

Experiments at MAMI/MESA

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The Institute for Nuclear Physics at the University of Mainz operates the electron accelerator MAMI [1]. It provides a polarized electron beam with an intensity of up to 100 μA and a polarization degree of about 80%. In the near future, the superconducting energy-recovering electron accelerator MESA [2] will also be commissioned. It will deliver significantly higher beam intensities, thereby enabling a new generation of high-precision experiments. In the energy-recovery mode, for internal targets beam intensities of up to 1 mA at a beam energy of 105 MeV are planned, while for external targets operated without energy recovery, intensities of up to 150 μA at 155 MeV are expected. The degree of polarization is anticipated to reach 85%. This article reports on polarized-electron beam experiments carried out at the existing accelerator and on planned experiments at the new facility currently under construction, with a particular emphasis on the P2 experiment at MESA.

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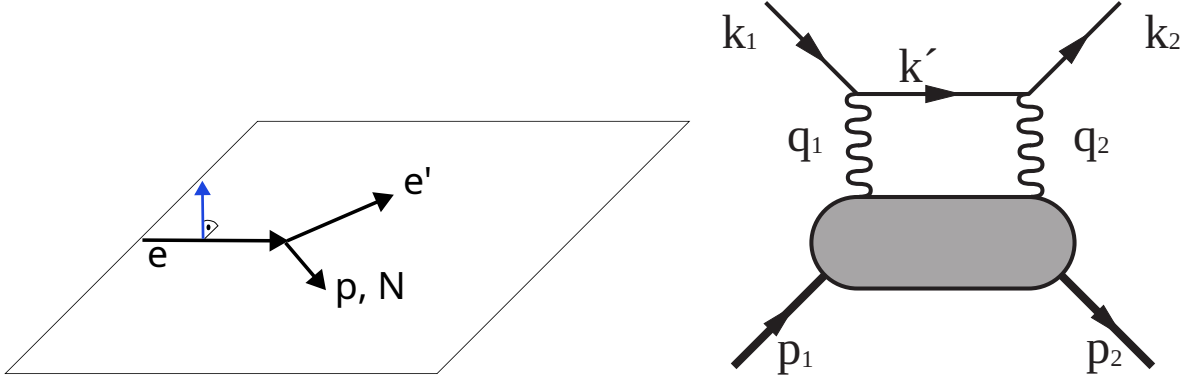


Figure 1: Left: Beam-normal single-spin asymmetries (BNSSA) arise when a transversely polarized electron is scattered from an unpolarized nucleon or nucleus. The asymmetry reaches its maximum magnitude when the electron-spin vector is perpendicular to the scattering plane. **Right:** Two-photon exchange in elastic electron–nucleus scattering. The shaded region indicates that intermediate nuclear excitations contribute to the scattering amplitude.

1. Beam Normal Single Spin asymmetries at MAMI

The asymmetry in the cross section for elastic scattering of polarized electrons from unpolarized nucleons or nuclei is commonly termed beam-normal-single-spin asymmetry (BNSSA) when the incident electron’s spin is perpendicular to its momentum direction (Figure 1 left). This asymmetry arises from the interference between the one-photon and two-photon exchange amplitudes (Figure 1 right). The shaded region in the graph indicates that calculating the two-photon exchange amplitude requires the inclusion of inelastic intermediate states of the nucleon or nucleus. Consequently, BNSSA measurements provide a direct test of theoretical models used in the calculations. Interest in such calculations intensified following discrepancies in nucleon form factor determinations, observed when comparing Rosenbluth separation techniques with polarization transfer methods, as two-photon exchange effects were found to resolve these inconsistencies [3–5].

The A4 collaboration at MAMI carried out precision measurements of beam-normal single-spin asymmetries at forward ($\theta = 35^\circ$) and backward ($\theta = 145^\circ$) scattering angles, employing beam energies from 210 MeV to 1508 MeV and hydrogen or deuterium targets [6–8]. The data provide clear evidence that contributions from excited intermediate states of the proton and deuteron are essential to explain the observed asymmetries. Recent measurements by the A1 collaboration at MAMI have extended BNSSA studies to medium- and heavy-mass nuclei, including ^{12}C , ^{28}Si and ^{90}Zr , across a wide range of Q^2 values [9, 10]. The data agree well with the theoretical predictions [11]. A particularly compelling extension to ^{208}Pb was motivated by the PREX and PREX-II/CREX experiment’s null result at Jefferson Lab [12, 13]. At MAMI, a significant, non-zero BNSSA was observed [14]. Ongoing measurements at MAMI aim to map the asymmetry on ^{208}Pb across additional kinematic points to test and refine theoretical models of two-photon exchange in heavy nuclei.

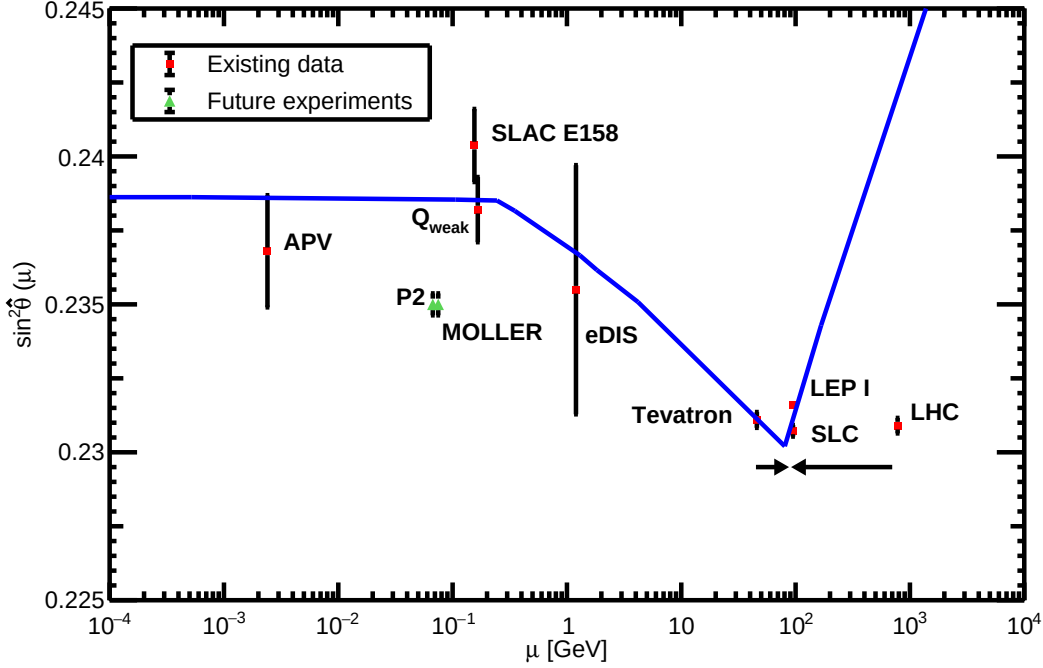


Figure 2: Standard model prediction for the running of the weak mixing angle $\sin^2 \hat{\theta}(\mu)$. Existing data are shown as red boxes. All measurements at the Z pole are performed at the same value of μ and are displayed over an extended horizontal range for improved visibility. The planned MOLLER and P2 measurements are shown as green triangles at their respective momentum transfers. Their vertical positions are chosen arbitrarily; the error bars indicate the projected uncertainties.

2. The P2 experiment at MESA

The P2 experiment at MESA [15] aims for a high-precision measurement of the weak mixing angle $\sin^2 \theta_W$ (Figure 2) at low momentum transfer $Q^2 \approx 4.5 \times 10^{-3} \text{ (GeV/c)}^2$.

2.1 Physics case of P2

The P2 experiment will test the running of the weak mixing angle $\sin^2 \theta_W$ predicted by the Standard Model (SM). Any deviation from the SM would constitute a clean signature of physics beyond the Standard Model (BSM), as the observable - the parity violating single spin asymmetry A_{PV} - is theoretically very clean, receiving corrections only from electroweak radiative effects. The asymmetry is defined as:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} [Q_W^p + F_{\text{had}}(Q^2)] \quad (1)$$

where

- $\sigma_{R/L}$ are the cross section for right/left-handed longitudinally polarized electrons,
- G_F is the Fermi constant,

- Q^2 is the squared four-momentum transfer,
- $Q_W^p = 1 - 4 \sin^2 \theta_w$ is the weak charge of the proton,
- α is the fine structure constant, and
- F_{Had} is a small ($\approx 1\%$) hadronic structure correction, calculable from existing form-factor data.

The tiny size of the A_{PV} (a few $\times 10^{-8}$) makes the measurement statistics-limited, demanding a continuous-wave high current highly polarized electron beam together with a long liquid hydrogen target and a detector that covers a large solid angle and operates in integrating mode. From the proton's weak charge Q_W^p the weak mixing angle $\sin^2 \theta_w$ can be extracted with a relative precision of 0.15%. The measurement will provide a low-energy analogue of the Z-pole measurement at LEP, but at a momentum transfer where possible new-physics contributions from heavy Z' bosons or lepto-quarks are enhanced [17, 18].

2.2 Experimental Setup

The MESA accelerator delivers an electron beam with an intensity of $I = 150$ mA and an energy of $E = 155$ MeV. Together with a 60 cm long liquid hydrogen target a luminosity of $\mathcal{L} = 2.4 \times 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$ is reached. A superconducting solenoid guides the scattered electrons to the detector consisting of 72 fused silica bars equipped with photomultiplier tubes (PMT). The current of the PMTs is digitized by sampling ADCs. From these values, the parity violating asymmetry A_{PV} will be determined. A tracking detector based on High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) reconstructs electron tracks for an accurate determination of the four-momentum transfer Q^2 [16]. A backward angle detector (BASKET) is positioned to cover large scattering angles. It consists of three planes equipped with Micromegas detectors. Their measurement will help to reduce hadronic uncertainties in the forward angle measurement stemming from strange quark and effective axial form factor contributions. Precision polarimetry provides a measurement of the beam polarization to a relative precision better than 1%.

2.3 Current Status

The project is under active construction. Major hardware components like the 20-ton superconducting solenoid magnet or the vacuum chamber have been delivered. Ongoing work includes detector assembly, detailed simulations, and beam tests for detector components and readout electronics.

3. Spin asymmetries at MAGIX

MAGIX at MESA is an electron–gas-jet scattering experiment using the high-intensity, energy-recovering MESA electron beam together with an internal windowless gas-jet target and two high-resolution magnetic spectrometers for coincidence measurements [19]. The MAGIX collaboration plans high-precision electron scattering measurements to determine hadronic and nuclear form

factors and radii, study electroweak processes, and search for physics beyond the Standard Model such as dark photons. The MAGIX experimental setup is also suitable for measuring beam-normal single-spin asymmetries (BNSSA). In particular, it offers the potential to probe low-lying inelastic nuclear states up to the giant dipole resonance. These asymmetries constitute a background in high-precision measurements of parity-violating asymmetries, which are used to determine the neutron skin thickness of heavy nuclei; thus, their measurement is valuable for background control and systematic error reduction. Studies exploring the feasibility of BNSSA measurements at MAGIX are currently in an early stage.

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