Vertical Beam Polarization at MAMI

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Abstract

For the first time a vertically polarized electron beam has been used for physics experiments at MAMI in the energy range between 180 and 855 MeV. The beam-normal single-spin asymmetry $A_n$, which is a direct probe of higher-order photon exchange beyond the first Born approximation, has been measured in the reaction $^{12}$C($\vec{e}, e'$)$^{12}$C. Vertical polarization orientation was necessary to measure this asymmetry with the existing experimental setup. In this paper we describe the procedure to orient the electron polarization vector vertically, and the concept of determining both its magnitude and orientation with the available setup. A sophisticated method has been developed to overcome the lack of a polarimeter setup sensitive to the vertical polarization component.

Keywords: Electron accelerator, Vertical polarization, Wien filter, Compton polarimeter, Mott polarimeter, Møller polarimeter

1. Introduction

Electron scattering is an excellent tool to study the structure of nucleons and atomic nuclei. In addition to conventional observables like unpolarized scattering cross sections, polarization observables allow novel access to relevant quantities. In particular, the use of longitudinally polarized electron beams turns out to be very beneficial, and dedicated experiments have been performed at various places. At the Mainz Microtron (MAMI) electron accelerator [1, 2], for instance, the electric to magnetic form factor ratios were measured for the proton as well as for the neutron (see [3, 4] and references therein). Moreover, parity-violating (PV) single-spin asymmetries in elastic electron scattering were measured to investigate the distribution of strange quarks within the nucleon [5]. In these PV experiments, possible small transverse beam polarization components can lead to significant background through contributions from the beam-normal single-spin asymmetry $A_n$. Therefore, the measurement of $A_n$ is mandatory in order to constrain the systematic error. $A_n$ itself provides an interesting challenge for theoretical predictions, because this observable is a direct probe of multi-photon exchange processes.

A recent measurement of $A_n$ in elastic scattering off $^{208}$Pb revealed a significant disagreement between the data and the prediction [6]. The sources of the disagreement are presently not understood and motivate more measurements for target nuclei in the intermediate mass range. In this context, $A_n$ of carbon has been recently measured at MAMI by using the spectrometer setup of the A1 collaboration [7].

To observe $A_n$, the beam polarization vector must have a component normal to the scattering plane, which is spanned by the incident and scattered electron momenta. Because the A1 spectrometers accept horizontally scattered electrons, the beam polarization must be
set vertical for maximum sensitivity.

Although MAMI does not provide vertical beam polarization in conventional operation, it was possible to use the existing setup – with minor modifications – to run, for the first time, a high energy vertically polarized beam over several weeks. The direction of the polarization was controlled by a combination of two beam line instruments, a Wien filter spin rotator and a double solenoid. However, an accurate determination of the vertical polarization component was challenging, since a polarimeter sensitive to this polarization component was not available. Hence, we investigated a method to deduce the vertical polarization component from a determination of the total beam polarization and the residual horizontal polarization components.

The total beam polarization was measured by using a Møller polarimeter with the beam polarization oriented longitudinally in the experimental hall. After rotation of the polarization vector in the vertical direction, the same polarimeter was used to measure the residual longitudinal polarization component, which should vanish for perfect vertical polarization alignment. The transverse horizontal component could be evaluated by measuring again with the Møller polarimeter, but at a different beam energy.

Besides dedicated measurements to estimate the contribution from false asymmetries to the Møller polarimeter results, we have also performed polarization measurements with Mott and Compton polarimeters, which are located close to the electron source. A careful comparison provides a powerful test of our understanding of systematic effects.

The paper is organized as follows. We briefly review the operating principle of MAMI and its polarized electron source in Sec. 2. In Sections 3 and 4, the precession of the polarization vector in the bending fields of the accelerator as well as in the fields of the Wien filter and the double solenoid is described. The results from the alignment procedure at the beginning of the experiment are shown in Sec. 5. Supplementary polarimeter data dedicated to systematic error estimates of the individual polarimeter measurements are evaluated in Sec. 6. Finally, the data from different measurements are combined in Sec. 7, and the long-term stability of the polarization alignment is considered in Sec. 8. A summary follows in Sec. 9.

2. The polarized electron source at MAMI

The normal-conducting continuous-wave electron accelerator MAMI consists of a cascade of three race-track microtrons followed by a harmonic double-sided microtron. The source of polarized electrons provides longitudinally polarized electrons. They are produced by using a strained GaAs/GaAsP superlattice photocathode illuminated with circularly polarized laser light. The helicity of the electron beam is selected by setting the high voltage polarity of a Pockels cell. Dedicated tests have been performed to unambiguously determine the absolute sign of the helicity at the source by examining the asymmetries of Mott and Møller polarimeter measurements. By insertion of a 1/2 plate between the laser system and the photocathode, the polarization orientation of the electron beam can be reversed. This allows a test of the understanding of systematic effects. The measurements presented in the following have been taken without the 1/2 plate being inserted unless specified otherwise.

The total beam polarization was measured with a Møller polarimeter (see [12–14] and references therein) at the beginning of the beamtime. The measurements were performed at a beam energy of 855 MeV, because systematic errors related to detector acceptances and signal amplitudes are minimal for this energy. The electron polarization vector was aligned longitudinally (compare Sec. 3 in the spectrometer hall to maximize the sensitivity. The result is \( P = 82.7\% \pm 0.3\%(\text{stat}) \pm 1.1\%(\text{syst}) \). To monitor the beam polarization throughout the beamtime, we performed several measurements with a Mott polarimeter [15] [16] for transverse horizontal alignment of the polarization. The absolute scale of the Mott polarimeter measurements was not calibrated before the experiment, therefore we rescaled the results by a factor 1.018 to match the first Mott polarimeter result with the Møller polarimeter result. The results are shown in Fig. 1.

3. Rotation of the polarization vector in the horizontal plane

The electron polarization vector precesses on the way through the accelerator to the experimental hall in the fields of the accelerator’s bending magnets. The precession in an electromagnetic field due to Larmor and Thomas precession is described by the Thomas-BMT equation [17]. For the special case of vertical magnetic fields in the recirculating dipoles, only the horizontal components precess with a frequency \( \omega = (1 + a_e \gamma) \omega_c \), where \( \gamma \) is the Lorentz factor and \( \omega_c \) the cyclotron frequency [18]. Due to the anomalous magnetic moment \( a_e \) of the electron, the polarization precesses faster than the momentum. Therefore the horizontal polarization orientation at the experiment substantially depends on the energy of the extracted beam.
Figure 1: Measurement of the total beam polarization. The absolute value was measured with the Møller polarimeter. The Mott polarimeter was used to monitor the usual long-term increase of the polarization, and the drop of the polarization after a necessary regenerating procedure applied to the source crystal.

The polarization vector can be rotated in the horizontal plane by using a Wien filter [18], which is situated in the injection beam line. For conventional polarized experiments, the Wien filter is used to rotate the polarization vector so that it is aligned longitudinally in the experimental hall to maximize the sensitivity of experimental observables. The rotation angles of the polarization vector through the accelerator have been simulated for standard MAMI energies in [19]. In addition, the rotation angles have been determined for relevant beam energies by measuring the longitudinal beam polarization in the spectrometer hall as a function of different rotation angles of the Wien filter. Fitting these results with a cosine function yields the rotation angle of the polarization vector. The achieved accuracy is on the order of 2°. The rotation angles for the beam energies 570 MeV (the beam energy used during the A_n experiment) and 600 MeV (additional Møller measurements were performed at this energy) were determined to be 55° and 189°, respectively.

4. Rotation of the polarization vector into the vertical direction

The beam polarization vector can be rotated around the beam line axis by applying a solenoidal magnetic field aligned with the beam line axis. Hence, in the ideal case, one can first use the Wien filter to rotate the polarization vector to a transverse horizontal orientation, then apply a solenoidal field of appropriate strength to rotate it to the vertical direction. We have used a double solenoid which is located shortly behind the Wien filter, see Fig. 2. It consists of two 46 mm long solenoids (25 mm coils) with an aperture of 30 mm. We have operated the two solenoids with the same polarity and with the same current to produce one continuous solenoidal field. The rotation angle of the polarization vector is then proportional to the integral of the longitudinal magnetic field.

Usually the magnets are operated in such a way that the fields are of opposite orientation and equal in strength, and serve as focusing elements with a focal length of approximately 24 cm inversely proportional to the integral of the squared longitudinal magnetic field. The polarity swap as well as a variation of the solenoid currents changes the focal length. Either the restoration of the original focal length could have been achieved with asymmetric currents in the double solenoid [20], or the effect could have been compensated by tuning of neighboring double solenoids. In practice, none of these methods was necessary. Specifically, during scans of the current in a limited range to optimize the double-solenoid setpoint, the change in focal length was small enough that the phase space of the beam still matched the acceptance of the injector linear accelerator.

4.1. Depolarization effects

Fringe fields and inhomogeneities of the Wien filter and the solenoidal field could, in principle, result in a depolarization of the beam when electrons experience different fields due to the finite phase space volume of the beam.

However, to guarantee the same beam quality for every beamtime the same optimization procedure is performed routinely and results in a well centered beam in every single focusing element. For the small emittance of the MAMI beam at these locations of less than 1 π mm mrad and due to the fact that most fringe fields are very similar at the element entrance and exit, the effect is nevertheless negligible and it is not measurable with the MAMI polarimeters.

Depolarization further along the beam line is also negligible: in Refs. [19,21], depolarization effects for
a horizontally polarized beam were evaluated and they
were found to be very small. For a vertical beam po-
larization alignment, the effects are even smaller due to
the small horizontal magnetic field components that the
beam experiences. The vertical component is therefore
conserved.

In particular, since the depolarization effects are negli-
gible, the vertical polarization component can be de-
duced from a determination of the total beam polarization “minus” the measured residual horizontal polarization
components.

4.2. Consequences of misadjustments of the parameters

When the parameters of the Wien filter and the dou-
bble solenoid are optimally adjusted, the polarization
vector points in the vertical direction directly after the
solenoids. Since there are no significant horizontal mag-
netic field components and depolarization effects, the
beam polarization vector will remain vertically aligned
throughout the transfer to the experimental hall with the
same polarization degree.

A misadjustment of the parameters however results in
significant residual polarization components in the
horizontal plane behind the solenoids, thus a reduced
vertical beam polarization component. Moreover, the
horizontal components can give rise to false asymmetry
contributions to experimental observables.

If the rotation angle of the Wien filter is slightly
smaller than 90°, a small longitudinal polarization com-
ponent remains. In the solenoidal field, that component
is not changed. Due to subsequent polarization vec-
tor precession in the accelerator, that component will be
rotated horizontally by +55° relative to the moment-
tum direction, for the beam energy of the A_n experiment
of 570 MeV (compare Sec. 3). For a Wien filter angle
slightly larger than 90°, the corresponding polarization
component points in the opposite direction in the exper-
nmental hall.

In case the field strength of the solenoids is slightly
too small or too high to rotate the transverse horizontal
component into the vertical direction, some polar-
ization component remains in the transverse horizontal
direction behind the solenoids and ends up in the spec-
trometer hall, with an additional relative rotation angle
of +55° again.

Optimization of the Wien filter and double solenoid
parameters is performed by considering measurements of the horizontal polarization components as described
in detail in the next section.

5. Vertical alignment procedure

The vertical polarization alignment can accurately be
accomplished by minimization of the horizontal polar-
ization components. These can be measured at two dif-
f erent locations: close to the source with a Compton
[22,23] and a Mott polarimeter and in the experimental
hall by using the Møller polarimeter.

The Compton and Mott polarimeters are positioned
behind the injector linear accelerator (ILAC), where the
3.5 MeV electrons have already passed the Wien filter
and the double solenoid. They are sensitive to the lon-
gitudinal and the transverse horizontal components, re-
spectively. The Compton polarimeter is therefore well-
suited to optimize the rotation angle of the Wien filter.
With the Mott polarimeter, the applied field strength of
the solenoids can be optimized. Due to the polarization
precession in the accelerator, these components are re-
lated to the components in the experimental hall by a
rotation, see Fig. 3.

Let us denote the transverse horizontal, the vertical,
and the longitudinal polarization components in the ex-
perimental hall by \( P_x, P_y, \) and \( P_z \), respectively. \( P_z \) can
be measured directly with the Møller polarimeter. A
possibility for inferring \( P_z \) at the experiment is to tem-

![Figure 3: Overview of the polarization components that can be determined with the individual polarimeters. The Møller polarimeter is sensitive to \( P_z \). With the Compton (Mott) polarimeter, the longitudinal (transverse horizontal) component can be measured behind the ILAC. Due to the precession in the accelerator, this component ends up rotated by +55° in the spectrometer hall, the corresponding axis is depicted as \( P_{ILAC}^z \) (\( P_{ILAC}^x \)). The component along the axis labeled as \( P_{600\,MeV}^z \) is measured with the Møller polarimeter, when the beam energy is temporarily set to 600 MeV.](image-url)
This polarization component is labeled as $P_{zf}$ with the Mott polarimeter for di during the beamtime (Sec. 7). During the experiment we performed measurements at the beginning of the experiment and we optimized with Mott and Møller polarimeter measurements, the second one of these components has been already minimized by using Mott polarimeter measurements, the second component can be subsequently examined by using the Møller polarimeter. The results are shown in Fig. 5. We found 88.4° as the optimum value for the nominal rotation angle of the Wien filter. With this new Wien filter setting, another measurement was performed with the Mott polarimeter (triangular data points in Fig. 5). Due to the good agreement with the previous data points, these settings were used as final values for the beam-normal single-spin asymmetry measurements throughout the beamtime.

6. Systematic errors in the polarimeter measurements

The sensitivity of horizontal component measurements to a misalignment of the polarization vector is high, at the same time systematic effects can have a significant influence and deserve special attention.

Uncertainties related to factors entering the polarization determination like analyzing powers of the reactions, absolute target/absorber polarizations, unpolarized background, or necessary extrapolations to vanishing target thicknesses usually dominate the systematic errors. However, these are negligible when small polarization components are measured, because the relative uncertainties of these sources do not change, but the absolute uncertainties become small compared to the statistical precision.

In contrast, false asymmetries do not scale with the size of the measured polarization components and become dominant when the “true” polarization components are small. Examples are an inaccurate helicity-dependent luminosity determination used for normalization of the raw polarimeter count rates, a slight misalignment of the polarimeter setup, contributions
from another analyzing power component of the scattering process utilized for the polarimetry, or a helicity-dependent beam position on the polarimeter target resulting in an additional false asymmetry of the count rates.

To get a handle on the systematics, we took data dedicated to a direct estimate of false asymmetries. Additionally, we compared the data from the different polarimeters, which have different systematics.

To estimate false asymmetries one needs to perform precise asymmetry measurements of known asymmetries. One might use for instance an unpolarized beam, an unpolarized absorber (Compton polarimeter), or an unpolarized target (Møller polarimeter).

### 6.1. False asymmetry estimate of Møller polarimeter measurements

Performing measurements with the Møller polarimeter with an unpolarized target can be used to estimate false asymmetries, since the expected asymmetry is zero. Depolarizing the standard iron foil might be hard to achieve with the desired accuracy and raises the problem that the target magnetic field is finally turned off, thus slightly changing the trajectories of the electrons. Therefore, we used a copper foil instead. The beam polarization was oriented vertically during these measurements. Since copper is diamagnetic, vanishing asymmetries are expected. The size of false asymmetries can then be estimated from the deviation of the measurement from zero. Measurements were performed for both relevant beam energies (570 MeV and 600 MeV), and for both λ/2 plate states. The results are shown in Fig. 6. For better comparison, we converted the observed asymmetries to apparent polarization values that can then be estimated from the deviation of the measurement from zero. Measurements were performed for both relevant beam energies (570 MeV and 600 MeV), and for both λ/2 plate states. The results are shown in Fig. 6. For better comparison, we converted the observed asymmetries to apparent polarization values that would be extracted if these asymmetries were measured with the commonly used ferromagnetic target (i.e., we multiplied the observed asymmetries by a factor of ≈ 16, which corresponds to a division by the experimental analyzing power and the e16, which corresponds to a division by the experimental analyzing power). This averaged result of the data for the same beam energy, but with the λ/2 plate inserted: A two-sample t-test for the null hypothesis that these two data samples originate from the populations with equal means (assuming that they have identical variances) gives a p-value of 0.0013. This strongly indicates that the two population means are not equal. It is more likely that the means are equal in magnitude but have a different sign (p = 0.73). This is an indication that the dominant part of the false asymmetries is related to beam properties (like helicity-dependent beam positions or aberrations) rather than to polarimeter issues. However, the deviation from zero is quite small (e.g., 0.42% absolute for the λ/2 plate out data set, which corresponds to an instrumental asymmetry of 0.026%), and the result for 600 MeV is even compatible with zero. Based on these results, we use the deviations from the zero-asymmetry measurements and their precisions (individually for both λ/2 plate states and beam energies) for a false asymmetry correction and its corresponding systematic error.

### 6.2. False asymmetry estimate of Mott polarimeter measurements

To estimate false asymmetry contributions to the Mott polarimeter measurements, auxiliary measurements have been performed with longitudinally polarized electrons at the Mott target. Since the Mott polarimeter is not sensitive to the longitudinal polarization component, such measurements should result in a vanishing asymmetry.

Longitudinally polarized electrons are guided directly to the Mott polarimeter when the Wien filter and the solenoids are not used to rotate the polarization. In a strict sense, the polarization orientation is, even in this case, not exactly longitudinal at the Mott target. An α-magnet at the very beginning of the electron beam line bends the 100 keV beam by 270° and results in a polarization vector rotation of approximately 0.37°. Therefore there is a small polarization component in the vertical direction, to which the Mott polarimeter is not sensitive. However, two dipole magnets in the ILAC beam line that are used to bend the beam by 30° to the Mott polarimeter setup, also cause a slight rotation of the beam polarization in the horizontal plane by 0.27° relative to the beam direction. The expected polarization component measurable by the Mott polarimeter is then approximately 0.005 · P_{total}.

We measured a residual polarization of −0.41% ± 0.07% (0.39% ± 0.07%) for the λ/2 plate not inserted (inserted), whereas the expectation due to the dipole bending is 0.39% (−0.39%). We have repeated such measurements in a following beam test, the results were similar. To investigate the source of this deviation, we performed additional systematic tests. After all, the origin of the inconsistency remains unclear. The present estimate for the systematic uncertainty is 0.8% absolute (this value matches the reported deviation). Clarifying this issue thus reducing the magnitude of the total systematic error associated with the polarization measurement is beyond the scope of this paper, but thorough
measurements will be performed in the near future to understand the deviation.

7. Determination of the polarization orientation

In order to reconstruct $P_x$ and $P_z$ and to draw a quantitative conclusion about the polarization orientation, different types of polarization measurements are performed and combined.

7.1. Measurements with optimized settings

The results for the optimized Wien filter and double solenoid configurations are depicted in Fig. 7(left). The Möller polarimeter measurements performed at the beam energy of the $A_n$ experiment (570 MeV) are sensitive to $P_z$. The measurement result is represented as a line perpendicular to the $P_z$ axis with corresponding error bands. Here, the correction mentioned in Sec. 6.1 has been applied. The results of the Compton and Mott polarimeter measurements performed at 600 MeV are displayed similarly. The inner and outer bands correspond to the statistical and the statistical and systematic errors added in quadrature, respectively. For the Möller measurements, the two bands are hardly distinguishable since the statistical uncertainty is considerably larger than the estimated systematic error.

To estimate $P_x$ and $P_z$ simultaneously from the different polarimeter measurements, we used a maximum-likelihood fit with inputs the measured results and the polarization vector precession angles through the accelerator. Errors considered in the fitting procedure are the quadratically added statistical and systematic uncertainties of the individual measurements. An additional uncertainty enters through the imperfect knowledge of the polarization vector rotation angles through the accelerator. The influence has been checked by varying these angles in the limits of their uncertainties and was found to be negligible.

The result of a fit considering only the Compton and the Mott polarimeter measurements is represented by the vertically hatched ellipse (the 1σ error ellipse corresponding to the estimated covariance matrix). Fitting the two Möller polarimeter results yields the horizontally hatched (blue) ellipse. Despite the different errors, the fit results are very similar. Finally, the result of a fit considering all available polarimeter measurements is shown as the solid ellipse in the figure. The results for $P_x$, $P_z$, and the covariance matrix $C$ are

$$(P_x, P_z) = (0.39\%, -0.35\%),$$

$$C = \begin{bmatrix} (0.28\%)^2 & +(0.24\%)^2 \\ +(0.24\%)^2 & (0.48\%)^2 \end{bmatrix}. $$

With a total polarization of approximately 79% at the end of the beamtime, this corresponds to an angle misalignment of merely 0.38°. Therefore, the degree of vertical polarization differs only marginally from the total degree of polarization $(P_{\text{total}} - P_y)/P_{\text{total}} = 2 \cdot 10^{-5}$.

7.2. Variation of the Wien filter and solenoid settings

We also tested our underlying assumption about how the Wien filter and the solenoidal fields rotate the polarization orientation. In Fig. 7(right), the same ellipses as in the left panel are shown. In addition, the fit results for measurements with changed settings of the Wien filter and the solenoids are drawn. Either the nominal Wien filter angle (optimized value: 88.4°) was varied by ±4.3°, or the current of the solenoids (optimized...
value: 0.817 A) was changed by ±0.017 A. Compton polarimeter measurements were not performed for the latter settings. The individual results approximately coincide with the expectations (circles labeled by $S^+, S^-, W^+, W^-$).

8. Stability during the beamtime

To check the stability of the polarization alignment on the three-week time scale of the experiment, several measurements with the Mott polarimeter and the Möller polarimeter at 570 MeV beam energy have been performed throughout the beamtime, see Fig. 8. The agreement between the individual Mott measurements is very good. There is a systematic difference between data collected with and without the $\lambda/2$ plate inserted. A small detune of the double solenoid current would cause exactly such an effect. The magnitude of the systematic errors associated with these measurements, as outlined in Sec. 6.2, hampers a verification of such an assumption.

There is a larger spread of data values for the Möller polarimeter measurements. However, these data do not indicate variations of the residual horizontal polarization components above the 1% level. The correspond-
ing uncertainties for the analysis of the $A_n$ experiment are sufficiently small compared to the achieved statistical precision [8].

9. Summary

The $A_n$ experiment of the A1 collaboration was dedicated to the measurement of the beam-normal single-spin asymmetry in elastic scattering from $^{12}$C. For this asymmetry measurement, the beam polarization was rotated from an initial longitudinal to a vertical orientation. A Wien filter spin rotator (located in the injector linear accelerator beam line) has been used to first rotate the polarization into the transverse horizontal plane. Afterwards the polarization was rotated into the vertical direction by means of a solenoidal field of appropriate strength.

In order to measure the total beam polarization, to achieve a good vertical beam polarization alignment and to provide an estimate of remaining horizontal beam polarization components, numerous polarimeter data have been collected. The absolute beam polarization (around 80% throughout the beamtime) was determined with a Møller polarimeter by using the most favourable beam energy for that measurement. The variation of the polarization degree with time was measured with a Mott polarimeter.

To optimize the solenoid current and the Wien filter angle, polarization measurements with the Mott and the Møller polarimeter served as benchmark by providing results for the horizontal polarization components to be minimized. Dedicated tests have been performed to confirm the expectation for the horizontal polarization components, numerous polarimeter data have been collected. The absolute beam polarization (around 80% throughout the beamtime) was determined with a Møller polarimeter by using the most favourable beam energy for that measurement. The variation of the polarization degree with time was measured with a Mott polarimeter.

Afterwards the polarization was rotated into the vertical orientation. To allow a quantitative estimate of remaining horizontal beam polarization components, numerous polarimeter data have been collected. The absolute beam polarization (around 80% throughout the beamtime) was determined with a Møller polarimeter by using the most favourable beam energy for that measurement. The variation of the polarization degree with time was measured with a Mott polarimeter.

will allow future precision studies with polarized beam at MAMI.

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