FINAL-DRAFT-Committee Report-FINAL-DRAFT
Director's Review of MOLLER (E12-005-009)
Jefferson Lab
Jan 14-15, 2010

I. Overview

This report summarizes the Review Committee's findings and recommendations of the MOLLER proposal, E12-005-009, resulting from a two day meeting at Jefferson Lab, January 14 - 15, 2010. The Committee members, the agenda, and the Director's Charge to the Committee can be found in the appendix. Although the scientific relevance and goals were part of the discussions, this review was primarily focussed on technical issues with the intention of establishing feasibility and impact on the lab.

The MOLLER proposal requests approximately 40 weeks of running at 11 GeV in Hall A at 75 μA. The running would be broken up into more than one period because the overall length exceeds what is usually available in a calendar year. The proposal is the first to request use of the 12 GeV Upgrade beam in Hall A. The MOLLER experiment would use the polarized electron beam on a liquid hydrogen target to study the scattering of the beam electrons off the target electrons (the Møller process). It seeks to measure the electroweak effects, characterized by the weak parameter $\sin^2\Theta_W$, to high precision. The precision would match the precision of the same parameter measured at the Z-pole, but at a much lower center-of-mass energy. MOLLER is sensitive to a number of conjectured beyond-the-Standard Model processes through interference with known processes responsible for Møller scattering. These effects would not be seen in the Z-pole measurements where the interferences are absent. Thus MOLLER, by exploiting the best qualities of the Jefferson Lab electron beam, brings new information to bear on, and to constrain interpretations of, any new physics that may result at the LHC and elsewhere.

The MOLLER Collaboration consists of many individuals with considerable experience in previous polarized electron beam experiments. The Committee asked many detailed questions during the review. The responses were detailed and technically sound, exhibiting the depth of experience in the Collaboration. The Committee appreciated the responsiveness to our questions, and felt the Collaboration deserves a good measure of credibility. The Committee could find no technical reasons the goals of MOLLER could not be reached. The MOLLER Collaboration for its part was quite optimistic it would achieve the goals in the proposal. Based on the importance of the physics and the competence of the group, the Committee felt the project should move forward. However we note that although the Charge requested that we *"Review the understanding and credibility of the resources requested….",* detailed cost and schedule information was not presented at a level that would allow the Committee to validate the Collaboration's estimates at this time.

Recommendation: The Review Committee unanimously recommends that the Director undertake planning for MOLLER now, to be ready for the 12 GeV Upgrade era.

II. The Review Committee's considerations, comments, and other recommendations

This Review was the first to delve into the more detailed technical issues of MOLLER. Although some aspects of the apparatus are at this point purely conceptual, the overall general strategy and design stem from earlier experiments at SLAC (E158, successfully concluded in 2005) and JLAB (G0 and HAPPEX I and II). E158 studied the Møller process at higher beam energy (48 GeV) and achieved a successful measurement, but with considerably larger errors than are proposed for MOLLER. G0 and HAPPEX I and II studied parity violation (PV) off nuclei using the 6 GeV polarized electron beams at JLAB. The excellent beam at JLAB, combined with an optimized detector for Møller scattering in Hall A, would allow reducing the experimental error by a factor of ~30, and the corresponding error in $\sin^2\Theta_W$ to 0.1 %. This would be comparable to the earlier Z-pole measurements from LEP and the SLC. The proponents of the MOLLER proposal, who have a large overlap with the E158, G0, and HAPPEX, bring a detailed understanding of the techniques and the issues that contribute to the systematic errors of the measurements. Some of these individuals also are active in PV experiments which are planned to run in the near future before the 12 GeV Upgrade occurs. The MOLLER collaborators expressed confidence in their ability to reach the proposal's goals. Nevertheless, MOLLER is a very challenging project. It pushes the JLAB capabilities to its limits. No one expects MOLLER to be successful without a great deal of work and careful attention to many details. The members of MOLLER seem ready and anxious to get started.

The Committee asked probing questions during the one-and-a-half days of presentations. The following summarize some of the main considerations, comments, and recommendations.

a) The Spectrometer

The spectrometer magnets consist of two toroidal fields generated by warm-coil windings covering the full azimuth centered on the beam line. The first of the two magnets is a very simple design, so little concerns were expressed for this magnet. The second magnet involves a novel design to produce the required non-uniform field for focussing.

The committee was presented with a pre-conceptual design of the coil geometries. Due to the high photon radiation load expected in the MOLLER experiment, the coils are of conventional construction envisioned to employ water cooled copper conductors. The geometry of both coils is toroidal with seven fold symmetry. The coils are located behind collimators and shielding to protect them from radiation damage. The open portion of the spectrometer accepts both forward and backward Møller electrons such that the spectrometer azimuthally has full acceptance.

The coil geometry described to the committee and used for the simulation has not received any significant amount of engineering. The coil design should be looked at by a magnet design engineer rather than just GEANT simulators. The coil designs shown did not have realistic radii of curvature nor were some of the 3-D design issues addressed. A region with "negative curvature" was shown in the outside of the downstream toroid that was intended to better focus the Møller electrons. Such features complicate the coil geometry increasing the cost with little benefit. It seems likely that overall design can be simplified, particularly the downstream toroid. Modern magnetic design programs (e.g. ANSYS) could be used to optimize the coil geometry and current distribution for optimal focus of the electrons from Møller and elastic ep scattering while maintaining reasonable coil design parameters. Splitting the coils such that half of the amp-turns were near each open aperture (ie., 14 vs 7 coils) would likely improve uniformity of integral Bdl versus azimuth φ, without adding significant cost, etc. The assumed current density 1100 A/cm^2 seems on the high side and not optimal for a DC magnet that would run for years (ie., tradeoff of capital cost versus operating cost.) The typical design parameter FNAL uses for accelerator or analysis magnets that need to run for years is usually more like 400 A/cm^2.

It was stated that a Monte Carlo, combined with data, will be used to calculate the Q^2 acceptance of the detector elements and that this needed to be known to 0.5% The measurement methodology and corresponding accuracy required for the magnetic field map was not described. The geometry of the toroid magnets, especially the downstream one, is unusual. The coils will require support structures to withstand magnetic forces and must be designed to operate in a high radiation area for several years. Because of the unusual geometry and radiation damage issues, costs probably do not follow simple scaling laws (e.g. B^2 x volume) from other magnets.

In the absence of some sort of preliminary engineering design it is difficult to understand how they arrived at the cost estimate shown and the associated uncertainty.

Spectrometer Recommendations:

1. **Engage rather soon an experienced magnet engineer to work closely with the physicists on the development of the spectrometer magnet designs and to estimate associated costs.**
2. **Conduct formal technical design reviews by an external panel once more detailed designs are developed.**

b) The Target:

The target, while challenging, is an extension of previous targets and the Collaboration builds upon both the designs and the personnel from these previous targets. The experience that will be gained in the Qweak target is particularly important. The use of Computational Fluid Dynamics (CFD) modeling for target design is innovative but still untested. However, as this approach was used in the Qweak design, experience from this experiment can be used to help benchmark the CFD analysis. Correctly predicting the details of the generation of small bubbles within the liquid hydrogen is probably the hardest task to accomplish. This aspect will have to be watched carefully in the MOLLER experiment. No obvious showstoppers in the conceptual approach to the target are seen, nor is the need seen for any significant changes in approach. The target design is still conceptual and a very significant amount of detailed engineering is required to complete the design. This work needs the appropriate amount of schedule and resources to be successful.

Target Recommendations:

1. **Assume that MOLLER will need the equivalent of 2 full time engineers and 2 – 3 full time designers per year to carry out the target design.**
   These numbers can probably be reduced later once the final designs are accomplished. Note that in our opinion Qweak did not have sufficient engineering and designer support at the beginning.

2. **Ensure that sufficient time and effort is expended in the Qweak experiment to generate all the data needed to help verify the MOLLER target design.**

3. **Conduct formal technical design reviews by an external panel once more detailed designs are developed.**
   It would be particularly useful to do this once the Qweak experience has been fed back into the MOLLER target design. Safety aspects of the target design should be included in these reviews or in a separate dedicated review.

c) Cryogenic Capacity Comments

The target will take a significant amount of cryogenic capacity. The amount of capacity proposed (5182 W at ~ 20 K) seems about right based on what is known at the moment. However, to be conservative and to allow for operating margin and future problems, this should be multiplied by 1.2 (E158 had this level of cooling contingency) for a total capacity of 6.2 kW at ~ 20 K.

The proposal to use the existing transfer line with the altered use of the pipes to provide the target cooling appears to be a reasonable concept.

The amount of estimated cryogenic capacity required for halls B&C (1.3 kW) is more than the existing ESR capacity (1.2 kW).

Cryogenic Capacity Recommendations

1. **Carry out the planned review of the entire cryogenic capacity of the JLAB and its implications for the MOLLER target, Halls B&C and future experiments.**
   (Note: This appears to be underway soon)

2. **Provide at least 6.2 kW at ~ 20 K for the MOLLER target. This could be done via a new refrigeration plant or by connections to excess capacities of**

existing plants.
The solution will likely flow from the JLAB cryogenic capacity study above.

d) Beam systematics:

Successful implementation of the MOLLER experiment requires that properties of the electron beam be identical to a very high degree in each helicity state. Variations in beam properties (e.g., current, position, size) for the two spin states, are referred to as helicity correlated beam asymmetries (HCBAs). All HCBAs originate at the Pockels cell, an electro-optical device used to create left and right circularly polarized laser light. HCBAs could be zero if the Pockels cell produced perfectly polarized light, however Pockels cells are not perfect – the electric field within the cell is not uniform, the dimensions of the cell differ between each state, piezo-electric behavior causes them to "ring", etc. These realities, combined with a birefringent vacuum window and photocathodes with QE anisotropy, are the source of HCBAs.

The HAPPEX collaboration has made good progress understanding the subtle effects of Pockels cells, and they have developed an alignment procedure to minimize "first order" HCBAs, charge and position asymmetry. Careful Pockels cell alignment, combined with feedback adjustments to Pockels cell voltages, Pockels cell x/y position and the orientation of a downstream rotating halfwave plate provide the means to null these HCBAs, seemingly to the extent required by MOLLER.

Past experience conducting PV experiments has been with Pockels cell flipping at 15Hz (corresponding to 30 Hz clock rate), and with some tests at 500 Hz. MOLLER proposes to increase the flip rate to 1 kHz (2 kHz clock rate) to control anticipated target density fluctuations. Increasing the Pockels cell flip rate will require modification to the fast opto-switch constructed at JLAB, namely to obtain faster rise and fall times and with relatively stable final state voltage, to avoid a significant deadtime and to avoid introducing unintended HCBAs.

After carefully aligning the Pockels cell, HCBA residual effects can still remain. These are controlled by auxiliary spin flips consisting of 1) periodic insertion of an optical halfwave plate upstream of the Pockels cell; 2) reversing the direction of the field in a solenoid in the double Wien filter rotator at the injector; 3) g-2 rotation of spin by 180 degrees by a small change of beam energy. To date, only the insertable halfwave plate technique has been employed. The g-2 precession technique was successfully employed at SLAC during E-158. It is not yet known if the double Wien filter will provide the extra cancellation of HCBAs, particularly the HCBA related to beam size variation. Time will possibly tell; exercising the double Wien filter is anticipated during PREX and Qweak.

The beam quality appears good enough today to meet the MOLLER requirements. The high precision specified in the MOLLER proposal comes largely from the long running time and use of active feedback on the charge asymmetry. This assumes that the 1 kHz flipping (2 kHz clock) can be accomplished without introducing new HCBAs. Optical bench tests are ongoing at the University of Virginia to study the effects of rapid pulsing of the Pockels cell. In the opinion of the Committee, these tests are critical to the overall success of MOLLER, and should be rigorously studied. Note: the other experimental halls must be able to accommodate faster Pockels cell flipping too, since the same Pockels cell is used to generate polarized beam for all halls. The collaboration should discuss with neighboring hall leaders the implication of faster Pockels cell flipping on their future running plans.

Measuring ground loops and helicity correlated electronic pickup will be extremely important.

Operational stability at the injector is very important. Improvements at the injector are continually underway. JLAB needs to be able to achieve desired beam quality in a relatively calm, reliable and reproducible manner, otherwise MOLLER risks burning out key accelerator staff. Very loosely, based on past experience, the ability to conduct more demanding PV experiments has gone hand-in-hand with implementing non-trivial photoinjector modifications: improved gun vacuum and designs, improved spin manipulator, new photocathodes with smaller analyzing power and higher polarization, and stable and more powerful drive lasers with better spatial mode quality.

The following photoinjector modifications would help:

1) Improve photogun vacuum to improve lifetime and minimize deleterious HCBA effects related to “QE hole” .
2) Increase photogun bias voltage to improve transmission through injector apertures A1, A2 and chopper master slit. Especially important with respect to the charge asymmetry specification (i.e., beam scraping on apertures is very bad for charge asymmetry).
3) Install an improved ¼ cryomodule (CM) with appropriate HOM damping to eliminate the x/y coupling introduced on the beam by today’s ¼ CM. Today’s “flawed” ¼ CM limits the ability to obtain theoretical maximum adiabatic damping and small HCBA position asymmetry.

The Source Group is working on items 1 and 2, with a timeline appropriate for MOLLER. Item 3 is more difficult and not presently funded.

Some specific comments on helicity correlated position asymmetry: It is unlikely MOLLER will get the anticipated adiabatic damping mentioned in the Proposal (factor of 100 reduction in helicity correlated position asymmetry measured at the source). Emittance damps as beam accelerates through the machine, at least when the beam envelope is properly matched across accelerating sections. But above ~ 8 GeV beam energy, the beam will suffer synchrotron radiation which will negate damping on some level. Fortunately, MOLLER's HCBA position asymmetry specification is not too demanding (0.5 nm run average). Electrically isolated steering magnets at the 5 MeV section of the machine could be used for active feedback on position asymmetry.

Recommendation: The collaboration should consult the Beam Physics Group for help understanding the ill-effects of synchrotron radiation, particularly with regard to position asymmetry. Evaluate the issues related to the "flawed ¼ CM" and whether an upgrade is required for MOLLER.

Note on Compton Polarimeter and quest for 0.4% polarimetry:

The accelerator operators have a hard time steering beam through the today's Hall A Compton polarimeter and maintaining low background rates. Energy tail seems to be the biggest culprit, which could be worse at 11 GeV. A redesign of the apertures and Compton vacuum chamber seems warranted – but not proposed. RF-pulsed lasers with high peak power could really help (no mirrors, no shielding apertures required near the beamline, etc.) This should be pursued, and could easily constitute an R&D project that could begin today.

Recommendation: The Collaboration should make a careful evaluation of the Compton Polarimeter and recommend modifications required to remove known problems.

e) Detector Issues:

The weak decay backgrounds are a very serious concern for this Committee. Notwithstanding the relatively small asymmetry measured by the back detectors in E158, understanding the potential size of the contribution of these events to the main detectors in this experiment is critical. Detailed Monte Carlo is required, considering some events that are not measured in the back detectors and events from scattering off the apparatus structure will be particularly important.

Soft backgrounds are major concern. The 17.5% radiation length target will generate a large soft photon spray. Collimation of this spray will be critical. The design of the collimators requires an accurate detailed understanding of the location of all spectrometer and detector elements. The Committee was told that "most" of the one-bounce trajectories would be intercepted by collimators. What about the rest? An ideal design would intercept ***all*** one-bounce trajectories.

There should be very careful attention paid to staging and developing the capabilities that will be required – especially for items that will change at 12 GeV (polarimetry, polarized beam development - especially adiabatic damping). For this type of precision experiment, we often think of how many times we will have to actually make the measurement to make it correctly. There has to be time for the experiment to figure out how to get to the next level in systematic uncertainties.

The most likely failure mode is a systematic uncertainty at the 2-4 ppb level.

f) Manpower, costs, and planning:

The group's experience relevant to the proposed experiment is comprehensive. The review was well organized and thorough and, importantly, did not shy away from addressing difficult or unresolved issues whether these issues involved physics, measurement plan, personnel, resources needed from the Lab, or cost and schedule. The group members have been significant or lead participants in all recent PV efforts and ongoing ones (E158, PREX, Qweak). The review touched on questions of physics, background, apparatus, uncertainties, simulation and needed running time and in each case the group had a definite statement or an understanding of the remaining issues that allowed them to formulate a plan to resolve the issue. This does not mean all matters are laid out to satisfaction, by no means, but does suggest the collaboration has the core resources to formulate concept and address matters of technical choices, detector prototyping, open background questions, analysis approach and controls, and the needed project and personnel planning that a new effort of this scope will require. The sustained effort on prior projects and invested in those experiments such as PREX and Qweak which are only now being mounted does suggest that the collaboration understands and accepts the lengthy timescale and sustained effort that will be required. There are areas where expanded skill sets and engineering support are needed and also where broader exposure to formal project planning will be needed as the experiment goes forward.

On the technical side the experience with sources, detectors, electronics and simulation work resulted in a thorough description of issues and planned solutions. The target clearly requires further development but will build on the experience soon to be gained with operating that for Qweak. Having persons available to focus on the computational fluid dynamics questions for the target and compare computed results to those of measurement for the Qweak target would benefit the design for the MOLLER experiment target and retire what are sure to be seen as central elements of the risk analysis for the experiment. There is less experience in designing magnets of the non-simple field shapes desired, and this is an area where added expertise will be needed in the future. Exposure to the requirements and expectations of DOE project management sooner rather than later will help set a realistic expectation for the experiment cost and timeline and prepare the project leadership for the coming extensive discussions with DOE leaders.

Experiments of the anticipated scale in recent times are classified as major items of equipment by the Office of Nuclear Physics and require approval by DOE headquarters, which can well be expected to require review at the level of NSAC or a subcommittee of NSAC. The collaboration benefits from senior members who have served on NSAC, the Long-Range Plan committee and other NSAC subcommittees and thus are versed in explaining and presenting their science to colleagues in other areas of the field. They also understand the continuing competition for resources, both at Jefferson Lab which must carry out the 6 GeV program to completion and ready the 12 GeV program, as well as nationally where many competing efforts are planned and indeed already advanced, with sustained advocacy for the physics and accountability for the planned (and, one hopes, eventually executing) project thus required from the collaboration and its leadership. One might consider making common cause with other advocates of experiments in the ‘fundamental symmetry’ area pursued by the Office of Nuclear Physics; such efforts now include the double beta-decay searches, the electric dipole moment searches, neutrino properties and oscillation measurements, and measurements of electroweak properties.

There is a reliance on PREX and Qweak as test beds for MOLLER, as well as a reliance on a certain degree of success of those experiments in reaching projected sensitivities. It would benefit MOLLER to identify key personnel now working on those experiments who would (or at least could) perform similar duties for MOLLER and lay out a plan for how they would transition from present to needed duties. One observes a certain large degree of overlap of personnel on the different experiments. Thus a discussion to be expected with colleagues and funding agencies will need to address how involvement in current experiments is ended gracefully in the future, in such a way as to complete the earlier experiments and gain the needed expanded expertise in controlling uncertainties, but also in such a way as not to starve MOLLER of needed design manpower over the next 2-3 years when the baseline for the effort must be established and successfully defended to DOE. The earlier this is mapped out by the collaboration leadership and presented to the Lab and the DOE, the better. Such a plan could serve soon as a basis for discussion with the agencies about e.g. targeted hires at the postdoctoral level to address central areas of concern for MOLLER. Absent such a plan, in a stringent budget climate, the expected funding agency response is just to redeploy existing personnel, which saps the needed work on the present experiments.

The collaboration enjoys the participation of many or most experts in the PV field. One might consider deliberately recruiting collaborators from outside this community who can think outside the box and avoid “group think”. It would be valuable to have colleagues examining the experiment proposal “from within” without the experience and thus importantly perhaps without the mind-set of prior experiments.

University and Lab contributions appear to be in good balance. There is an impressive list of collaborators; an effort to broaden this to outside the USA would be prudent, with first steps taken with the Mainz group. This also provides a route to prepare the needed scope of the experiment without resorting only to reliance on DOE resources. Given the desire to keep expected costs well below the $20M line of demarcation, the collaboration should seek to develop such contacts further.

On the matter of costs and thus needed resources, the collaboration should be as comprehensive as possible in presenting possible needs to the Laboratory. Cost information presented to the Committee was very sketchy and the claim of $16 M cap was not supported by the information supplied to the committee. In due time this will need more detail and a better basis for the estimate. It would be a major mistake to let a perceived need for cost containment at this early stage lead to overly optimistic assumptions about cost, schedule and manpower needs. Without engaging in recounting specific anecdotal tales of the difficulty in finding critical resources with little lead time, we note that the better the Laboratory understands the full scope of the experiment’s needs and their duration, the better it is able to advocate for them, find serendipitous solutions for some, and allow the DOE the unavoidable two or more year lead time to (re)allocate resources to MOLLER. The cryogenic needs of the experiment were discussed at the review, with the benefit that they can soon, even now, be folded in to the needed much larger planning exercise for cryogenics the Lab must do now in light of ongoing efforts and construction projects. The Laboratory has a formal project management group which can advise and assist the collaboration on the navigating the DOE Critical Decision series and establishing a defensible baseline plan, as well as in familiarizing them with formal risk and contingency analysis, which are essential for funding approval.

A few comments on timing may be of use. DOE might establish CD-0 (mission need) for MOLLER in 2010 or 2011. A technical choice and cost range, CD-1, might follow in 2011 or 2012. If the scale is under $15M or thereabouts, a combined CD-2 (baseline) and CD-3 (start of construction) or at least CD-3a (start long lead-time items) might follow in 2012 or 2013. The Laboratory does have formal plans for a 6-month shutdown in May-October 2011 and a 12-month shutdown in May 2012-May 2013, during which 12 GeV project efforts must proceed apace to realize that effort's baseline plan. The overlap of timescales and thus competition for limited engineering and technical resources is evident. This is not cause for alarm or despair but it is definitely cause for realism and for activism by the collaboration's leadership to seek outside resources where possible, to move the planning and design for MOLLER along in a timely manner.

III Responses to the Charge:

1. Review the relevance and potential risk to the physics case. This should include:

1a. The completeness and credibility of the proposed error estimate:

The committee considered both the proposed statistical and systematic uncertainties. The asymmetry in the proposed experiment is about 1/5 that of the smallest so far measured in electron-scattering parity violating experiments (E158 Møller at SLAC – carried out by much of the same collaboration) and about 1/40 of the smallest measured so far at Jefferson lab (also many of the same people). The proposed uncertainties for the new experiment represent more than an order of magnitude improvement in the uncertainties published by the E158 collaboration. We believe they represent very ambitious, but appropriate, goals for the next generation of such measurements. In the following, we comment separately on the statistical and systematic uncertainties.

The goal for the measured statistical uncertainty is 0.54 ppb, or 2% of the measured asymmetry of about 28 ppb (assuming 80% polarization). This is accomplished with about 5450 hours of running at a beam current 75 μA, a liquid hydrogen target with a length of 150 cm and a spectrometer with an acceptance of nearly 1 msr at forward scattering angles of $0.3\text{-}1^{o}$; the collaboration expects an effective overall running efficiency of about 50%, leading to calendar running time of roughly 65 weeks for the core data-taking.

Based on the experience of several previous parity violation experiments in both integration and counting modes, we believe it is reasonable that the contribution of counting statistics to the statistical uncertainty scales as $1/\sqrt{N}$ as presented. There are a number of other potential contributions of noise to the overall statistical uncertainty: target density fluctuations, beam charge measurement, photon statistics in the main Cherenkov detectors and noise in the data acquisition electronics. Each was addressed in the presentations; we believe the most likely source of additional uncertainty is from density fluctuations in the target. We applaud the developments in the modeling of the target using computational fluid dynamics, including the inclusion of a mechanism to model liquid boiling. It will be important to continue to develop this model; in particular, benchmarking against results from the Qweak target. Although such studies are important, the measurement and extrapolation of density fluctuations in the Qweak target are the key to ensuring the density fluctuations for the MOLLER experiment do not contribute significantly to the statistical uncertainty (as anticipated in the proposal). Achieving the desired 10 ppm resolution in the cavity charge monitors appears to be straightforward as they are presently detuned from their maximum Q in order to broaden their response and reduce sensitivity to thermal drifts (which are much less important for this asymmetry measurement than for, for example, precision cross section measurements). We agree that the other noise contributions from the detectors and electronics are likely to be smaller and therefore not significant.

Systematic uncertainties are the most likely to be underestimated. We are particularly concerned about the measurement of beam polarization, Q^2 , and backgrounds. Although the helicity-correlated uncertainties bear careful attention, we expect these specifications will be the easiest to meet. In all cases, specific teams of collaborators focusing on each of these areas will be required.

Of the three devices proposed to measure beam polarization, Compton, and ferromagnetic and polarized hydrogen Møller polarimetry, the system most likely to reach the required uncertainty of 0.4% is the Compton polarimeter. However, a significantly more complete understanding of acceptances and backgrounds will be necessary to reliably reach the goal. New effects from the upgrade to the doubled (532 nm) laser and the increase in beam energy (and likely changes in beam background, shape, etc.) will each require substantial effort to understand. Some effort should be put into improving the understanding of the existing iron Møller polarimeter as a cross-check; a hydrogen Møller polarimeter would be very valuable, but represents a large R&D program of its own.

The uncertainty in Q^2 is listed as the largest single systematic uncertainty. A very preliminary sketch of how Q^2 will be measured was presented, but at the current level of the magnet design it isn't possible to demonstrate the uncertainties. The Q^2 measurement will clearly require careful characterization of the as-built system of collimators and magnetic fields in conjunction with data and a thorough simulation. Particular attention to the effects of the very long target and its varying acceptance will be required. Measurement to 0.5% of Q^2 in the Qweak experiment will provide a valuable platform from which to develop the techniques necessary here.

Backgrounds are likely to dominate the final systematic uncertainties as anticipated in the table presented by the collaboration, and as they did in E158. Of necessity, the main detector system is relatively simple and provides limited possibilities in hardware for distinguishing Møller electrons from background. In addition to dilutions from photons and to the ep-related backgrounds with their multi-ppm level asymmetries, we are most concerned with decay products from hyperons. Although the total production cross sections are at the μb level (as compared with the 45 μb Møller cross section), the weak decays have asymmetries of order one, and have large polarization transfer coefficients in the energy range currently measured. We expect a significantly more sophisticated auxiliary detector system will be required to demonstrate the level, and possibly the asymmetry, of background contaminations. We further expect it will be necessary to characterize directly the main detector response using the auxiliary system in special runs. Such a detector system would have to be developed in close association with a detailed simulation of the experiment. We agree with the collaboration goal of a maximum 10% correction to the Møller asymmetry from backgrounds – it will be a challenge to demonstrate.

Recommendation: The Collaboration should devote particular attention to the background detectors until satisfactory solutions to the problems described above are found.

The Collaboration has a good plan to address the challenges of helicity-correlated false asymmetries. The required monitor resolutions appear to be within striking distance with changes to BCM electronics (running closer to resonance) and perhaps an increase in the BPM cavity Q value (taking advantage of Hall B style Cu-coated cavities). The beam fluctuation requirements seem likely to be met with no changes, although potential changes in beam properties resulting from the energy upgrade from 6 to 11 GeV should not be underestimated. Careful work on both beam current and position feedback are likely to be required to meet the stringent run-averaged goals, especially for position and angle. It is critical that the accelerator be able to provide near the theoretical maximum adiabatic damping to reduce the helicity-correlated position uncertainties in the polarized source. Three electronics-independent flips (insertable half-wave plate, double Wien and g-2 precession) are provided to eliminate so-called second order beam effects. Some effort will be required to ensure all potential sources of, for example, helicity-dependent beam size effects (only some of which reverse with the insertable half-wave plate) are accounted for. Finally, the transverse asymmetry, a factor of about 100 larger than the PV asymmetry, will provide a very helpful cross-check in test situations where various helicity-correlated effects can be artificially amplified and then measured relatively quickly (although a direct cross-check at the 1 ppb level is not possible, not least because of running time limitation).

b. The implications for the relevance of the result should the ultimate error

exceed that in the proposal.

The proposed MOLLER experiment aims for a +/- 2.3% measurement of the parity violating left-right asymmetry in polarized ee scattering. At that level it would improve the low energy determination of the weak mixing angle by about a factor of 5 over experiment E158 at SLAC. The error would then be comparable to the best Z-pole studies at CERN and SLAC as well as the indirect determinations found from combined precision measurements of alpha and the Fermi constant, along with W and Z boson masses. Comparison of those distinct weak mixing angle values would test the Standard Model at the level of its electroweak loop corrections and probe for new physics effects, such as Z' bosons, extra dimensions, supersymmetry, strong dynamics etc. with sensitivity complementary to the LHC. The proposal is, however, aggressive in its estimated statistical and systematic uncertainties and could be somewhat compromised. If, for example, the statistics are a factor of 2 lower than expected and the systematic uncertainty turns out to be larger by a factor of 2, the overall error in the asymmetry and weak mixing angle would increase by about 50%. Nevertheless, it would still be the best determination of the weak mixing angle at low energies and would continue to provide an important probe of new physics. The scale of Z' bosons, extra dimensions, higgs scalars, compositeness, etc. probed would be reduced by 25% while sensitivity to some manifestations of strong dynamics (eg. S & T parameters) would be reduced by 50%. Those reductions would be unfortunate, but not disastrous. Since the experiment is expected to be statistics limited, it is important that efforts be made to attain or exceed the requested statistics. The lab should make every effort to provide the requested running time and the collaboration should strive to improve their data taking efficiency.

2. Review the viability of the approach used in the project with respect to the general experimental technique proposed to measure the weak mixing angle. This should include the evaluation of credible plans for:

a. R&D required to meet the technical challenges of the experiment.

The MOLLER proposal is largely conceptual at this time, based on previous experience. Most of the systems need concrete designs; some of the systems need more fundamental considerations before design can be started. Some R&D may be needed in most systems before design can commence. The list below covers the major systems.

(1) The **spectrometer** consists of two warm-coil toroidal magnets, one being quite conventional, and the second one being of some concern.

The spectrometer needs a magnet engineer early in the project to take the initial concept and implement the ideas while conforming to realistic constraints.

The engineer should optimize the various tradeoffs and coordinate closely with the physicists who calculate field geometries, track particles, and can validate the resulting optics.

(2) The **target** is a reasonable extrapolation from previous targets. Experience from

the Qweak target will be very useful. An engineer experienced in high power targets and familiar with CFD code should be responsible for the target design at an appropriately early time so that costs can be evaluated. Density fluctuations are a considerable concern, and the need to minimize these has resulted in increasing the beam polarization flip rate to 2 KHz. This rate needs careful attention. It affects the Pockels cell, and the detector electronics, and possible beam monitoring. Beam tests should be done, dedicated to studying the high rate flipping of the Pockels cell.
(3) **Detectors** are well understood from many past projects and lab/university R&D activities. However specific choices need to be made, and prototype examples need to be constructed and put through tests. Both integrating detectors and tracking detectors are being proposed. The integrating detectors need to satisfy light collection, gain, linearity, noise requirements. The **tracking detectors** are not yet defined. Once these are designed, the responsible persons and institutions must undertake building prototypes and testing them for meeting all the specifications.
(4) A **Pockels cell** lies at the heart of the experiment. Fast pulsing to reverse the laser beam polarization is anticipated. Studying the Pockels cell and the related effects on the laser beam is underway on an optical bench at the University of Virginia.
(5) Polarimetry - The current state of the **Compton polarimeter** is probably adequate for reaching the 0.4% accuracy needed for MOLLER. No major changes are needed. The bending angles of the Compton system must be reduced to accommodate the 11 GeV beam. Some discussion of a RF pulsed laser was presented. The advantages for changing to a RF pulsed laser would be a larger crossing angle and larger beam apertures, reducing the possibility of backgrounds from possible beam halo at 11 GeV, arising from increased synchrotron radiation effects. An **RF pulsed laser** would require some R&D activity.
(6) **Møller polarimeters** come in two types, the ferromagnetic alloy target, and the atomic hydrogen target. Current accuracy of the ferromagnetic alloy target in Hall A is 2%. Careful attention to details could reduce this to 0.8%. Converting the Møller system to a 3 T solenoidal field and a target foil perpendicular to the B field (like Hall C) could achieve 0.5%. Some R&D would be needed to achieve this.
(7) The **atomic hydrogen Møller target** is conceptual at this time. It would use a 100% polarized atoms with a storage cell in a 8 T solenoidal field to achieve a density of $3x10^{15}$-$3x10^{17}$ atoms per cm^{-3} and with the electrons 100% polarized. Systematic effects would be greatly reduced, and an accuracy of 0.35% is projected. The atomic hydrogen target could reside continually in the 11GeV beamline without affecting the MOLLER experiment, thus providing continual polarization monitoring. Considerable R&D would be required to bring this concept to reality.
(8) **Charge Monitors** contribute directly to the asymmetry measurements. Charge asymmetry is a major concern. Extensive data from previous experiments exist. In the upcoming experiments Qweak and PREX, charge asymmetries will be closely watched. The lessons learned and positive developments will be applied to MOLLER. These may include improvements in the RF electronics, increases in cavity Qs, and possibly adding ferrite-core toroid monitors. However, based on the present monitor performance, active feedback and long data runs should already achieve convergence to the 10 ppb MOLLER goal.

R&D recommendation: The MOLLER Collaboration should prepare a comprehensive R&D plan.

Not all of the R&D activities are specific to MOLLER. The R&D plan should identify those needs that are specific to MOLLER, and those that are generic to beams for other experiments. The "plan" needs to be not only a list of work to be done, but also discuss the people, money, and time involved. Involvement of the various collaborating institutions would be important and essential.

b. Proposed magnet concept and choice.

The Committee discussed this in some detail. See Section II a.

c. Cryotarget target system concept.

The target was likewise discussed in detail. See Section II b.

d. Beamline design, including collimation and shielding.

MOLLER requires a high power 150 cm long liquid hydrogen target placed 7 meters before the HRS pivot center. No material can be tolerated in the beam, either before or after the target, to avoid unwanted backgrounds. Beam windows before or after the scattering chamber, except for the liquid hydrogen target itself, cannot exist.

An aluminum vacuum beam pipe extends from the target chamber to the beam dump. This chamber is approximately 2 x the diameter of the present beam pipe. Because of the forward location of the target, optical elements in the beam line before the target must be rearranged. New quadrupole elements may be required. New beam pipe segments before the target would be needed as well.

The long target creates high radiation levels. Concrete shielding around the target and along the beamline will be required. Preliminary concepts need to be validated through use of appropriate code. The concrete will be specific to the shapes of target and detector components of MOLLER, and will be designed to be readily moved in and out to accommodate other experiments in HALL A. Use of existing blocks will be used wherever possible.

Because of the forward scattering kinematics in MOLLER, the overall MOLLER system has the aspect ratio of a "pencil". Collimation must exclude all soft photons both by direct line-of-sight paths and "one-bounce" paths which can reach the active detectors. The current plans state that *most* "one-bounce" trajectories are blocked by judicious location of collimators. The collimator elements will be modest in size, but the location and alignment will be critical. Design of the collimators must await a detailed design of the magnets. The non-blocked one-bounce trajectories need to be identified and carefully studied; removing these "gaps" seems essential to the collimation scheme.

Some collimators will require water cooling. The total heat absorbed will be modest, but the cooling water must be on a closed system with a heat exchanger and a deionizer element in the loop.

e. Proposed detector concept and associated calibration/background measurements, including helicity-correlated and beam-target generated backgrounds.

The MOLLER detector concept is patterned after the E158 design with refinements appropriate to the differences in the Hall A experimental environment. The detector array is placed very forward, as required by the kinematics, and covers a radius of 0.6 to 1.2 m at a distance of 28m from the target corresponding to scattering angles in the range 4 to 19.2 mrad. The azimuth is broken in seven places, for the sake of supports and shielding, maintaining nonetheless a seven-fold symmetry. Azimuthal symmetry is the key to controlling systematic bias from helicity-correlated asymmetries, and a good coverage of ϕ is achieved through cleverly exploiting the fact that the beam and target particles are identical.

The Møller signal is too intense for traditional counting electronics, so an integrating technique is employed. The main detectors rely on Cerenkov photons produced in artificial fused silica detector elements, with the light guided to PMTs that are well shielded from backgrounds. The geometric arrangement separates the main ee and ep signals at different radii, for fixed bins in ϕ. Care is taken to minimize cross talk generated in the light guides. The electronics required to amplify the PMT signals are based on the boards made for Qweak, and do not represent a major challenge. Prototypes have been tested successfully.

The radiation dose on these detectors is very high; a total dose as high as 50 Mrad is anticipated. The detector materials must withstand this dose. The detector radiator material of choice is synthetic quartz, well characterized for radiation hardness optically. Experience with this material was good in E158. Qweak incorporates this style detector in its design, so Qweak will be an important cross check during its upcoming run.

The background, especially the radiative tail from elastic ep scattering, populates the detector in radius and ϕ in a way that differs from the signal. The granularity is adequate for assessing and monitoring this background, provided that the simulation has been tuned well. For this, the MOLLER team proposes to deploy special detectors to scan in radius at fixed ϕ, which will provide much more detailed view of the scattered electron flux. The scanning detectors are presently in the conceptual stage, and much more R&D work is needed to come up with a good design. The Committee suggested they augment the position-sensitive device with a precision electromagnetic calorimeter in order to obtain the scattered electron energy as a function of radius.

Other backgrounds from inelastic processes are a serious concern. They will be small, but may carry large asymmetries, and both the contamination and its asymmetry will be a priori unknown. Some information comes from measurements done in E158, but the Committee was not convinced that the MOLLER experiment, with its goal of measuring accurately a 30x smaller asymmetry, was safe from bias without direct and careful measurements of these backgrounds.

The MOLLER team discussed briefly placing a scintillator telescope and some thick absorber to identify pions produced inelastic processes. While this would be a step in the right direction, the conceptual design was extremely vague and there was little by way of simulation or estimation of the rate of pions to be detected or the efficiency of detection, and how they would be used to limit systematic biases. While there is little doubt that pions can be detected beyond a thick absorber, significantly more work is needed here before this aspect of the proposal can be considered seriously.

Target density fluctuations will be monitored using very forward detectors made of quartz – these are referred to as "luminosity monitors." These detectors must survive large radiation doses, on the order of 20 Grad, which is an order of magnitude higher than the luminosity monitors from Qweak. The design is not very advanced – some work is needed here.

Other concerns expressed by the committee relate to the alignment of the detectors and knowledge of the magnetic field (discussed elsewhere). The extraction of $\sin^2\theta_W$ from the raw asymmetry requires a precise knowledge of the mean Q^2 of the data sample, and this comes from simulation. The detector simulation must match reality very well in order to obtain a correct result. While experience from E158 is very valuable, the Committee recommends that more thought be put into techniques for determining the alignment of all detectors, shields and collimators and on constraining systematic uncertainties on the mean Q^2 of the data.

f. Beam polarimetry requirements.

The goal of the polarimetry is to achieve three complementary measurements with comparable precision around 0.5 %. The three techniques being considered are Compton scattering, Møller scattering, and a cross check using the QED transverse asymmetry.

The Compton polarimeter would be similar to the existing one in Hall A, but upgraded. Magnets in the chicane would have to be moved to smaller bending angles because of the higher beam energy, 11 GeV. The Compton scattering process sends both electron and photons in the forward direction. Detectors would be arranged to intercept both electrons and photons and to analyze the asymmetries associated with each. A new laser operating at 532 nm will soon replace the existing infrared laser at 1064 nm. This should provide an immediate improvement. A yet newer pulsed RF laser is being considered. It would eliminate one window (a source of some uncertainty in the laser polarization) and open up the aperture for the electron beam (a source of some background). The Compton polarimeter would achieve an estimated 0.37% precision for the laser polarization from the scattered electrons, and a 0.47% precision from the scattered photons. (Note: The Compton polarimeter used at the SLD at SLAC, similar in concept, achieved a 0.5% precision after much work.)

The Møller polarimeter is being considered in one of two forms: (1) a 3T solenoidal field with a ferromagnetic foil oriented at 90 degrees has achieved 0.5% in Hall C. One possibility would be to upgrade the Hall A polarimeter to a similar design. Heating of the ferromagnetic foil is a problem, and rastering the beam is a potential solution. The design is estimated to realistically achieve 0.8% precision, and with R&D and some hard work could optimistically reach 0.5%.
(2) a 100% polarized atomic hydrogen gas storage cell could achieve 0.35%. The atomic storage cell could run continually along with the data collection, and the systematic problems, such as unwanted gas, are inherently small. However, much R&D would be needed to establish a detailed design and confidence in the projections for high precision. The R&D could likely be done by a university group, and UVA and/or Mainz are possibilities.

The third check on beam polarization comes naturally in the Møller process. Transverse asymmetries are accurately calculable in QED, and measurement of the asymmetries serve to analyze the beam polarization. Tuning of the beam spin to a transverse orientation is required. The asymmetries are large, so that only short runs are needed to achieve sufficient statistics. This process was successfully used in the E158 experiment at SLAC.

g. Any beam-induced helicity-correlated systematic uncertainties.

Measuring a physics asymmetry 30 to 40 times smaller than any measured before at JLAB, and with 10 to 20 times more precision, places big demands on helicity-correlated beam systematic errors. It was reassuring to hear the present beam quality is good enough (i.e., beam-induced helicity-correlated systematic uncertainties are sufficiently small) and that MOLLER will achieve the desired precision by running a long time. However the collaboration did not consider that above 8 GeV beam energy, there will be considerable synchrotron radiation generated in the arcs that will likely hinder their ability to obtain as much emittance damping as expected. As such, it might be difficult to obtain the stated 0.5 nm run-average helicity correlated position difference between the two spin states. And if the position of the beam cannot be maintained with desired precision, it would be difficult to achieve the stated run-average helicity correlated angle difference of 0.05 nrad between spin states. The impact of synchrotron radiation on helicity correlated beam systematic errors, particularly position and angle, should be considered in detail.

3. **Review the understanding and credibility of the resources estimated in both manpower and cost. In addition to the experimental apparatus, this should include:**

a. Experience, expertise and quantity of the scientific and technical manpower for the project.

These issues are addressed in Section II f).

b. Accelerator, Jefferson Lab refrigeration capacity and polarized source requirements.

Two issues relating to accelerator performance were raised during the review. The Proposal assumes adiabatic damping during acceleration to 11 GeV will substantially reduce the helicity-correlated position differences at the MOLLER target. This assumption may not be fully realized. The second concern has to do with increased synchrotron radiation at 11 GeV beyond what is seen at present. Beam halo may increase, leading to more scattering off windows and collimators in the beamline. Section II d) discusses these concerns and recommends that the MOLLER Collaboration consult with the Beam Physics Group during the development phases of MOLLER.

The cryogenic refrigeration capacity is addressed in II c). MOLLER should take an active role in the Lab's overall cryogenics capacity planning.
Considerations related to the photoinjector are discussed in II d).

The cost and manpower issues in support of MOLLER's requirements were not presented in any detail.

c. General experiment installation and alignment issues, including potential interaction with other Hall A programs and operations.

MOLLER involves very forward scattering, so the apparatus will be located close to and along the beam line in Hall A. The target is located 7 meters in front of the HRS spectrometer pivot, while the toroidal magnets and detectors are located downstream along the beam line ending close to the exit from Hall A. Optical elements for the incoming beam will be moved forward to accommodate the new target position. The Møller polarimeter would be integrated into the beam line forward of the target and compatible with the beam line optics. The cost of the exit beam line was estimated to be $335k; the cost for modifying the incoming line was estimated at $500k.

Concrete shielding is a major issue. Detailed design has not been done, but the overall concept and scale are fairly well understood. Unique shapes will be required, while existing concrete blocks will be used to the extent possible. The cost for new blocks and the manpower for installation were estimated at $930k, based on the experience with costs for Qweak.

Cooling of the collimators will be required; a closed loop LCW circuit with heat exchanger and a deionizer was estimate to cost $200k. The cost of the cryogenics for MOLLER was not given. Likewise alignment was not discussed, and the cost for that was therefore not given.

Interaction between MOLLER and other Hall A experiments was briefly mentioned. The target is remotely moveable; the internal elements can be raised out of the incoming beam, while the scattering chamber remains in place. Concrete blocks, where they interfere with HRS angles, will need to be removed.

Realignment issues for returning MOLLER to the beam line would be involved, but were not discussed.

Appendix:

a) **Committee Members**
b) **Charge to the Committee**
c) **Agenda**

Committee Members

Doug Beck
University of Illinois
ph: 217-244-7994
dhbeck@illinois.edu

Dave Hertzog
University of Illinois
ph: 217-333-3988
hertzog@npl.uiuc.edu

Bob Kephart
Fermilab National Accelerator Lab
ph: 630-840-3135
kephart@fnal.gov

Bill Marciano
Brookhaven National Lab
ph: 631-344-3151
marciano@bnl.gov

Matt Poelker
Jefferson National Accelerator Facility
ph: 757-269-7357
poelker@jlab.org

Charles Prescott (Chair)
SLAC National Accelerator Lab
ph: 650-926-2856
prescott@slac.stanford.edu

Michael Schmitt
Northwestern University
ph: 847-467-6593
schmittm@lotus.phys.northwestern.edu

Glenn Young
Jefferson National Accelerator Facility
ph: 757-269-6409
gyoung@jlab.org

John Weisend
SLAC National Accelerator Lab
ph: 650-926-5448
weisend@slac.stanford.edu