Hadronic Contributions in PVES at the P2 Experiment

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A central prediction of the Standard Model is that coupling constants are not fixed numbers but evolve with energy scale, a phenomenon known as "running." The weak mixing angle, $\sin^2\theta_W$, which determines the relative strength of electroweak interactions, is a well-known example of this. At the Z-boson mass scale ($M_Z \simeq 91$ GeV), its value is measured with high precision to be $\sin^2\theta_W(M_Z^2) \approx 0.231$. However, renormalization group equations imply that at much lower momentum transfers, quantum corrections increase its effective value to about 0.238. Measuring this "running" provides a stringent test of the Standard Model and a sensitive probe for new physics such as additional neutral currents or dark-sector interactions.

Parity-violating electron scattering (PVES) has emerged as one powerful low-energy tool to access the weak mixing angle. In PVES, polarized electrons scatter elastically from unpolarized targets. Because the weak neutral current violates parity, the cross sections for right- and left-handed electrons differ slightly, producing a measurable asymmetry,

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

This asymmetry originates from the interference between photon and Z-boson exchange amplitudes and, although typically of order 10^{-6} to 10^{-8}, its dependence on $\sin^2\theta_W$ makes it a highly sensitive probe.

The P2 experiment at the MESA facility in Mainz will measure A_{PV} in elastic electron–proton scattering at very low momentum transfer, $Q^2 \sim 0.005$ GeV^2, with the aim of determining $\sin^2\theta_W$ to a relative precision of 0.15%. This will represent the most precise low-energy measurement of the weak mixing angle to date, providing a crucial test of the predicted running and a unique window onto possible new interactions.

Achieving this precision requires careful control of the hadronic contributions from the nucleons. Although small at such low Q^2, these contributions are not negligible. They include uncertainties from the proton's strange-quark content, and the precise determination of electromagnetic and axial form factors. Addressing these effects relies on a combination of experimental input from global electron scattering data, theoretical calculations, and increasingly, lattice QCD results.