PROCEEDINGS OF SCIENCE

The MOLLER Experiment: An Ultra-Precise Measurement of the Weak Mixing Angle Using Møller Scattering

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The MOLLER (Measurement Of a Lepton Lepton Electroweak Reaction) experiment aims to measure the parity-violating asymmetry A_{PV} in the scattering of longitudinally polarized electrons off unpolarized electrons with an uncertainty of 0.8 ppb. This measurement can be used to directly determine the weak mixing angle at low Q^2 with the best precision ($\delta(\sin^2\theta_W) = \pm 0.00028$) that matches Z-pole measurements. This precise A_{PV} measurement will be sensitive to the interference of the electromagnetic amplitude with new neutral current amplitudes as weak as $10^{-3}\cdot G_F$ from as yet undiscovered dynamics beyond the Standard Model. The resulting discovery reach is unmatched by any proposed experiment measuring a flavor- and CP-conserving process at low energy over the next decade, and yields a unique window to new physics at MeV and multi-TeV scales, complementary to direct searches at high energy colliders such as the Large Hadron Collider (LHC). The experiment takes advantage of the unique opportunity provided by the upgraded electron beam energy, luminosity, and stability at Jefferson Laboratory and the extensive experience accumulated in the community after a round of recent successfully completed parity-violating electron scattering experiments. This proceeding provides an overview of the physics motivation, the experimental setup, and the anticipated outcomes of the MOLLER experiment.

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1. Introduction

Electroweak measurements play a crucial role in testing the Standard Model (SM) of particle physics and probing for potential physics beyond its framework. The MOLLER experiment [1], will be situated at Thomas Jefferson National Accelerator Facility, is designed to significantly enhance our understanding of electroweak interactions by focusing on the parity-violating electron-electron scattering process.

The heart of the MOLLER experiment lies in its state-of-the-art experimental setup. The experiment aims to achieve a fractional accuracy of 2.4% in measuring the parity-violating asymmetry in longitudinally-polarized electron scattering from atomic electrons in a liquid hydrogen target, corresponding to an absolute accuracy of ± 0.8 ppb. This high precision is expected to provide the most accurate measurement of the weak mixing angle, making it highly sensitive to potential new neutral current amplitudes beyond the Standard Model. Achieving this goal will require very high statistics. This proceeding will summarize the experimental design and discuss the key subsystems of the MOLLER experiment.

2. Parity-Violating Electron Scattering

The measured quantity asymmetry in the parity violation in electron scattering (PVES) is defined as

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)^2} Q_W^e \tag{1}$$

with σ_R (σ_L) representing the cross section for electrons with the right (left) helicity and A_{PV} is proportional to the weak charge of the electron (Q_W^e), directly linked to the electron's vector and axial-vector couplings to the Z^0 boson. Given the conservation of parity by electromagnetism, any non-zero value of A_{PV} indicates the involvement of the weak interaction, either through the exchange of the Z boson in the SM or potential new physics beyond the SM (BSM) [2]. The electroweak theory predicts Q_W^e at tree level in terms of the weak mixing angle, $\sin^2\theta_W$, is $Q_W^e = 1 - 4\sin^2\theta_W$. Due to electroweak radiative corrections, $\sin^2\theta_W$ varies with Q^2 and it serves as a key parameter for tracking and comparing the coherence of weak neutral current measurements across the entire Q^2 range, as illustrated in Figure 1.

The anticipated A_{PV} for the MOLLER experiment is approximately 33 parts per billion (ppb), with the goal of achieving a 0.8 ppb precision. This precision yields a 2.4% measurement of Q_W^e and this leads to improved fractional accuracy in the determination of weak mixing angle about 0.1%. This level of precision aligns with the best determinations from measurements of weak mixing angle in Z^0 decays at e^+e^- colliders LEP and SLC. A summary of MOLLER estimates of the key systematic errors is summarised in Table 3 of [3].

Precision measurements of derived parameters, including M_W and $\sin^2\theta_W$, are employed to test the theory's consistency in electroweak radiative corrections and explore indications of BSM physics. MOLLER's unique contribution is its measurement of the A_{PV} at $Q^2 \ll M_Z^2$, offering a low Q^2 measurement matching the precision of high-energy measurements at the Z^0 resonance. This enhances sensitivity to new physics, extending the discovery reach to multi-TeV scales and light new degrees of freedom.

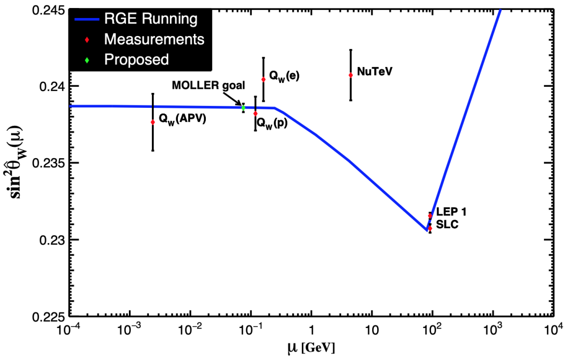

Figure 1: The measurement of the weak mixing angle as a function of the energy scale μ. The predicted MOLLER uncertainty is shown at the appropriate μ value with the nominal SM prediction as the central value. The figure is taken from [3].

3. Experimental Design

The design of the MOLLER experiment is primarily shaped by the necessity to measure a very small parity-violating asymmetry, requiring the measurement of the scattered electron flux at an exceptionally high rate and careful attention to suppressing the various false systematic effects. The CAD-generated representation of the MOLLER apparatus in Hall A at JLab is illustrated in Figure 2. The experimental setup involves an 11 GeV, 65 μA electron beam with 90% longitudinal polarization. This electron beam will be incident on a 1.25 m liquid hydrogen target and Møller scattered electrons will cover the full azimuthal range. These Møller electrons are separated from the background and focused using an open spectrometer system, eventually intercepted by quartz detectors generating Cherenkov light for scattered electron flux measurement. Each of these subsystems is discussed in the following sections.

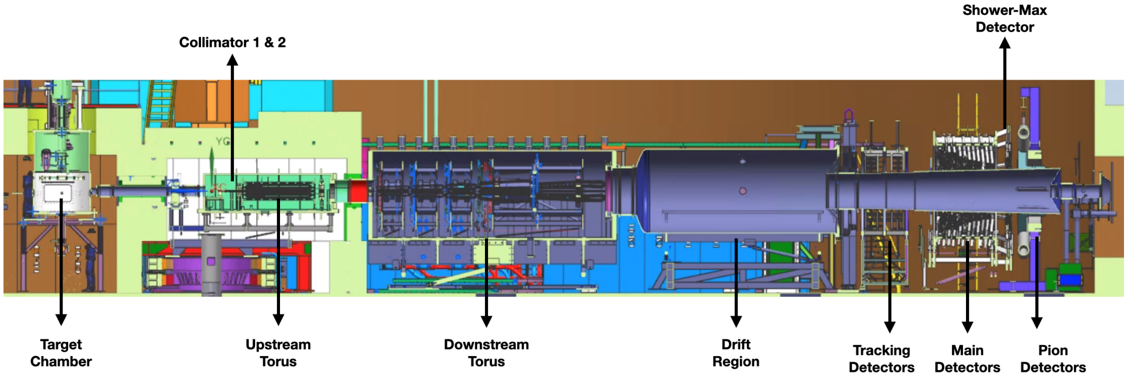

Figure 2: CAD layout of the MOLLER experimental apparatus [4].

The helicity of the electron beam will be rapidly reversed to counteract slowly drifting background effects, and corrections will be applied for any correlations with beam properties. The extraction of A_{PV} involves assessing the fractional difference in the Cherenkov light response during helicity reversals.

The precision measurement of the parity-violating asymmetry is closely tied to the accurate determination of the electron beam's longitudinal polarization. To measure the beam polarization, two independent polarimeter systems will be used. A Compton polarimeter [5], complemented by periodic measurements with a Møller polarimeter [6, 7], will ensure precise beam polarization determination at the level of 0.4%. The use of independent analysis for scattered photons and electrons ensures continuous measurements with a high level of systematic error independence.

The liquid hydrogen target, 1.25 m long, is a cryogenic system capable of handling a 3.1 kW beam heat load, drawing from successful Q_{weak} [8, 9] target operations. The design focuses on suppressing density fluctuations at the helicity flip rate (1.92 kHz) timescale to maintain statistical accuracy in the flux integration technique. Preliminary estimates suggest that density variations can be controlled within acceptable limits, ensuring a <5% excess noise level.

The spectrometer system [10] will consist of two sets of toroidal coils and precision collimators. It will be 26.5 m long and placed between the target and main detector region. The precision collimation system will be used to minimize backgrounds and will accept all the Møller scattered electrons within the polar angle range of $\theta_{COM} = 60°$ to 120°. Achieving 100% azimuthal acceptance is possible due to the special nature of identical particle scattering and the choice of an odd number of coils (the current design consists of seven coils). This arrangement allows the acceptance of both forward and backward Møller particles in each azimuthal sector, facilitating statistical representation in both sectors. Two toroidal magnets will allow us to focus and separate the scattered Møller electrons from background events (i.e. elastic and inelastic electron-proton scattering).

The MOLLER apparatus incorporates various detector systems, including main integrating detectors operating in integrating mode for asymmetry measurements of signal and background, as well as beam and target monitoring. Additionally, four planes of GEM tracking detectors in low-current counting mode are used for spectrometer calibration and background measurements. The main integrating detector has 6 rings and they consist of quartz tile connected to the photomultiplier tube by an air light guide, as shown in Figure 3. The toroidal spectrometer design will focus Møller electrons onto ring 5. This Møller ring is further divided into 84 segments, the other rings are divided into 28 segments, so there will be 224 quartz tiles in total. The dilution-weighted asymmetry values as a function of the radial location at the main detector's focal plane are shown in Figure 4. As can be seen, the Møller signal will peak in Ring 5, while there is a radiative tail that is coming from the elastic, inelastic scattered electrons. Therefore, it is crucial to directly measure both the dilution fraction and the parity-violating asymmetry of different backgrounds. The radial and azimuthal segmentation of the detector will allow us to deconvolute the main Møller signal from these backgrounds and also shower-max and pion detector systems will provide a supplemental measurement.

Behind the main integrating detector, a shower-max detector will be placed. It will consist of an array of quartz-tungsten electromagnetic sampling calorimeters. It is designed to independently measure Møller signal intercepted by the main Ring 5 ring. The Shower-max serves as a powerful cross-check for the main measurement due to its different analyzing power and background systematics.

The pion detector will consist of 28 identical acrylic Cherenkov detectors, positioned downstream of the shower-max detectors. The pion detectors are designed to measure the asymmetry of an approximately equal mix of pions and Møller electrons, requiring them to suppress the Møller electrons by a factor greater than 10^3.

The small-angle monitors (SAM), large-angle monitors (LAM), and diffuse beam monitors (DBM) will be used to monitor potential false asymmetries in the background arising from the primary scattered beam interacting with downstream collimators, beampipe, and shielding.

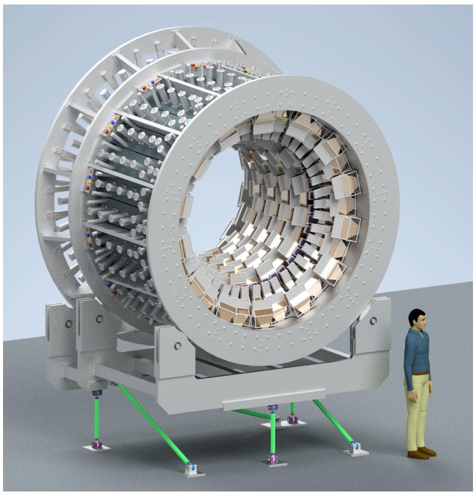

Figure 3: CAD layout of the MOLLER main integrating detector [11].

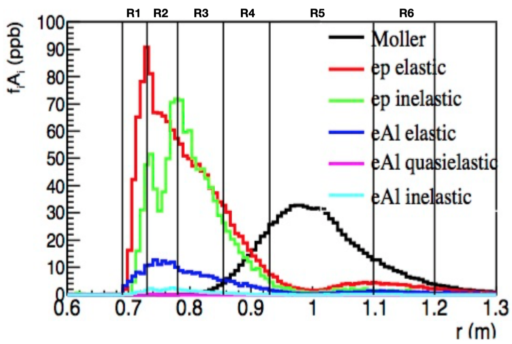

Figure 4: The average asymmetry distribution of simulated signal and backgrounds at the main detector. The Møller electron signal is in black, elastic scattering on the proton is red, inelastic scattering from the proton in green, and elastic, quasielastic, and inelastic scattering from the Al target windows in blue, magenta, and cyan, respectively. The figure is taken from [3].

4. Summary

The MOLLER experiment aims to achieve a very high precision measurement of the parity-violating asymmetry, by using an 11 GeV longitudinally polarized electron beam in Hall A at Jefferson Lab. This project represents a great opportunity to explore physics beyond the Standard

Model, offering insights into new phenomena at both MeV and multi-TeV scales. For purely leptonic interactions, MOLLER is accessing discovery space that cannot be reached until there is a new lepton collider or neutrino factory [12].

The MOLLER collaboration, comprising around 180 members from 34 institutions across 4 countries, plans to finish apparatus construction by late 2024, followed by installation in Hall A and production running in the 2026-2028 timeframe [13]. The collaboration eagerly anticipates the construction and deployment of the MOLLER apparatus and subsequent data collection and analysis phases of the project.

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