Compton Back Scattering Polarimetry for Storage Ring Electron EDM Experiment

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In this study, we present the result of feasibility study on the Compton polarimeter as a candidate for storage ring electron EDM experiment. The cross sections and analyzing powers of the scattered photons are calculated for both longitudinal and transverse electron polarizations. The optimum photon energy is calculated to be 8.9 keV for electrons with momentum of 15 MeV/c. The polarimeter figure of merit is calculated and compared with p-C interaction case.

1 Introduction

A well-known polarimeter concept for the storage ring proton EDM experiment is the nuclear elastic scattering method. This method is very effective (high analyzing power \(\sim 0.6\)) especially for the proton-Carbon interaction around the proton magic momentum of 701 MeV/c [1, 2, 3, 4]. However, since this method is based on the hadronic elastic interaction between the spin polarized proton and carbon nuclei, it cannot be used for leptonic particles.

For the leptonic particles such as electron or muon, several different physics processes can be considered as polarization analyzers. First, Mott scattering is an electron scattering by the Coulomb field of a heavy nucleus. Møller polarimeter is utilizing collisions between polarized beam electrons and outer shell electrons of target material which are also polarized. In this study, we discuss the feasibility of Compton back scattering method as the electron polarimeter for storage ring electron EDM measurement. The calculation results of cross sections, analyzing powers, figure of merit and other experimental parameters are discussed and compared with other methods.

2 Interaction of circularly polarized photons with spin polarized particle beam

The interaction between polarized photon and spin polarized electron is well described in the references [5, 6]. Let’s assume that a photon, whose Stokes vector is represented as \(\vec{\xi} = (1, \xi_1, \xi_2, \xi_3)\), is interacting with an electron having spin vector \(\vec{\zeta} = (\zeta_1, \zeta_2, \zeta_3)\). The
resulting final form of the differential cross section of the scattered photons is \[7\]
\[
d\sigma = \frac{1}{2} r_0^2 \left( \frac{\omega'}{\omega_0'} \right)^2 (\Phi_0 + \Phi_1 + \Phi_2),
\]
with
\[
\begin{cases}
\Phi_0 = 1 + \cos^2 \theta' + \frac{1}{m_e} (\omega_0' - \omega')(1 - \cos \theta') \\
\Phi_1 = (\xi_1 \cos 2\varphi' + \xi_2 \sin 2\varphi') \sin^2 \theta' \\
\Phi_2 = -\xi_3 \frac{1}{m_e} (1 - \cos \theta') \vec{\zeta} \cdot (\vec{k}_0' \cos \theta' + \vec{k}')
\end{cases}
\]

Where \(r_0 = e^2/mc^2\) is the classical radius of electron, \(\vec{k}_0', \vec{k}'\) are initial and final photon wave vectors normalized by the electron mass energy, \(\vec{\zeta}\) is the electron spin vector (vector in 3-dim space, not Stokes vector), and \(\theta'\) is the scattering angle of outgoing photons. The primes indicate electron rest frame values and all units are in natural units, thus \(\hbar = c = 1\).

\(\vec{k}_0' - \vec{k}'\) plane determines the \(y'\) axis and accordingly \(x'\) axis by the right-hand rule. Note that the spin polarization \((\vec{\zeta})\) dependent interaction term appears only in the \(\Phi_2\) and is only sensitive to circularly polarized photons \((\xi_3)\).

Let’s assume that we have photons with Stokes vector \(\vec{\xi} = (1, 0, 0, P_{\gamma})\) and electrons whose spin vector is described by \(\vec{\zeta} = (\zeta_1, \zeta_2, \zeta_3)\). Then, we can define asymmetry in the photon scattering cross section with different photon polarizations, \(P_{\gamma} = +1, -1\) (right and left circularly polarized, respectively).

\[
A = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} = \frac{\Phi_2}{\Phi_0} = -P_{\gamma} P_p F(\theta', \omega_0')
\]

with
\[
F(\theta', \omega_0') = \frac{\omega' \sin \theta' (1 - \cos \theta')}{(1 + \cos^2 \theta') + (\omega_0' - \omega')(1 - \cos \theta')},
\]
and
\[
F(\theta', \omega_0') = \frac{(\omega_0' + \omega') \cos \theta' (1 - \cos \theta')}{(1 + \cos^2 \theta') + (\omega_0' - \omega')(1 - \cos \theta')}
\]

where \(\omega_0', \omega'\) are initial and final photon energies normalized by the electron mass energy, \(d\sigma_+, d\sigma_-\) are scattering cross-sections measured with right/left circularly polarized photons, respectively. Equations (3) and (4) are analyzing powers for transverse electron polarization and longitudinal electron polarization, respectively.

### 3 Optimal photon energy

In storage ring electron EDM experiment, we will be storing polarized electron beam at the momentum of 15 MeV/c (the magic momentum). In this case photon energy required for maximum analyzing power can be calculated using the relationship

\[
\omega_0' = 2\gamma \omega_0,
\]

where \(\omega_0\) is the initial photon energy measured in lab frame and \(\gamma\) is Lorentz factor of moving electron. Here, recall the prime is for electron rest frame values. The analyzing power increases
with photon energy and is maximum at $\omega'_0 = 1$ for the transverse electron polarization. This can be easily shown by plotting the Eq. (3). By using the relationship between $\gamma$ ($=29$ for electron magic momentum of 15 MeV/c) and photon wavelength $\lambda$,

$$\lambda = \frac{2.48\gamma}{m_e [eV \cdot \mu m]},$$

one can get the optimal wavelength of 0.14 nm which corresponds to the energy of 8.9 keV.

For the longitudinal electron polarization case, if the same energy of photon ($\omega'_0 = 1$) is used, the analyzing power $F$ is 0.8 and this is about 2.4 times bigger than the transverse electron polarization case ($F=1/3$). As a conclusion, the longitudinal polarization is more sensitive than the transverse polarization. Thus, we propose to use longitudinal polarization for the electron polarization analysis.

### 4 Figure of merit

The polarimeter figure of merit is defined by the Eq. (7).

$$FOM \equiv 2N_0\Pi^2, \text{ or } \sigma\Pi^2 \quad (7)$$

where $2N_0$ is total number of particles used in the measurement and $\Pi$ is analyzing power. Fig. 1 shows the resulting figure of merit as a function of scattering angle $\theta'$ along with the differential cross section and analyzing power. As can be seen in Fig. 1 (c), the best FOM can be achieved in the angle range of $\theta' = \pi/2 \sim 3\pi/2$ for the longitudinal electron polarization case. The FOM is an important parameter for assessing polarimeter efficiency. In this study, we assumed an example experimental conditions and the resulting figure of merit for this Compton polarimeter was about $4.5 \times 10^3$. The detailed calculation will be published elsewhere.

One can do a similar calculation for p-C polarimeter case. Let’s assume that we have $10^{11}$ protons/storage and extract them for $10^3$ s. This gives $10^8$ protons/s on target. Assuming 1% of detector efficiency, the total number of protons arriving on the detector plane is $10^{6}$/s. If we use average analyzing power of 0.6 for the p-C scattering for the angle range of 5~20 deg, the approximate FOM becomes $FOM_{pC} = 10^6 \times 0.6^2 = 3.6 \times 10^5$. Comparing this result with the Compton case, p-C scattering polarimeter is more efficient by...
2 orders of magnitude. This is because the p-C interaction have higher hadronic elastic cross sections compared to Compton back scattering.

As mentioned above, all these calculations are based on the assumptions with some experiment parameters. In order to get realistic numbers, all the parameters used in the calculation have to be replaced with real numbers of the experiment setup.

5 Summary and conclusion

In this study, we used circularly polarized photons as an analyzing tool for electron polarization measurement. We calculated the cross sections of back scattered photons off both transversely and longitudinally polarized electron beams and found the longitudinal beam was more sensitive for the polarization analysis. The optimal energy of the photon was calculated to be 8.9 keV. At this energy, the maximum analyzing power was about 0.8. By using some experimental parameters as an example, the figure of merit is calculated and compared with the case of p-C scattering polarimeter which is being developed for storage ring proton EDM experiment. Based on all the calculations we made in this study, we conclude that the Compton back scattering method could be a good candidate for the storage ring electron EDM measurement.

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References