Vector polarimetry at MaMi - Measurements of tensor correlation coefficients in $e^-$ bremsstrahlungs processes

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Abstract. Electron/photon tensor-correlation coefficients may allow to design a polarimeter that can measure all components of beam polarization simultaneously—a so-called vector polarimeter. Besides its purpose as a beam diagnostic device this vector polarimeter would also allow to test theoretical predictions for the electron-photon polarization correlations at energies between 1 MeV and 3.5 MeV. As a first step we have set up a measurement of the helicity transfer to the photon as a function of energy which is based on the Compton absorption method.

1. Introduction
Since the beam polarization is a vector, it is interesting to measure all its polarization components simultaneously\(^1\). An already existing polarimeter at MAMI [2] is based on elastic electron Mott scattering at an electron energy of 3.5 MeV. It is only able to measure the component of beam polarization which is perpendicular to its scattering plane, defined by the direction of the incident electron beam and the scattered electron. It is possible to measure the second transverse component by installing another Mott detector with a detection plane that is rotated by 90 degree. However, this approach requires considerable effort due to space restrictions under the extreme backward angles required. The longitudinal component is not accessible at all for the Mott polarimeter, since the scattering asymmetry is zero, due to parity conservation.

An alternative approach is to analyze the polarization of bremsstrahlung photons. The outgoing photon then defines the scattering plane together with the incoming electron beam. The correlation between the polarization components of incoming electron and the outgoing photon is given by a tensor $C_{ij}$ introduced by [3] with $i,j = 0,1,2,3$. The first index stands for the electron components

\[
\begin{align*}
0 & = \text{intensity}, \\
1 & = \text{transverse polarization in scattering plane}, \\
2 & = \text{transverse polarization perpendicular to scattering plane and} \\
3 & = \text{longitudinal polarization}.
\end{align*}
\]

\(^1\) It is of course not possible to measure more than one component of the spin of a single electron. Here, we analyze an electron beam by detecting scattering events from different electrons, which allows to define the polarization vector as an expectation value over the ensemble, see [4] page 12 for details.
The second index for the photon components is chosen as the Stokes parameters:

\[
\begin{align*}
0 & = \text{intensity}, \\
1 & = \text{linear diagonal polarization (45°/135°),} \\
2 & = \text{circular polarization and} \\
3 & = \text{linear polarization in horizontal or vertical direction.}
\end{align*}
\]

Two out of the eight non-zero components of \( C_{ij} \), namely \( C_{20} \) and \( C_{32} \), are of particular interest for our purposes. After a brief discussion of \( C_{20} \) we will focus on \( C_{32} \) throughout this paper. The coefficient \( C_{20} \) describes a correlation of photon intensity with transverse electron polarization. Measuring the intensity for opposite transverse electron polarisations leads to an intensity asymmetry. This observable is similar to the Mott asymmetry and therefore allows to measure two transverse polarization components if two detection systems are operated with scattering planes perpendicular to each other. Calculations by Tseng [4] show that the absolute value of \( C_{20} \) is comparable with the Mott analyzing power for MeV energies.

It remains to be demonstrated which principle (Mott or \( C_{20} \) gamma asymmetry) is more suitable, but it is evident that the detection of the transverse components is possible. The remaining longitudinal component of electron polarization can be measured by utilizing the coefficient \( C_{32} \) which stands for the generation of circularly polarized gamma radiation from the longitudinal electron polarization component. The transfer of helicity from longitudinally polarized electrons to circular polarized photons was calculated by Olsen and Maximon for ultra-relativistic electrons [5]. The helicity transfer according to this approximation is shown as a function of photon energy in figure 1. It is well known that the circular polarization of \( \gamma \) rays can be measured by spin dependent absorption in magnetized iron [6]. In a second paper within these proceedings [7] it is demonstrated that this absorption technique is especially effective in an energy range between 2.5 MeV and 10 MeV. Even if the intensity of the integral of the photon flux is measured, asymmetries of the order of 1% can be observed. Together with the very high gamma flux in forward direction this creates ideal conditions for fast and precise integral (i.e. not energy resolved) measurements.

The correlation coefficients are depending on beam and photon energy, the scattering angle and on the nuclear charge. In the intermediate (i.e. not ultra-relativistic) energy range, more refined theoretical calculations [4] show significant deviations from the values predicted by Olsen. To our knowledge, almost no measurements of such correlation coefficients have been done in the multi MeV range. The considerations for a vector polarimeter based on detection of bremsstrahlung therefore also lead to the possibility to test these theoretical predictions. We present here an experiment exploring the possibilities for a measurement of \( C_{32} \) in the forward direction at 3.5 MeV. The gamma radiation was produced on a lead target (\( Z=82 \)).

### 1.1. Calculation of the transmission asymmetry

For longitudinal polarized electrons, the photon flux has no asymmetry in intensity. The bremsstrahlung spectrum \( I_0 (E_\gamma) \) can be calculated by the Bethe-Heitler formula [8]. This spectrum has an energy dependent degree of circular polarization \( \xi(E_\gamma) \) which is proportional to the electron polarization. The circular polarization approaches the electron polarization at the high energy edge of the spectrum (figure 1). Before being detected, the photons have to pass an iron absorber. The main effect of the absorber is to scatter the forward angle emitted photons out of the acceptance of the detector, from the point of the detector this represents an 'absorption'.

The observed attenuation is then \( \propto \exp\left(-\sigma_0 \pm h \sigma_\rho \right)N_AL_\rho \cdot d/A \), with \( \rho \) and \( d \) density and thickness of the absorber and \( N_AL_\rho \) Avogadro's number and atomic mass of the absorber. For the different helicity states of the photons we have \( h = \pm 1 \). The cross section \( \sigma_0 \) is the
Degree of circular polarization $\xi / P_e$ as a function of photon energy. Electron beam kinetic energy $3.5 \text{ MeV}$.

unpolarized (helicity averaged) cross section - usually dominated by the Compton cross section in our energy range, though photo absorption and pair production also contribute. The cross section $\sigma_p$ is polarization dependent, which is taken into account by multiplying it with $h$, the only contributing process at relevant level is Compton scattering\(^2\). In order to obtain $\sigma_0$ the elementary (gamma/e) unpolarized Compton cross section has to be multiplied by the number of electrons per atom ($Z$), whereas the elementary polarized cross section must be multiplied by the number of polarized electrons per atom (typically $\approx 2$ in magnetized iron) to obtain $\sigma_p$. When switching the longitudinal polarization of the electron beam, the sign of $h$ is flipped. Since the asymmetry is defined as $A = \frac{I(+) - I(-)}{I(+) + I(-)}$ all helicity independent terms cancel and the asymmetry for completely polarized photons is

$$A_{\text{full}}(E_\gamma) = \frac{e^{-\sigma_p N A \rho d / A} - e^{+\sigma_p N A \rho d / A}}{e^{-\sigma_p N A \rho d / A} + e^{+\sigma_p N A \rho d / A}} = -\tanh(\sigma_p N A \rho d / A). \quad (1)$$

A partially circular polarized photon beam can be described as incoherent superposition of two totally polarized substates of different intensity $I_{(\text{left} - \text{circ})} = \frac{1}{2}(1 - P_{\text{circ}})$ and $I_{(\text{right} - \text{circ})} = \frac{1}{2}(1 + P_{\text{circ}})$. The two subspecies will have asymmetries $\pm A_{\text{full}}$ which are added to $A = A_{\text{full}}(I_{(\text{right} - \text{circ})} - I_{(\text{left} - \text{circ})}) = P_{\text{circ}} A_{\text{full}}$. The circular polarization in turn is given by $P_{\text{circ}} = P_{\text{e}} C_{32}$ (from the same argument) and therefore the asymmetry should be

$$A(E_\gamma) = -P_{\text{e}} C_{32} (E_\gamma) \tanh(\sigma_p (E_\gamma) N A \rho d / A) \approx -P_{\text{e}} C_{32} (E_\gamma) \sigma_p (E_\gamma) N A \rho d / A. \quad (2)$$

The approximation holds if $E_\gamma \sigma_p (E_\gamma) N A \rho d / A \ll 1$. In order to obtain a prediction for $A(E_\gamma)$ the theoretical values for $C_{32}(E_\gamma)$ from [3] and the polarization dependent cross section from [6] where used. Besides this, the spin density of the electrons had to be plugged in, for which we have used 8%. The resulting prediction is shown by the blue curve in figure 3.

\(^2\) A more quantitative discussion of $\sigma_0, \sigma_p$ can be found in [7].
1.2. Principle of the measurement

The experiment took place at the 3.5 MeV beamline of MAMI which is presented in more detail in [7]. The photon absorption experiment was installed in the beam dump of the Mott polarimeter, located about 2 m downstream from it. During the measurements the Mott targets where removed and the beam entered the device shown in figure 2.

The electron beam can leave the vacuum of the accelerator through a thin aluminum window and hit a lead foil of 4 mm thickness. There, the electron beam produces circular polarized photons in bremsstrahlung processes. Passing a magnetized cylinder the number of photons detected behind this absorber depends on the degree of circular polarization of the photon beam and the degree of magnetization. It is advantageous to measure in a regime where the magnetization of the absorber is saturated. The asymmetry also depends upon the number density of polarized electrons inside the material, so it has to be a material with a high magnetic saturation field.

1.3. Hardware design

- **Magnetic absorber**: The magnetic absorber is made of VACOFUX50 which is a Cobalt-Iron alloy that has a maximum saturation polarization at 2.35 T. The core is 60 mm in diameter and 200 mm long. A copper coil with 500 turns was wound on the surface to excite the core.

- **Photon detector**: The photon spectrum is detected with a fast scintillation crystal. LYSO\(^3\) has the advantages of a high density, a fast decay time and good light output and energy resolution.

- **Read out electronics**: For read out, the electronic lab of our institute has developed a fast ADC and histogram unit. The pulse identification works with a CFD. The ADC has 12 Bit resolution and data transfer is realized via VME bus.

Taking these components together it is possible to test the hardware setup with a \(^{60}\)Co source. The detector contains the radioactive isotope \(^{176}\)Lu, a naturally occurring \(\beta\) emitter. \(^{176}\)Lu decays via \(\beta\) decays to \(^{176}\)Hf almost exclusively to the 597 keV excited state. This state decays with a three \(\gamma\) ray cascade of 307 keV, 202 keV and 88 keV. This natural spectrum can be used for energy calibration.

\(^3\) Cerium-doped Lutetium Yttrium Orthosilicate
Figure 3. Calculated (blue circles) and measured (red crosses) asymmetry in percent versus photon energy in electron masses. The error bars are statistical errors only.

2. Results
Taking two spectra for opposite beam polarizations, it is possible to determine the asymmetry as a function of photon energy as shown in figure 3. For photon energies higher than four electron masses theoretical prediction and measurements are in agreement. For lower energies considerable discrepancies occur, note especially the predicted sign change of asymmetry at 1.2 electron-masses, which is not observed. We suspect that at low energies a contamination from high energy quanta occurs: Due to the small scintillator size many of these quanta are not fully absorbed in the scintillator and are therefore registered as a low energy signal. The high energy quanta carry a large positive asymmetry and will therefore shift the signal upwards. Such an effect cannot explain the discrepancy with opposite sign in the region between 2 and 4 electron masses, but many explanations, including using a more realistic calculation of \( C_{32} \) are possible and have to be considered.

For this reason we cannot yet extract \( C_{32}(E_\gamma) \) from the data. A careful consideration of signal diluting backgrounds is necessary, in order to define the systematic errors. The relative size of these errors will increase with decreasing photon energy. Other systematic error sources are for instance the electron beam polarization (\( \approx \Delta P_e/P = 2\% \)) and uncertainties caused by the absorber magnetization, especially in the end caps of the core, where the magnetization is not complete. Furthermore, a deconvolution of the spectra due to the finite energy resolution has to be performed.

3. Summary & Outlook
We have measured the photon transmission asymmetry \( A(E_\gamma) \) which is induced by \( C_{32}(E_\gamma) \) for photon energies up to 3.5 MeV by developing a detector system based on LYSO scintillation crystals and fast read out hardware. This detection system will also be used in future measurements of \( C_{20} \) to get access to the transverse components of the polarization vector. This will enable the system to work as a vector polarimeter.
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References
[1] Kessler J 1985 Polarized electrons Springer series on atoms + plasmas (Springer-Verlag) ISBN 9783540157366 URL http://books.google.de/books?id=pM0y9AMj6B
[2] Aulentaicher K and Tioukine V 2009 AIP Conference Proceedings 1149 1155-1159 URL http://link.aip.org/link/?APC/1149/1155/1
[3] Tseng H K and Pratt R H 1973 Phys. Rev. A 7 1502-1515
[4] Tseng H 1999 Chinese Journal of Physics 37
[5] Olsen H and Maximon L C 1959 Phys. Rev. 114 887-904
[6] Shopper H 1958 Nuclear Instruments 3 158 - 176
[7] Banday R 2010 Contribution to this conference
[8] Bethe H and Heitler W 1934 Proceedings of the Royal Society of London. Series A 146 83-112 (Preprint http://rspa.royalsocietypublishing.org/content/146/856/83.full.pdf+html) URL http://rspa.royalsocietypublishing.org/content/146/856/83.short