VECTOR POLARIMETER FOR PHOTONS IN keV-MeV ENERGY RANGE

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Abstract

Light's linear and circular polarizations are analyzed simultaneously by vector polarimeters mainly in astrophysics. At higher energies Compton scattering or absorption is applied for linear or circular polarization measurements in satellites and accelerators. Here we propose a Compton scattering only vector polarimeter for monitoring photon beams in a non-invasive way. The setup is adjustable to match the initial photons' energy and can be used for diagnosing electrons' passage through undulators. In perspective the proposed device could also be explored to measure topological charge of the novel vortex photon beams.

INTRODUCTION AND OVERVIEW

As a consequence of the photon spin a beam of photons could possess an average spin which is often described in classical terms as an elliptical polarization [1]. That is a mixture of linear and circular polarizations - similar to transverse and longitudinal polarizations for a massive spinning particle.

Polarization is an important tool for generating and manipulating light in modern lasers as well as in a fast growing field of X-ray or gamma FEL(Free Electron Laser) research and applications. Recently FELs with tunable [2] or fast switching [3] polarizations have been developed for research in biology, chemistry, physics and material sciences.

For controlling the average spin one needs fast and precise measurement of light beam polarization which is increasingly difficult for high energy photon beams. That is why, the polarimeters, at high energies, are specialized for measuring either the linear or the circular polarization of the beam. In a keV-MeV energy range circular Compton polarimeters are designed [4] or used [5] for FEL radiation diagnostic while examples of linear Compton scattering polarimeters are found, apart from the accelerators, in astronomy (see Ref. [6] and references therein).

Advances in the above mentioned elliptical polarization generating FEL undulator devices require vector polarimeters to measure the linear and circular polarizations simultaneously. Such polarimeters are readily available for low frequency or energy photons within visible or near UV or IR parts of the electromagnetic spectrum (a recent example in astrophysics is described in Ref. [7]; for an undulator radiation see Ref. [8]).

Here we propose a high energy vector polarimeter based on Compton scattering.

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COMPTON KINEMATICS, CROSS SECTION AND SPIN ASYMMETRY

We review briefly some of the basic features of the Compton scattering process.

Definitions:

ω_0 and ω are the initial and final photon energies;
$E_0 = mc^2$ and E are the initial and final energies of the recoil electron;
θ and θ_e are the scattering angles of the photon and the electron.

The energies are related through energy conservation

$$\omega_0 + mc^2 = \omega + E \tag{1}$$

Furthermore, from momentum conservation follows

$$\omega = \frac{\omega_0}{1 + (\omega_0/mc^2)\,(1 - cos\,\theta)} \tag{2}$$

The scattered photon and the scattered electron angles relative to the photon beam direction are

$$cos\,\theta = 1 - \frac{mc^2}{\omega_0}\left(\frac{\omega_0}{\omega} - 1\right) \tag{3}$$

$$tg(\theta_e) = \frac{ctg(\theta/2)}{1 + \omega/mc^2} \tag{4}$$

The spin-dependent differential Compton cross section is

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\,(1 + P_\gamma^L A_L + P_\gamma^C P_e A_C) \tag{5}$$

with the unpolarized part

$$\frac{d\sigma_0}{d\Omega} = \frac{{r_0}^2}{2}\left(\frac{\omega}{\omega_0}\right)^2\left(\frac{\omega_0}{\omega} + \frac{\omega}{\omega_0} - sin^2\,\theta\right) \tag{6}$$

where r_0 is the classical electron radius and

$$\frac{r_0^2}{2} = 39.71\,mb \tag{7}$$

and P_γ^L, P_γ^C and P_e are the linear, circular and longitudinal polarizations of the initial beam photon and the target electron respectively.

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The spin asymmetries are given by

$$A_L = \frac{d\sigma_{L\perp} - d\sigma_{L\parallel}}{d\sigma_{L\perp} + d\sigma_{L\parallel}} = \frac{sin\ \theta^2}{\omega_0/\omega\ +\ \omega/\omega_0\ -\ sin^2\ \theta}, \quad (8)$$

for the linear and

$$A_C = \frac{d\sigma_{1/2} - d\sigma_{3/2}}{d\sigma_{1/2} + d\sigma_{3/2}} = \frac{(\omega_0/\omega\ -\ \omega/\omega_0)\ cos\ \theta}{\omega_0/\omega\ +\ \omega/\omega_0\ -\ sin^2\ \theta}, \quad (9)$$

for the circular photons. The cross-section indices in Eq.(8) stand for photon linear polarization perpendicular($\perp$) or parallel($\parallel$) to a fixed direction (along the axis x) and in Eq.(8) The indices in Eq.(9) correspond to parallel (3/2, along the axis z) and anti-parallel (1/2) spin orientation of the initial photon and electron.

The energy spectra of the scattered photon and electron are mirror images of each other because of equation (1). The spectra are continuous and extend from a minimum photon energy ω_{min} for backward scattering ($\theta = 180^o$)

$$\omega_{min} = \frac{mc^2}{2\ +\ mc^2/\omega_0} \quad (10)$$

all the way up to the beam energy ω_0 for forward scattering ($\theta = 0$).

In Fig.1 we give the unpolarized differential cross section $d\sigma/d\Omega$ as a function of the photon scattering angle θ for monochromatic beam energies of 50, 400 keV and 1 MeV;

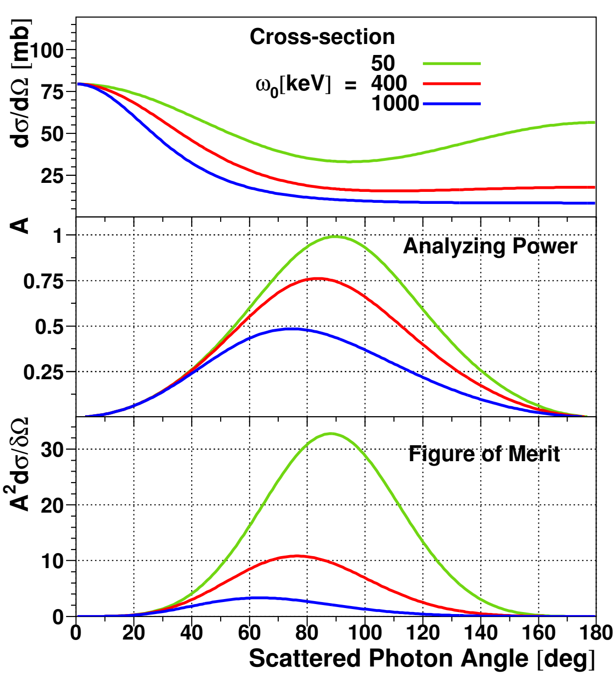

Figure 1: Linearly polarized photons Compton scattering cross-section, analyzing power and figure of merit for polarimetry. Dependence on photon's scattering angle are displayed for 50 keV, 400 keV and 1 MeV initial photon energies.

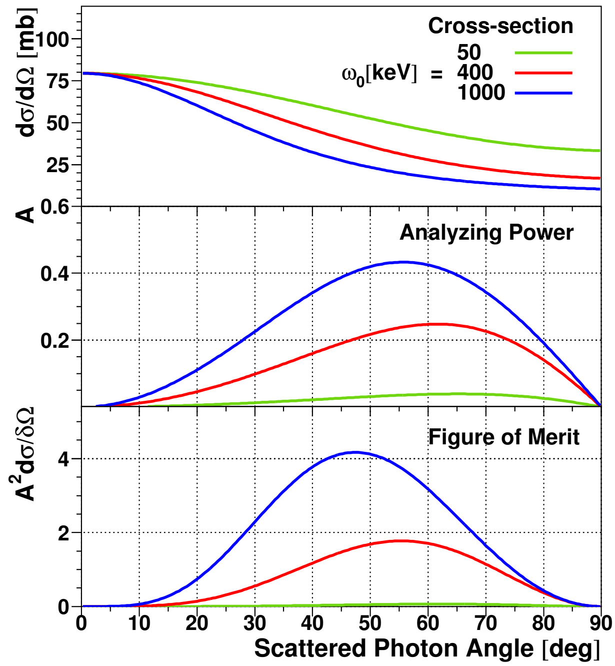

Figure 2: Circularly polarized photons Compton scattering cross-section, analyzing power and figure of merit for polarimetry. Dependence on photon's scattering angle are displayed for 50 keV, 400 keV and 1 MeV initial photon energies.

furthermore the spin asymmetry A and the figure of merit $A^2 d\sigma/d\Omega$ are plotted for the linearly polarized initial photon.

The same quantities are shown in Fig.2 for the circularly polarized initial photon. As it follows from Eq.(8) and Eq.(9) the asymmetries are relative differences of the cross-sections at $P_\gamma^L = \pm 1$ and $P_\gamma^C = \pm 1$ (with P_e=1) for the linear and circular photon polarizations correspondingly. Hence, the calculated asymmetries are Compton process analyzing powers for measuring the photon polarizations.

Within the keV-MeV energy range the formulas and plots indicate a high sensitivity of the Compton scattering to the photons' linear polarization at the lower, keV, energies which is degrading toward the higher, MeV, energies. For the circular photons, contrary to the linear case, the polarized Compton process sensitivity is low at keV energies growing higher at MeV scale.

EXPERIMENTAL CONFIGURATION

In order to obtain the photon beam polarization vector P_γ one needs to measure linear and circular spin asymmetries A_{lin}, A_{circ} as it defined by cross-section indices in Eq.(8) and Eq.(9) and normalize that to corresponding analyzing powers. Then, using Eqs.(8),(9) together with Eq.(5) one obtains polarization degrees:

$$P_\gamma^L = \frac{A_{lin}}{A_L}, \quad (11)$$

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for the linear, and

$$P_\gamma^C = \frac{A_{circ}}{A_C P_e}, \tag{12}$$

for the circular case to derive the polarization vector magnitude

$$P_\gamma = \sqrt{(P_\gamma^L)^2 + (P_\gamma^C)^2}. \tag{13}$$

An experimental setup to measure the spin asymmetries A_{lin} and A_{circ} is displayed in Fig. 3 where a Compton target is placed in a reversible magnetic field of a solenoid and the scattered photons are registered by azimuthally displaced detectors.

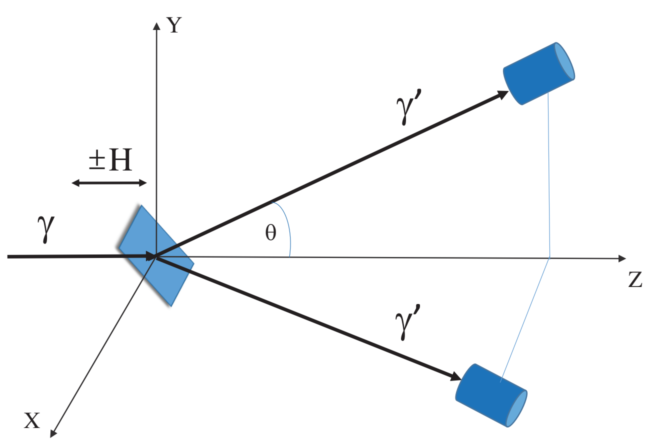

Figure 3: Experimental configuration for measuring photon beam linear and circular polarization.

In the Fig. 3 the photon beam enters from the left and strikes the polarized electron target (at z=0) which consists of a thin ferromagnetic foil tilted by a shallow angle against the beam direction. The foil is magnetized in the z direction by a modest external field $\vec{H}$ to polarize the target electrons to an average degree of $P_e = 8\%$ [9].

Scattered photons are then detected by calorimeters which measure the integrated energy deposition. The scattering angle and the covered solid angle are fixed by the position and aperture of the detector.

In such configuration an asymmetry between horizontal and vertical detector signals $A_{lin} = (S_H - S_V)/(S_H + S_V)$ will be proportional to linear polarization according to Eq.(11). Direction of the linear polarization could be measured either by 45^o rotation of the detectors or by adding a third detector between the two and forming additional asymmetry relations.

The circular polarization will be extracted using Eq.(12), from a measured asymmetry $A_{circ} = (S_+ - S_-)/(S_+ + S_-)$ of the detector signals induced by the solenoid's magnetic field flips.

DETECTORS OPTIMAL POSITIONS FOR VECTOR POLARIMETRY

The figure of merit in the Fig.1 or Fig.2 is changing versus scattered photon (detector) angle. Hence, for maximizing the figure of merit (combination of the signal amplitude and the analyzing power) the detectors should be installed at certain positions to view the target at an optimal polar angle. The optimal angle depends on the initial photon energy and type of measured polarization - linear or circular.

In order to find the optimal detection angle for a given energy of analyzable photon, a maximum of the figure of merit is calculated analytically by zeroing a differential of that expression and solving for θ - the polar angle.

This procedure is done separately for the linear and circular photons with results presented on Fig. 4.

In a vector polarimeter, however, the detector position should be optimized for analyzing both polarizations simultaneously. For that a sum of the linear and circular figure of merits is maximized to achieve the optimal performance. Analytic derivation of the optimal angle for the vector polarimetry is done similar to the linear or circular polarimeters and is plotted on the Fig. 4 versus primary photon energy.

The curves in Fig. 4 show ranges where optimal angles for the vector polarimetry are merging with the linear (below about 100 keV) and the circular (above about 10 MeV) polarimetry angles. These are the energy regions where the Compton scattering is sensitive only to the photons linear (low energy) or the circular (high energy) polarizations. Therefore, at the mentioned energies other photon induced processes should be explored for polarimetry: polarized photoeffect for the circular (<100 keV) and pair creation for the linear photons (>5 MeV) [10].

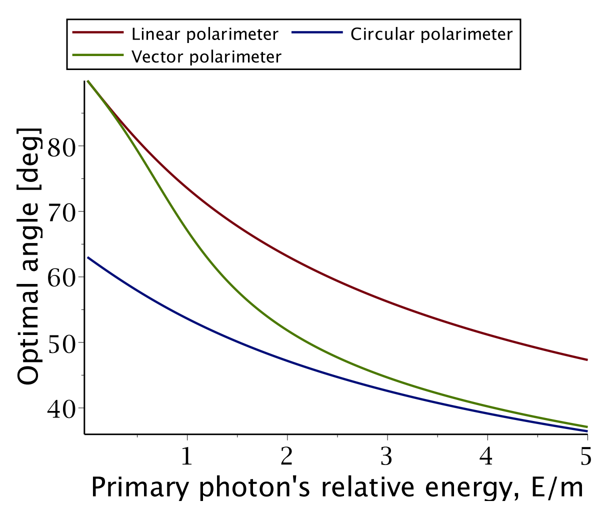

Figure 4: Compton scattered photons optimal detection angle dependence on the energy of the initial photon. Lines at top and bottom correspond to linearly and circularly polarized photons respectively while the middle line shows the maximized figure of merit for the mixed case.

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VORTEX TOPOMETRY

Photons with a phase singularity $e^{im\phi}$ possess an orbital angular momentum and are called vortex or twisted photons [11]; here the ϕ is the azimuthal angle and the integer scale factor m is the topological charge. Vortex optical beams are extensively explored in recent decade or so in photonics and astronomy [12]. There are also prospects to obtain higher energy vortex photons using laser Compton scattering [13] though verifying photons' vortex nature by measuring the topological charge remains a theoretical and experimental challenge. A major gap in knowledge is a missing quantitative description of high energy twisted photons quantum interactions.

Since the orbital angular momentum is described by similar formalism as the light circular polarization, the vector Compton polarimeter described here could be explored to interact with possible beams of high energy twisted photons. As an initial approximation could serve the doubly polarized term in the Compton scattering cross-section proportional to $P_\gamma^C P_e$. Then, a spatial spin-orbital interaction of a vortex photon could possibly be regarded as a correction. Measured asymmetries induced by flips of the topological charge or the electron spin direction at different scattering angles will provide an experimental input for a complete twisted photon quantum theory.

SUMMARY AND CONCLUSION

We applied polarized Compton scattering formulas to derive and demonstrate feasibility of a vector Compton polarimeter. The device can simultaneously measure linear and circular polarizations of a photon beam in a tens of keV to few MeV energy range. Calculations show that outside of this range, at higher(lower) energies, the polarimeter is sensitive to circular(linear) polarization only. Maximizing a convolution of analyzing power and scattered beam intensity, the optimal detection angles are derived for the linear, circular and vector Compton polarimetry. The proposed device could be used at accelerators for undulator radiation polarimetry as well as in X-ray or gamma astronomy. It could also serve in a research and development of the novel high energy vortex photon beams.

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