Weak mixing angle at low $Q^2$
(JLab/Mainz parity violating electron scattering experiments)

Frank Maas
(Helmholtz Institute Mainz, Institute for Nuclear Physics, PRISMA cluster of excellence
Johannes Gutenberg University Mainz)

Ultimate Precision at Hadron Colliders, November 29, 2019
Møller Scattering

- Purely Leptonic

Q-Weak (JLab)
P2 (Mainz/MESA)

- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS

- Isoscalar quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation

- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376 \ C_{1u} - 422 \ C_{1d}$

Neutrino Scattering

- Quark scattering (from nucleus)
- Weak charged and neutral current difference

S. Su

Courtesy of P. Reimer and R. Arnold
### Weak charge $Q_w(p)$ and weak mixing angle $\sin^2 \theta_w$

The **relative strength** between the weak and electromagnetic interaction is determined by the **weak mixing angle**: $\sin^2 \theta_w$

Left-right symmetric

- Electric charge of the proton: $Q_e(p) = +1$
- Weak charge of the proton: $Q_w(p) = 1 - 4 \sin^2 \theta_w = 0.05$

Small modification of $\sin^2 \theta_w$: amplified in $Q_w(p)$

**$\sin^2 \theta_w$: a central parameter of the standard model, sensitive to physics beyond the standard model**
$\sin^2\theta_W(\ )$ vs. [GeV]

- Measurements
- Completed data taking
- Proposed

- APV
- Qweak
- eDIS
- SLAC-E158
- NuTeV
- Tevatron
- LEP 1
- SLC
- LHC
- MOLLER
- P2
- SoLID

P2: Mainz
MOLLER, SoLID: JLab
Universal quantum corrections: can be absorbed into a scale dependent, "running" $\sin^2 \theta_{\text{eff}}$ or $\sin^2 \theta_W(\mu)$

On Z resonance: $A_Z$ is imaginary

$$\left| A_Z + A_{\text{new}} \right|^2 \rightarrow A_Z^2 \left[ 1 + \left( \frac{A_{\text{new}}}{A_Z} \right)^2 \right]$$

No interference term

$\delta(Q^e W)$ (theory) = 0.6%, factor of 2 improvement with full two-loop calculation
Sensitivity to new physics beyond the Standard Model

- Extra Z
- Mixing with Dark photon or Dark Z
- Contact interaction
- New Fermions
Running $\sin^2 \theta_W$ and Dark Parity Violation

$Z = \cos \theta_W W_3 - \sin \theta_W B$

$A = \sin \theta_W W_3 + \cos \theta_W B$

$m_{\text{dark}Z} = 100 \text{ MeV}$

$m_{\text{dark}Z} = 200 \text{ MeV}$

Bill Marciano
Complementary access by weak charges of proton and electron

Weak charge of the proton:

\[ Q^p_{W} = 0.0716 \pm 0.0029 \]

Experiment

SUSY-Loops

\[ E_6 Z' \]

RPV SUSY

Leptoquarks

SM

(Jens Erler, Ramsey-Musolf, 2003)

Weak charge of the electron:

\[ Q^e_{W} = -0.0449 \pm 0.0051 \]

SM
Weak Charge Of Proton: $Q_{\text{weak}}$ (Jlab), $P2$ (MESA)

Weak Charge Of Electron: MOELLER (JLAB)

Weak Charge Of Quarks: SOLID (PVDIS) (JLAB)
Proton: special case

Proton Weak charge: \( Q_w(p) = 1 - 4 \sin^2 \theta_w \)

Error: \( \Delta Q_w(p) = 4 \Delta \sin^2 \theta_w \)

Rel. error: \( \Delta Q_w(p)/Q_w(p) = 4/\left( (1/\sin^2 \theta_w) - 4 \right) \) \( \Delta \sin^2 \theta_w/\sin^2 \theta_w \)

Rel. error \( \Delta \sin^2 \theta_w/\sin^2 \theta_w = \frac{(1/\sin^2 \theta_w) - 4}{4} \Delta Q_w(p)/Q_w(p) \)

Example: \( \sin^2 \theta_w (50 \text{ MeV}) = 0.238 \)

\[ 4/\left( (1/\sin^2 \theta_w) - 4 \right) \approx 20 \]

\( \Delta Q_w(p)/Q_w(p) = 2\% \) from Experiment

\( \Delta \sin^2 \theta_w/\sin^2 \theta_w = 0.1 \% \) same precision as LEP, SLAC

Neutron Weak charge:

\( \Delta Q_w(p)/Q_w(n) = \Delta \sin^2 \theta_w/\sin^2 \theta_w \)
Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4\pi$)

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<thead>
<tr>
<th></th>
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<th>$\Lambda_{\text{new}}$ (expected)</th>
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Parity Violating Asymmetry in elastic electron proton scattering

\[ \sigma \approx +2\text{Re}(V^-A)_e(V^-A)_p + (V^-A)_e(V^-A)_p + A_e V_p + V_e A_p \]

V-A coupling: parity-violating cross section asymmetry \( A_{LR} \)
longitudinally pol. electrons
unpolarised protons
Conceptually very simple experiments

\[ A = \frac{(N^+-N^-)}{(N^++N^-)} \quad \Delta A = (N^++N^-)^{-1/2} = N^{-1/2} \]
\[ A = 20 \times 10^{-9} \quad 2\% \text{ Measurement} \quad N = 6.25 \times 10^{18} \text{ events} \]

Highest rate, measure \( Q^2 \): Large Solid Angle Spectrometers
Apparative (false) asymmetries:

Extreme good control of beam and target
Flip Helicity fast
Extra spin flip
Counting Technique

Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy
Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process
Mainz Energy-Recovering Superconducting Accelerator (MESA)

Key parameters electron accelerator MESA
- Max. beam energy 155 MeV
- Beam current >1 mA (ERL mode)
- Superconducting cavities
- Commissioning 2021

New underground (-11m) experimental hall currently under construction (Art. 91b Forschungsbau)

MAGIX experiment (internal gas target)

P2 experiment (extracted beam mode)
$A_{LR}^{\text{exp}} = \frac{\sigma(e^{-}) - \sigma(e^{-})}{\sigma(e^{-}) + \sigma(e^{-})} = P \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} (Q_W(p) - F(Q^2))$

Cross section asymmetry $A_{LR}^{\text{exp}}$

Magnetic spectrometer

Cherenkov detector

Read-out electronics

Data acquisition

Beam polarisation $P$

Polarimetry

Momentum transfer $Q^2$

Tracking system

Hadron structure $F(Q^2)$, Strangeness form factors

Axial form factor

QED and EW corrections

Theory

$e^{-}$

p-Target

$N^+$
 Contributions to $\Delta \sin^2 \Theta_W$ for 35° central scattering angle, $E=150$ MeV, 10000 h of data taking
\( A_{exp} \) & \(-24.03 \text{ ppb}\) \\
\( \Delta A_{\text{stat}} \) (2.1 \%) & \( \pm 0.50 \text{ ppb} \) \\
\( \Delta A_{P} \) (0.50 \%) & \( \pm 0.12 \text{ ppb} \) \\
\( \Delta A_{\text{false}} \) (0.42 \%) & \( \pm 0.10 \text{ ppb} \) \\
\( \Delta A_{\text{t.w.}} \) (0.79 \%) & \( \pm 0.19 \text{ ppb} \) \\
\( \Delta A_{\text{t.p.}} \) (0.04 \%) & \( \pm 0.01 \text{ ppb} \) \\
\( \Delta A_{\text{tot}} \) (2.4 \%) & \( \pm 0.58 \text{ ppb} \) \\

\[ \sin^2 \theta_W \] & 0.23116 \\
\[ \Delta \square_{\gamma z} \sin^2 \theta_W \] (0.02 \%) & \( \pm 0.0004 \) \\
\[ \Delta_{\text{FF}} \sin^2 \theta_W \] (0.05 \%) & \( \pm 0.00012 \) \\
\( \Delta \sin^2 \theta_W \) & \( \pm 0.00037 \) \\
\( \Delta \sin^2 \theta_W / \sin^2 \theta_W \) & 0.16 \%

Including:
- Detector response
- Validated by MAMI test beam measurements
- Effects from target
- Measured field map
- 10,000 h data taking
- Additional backward angle measurement
- 1 loop corrections

\[ \int \mathcal{L} dt \approx 8.6 \text{ ab}^{-1} \]
Superconducting solenoid

Scattering chamber

Liquid hydrogen target

Kevlar window

Cherenkov ring detector

Lead Shield

Tracking detectors

Steel support

Beamline

P2-Experimental Setup
Funding:

- Detector system (quartz-based) including electronics: €2.0 M
- Solenoid magnet: €1.5 M
- He-refrigerator for the hydrogen target: €1.7 M
- Silicon tracker system for $q^2$-measurement development: €0.5 M
- Double Wien filter for MESA: €0.4 M
- Hydro-Moeller detector system: €0.4 M
- Hydrogen target system: €0.35 M

Enhanced sensitivity to new physics by combining measurements on Hydrogen with a measurement on Carbon.

Graph: 

Combine measurements on Hydrogen with a measurement on Carbon.
Exciting possibility: If PREX confirms that $R_{\text{skin}}$ is large and LIGO-Virgo that NS-radius is small, this may be evidence of a softening of the EOS at high densities (phase transition?)

The very first observation of a BNS merger already provides a treasure trove of insights into the nature of dense matter!
 Equation of state of heavy nuclei describes also neutron stars (NS)

→ Correlation btw. radius $R_{\text{NS}}$ and neutron skin thickness of nuclei $^{208}\text{Pb}$

→ Neutron star deformability correlated with $R_{\text{NS}}$ and measured in neutron star merger via gravitational waves

\[
E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2 + 
\]

\[
\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)
\]

**MREX@MESA** (modified P2 detector):

Programme to measure neutron thickness of heavy nuclei ($^{208}\text{Pb}$) via parity violation
A future high-precision measurement of the electroweak mixing angle at low momentum transfer

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15 Physics Division, Argonne National Laboratory, Argonne, USA
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17 Mississippi State University, Mississippi State, MS, USA
The 12 GeV Upgrade of JLab
First physics beams to Hall A in 2014

12 GeV

11 GeV

Add 5 cryomodules

20 cryomodules

CHL-2

Add arc

20 cryomodules

Add 5 cryomodules

Two 1.1 GV linacs

Upgrade magnets and power supplies

Enhanced capabilities in existing Halls

Lower pass beam energies still available
Parity-Violating Fixed Target 11 GeV electron-electron (Moller) scattering

MOLLER at JLab

Unique opportunity leveraging the 12 GeV Upgrade investment

Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 μA 90% polarized electrons

Special purpose installation in Hall A

$A_{PV} = 35$ ppb

$\delta(A_{PV}) = 0.73$ parts per billion

$\delta(Q_{eW}) = \pm 2.1 \% \text{ (stat.)} \pm 1.1 \% \text{ (syst.)}$

$\delta(sin^2\theta_W) = \pm 0.00028$
MOLLER Apparatus

Technical Challenges

- ~150 GHz scattered electron rate
- 1 nm control of beam centroid on target
  - 1.5 m: ~5 kW @ 85 μA
- > 10 gm/cm² liquid hydrogen target
- Full Azimuthal acceptance with $\theta_{lab} \sim 5$ mrad
  - novel toroidal spectrometer pair
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
• Parity violating electron scattering: “Low energy frontier” comprises a sensitive test of the standard model complementary to LHC
• 7 years of R&D in Mainz, components are ready to be built
• P2-Experiment is funded to 90%, Q1/2021 building will be ready
• Determination of $\sin^2(\theta_W)$ with high precision (similar to Z-pole)
• New MESA energy recovering accelerator at 155 MeV, target precision is 2 % in weak proton charge i.e. 0.15% in $\sin^2(\theta_W)$
• Sensitivity to new physics up to a scale of 50 MeV up to 50 (70) TeV
• Much more physics from PV electron scattering
• Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) very sensitive test of standard model and possibility to narrow in on Standard Model Extension
Full GEANT4 simulation

- PMT
- Spectrosil 2000
- Highly UV-reflective aluminium
- Light tight vinyl foil

Kathrin Gerz
Full GEANT4 simulation
Collaboration
The P2 Experiment

A future high-precision measurement of the electroweak mixing angle at low momentum transfer

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16 Physics Division, Physics Department, Argonne National Laboratory, Argonne, Illinois, USA
17 Accepted for publication, will be EPJ A highlight
\( \sin^2 \theta_w \)
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S. Su

Courtesy of P. Reimer and R. Arnold
Summary: Measurements of $\sin^2 \theta_W^{\text{effective}}$

- Proposed: Precision of MOLLER EXP
- Proposed: Precision of PVDIS/SoLID
- LEP and SLD Average $0.23153 \pm 0.00016$
- Proposed: Precision of Mainz/Mesa P2
- Anticipated Final Precision JLab Qweak Result
- PVDIS (JLab 6 GeV) $0.2299 \pm 0.0043$
- $A_{tb}^0$ $0.23099 \pm 0.00053$
- $A_{t(P)}$ $0.23159 \pm 0.00041$
- $A_{l(P)}$ (SLD) $0.23098 \pm 0.00026$
- $A_{tb}^{0,b}$ $0.23221 \pm 0.00029$
- $A_{tb}^{0,c}$ $0.23220 \pm 0.00081$
- $Q_{tb}^{\text{had}}$ $0.2324 \pm 0.0012$
- $A_{FB}^{\text{FB}}$ (CDF), 2.0 fb$^{-1}$ $0.2328 \pm 0.0011$
- $A_{FB}^{\mu \mu}$ (CDF), 9 fb$^{-1}$ $0.2315 \pm 0.0010$
- $A_{FB}^{\text{DO}}$ (DO), 9.7 fb$^{-1}$ preliminary $0.23106 \pm 0.00053$
\[ \sin^2 \theta_W^{\text{eff}} \]

- **SLD (A)\)**
- **LEP (A_{fb}^{0,b})\)**
- **P2**

\[ m_{\text{Higgs}}: \pm 1\% \]

\[ \Delta \alpha_{\text{had}}: \pm 0.22\% \]

\[ m_{\text{top}}: \pm 0.6\% \]
Electroweak:
\gamma Z\text{-box}
- $\gamma Z$ box graph contributions obtained by modelling hadronic effects:

- Hadronic uncertainties suppressed at lower energies

- Low beam energy experiment: P2 @ MESA

Progress in Theory
- Theory uncertainties in box diagrams
- 2 loop corrections
- Hadronic contributions in loops
- Auxiliary measurements
- PV-asymmetry in Carbon
Isospin breaking
Strange quarks
present A4: reduce old SAMPLE error in $G_M$, $G_A$ by factor 2

$G_A^p(Q^2 = 0 \text{ GeV}^2/c^2) = -1.135(411)$

36% Error
Sensitivity to new physics
Example: supersymmetric Standard Model extensions
Physics sensitivity from contact interaction (LEP2 convention, \(g^2 = 4\pi\))

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ATLAS
FIG. 3. Distribution of the number of events with dilepton mass above $m_{\ell\ell}^{\text{min}}$ for data (points) and SM prediction from Monte Carlo simulation (filled histograms, shaded gray) in the dielectron channel (top panel) and dimuon channel (bottom panel). The open solid and dashed histograms correspond to the expected distributions in the presence of contact interactions or large extra dimensions for several model parameters. The bin width is constant in $\log(m_{\ell\ell}^{\text{min}})$. 

**ATLAS**

ee: \( \int L \, dt = 4.9 \, \text{fb}^{-1} \)
\[ \sqrt{s} = 7 \, \text{TeV} \]

\( m_{\ell\ell}^{\text{min}} \) [GeV]

Number of events above $m_{\ell\ell}^{\text{min}}$

\( \mu\mu: \int L \, dt = 5.0 \, \text{fb}^{-1} \)
\[ \sqrt{s} = 7 \, \text{TeV} \]

\( m_{\mu\mu}^{\text{min}} \) [GeV]

Number of events above $m_{\mu\mu}^{\text{min}}$
Figure 1: Dilepton invariant mass distributions obtained from the event selections described in the text, for the (a) CC electron, (b) CF electron and (c) muon channels. Data are shown by open circles and the total expectation is shown as a line with a band representing the total uncertainty (statistical and systematic added in quadrature). The data-driven estimate for the multi-jet background and the simulation-based estimates for all other backgrounds are shown by the shaded areas.
\begin{table}  
\centering  
\begin{tabular}{|l|c|}  
\hline \multicolumn{2}{|c|}{$\sin^2 \theta_{\text{eff}}^{\text{lept}}$} \\
\hline CC electron & $0.2302 \pm 0.0009\text{(stat.)} \pm 0.0008\text{(syst.)} \pm 0.0010\text{(PDF)} = 0.2302 \pm 0.0016$ \\
CF electron & $0.2312 \pm 0.0007\text{(stat.)} \pm 0.0008\text{(syst.)} \pm 0.0010\text{(PDF)} = 0.2312 \pm 0.0014$ \\
Muon & $0.2307 \pm 0.0009\text{(stat.)} \pm 0.0008\text{(syst.)} \pm 0.0009\text{(PDF)} = 0.2307 \pm 0.0015$ \\
El. combined & $0.2308 \pm 0.0006\text{(stat.)} \pm 0.0007\text{(syst.)} \pm 0.0010\text{(PDF)} = 0.2308 \pm 0.0013$ \\
Combined & $0.2308 \pm 0.0005\text{(stat.)} \pm 0.0006\text{(syst.)} \pm 0.0009\text{(PDF)} = 0.2308 \pm 0.0012$ \\
\hline  
\end{tabular}  
\caption{The $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ measurement results in each of the three studied channels: electron central-central, electron central-forward and muon. Results of the statistical combination of both electron channels and all three channels are shown as well.}  
\end{table}

\begin{table}  
\centering  
\begin{tabular}{|l|c|c|c|c|}  
\hline Uncertainty source & CC electrons $[10^{-4}]$ & CF electrons $[10^{-4}]$ & Muons $[10^{-4}]$ & Combined $[10^{-4}]$ \\
\hline PDF & 10 & 10 & 9 & 9 \\
MC statistics & 5 & 2 & 5 & 2 \\
Electron energy scale & 4 & 6 & – & 3 \\
Electron energy resolution & 4 & 5 & – & 2 \\
Muon energy scale & – & – & 5 & 2 \\
Higher-order corrections & 3 & 1 & 3 & 2 \\
Other sources & 1 & 1 & 2 & 2 \\
\hline  
\end{tabular}  
\caption{Contributions to the systematic uncertainties on the $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ values extracted from the three analysis channels and on the combined result. Null entries (denoted by “–”) correspond to uncertainties that do not apply to a specific channel. Higher-order corrections include NLO QCD and NLO EWK contributions. Other sources include the effect of pileup, background uncertainties, lepton trigger/reconstruction/identification efficiency uncertainties, muon momentum resolution and effects of detector misalignment.}  
\end{table}
Three PV experiments
Weak Charge Of Proton: $Q_{\text{weak}}$ (Jlab), P2 (MESA)

Weak Charge Of Electron: MOELLER (JLAB)

Weak Charge Of Quarks: SOLID (PVDIS) (JLAB)
Complementary access by weak charges of proton and electron

Weak charge of the proton:

\[ Q_W^p = 0.0716 \pm 0.0029 \]

Experiment

SUSY-Loops

\( E_6 Z' \)

RPV SUSY

Leptoquarks

SM

(Jens Erler, Ramsey-Musolf, 2003)

Weak charge of the electron:

\[ Q_W^e = -0.0449 \pm 0.0051 \]

SM
Parity violating electron scattering
Parity Violating Asymmetry in elastic electron proton scattering

\[ \sigma \approx (V-A)_e(V-A)_p + 2 \text{Re} A_e V_p + V_e A_p \]

V-A coupling:
parity-violating cross section asymmetry \( A_{LR} \)
longitudinally pol. electrons
unpolarised protons

p-Target
Parity violating cross section asymmetry

\[ A_{ep} = \left[ \frac{G_F Q^2}{4\pi \alpha \sqrt{2}} \right] \epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4 \sin^2 \theta_W) \epsilon' G_M^\gamma G_A^Z \frac{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \]

\[ A_R = A_V + A_A + A_S = A_0 \]

\[ \begin{align*}
A_V &= -a \rho'_e \left[ (1 - 4 \sin^2 \theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \right] \\
A_A &= a \frac{(1 - 4 \sin^2 \theta_W) \sqrt{1 - \epsilon^2} \sqrt{\tau (1 + \tau) G_M^p \tilde{G}_A^p}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \\
A_S &= a \rho'_e \frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \\
a &= -\frac{G_F q^2}{4\pi \alpha \sqrt{2}}, \quad \tau = -\frac{q^2}{4M_p^2}, \quad \epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \theta / 2 \right]^{-1}
\]
Parity violating cross section asymmetry

\[ A_{LR} = \frac{\sigma(e \uparrow) - \sigma(e \downarrow)}{\sigma(e \uparrow) + \sigma(e \downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} (Q_W - F(Q^2)) \]

\[ Q_W = 1 - 4\sin^2\theta_W(\mu) \]

\[ F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2) \]
Sensitivity
\[ \sigma(\sin^2(\theta_W)) \text{ at } (E = 150.00 \text{ MeV}, \Delta\theta = 4.00 \text{ deg}) \]
Accuracy

\( \sigma(\sin^2(\theta_w)) \) @ (\( E = 150.00\ \text{MeV}, \Delta\theta = 6.00\ \text{deg} \)
\[ \sigma(\sin^2(\theta_w)) \] @ (E = 150.00 MeV, \( \Delta \theta = 8.00 \) deg)
\( \sigma(\sin^2(\theta_W)) \) @ (E = 150.00 MeV, \( \Delta\theta = 10.00 \) deg)
$\sigma(\sin^2(\theta_w))$ @ (E = 150.00 MeV, $\Delta \theta = 12.00$ deg)
$\sigma(\sin^2(\theta_W)) \at \ (E = 150.00 \text{ MeV}, \Delta\theta = 14.00\text{ deg})$
Accuracy
Accuracy
\( \sigma(\sin^2(\theta_W)) \) @ (E = 200.00 MeV, \( \Delta \theta = 20.00 \) deg)
\[ \sigma(\sin^2(\theta_W)) \] @ (\(E = 210.00\) MeV, \(\Delta\theta = 20.00\) deg)
Carbon/Lead
MESA:
- 150μA
- 150MeV-200MeV
- Polarimetry

Enhanced sensitivity
To new physics

Extended 5-finger $^{12}$C-target

Polarized electron beam

$e^-$ from el. $e^{-^{12}}C$-scattering

e$^{-}$-Bremsstrahlung

Collimators

Detectors

Solenoid magnetic field

$N = \frac{G_F Q^2}{2πα\sqrt{2}} \left[ \sin^2 θ_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$

$\approx 0$
- Detector system (quartz-based) including electronics: 2.0 M€
- Solenoid magnet: 1.5 M€
- He-refrigerator for the hydrogen target: 1.7 M€
- University (through "Großgeräte"): 0.5 M€
- Silicon tracker system for $Q^2$-measurement development: 0.5 M€
- Double Wien filter for MESA: 0.4 M€
- Hydro-Moeller detector system: 0.4 M€
- Hydrogen target system: 0.35 M€
- Enhanced sensitivity to new physics
Neutron Skin for beginner

Where do the neutrons go?

Pressure forces neutrons out against surface tension

→ EOS
Neutron Skin for beginner

Where do the neutrons go?

Pressure forces neutrons out against surface tension

→ EOS
Detector geometry
Detector

- Quartz dimensions: 300 x 70 x 10-15 mm^3 – 5-10mm
- PMTs at 45°
- PMTs to be used? **Hamamatsu or Electron Tubes**
- Ring Inner and Outer diameter? **450-900-quartz longer**
- Quartz angles?
# Lead Shield

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>Dist to 0</th>
<th>Ri</th>
<th>Ro</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>100</td>
<td>970</td>
<td>250</td>
<td>530</td>
<td>730</td>
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<tr>
<td>Inner Cylinder</td>
<td>1929</td>
<td>1070</td>
<td>380</td>
<td>480</td>
<td>5910</td>
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<tr>
<td>“Teeth”</td>
<td>2000</td>
<td>1070</td>
<td>480</td>
<td>530</td>
<td>1770</td>
</tr>
<tr>
<td>Outer Cylinder</td>
<td>101</td>
<td>2899</td>
<td>1000</td>
<td>1300</td>
<td>2480</td>
</tr>
</tbody>
</table>

~11 tons
Lead Shield Support

- Geometry? Inner cylinder
- Material? Steel, Aluminum? nothing magnetic
- Space in the hall? -Juergen
- Impact on the magnetic field
- Impact of the magnetic field on the support
Lead Shield Support

- Aluminium
  - Safety factor: 3
  - Displacement: 3mm
Solenoid

- FOPI Solenoid
  - Length: 3.8m
  - Inner diameter: 2.4m
  - Weight: 108.7 tn – Juergen, floor?
Solenoid

- Field Map available
- Waiting for
  - Drawings
  - Coil specifications
Solenoid

- Simulations for
  - Impact in the magnetic field
  - Impact by the magnetic field
- CST Software
Complete Setup

Change colours
No axis system
Highlight the Quartzes
3D PDF
Integrating detectors: quartz bars, PMT read out

Photomultiplier for readout

Rectangular quartz bars with 45° cut
Solenoid
Barrel Shielding
1:20
Field component along beam axis
PMT position
PMTs far from beam axis

Event rate distribution @ z = 3000.00 mm

Photo electron rate distribution @ z = 3000.00 mm
Ray traces
Raytrace simulations in the magnetic field

Magnetic field: OFF

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$

Target
Solenoid
Raytrace simulations in the magnetic field

Magnetic field: 0.06 T

Beam energy = 155 MeV
Møller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.12 T

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.18 T

Beam energy = 155 MeV
Møller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.24 T

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$

FOMR real solenoid, $B_{\text{max}} = 0.80$ T
$B = 0.40 B_{\text{max}}$
Target center @ $z = -700$ mm
$E_{\text{beam}} = 155.0$ MeV
e-e-scattering: $\theta \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
e-e-scattering: $\theta \in [25.00 \text{ deg}, 45.00 \text{ deg}]$
Raytrace simulations in the magnetic field

Magnetic field: 0.3 T

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$  
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$  
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.36 T

Beam energy = 155 MeV
Möller, $\theta \in [0^\circ, 90^\circ]$  
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$  
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.42 T

Beam energy = 155 MeV
Moller, \( \theta \in [0^\circ, 90^\circ] \)
Elastic e-p, \( \theta \in [25^\circ, 45^\circ] \)
Elastic e-p, \( \theta \in [0^\circ, 90^\circ] \)
Raytrace simulations in the magnetic field

Magnetic field: 0.48 T

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.54 T

Beam energy = 155 MeV
Møller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$

FOMR real solenoid, $B_{max} = 0.80$ T
Target center @ $z = -700$ mm
$E_{beam} = 155.0$ MeV

el. e-p-scattering: $\theta \in [25.00 \text{ deg}, 45.00 \text{ deg}]$
el. e-p-scattering: $\theta \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
el. e-e-scattering: $\theta \in [0.00 \text{ deg}, 90.00 \text{ deg}]$
Raytrace simulations in the magnetic field

Magnetic field: 0.6 T

Beam energy = 155 MeV
Møller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-p, $\theta \in [0^\circ, 90^\circ]$
Raytrace simulations in the magnetic field

Magnetic field: 0.6 T

Beam energy = 155 MeV
Moller, $\theta \epsilon [0^\circ, 90^\circ]$
Elastic e-p, $\theta \epsilon [25^\circ, 45^\circ]$
Elastic e-p, $\theta \epsilon [0^\circ, 90^\circ]$

Shielding
Raytrace simulations in the magnetic field

Magnetic field: 0.6 T

Quartz

Shielding

Beam energy = 155 MeV
Moller, $\theta \in [0^\circ, 90^\circ]$
Elastic e-p, $\theta \in [25^\circ, 45^\circ]$
Elastic e-e, $\theta \in [0^\circ, 90^\circ]$
Geant4 Simulation of detector module response

Tracking of optical photons in detector module

Photo electron yield distribution, E = 155 MeV

Create parametrization of photo electron yield for different
- Active materials
- Geometries
- Particle types
- Particle energies
- Impact angles
Particle rates
Overview of Particle rate- and asymmetry contributions:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>rate/s^{-1}</th>
<th>(rate*asymmetry)/(total rate)/ppb</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp total</td>
<td>9.81e+10</td>
<td>-46.25</td>
</tr>
<tr>
<td>mc total</td>
<td>5.06e+11</td>
<td>-13.67</td>
</tr>
<tr>
<td>mc signal_electrons_elep</td>
<td>7.92e+10</td>
<td>-7.20</td>
</tr>
<tr>
<td>mc primary_electrons_elep</td>
<td>4.59e+10</td>
<td>-2.18</td>
</tr>
<tr>
<td>mc secondary_electrons_elep</td>
<td>1.13e+09</td>
<td>-0.14</td>
</tr>
<tr>
<td>mc secondary_photons_elep</td>
<td>3.32e+10</td>
<td>-4.06</td>
</tr>
<tr>
<td>mc secondary_positrons_elep</td>
<td>6.61e+08</td>
<td>-0.08</td>
</tr>
<tr>
<td>mc primary_protons_elep</td>
<td>1.14e+07</td>
<td>-0.01</td>
</tr>
<tr>
<td>mc secondary_electrons_target_shower</td>
<td>2.34e+08</td>
<td>0.00</td>
</tr>
<tr>
<td>mc secondary_photons_target_shower</td>
<td>3.46e+11</td>
<td>0.00</td>
</tr>
<tr>
<td>mc secondary_positrons_target_shower</td>
<td>0.00e+00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Overview of Photoelectron rate- and asymmetry contributions:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>rate/s^{-1}</th>
<th>(rate*asymmetry)/(total rate)/ppb</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp total</td>
<td>9.81e+10</td>
<td>-46.25</td>
</tr>
<tr>
<td>mc total</td>
<td>4.80e+12</td>
<td>-34.90</td>
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<td>mc signal_electrons_elep</td>
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<td>mc secondary_photons_elep</td>
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<td>0.00</td>
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<td>mc secondary_electrons_target_shower</td>
<td>0.00e+00</td>
<td>0.00</td>
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<td>mc secondary_photons_target_shower</td>
<td>4.30e+09</td>
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<tr>
<td>mc secondary_positrons_target_shower</td>
<td>0.00e+00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Total suppression of photons by a factor 204
dilution by photons $10^{-3}$
Simulations spectra spectra
Event rate distribution @ z = 3000.00 mm
$Q^2$ distribution of signal electrons (25 deg < $\theta$ < 45 deg)
$Q^2$ distribution of primary electrons
Hit distribution of signal electrons ($25 \text{ deg} < \theta < 45 \text{ deg}$) @ $z = 3000.00 \text{ mm}$
Hit distribution of primary electrons @ z = 3000.00 mm
Hit distribution of secondary photons @ $z = 3000.00$ mm
Energy distribution of signal electrons (25 deg < θ < 45 deg) @ z = 3000.00 mm
Energy distribution of primary electrons @ z = 3000.00 mm
$E'$ @ vertex of secondary photons @ $z = 3000.00$ mm

Event rate per mm$^2$ (s$^{-1}$ mm$^{-2}$)
Photo electron rate distribution @ z = 3000.00 mm
Spin angle on detectors
Impact angle on detectors
Angular distribution in event generator plane of detector simulation @ z = 3000.00 mm
Tracking system
P2:
About 3m² active area
4 sectors of 20° each
Each sector 4 layers
About 2-3 €/m²
Weak mixing angle measurement requires determination of momentum transfer $Q^2$

- Tracking detector in solenoid field
- Valuable for systematic studies
- Challenging high-rate, low momentum environment:
  
Use High-Voltage Monolithic Active Pixel Sensors (HV-MAPS), in two double planes
• High Voltage Monolithic Active Pixel Sensors (HV-MAPS)
• Developed jointly with the Mu3e Collaboration
• First Large Prototype (Mupix 8, 2 cm x 1 cm) fulfils specifications (30 MHz hits per chip, 99.9% efficiency)
• Excellent time resolution (< 6 ns)
• Readout over ultra-thin Kapton/Aluminium flexprints working
• 2 cm by 2 cm chip being designed
- Detailed CAD design
- Includes helium gas cooling channels and readout and powering PCBs
• CFD simulation of helium gas cooling
• Can keep temperatures at a safe level for the sensors
• Large gradients
- Parametrization-based track finding
- Robust up to nominal electron rate
• Complicated by inhomogeneous magnetic field in tracker region
• Use a general broken lines algorithm with a Rung-Kutta-Nyström propagator
• Resolution well sufficient for a good $Q^2$ reconstruction
- Heatable single-strip prototype with temperature sensors
- Measurements in good agreement with CFD simulation
• Full-scale heatable tracker module
• Helium box
• Currently under test
• Reconstructed $Q^2$ is strongly affected by effects in target:
• Effects need to be well modelled
• Radiative corrections to hard scattering: Incorporate theory calculations
• Multiple Coulomb scattering in hydrogen: various models in GEANT4 to be evaluated against data
• Unfolding of the resulting distribution: develop algorithm
• Transport data out of the detector
• Sort in time and space
• Find tracks online
• Based largely on the experience in the Mu3e experiment
False asymmetries
Apparative (false) asymmetries:

Extreme good control of beam and target
Flip Helicity fast
Extra spin flip
• >10 years of experience of beam delivery to a parity violation experiment

**Systematics of A4 @210MeV, extrapolated to 10000h of data taking:**

- Beam angle $x$
- Beam angle $y$
- Beam position $y$
- Beam position $x$
- Beam energy
- Beam current

**Need to improve by factors of 10 ~ 100, in total max. 0.1ppb!**

**dedicated simulations for P2 in preparation**
- cavity monitors measure beam position (XYMOs)
- steering magnets correct beam direction (WEDLs)
For suppression of helicity correlations (ppb level!):

- measure helicity correlations (stabs off) → feed forward parameters
- turn on feed-forward (suppress correlations) → $A_i \to 0$
- turn on feed-back (reduce uncorrelated noise) → $\Delta A_i \to 0$

First demonstration using outdated FPGA evaluation board:

- fast WEDLs can do at least $\pm 24 \, \mu$rad in $< 10 \mu$s @ 150 MeV
- need to test this with beam!
PCs for runcontrol, electronic logbook (ELOG), and data storage

embedded PC (stabtrig)
Spartan-6 FPGA board with IP cores for i2c and trigger

Zynq7000-based DAQ boards
2 ADCs, 2 DACs each, all 125 MSa/s

ADCs and DACs for readout and control of beamline elements: XYMOs (beam position monitors), fast steerers
• gain experience steering <200 MeV beam through s.c. solenoid
• operate beam position / angle stabilization “across” solenoid – modifications to control loop?
• prob. use 3Tmax. s.c. solenoid (fallback solution: 5T from A2)
• most realistic test of polarimetry+beam stablization for P2 possible before MESA put into operation
First digital beam stabilization tests for P2 with 180MeV@MAMI

- using RedPitaya internal PID blocks (used only PI)!
- not yet optimized transfer functions!

-50dB @50Hz, -50 dB @100Hz, -20dB @1000Hz

(A4/MAMI: -40dB@50Hz)

PhD thesis Ruth Herbertz
Planned Setup Beam Control in MESA
### Asymmetry Uncertainties Results

**Expected Asymmetry Uncertainties after 10kh measuring time at 150μA**

- Effective resolution: 8.7e-6 ppb
- Electronic noise: 1.3e-5 ppb
- Stabilized beam: 0.11 ppb
- Current: 0.29 ppb
- Energy: ?

- Position and current based on signal widths measured in Tests at MAMI
- Scaled to 150μA in 10kh and averaged over 8192 samples of 8ns.
- Energy asymmetry is estimated from A4 data. 0.1 ppb feasible but not yet demonstrated. Relative energy width of $10^{-5}$ needed.
Polarimetry
Double scattering polarimeter

DSP: opened top flange

- Für $S_T = S_{\text{eff}}$ (unpolarisiert): $A = \frac{N_L - N_R}{N_L + N_R} = S_TS_{\text{eff}} = S^2_{\text{eff}}$
Double scattering at two foils, 35 nm gold thickness

ca. 1900 measurements a 60 s ~ 164 h measurement time

A = 9,25 + 0,06 %

\( dA/A = 0,66 \% \) (statistical error)

Analyzing power  calibration could be feasible at the <1% level (or even better)!
Open questions: Target stability (radiation damage!), reproducibility, consistency checks,
Hydro Moller Polarimeter

The promise: (*)

- **Hydro-Möller**: Atomic trap with completely electron-spin polarized Hydrogen
- **Online capability**, high accuracy (<0.5%)
- **Statistical efficiency** approaches 0.5% in 2 hours (Target: $3 \times 10^{-16} \text{ cm}^{-2}$)
- **Acceptance similar to conventional Möller**


Complete trap with 77mm diam.  
Cold bore 7T Solenoid  
$\Delta B/B < 10^{-5}$ (1cm$^3$ Volume)**

(**) T. Roser et. al. NIM A 301 42-46 (1990)
(**) W. Kaufmann et. al. NIM A 335 17-25 (1993)

1.1K Stage heat exchangers  
Presently in fabrication in KPH Machine shop

Patricia Bartolome, Valerie Tyukine
<table>
<thead>
<tr>
<th>Module</th>
<th>Ready</th>
<th>Status</th>
<th>Remarks &amp; Problems</th>
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<tbody>
<tr>
<td>Cryostat housing</td>
<td>End 2014</td>
<td>R&amp;D Construction</td>
<td>Con: Using Super-MLI Accurate positioning of solenoid</td>
</tr>
<tr>
<td>Stage 1.10 K</td>
<td>End 2014</td>
<td>Development Construction</td>
<td>HT-HE Pre-HE LT-HE Valves</td>
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<tr>
<td>Stage 0.25 K</td>
<td>End 2015</td>
<td>R&amp;D</td>
<td>Final-HE Mixing Chamber Film burners Technologies not yet under control!</td>
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<tr>
<td>Hydrogen feed system</td>
<td>End 2016</td>
<td>R&amp;D</td>
<td>Literature references Transition unit not ready</td>
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<tr>
<td>Super conducting solenoid</td>
<td>End 2014</td>
<td>Test</td>
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</tr>
<tr>
<td>Detection system</td>
<td></td>
<td>R&amp;D</td>
<td>Collaboration ?</td>
</tr>
<tr>
<td>Pumping system</td>
<td>Summer 2016</td>
<td>Not yet funded</td>
<td>$^3$He Still $^4$He Evaporator $^4$He Separator $^4$He Pre-HE</td>
</tr>
<tr>
<td>$^3$He - Filling</td>
<td>End 2016</td>
<td>Not yet funded</td>
<td>Volume = 200 l STP</td>
</tr>
<tr>
<td>Target test</td>
<td>End 2017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.1K Stage heat exchangers
Double Mott scattering polarimeter (DSP)
- Goal $\Delta P/P = 0.3\%$, offline
- 2$^{nd}$ FP: functionality demonstrated
- several reasons for remaining systematic uncertainties identified
- 3$^{rd}$ FP: installation at MESA in 2020, (enabled by accelerated installation scheme) reduction of remaining uncertainties, and comparison with MP at 5 MeV,

Atomic hydrogen trap (Hydro-Møller)
- Goal $\Delta P/P = 0.5\%$, online
- 2$^{nd}$ FP: He3/He4 dilution cryostat designed, several parts already fabricated
- Accelerator lattice adapted for installation of detection system (chicane)
- 3$^{rd}$ FP: operation cryostat, trapping H-atoms and operation with beam

DSP-Schematic

Hydro-Møller- Schematic
Present status of DSP analysis of analysing power using different methods.
Green band corresponds to 3%
\[ A_0 = P_0 S_{eff,2} \]
\[ A_T = P_0 S_{eff,1} \]
\[ A_\uparrow = P_\uparrow S_{eff,2} = \frac{S_{eff,1} + \alpha P_0}{1 + P_0 S_{eff,1}} S_{eff,2} \]
\[ A_\downarrow = P_\downarrow S_{eff,2} = \frac{S_{eff,1} - \alpha P_0}{1 - P_0 S_{eff,1}} S_{eff,2} \]
\[ A = S_{eff,1} S_{eff,2} \]

3 arrangements, 4 experiments, 5 Observables, assuming \( P_0 \) can be switched to \(-P_0\) resulting in \( P_\uparrow \) and \( P_\downarrow \) after the first scattering

\( \alpha = \) Depolarisation in Target (only double scattering with pol. incident beam)

a) **Switch-Asym.**  second Target in pol. beam
b) **Switch-Asym.**  first target in pol. beam
b) **Double scat. Asym for ** \(+P\)-beam
b) **Double scat. Asym for ** \(-P\)-beam
c) **Double scat. Asym for unpol. beam**

Cryostat design with several stages of heat exchangers, 3He/4He mixing circuit, superconducting solenoid and cold hydrogen dissociator

Left: Central piece of cryostat – “evaporator pump line”, heat exchanger support and beam pipe. Right: heat exchangers in “all welded” technology. Fabricated by KPH machine shop supported & several industry suppliers
Some estimations concerning polarization dilution:

Ideally, the trapped gas polarization is nearly 100% ($\sim 10^{-5}$ contamination).

No Beam

- Hydrogen molecules $\sim 10^{-5}$
- Upper states $|c\rangle$ and $|d\rangle < 10^{-5}$
- Excited states $< 10^{-5}$
- Helium and residual gas $< 0.1\%$ - measurable with the beam

At 100.0 $\mu$A e-beam

- Depolarization by beam RF $< 2 \times 10^{-4}$
- Ion, electron contamination $< 10^{-5}$
- Excited states $< 10^{-5}$
- Ionization heating $< 10^{-10}$
- Expected depolarization $< 2 \times 10^{-4}$
Polarized source

Polarized source STEAM in it’s operational position in Hall-3

- Standard operation 100kV with higher field as the MAMI operational source for better beam quality at P2 current.
- Source high voltage test successful, 165 kV achieved without problems.
- Beam test expected 12/2017
Magnification of double scattering chamber.

- Rotation of two polarization/normalization counters allows to obtain double ratio
- But normalization counters still needed, due to possible misalignment of rotation axis and scattered beam axis
- Requires correct relative distance of polarization/normalization counters
Double scattering polarimeter - PhD work Matthias Molitor

Systematic studies:

- Long term stability, reproducibility: o.k.
- Operation with polarized beam, + Wien filter allows to do different single/double scattering experiments with different directions of polarization.
- Redundant set of observables (5 Observables, four unknowns)
- Results in 5 independent methods to extract analyzing power: measurements done
- Depolarization factor not yet taken into account, -- work in progress
Calculation of the effective analyzing power in 5 different ways.

1. \[ S_{\text{eff}}^2 = \frac{A_0}{A_T} \left[ A_\uparrow (1 + A_T) - A_0 \right] \]
2. \[ S_{\text{eff}}^2 = \frac{A_0}{A_T} \left[ A_\downarrow (1 - A_T) + A_0 \right] \]
3. \[ S_{\text{eff}}^2 = \frac{1}{4A_T} \left\{ \left[ A_\uparrow (1 + A_T) \right]^2 - \left[ A_\downarrow (1 - A_T) \right]^2 \right\} \]
4. \[ S_{\text{eff}}^2 = \frac{A_0 A}{A_T} \]
5. \[ S_{\text{eff}}^2 = A \]

Statistical error <1% rel.
2 m long cryostat  Engineering challenge!

Vacuum Vessel

Insertion  with solenoid and hydrogen injector

Purchase of solenoid and pumping system
Possible if PRISMA+ is successful.

Hydro Möller

Design parameters

- Dilution Cryostat – Mixing He3 in He4
- $P_{\text{cooling}} \sim 60.0 \text{ mW}$ at $T_{mc} = 0.25 \text{ K}$ and $\dot{n}_{\text{He3}} = 22.5 \frac{\text{mmol}}{\text{s}}$
- $P_{\text{precooling}} \sim 150.0 \text{ W}$
- Insert (up)
- Housing (middle)
- Magnet and MLI (down)
Mott polarimeter at MESA at 5 MeV
Double Mott polarimeter at 100 KeV
Møller polarimeter with polarized iron target at 100 - 1600 MeV
New: Møller polarimeter with polarized atomic hydrogen target at 50 - 1600 MeV
Nondestructive measurement
HT-HX from SS complete welded system

HT-HX from SS before welding

Dimensions: \(D196\times H25\) mm, heat transfer between cold \(^3\)He, \(^4\)He and warm \(^3\)He

HT-HX plate before soldering

HT-HX from OFHC-Cu

Dimensions: \(D196\times H25\) mm, heat transfer between cold \(^3\)He, \(^4\)He and warm \(^3\)He
goals for the next funding period

- improve accuracy of DSP Mott polarimeter
- Design and construction of additional 5MeV Mott polarimeter for MESA, based on existing Mott at MAMI operating at 3,5 MeV (at present limited in accuracy by theoretical uncertainties)
- Build Hydro Möller atomic trap and test it with beam (MAMI beam useful)
- Assemble and commission MESA until end of funding period → first P2 beam at MESA by 2023.
Detector studies
Prototype tests @ MAMI

Measured the yield of photo electrons for different

- materials (quartzes, wrappings, lightguids, PMTs)
- geometries
- impact positions
- angles of incidence

θ scan data:

[Graph showing θ scan data with different angles labeled: Angle 30 deg, Angle 35 deg, Angle 40 deg, Angle 45 deg, Angle 50 deg, Angle 60 deg, Angle 75 deg, Angle 90 deg. The graph plots counts against ADC channel.]
Detector module prototype tested at MAMI

Outline of different setups and scan series 01/2014

Angular scans
- PMT
- 135° / 30°

Position scans
- PMT
- 90°

Quartz materials
- Heraeus Suprasil 2A
- Heraeus Spectrosil 2000

Geometries
- Quartz bars 10mm / 15mm
- w/ and w/o "outlet optic" (45° cut)
- Measurements w/ and w/o LG

Polishes
- Flamepolished
- Mechanical
- Optical polish

Reflective materials for wrap and LG
- Mylar
- Alcanod 4300UP
- Millipore ImmobilonP

~350 runs in January 2014 beam time
~400 runs in December 2015

300 mm
Prototype Detector test at MAMI

- Quartz block
- Trigger scintillators
- Light guide
- Beam line
- Rotation and translation table

Detector test after 2nd stage of MAMI @855MeV
Photomultipliers

Tubes in test:

Hamamatsu R11410

ET Enterprises 9305QKMB

Quantum Efficiencies of Tubes in beam time 01/2014

Suprasil, center, center, 90°

$N_{PE} = 111.36 \pm 1.05$

$N_{PE} = 77.88 \pm 0.76$
Loss in Light Guide

Our geometry:

Comparison of Signal with and without use of light guide

<table>
<thead>
<tr>
<th>ANGLE</th>
<th>N w/ LG</th>
<th>N w/o LG</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>12.4</td>
<td>53</td>
</tr>
<tr>
<td>70</td>
<td>11.6</td>
<td>55.4</td>
</tr>
<tr>
<td>80</td>
<td>11.8</td>
<td>56</td>
</tr>
<tr>
<td>90</td>
<td>12.8</td>
<td>77.9</td>
</tr>
</tbody>
</table>

Next beam time:
Test other geometry
P2 Experimental setup (second testbeam January 2014)

- Trigger scintillators
- PMT
- Quartz
- MAMI-beamline
- Lightguide
- Remotely movable table
Reproducibility Check

Comparison of experimental data with Simulation:

Dependence of signal amplitude on electron angle

- Experiment
- Simulation
Development of PMT base with remotely switchable gain (high and low current mode)

Test measurements with LED pulses (low and high gain)
P2 setup overview
Quartz Cherenkov detector concept

- Cherenkov detector ring consisting of 80 fused silica bars
- Covering
  - full azimuth
  - 25° - 45° polar angle

Visualization of one electron event in Geant4
Detector response to signal electrons

Detector prototype tests at MaMi compared to Geant4 simulation results

![Graph showing detector response to signal electrons]

- MonteCarlo
- Measurement 1
- Measurement 2

Number of photoelectrons per cm vs. Angle of electron incidence on quartz [deg]
Radiation hardness tests

Hit rates onto Cherenkov detector ring

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Hit rate ([s^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary electrons, (\theta \in [25^\circ, 45^\circ])</td>
<td>(7.10 \cdot 10^{10})</td>
</tr>
<tr>
<td>Primary electrons, (\theta \in [25^\circ, 45^\circ])</td>
<td>(3.21 \cdot 10^{10})</td>
</tr>
<tr>
<td>Secondary electrons</td>
<td>(1.33 \cdot 10^{10})</td>
</tr>
<tr>
<td>Electrons from background processes</td>
<td>(4.05 \cdot 10^{10})</td>
</tr>
<tr>
<td>(\Sigma) electrons</td>
<td>(1.57 \cdot 10^{11})</td>
</tr>
</tbody>
</table>

+ neutronic and photonic background

35Mrad purely from electrons!
Radiation hardness tests

Samples of Spectrosil 2000 and Suprasil 3A were exposed at the 180MeV MaMi beam

<table>
<thead>
<tr>
<th>Time</th>
<th>Current</th>
<th>Radiation Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>8300s @ 100nA</td>
<td>≙ 10-fold P2 dose</td>
<td></td>
</tr>
<tr>
<td>4150s @ 100nA</td>
<td>≙ 5-fold P2 dose</td>
<td></td>
</tr>
<tr>
<td>4150s @ 20nA</td>
<td>≡ P2 dose</td>
<td></td>
</tr>
<tr>
<td>2075s @ 20nA</td>
<td>≡ half P2 dose</td>
<td></td>
</tr>
</tbody>
</table>
Radiation hardness tests

Samples of Spectrosil 2000 and Suprasil 3A were exposed at the 180MeV MaMi beam.
Radiation hardness tests
PMT, Electronics
Synergy with MOLLER; University of Manitoba

Schematic layout of the read-out signal path for the P2 experiment at MESA
Two operation modes:

- High beam current
  - integration mode for asymmetry measurement
  - PMT voltage divider can be operated in low gain mode

- Low beam current
  - pulse mode for kinematics and background study
  - PMT voltage divider can be operated in high gain mode

-Selectable transimpedance amplifier of the preamplifier controlled and switchable externally by use of a raspberry PI
The first tests of the second prototype can begin …

Voltage divider

Preamplifier
Preamplifier test with transimpedance gain = 1,
pulsed input signal of 1Vpp@600nA
feedback resistor 1MΩhm, 1pF

Offset check (without input signal),
with supply voltage +/- 5 V

Integration mode: offset at the output

Event mode: offset measured at the single output
Integration mode

Event mode

Single Output

Raspberry PI Switch Control

Preamplifier

Voltage Divider

Photo Electron Tube 9305QKA

Differential Output

Integration mode

Single Output

Event mode

High Voltage
Threaded rods fix the pin plate to the holding block

Holding block for the PMT

Spring to gently push the PMT to the quartz

The PMT socket with the electronics (PCB)

Due to lack of space, the preamplifier and the voltage divider will be on the same PCB

Copper insulation box around the PCB
Topic C: Experimental design

Qweak electronics

875 MHz  
Detector  
3 μA  
\(~ 50 \text{ pe per event}\)  
\(\times 440 \text{ Gain}\)  

\[\begin{array}{c}
2 \Omega \\
\downarrow \\
\text{I-V Pre-amplifier} \\
\leftarrow 6 \text{ V} \\
\end{array}\]

<table>
<thead>
<tr>
<th>Inside Hall</th>
<th>Outside Hall</th>
</tr>
</thead>
</table>

VME based Filter  
ADC  
FPGA  
DAQ

P2 electronics (large synergy with MOLLER)

5 GHz  
Detector  
13 μA  
\(~ 20 \text{ pe per event}\)  

\[\begin{array}{c}
0.5 \Omega \\
\downarrow \\
\text{I-V Pre-amplifier} \\
\leftarrow 6 \text{ V} \\
\end{array}\]

M. Gericke: U Manitoba  
New prototype, as of November 15, 2018
Theory
Shift in momentum transfer due to photon radiation

Shifted kinematics:

\[ Q^2 = -(l_1 - l_2)^2 \rightarrow Q'^2 = -(l_1 - l_2 - k)^2 \]

\( Q'^2 \) can be on average much smaller than \( Q^2 \).

The average shift in momentum transfer squared due to hard-photon bremsstrahlung can be defined as

\[
\langle \Delta Q^2 \rangle = \frac{1}{\sigma} \int \frac{d^4\sigma_{1\gamma}}{dE' d\theta_1 dE_\gamma d\theta_\gamma} dE' d\theta_1 dE_\gamma d\theta_\gamma \Delta Q^2,
\]

with

\[
\Delta Q^2 = Q'^2 - Q^2,
\]

\[
\sigma = \sigma_{1-\text{loop}}^{1\gamma_{E_\gamma<\Delta}} + \sigma^{1\gamma_{E_\gamma>\Delta}}.
\]
Second-Order QED Corrections

1-loop and 1-photon bremsstrahlung

2-loop and 2-photon bremsstrahlung

1-loop for 1-photon bremsstrahlung
QED at order $O(\alpha^2)$

Leptonic QED second-order corrections:

Monte Carlo event generator program: Ready to study details of kinematic distributions

arXiv:1811.04970
Bremsstrahlung at order $O(\alpha^2)$: $Q^2$ shift

$E = 155$ MeV
$E'_{\text{min}} = 45$ MeV

$\langle \Delta Q^2 \rangle / Q^2 \approx 4.6\%$

QED corrections for the asymmetry:
$Q^2$ shift is a kinematic effect: $1\gamma$ radiation has it all
Very small $O(\alpha^2)$ correction
Dedicated Workshop on $^{12}$C at UNAM Mexico in Spring 2019: DFG+CONACyT SP 778/4-1
Instituto de Física de la Universidad Nacional Autónoma de México (IF-UNAM)
March 18 to April 5, 2019.
HPNC @ MESA+

PV πN coupling

\[ \mathcal{L}_{PV} = -i h_{\pi}^1 \pi^+ p^+ n + h.c. + \ldots \]

Non-derivative coupling, dominate at low energies; Origin: effective PV 4-quark operators
Recent result from \( \bar{n}_p \rightarrow d \gamma \) experiment @ Los Alamos: Blyth et al [NPDGamma] '2018

\[ h_{\pi}^1 = (2.6 \pm 1.2 \pm 0.2) \times 10^{-7} \quad A_{PV} \sim 0.1 h_{\pi}^1 \sim 10^{-8} \text{ hard to measure; low rate; polarized UCN} \ldots \]

Chen, Ji 2001: semi-inclusive threshold π production w. polarized e-
Larger signal: \( A_{PV} \sim 0.5 h_{\pi}^1 \)

Sensitivity to \( h_{\pi}^1 \): beam energy close to π threshold
e' undetected - quasi-real photon \( \langle Q^2 \rangle \sim 0.001 \text{ GeV}^2 \)
Z-exchange suppressed: \( A_{PV}^{Z} \approx - \frac{G_F \langle Q^2 \rangle}{2\sqrt{2}\pi \alpha} \sim -2 \times 10^{-7} \)

\( h_{\pi}^1 \) partially cancels Z-exchange; but Z-exchange is known (P2 + A2@MAMI)
P2: \( A_{PV} = -4 \times 10^{-8} \) to 1.5%; PV π production: \( A_{PV} = -2 \times 10^{-7} \) to 10-20%

Z-exchange only

Z-exch. + \( h_{\pi}^1 \)

Shaded band: uncertainty due to \( h_{\pi}^1 \)

\[ E = 200 \text{ MeV} \]
\[ \theta = 30^\circ \]

\[ E = 200 \text{ MeV} \]
\[ \theta = 150^\circ \]

\[ E = 180 \text{ MeV} \]
\[ \theta = 150^\circ \]