Accurate Electron Spin Optical Polarimetry (AESOP)

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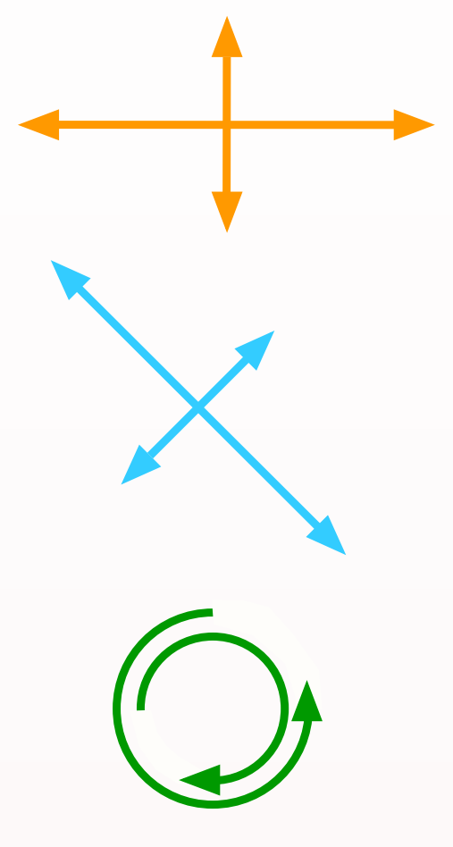
Introduction

The upcoming third generation parity-violation experiments involving high-energy (3-12 GeV) longitudinally-polarized electron scattering will require a measurement of the electron polarization, P_e, to an unprecedented accuracy of 0.5% of itself [1]. Though efforts are currently underway to make measurements with the 5 MeV Mott polarimeter at the CEBAF injector at JLab to a *precision* of ~0.3%, the *accuracy* of Mott polarimetry ultimately relies on a theoretical calculation of the Sherman function [2]. A conservative estimate of the accuracy with which we can know the 5 MeV Sherman function is 1%, yielding an overall accuracy at about the same level. In order to achieve a Mott measurement with an accuracy of 0.5%, an independent calibration with this level of accuracy will be required. We propose to do this using the technique of Accurate Electron Spin Optical Polarimetry (AESOP). Here, we discuss recent efforts toward achieving our preliminary, proof-of-principal goal of measuring the polarization of laser light, passed through a beam expander, to an accuracy of 0.1% of itself.

Optical Electron Polarimetry

Optical electron polarimetry uses atomic fluorescence polarization measurements to determine the polarization of a beam of electrons: the polarized electrons to be measured excite atoms through an exchange reaction [3, 4]. The electron spin is converted in part to orbital orientation by spin-orbit coupling in the excited target state. Upon decay, the fluorescence polarization can be connected kinematically to P_e:

$$\boxed{P_e = \frac{P_3}{a + bP_1}}$$



P_1 → Determines the analyzing power of the polarimeter

P_2 → Establishes the validity of kinematic assumptions

P_3 → Determines the electron polarization, P_e

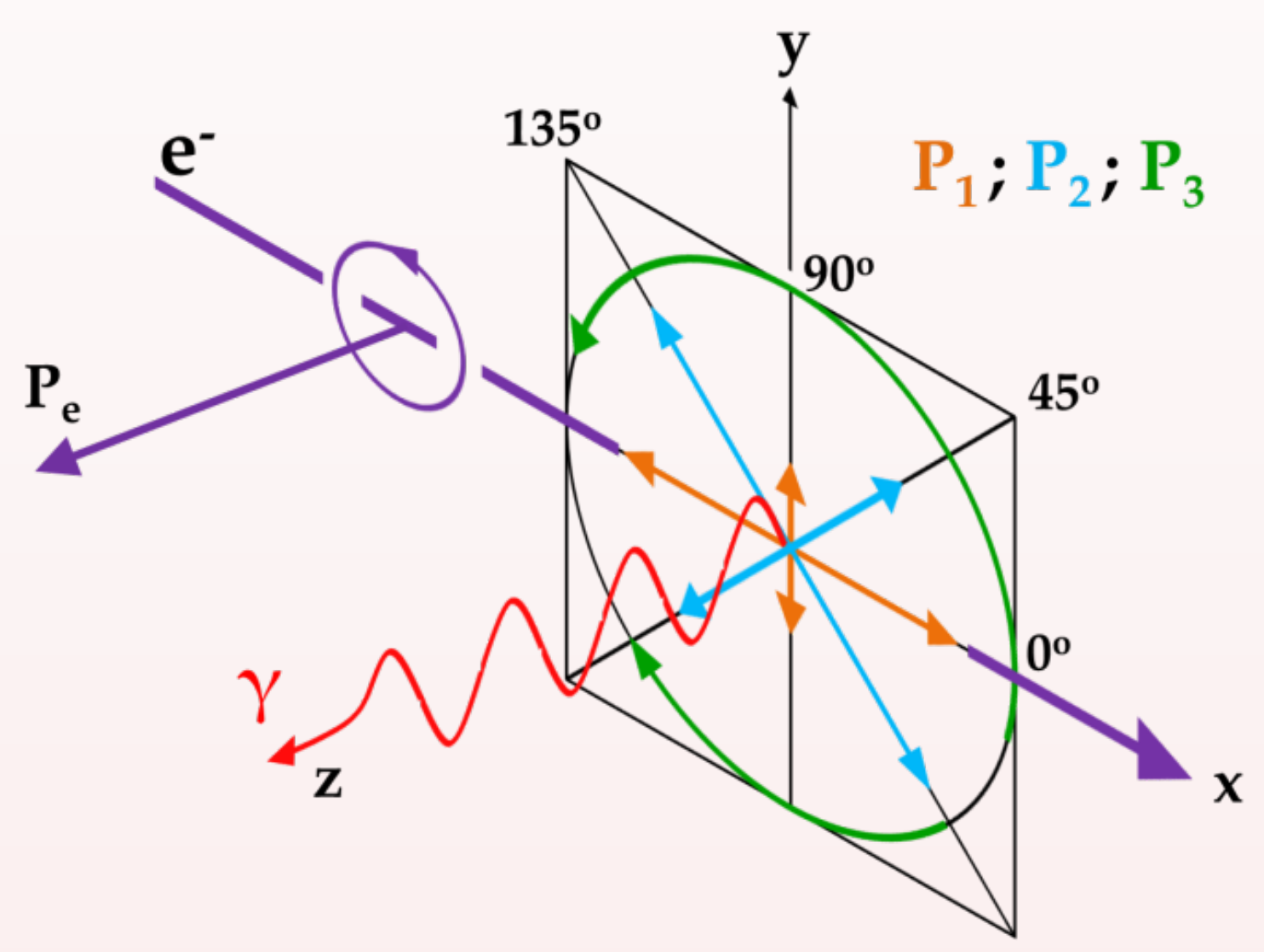


Figure 1. A typical geometry for electron optical polarimetry. Electrons having transverse polarization along the z-axis are incident on the target along the x-axis.

Advantages

- ✓ Provides an absolute measurement of P_e
- ✓ Has higher analyzing power than Mott scattering – up to 70% for heavy noble gases

Disadvantages

- × Electron optical polarimeters are inefficient
- × Require low energy input beams corresponding to valence shell excitation, 10-20 eV

Setup and Analysis

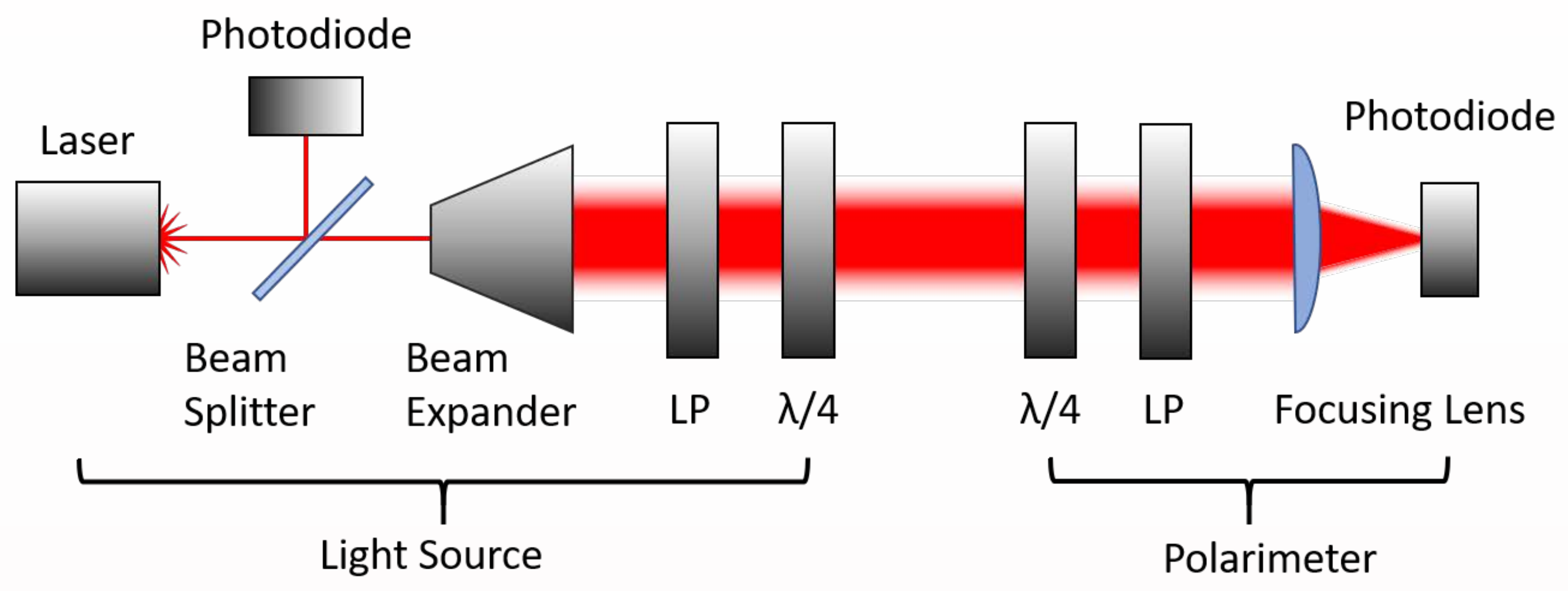


Figure 2. Polarimeter Setup. From left to right: laser, beam splitter and photodiode for drift normalization, beam expander to increase illuminated area of 2-inch polarization optics, polarization-state-defining linear polarizer (LP) and quarter waveplate (λ/4), stepper-motor-controlled analyzing quarter waveplate and linear polarizer, focusing lens, and photodiode.

Berry *et al.* provide the recipe for measuring the polarization of light in terms of its Stokes parameters [5]:

Measure the transmitted intensity for various angular positions of the quarter waveplate (β). This intensity can be written as a Fourier series: $I_T(\beta) = C_0 + C_2 \cos 2\beta + C_4 \cos 4\beta + S_2 \sin 2\beta + S_4 \sin 4\beta$

Find the coefficients via Fourier transform:

$$C_{\omega k} = \frac{2}{N} \cdot \frac{1}{1+\delta_{k0}+\delta_{kL}} \cdot \sum_{i=1}^{N} I_{Ti} \cos \omega_k \beta_i \qquad S_{\omega k} = \frac{2}{N} \cdot \frac{1}{1+\delta_{k0}+\delta_{kL}} \cdot \sum_{i=1}^{N} I_{Ti} \sin \omega_k \beta_i$$

where $\omega_k = \frac{2\pi}{N} \cdot \frac{k}{\Delta\beta}, \beta_i = (i-1)\Delta\beta$, and $k = 0,1,\ldots,L$

Calculate the Stokes parameters:

$$I = C_0 - \frac{1+\cos\delta}{1-\cos\delta}\left[C_4 \cos(4\alpha+4\beta_0) + S_4 \sin(4\alpha+4\beta_0)\right] \qquad M = \frac{2}{1-\cos\delta}\left[C_4 \cos(2\alpha+4\beta_0) + S_4 \sin(2\alpha+4\beta_0)\right]$$

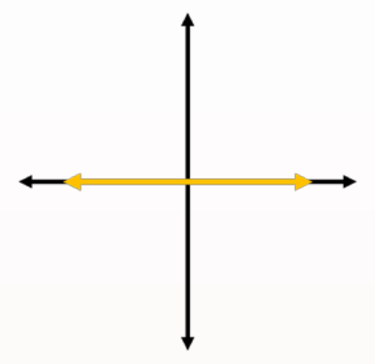
$$C = \frac{2}{1-\cos\delta}\left[S_4 \cos(2\alpha+4\beta_0) - C_4 \sin(2\alpha+4\beta_0)\right] \qquad S = \frac{-S_2}{\sin\delta \cos(2\alpha+2\beta_0)}$$

Express as normalized Stokes parameters:

$$P_1 = \frac{M}{K_{inc}I} \qquad P_2 = \frac{C}{K_{inc}I} \qquad P_3 = \frac{S}{K_{inc}I}$$

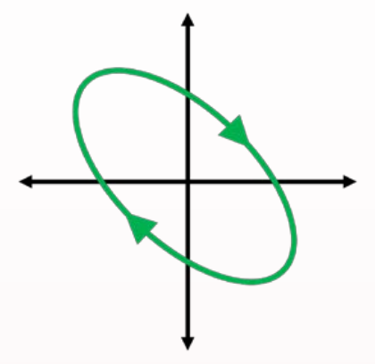
Optical Polarimetry

Using the above procedure, we test the performance of our polarimeter with, first, unexpanded light for various polarization states. Shown below are typical polarimetry measurements:

Linear, horizontally polarized light: 

$$\vec{S} = \begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} 1 \\ 0.991071(829) \\ 0.008118(7) \\ -0.021409(9) \end{pmatrix}$$

% Error of itself	
P_1	0.0836
P_2	0.0862
P_3	0.0420

Elliptically polarized light: 

$$\vec{S} = \begin{pmatrix} 1 \\ 0.446512(271) \\ 0.547650(333) \\ 0.698904(138) \end{pmatrix}$$

% Error of itself	
P_1	0.0607
P_2	0.0608
P_3	0.0197

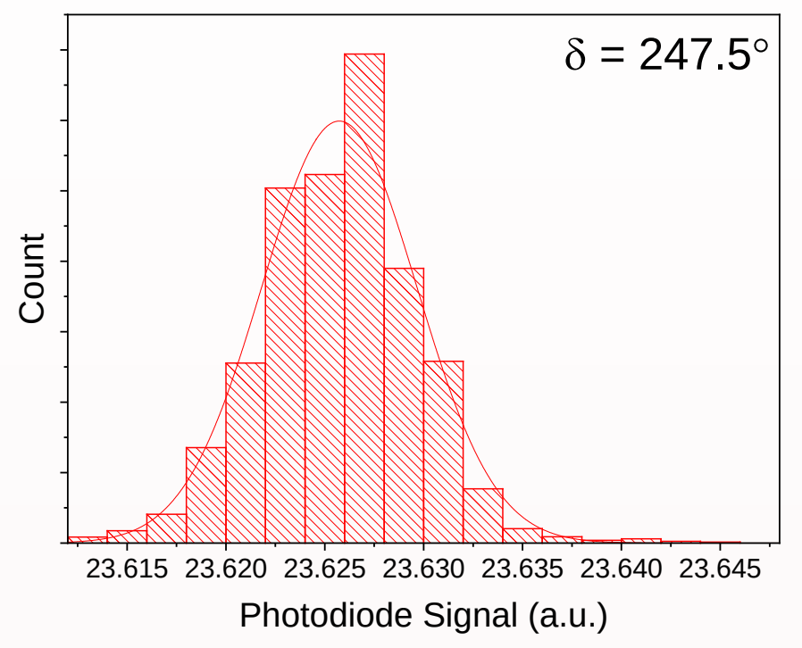
After carefully identifying and mitigating the numerous sources of error, repeated measurements show that our optical polarimeter is capable of simultaneously measuring all three Stokes parameters of unexpanded light of various polarization states to a precision better than 0.1%.

Hierarchy of Error

There are numerous factors contributing to error in optical polarimetry. To achieve an accuracy of 0.1%, it is crucial to have detailed knowledge of the many sources of error in the measurements. To that end, extensive efforts have been made to identify all sources and respective magnitudes of error, as well as appropriate mitigation techniques.

Statistical

Scales inversely with the square root of the amount of data collected for each measurement. For example, the value of P_1 corresponding to the intensity measurement shown, has a 0.001% error due to these random fluctuations.

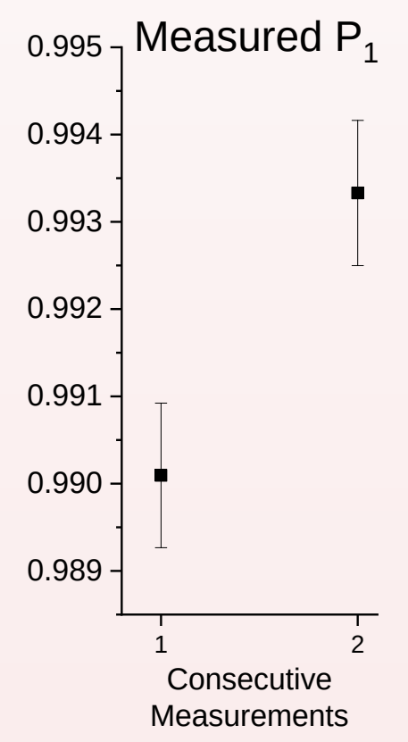


Optical parameter uncertainty, 1mm beam

The uncertainty in the optical parameters, e.g. the retardance of the quarter waveplate, is accounted for via error propagation. Ray tracing simulations indicate this contribution to uncertainty is significant. The uncertainty of the measured Stokes parameters due to this contribution is on the order of 10^{-4}.

Environmental

Currently the limiting error in our measurement protocol. Polarimetry measurements taken 1 day apart can vary by about 0.35% as shown. Can be corrected with careful control of the measurement environment.



Optical parameter uncertainty, expanded beam

Upon beam expansion, necessary to simulate the eventual measurement of fluorescence photons, the uncertainty in the optical parameters is expected to increase, necessitating optics of the highest quality. We anticipate that this will be the limiting error of our polarimeter.

Conclusions

- Initial, proof-of-principal measurements indicate that it is indeed possible to measure the Stokes parameters of light to a precision better than 0.1%. Consecutive measurements, however, can be up to 0.35% different, limiting the accuracy of our measurements.
- Careful error analysis suggests that this disagreement is due to a loss of temporal correlation in environment conditions.
- With the implementation of stricter environmental controls (primarily with respect to temperature stability and elimination of background light), combined with our rigorous error analysis, we believe the requisite 0.1% error threshold can be achieved.

Acknowledgements and References

[1] Chudakov E 2013 *AIP Conf. Proc.* **1563**, 29 and references therein
[2] Gay T J and Dunning F B 1992 *Rev. Sci. Instrum.* **63** 1635
[3] Farago P S and Wykes J S 1969 *J. Phys. B* **2** 747
[4] Gay T J, Furst J E, Trantham K W and Wijayaratna WMKP 1996 *Phys. Rev. A* **53** 1623
[5] Berry H G, Gabrielse G, and Livingston A E 1977 *Appl. Optics* **16**, 3200

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