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A proton polarimeter based on the elastic pe-scattering

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Abstract

The analyzing power of multi-GeV protons scattering on electrons is estimated. The possibility to use such polarimeters based on pe-scattering for the measurement of the longitudinal and transverse polarization of the protons is demonstrated. Various types of the electron polarized targets have been considered: solid, gas jet, free electron and electron beam.

Keywords: Polarimeter; pe-scattering; Double spin asymmetries; Electron targets

1. Introduction

Previous experience with high energy particle polarimeters has shown that using a few distinct methods of the beam polarization measurement is very advantageous [1]. Now three types of proton polarimeters are suggested for use at high energy: one based on the Primakoff effect (the asymmetry ratio reaches $A \cong 0.5$), the second uses the Coulomb nuclear interference in elastic pp-scattering ($A \leq 0.05$) and the third uses the asymmetry of the inclusive pion production at high x ($A \sim 0.2$). The use of any of these techniques as absolute polarimeter depends on theoretical uncertainties, primarily connected with the hadronic part of an amplitude. We propose to use an pe-elastic polarimeter for which the analyzing power can be calculated in a straightforward way and to high accuracy in the one-photon approximation and does not depend on the model. Earlier in a series of reports [2,3] we have discussed possible applications of the pe-polarimeter. The purpose of this paper is to reproduce in more details the results of theoretical estimates and to consider possible variants of the polarized electron target.

2. Double spin asymmetries in proton-electron scattering

The experimental polarization asymmetry for the elastic pe-scattering A_{ij}^{exp} is given by the product of the beam P_i^{p} and target P_j^{e} polarizations along i and j directions respectively and the spin correlation asymmetry A_{ij}

$$A_{ij}^{\text{exp}} = P_i^{\text{p}} P_j^{\text{e}} A_{ij}, \tag{1}$$

where A_{ij} is defined as

$$A_{ij} = \frac{\mathrm{d}\sigma/\mathrm{d}\Omega\,(\widehat{i},\widehat{j}) - \mathrm{d}\sigma/\mathrm{d}\Omega\,(\widehat{i},-\widehat{j})}{\mathrm{d}\sigma/\mathrm{d}\Omega\,(\widehat{i},\widehat{j}) + \mathrm{d}\sigma/\mathrm{d}\Omega\,(\widehat{i},-\widehat{j})}. \tag{2}$$

Here $\mathrm{d}\sigma/\mathrm{d}\Omega(\widehat{i},\pm\widehat{j})$ are the differential cross sections for the "pure spin states" of the proton polarized along the $\widehat{i}$ direction and the electron polarized along or against the $\widehat{j}$ direction. We designate the four momenta of the initial and final protons and electrons by $P_1(\boldsymbol{p}_1, E_1)$, $K_1(\boldsymbol{k}_1, e_1)$, $P_2(\boldsymbol{p}_2, E_2)$, $K_2(\boldsymbol{k}_2, e_2)$ and their masses by M and m, respectively. The invariant amplitude of the elastic pe-scattering is written in the one photon approximation in the following form:

$$M_{fi} = \mathrm{i}e^2 t^{-1} \bar{u}(K_2)\gamma_\alpha u(K_1)\bar{u}(P_2)[\gamma_\alpha(F_1(t) + F_2(t)) + \mathrm{i}(P_1 + P_2)_\alpha F_2(t)/2M]u(P_1), \tag{3}$$

where $t = -(K_1 - K_2)^2$ is the square of the momentum transfer, F_1 and F_2 are the proton electromagnetic form factors. Then in an arbitrary reference frame a spin correlation asymmetry may be written as [4]

$$A = \frac{1}{X}\{2mM(F_1(t) + F_2(t))t[(\xi\cdot\zeta + \frac{\xi\cdot K\zeta\cdot K}{t})F_1(t) + \frac{t}{4M^2}(\xi\cdot\zeta - 2\frac{\xi\cdot P_1\zeta\cdot K}{t})F_2(t)]\}, \tag{4}$$

with the definition

$$X = \{[2a(2a - t) + tM^2](F_1^2(t) - t/(4M^2)F_2^2(t)) + \tfrac{1}{2}t(t + 2m^2)(F_1(t) + F_2(t))^2\},$$

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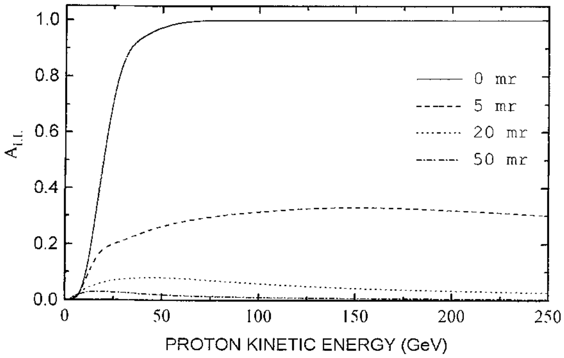

Fig. 1. The energy dependences of the spin correlation parameter A_{LL} for the elastic scattering of the longitudinally polarized protons on the longitudinally polarized rest electrons at different angles.

which is connected with the Rosenbluth cross section [5]

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha}{t^2} \frac{1}{(a^2 - m^2M^2)^{1/2}} \times \frac{|k_2|^2}{|k_2|(e_1 + E_1) - e_2|k_1 + p_1|\cos\theta_e} X. \tag{5}$$

Here $a = K_1P_1$, the recoil angle θ_e is the angle between $k_1 + p_1$ and k_2, $K = K_1 - K_2$, $\alpha = 1/137$ is the fine structure constant. The unit 4-vectors ξ and ζ are the electron and proton polarization vectors for the "pure states", whose components are expressed in terms of the particle spins in its corresponding rest frames as,

$$\xi = \left(\hat{s}_1 + \frac{\hat{s}_1 \cdot k_1}{m(m+E_1)} k_1, \frac{\hat{s}_1 \cdot k_1}{m}\right) \tag{6}$$

for the electron and the analogous expression for ζ of the proton. Here $\hat{s}_1$ is the unit vector in the direction of the spin of the fermion in its own rest system.

We use the dipole representation for the electric $G_E(t)$ and magnetic $G_M(t) \approx \mu G_E(t)$ form factors of the proton (μ is the anomalous magnetic moment of the proton), so that

$$F_1(t) = \frac{4M^2 - 2.79t}{4M^2 - t} \frac{1}{(1 - t/0.71)^2},$$

$$F_2(t) = 1.79 \frac{4M^2}{4M^2 - t} \frac{1}{(1 - t/0.71)^2}.$$

We have calculated the spin correlation parameters for the proton and electron polarized along the direction of the proton beam motion $\hat{l}$, along the normal $\hat{n}$ to the scattering plane, along the unit vector $\hat{s} = \hat{l} \times \hat{n}$ and the elastic scattering differential cross section as functions of the kinetic energy of the proton in the range $5 < E_p < 250$ GeV at several recoil electron angles.

The first outcome of our calculations is that spin correlation parameters have noticeable sizes in the energy range under consideration. In this paper we shall pay more attention only to spin correlation parameters A_{LL}, A_{NN} and A_{SL}.

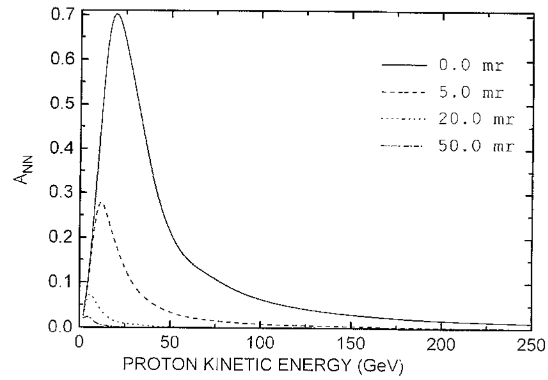

Fig. 2. The energy dependence of the spin correlation parameter A_{NN} for the elastic scattering of the transversely polarized protons on the transversely polarized rest electrons for different angles.

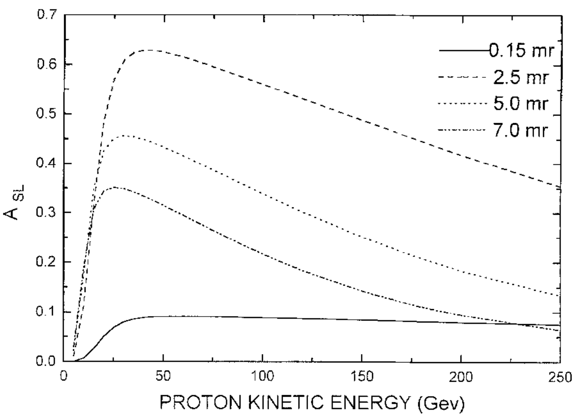

Fig. 3. The energy dependence of the spin correlation parameter A_{SL} for the elastic scattering of the transversely polarized protons on the longitudinally polarized rest electrons for different angles.

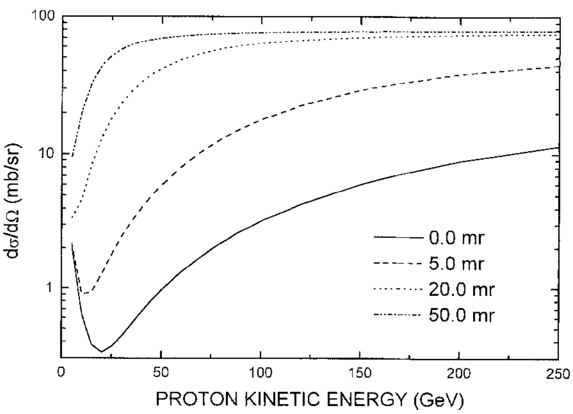

Fig. 4. The differential cross section of the proton elastic scattering on the rest target electron at different electron recoil angles.

In Figs. 1–4 the energy dependence of A_{LL}, A_{NN}, A_{SL} and the unpolarized elastic scattering cross section are given for different electron recoil angles in case of the target electron being at rest. One can see that A_{LL} is most suitable for the polarization measurement at $E_1 > 25$ GeV, and A_{NN} is most appreciable at 10–30 GeV for the angular region $\theta_e < 4$ mrad where they are large enough. The spin correlation parameter A_{SL} has a sufficiently large value in the whole interval of the energies under consideration for the same angular region and has the maximum at the angles of about 2.5 mrad, so it can be used to measure the transverse polarization of the proton beam. Though the cross section diminishes with the decrease of the recoil electron angle the small angle region is more adequate for polarization measurement on the rest electrons, because the effective spin correlation parameter $A_{ij}^2\,\mathrm{d}\sigma/\mathrm{d}\Omega_e$ has a considerable value in the region with a large value of the asymmetry.

3. Polarized electron target

We have explored the feasibility of four types of targets for our purposes:
(i) solid target (ST),
(ii) gas jet target (GJT),
(iii) free electron target (FET),
(iv) electron beam target (EBT).

(i) Permendur wire has been taken as a ST. When placed in a magnetic field strength more than 100 G the ST provides the electron polarization at a level of 8%. The employment of the ST calls for a treatment of two substantive issues associated with
- an increase of the proton beam emittance through multiple Coulomb scattering in the ST and
- target heating.

The emittance growth $\delta\varepsilon$ of the proton beam as a result of a proton interaction with the target is connected with the rms of the multiple scattering angle θ_0 and the betatron amplitude function β at the target location point

$$\delta\varepsilon = 6\pi\theta_0^2\gamma\beta, \tag{7}$$

where γ is Lorentz-factor of the proton.

If the diameter d of the wire target is much less than the proton beam size, the effective thickness of the target x_t in an expression for the rms angle

$$\theta_0 = (13.6\times 10^3/p_1)\sqrt{x_t/X_0} \tag{8}$$

can be written as

$$x_t \simeq (\pi f d^2/16rn)\,t_m, \tag{9}$$

where p_1 is the proton momentum, X_0 is the radiation length of the material of the target, f is the bunch frequency, n is the number of the bunches in each ring,

$$r = \sqrt{\varepsilon\beta/6\pi\gamma} \tag{10}$$

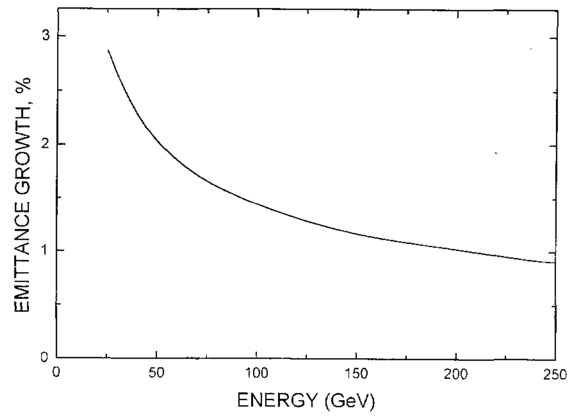

Fig. 5. The emittance growth of the RHIC proton beam caused by the proton scattering on a wire iron target of the diameter 1 μm during 1 s.

is the rms radius of the proton beam, ε is 95% emittance of the beam, and t_m is the measurement time.

For an example, Fig. 5 shows the dependence of the emittance growth of the RHIC proton beam, which occurs as a result of the proton scattering on a wire iron target of the diameter 1 μm during 1 s. The beam emittance and the betatron amplitude function were taken as $20\pi\times 10^{-6}$ m and 25 m correspondingly.

The necessary time of a measurement is defined basically by the required statistical accuracy ΔP of the polarization measurement P and is given by the formula

$$\left(\frac{\Delta P}{P}\right)^2 = \frac{1}{2L(\mathrm{d}\sigma/\mathrm{d}\Omega)\Delta\Omega t_m}\left(\frac{1}{A^2P^2}-1\right), \tag{11}$$

where $\Delta\Omega$ is the solid angle of the detector, $\mathrm{d}\sigma/\mathrm{d}\Omega$ is the value of the pe-scattering differential cross section, A is the analyzing power of the pe-scattering. At the Gaussian distribution of the protons in the beam and the target location on the axis of the beam the luminosity L is connected to parameters of the beam and target as follows:

$$L = f(N_p n_e/\sqrt{2\pi}r), \tag{12}$$

where N_p is the number of protons per bunch and n_e is the linear density of the electrons in the wire target.

If the detectors measure the pe-scattering asymmetry in the solid angle 10^{-5} sr near to the zero electron recoil angle, where the analyzing power has a maximum, then, after reaching 5% accuracy of measurement of polarization, the increase of the beam emittance will account for 20% and 100% at a proton energy of 250 and 100 GeV, respectively. It results in destruction of the beam.

The temperature variation in the interaction volume of the proton beam and the wire target is defined by the differential equation of balance

$$\mathrm{d}T = [(P_{\mathrm{ion}} - P_{\mathrm{rad}})/(\rho V c)]\,\mathrm{d}t_m. \tag{13}$$

Here T is the wire temperature, V is the average volume of the interaction region, ρ is the density and c is the specific heat of the wire material.

The power released in the wire equals

$$P_{\rm ion} = N_{\rm p} f k (\,{\rm d}E/\,{\rm d}x) t_{\rm av}, \tag{14}$$

where k is the average beam-target overlapping coefficient, $\mathrm{d}E/\mathrm{d}x$ is the proton energy loss per unit length within the target, and $t_{\rm av}$ is the average wire thickness. The radiated power is written in the following form

$$P_{\rm rad} = \sigma_{\rm B} S T^4, \tag{15}$$

where $\sigma_{\rm B}$ is the Boltzmann constant and S is the average radiating area of the wire.

Then Eq. (13) takes the form

$$\mathrm{d}T/\,\mathrm{d}t_{\rm m} = -AT^4 + B, \tag{16}$$

where

$$A = 4\sigma_{\rm B}/d\rho c, \quad B = (N_{\rm p} f/4r^2 \rho c)\,\mathrm{d}E/\,\mathrm{d}x. \tag{17}$$

Here B does not depend on the wire thickness if $d < r$.

When $\mathrm{d}T/\mathrm{d}t_{\rm m} = 0$, we have the equilibrium temperature

$$T_{\rm eq} = \left(B/A\right)^{\frac{1}{4}}. \tag{18}$$

Within the temperature region where $(T/T_{\rm eq}) << 1$ the solution of Eq. (16) is

$$t_{\rm m} = \frac{T - T_0}{B} + \frac{T_{\rm eq}}{B}\left[\left(\frac{T}{T_{\rm eq}}\right)^5 - \left(\frac{T_0}{T_{\rm eq}}\right)^5\right], \tag{19}$$

where T_0 is the initial temperature in K.

For $T < 0.5T_{\rm eq}$ the added term connected with the radiation is small and

$$t_{\rm m} \approx (T - T_0)/B \equiv \Delta T/B. \tag{20}$$

Practically T must be less than the Curie temperature of the ferromagnet.

The expression used to compute the target temperature growth due to heating by the beam is [6]

$$\Delta T = 3.8 \times 10^{-18} (N_{\rm p} f/v h_{\rm eff} c)\,\mathrm{d}E/\,\mathrm{d}x, \tag{21}$$

where v is the wire speed and $h_{\rm eff}$ is the effective beam size (m) ($h_{\rm eff} = \sqrt{2\pi}\sigma$ for a Gaussian).

The above expression clearly gives a far too pessimistic estimate of the temperature rise [7]. The reason can be understood if one considers the fact that the energy transferred from the proton to the electron in material due to multiple Coulomb scattering is not all trapped in the wire. Electrons with sufficient energy will escape and not contribute to the heating. The effect can be very high and depends on the wire diameter.

Our estimations with the help of Eq. (20) has shown that ST can be expediently used in case of low ($< 10^{17}$ protons/s) beam intensity or in an extracted proton beam.

(ii) The most optimal GJT is an atomic hydrogen target. The target thickness in this internal GJT is nearly 10^{12}–10^{14} $\mathrm{e}^-/\mathrm{cm}^2$ [8]. The advantages of this polarized target are
- low target density and
- feasibility of 100% electron polarization.

The chief drawback of the GJT is strong hadronic background due to pp-collisions which is three orders of magnitude higher than the scattering cross section in the kinematic region where the highest analyzing power is achieved.

(iii) The use of free electrons as a target in a polarimeter offers some benefits. As compared with the permendur wire target, the FET can provide a higher degree of polarization and allows measurements to be made with no deleterious effect on the proton beam lifetime. Moreover, while using the FET, the hadronic background is several orders of magnitude lower than with the GJT. Now, a GaAs photocathode exposed to circularly-polarized laser light is the most promising polarized electron source. The degree of the longitudinal electron polarization is as high as 80% [9]. The characteristics of the electron gun at SLC [10] where the electron current density is 2.5 $\mathrm{A/cm^2}$. For an extended GaAs cathode of 50 cm length, incident parallel to the proton beam with electrostatic focusing of electrons in a plane, the target thickness can be up to 10^{13} $\mathrm{e^-/cm^2}$. A FET thickness of the same order of magnitude has been obtained with Penning traps [11].

(iv) The particular important problem is the determination of the transverse proton polarization. It can be solved with the pe-polarimeter by measuring the A_{SL} asymmetry that is sufficiently large within the whole energy interval (see Fig. 3). The use of the pe-polarimeter with the above considered electron targets to determine the transverse polarization by measuring $A_{NN}^{\rm exp}$ asymmetry has an essential defect – the narrow range of the proton energy in which the analyzing power is reasonably large (see Fig. 2). This defect can be overcome, if an accelerated polarized electron beam is used as an electron target. The selection of the electron energy allows to make the measurement of polarization at such a total center of mass energy $\sqrt{s}$ at which the asymmetry of the elastic pe-scattering has the maximum. In Fig. 6 the parameter A_{NN} is shown as a function of the initial kinetic energy of the electrons moving in the same direction as the proton. The presence of two maxima is connected with two values of energy of the initial electron for the given $\sqrt{s}$ at which the relative proton and electron velocities are equal and have the opposite direction. For the second maximum the scattered electrons emerge in a wide cone of angles and the differential cross section decreases slowly with an increase of the scattering angle of the electron. The use of the second maximum for the measurement of the transverse proton polarization will be probably useful for the colliders of the HERA and LHC (ep performance) type if the electrons collide with the protons.

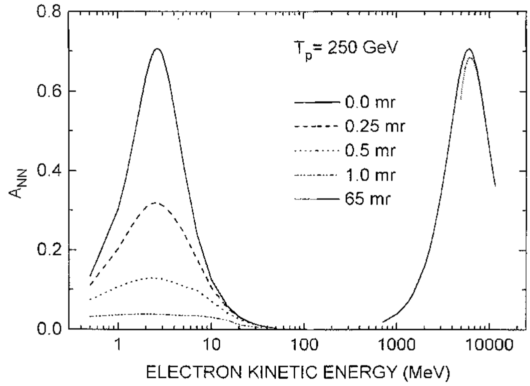

Fig. 6. The energy dependence of the A_{NN} spin correlation parameter for the elastic scattering of the transversely polarized protons with the kinetic energy $T_p = 250$ GeV on the transversely polarized electrons moving along the direction of the proton beam for different angles of the scattered electron.

4. Conclusion

In summary, the polarimeter based on the elastic pe-scattering gives a good opportunity to reliably measure as the longitudinal proton beam polarization as transverse. Our calculations have shown that the spin correlation parameters A_{LL}, A_{NN}, A_{SL} have noticeable sizes in the energy range under consideration at small electron recoil angles. Although the scattering cross section diminishes with the decrease of the recoil electron angle the region of the small angles is more than adequate for the polarization measurement, because the effective spin correlation parameter $A_{ij}^2\, d\sigma/\, d\Omega_e$ has a considerable value in the region together with large values of the asymmetry.

It has been shown that ST can be expediently used in case of low ($< 10^{17}$ protons/s) beam intensity or with an extracted beam of the protons. The use ST and GJT is also limited by the large hadronic background of the elastic pe-scattering. It is the FET or EBT that is best able to handle the problem of the proton beam polarization measurement.

The use of the electron beam target for the determination of the transversal proton polarization in a wide region of the proton energy and based on the measurement of the A_{NN}^{exp}-asymmetry will probably appear useful.

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