Study of quantum spin correlations of relativistic electrons

Michał Drągowski

M. Adamus P. Caban J. Ciborowski M. Dehn J. Enders
Y. Fritzsche J. Rembieliński V. Tioukine

2019 Workshop on Polarized Sources, Targets, and Polarimetry,
September 23, 2019

UNIVERSITY OF WARSAW

2POL

Correlation function

$$C(A, B) = \sum_{\alpha\beta} \alpha\beta P_{\alpha\beta}$$

$P_{\alpha\beta}$ – probability of obtaining α and β as a result of measurement of observables A and B, respectively

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Observables A and B – spin projections on given directions, measured by two distant observers

$$C(\vec{a},\vec{b}) = P_{++} + P_{--} - P_{+-} - P_{-+}$$

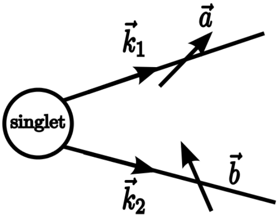
Experiments with massive particles

- experiments with protons:

Lamehi, Rachti, Mittig	1976	Saclay (France)
Hamieh *et al.*	2004	KVI (Holland)
Sakai *et al.*	2006	RIKEN (Japan)

- measurement of correlation function and violation of Bell inequalities for massive non–relativistic particles
- non–relativistic quantum mechanics only (too low energies)

Example: fermions in singlet state



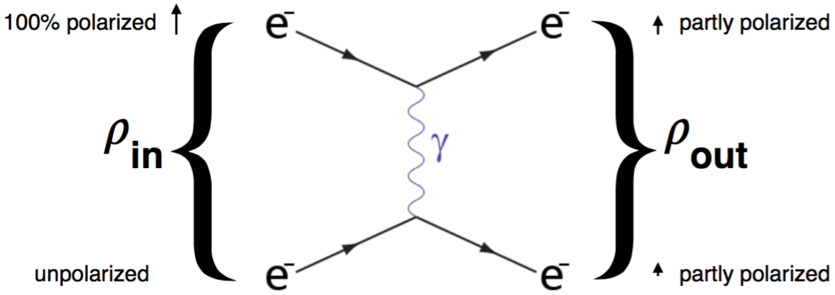
- spin $\frac{1}{2}$
- k_1, k_2 – particles four–momenta
- relativistic correction to the correlation function dependent on particles momenta

$$\text{singlet} \rightarrow k_1 \; k_2$$

$$\mathcal{C}(\vec{a}, \vec{b}) = -\vec{a} \cdot \vec{b} \; +$$

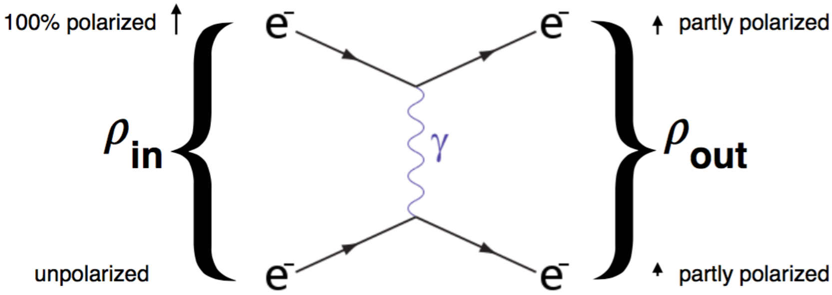
$$+ \underbrace{\frac{\vec{k}_1 \times \vec{k}_2}{m^2 + k_1 k_2} \left[\vec{a} \times \vec{b} + \frac{(\vec{a} \cdot \vec{k}_1)(\vec{b} \times \vec{k}_2) - (\vec{b} \cdot \vec{k}_2)(\vec{a} \times \vec{k}_1)}{(k_1^0 + m)(k_2^0 + m)} \right]}_{\text{relativistic correction}}$$

Møller scattering



statistical mixture of singlet and triplet state

Møller scattering

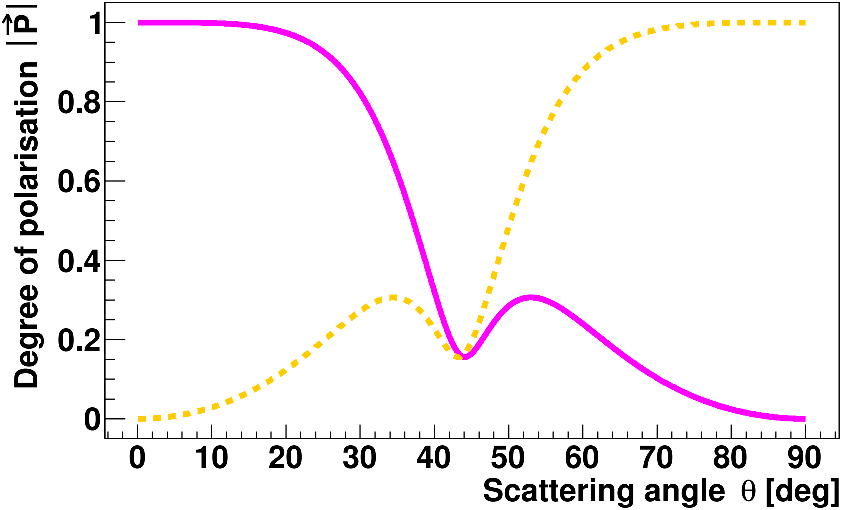


statistical mixture of singlet and triplet state

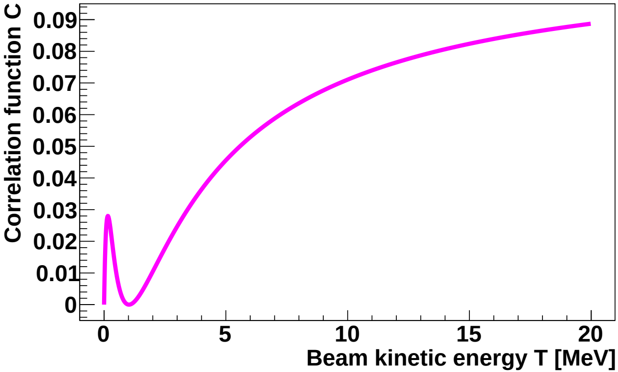
$$\rho_i = \mathrm{Tr}_j \rho_{out}, \quad i,j = 1,2$$

$$\vec{P}_i = \mathrm{Tr}\left(\rho_i \cdot \boldsymbol{\sigma}\right), \quad \boldsymbol{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$$

Møller scattering (100 keV)



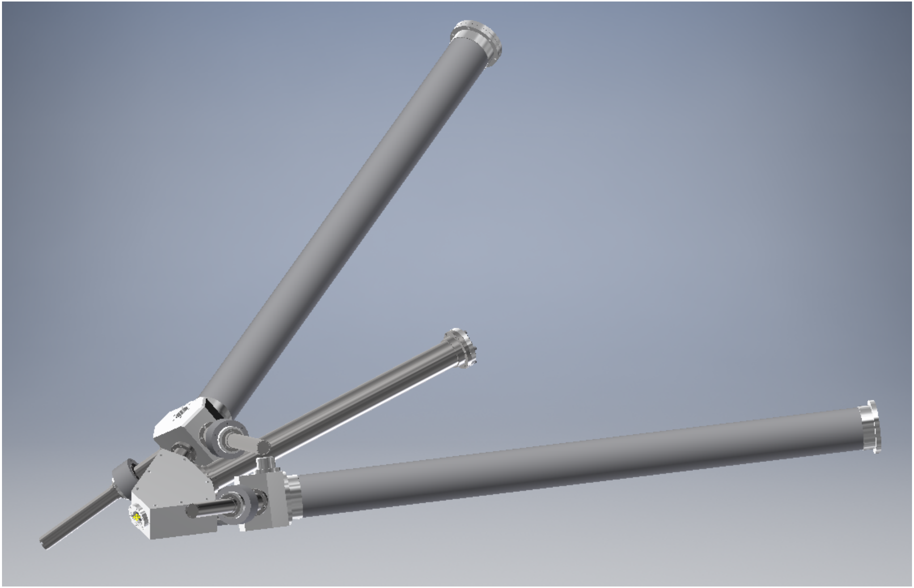
Møller scattering



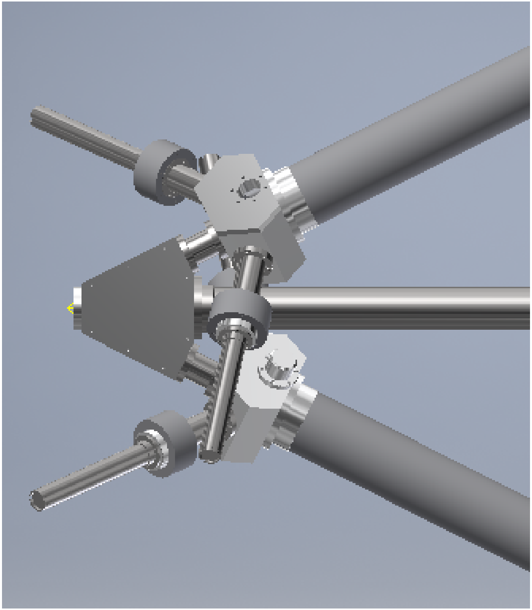
- polarized beam, unpolarized target
- $\vec{a}$ i $\vec{b}$ in Møller scattering plane
- symmetric scattering
- C does not depend on beam polarization, but $P_{\pm\pm}$ do

P. Caban, J. Rembieliński and M. Włodarczyk, *Phys. Rev. A* 88, 032116 (2013)

2POL Experiment

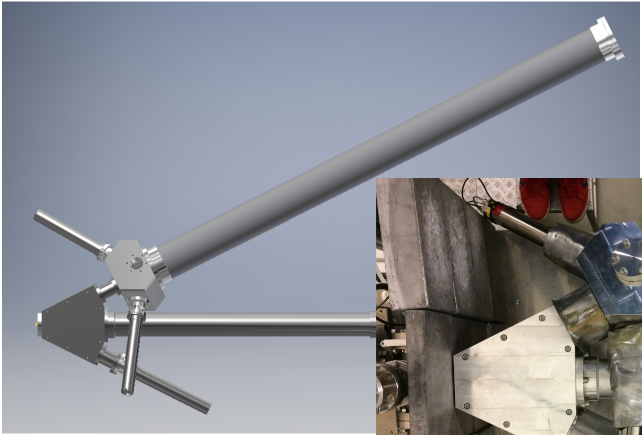


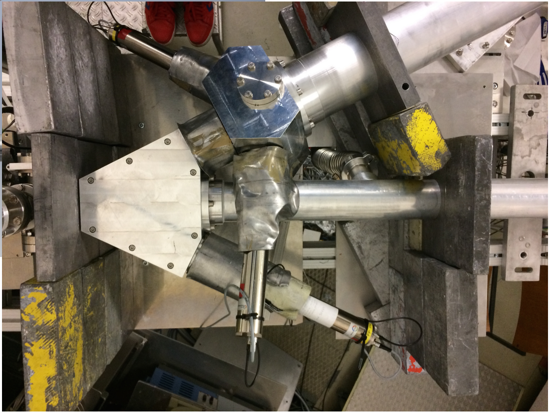
2POL Experiment



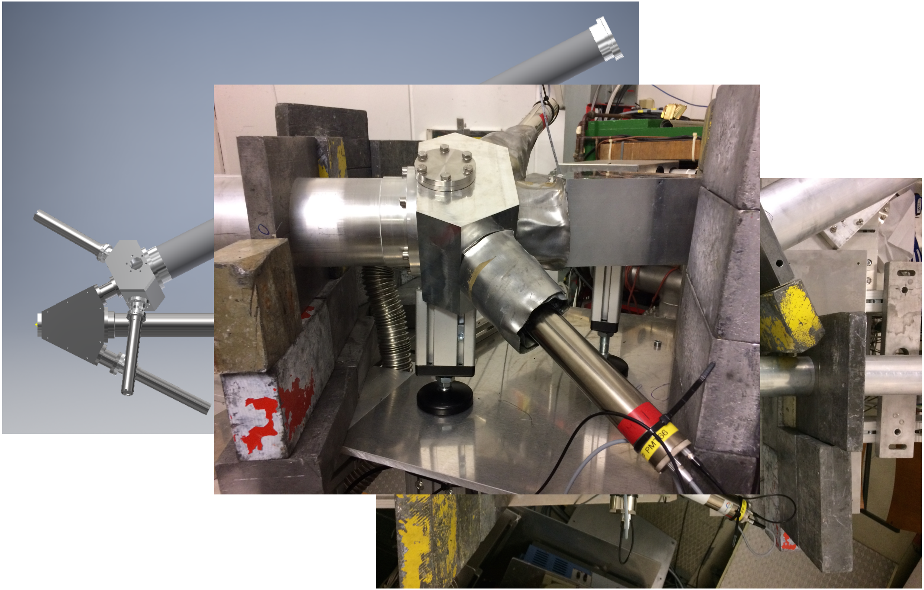
- 2 / 3 MeV polarized beam
- Møller scattering off atomic electrons in 100 μm Be target
- 2 Mott polarimeters: 10 μm Au target, 120 $\pm$ 4 deg
- detectors: scintillator + PMT

Test setup

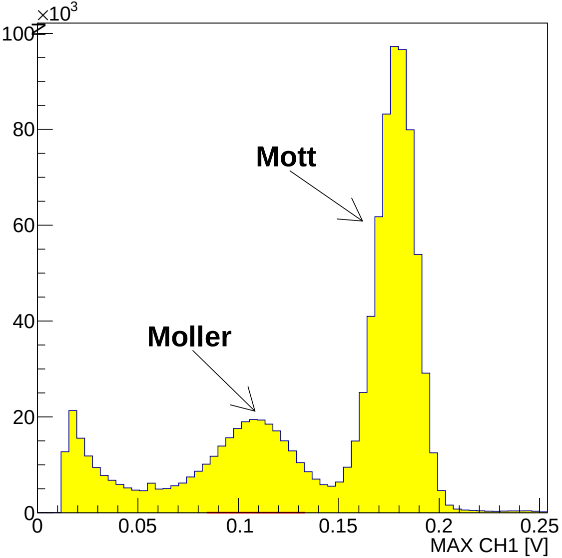




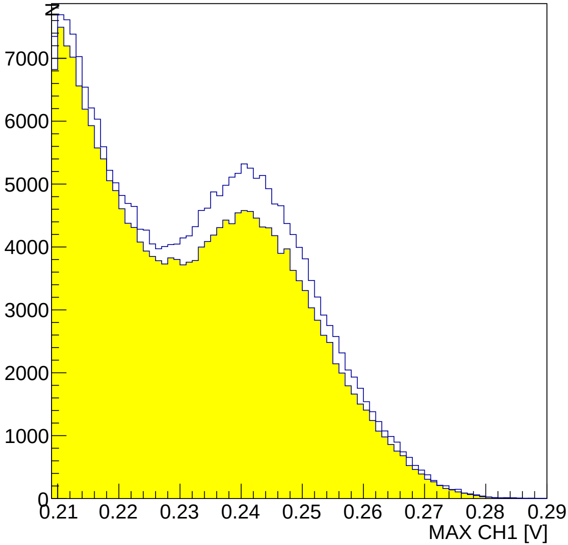
Test setup



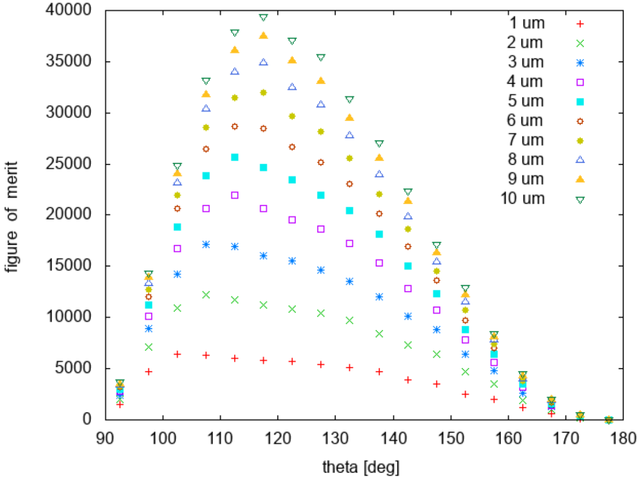
Energy spectrum



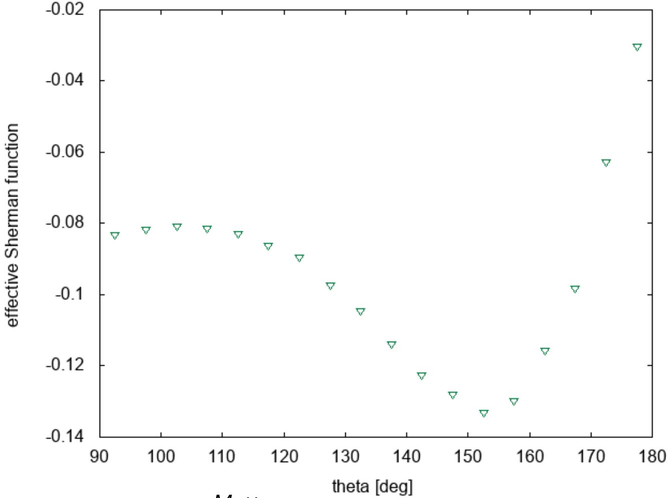
Beam polarization



Monte Carlo simulation



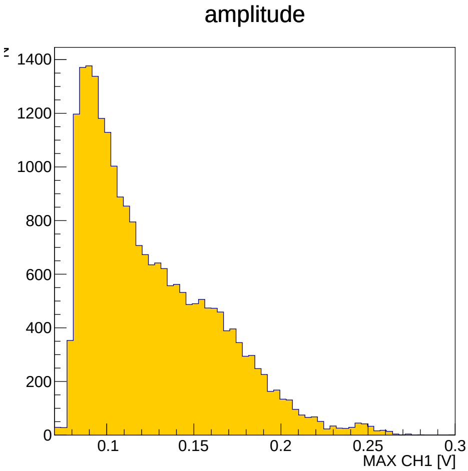
Monte Carlo simulation



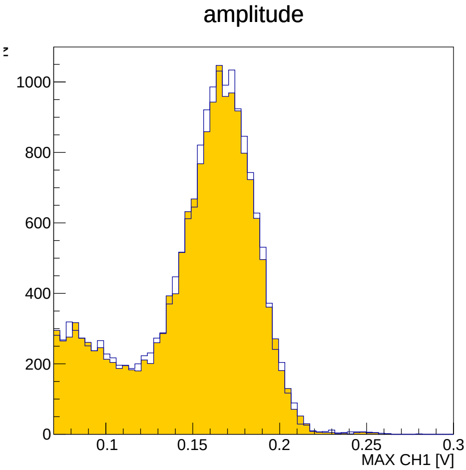
$$A_{exp}^{Mott} = -0.068 \pm 0.004$$

$$A_{theory}^{Mott} = SP\cos 30^\circ = -0.062 \pm 0.002 \ (\mathrm{stat.})$$

Møller electrons

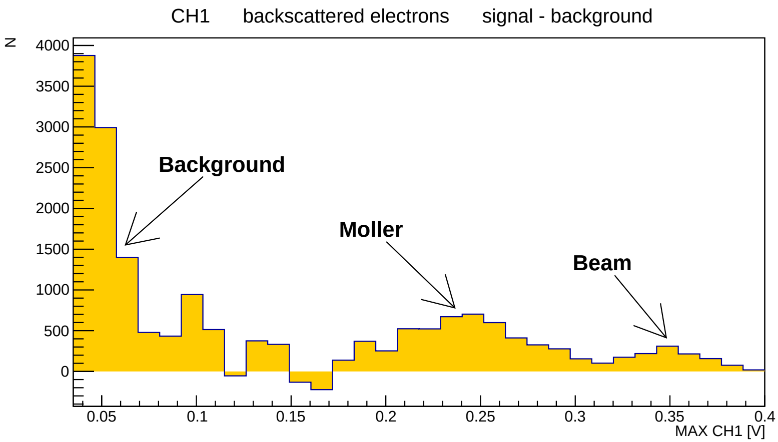


raw coincidence data



energy + timing selection

Møller electrons



shielding + background subtraction

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3. the principle of operation has been confirmed,
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This work was supported from the funds of the National Science Centre as a part of the research project 2017/25/N/ST2/00619.