U.S. DEPARTMENT OF ENERGY

Office of Science

Department of Energy
Office of Nuclear Physics Reviewer Excerpts

from the

Science Review

of the

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

September 10-11, 2014

EXCERPTS FROM PANEL MEMBER REPORTS

The Department of Energy (DOE) Office of Nuclear Physics (NP) held a Science Review of the proposed Measurement of Lepton-Lepton Electroweak Interaction (MOLLER) Experiment to be implemented at Thomas Jefferson National Accelerator Facility (TJNAF). The review was held at the University of Massachusetts, Amherst on September 10-11, 2014. Provided below are excerpts from the reports of the review panel members regarding their findings in response to the review criteria they were asked to address.

The significance of scientific questions identified by the MOLLER Collaboration and Thomas Jefferson National Accelerator Facility:

Reviewer:
"Determining the parity violating asymmetry for Moller electron-electron scattering is very significant. The standard model provides a precise prediction for this elementary process because it directly involves only leptons. Uncertainties from hadronic corrections are likely small. In contrast, many other potential low energy measurements involve much larger strong interaction corrections and these could increase the uncertainties in their standard model predictions. As a result, it is very likely that this proposed Moller measurement could be cleanly interpreted to constrain new, beyond standard model, physics."

Reviewer:
"MOLLER Collaboration proposes to measure the parity-violating asymmetry A^e_{PV} in elastic electron-electron scattering at a relatively low momentum transfer, $Q^2 \sim (0{:}1\ \text{GeV})^2$. The goal of the experiment is to achieve a factor of 5 improvement in precision with respect to the current best measurement of this asymmetry. The Standard Model (SM) of particle physics provides a very precise and theoretically clean prediction for this observable. Comparing the MOLLER measurement with this prediction will provide a sensitive test of the SM description of parity violation. The Standard Model is a spectacularly successful theory. There are strong theoretical reasons to believe that it is not the final word, and that new physics beyond the SM (BSM) exists and will eventually be discovered, but so far there is no experimental evidence for BSM physics. Any deviation from the SM prediction for A^e_{PV} observed by MOLLER would provide an unambiguous signature of BSM phenomena. Such a discovery would certainly have a tremendous scientific impact, whether or not it is the first experimental sign of BSM. (I will comment on potential interplay of MOLLER with other experiments which may discover BSM physics below). If no deviation from the SM prediction is observed, MOLLER would still provide very valuable information in the form of constraints on the space of BSM theories. In any scenario, as long as the stated precision goal is achieved, the MOLLER measurement will represent a significant advance in our understanding of parity violation in elementary particle physics."

Reviewer:
"The Collaboration proposes to study the process of electron-electron scattering, a.k.a. Moller scattering, and measure the asymmetry in the scattering cross-sections between the left-handed and right-handed beam electrons. Here the target electrons are unpolarized.

"The previous measurement of this asymmetry, performed by the SLAC E-158 collaboration and published in 2005, has resulted in the first direct demonstration of the "running" of the Weak Mixing Angle with over 6σ significance, and measured its value ($\sin^2\theta_W$) to a fractional accuracy of 0.5% at a medium energy scale (Q ~ 0.1 GeV) far away from the Z^0-pole (Q = 91 GeV). To date, this is still the most accurate medium-energy measurement, although a more accurate value (perhaps by a factor of 1.5) may be announced by the JLab Qweak collaboration in 2015. The proposed MOLLER experiment aims to improve the accuracy to 0.1%, or 5 times better than the E-158 value. This would certainly represent a very significant advance. Slide #9 of the Review presentation by W. Marciano gives a clear visual representation of all the measurements, past and proposed.

"Since the process is purely leptonic in the leading order, its asymmetry is cleanly and accurately calculated within the Standard Model (SM). The SM prediction is already a factor of 4 more accurate than the MOLLER goal, and can potentially be improved by yet another factor of 2. In other words, there is plenty of room (another order of magnitude) beyond MOLLER for future experiments to explore. This problem thus presents both a great challenge and a great opportunity. It is my belief that measurements of a fundamental physical quantity should always strive to match or beat the accuracy of the theoretical prediction – such is a proven strategy for discoveries.

"At the Z^0-pole (Q = 91 GeV), the Weak Mixing Angle has been determined to a much higher accuracy, already claiming the level at which MOLLER aims to achieve. Moreover, it was commented during the Review that the recent determination of the Higgs mass can also be viewed as a measurement of the Angle, reaching an accuracy even higher than the Z^0-pole value. This, however, does not exclude the medium energy measurements, such as MOLLER, from discovering new physics beyond the Standard Model (BSM). Indeed, several classes of BSM models were presented at the Review showing potential deviations from SM values occurring at the medium energy, but not at the Z^0-pole.

"The expected release of a new Qweak result in 2015 will be keenly watched. If the value deviates from the SM prediction by more than 2σ, as has occurred in NuTeV, then MOLLER would become even more important and urgent."

Reviewer:
"The MOLLER proposal aims to measure the weak mixing angle, denoted as $\sin^2\theta_W$ in e^-e^- parity-violating "Moeller" scattering to an absolute precision of 0.00027 (0.1%), a level that is competitive with direct *Z* pole determinations and superior to existing and proposed off-*Z* pole measurements that rely on the running of the weak charge at

different energy scales. The quantity of interest is indeed a fundamental one in electroweak physics, a quantity one would like to know to the highest interpretable precision allowed. Because the theoretical predictions at the kinematics of MOLLER are known to a very high degree, even the 0.1% precision goal of the experiment will be well within theoretical uncertainties (which are a factor or 4 -5 lower).

"It will not be "timely" in that sense and physics might change drastically, but the Collaboration should boldly start this journey. Experience would suggest that such a fundamental measurement will be valuable whenever it is finally available.

"In summary, I concur that the MOLLER proposal is recognized as a flagship experiment at TJNAF's 11 GeV machine. The science case is solid, the team is experienced, and the laboratory is capable of hosting this very unique measurement. It should be considered a "must do" in the fundamental symmetries portfolio of Nuclear Physics. It will have an impact well beyond the NP community alone."

Reviewer:
"The Standard Model (SM) provides an excellent description of almost all experimental data including the properties of the long-anticipated Higgs boson which was recently discovered at the LHC. Despite this to-some-extent-unexpected success, there are many reasons why it is believed that the SM is an incomplete description of Nature. For example, we know that the SM does not contain a candidate particle for dark matter and does not provide a mechanism to generate either neutrino masses or the baryon asymmetry. Furthermore, it does not explain the observed patterns of the three generations of fermion families. However, all of the Beyond the Standard Model (BSM) scenarios which do attempt to address any of these outstanding issues predict the existence of new particles and interactions which have not as yet been directly observed in any experiment. Given this situation it behooves us to look everywhere possible for signals of new physics and to test all the various sectors of the SM as thoroughly as we can.

"One of the best ways to probe the detailed nature of the SM, and also the structure of whatever the theory is that might replace it in the future, is through high precision measurements made at relatively low energies compared to, e.g., the LHC. This generic type of experimental effort has been traditionally referred to in Snowmass language as the Intensity Frontier. The proposed MOLLER experiment at JLab provides an excellent example of this class of experiments. MOLLER employs fixed target e^-e^- elastic, i.e., Moller, scattering using a polarized 11 GeV e^-. Within the SM, e^-e^- elastic scattering at leading order occurs via the exchange of both the γ and Z gauge bosons, the latter having parity violating couplings to the electron. Because of this, electrons with either left- and right-handed longitudinal polarization will experience different interaction cross sections and this difference can be expressed as a parity-violating asymmetry, A_{PV}. At the low- Q^2 value of the MOLLER experiment, $Q^2 \sim (0.1\text{GeV})^2 << M_Z{}^2$, it is the small interference term between these two exchanges that produces the observed asymmetry. Since only electrons are directly involved in this scattering process and since the interaction kinematics are relatively straightforward, the results for A_{PV} can be simply expressed in terms of the so-called weak charge of the electron, $Q^e{}_W$ In the SM this quantity is essentially given, apart from an overall numerical factor, by the rather small difference $1 - \sin 2\, \theta_w\, (Q^2)$, with $\sin^2 \theta_w\, (Q^2)$ being the value of the (running) weak mixing angle evaluated at the $Q^2 \approx 0$ appropriate to the MOLLER experiment. Since $\sin^2 \theta_w\, (Q^2 \approx 0) = \sin^2 \theta_{eff}$ is numerically not far from 1/4, a precise measurement of A_{PV} then leads to an even more precise value of the weak mixing angle near $Q^2 = 0$. Also, with this large cancellation taking place in the SM prediction for $Q^e{}_W$, one potentially gains added sensitivity to any parity violating BSM physics which might also make a significant contribution to elastic e^-e^- scattering. Furthermore, within the SM context, one can directly compare the value of the weak mixing angle obtained by the MOLLER experiment at $Q^2 \approx 0$ with those obtained at higher energies, $Q^2 \approx M_Z{}^2$, by using the running predicted by the SM renormalization group equations (RGEs). It should be emphasized that the MOLLER experiment is a very clean, almost classic, test of the SM and that any sizable deviation from the SM expectations would then be attributable to BSM physics."

Reviewer:
"The MOLLER experiment has as its goal the measurement of parity-violating (PV) electron-electron scattering, i.e., PV MØller scattering. The focus is placed on the determination of the weak charge $Q_W{}^e$, where the "e" denotes the purely leptonic observable, to distinguish it from the semileptonic weak charge $Q_W{}^p$ determined in PV ep scattering as in the Q_{weak} experiment at TJNAF or the P2 experiment planned for the MESA facility at Mainz. As such the MOLLER experiment is proposed to measure the PV asymmetry to a precision of 0.7 ppb and thereby to determine $Q_W{}^e$ to a fractional accuracy of 2.4%, providing a factor of about five improvement over the only existing experiment of this type, namely E158 at SLAC. Stated another way, the MOLLER experiment performed at the proposed level would determine $\sin^2\theta_w$ 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 the running of $\sin^2\theta_w$ to lower energy. Accordingly, the experiment has the potential to be the most precise SM test using PV electron scattering at low energies.

"The purely leptonic MOLLER experiment and semileptonic experiments such as Q_{weak} are complementary: when various effects that go beyond the Standard Model are invoked these are often found to play different roles in the two types of measurements. Specific BSM models have been considered − supersymmetry, models with doubly-charged scalars, models involving the potential exchange of a heavy or light Z' − and the effects of including such ingredients are predicted to be different in measurements of $Q_W{}^e$ and $Q_W{}^p$. Hence it is of crucial importance to have high-precision measurements of both types to be able to distinguish which, if any, BSM effects exist. While perhaps some of the new BSM physics to which MOLLER is sensitive might be called "exotic," nevertheless the ability to address fundamental issues such as the potential existence of a light dark-matter particle is clearly of interest. At the low energy of the measurement one might, for instance, observe effects related to a low-mass propagator in contrast to high-mass effects which can be subsumed into contact interactions. Even if the experiment confirms the SM prediction it will provide important constraints on such BSM scenarios."

<u>The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities:</u>

Reviewer:
"The impact of the Moller measurement, with its proposed accuracy, will likely be very large. It would provide an independent low energy determination of Sin^2 of the weak-mixing angle, a fundamental quantity in the standard model, with accuracy comparable to the best present Z pole determinations. Furthermore, there will likely not be a better high-energy measurement of the weak-mixing angle during this time frame. Note that the impact of this measurement, likely, depends strongly on its accuracy. Therefore it is very important that the proposed statistical and systematic error goals are actually achieved. The Moller program, in concert with other JLAB parity violating experiments will further advance technical capabilities to make precise measurements of electron scattering parity violating asymmetries for several systems."

Reviewer:
"As far as I know, no experiments directly competing with MOLLER on A^e_{PV} have been discussed. Other experiments, such as Qweak, pursue measurements of parity-violating asymmetries in electron-proton and/or electron-nucleus scattering. Next-generation experiments of this sort, such as the MESA experiment at Mainz, are expected to occur on roughly the same time scale as MOLLER, and have similar precision goals. However, given the composite nature of proton and nuclei, theoretical predictions for these observables are not nearly as clean as that for A^e_{PV}, making it difficult to interpret them as SM tests. In this sense, MOLLER is unique.

"In a broader context, it should be noted that BSM theories which predict an observable signature in MOLLER can typically also be probed by experiments at much higher energies. This includes the program of \precision electroweak measurements," performed at CERN, SLAC, and Fermilab over the past two decades, as well as recent and near-future experiments at the Large Hadron Collider (LHC) at CERN. Discovery potential of various experiments depends on the specifics of the BSM model. Since we do not know which (if any!) of the models proposed by theorists is correct, it is impossible to unambiguously rank these experiments based on their potential. The following comments illustrate the relationship of MOLLER to past and future high-energy particle physics experiments: Many models capable of producing a strong (3–5σ level) deviation from the SM at MOLLER are already disfavored or ruled out by precision electroweak measurements, LHC data, or both. Examples include minimal supersymmetric models, models with extra TeV-scale gauge bosons (Z's), and a broad class of models where corrections to electroweak observables are oblique." This is not surprising, given that the precision electroweak program measured observables similar to A^e_{PV}, albeit at much higher Q^2, with precision comparable to MOLLER's goal. However, some kinds of new physics, e.g. doubly-charged Higgs boson and low-mass dark photons", can evade all current constraints and still be discoverable at MOLLER. This is due to unique features of MOLLER, such as the initial state with net electric charge -2e and a low value of Q^2. Thus, MOLLER certainly has real discovery potential.

"Some of the new physics models that MOLLER is sensitive to, such as doubly-charged Higgs, may be discovered at the LHC first. If this is the case, MOLLER measurement would still be extremely valuable, providing new complementary information about these exotic particles. Likewise, there are many ongoing and planned searches for dark photons, and it is also possible that a discovery is made before MOLLER. However, all these searches use exclusively parity-even observables, so in this case MOLLER would provide the first test of parity violation in the dark sector. I can say that in any scenario I can think of, a discovery of BSM physics somewhere else would make me more interested in seeing the MOLLER result, not less.

"If no statistically significant deviation from the SM is seen at MOLLER, its measurement of A^e_{PV} can be combined in a global fit with the high-energy precision electroweak data. Such global fits have been very valuable for constraining possible BSM models, and they will remain important even after direct searches at the LHC. Since MOLLER precision is comparable to the precision achieved for the best high-energy observables, adding MOLLER to the global fit will significantly improve the constraints."

Reviewer:
"MOLLER builds upon generations of parity violating electron scattering experiments that have been successfully carried out at SLAC, MIT Bates, JLab, and Mainz. This community has dramatically advanced both physics and technology, and accumulated experience over the past four decades. MOLLER at JLab, along with MESA in Mainz, will continue to push this frontier.

"Carrying out MOLLER would push the limits of technologies in the area of the accelerator, polarimetry, and detector. Such advances would undoubtedly benefit the rest of the nuclear physics field and beyond. Same can be said about its impact on the education of the next-generation nuclear physicists."

Reviewer:
"The complete electroweak (EW) fits tie together the Higgs mass, the W mass, the Fermi constant, the fine structure constant, and more. The recent sub-percent precision determination of the Higgs mass resolves a lingering ambiguity at the Z pole where the two existing high-energy "direct" measurements from LEP and SLD are in disagreement with one another by 3-sigma, even though their average value corresponds to EW expectations. The Higgs measurement confirms that this EW expectation is correct and equal to the average of the previous experiments to a remarkable degree. What does this mean for MOLLER or other proposed off-Z pole measurements? It means that any new measurement of $\sin^2\theta_W$ at different kinematics, and with competitive precision, becomes a test of "Beyond the Standard Model" (BSM) physics rather than a contribution to resolving the ambiguity at the Z pole from LEP and SLAC. This focusses the purpose of MOLLER and, in turn, elevates the importance of the question of what kind of BSM physics does a Moeller, or Q_{WEAK} or MESA-P experiment address (where the latter two are ep scattering parity-violating channels, which can determine $\sin^2\theta_W$ as well).

“The physics cases presented took into account the core characteristics of this process, namely that it is purely “leptonic,” flavor conserving, and chirality conserving. These distinctions are important when considering the kind of new physics models that might, or might not, induce an effect, where an “effect” here corresponds to a deviation of from the $\sin^2\theta_W$ prediction at the Q value of the experiment, both in magnitude and sign. For example, the case of supersymmetry (SUSY) was reviewed. Its effect on ee and ep PV scattering is different and in principle, one would need very precise versions of both types of experiments to eliminate models and favor others. Unfortunately, even at the most optimistic precision possible for MOLLER (and the ep sister efforts), the effect from SUSY is too small to be detected. SUSY is not a motivator here. In contrast, models with a doubly charged Higgs could produce a large deviation. In fashion lately is also consideration of the so-called “dark sector” with dark photons being light scalar bosons with very weak couplings. Adding in a Dark Z, allows for a parity-violating channel that would affect $\sin^2\theta_W$, especially at low Q (closer to the atomic measurements, but enough of a signal at the MOLLER kinematics to be quite significant). These ideas are among models that come and sometimes go. One cannot be guaranteed they will not be ruled out by the time the experiment produces a result, but also one cannot fully anticipate the new models that will be generated between now and then that might address, for example, some new physics discovered at the LHC or elsewhere. No matter what some new physics hint might be, one can imagine a calculation of whether a MOLLER signal would be affected or not, and if so, by how much and with what sign. The purpose of fundamental measurements like this will likely be that a high-precision measurement will be in the “physics conversation” either supporting a new theory or helping to rule it out. Either way, it can be quite important. To summarize these comments, an achieved result at the stated precision will be a “textbook” measurement.”

Reviewer:
“There are a number of issues related to this measurement that need to be highlighted as they are potential sources of concern; all of them are known to the MOLLER collaboration and are being addressed in one form or another. In order to obtain the required statistical precision on the value of $Q^e{}_W$, the MOLLER experiment will need to acquire the necessary ‘integrated luminosity’. This is critical because the results of the MOLLER experiment would rapidly become uninteresting if the final value of $\delta Q^e{}_W$, or $\delta(\sin^2\theta_{eff})$ in SM language, were to begin to drift upward. Certainly a measurement that produces a value of $\delta(\sin^2\theta_{eff})$ which is a factor of 2 or even 1.5 times larger than that quoted above will likely no longer be interesting. This certainly would be the case in the over ~ 10 years time it will take to achieve their final result. It is important to be reminded that other precision electroweak measurements will be performed during a similar time period at both low- and high- Q^2 although these may not be as theoretically clean as MOLLER. For example, we anticipate an improved value of the W mass ≈ 10 MeV from the Tevatron in the near future. Similarly, the LHC may reach an uncertainty of ≈ 5 MeV during the next decade, this corresponding to a fractional error of $\delta M_W / M_W \approx 0.65 \cdot 10^{-4}$. In terms of the standard oblique parameters that are used to probe certain classes of BSM physics, denoted by (S, T), the second of these measurements would be more constraining on any BSM physics that contributes to these quantities than that which would be obtained from a $\approx 10^{-3}$ fractional error on the weak mixing angle. I

note, however, that the S and T dependencies differ for the two quantities M_W and $A^e{}_W$ so that they would produce somewhat complementary results. Furthermore, it is likely that new measurements will also be made available from both the Tevatron and the LHC over the next decade of $\sin^2\theta_w$ ($Q^2 \approx M_Z{}^2$). By combining results in the e and μ channels, both the Tevatron and LHC should reach precisions comparable to SLC and LEP. Such results would be obtained from measurements of the leptonic forward-backward asymmetry in the Drell-Yan channel in and above the Z -pole region. However, such measurements will potentially suffer from the uncertainties in the parton densities. Within this wider context, MOLLER must perform well to have a significant impact on the overall fit to the electroweak parameters; in principle, the MOLLER experiment has the potential to make an important 'order-one' impact here.

"The MOLLER experiment clearly provides an excellent test of the SM through its ability to precisely measure the weak mixing angle at low-Q^2. However, one aspect of the MOLLER experiment that is hard to clearly evaluate directly is its sensitivity to wide classes of potential BSM physics; this is a rather complex question. Of course the specific issue here, especially after the so far null results of the LHC, is that no one really knows what form BSM physics might take; maybe we are somewhat biased in our views and remain agnostic. In the rather more familiar BSM scenarios, such as R-Parity conserving Supersymmetry or Grand Unified Theory-inspired extensions of the SM gauge sector, present exclusions of large regions of their corresponding model parameter spaces by the LHC or other experiments preclude any sizable potential signal in MOLLER. For example, 3σ evidence could be obtained by MOLLER for a $Z\chi$ of mass ~ 0.9 TeV but the LHC 95% CL exclusion for this state is already ~ 2.7 TeV. To some extent the reason for this is that these types of new physics couple to both quarks and leptons in a somewhat democratic manner as do the gauge bosons of the SM. Hence, this kind of BSM physics is relatively easy to discover at the LHC if it is kinematically accessible and its coupling strengths are qualitatively similar to those that we observe in the SM. However, it may very well be that BSM physics is nothing like this and we need to be able to search for it in every possible way. MOLLER provides a unique tool to do this since it probes essentially purely leptonic interactions.

"The MOLLER experiment is particularly sensitive to new TeV-scale BSM physics which is leptophyllic and largely hadrophobic so that it predominantly couples to leptons and thus avoids, e.g., potentially strong LHC search constraints. The proof of principle example given for this type of new physics which might lead to a 5σ signal at MOLLER is the doubly charged Higgs boson. Such states are predicted to exist in the Left-Right Symmetric Model as well as in other scenarios of neutrino mass generation that involve weak scalar isotriplets with non-zero hypercharge. At the LHC such states are pair produced in the Drell-Yan channel resulting in a 4-lepton final state where the invariant masses of like-sign lepton pairs form the doubly charged Higgs mass. Although this is a very clean final state at the LHC the production rate is rather small limiting the search reach. Another class of models to which the MOLLER experiment may be potentially sensitive are those with rather light (typically ~ 1 GeV or even significantly less) new gauge bosons that have very weak, yet parity violating couplings to the SM fermions which are induced by kinetic mixing with the SM Z. A specific realization of this model class, used as a proof of principle, is the Dark-Z scenario which correlates the apparent deviation in the value of the muon's $g - 2$ with the observed dark matter relic density. It should be emphasized again that we have no idea what form BSM physics might take so that even though these benchmark models may seem somewhat far-fetched they demonstrate what the power of the MOLLER measurement might be once BSM physics is discovered."

Reviewer:
"The precision projected for the MOLLER experiment is comparable to that achieved in the best measurements of $\sin^2\theta_w$ to date, namely, the precision electroweak program undertaken at LEP, SLD and the Tevatron at much higher values of Q^2 (~ 100 $(GeV/c)^2$) than at the much smaller value for the kinematics of MOLLER (Q^2 ~ 0.0056 $(GeV/c)^2$). For some BSM models the effects would be similar at both low- and high-Q^2, making the already-performed high-precision measurements at high energy hard to surpass; for example SUSY as presently modeled would be unlikely to generate a significantly definitive result in the MOLLER experiment at low energies. On the other hand, some models such as the doubly-charged Higgs model have the potential to impact the two energy regions differently and could appear as a 3-5 σ effect. Accordingly, the MOLLER experiment, in addition to being complementary to semileptonic experiments such as Q_{weak}, has the potential to be complementary to high-energy measurements at the Z pole or possible future high precision extensions of experiments such as NuTeV.

"In summary, the MOLLER experiment appears to be very well motivated and very thoroughly planned. Its impact on the experimental program at TJNAF will be significant and it will mean that other parts of the program will likely have to be postponed when the main data-taking period is in full swing. Nevertheless, a measurement at the proposed fractional accuracy of 2.4% is surely of major importance for the studies of PV MØller scattering and thus for explorations of potential BSM physics. That said, if the proposed accuracy cannot be obtained, for technical reasons or for programmatic reasons, and (say) a fractional accuracy 2x worse were all that could be achieved, then (in my opinion) it would be much less clear that the large investment in equipment cost, three years of beam at TJNAF and personnel would be so strongly justified."

The new experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program:

Reviewer:
"The measurement is potentially sensitive to new low mass particles related to dark matter. This possibility is very interesting and should be explored further.

"Radiative corrections to the parity violating Moller asymmetry are very large. While this increases the sensitivity to new physics, it also demands that these corrections be calculated reliably. Presently the full one loop, and some two loop, radiative corrections have been calculated. The Moller proposal mentions a plan to perform full two loop radiative corrections. It is important that these full two loop calculations be completed soon. Even if all of the two loop corrections are indeed small, the completed full two loop calculations will increase confidence in the community that radiative corrections are completely under control.

"The Moller experiment will have some backgrounds from elastic and inelastic e-p and e-Al (from the target windows) scattering. While the elastic backgrounds may be straightforward to model, additional calculations and simulations should be performed soon to model possible inelastic (both e-p and e-Al) backgrounds.

"The measurement requires long running time to accumulate statistics and this will significantly impact Jefferson Laboratory. If feasible, both the collaboration and Jefferson Laboratory should explore ways to accumulate statistics more quickly. This could be achieved by, for example, increasing the total beam current that would be available at the Laboratory to both Moller and other simultaneous experiments."

Reviewer:
"On the theoretical side, the crucial issue is to get a precise and trustworthy SM prediction. Calculations of A^e_{PV} within the SM perturbation theory are well advanced. However, it seems that only a single group (Erler and Ramsey-Musolf) has performed the most precise perturbative calculation which MOLLER relies on. It would be very helpful to have a confirmation of this prediction (and uncertainty estimates) by independent authors. It is also important to complete the full two-loop calculation of the asymmetry, as planned by the collaboration. In addition, modifications to the theoretical predictions due to the specific geometry of the experiment need to be considered. Regarding non-perturbative corrections, estimates suggest that they are too small to affect the interpretation of MOLLER. Still, it would be useful to confirm this with a first-principles calculation of these corrections, which should eventually be feasible using lattice QCD (the calculation is similar to vacuum polarization contribution to muon g-2).

"Another crucial issue required to establish the credibility of the MOLLER measurement is a reliable estimate of the backgrounds, with properly quantified error bars. In this regard, the asymmetry contributed by background from inelastic ep collisions needs to be considered more carefully, because it involves non-perturbative QCD and cannot be calculated from first principles. The collaboration proposed a method which relies on a combination of Monte Carlo modeling and extrapolations from “control regions." It is 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.”

Reviewer:
“The collaboration is bold in setting the new goal and, at the same time, thorough in examining possible systematic effects. The beam position, or, more precisely, the center-of-mass of the beam, can be measured at the nano-meter precision level. A very impressive feat! A more 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 by introducing additional reversals.

“An accurate (0.4%) determination of the beam polarization is required for the ultimate MOLLER goal. The collaboration plans to install both a Compton-type and a Moller-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.”

Reviewer:
“The tools needed to carry out this research extend naturally from the considerable experience of the Collaboration and TJNAF accelerator scientists. Requirements include state-of-the-art target development, polarized beam delivery and control, polarimetry, and spectrometer design. These techniques are of general interest to nuclear physicists. It is encouraging that an Early Career award has been granted for work on the important computational fluid dynamics modelling to develop the challenging 1.5-m long hydrogen target. The recent work at MIT on the hybrid-toroid spectrometer is impressive. Other examples of advanced work, pre-conceptual design work, and the modeling of systematic uncertainties are mature at this stage. Even though this was not a technical review, we recognize the degree of progress in the planning that has already occurred and encourage continued funding of advanced work in preparation for a full Project proposal.”

Reviewer:
“In all these cases, however, in order to either claim new BSM physics or to constrain it, the values of the relevant experimental quantities must be well understood within the context of the SM. In the case of the MOLLER experiment, this requires verification by a re-evaluation the low- Q^2 quantity $\sin^2 \theta_{eff}$ at the one-loop level as a check of the existing calculation. Afterward, a complete two-loop calculation that also accounts for the kinematics and geometric acceptance of the experimental setup is needed. Presently, these two-loop corrections are only partially known but indications are that they are relatively benign and that the projected experimental error on the weak mixing angle from MOLLER will be several (~ 5) times larger than the corresponding SM theory error. One reason for this is that the relative size of the uncertainty coming from the hadronic vacuum polarization contribution to Q^e_W is significantly smaller than in the corresponding calculation of the $g - 2$ of the muon since a different region of the

hadronic Q^2 space dominates the dispersion integral. These preliminary findings should be verified before data taking by MOLLER commences.

“The threat to the ‘cleanliness’ of the MOLLER experiment arises from several potential parity violating background sources: polarized e^- scattering, both elastic and inelastic, off of target protons or Al (from the target window), with the protons being the dominant concern. These backgrounds arise in a manner similar to the parity violation in Moller scattering itself, i.e., the Z couplings to the quarks within the target nucleons are also parity violating in the SM. To some extent in practice the elastic scattering backgrounds should not be overly important since they can be measured and are under good theoretical control at the level required in the kinematic region of interest to MOLLER. If this is so, they will not be directly relevant to the interpretation of the asymmetry measurement. The inelastic scattering backgrounds are perhaps a more serious issue especially since they are not directly calculable in a completely satisfying manner even within the SM. Here the MOLLER experiment intends to measure these contributions in several kinematic control regions outside of that of the A_{PV} signal region and then to extrapolate these measurements for both the background cross section and the asymmetry by employing a theoretical Monte Carlo model; they then assign appropriate systematic errors to this extrapolation. The success of this approach relies upon how well one can trust this Monte Carlo code and how valid this extrapolation might be. It is grounds for some concern but the MOLLER Collaboration claims that the associated systematic error will be no larger than that for the polarization measurement itself (which I discuss in the next paragraph). A demonstration that these backgrounds can be controlled to the required level through validation measurements etc. would be very important. Anything that can be done to give the community confidence in this extrapolation would be very helpful.

“Another concern on the experimental side already alluded to above is the control of systematics. Although there are potentially large systematic errors associated with the experimental kinematics, perhaps the most important component of this in my mind is having very precise knowledge of the incoming e^- longitudinal beam polarization since this is directly related to the asymmetry observable that is being measured. Not only must the net polarization be large but its value must be known with rather high precision, $\delta P/P \approx 0.4\%$, even more precisely than at either SLD or E-158. MOLLER plans to have two distinct measurements of this polarization via a Compton polarimeter, which is somewhat traditional in the sense that it was employed success- fully by SLD, as well as a ‘Moller’ polarimeter. The stated goal is to be able to cross check these two separate polarization measurements to obtain an uncertainty which is somewhat smaller than that obtained previously. Clearly this remains a challenge which has yet to be demonstrated by MOLLER. I note that much work is going into both $e^{\pm}$ beam longitudinal polarization determinations elsewhere around the globe as part of the planned capability of the future ILC; there the goal is to reach an uncertainty of $\delta P/P \approx 0.25\%$ as the target, which is even smaller than MOLLER’s planned target value. Of course there are other systematic error sources and all of them require detailed understanding.

Reviewer:
"Another very appealing feature of focusing on the purely leptonic PV asymmetry is the very high precision of the SM prediction which is stated to have uncertainties that are about five times smaller than the PV asymmetry, making this unique among the low-Q^2 probes of the SM. In particular, radiative corrections are found to be very large, but calculable for the MØller asymmetry. Thus far only one group has explored the 1-loop corrections and the 2-loop analysis is incomplete. It would be at least comforting to have another study of the former. The 2-loop corrections are being studied and it is important to complete the full analysis to that level, again, ideally with parallel efforts from two groups. While the present understanding is that the 2-loop corrections are small, rendering the Q_W^e unambiguous, nevertheless one would like to be sure that there are no surprises in the interpretation of the measurement.

"Significant technological advances are required to achieve the proposed level of precision of the measurement. These include state-of-the-art target development for the liquid hydrogen target now being undertaken using modern computational fluid dynamics modeling, spectrometer design (specifically the novel design of the hybrid toroidal magnetic spectrometer) and the challenges of both delivery of polarized beam and measurement of its polarization via state-of-the-art polarimetry. All of these are being addressed by the collaboration in concert with TJNAF and, while challenging, do appear to be attainable on the timescale of the experiment. With regard to the last, an accurate (0.4%) measurement of the polarization is required. Plans exist to upgrade both Compton- and MØller-type polarimeters in the halls at TJNAF and it projected that the required accuracy can be achieved. Some systematic effects need more attention: one such is the possibly variation of the beam shape and how it is correlated with the helicity flip. The Collaboration has proposed ways to study and mitigate this effect by improving laser optics and introducing additional helicity reversals.

"A strong component of the MOLLER Collaboration is the direct involvement of World-leading theorists who appear to be dedicated to providing the necessary higher-order corrections to the basic PV asymmetry and to evaluating the impact of BSM modeling on what is to be expected from the measurement. As the latter is a constantly shifting issue, both where new theoretical ideas are being introduced and where other measurements (for example at the LHC) have the potential to influence the expectations, it is important to have such strong theoretical support for the MOLLER experiment."

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:

Reviewer:
"The approach seems feasible, given extensive work to control systematic errors, and given considerable Jefferson Laboratory resources. This is an excellent collaboration with vast experience in both Moller and other parity violating electron scattering measurements. This proposal builds on capabilities the collaboration has already partially demonstrated in earlier experiments (for example in controlling systematic errors from helicity correlated beam properties). Given this extensive experience, the likelihood of achieving significant results is high. Perhaps the largest risk is in not obtaining the full proposed statistics. This could be due to experimental problems or to constraints on Jefferson Laboratory resources. A smaller secondary risk could be that there might be a delay in completing the production runs. These risks seem manageable, given strong commitments from both the collaboration and the Laboratory."

Reviewer:
"Overall, it seems to me that this is a serious, well-developed proposal by a top-notch experimental team. I did not hear any comments from my colleagues on the panel that would make me doubt that MOLLER can deliver the promised performance."

Reviewer:
"The proposal is very well developed over many years by the leading experts consisting of both theorists and experimentalists. This is the A-team of our field. Although every ambitious endeavor carries its unavoidable risks, I am confident in the Collaboration's ability to perform this experiment."

Reviewer:
"We note the impact will be decreased rapidly if the precision goal is not met, or if any ambiguities arise in the theoretical predictions. Valuable will be an effort to independently compute the large radiative corrections to 2nd order, and, with the kinematic cuts used in the experiment. Because of the nature of these calculations, an independent check on former work is critical. This is anticipated in the MOLLER plan. One might push the experimentalists a bit to be as diligent as possible to make sure the proposed goal is reached or possibly even exceeded as the test for new physics rapidly rises with a decreased uncertainty in this channel.

"MOLLER is challenging. It will require a very high degree of beam polarization at high current. It will require 3 years of production running once tuned and operational. It will require sustained effort from the Collaboration and from the Laboratory. The main reason we deem this to be feasible is the successful track record of doing such delicate parity-violating scattering experiments at this (and other) laboratories that the team has amassed. Even so, with a technically driven schedule, a final result is not likely before ~2022."

Reviewer:

"The plans of the MOLLER experiment call for a measurement of A_{PV} with an uncertainty of 0.73 ppb which implies a corresponding uncertainty of $\delta Q^e{}_W$ of ±2.4%. In the SM this translates into an uncertainty on the weak mixing angle of $\delta(\sin^2\theta_{eff}) \approx$ 0.00027, *i.e.*, a fractional error of roughly $\approx 10^{-3}$, which is comparable to the most precise measurements performed at the Z - pole by both SLC and LEP. This measurement then will allow a comparison of these two values of mixing angle values obtained at different scales by the RGEs. It is both this high level of precision plus the 'cleanliness' associated with $e^- e^-$ elastic scattering, it being a purely leptonic process, which makes this experiment both interesting and worth performing. Any complication that might potentially lead to a significant reduction in this expected experimental precision or in the corresponding theoretical cleanliness of the result must be taken seriously and dealt with in an appropriate manner."

Reviewer:

"Aside from the basic electron-electron, PV MØller asymmetry, there are backgrounds that at some level compete with the desired signal. One source of such backgrounds is the ep PV asymmetry arising from the hydrogen target, and this has two aspects, one being the elastic ep PV asymmetry which is quite well measured and should not contaminate the PV MØller signal, while another is inelastic PV ep scattering. The latter might be more problematic and deserves more detailed study. While the parity-conserving ep scattering inelastic cross section is relatively (perhaps sufficiently) well known, more modeling (or dedicated measurements) may have to be undertaken for the PV asymmetry. Furthermore, there can be PV backgrounds from the Al target container windows – since at least the weighting of the elastic e-Al PV asymmetry goes as Z^2 even a small amount can be significant, as was found for the Q_{weak} experiment. These contributions probably provide uncertainties that are smaller than the projected uncertainty of the measurement, although perhaps more detailed modeling of what is expected is warranted.

"The MOLLER collaboration builds on generations of previous studies of PV electron scattering experiments carried out at SLAC, MIT/Bates, Mainz, and TJNAF. This community has been outstanding in advancing the technology required for such challenging high-precision measurements. They have demonstrated the commitment and organizational skills required for experiments of this type. The experimental Collaboration is very strong with World-class experience in previous PV electron scattering experiments. Nevertheless, given the projected long timescale required to build the equipment, commission the experiment and undertake the roughly three years of dedicated running, this will require continued diligence. It is clearly important to make sure that the level of commitment to this experiment remains high throughout the decade it is expected to be in progress, given the importance it has, both in its own right and as a flagship effort for TJNAF and the nuclear physics community."