contribution very well.

To determine the full GDH integral from the Mainz data, one must use theoretical estimates for the lower and higher energy regions. These give rather large contributions of both signs ($k < 0.2$ GeV: -27 ± 2 μb; $0.8< k <1.65$ GeV: 39 ± 14 μb; $k > 1.65$ GeV: -25 ± 6 μb),[12] adding up to a small total correction which is compatible with the sum rule. The value for $k >$ 1.65 GeV comes from a recent phenomenological analysis by Bianchi and Thomas[12] which uses a Regge parametrization of polarized deep inelastic lepton scattering data to predict the multi-pion contributions to the GDH sum rule at $Q^2=0$. There exist no real-photon measurements to substantiate the predictions for photon energies above 0.8 GeV.

The status of other ongoing and proposed experiments relevant to this proposal is summarized in Appendix A. The essential fact is that **none of these programs will fulfill the goals of Experiment 91-015**: a measurement of the helicity asymmetry in exclusive pion photoproduction processes at energies above 800 MeV.

3. Membership of the collaboration

A current list of collaborators appears on the title page of this note. Mahbub Khandaker of Norfolk State University and Donald Crabb of the University of Virginia join the proposal as co-spokespersons. The continuation of this proposal has also been endorsed by the Real Photon Working Group of the CLAS Collaboration.

4. Technical readiness of the experiment

4A. Frozen spin target status

Proposal 91-015 proposed making measurements using the same high-field, dynamically-polarized target as was required by the (e,e'X) experiments, but stated that the experiment could be substantially improved by acquiring a frozen spin target, whose use would be limited to photon-beam runs. PAC5 approved the experiment for 18 days of beam time in Hall B as requested, but appended as a recommendation:

> "The possibility of using a frozen spin target should be seriously explored, especially as an investment for future experiments."

The absence of such a target, together with the fact the that the start of the Mainz program pre-empted the "first look" feature of the proposal, is what kept us from using the approved beam time as part of the eg1 run periods. For a time, it was hoped that there was a possibility of bringing to Jefferson Lab the Bonn-Bochum-Mainz frozen spin target which is currently in use in the GDH program at Mainz and Bonn. However, this target has now become an essential part of a long-range program at the two German laboratories, and is unlikely to be available in the foreseeable future.

A description of the advantages of a frozen spin target, together with preliminary plans for producing such a target for Hall B, is given in Appendix B. This target can be effectively developed as a collaboration between the Jefferson Lab target group and the University of Virginia. We urge that Jefferson Lab find the resources to construct this target.

4B. Other experimental equipment

Because of the large flight times from the target to the CLAS time-of-flight counters, photon beam running requires a "start counter" close to the target to suppress accidental coincidences in the trigger. Thus the target cryostat and holding magnet must be designed to be compatible with either the existing CLAS start counter or with the new start counter which is under development. There are no fundamental incompatibilities between the start counter and target cryostats of the sort discussed in Appendix B. The only detail to be worked out is the shielding of the start counter photomultipliers from the fringe field of the holding magnet.

Aside from the target and start counter, no other modifications of the standard Hall B equipment are required for this experiment. The circular polarization of the bremsstrahlung photons can be calculated precisely from the longitudinal polarization of the electron beam, so no beam polarimetry beyond the standard electron-beam Møller polarimeter is required.

4C. Data analysis

We will attempt to extract the helicity dependence of the cross section from the data in the form of both $\Delta(d\sigma)$ and E. $\Delta(d\sigma)$ is determined by subtracting the normalized yields in the two polarization states; since the bound nucleons are unpolarized, the dilution factor (the ratio of total nucleons to free protons in the target) is not used in the calculation of the result, but only affects the statistics of the subtraction. This method is being used in the analysis of the Mainz GDH experiment.[9,10,11] For each method, the systematic uncertainty contains contributions from beam and target polarization, which should each be under control at the level of 3%, and from the method used to separate single-pion from multi-pion processes. The systematic uncertainty in $\Delta(d\sigma)$ also contains the uncertainty in the photon flux ($\approx$3%) and in the areal density of free protons ($\approx$5%). The determination of the asymmetry E is independent of target thickness and beam flux, but requires knowledge of the effective dilution factor. Since we will identify events produced on the free protons by kinematic cuts, the effective dilution factor can be made much smaller than its nominal value (7.4 for butanol.).

The original proposal contained kinematic simulations which predict that the signal-to-noise ratio between free-proton and bound-nucleon events after missing-mass cuts should be of order 1:1 for $n\pi^+$ (and 1:2.5 for $p\pi^0$) for energies up to ~2 GeV. The analysis in progress of the reaction $ep \rightarrow en\pi^+$ from data taken with the CLAS high-field polarized target shows that the estimated missing-mass resolution and signal-to-noise estimates are realistic (Fig. 1). The resolution of the subtracted (free-proton) peak near W = 1.7 GeV is consistent with simulations, and is adequate to separate single-pion from multi-pion events in this region.

At energies above about 1.5 GeV, selection of free-proton events by missing mass alone may not be fully effective, but for the single-pion processes, coplanarity and other kinematic constraints can easily be imposed by detecting the neutral particle in coincidence with the charged particle. The CLAS calorimeter, which subtends angles up to 45° in all sectors (and up to 70° in two sectors), has approximately 60% detection efficiency for neutrons above about 2

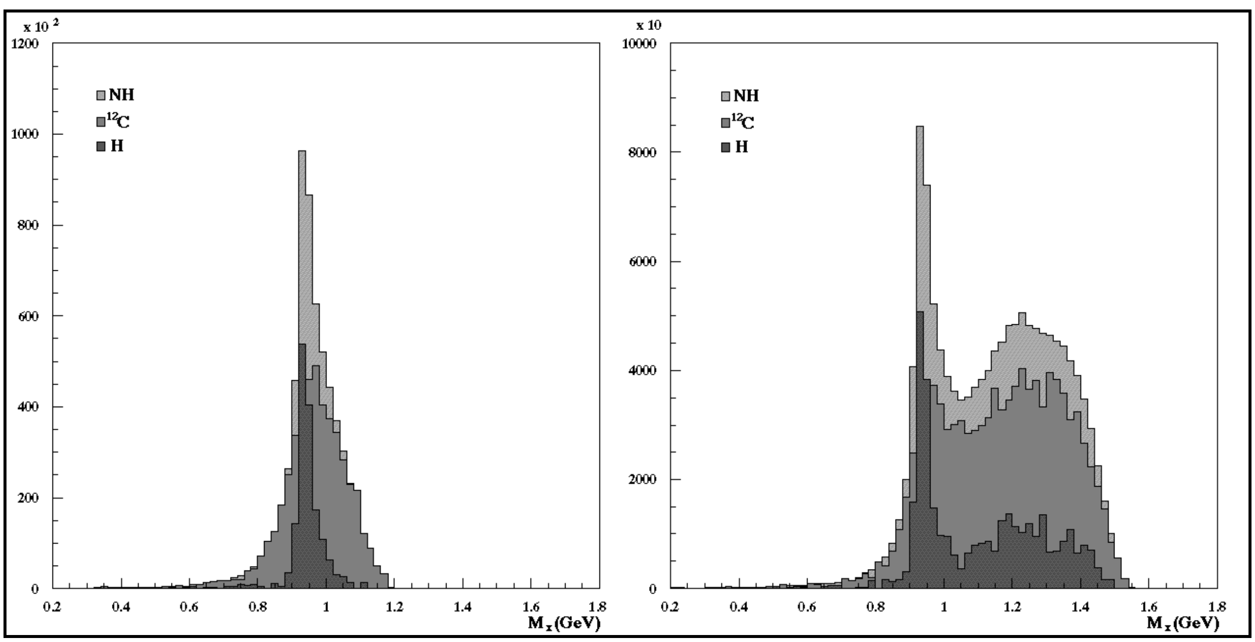

Figure 1. Missing mass of $ep \rightarrow e\pi^+X$ from data taken on CLAS high-field polarized target (analysis of Exp. 93-036 by R. DeVita.) *Left:* 1.24 < W < 1.36 GeV (corresponding to E_γ = 0.34 – 0.51 GeV. *Right:* 1.60 < W < 1.72 GeV (E_γ = 0.9 – 1.1 GeV). The three shaded regions show data from NH_3, carbon (normalized), and subtracted.

GeV/c, and the time-of-flight counters have neutron efficiencies of 6%–10% near 200 MeV/c,[13] The calorimeter also has a reasonably high efficiency and acceptance for $\pi^0 \rightarrow \gamma\gamma$ above 1 GeV.

4D. Revised run plan

The 18 days requested and approved for Exp. 91-015 assumed running at three different beam energies, 0.8, 1.6 and 2.4 GeV, in order to cover the photon energy range from 0.3 to 2.3 GeV. (The polarization transfer to the photons is roughly proportional to k/E_0, so only photon energies above $\approx 0.4E_0$ are useful.) In view of the excellent data available and forthcoming from Mainz up to 800 MeV, we consider 800-MeV running at CLAS to be no longer useful, and propose covering the energy region from 0.7 to 3.8 GeV by running at 3 endpoint energies: 1.6, 2.4 and 4.0 GeV.

The motivation for the 4.0 GeV run is based primarily on 2 facts:

1) The Bonn GDH experiment intends to measure the total cross section difference up to 3.1 GeV with little or no selectivity for individual exclusive processes. Differential cross section information on exclusive 1- and 2-pion processes at energies in this region will be very useful in motivating the necessary angular acceptance corrections.

2) The phenomenological analysis of polarized electroproduction data by Bianchi and Thomas[12] predicts a substantial contribution to the GDH sum rule at energies well above 2 GeV, and in fact an experiment has been approved at SLAC to measure GDH contributions between 5 and 40 GeV.[14] Although the single-pion contribution is only a small fraction of the total cross section in this region, measurements of the 2-pion exclusive channels at CLAS in the 2.5-4 GeV region would be very useful in estimating possible corrections to GDH tests as well as in searching for the dominant processes if this prediction of large spin asymmetry is supported by the data.

Table I shows proposed run conditions for the three energies, with the statistical goals of the measurement and the time required for each energy. We assume the following conditions:

Target thickness	1.5 g/cm^2 of butanol (C_4H_9OH)
Beam spot collimation	1.0 cm diameter at target
Average target polarization	70%
Electron beam polarization	70%
Maximum CLAS trigger rate	3000 triggers/sec

The beam time requested should be sufficient to determine the helicity asymmetry E (see Section 2B) to a statistical uncertainly $\delta E = \pm 0.05$ in each bin of differential cross section at the two lower beam energies, and to ±0.07 at the highest energy. The systematic uncertainty in E is estimated at $\delta E/E \approx 5\%$ due primarily to the knowledge of beam and target polarization. The tagging range for the 1.6 GeV run extends down to 450 MeV, to give substantial overlap with the Mainz measurements in the resonance region.

We assume that it will not be possible to place a carbon target in the beam, and that therefore no bound-nucleon background shape subtractions will be possible. (Various options for mounting a carbon target outside the cryostat are under consideration, but no obvious solution exists.) We assume that kinematic cuts are used to reduce the effective dilution factor (total nucleons/free nucleons) from 7.4 to values as low as ≈2 (for $\gamma p \to \pi^+ n$ in the 1.6 GeV run), improving the statistical uncertainties of the subtractions. The table includes 4 days for target polarization, assuming that repolarization of the frozen spin target will be required approximately every 4 days of running, and that, with a new system being commissioned, beam loss will be a full day for each repolarization.

Table 1. Requested run time for the 3 beam energies. The criterion is the statistical uncertainty desired in the helicity asymmetry E for for $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$.

Beam Energy (GeV)	Tagged photon energy (GeV)	Tagging rate	Angle bin	Energy bin (MeV)	Hours beam on target	δE for $\gamma p \to \pi^+ n$	δE for $\gamma p \to \pi^0 p$	Days
1.6	0.45–1.52	28 MHz	15°	25	115	.039	.050	5
2.4	1.45–2.28	14 MHz	15°	50	176	.049	.050	7
4.0	2.15–3.80	12 MHz	30°	100	77	.070	.070	3
							Target polarization time	4
							Total run	19

Appendix A. Ongoing and proposed experiments to measure contributions to the GDH sum rule on the proton

Mainz See section 2C.

Bonn

As part of the same experimental program as in Mainz, and using the same polarized target, a measurement of $\Delta\sigma$ at energies from 680 to 3100 MeV is being performed at Bonn[15] using a total-cross-section detection device with only limited ability to distinguish individual final states.

LEGS

The LEGS facility at Brookhaven National Laboratory is planning measurements of all γp and γn differential cross sections up to 470 MeV, using a new frozen-spin HD target known as "SPHICE". Due to technical difficulties, a working polarized target has not yet been put in the beam.

GRAAL

The GRAAL laser-backscattering facility at Grenoble also plans to use a SPHICE-type HD target (called "HYDILE") to measure the GDH contribution and some exclusive cross sections up to 1.5 GeV. A working polarized target has not yet been put in the beam.

Spring-8

Tentative plans to measure $\Delta\sigma$ (total cross section only) at photon energies from 1.8 to 2.8 GeV using a frozen-spin CH_2 target appear to be on hold because of other commitments for the target.

SLAC

An experiment[14] has been approved to measure $\Delta\sigma$ from 5 GeV to 40 GeV using a total-cross-section detection device, a frozen spin target, and a collimated coherent bremsstrahlung beam.

Jefferson Lab

Experiment 94-117 (Z. Li, J.P. Chen, S. Gilad, S. Whisnant - conditionally approved) proposes to measure the helicity decomposition of pion photoproduction on the **neutron** using a SPHICE-type target in Hall B. The conditional approval was based on the unproven status of the target technology.

Experiment 91-023 (V. Burkert, D. Crabb, R. Minehart) measures the Q^2 evolution of the GDH sum rule in $p(e, e'X)$ in Hall B. Experiment 93-036 (H. Weller, R. Minehart) measures the exclusive final states $ep \to e\pi^0 p$ and $ep \to e\pi^+ n$ in the same run.

There are also three other approved GDH-related electron scattering experiments (93-009, 94-010 and 97-110) using **neutron** (deuteron or ^{3}He) targets.

Appendix B. Justification and proposal for a frozen spin target for Hall B

A “standard” polarized target, with high magnetic field (≈5 T) required for polarizing, is necessary for experiments in which the incident beam deposits appreciable energy in the target , but has several serious disadvantages. The magnet needed to produce such a large and uniform field occupies much of the space around the target sample, leaving only a relatively small acceptance for outgoing particles, and the useful acceptance for low-momentum charged particles may be further reduced by large deflections in the magnetic field. For experiments using a large-aperture spectrometer like CLAS in conjunction with a tagged photon beam, which deposits negligible energy in the target, a more attractive option is to use a frozen spin polarized target.

In a frozen spin target, the material is polarized in the standard way with microwave irradiation in a high magnetic field. Then, with the microwaves off, the temperature of the material is lowered as much as possible, so that the relaxation time of the polarization becomes very long, hence the term “frozen spin”. The actual value of the relaxation time is a strong function of the ratio *B/T*, where *B* is the value of the magnetic holding field and *T* the material temperature. By operating at a sufficiently low temperature, it is possible to reduce the holding field to a value ≲ 0.5 T while still preserving a high polarization for times acceptable for running the experiment. The low holding field can be supplied by another magnet, the geometry of which can be tailored to the particular experiment to provide a much larger acceptance than obtainable with a high-field magnet. For example, the polarized target for the Mainz-Bonn GDH experiments (Fig. 1) uses a holding field produced by a very thin (500 μm) superconducting solenoid, which offers virtually no obstruction to the outgoing particles.

A $^3He/^4He$ dilution refrigerator is used to provide the lowest temperatures and reasonable cooling power when polarizing. Typical values would be 50 mK for frozen spin operation and

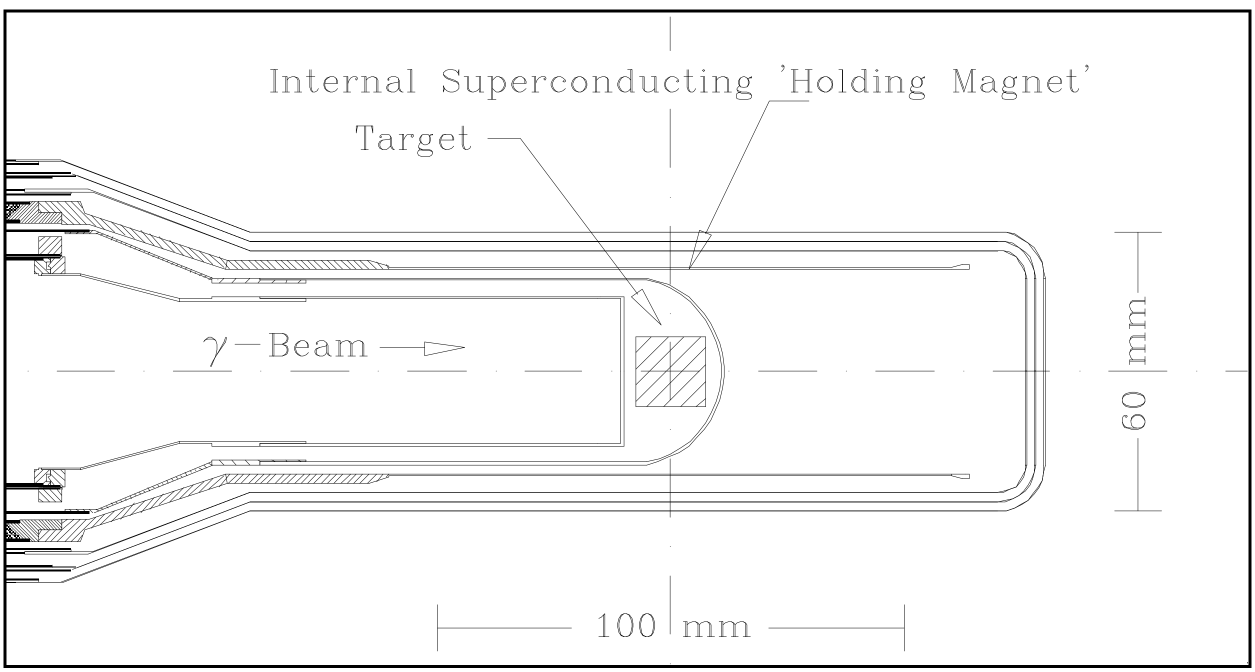

Figure 2. Polarized target used in the Mainz GDH experiment. The target is located inside the internal superconducting solenoid at the end of the dilution refrigerator.

200-400 mK with $\leq$50 mW cooling power when polarizing. A possible scenario for obtaining such a refrigerator has been proposed by the University of Virginia group.*

Movement of the refrigerator or polarizing magnet within CLAS will be required in order to transfer the target from the strong polarizing field to the weaker holding field. A number of magnetic configurations are possible, the optimum arrangement depending on the experimental requirements and whether transverse polarizations as well as longitudinal are required. Options for the holding field include positioning the target in the fringe field of the polarizing magnet, or installing a small holding coil inside the refrigerator like the one used in the Mainz GDH experiment[16,17,18] (Fig. 1). A general review of present-day polarized target technology is found in Ref. 18.

In summary, a frozen spin polarized target can be constructed for operation in CLAS, using a dilution refrigerator together with a 2.5 T polarizing magnet and a holding field of ~0.5 T . Microwaves at 70 GHZ would be used to polarize, and a standard Liverpool Q-meter would measure the polarization. For a butanol target, initial proton polarizations of about 90% are achievable with hold times of up to 200 hours, while deuteron polarizations for deuterated butanol could reach 50% with longer hold times. This target system could efficiently be produced by a collaboration between UVA and the Jefferson Lab target group.

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* The University of Virginia (UVA) has the capability of providing such a refrigerator which can be assembled from major components currently in its laboratory. This dilution refrigerator was fabricated at CERN but never assembled; however, three others of the same design have been used very successfully in other experiments at the CERN PS and LEAR [J. Zhao *et al.*, Nucl. Instr. and Meth. **A 356**, 133 (1995); H. Dutz *et al.*, Nucl. Instr. and Meth. **A 356**, 111 (1995)

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