IL NUOVO CIMENTO Vol. ?, N. ? ?

The MOLLER Experiment

J. Mammei([1]) for the MOLLER Collaboration
([1]) *University of Massachusetts, Amherst*

Summary. — The MOLLER experiment will measure the weak charge of the electron, $Q^e_W = 1 - 4\sin^2\theta_W$, with a precision of 2.3% by measuring the parity-violating asymmetry in electron-electron (Møller) scattering. This measurement will provide an ultra-precise measurement of the weak mixing angle, $\sin^2\theta_W$, which is on par with the two most precise collider measurements at the Z^0-pole. The precision of the experiment, with a fractional accuracy in the determination of $\sin^2\theta_W \sim 0.1\%$, makes it a probe of physics beyond the Standard Model with sensitivities to mass scales of new physics up to 7.5 TeV.

PACS `12.15.-y` – Electroweak Interactions.
PACS `12.15.-Mm` – Neutral Currents.
PACS `11.30.Er` – Parity Violation.

1. – Introduction

The parity-violating asymmetry, A_{PV}, arises due to the interference between photon and Z^0 boson exchange. Polarized electron scattering off unpolarized targets provides a clean window to study weak neutral current interactions by measuring this asymmetry, which is defined by

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} , \tag{1}$$

where σ_R (σ_L) is the scattering cross-section using incident right (left) handed electrons. The asymmetry is dominated by the interference between the weak and electromagnetic amplitudes at $Q^2 \ll M_Z^2$ [1]. The leading order Feynman diagrams relevant for Møller scattering, involving both direct and exchange diagrams that interfere with each other, are shown in Fig. 1, and the resulting asymmetry is given by [2]

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q^e_W = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q^e_W , \tag{2}$$

where α is the fine structure constant, E is the incident beam energy, m is the electron mass, θ is the scattering angle in the center of mass frame and $y \equiv 1 - E'/E$ where E'

is the energy of one of the scattered electrons. Q_W^e (proportional to the product of the electron's vector and axial-vector couplings to the Z^0 boson) is the weak charge of the electron.

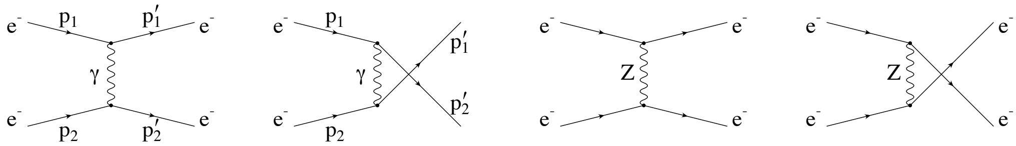

Fig. 1. – *Feynman diagrams for Møller scattering at tree level (reproduced from Ref. [3])*

Within the Standard Model, weak neutral current amplitudes are functions of the weak mixing angle $\sin^2\theta_W$. The world average of the two most precise independent determinations of $\sin^2\theta_W$ is consistent with other electroweak measurements and constraints on the Higgs boson mass M_H, but they actually differ by 3 standard deviations. Choosing one or the other central value ruins this consistency and implies very different new high-energy dynamics. The proposed A_{PV} measurement, which will achieve a sensitivity of $\delta(\sin^2\theta_W) = \pm 0.00029$, is the only method available in the next decade to directly address this issue at the same level of precision and interpretability.

This measurement presents a compelling new opportunity because it is sensitive to interaction amplitudes as small as 1.5×10^{-3} times the Fermi constant, G_F. This will be *the* most sensitive probe of new flavor and CP-conserving neutral current interactions in the leptonic sector until the advent of a linear collider or a neutrino factory. New neutral current interactions are best parameterized model-independently at low energies by effective four-fermion interactions [4]:

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j \ , \tag{3}$$

where $e_{L/R} = \frac{1}{2}(1\mp\gamma_5)\psi_e$ are the usual chirality projections of the electron spinor, Λ is the mass scale of the new contact interaction, $g_{ij} = g_{ij}^*$ are coupling constants, and $g_{RL} = g_{LR}$. For the proposed measurement with 2.3% total uncertainty (and no additional theoretical uncertainty) the resulting sensitivity to new 4-electron contact interaction amplitudes is ∼7.5 TeV. The proposed measurement will greatly extend the current sensitivity of 4-electron contact interactions, both qualitatively and quantitatively, and is complementary to direct searches.

It is straightforward to examine the reach MOLLER will have in specific models (the mass scale depends on the size of the coupling) [5]. As a specific example, a comprehensive analysis of the MOLLER sensitivity to TeV-scale Z's has recently been carried out [6] for a fairly large class of family-universal models contained in the E_6 gauge group. Z' bosons in these models with the same electroweak charges to SM particles are still motivated because they also arise in many superstring models as well as from a bottom-up approach [7]. These models are spanned by two parameters α and β in the range $\pm\pi/2$. $\alpha = 0$ corresponds to the E_6 models considered for example in Ref. [8], while $\alpha \neq 0$ can be interpreted as non-vanishing kinetic mixing, assuming that this kinetic mixing has been undone by field re-definitions. $\beta = 0$ correspond to $SO(10)$ models, which include models based on left-right symmetry.

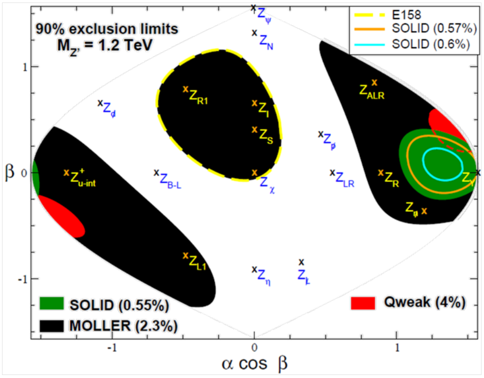

Fig. 2. – 90% C.L. exclusion regions for a 1.2 TeV Z' from the E_6 gauge group for E158, and assuming future experiments measure the SM value.

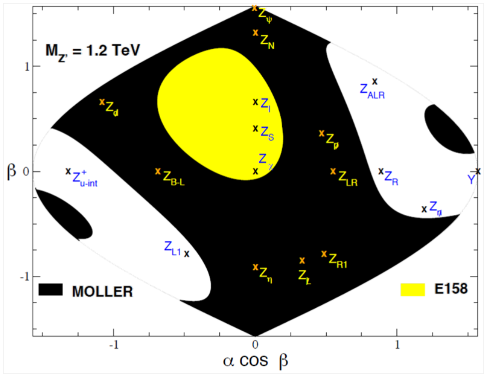

Fig. 3. – 90% C.L. exclusion regions for a 1.2 TeV Z' from the E_6 gauge group for E158, and assuming the MOLLER value is half-way between E158 and the SM.

The MOLLER reach for a 1.2 TeV Z' from this model class, assuming the value predicted by the SM is measured, along with the current region excluded by E158, is shown in Fig. 2. If MOLLER measured a value half-way between the SM value and the E158 central value. Then, a certain region of parameter space in this class of Z' models would be favored, as shown in Fig. 3. Thus, the combination of potential MOLLER and LHC anomalies would point to a small list of Z' models, whose effects on other precision EW observables can then be further explored at LHC and elsewhere. On the other hand, if MOLLER measures a central value consistent with E158, then a clear violation of the SM would be established at more than 5σ. However, no Z' from the above mentioned model class can explain such a MOLLER deviation.

2. – Experimental Overview

MOLLER will run in Hall A at Jefferson Laboratory, making use of the 11 GeV longitudinally polarized (~85%) electron beam. The target is a 1.5 m liquid hydrogen target capable of dissipating 5 kW of beam power. Møller electrons in the full range of the azimuth and spanning the polar angular range 5 mrad $< \theta_{lab} <$ 17 mrad, will be separated from background and brought to a ring focus $\sim$ 30 m downstream of the target by a spectrometer system consisting of a pair of toroidal magnet assemblies and precision collimators. The upstream magnet is a traditional resistive toroidal magnet, while the downstream magnet has a novel shape designed to focus the large range of scattered electron angles and energies. The Møller ring will be intercepted by a system of quartz detectors and the resulting Cerenkov light will provide a relative measure of the scattered flux. Longitudinally polarized electrons are generated via photoemission on a GaAs photocathode by circularly polarized laser light, enabling rapid polarization (helicity) reversal and suppression of spurious systematic effects. A_{PV} will be extracted from the fractional difference in the integrated Cerenkov light response between helicity reversals. Additional systematic suppression to the sub-ppb level will be accomplished by periodically reversing the sign of the physics asymmetry. We plan to introduce this "slow helicity reversal" with three independent methods; the introduction of an additional half-cycle $g-2$ rotation to the electrons in the recirculating arcs of the accelerator, the use

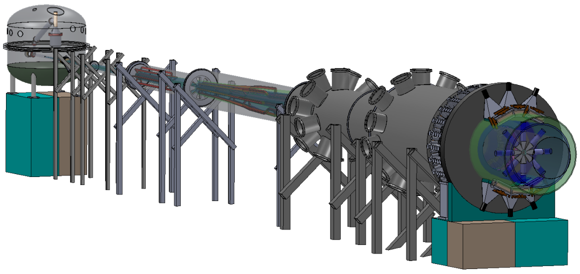

Fig. 4. – SolidWorks model of the conceptual layout of the experiment, looking upstream.

of an insertable half-wave plate in the injector, and a full flip of the beam polarization direction with a aid of two Wien rotators and a solenoid lens (the "Double-Wien").

The prediction for A_{PV} for the proposed experimental design is ≈ 35 parts per billion (ppb) and our goal is to measure this quantity with a statistical precision of 0.73 ppb. We tabulate our estimates of the most important systematic errors in decreasing order of importance in Table I. The raw asymmetry is about 32 ppb and that the raw statistical error is 0.6 ppb or about 2%. Simultaneously with data collection, the fluctuations in the electron beam energy and trajectory and its potential systematic effects on A_{PV} will be precisely monitored, active feedback loops will minimize beam helicity correlations, and detector response to beam fluctuations will be continuously calibrated. Background fractions and their helicity-correlated asymmetries will be measured by dedicated auxiliary detectors. The absolute value of Q^2 will be calibrated periodically using tracking detectors. The electron beam polarization will be measured continuously by two independent polarimeter systems.

TABLE I. – *Summary of projected fractional systematic errors on the measurement of Q^e_W. The fractional statistical error is 2.1%.*

Error Source	Fractional Error (%)
Absolute value of Q^2	0.5
beam (second order)	0.4
beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
beam (position, angle, energy)	0.4
beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to \pi + X$	0.3
Transverse polarization	0.2
neutrals (soft photons, neutrons)	0.1
Total systematic	**1.1**

3. – Experiment Status and Plans

We are proposing to take data in three separate run periods to ensure that important technical milestones are met and that each run will provide publishable results that will significantly add to our knowledge of electroweak physics to date. While the MOLLER apparatus is being designed for a beam current of 85 μA at 11 GeV, we have assumed a beam current of 75 μA and a beam polarization of 80% to formulate the run plan. If higher beam current and/or higher beam polarization are considered routine, the amount of time needed to run could correspondingly be reduced using the appropriate P^2I factor.

In order to estimate the time needed to reach the desired statistical accuracy it is necessary to take into account both the overall efficiency and how close one can approach counting statistics in an instantaneous raw asymmetry measurement. The overall efficiency depends on the efficiency of the apparatus itself and the accelerator efficiency, which we estimate as 90% and 70% respectively, for an overall efficiency of 60%. At 960 Hz, the width of the measured asymmetry per pulse pair, $\sigma(A_i)$, is 83 ppm, but this width depends on the sources of additional fluctuations. However, we are unlikely to achieve the best efficiency or asymmetry width at first, so we assumed total efficiencies of 40, 50 and 60% respectively and asymmetry widths of 100, 95 and 90 ppm respectively for the three running periods. This leads to run periods of 11, 30 and 60 weeks (including commissioning) with expected statistical errors of 11%, 4.04% and 2.43% respectively.

MOLLER is, in some sense, a fourth generation parity-violation experiment at Jefferson Laboratory. Apart from the obvious challenge of measuring a raw asymmetry with a statistical error less than 1 ppb, an equally challenging task is to calibrate and monitor the absolute normalization A_{PV} at the sub-1% level. The collaboration continues to gain extensive experience on all aspects of such measurements as work continues on executing the third generation experiments PREX [9] and Qweak [10]. Simulation and design of the various aspects of MOLLER are ongoing, and work is being done to improve beam transport and instrumentation. In addition, upgrades to the Compton and Møller polarimeters are being planned. It is envisioned that construction and assembly will take three years, to be followed by three data collection periods with progressively improved statistical errors and systematic control over a subsequent three to four year period.

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Thanks to the organizers for a wonderful meeting. This work is funded in part by US Department of Energy Grant No. DE-FG02-88R40415-A018.

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