LASER COMPTON PROTON POLARIMETRY REVISITED

Arnold Stillman, 17 Cider Mill Lane, Huntington, NY 11743, U.S.A.

Abstract

Compton polarimetry of polarized proton beams is more feasible now than it was in 1995[1], when I first estimated the laser requirements of a polarimeter for Brookhaven's polarized proton beam at the AGS. New methods of high energy photon generation make the technique of Compton proton polarimetry a viable option for polarized proton beams. Since the analyzing power of a Compton polarimeter increases with photon energy and the count rate of the polarimeter increases with the laser intensity, the new laser technologies available today imply the construction of a working device with reasonable effort. I estimate the device parameters necessary for a working Compton polarimeter at RHIC using several methods of high energy photon generation.

BACKGROUND

Proton polarimetry at AGS polarized proton energies has not been amenable to Compton polarimetry methods given the large reduction in the cross-section for spin dependent Compton scattering from protons. This cross-section is proportional to $(m_e/m_p)^3$ which is $\approx 1.6\times10^{-10}$ that of the cross-section for electron Compton scattering. Laser photons are the obvious choice to try to enhance the scattering rate to observable levels, but laser intensities, at least in 1995, were not quite sufficient to create a working polarimeter [1]. At the time, with laser photons of 300nm wavelength, calculation showed that the laser energy required would be on the order of 4-5J, which was possible, but that the counting rate of back-scattered photons would need to be on the order of 100GHz to produce an asymmetry measurement of sufficient accuracy. Such a combination of laser energy and counting rate was conceivable, but so unpractical as to be essentially unworkable. The time to complete a polarization measurement of sufficient accuracy would have been about 165 hours.

There are two ways to overcome the rate and energy limitations to Compton polarimetry; one is to increase the laser intensity and the other is to decrease the laser wavelength. Increasing the laser intensity of visible photons is the lesser of the two methods, since it implies increasing the count rate of detected photons beyond 100GHz. The better method is to increase the photon energy. The asymmetry in Compton scattered polarized photons of two different initial polarizations increases quickly with initial photon energy. The difference in asymmetry for a $\mathbf{10^{-4}}$nm initial photon and a 300nm photon is about $\mathbf{10^{6}}$, which can reduce the time to make a polarization measurement by about $\sim\mathbf{10^{-8}}$. The previous calculation of 165 hours potentially reduces to seconds.

DIFFERENTIAL CROSS SECTION

The simplest approximation to the cross section for polarized Compton scattering from protons is to substitute the proton mass for the electron mass in the cross section [2][3],

$$d\sigma = \frac{1}{2} r_e^2 \left(\frac{\omega'_f}{\omega'_i}\right)(\Phi_0 + \Phi_1 + \Phi_2). \qquad (1)$$

Here r_e is the electron radius in natural units (*i.e.* $h = c = 1$) and,

$$\Phi_0 = (1+\cos^2\theta') + \frac{1}{m_e}(\omega'_i - \omega'_f)(1-\cos\theta'); \qquad (2)$$

$$\Phi_1 = (\xi_1 \cos 2\varphi' + \xi_2 \sin 2\varphi') \sin^2\theta'; \qquad (3)$$

$$\Phi_2 = -\xi_3 \frac{1}{m_e}(1-\cos\theta')\, \vec{\zeta}\cdot(\vec{k_i}\cos\theta' + \vec{k}_f); \qquad (4)$$

where θ' is the scattering angle of the photon in the rest frame of the electron, φ' is the polar angle of the scattered photon with respect to the incident photon, m_e is the electron mass, k_i, k_f and ω'_i, ω'_f are the initial and final wave vectors and frequencies of the photon, respectively, and $\vec{\zeta}$ is the electron spin vector. Primes indicate electron rest frame quantities. The Stokes parameters $\vec{\xi} = (\xi_1, \xi_2, \xi_3)$ form the components of the photon polarization vector. For positive and negative helicity photons scattering from longitudinally polarized electrons, only ξ_3 is relevant and $\vec{\zeta}$ has polarization components (0, 0, +/-P_e) only along the velocity of the electron.

In this simplest approximation, the proton mass substitutes for the electron mass in the cross section and the photon energy scales accordingly, so that a photon with $\omega' = 1$ has an energy of 1GeV in the lab frame. Asymmetrical scattering of laser photons from protons then has the same form as that for electrons, but its magnitude is significantly different. The asymmetry in the scattering rate for opposite helicities of the proton is [3],

$$A_{\pm} = \frac{d\sigma_+ \pm d\sigma_-}{d\sigma_+ + d\sigma_-}, \qquad (5)$$

and the total asymmetry is

$$A = \frac{A_+ - A_-}{2} = \frac{\Phi_2}{\Phi_0} = P_p P_\gamma \cos\varphi' F(\theta', \omega'_i). \qquad (6)$$

For polarizations $\vec{\xi} = (0, 0, \pm P_\gamma)$, $\vec{\zeta} = (0, 0, P_p)$, $\vec{\zeta}\cdot\vec{k} = \zeta_3 \omega'_f \sin\theta' \cos\varphi$; at the optimal scattering angle $\theta' = \frac{\pi}{2}$, the function $F(\theta', \omega'_i)$ then is;

$$F\left(\frac{\pi}{2}, \omega'_i\right) = \frac{\omega'_i}{1 + \omega'_i + \omega'^2_i} \qquad (7)$$

Fig. 1 is a plot of this function; note that its steepest rise is at low energies. The photon frequency scale is now in units of the proton mass, so for laser photons of 1MeV, for example, $F(\frac{\pi}{2}, \omega'_i) \approx 10^{-3}$.

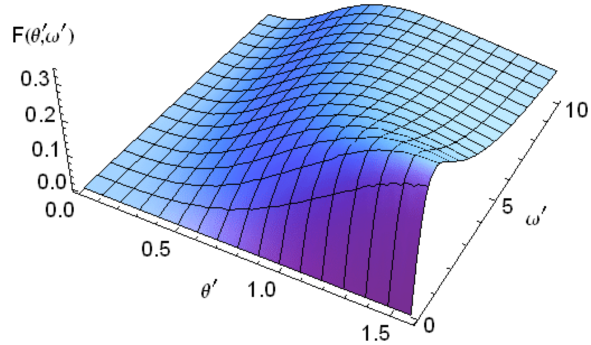

Figure 1: The function $F(\theta', \omega'_i)$ as a function of ω'_i.

POSSIBLE IMPLEMENTATIONS

The only feasible way to generate laser photons of sufficient energy to increase polarization count rates is to use a "double-bounce," scheme in which a standard optical laser scatters from a moving electron target to generate a back-scattered beam which becomes the analyzing beam for the polarized protons. The obvious example is the proposed "eRHIC" electron beam [4], in which the oncoming electrons boost laser photons to GeV energies. Other schemes are possible as well, such as flying mirrors [5].

Since both of these methods involve the Compton back-scattering of photons, the photon energy boost increases as $\sim\gamma\gamma$. The flying mirror prototype in [5] obtained energies of 0.09 keV and a wavelength shorter by 56 times that of the input laser wavelength. This energy corresponds to a value $F(\frac{\pi}{2}, \omega'_i) \approx 10^{-4}$, a quite reasonable number even if photons of this energy were to analyse the proton beam directly. However, these upshifted photons now serve as the analyzing beam for the oncoming proton beam.

A counter-rotating electron beam provides a similar but much more effective analyzing beam of photons, and the proposal to install just such a beam at Brookhaven's RHIC opens up the opportunity actually to implement a Compton polarimeter. Not only does the much higher electron energy generate the required high energy photons, but the narrow scattering angle of the back-scattered photons, of the order of $1/\gamma$, maximizes their interaction with the polarized proton beam.

THE SCATTERING RATE

The polarimeter operates by discriminating the differential polarized scattering rate from the unpolarized background rate. There is an optimal wavelength for the analyzing incoming photons that maximizes this rate [1], given by,

$$E_\gamma E_{beam} = m_p^2/2, \tag{8}$$

where E_γ is the photon energy and $E_{beam}$is the polarized proton beam energy. For a RHIC energy of 100GeV, this corresponds to a photon energy of ~460MeV. This ebnergy is attainable in the double bounce scheme using the colliding electron beam. The flying mirror technique would fall short of this optimal energy, but is much easier to implement, given no electron beam.

Including the double scattering in equation (8) gives a relation between the polarized beam energy and the initial laser photons;

$$E_\gamma = \frac{m_p}{2\gamma_e^2\gamma_p}, \tag{9}$$

where γ_e is the electron beam relativistic Lorentz factor and γ_p is the proton beam Lorentz factor. For $\gamma_e = 1000$, and $\gamma_p = 100$ the input laser need only have an energy of ~5eV.

Since this energy is at the optimal energy for analyzing power, $A^2 \approx 0.1$, the time needed to make a polarization measurement is shortened considerably from that calculated in [1].

CONCLUSION

Double Compton scattering of laser pulses from a counterpropagating electron target is a viable means of making polarization measurements on high energy polarized proton beams. The laser power required to generate a sufficient count rates diminishes significantly due to the energy boost of the initial photons. This boost allows the asymmetry to be optimal by increasing the polarized cross section by several orders of magnitude. The possibility of a constructing a colliding electron beam at RHIC to supplement the polarized proton program provides an opportunity to include a laser-based polarimeter that would make quick, accurate and non-destructive polarization measurements on the RHIC polarized proton beam.

REFERENCES

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