Hadron free measurement of electron beam polarization

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Outline

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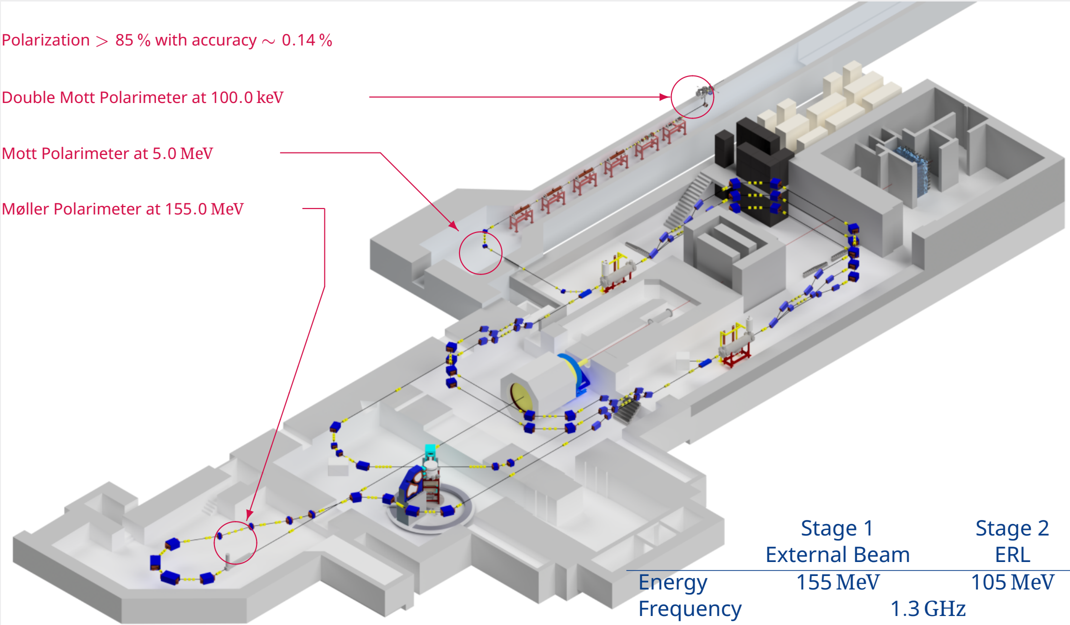
MESA accelerator

Polarization $>$ 85 % with accuracy $\sim$ 0.14 %

Double Mott Polarimeter at 100.0 keV

Mott Polarimeter at 5.0 MeV

Møller Polarimeter at 155.0 MeV



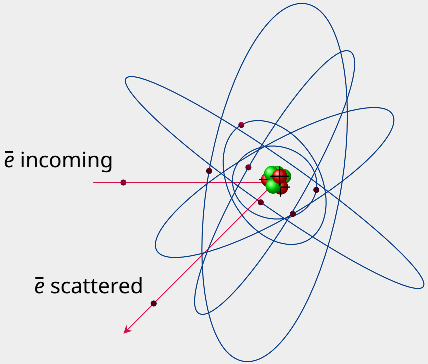
	Stage 1 External Beam	Stage 2 ERL
Energy	155 MeV	105 MeV
Frequency	1.3 GHz	
Current	150 μA / 1 mA	150 μA / 10 mA
Emittance	0.1 mm mrad	$<$ 1.0 mm mrad

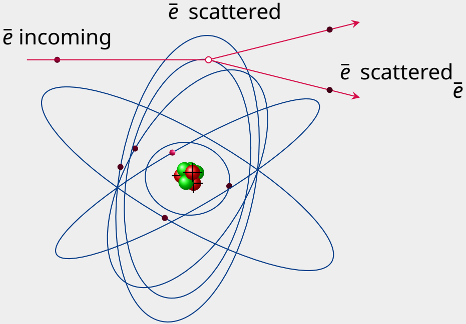
Outline

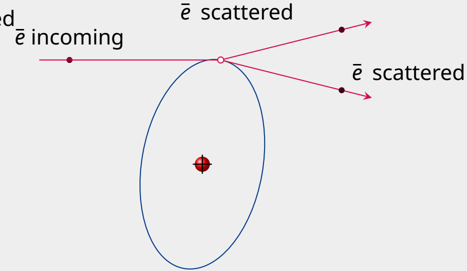
Introduction into the COMP experiment

- Motivation: Future parity violation (PV) experiments require unprecedented electron beam polarimetry accuracy of 0.1%.
- Challenge: Achieving this accuracy is challenging with existing methods, necessitating innovative approaches like the Colliding Beam Møller Polarimeter (COMP).
- Idea is to use hadron free target to avoid or reduce influence of hadrons

Basic principle





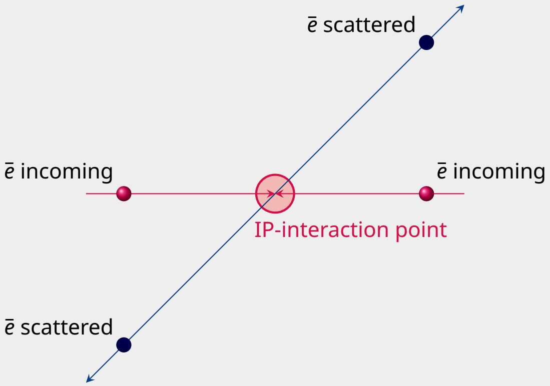


- Mott
- Target Au Z=79, A=197

- Conventional Møller
- Target Fe Z=26, A=59

- Hydrogen Møller
- Target H, Z=1, A=1

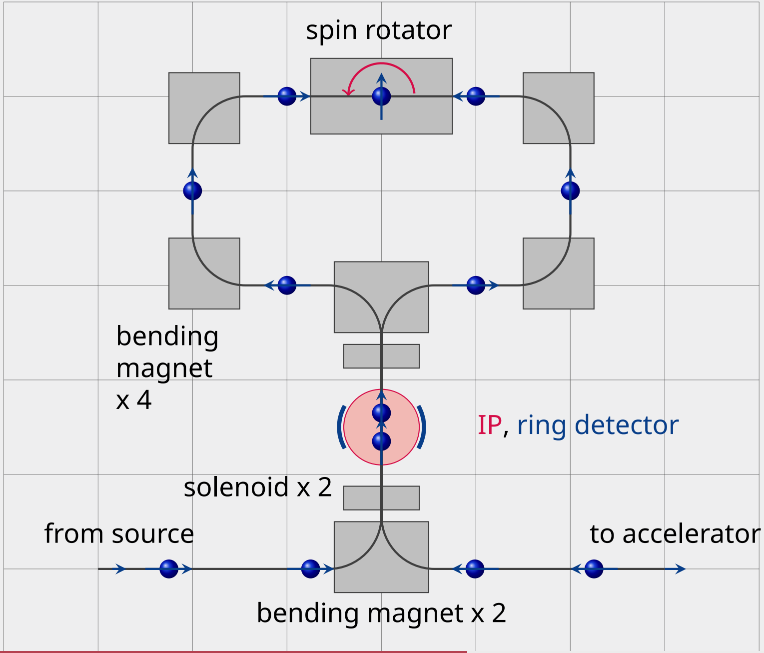
Maybe try hadron free?



- Scattering electron on electron
- Electron bunch atcs itself as target
- No any hadrons in interaction point
- Background free
- Energy range ...?
- Current up to ... ?
- Overall accuracy is to be estimate

Outline

Scheme COMP experiment, Measurement Principle



- Proposed by Prof. K.Aulenbacher
- Bending magnets, solenoids or quadropoles are similar to MESA/MAMI magnets
- Colliding bunches: longitudinally polarized electron bunches are recirculated and collided at an interaction point (IP) in a reflexotron geometry.
- Spin Rotator: Double Focusing Wien Filter allows switching the spin direction at the IP
- Beam polarization P_{beam} is derived from A_{exp} and the analyzing power A_{zz} as:

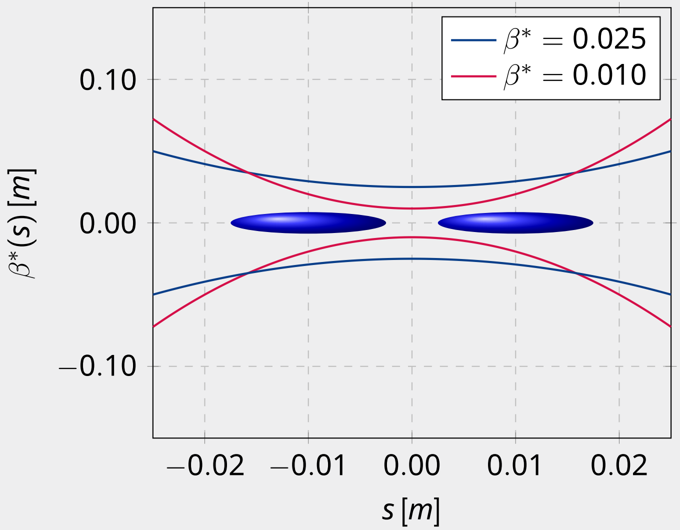
$$P_{beam} = \sqrt{\frac{A_{exp}}{A_{zz}}}$$

Møller Scattering Details and Luminosity and Rate Scaling

- Cross Section: The Møller cross section is given by $\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s} \cdot \frac{(3+\cos^2\theta)^2}{\sin^4\theta}$, scaling with the inverse square of the total energy.
- Analyzing Power: A_{zz} varies with the Lorentz factor γ and scattering angle θ. For $\gamma \gg 1$ and $\theta = 90^\circ$, $A_{zz} = -\frac{7}{9}$ in CM system.
- Solid Angle: A large solid angle (≥ 1 sr) can be utilized due to the weak angular dependence of the cross section and analyzing power around 90°.
- Luminosity Formula: $L = f_{\text{coll}} \cdot N_B^2 \cdot k \cdot \pi r_{\text{IP}}^2$, where f_{coll} is the collision frequency, N_B is the bunch charge, and r_{IP} is the beam radius at the IP.
- Rate Scaling: The signal rate R scales with $\frac{1}{E_{\text{beam}}}$ due to the inverse square dependence of the cross section on energy and the linear increase of luminosity with energy.
- Optimization: High bunch charges and optimized beam optics (β_{IP}) are crucial for achieving high luminosities and, consequently, high signal rates.

Outline

Beta Star Profile in Hourglass



- Definitions β^* – reference to minimum beta-star value, which fixes the beam size at the interaction point; s – longitudinal coordinate along the beam axis; $\beta(s)$ – beta star value at the position s.
- Beta-star profile equation

$$\beta(s) = \beta^* \left(1 + \left(\frac{s}{\beta^*}\right)^2\right)$$

Luminosity calculation, collision 0.2 MeV vs 0.2 MeV beam

- Beam and particle parameters:

$$I_\text{beam} = 150 \times 10^{-6}\,\mathrm{A}, \quad T = 200\,\mathrm{keV}, \quad m = 510.9\,\mathrm{keV}, \quad q = 1.6021 \times 10^{-19}\,\mathrm{C}$$

- Relativistic factors:

$$\gamma = \frac{T+m}{m} \approx 1.391, \qquad \beta = \sqrt{1 - \frac{1}{\gamma^2}} \approx 0.695$$

- Collision parameters:

$$f = 20 \times 10^6\,\mathrm{Hz}, \quad n_\text{bunch} = \frac{I_\text{beam}}{q f} \approx 4.68 \times 10^7, \quad q_\text{bunch} = \frac{I_\text{beam}}{f} \approx 7.5 \times 10^{-12}\,\mathrm{C}$$

- Beam optics:

$$\varepsilon_n = 1 \times 10^{-6}\,\mathrm{m \cdot rad}, \quad \beta^* = 0.01\,\mathrm{m}, \quad r_\mathrm{IP}^2 = \frac{\varepsilon_n \beta^*}{\beta\gamma} \approx 1.20 \times 10^{-8}\,\mathrm{m}^2$$

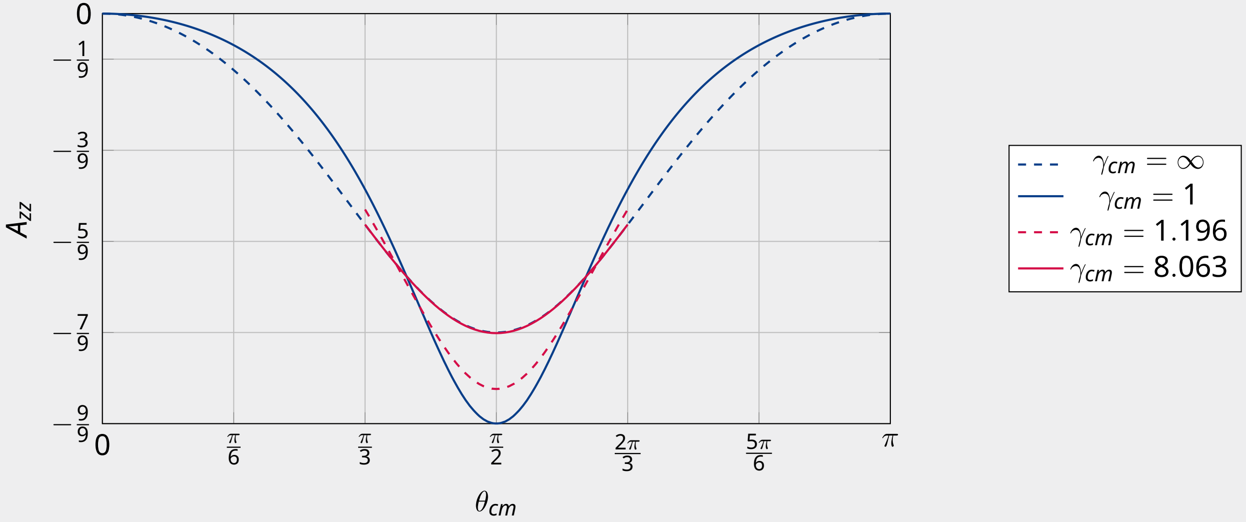
- Luminosity:

$$\mathcal{L} = \frac{I_\text{beam}}{q} \frac{n_\text{bunch}}{4\pi r_\mathrm{IP}^2} \approx 2.91 \times 10^{29}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$$

- Cross-section and result:

$$\sigma = 0.148 \times 10^{-28}\,\mathrm{m}^2, \qquad R = \mathcal{L}\,\sigma\,2\pi \approx 31\,\frac{1}{s}$$

Asymmetry $A_{zz}(\theta_{cm})$ for different γ_{cm} in CM-system



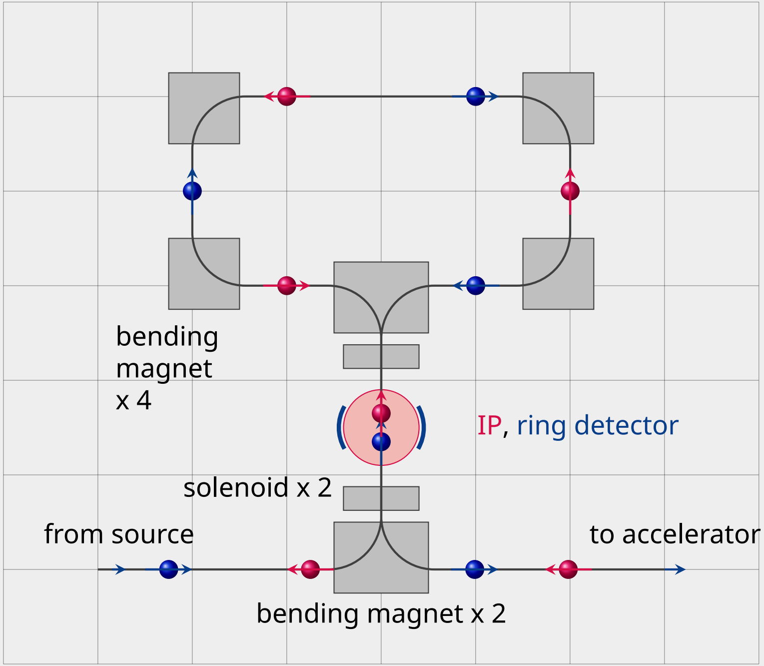
- $A_{zz}(\theta_{cm}) = \dfrac{\sin^2(\theta_{cm})\left((\gamma_{cm}^4 - 1)\sin^2(\theta_{cm}) - (2\gamma_{cm}^2 - 1)(4\gamma_{cm}^2 - 3)\right)}{(2\gamma_{cm}^2 - 1)^2(4 - 3\sin^2(\theta_{cm})) + (\gamma_{cm}^2 - 1)^2(4 + \sin^2(\theta_{cm}))\sin^2(\theta_{cm})}$
- Blue theory, red in detector acceptance

COMP-TE - Test Experiment

- Objective: Investigate background conditions and luminosity fluctuations using the existing PKA2 source.
- Setup: Utilize PKA2's capability to deliver 100 keV beams with currents up to 3 mA for background studies and luminosity control experiments.
- Detector: Employ existing surface barrier detectors from the 100 keV-Mott setup for initial measurements.

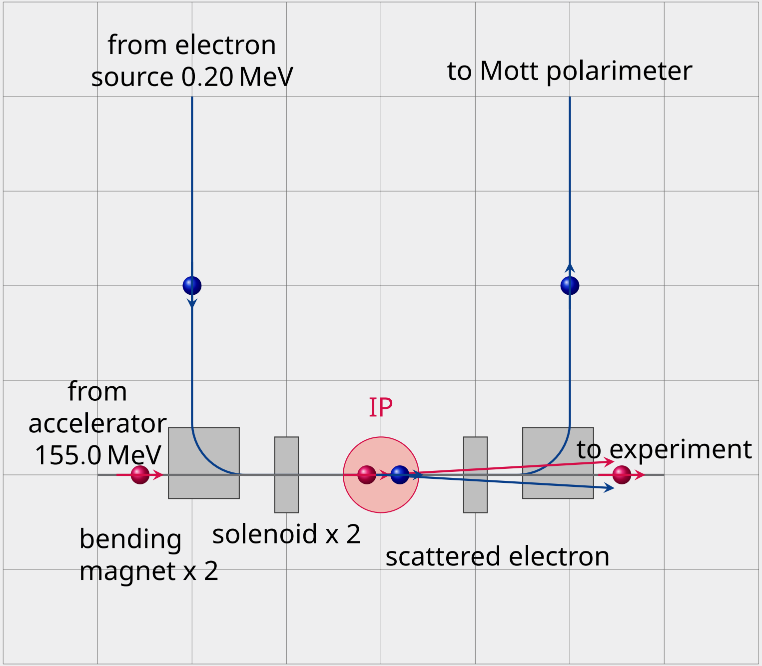
Outline

Scheme with two lasers



- Spin rotator removed
- Wien Filter critical component
- Two lasers with photon beam opposite helicity
- Laser capable of switching polarization of individual pulses
- additional control of beams position in IP

Scheme electron race



- Two independent electron beams
- Accelerator beam 155 MeV
- Target beam 0.2 MeV
- Continuously measurements possible
- Magnet system from two bending magnets and two solenoids for 0.2 MeV beam
- No influence on 155 MeV beam
- Scattered electrons to standard Møller detector

Kinematics, angles transformations, differential cross section

- Input: kinetic energies T_1, T_2 in the lab frame.
- Compute β_i, γ_i for each electron.
- Transform to CM system: obtain $\beta_{\mathrm{CM}}, \gamma_{\mathrm{CM}}$.
- In CM: $E' = \gamma' m$, $p' = \gamma' \beta' m$.
- Laboratory angles from CM angles:

$$\tan\theta_{\mathrm{lab}} = \frac{p' \sin\theta_{\mathrm{CM}}}{\gamma_{\mathrm{CM}}(p' \cos\theta_{\mathrm{CM}} + \beta_{\mathrm{CM}} E')}.$$

- Symmetric kinematics in CM $\rightarrow$ strongly asymmetric outcomes in the laboratory.
- In CM system at $\theta_{\mathrm{CM}} = 90^\circ$:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{CM}} = \frac{\alpha^2}{4m^2} \frac{(1 + 2\gamma'^2\beta'^2)^2 + 5\gamma'^4\beta'^4}{\gamma'^6\beta'^4}.$$

- Conversion to laboratory system:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{lab}} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{CM}} \cdot J, \quad J = \frac{d\Omega_{\mathrm{CM}}}{d\Omega_{\mathrm{lab}}}.$$

- Units: $1 r_e^2 \approx 0.0794$ barn.

Rate calculation 155.0 Mev vs. 0.2 MeV

- Beam and particle parameters:

$$I_{\text{beam}} = 150 \times 10^{-6}\,\mathrm{A}, \quad m = 510.9\,\mathrm{keV}, \quad q = 1.6021 \times 10^{-19}\,\mathrm{C}$$

- Relativistic factors:

$$T_1 = 155000\,\mathrm{keV}, \quad \gamma_1 = 304.386, \quad \beta_1 \approx 0.999995$$

$$T_2 = 200\,\mathrm{keV}, \quad \gamma_2 = 1.391, \quad \beta_2 \approx 0.6953$$

- Collision parameters:

$$f = 20 \times 10^6\,\mathrm{Hz}, \quad n_{\text{bunch}} = \frac{I_{\text{beam}}}{q f} \approx 4.68 \times 10^7, \quad q_{\text{bunch}} = \frac{I_{\text{beam}}}{f} \approx 7.5 \times 10^{-12}\,\mathrm{C}$$

- Beam optics:

$$\varepsilon_n = 1 \times 10^{-6}\,\mathrm{m \cdot rad}, \quad \beta^* = 0.01\,\mathrm{m},$$

- Luminosity:

$$\mathcal{L} = \frac{I_{\text{beam}}\, n_{\text{bunch}}}{q\, 2\pi \left(\frac{\varepsilon_n \beta^*}{\beta_1 \gamma_1} + \frac{\varepsilon_n \beta^*}{\beta_2 \gamma_2} \right)} \approx 9.66 \times 10^{29}\,\mathrm{m^{-2}\,s^{-1}}$$

- Cross-section and result:

$$\sigma = 0.0027 \times 10^{-28}\,\mathrm{m}^2, \qquad R = \mathcal{L}\,\sigma\, 2\pi \approx 1.14 \frac{1}{s}$$

Numerical Results

Case	γ'	β'	J	θ_{lab} (deg)	$\frac{d\sigma}{d\Omega}\Big\rvert_{\text{CM}}\ \frac{barn}{sr}$	Rate, $\frac{1}{s}$
0.1 MeV vs 0.1 MeV	1.196	0.548	1.000	90.0	0.329	47
0.2 MeV vs 0.2 MeV	1.391	0.695	1.000	90.0	0.148	31
155 MeV vs rest	12.356	0.997	154.166	4.63	0.00117	NA
155 MeV vs 0.2 MeV	8.063	0.992	367.861	3.00	0.00277	1.14

Table: Relativistic electron–electron scattering at $\theta_{\text{CM}} = 90^\circ$. Listed are γ', β' in the CM system, the Jacobian J, the corresponding laboratory angle θ_{lab}, and the differential cross section in the CM frame.

- Strong forward peaking in high-energy asymmetric cases.

Outline

Conclusion

- Feasibility: The colliding beam Møller polarimeter offers a promising approach to achieving 0.1% polarimetry accuracy, pending successful R&D on background and luminosity control.
- Next Steps: Experimental validation at PKA2 and further development of the polarimeter setup are crucial for future PV experiments and EDM searches.

References

1 D. Becker et al., Eur. Phys. J. A 54, DOI 10.1140/epja/i2018–12611–6 (2018).

Acknowledgments

PIFI progmam on CAS

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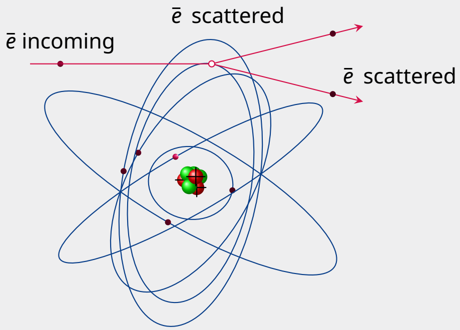
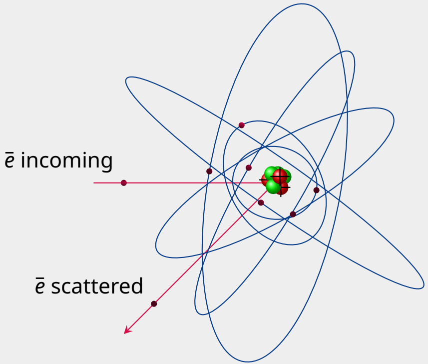
Thank you for your attention!

Connection to EDM Searches

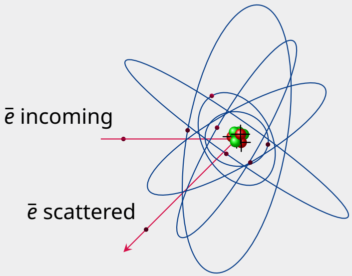
- Relevance: The colliding beam scheme is also applicable to Electric Dipole Moment (EDM) searches in electrostatic storage rings.
- Advantage: Counter-propagating beams reduce systematic errors and enable the use of the polarimeter scheme for spin diagnostics in frozen spin mode [1].
- Challenges: Proton EDM rings require significantly larger dimensions ($\sim$100 meters) compared to compact electron devices due to differing γ_{FS} values [1].

Møller and Mott scatterings



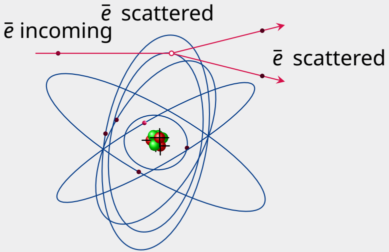


Mott polarimeters at MAMI and MESA



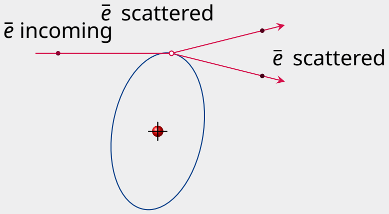
- MAMI 3.5 MeV
- MESA double 100 keV, 5.0 MeV
- Scattering on heavy nucleous
- $P=\frac{A_{exp}}{S_{eff}}$
- Target Au Z=79, A=197
- $\rho_{\mathrm{Au}} \times L_{\mathrm{Au}} = 6.0 \times 10^{18}\,\mathrm{cm}^{-2}$
- Current up to 20 μA
- Foil thickness $0.1 - 1.0\,\mu$m
- Problems: determination of S_0, radiative effects, extrapolation uncertainties of S_{eff} , target induced background reduces A_{exp}
- Overall accuracy of $\leq 1.0\%$

Møller polarimeter at MAMI 180.0-1500.0 MeV



- Scattering on heavy or ligth nucleous
- Target Fe Z=26, A=59
- $\rho_{\mathrm{Fe}} \times L_{\mathrm{Fe}} = 6.0 \times 10^{19}\,\mathrm{cm}^{-2}$
- Energy range $0.15 - 12.0\,\mathrm{GeV}$
- Current up to $1\,\mu\mathrm{A}$
- Foil thickness $5.0 - 10.0\,\mu\mathrm{m}$
- Problems: target saturation, Levchuk effect
- Overall accuracy of $\leq 1.0\%$

Hydrogen target for Møller polarimeters



- Scattering on hydrogen nucleous
- Target H, Z=1, A=1
- Ionization energy = 13.6 eV
- $\rho_{\mathrm{H}} \times L_{\mathrm{H}} = 6.0 \times 10^{16}\,\mathrm{cm}^{-2}$
- Energy range $0.15 - 12.0\,\mathrm{GeV}$
- Current up to $1000.0\,\mu\mathrm{A}$
- No Levchuk effect
- Overall accuracy of $\leq 0.14\%$

Scattering Invariants and Cross Section

$$s = 2m^2\left(1 + \gamma_1\gamma_2\left(1 - \beta_1\beta_2\cos\theta_{12}\right)\right)$$
$$t = 2m^2\left(1 - \gamma_1\gamma_3(1 - \beta_1\beta_3\cos\theta_{13})\right)$$
$$u = 2m^2\left(1 - \gamma_1\gamma_4(1 - \beta_1\beta_4\cos\theta_{14})\right)$$

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{\text{barn}}\frac{4\pi m^2\,dt}{2\pi s(s-4m^2)}\left[\frac{1}{t^2}\left(\frac{s^2+u^2}{2} + 4m^2(t-m^2)\right) + \frac{1}{u^2}\left(\frac{s^2+t^2}{2} + 4m^2(u-m^2)\right) + \frac{4}{tu}\left(\frac{s}{2} - m^2\right)\left(\frac{s}{2} - 3m^2\right)\right]$$