Department of Energy
Office of Nuclear Physics Report

on the

Science Review

of the

proposed Measurement of Lepton-Lepton Electroweak Interaction (MOLLER) Experiment

September 10-11, 2014

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Executive Summary

On September 10-11, 2014, the Department of Energy (DOE), Office of Science (SC), Office of Nuclear Physics' (NP) Physics Research Division conducted a Science Review of the proposed Measurement of Lepton-Lepton Electroweak Interaction (MOLLER) Experiment. The review was held at the University of Massachusetts, Amherst.

The MOLLER experiment aims to measure the weak mixing angle in low momentum transfer e^-e^- scattering, known as Moller scattering, to an absolute precision of (0.1%) of its value. The Moller process potentially can provide the most precise Standard Model (SM) prediction of all low energy electron scattering parity violating experiments. The theoretical cleanliness of this purely leptonic observable makes it unique among the low-Q^2 probes of the SM. Discovery of a deviation from the SM will have an enormous scientific impact, while confirmation of the SM will provide interesting and important constraints on new physics scenarios.

MOLLER's precision is comparable to that achieved in the best measurements of the weak mixing angle from high energy experiments at much higher momentum transfer. Given that a measurement can be performed at the proposed level of uncertainty, the measurement of a purely leptonic parity violating (PV) asymmetry is well motivated and the impact will be high. Specifically, because the theory underpinning this purely leptonic measurement would have a small uncertainty, the result of this experiment should serve as a benchmark which theoretical conjectures about possible new physics beyond the standard model will have to accommodate. If the measurement agrees with the SM prediction, it would serve to highly constrain speculative theories of new physics. It would be a convincing demonstration of the completeness of the understanding of the weak interaction to a very high degree. MOLLER would have a significant impact by adding a new data point to precision electroweak fits, leading to better sensitivity of the global fits. If, on the other hand, it significantly disagrees from the SM prediction, the experimental results would be used to help guide theoretical development of a new SM.

The uncertainty in the published SM prediction is sufficiently small compared with MOLLER's precision goal, although radiative corrections are very large for the Moller asymmetry. The state-of-the art SM predictions are in good shape but confirmation by another group and lattice calculations are suggested, and completion of the 2-loop corrections strongly recommended. Further studies of inelastic electron-proton and electron-Aluminum scattering backgrounds are also recommended.

MOLLER builds upon generations of parity violating electron scattering experiments that have been successfully carried out at SLAC National Laboratory (SLAC), Massachusetts Institute of Technology Bates Laboratory (MIT/Bates), Mainz, and Thomas Jefferson National Accelerator Facility (TJNAF or JLab). This community has dramatically advanced both the physics and the associated technology, and has accumulated experience over the past four decades. MOLLER at JLab would continue to push this frontier. The techniques required to carry out the measurement include advanced target development, polarized beam delivery and control, polarimetry, and spectrometer design.

Significant progress is evident in the design of the liquid Hydrogen target, which is based on modern computational fluid dynamic models; the novel design of the hybrid toroidal magnetic spectrometer is impressive. Addressing these technical challenges could advance the field of nuclear physics generally.

The experimental collaboration is strong with world-class experience in previous PV electron scattering experiments. The collaboration is bold in setting this new goal and, at the same time, thorough in examining possible systematic effects. The impact of the experiment relies on achieving the proposed level of uncertainty. While the panel members expressed confidence that this group is capable of carrying out the proposed experiment, the collaboration will need to attend to several remaining uncertainties that have not been fully addressed, such as the precision of the beam intensity monitors, the beam shape stability versus helicity, some detector performance assessments at high rate, an evaluation of the inelastic ep asymmetry, an accurate determination of the beam polarization, and an independent confirmation of the very precise radiative correction calculations. The planned measurements would require at least three full annual running periods at JLab plus an additional year in assembly and commissioning. This would require a stable level of commitment to this experiment throughout the decade long expected duration. The panelists believe the experiment has the potential to be a flagship effort for JLAB and the NP community.

Recommendations

- Complete the full two loop calculations of radiative corrections in order to document the theoretical prediction and submit a report to the Office of Nuclear Physics by September 15, 2016.
- Further studies of inelastic e-p and e-Al backgrounds should be reviewed and a report submitted to the Office of Nuclear Physics by December 3, 2015.

Introduction

On September 10-11, 2014, the Department of Energy (DOE) Office of Science, Office of Nuclear Physics (NP) held a Science Review of the proposed Measurement of Lepton-Lepton Electroweak Interaction (MOLLER) Experiment to be implemented at the Thomas Jefferson National Accelerator Facility (TJNAF). The review panel consisted of six external peer review experts: Dr. T. William Donnelly (Massachusetts Institute of Technology), Professor David Hertzog (University of Washington), Professor Charles J. Horowitz (Indiana University), Dr. Zheng Tian Lu (Argonne National Laboratory), Professor Maxim Perelstein (Cornell University), and Dr. Thomas Rizzo (SLAC National Accelerator Laboratory). The review was chaired by Dr. Timothy J. Hallman, Associate Director of the Office of Nuclear Physics and Acting Research Division Director for NP. Other attendees included Dr. Jehanne Gillo, Director of the Facilities and Project Management Division, and Dr. Gulshan Rai, Program Manager for Medium Energy Nuclear Physics.

Each panel member was asked to evaluate and comment on any relevant aspect of the proposed MOLLER Experiment. In particular, the purpose of this review was to assess all aspects of the project's plans—scientific, technical, cost, schedule, management, and environment, safety, and health (ES&H). The following charge elements were considered at the review:

- The significance of scientific questions identified by the MOLLER Collaboration and Thomas Jefferson National Accelerator Facility;
- The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities;
- The new experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program; and
- The feasibility of the approach or method presented to carry out the proposed scientific program and the likelihood that significant results can be obtained in the first three years of detector operations.

In addition, the panel was asked to consider the impact, if any, of detector implementation on the ongoing scientific program at TJNAF in any of the charge elements above.

The two-day review was based on formal presentations given by the proposal's proponents, separate follow-up discussions with the reviewers, and executive sessions. The second day included an executive session during which time the panel deliberated and prepared draft reports on their assigned areas of focus and ended with a brief closeout with the MOLLER experiment proposal proponents. The panel members were asked to submit their individual evaluations and findings in a "letter report" covering all aspects of the charge. The executive summary and the accompanying recommendations are largely based on the information contained in these letter reports. A copy of the charge letter and the agenda are included in Appendices A and B, respectively.

Significance

Findings:

The importance of the Measurement of Lepton-Lepton Electroweak Interaction (MOLLER) Experiment Q_W^e, interpreted as a unique low-energy measurement of the Standard Model (SM) weak mixing angle only involving leptons, was stressed in several presentations. The proposal aims to measure the weak mixing angle, denoted as $\sin^2(\theta_W)$, in e^-e^- "Moller" scattering to an absolute precision of 0.00027 (0.1%), a level that is competitive with direct Z pole determinations and far superior to off-Z pole measurements that rely on running of the coupling constant to lower energy. In addition, the Moller process has potentially the most precise SM prediction of all low energy electron scattering parity violating experiments. The potential impact on a variety of beyond the Standard Model (BSM) physics such as supersymmetry, doubly charged scalars, heavy Z's, and light Z's was presented. Furthermore, this measurement's sensitivity to new leptonic physics beyond the SM was emphasized.

Comments:

The panelists found this to be a very important opportunity to make a cleanly interpretable fundamental measurement. Furthermore, there will likely not be competing measurements with better precision, at the Z pole, in the proposed time frame. Testing the SM with increasing precision is extremely important, and discovery of a deviation from the SM will have an enormous scientific impact. If the measurement confirms the SM, it will provide interesting and important constraints on new physics scenarios. What makes this experiment especially appealing is the very high precision of the SM prediction: even with proposed improvement in the experimental precision, the theory error will be a factor of ~5 smaller. The theoretical cleanliness of this observable makes it unique among the low-Q^2 probes of the SM.

Given that this is a 'one number experiment' it is of particular importance that, whatever the actual result, it should be viewed within a wider context. Within the SM, the panel thought this a textbook measurement. However the role it might play if some BSM physics is observed is not easily evaluated. In such cases scientists would not only have the direct observation but a number of other 'indirect' tests to help then to identify it. It might be useful to show how, after some future discovery, the MOLLER Q_W^e measurement would be used. In the motivational examples presented, both SUSY and heavy Z's are quite 'canonical', but there is little sensitivity to such models given existing limits elsewhere (such as at the Large Hadron Collider, or LHC) unless one is generous. It is possible that a discovery of new physics elsewhere (e.g. at the LHC) could be rather 'special' in the 'leptonic' sense, making Q_W^e an especially valuable diagnostic. However, if not, Q_W^e would be one of a number of constraints on the new physics that one would look at. In addition, some of the new physics that MOLLER is sensitive to is somewhat exotic. New possibilities for light dark matter related particles are interesting. For example, the collaboration should further explore changes in the angular distribution of the Moller parity violating asymmetry as a "smoking gun" of a light Z'.

Recommendations:

- None

Impact of the Planned Scientific Program

Findings:

The proposed measurement determines $\sin^2(\theta_W)$ at low Q^2 to an accuracy comparable to the best Z pole measurements. Being purely leptonic, the experimental approach is unique and follows on the highly successful E158 measurement at SLAC National Accelerator Laboratory (SLAC) and related efforts at Thomas Jefferson National Accelerator Facility (TJNAF, or JLab) using the parity-violating electron scattering techniques. Related measurements include the Q_{WEAK} and the Mainz Energy-recovering Superconducting Accelerator (MESA) P2 experiments at JLab and Mainz, respectively. Both of these use ep scattering and are therefore possibly affected by different physics beyond the Standard Model influences.

MOLLER's precision is comparable to that achieved in the best measurements of $\sin^2(\theta_W)$ to date from precision electroweak programs at the Large Electron–Positron (LEP) Collider, SLAC Large Detector (SLD), and the Tevatron, which measure it at much higher $Q^2 \sim (100\ \text{GeV})^2$. Generically, physics beyond the SM at the TeV scale would contribute at roughly the same rate to both low-Q^2 and high-Q^2 values, making it difficult to find models that pass precision electroweak tests but generate a 3-5 σ effect in MOLLER as seen in the discussion of SUSY models. LHC constraints also limit the "phase space" accessible to MOLLER in some models, such as TeV-scale Z' models. Some models, e.g. with doubly-charged Higgs, avoid all these bounds and allow for a 5 σ effect in MOLLER. Also, low-mass, weakly-coupled particles such as "dark Z's" can be discovered at the 5 σ level in MOLLER.

Comments:

Given that a measurement can be performed at the proposed level of uncertainty, the measurement of a purely leptonic PV asymmetry is very well motivated and the impact will be quite high, even in a scenario where other (e.g. semi-leptonic) measurements achieve similar levels of uncertainty and do or do not see BSM effects.

The theoretical uncertainty associated with the SM prediction is very small and thus the measurement can be interpreted reliably. However, the implications of the measurement at the proposed precision will depend on what is found. If the measurement agrees with the SM prediction, it will serve to highly constrain speculative theories of new physics. It will be a beautiful demonstration of the completeness of the understanding of the weak interaction to a very high degree. If, on the other hand, it disagrees with overall significance from the SM prediction it will be used to guide theoretical development of the new standard model. The various scenarios that might cause such an effect are quite different, from Dark Z light bosons to doubly charged Higgs, to (remotely) supersymmetry. A full resolution in this case will require other input from the LHC and other precision low-energy measurements. In either case, it is a worthy measurement.

Some models which could provide 3-5 σ effects seem rather exotic, but as proofs of concept they are fine. More work is needed to demonstrate that the dark Z model presented is compatible with the full set of precision electroweak constraints. Even if there is no discovery by MOLLER on its own, MOLLER could have a significant impact by adding a new data point to precision electroweak fits, leading to better sensitivity of the global fits. It would be interesting to quantify MOLLER's impact on the global electroweak fits when combined with the high-Q2 data. Since MOLLER's precision is comparable to the best Z-pole observables, one might expect an "order-one" improvement in the combined sensitivity.

MOLLER builds upon generations of parity violating electron scattering experiments that have been successfully carried out at SLAC, MIT/Bates, Mainz, and JLab. This community has dramatically advanced both physics and technology, and accumulated experience over the past four decades. MOLLER at JLab, along with MESA at Mainz, will continue to push this frontier. The techniques required to carry out the measurement include state-of-the-art target development, polarized beam delivery and control, polarimetry, and spectrometer design. Addressing these challenges will advance the field of nuclear physics generally.

Recommendations:

- None

Needed Experimental and Theoretical Research Efforts and Technical Capabilities

Findings:

State-of-the-art SM predictions for the asymmetry were presented. Radiative corrections are very large for the Moller asymmetry. The uncertainty in the published SM prediction is sufficiently small compared with MOLLER's precision goal. The 2-loop corrections are in progress and are anticipated to be small, implying that the results of any Q_W^e measurement by MOLLER would be unambiguous as far as the SM was concerned.

The MOLLER experiment has some backgrounds from elastic e-p, inelastic e-p and elastic and inelastic e-Al (from the Aluminum windows).

Comments:

The SM predictions for the value of the weak mixing angle and correspondingly the size of the Moller asymmetry are in good shape. That said, only one group has performed the full 1-loop corrections, and the 2-loop corrections are still incomplete. It would be very useful to independently confirm the 1-loop corrections, possibly in a different renormalization scheme. Further, the complete 2-loop calculation needs to be finished. These calculations need to include the full experimental kinematics and acceptance. A lattice calculation could be extremely helpful as an additional check and to further improve the precision of the prediction.

Elastic backgrounds for e-p and e-Al are probably under control because of the well-known asymmetries. Inelastic backgrounds, which rely to some extent on a Monte Carlo, may need more work with respect to both the cross sections and the asymmetries. It will be necessary to quantify the uncertainty introduced by the use of the Monte Carlo model, and demonstrate that this uncertainty can be controlled (through validation measurements etc.) at the level required to make the asymmetry measurement with the stated precision.
Significant progress is evident in the design of the liquid Hydrogen target based on modern computational fluid dynamic models and the novel design of the hybrid toroidal magnetic spectrometer is impressive.

Recommendations:

- Complete the full 2 loop calculations of radiative corrections in order to document the clean theoretical prediction and submit a report to the Office of Nuclear Physics by September 15, 2016.
- Further studies of inelastic e-p and e-Al backgrounds should be completed and a report submitted to the Office of Nuclear Physics by December 3, 2015.

Feasibility of the Approach or Method

Findings:

A detailed description of the experimental apparatus was presented, along with a run plan which would achieve the required precision in 3 years (plus 1 year commissioning). The Collaboration is highly experienced in the science of precision parity-violating electron scattering. They have carried out variants of the proposed MOLLER experiment in the past. The technical plan has been worked out carefully with a keen eye on maximizing the precision reach by a novel development of a hybrid toroidal spectrometer having unusual magnetic field structures to focus the MOLLER events, and having an odd number of coils to provide full acceptance in the center of mass around the 90-degree scattering angle.

Comments:

The panel found the Collaboration to be bold in setting the new goal and, at the same time, thorough in examining possible systematic effects. One particularly difficult effect seems to be a possible variation of beam shape correlated with the helicity flip. The Collaboration has proposed ways to study and mitigate this effect by improving laser optics and introducing additional reversals. While the panel members expressed confidence that this group is capable of carrying out the proposed experiment, they will need to attend to several remaining uncertainties that have not been fully addressed, such as the Beam Intensity Monitors precision, the beam shape stability versus helicity, some detector performance assessments at high rate, an evaluation of the inelastic ep asymmetry, and an independent confirmation of the very precise radiative correction calculations.

An accurate (0.4%) determination of the beam polarization is required for the ultimate MOLLER goal. Plans exist to upgrade both a Compton-type and a Moeller-type polarimeter in close proximity and compare their measurements. An agreement between the two at the required level of precision would provide a definitive validation of both methods. This experimental check is expected to take place in 2016.

The planned measurements will require at least 3 full annual running periods at JLab plus an additional year in assembly and commissioning. Sustaining the discipline to collect high-precision data over such a long period will require a large, coherent, and dedicated collaboration. The collaboration must monitor the entire chain from polarized source to beam transport and polarimetry to the spectrometer. This is a larger task than usual. The experimental collaboration is very strong with world-class experience in previous PV electron scattering experiments. Nevertheless, it will be important to make sure that the level of commitment to this experiment remains high throughout the decade it is proposed to be in progress, given the importance it has, both in its own right and as a flagship effort for JLab and the NP community.

Recommendations:

- None

Appendix A: Charge Letter

The Physics Research Division of the Department of Energy (DOE) Office of Nuclear Physics is organizing a Science Review of the MOLLER Experiment proposed for implementation at Thomas Jefferson National Accelerator Facility (TJNAF). As you are aware, this review will take place at the University of Massachusetts at Amherst on September 10-11, 2014. A list of the members of the review panel and anticipated DOE participants will be forwarded shortly.

The purpose of this review is to assess:

- The significance of scientific questions identified by the MOLLER Collaboration and Thomas Jefferson National Accelerator Facility;
- The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities;
- The new experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program; and
- The feasibility of the approach or method presented to carry out the proposed scientific program and the likelihood that significant results can be obtained in the first three years of detector operations.

An important consideration for the panel in the above charge elements is the impact, if any, of detector implementation on the ongoing scientific program at TJNAF.

The Laboratory should submit on behalf of the MOLLER Collaboration any necessary updates of the proposal to the Office of Nuclear Physics by August 28, 2014.

Dr. Timothy Hallman will be the chair of this review and will be assisted by Dr. Gulshan Rai. Please coordinate with Dr. Rai concerning the contents of the proposal and other materials to be provided by the Laboratory to the reviewers. The first day will consist of presentations by the proponents and executive sessions. The second day will include an executive session, report writing, and a brief close-out. The panel members will be instructed to contact Ms. Brenda May at 301-903-0536 or Brenda.May@science.doe.gov regarding any logistics questions.

We greatly appreciate your efforts in preparing for this review. It is an important process that will allow our Office to assess the scientific merit of the proposed project in the context of the most compelling future directions in U.S. nuclear science.

Sincerely,

Timothy J. Hallman
Associate Director of the Office of Science
for Nuclear Physics

Appendix B: Agenda

MOLLER Review
September 10-11, 2014
Agenda

Wednesday, September 10, 2014

8:00 - 8:30 am	Executive Session	
8:30 - 8:45 am	Introductions and Logistics	(M. Ramsey-Musolf)
8:45 - 9:15 am	Introduction to MOLLER and Overview of Talks (20+10)	(K. Kumar)
9:15 - 10:15 am	Parity-Violating Moeller Scattering: Global Context (45+15)	(M. Ramsey-Musolf)
10:15 - 10:30 am	Coffee	
10:30 - 11:30 am	Weak Mixing Angle, Standard Model Radiative Corrections and New Vector Bosons (45+15)	(W. Marciano)
11:30 - 12:00 pm	Q&A on Science Motivation (30)	
12:00 - 1:30 pm	Lunch and Executive Session	
1:30 - 2:30 pm	Experimental Context and Overview of Technique (45+15)	(K. Kumar)
2:30 - 3:30 pm	Overview of MOLLER Subsystems (45+15)	(M. Pitt)
3:30 - 3:45 pm	Coffee	
3:45 - 4:30 pm	Statistics, Systematics and Run Phases (30+15)	(K. Paschke)
4:30 - 5:00 pm	Impact on JLab Scientific Program (15+15)	(JLab TBD)
5:00 - 6:00 pm	Executive Session	

Thursday, September 11, 2014

9:00 – 12:00 pm	Executive Session and Closeout