The Polarimeter chain for the MESA-PV experiment

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Outline

• The MESA-PV experiment at Mainz
• and the eight-fold way to achieve $\Delta P/P < 0.5\%$?
**Planned $\sin^2(\theta_W)$- Measurement at the MESA facility in Mainz**

MESA:
Mainz Energy Recovering Superconducting Accelerator

MESA-PV:
Operated as “Conventional” Machine (external polarized beam)

Beam Parameters
E=137 MeV, I=0.15mA, P=0.85
L~10^{39} cm^{-2}s^{-1}

MESA Accuracy goal: $\Delta A_{PV}/A_{PV}=1.6\%$

one (out of many) requirements

$\Delta P/P \sim 0.5 \%$

“Unimpeachable” polarization measurement: two independent polarimeters with $\Delta P/P < 0.5\%$ each.

Machine could be in operation in 2017 $\Rightarrow$ start polarimeter tests NOW!
Electron-Polarimeter chain at MAMI

MAMI-C: 1500 MeV c.w. machine beam power: up to 150kW operation time ~6000h/year >3000h polarized

- Laser-Compton- in Hall A4
- Möller in Hall A1 (also: A2)
- Mott at front end of MAMI
### Existing Electron-Polarimeter chain at MAMI

<table>
<thead>
<tr>
<th>Polarimeter</th>
<th>ΔP/P present (Potential)</th>
<th>Main uncertainty</th>
<th>Measurement Time @1% stat</th>
<th>Operating current</th>
<th>Energy range [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mott</td>
<td>0.05 (0.01)</td>
<td>Background</td>
<td>3s-1h</td>
<td>5nA - 40μA</td>
<td>1-4</td>
</tr>
<tr>
<td>Möller</td>
<td>0.02 (0.01)</td>
<td>Target pol.</td>
<td>30min</td>
<td>50nA</td>
<td>300-1500</td>
</tr>
<tr>
<td>LCP</td>
<td>0.02 (0.01)</td>
<td>Calibration, Target pol.</td>
<td>12 h</td>
<td>20μA</td>
<td>850-1500</td>
</tr>
</tbody>
</table>

Mott is not (yet) competitive in absolute accuracy but provides ‘linking’ capabilities due to wide dynamic range and good reproducibility.

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Some remarks

• low energy restriction of Mott scattering probably no cause for additional systematics at MESA
  (→ exact spin tracking possible, no resonances)
• LCP not possible at MESA due to small energy, Hydro-Möller could work
• Different concepts (‘paradigms’) of measurements:
  - Hydro Möller ‘double-polarization’
  - Mott ‘double scattering’
Solenoid traps pure H↑ which has a long lifetime due to He-coating of storage cell. All other species are removed quickly from the trap. → 1-ε Polarization can be reasonably well estimated, but measurement difficult.
Some remarks

• Beam/solenoid adjustment critical, due to high field and low energy \( \rightarrow \) consequences for PV-detector calibration ('dithering'), etc
• Scattered electrons may perform several cyclotron oscillations in solenoid field \( \rightarrow \) Detector acceptance determination?
• The Hydro-Möller follows a 'paradigma': „accurate determination of effective analyzing power is achieved by factorization of theoretical and experimental effects“

\[
A_{\text{exp}} = P_{\text{beam}} \underbrace{\text{Corr} P_T S_0}_{S_{\text{eff}}} \quad \text{Corr = i.e dilution by background}
\]
A different approach

How to avoid the systematic errors caused by individual factors?
Apparent attractiveness of standard (single-) Mott-scattering:

\[ A_{\text{exp}} = P_{\text{beam}} \frac{\text{Corr} S^y}{S_{\text{eff}}} \Rightarrow \text{No } P_T ! \]

(but no change of Paradigma)

In **double** elastic scattering \( S_{\text{eff}} \) can be measured! (...another paradigm...)

After scattering of **unpolarized** beam:
\[ P_{\text{sc}} = S_{\text{eff}} \]
(Equality of polarizing and Analyzing Power :)

After second "identical" scattering process
\[ A_{\text{exp}} = S^2_{\text{eff}} \]

with great effort to eliminate apparative asymmetries and to provide 'identical' scattering )
the claimed accuracy in \( S_{\text{eff}} \) is \(<0.3\%!\)

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A. Gellrich and J. Kessler
PRA 43 204 (1991)
Some remarks

- DSP works at ~100keV; ideal for 1mA-MESA-stage-1
- Original Kessler apparatus available
- Targets **not** extremely thin (~100nm)
- Elimination of apparatus asymmetry depends critically on geometrical arrangement of normalization counters
- Apparatus calibrates $S_{\text{eff}}$, but does not allow to measure $S_0$
- Inelastic contributions do not jeopardize the accuracy!
- Potential issues
  - how to use with polarized beam?
  - What if the two targets are NOT identical?

Hopster & Abraham (1989):
In this case the first target may be treated as an auxiliary target and the availability of (switchable) Polarization may be exploited for even better accuracy!
Kessler/Hopster/Abraham/Kessler Method

1.) measurement: Pol beam on second target
   \[ A_1 = S_\text{eff} P_0 \]

2.) with 'auxiliary target': \( S_T; + P_0 \)
   \[ A_2 = P_T S_\text{eff} = \frac{S_T + \alpha P_0}{1 + S_T P_0} S_\text{eff} \]
   \( \alpha = \) Depolarization factor for first Target

3.) with 'auxiliary target': \( S_T; - P_0 \)
   \[ A_3 = P_T S_\text{eff} = \frac{S_T - \alpha P_0}{1 - S_T P_0} S_\text{eff} \]

4.) unpolarized beam on aux. target
   \[ A_4 = S_T S_\text{eff} \]

5.) Scattering asymmetry from auxiliary target
   \[ A_5 = P_0 S_T \]

5 equations with four unknowns →
consistency check for apparative asymmetries!
→ Results achieved by Kessler were consistent <0.3%

S. Mayer et al
Some remarks

- Auxiliary target method was limited by statistical efficiency (today about 5 times better!)
- DSP invasive, but fast.
- Probably not feasible to operate DSP at > $100\mu$A current level, requires 'linking Polarimeter'
- Linking with high precision polarimeters to be installed at 5MeV (Mott/Compton-combination
- Mott/Compton combination invasive but extremely fast (O(seconds) <1% stat. accuracy), also control of spin angle
- In total eight measurements: 5 DSP, 2 linking, 1 Hydro Möller, \(\rightarrow\) ',the eight-fold way'
Linking capabilities

Dynamic Range:


Stability:


Polarization Drift consistently observed in transverse AND longitudinal observable at the <0.5% level (Measurement at 3.5 MeV, 35 μA) Compton is an analogue, Mott a counting measurement
ERL-DUMP

Injector

Main-Linac

Dark Photon Experiment

ERL-Option: Half-wave-recirculation

EB Option: (Parity-experiment): Full-Wave-recirculation

Former MAMI Beam tunnel

Polarized Source

Double-scattering Polarimeter

Compton Monitor

Recirculations

Hydro-Möller

to PV-Detektor

Shielding

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Conclusion:

MESA Spin chain

• low and a high energy polarimeter cross-check: negl. depolarization due to low energy gain of MESA
• Monitoring, stability and cross calibration can be supported by extremely precise Mott/Compton combination.
• Hydro Möller + DSP may obtain $\Delta P/P <0.5 \%$ each,

Status of MESA

• MESA accelerator & experiments are under design,
• Funding decision within next year.
• MESA-PV data taking possible in 2017/18 (10000h BOT).
Conclusion

• MESA operates in EB-mode for PV and in ERL-mode for Dark Photon experiment.
• Main cost factor – building - eliminated, other one –SRF- reduced by multi-turn recirculation.
• PV requires extreme beam parameter stability
• …and accurate polarization measurement by a polarimeter chain
• In ERL mode, the new issue is multi-turn recirculation
• no doubt that this project provides room for students and young researches!
“Unimpeachable” polarization measurement: two independent polarimeters with $\Delta P/P < 0.5\%$ (NOT: 1%) each.
MESA-experiments-2- Search for Dark photon at MAMI/MESA

H. Merkel et al. (A1 collab. at MAMI): suggest to measure e+/e- pair invariant mass with double spectrometer set up at MAMI.

Demonstration experiment at MAMI 100μA/855MeV on 0.4% rad. length Tantal (2 weeks runtime) (submitted to PRL)

Limits:
- Low energy regime (background)
- other decay modes of A’ ?
- runtime (several years ???)

MESA’s corner is adjacent to most of the a_μ region (interesting because of 3σ deviation of a_μ from SM )

MESA: Dedicated machine for m_{A’} <100MeV with optimized background
High beam power electron beam may be used for:

- ERL-mode: Production of nanodiamonds (see talk by F. Jelezko this afternoon)
- EB-mode: High brightness source of cold (polarized) positrons

Color: NV-centers introduced in Diamond. Irradiated at MAMI for 3 days, 50μA at 14MeV

(J. Tisler et al. ACS NANO 3,7 p.1959 (2009))


→ MESA can produce
~10⁹ positrons/s in a beam of <1cm diameter at 120eV
→ surface science: magnetic structure
→ positronium production
MESA accelerator project rationale and beam parameter goals

- Experiments require a new & innovative accelerator
- ….but energy is low, therefore accelerator ‘affordable’
- MAMI acc. team competence represents basis for development
- Project will be attractive for young students and researchers

Make use of innovations in SRF accelerator science:

1. Energy recovery linac (ERL)
2. Improvements on high gradient-c.w.-SRF

Beam parameter goals in two different modes of operation:

1.) EB-mode External spin-polarized c.w. beam (EB-mode) at 137 MeV
   \( Q^2 = 0.005 \text{GeV/c at 30 degree} \).
   \( L > 10^{39} \ \text{cm}^{-2}\text{s}^{-1} \)

2.) ERL-mode: 10mA at 100 MeV with \( L \sim 10^{35} \ \text{cm}^{-2}\text{s}^{-1} \)
KEY:
PS: Photosource (polarized or unpolarized beam)
IN: 2.5 MeV – injector
SC: 3 Superconducting cavities, @ 13 MV/m.
    Energy gain 34 MeV per pass.
RC: Beam recirculation 3 times
HW: Third recirculation option ‘half wave’:
    Energy Recovery Linac (ERL-) Mode
FW: Third recirculation option: ‘full wave’
    External Beam (EB-) mode
PIT: Pseudo Internal target (ERL mode)
PV: Parity violation experiment (EB-mode)
DU: 2.5 MeV beam dump in ERL-mode
EX: Experimental areas 1 and 2
    Existing walls: 2-3m thick shielding

EXPERIMENTAL BEAM PARAMETERS:
1.3 GHz c.w.
EB-mode: 150 μA, 137 MeV polarized beam
    (liquid Hydrogen target L~10^{39})
ERL-mode: 10mA, 104 MeV unpolarized beam
    (Pseudo-Internal Hydrogen Gas target, L~10^{35})
<table>
<thead>
<tr>
<th>Project/Purpose (status)</th>
<th>Av. Beam current (mA)</th>
<th># of Recirc.</th>
<th>Norm. emit. (μm)</th>
<th>Bunch charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MESA/ particle physics (under design)</td>
<td>10</td>
<td>3</td>
<td>10</td>
<td>7.7</td>
</tr>
<tr>
<td>JLAB/ light source (achieved)</td>
<td>10</td>
<td>1</td>
<td>7</td>
<td>7.7</td>
</tr>
<tr>
<td>BERLinPro/light source demonstrator (under design, funded)</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>77</td>
</tr>
<tr>
<td>eRHIC/particle physics (under design)</td>
<td>50</td>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MESA will **not** have to provide extreme bunch parameters
- New issue: **multi-turn recirculation** (two or three times?) → MESA may be useful as a test-bench for LHeC, eRhic, or others....
- The **challenge** is compliance between ERL and EB operation → see talk tomorrow!
  → Discuss now: specific issues for DM and PV
DM: Focusing through the PIT

\[ \varepsilon_{\text{Norm}} = 10 \mu m \text{ (or 3.2 } \pi \text{ mm}^* \text{ mrad}^* \text{ m}_e \text{c) (MESA goal)} \]

\[ \varepsilon_{\text{Geo}} = \frac{\varepsilon_{\text{Norm}}}{\sqrt{\gamma^2 - 1}} \implies \varepsilon_{\text{Geo}} (100\text{MeV}) \sim 50\text{nm}. \]

Beam diameter as a function of optical function \( \beta \):

\[ r_{\text{beam}}^2 (z) = \varepsilon_{\text{Geo}} \cdot \beta(z) \]

in the field free region around symmetry point \( z^* = 0 \)

\[ \beta(z) = \beta(z^*) + \frac{z^2}{\beta(z^*)} = \beta^* (1 + (z / \beta^*)^2) \text{ (choose: } \beta^* = 1m) \]

\[ \implies \text{Maximum beam diameter } \leq 0.62\text{mm over 2 Meters of length} \]
Assuming target density $N=2\times10^{18}$ atoms/cm$^2$ ($3.2\ \mu g/cm^2$, $5\times10^{-8} \ \chi_0$)
we have (at $I_0=10^{-2}$ A) luminosity of $L=\frac{I_0}{e*N}=1.2\times10^{35} \ \text{cm}^{-2}\text{s}^{-1}$
\rightarrow (average) ionization Energy loss: $\sim 17\text{eV}$
\rightarrow could allow to recuperate more energy than in conventional ERL (2.5MeV).
\rightarrow RMS scattering-angle (multiple Coulomb scattering): $10\mu\text{rad}$
\rightarrow single pass beam deterioration is acceptable Note: storage ring:
    - beam emittance lifetime $\sim 10\text{milliseconds}$ (stationary vs. variable background…)
\rightarrow beam halo & long tails of distribution due to Coulomb scattering have to be studied
PV is a simple experiment

\[ A_{\text{exp}} = \frac{(N_{\uparrow\downarrow} - N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow})} \]

For elastic scattering on Hydrogen

\[ A_{\text{exp}} = P \left( 1 - 4 \sin^2(\theta_W) \right) Q^2 \cdot Korr + F(G_{P,N}^{E,M}(Q^2), Q^2, E_0, \theta) \right) + A_{\text{FALSE}} \]

\[ Korr(\gamma Z) \propto (1 + k(\gamma Z)E_0) \]

\[ k(\gamma Z) \text{ is not very well known} \Rightarrow \text{see talks on PV} \]

Penalty for choosing low \( Q^2 \): \( A_{PV} \) becomes very small (roughly 50 ppb)

\( \Rightarrow \) Even at \( L > 10^{39} \) the experiment will need about 10000 hours BOT: Experiment cannot be done at MAMI without strong interference with ongoing program.

\( \Rightarrow \) \( A_{\text{False}} \) must be controlled to <0.4 ppb: Improve established techniques from PVA4 by about an order of magnitude (see accelerator talk tomorrow)

\( \Rightarrow \) \( \Delta A_{PV}/A_{PV} = 1\% \rightarrow \Delta P/P < 0.7\%, \text{ better} <0.5\% \).

(MAINZ05-project)
Beam polarimetry is a simple experiment

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{0,\text{proc}} \cdot \left(1 + \sum_{i=x,y,z} S_i(\theta) \cdot P_i^{\text{Beam}} + \sum_{i,j=x,y,z} S_{i,j}(\theta) \cdot P_i^{\text{Beam}} P_j^T\right)
\]

Process examples:
- Elastic Electron (Mott-)scattering: \( S_y \)
- Möller - or Compton - Backscattering: \( S_{zz} \)

\[
A_{\text{Mott}} = P_y^{\text{BEAM}} S_y(\theta, E...); \quad A_{\text{Möller}} = P_z^{\text{BEAM}} P_z^{\text{Target}} S_{zz}(\theta, E...)
\]

Ideal polarimeter would have simultaneously:
1. Online operation at experimental beam conditions,
2. \( \Delta P/P < 0.5\% \),
3. fast polarization monitoring.

Probably the best approach: The “Hydro-Möller”-Polarimeter
- Online operation possible
- low Levchuk effect (\( Z=1 \) vs \( Z=26 \) conventional)
- very high \( P_T S_{zz} \rightarrow \) good efficiency in spite of low count rate statistics to 0.5% within about 30min
- \( P^{\text{Target}}=1-\varepsilon \rightarrow \) small Target polarization error (\( \varepsilon \sim 10^{-5} \))
- Problem: Not realized yet \( \rightarrow \) how does it work?