INTRODUCTION

In ref. [1] the polarization measurements were performed for 180 GeV proton with polarimeters based on Primakoff effects (asymmetry ratio reaches $A \approx 0.5$) and on Coulomb-nuclear interference process (CNI) ($A < 0.05$). As proton energy increases the possibility of these absolute polarimeters seems to have some difficulties as analyzing power for strong interaction processes can not be calculated using the existing theoretical models without normalization uncertainties.

Thus to analyze multi-GeV-energy protons it is more convenient to utilize the p-e polarimeters based on electromagnetic interactions with well known analyzing power.

Polarimeters based on p-e scattering possess some advantages:

a) theoretically well defined analyzing power A,

b) simple two-particles identification scheme,

c) relatively large recoil electron exit angles (for 250 GeV proton scattering on the rest electron the maximum proton scattering angle θ_p = 0.56 mrad whereas the electron recoil angle θ_e = 4 mrad).

d) effective analyzing power $A^2\, d\sigma/d\Omega$ for scattering of multi-GeV protons exceeds the appropriate values for Primakoff process and Coulomb - nuclear interference.

ANALYZING POWER FOR p-e SCATTERING

The invariant amplitude of the pe-elastic scattering with $p_1 + k_1 = p_2 + k_2$ has been written in the following form

$$M_{fi} = ie^2\, t^{-1}\, \bar{u}(k_2)\gamma_\alpha\, u(k_1)\, \bar{u}(p_2)[\, \gamma_\alpha\, G_M(t) + in_\alpha\, F(t)]u(p_1)$$

where t is the square of the momentum transfer,

$$G_M(t) = F_1(t) + F_2(t), \quad F(t) = F_2(t)/2M,$$

F_1 and F_2 are the proton form factors, $n_\alpha = (p_1 + p_2)_\alpha$. In the center of mass system the differential cross section of the polarized proton on polarized electron scattering is [2]

$$\frac{d\sigma}{dt} = \frac{\pi\alpha^2}{4sp^2t^2} \{ \frac{G_E^{\,2}(t)}{1 - t/4M^2} [(s-u)^2 + (4M^2 - t)t]$$
$$- \frac{t}{4M^2} \frac{G_M^{\,2}(t)}{1-t/4M^2} [(s-u)^2 - (4M^2-t)(4m^2+t)]$$
$$+ 8M\, m\, G_M(t)t \, \{ F_1(t)[\frac{(q\xi)(q\zeta)}{t} + (\xi\zeta)]$$
$$- \frac{t}{4M^2} F_2(t) \, [\, 2 \frac{(q\xi)(p\zeta)}{t} - (\xi\zeta)]\}\}$$

Here s is the total energy squared, p stands for the magnitude of the three-momentum in c.m.s., $u=2M^2+2m^2-s-t$, M and m are the proton and electron masses correspondingly, $G_E=F_1+t/4M^2F_2$ denotes the electric form factor of the proton, $\alpha=1/137$ = fine structure constant. The unit 4-vectors ζ and ξ are electron and proton polarization vectors, which components are expressed in terms of the particle's spin in its rest frame, so the spin density matrix has the form

$$\rho(k)=1/2(1+i\gamma_5\hat{\zeta})(m-i\hat{k})$$

for the electron and analogous one for the proton.

Now we can calculate any spin effect and we do it for the longitudinally polarized proton and electron beams (A_{LL} spin correlation parameter) at the 250 GeV proton kinetic energy and the small (about 1 mrad) angles of the recoil electron in laboratory system where electron was at rest before the collision. We take the dipole representation for the form factors

$$G_M(t)=\mu G_E(t),\ \mu=2.793,$$
$$G_E(t)=(1-t/0.71)^{-2},$$

as is usually done for such problems and assume that $G_E G_M>0$. The momentum transfer t has been calculated from the electron recoil energy ϵ_2,

$$t=-2m(\epsilon_2-m),$$

that, in turn, depends on its recoil angle θ and initial proton energy E_1 and momentum p_1

$$\epsilon_2=m\ \frac{(m+E_1)^2+p_1^2\cos^2\theta}{(m+E_1)^2-p_1^2\cos^2\theta}$$

The double helicity asymmetry A_{LL} which is defined as

$$A_{LL}=\frac{d\sigma(\uparrow\uparrow)-d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow)+d\sigma(\uparrow\downarrow)}$$

and is equaled in c.m.s.

$$A_{LL}=\frac{1}{X}(8G_M(t)t[F_1(t)(p^2+\varepsilon E(1+\frac{t}{4M^2})-\frac{t}{4}F_2(t)])$$

Here X is proportional to the Rosenbluth cross-section

$$X=\frac{G_E^2(t)}{1-t/4M^2}[(s-u)^2+(4M^2-t)t]-$$
$$-\frac{t}{4M^2}\frac{G_M^2(t)}{1-t/4M^2}[(s-u)^2-(4M^2-t)(4m^2+t)],$$

and the electron and proton c.m.energies are

$$\varepsilon=\frac{s-M^2+m^2}{2W},\ E=\frac{s+M^2-m^2}{2W},\ W=\sqrt{s}.$$

Arrows refer to beam and target particle spin states.

Fig.1 shows the $A^2d\sigma/d\Omega$ dependence on scattering angles in laboratory system for CNI (above) (proton energy E_1= 185 GeV [1]) and for p-e scattering at E_1 = 250 GeV (below). For the proton scattering angle θ_p = 0.5 mrad (corresponding electron recoil angle is about 2.4 mrad) enhancement is

$$\frac{(A^2 d\sigma/d\Omega)_{p-e}}{(A^2 d\sigma/d\Omega)_{CNI}} = 4$$

Note that p-e analysing power grows with the electron emergency angle and easily exceeds the appropriate value for strong interaction [1].

Figs. 2,3 show the elastic scattering cross section and asymmetry ratio for longitudinally polarized 0.25 TeV and 1 TeV protons scattered off the longitudinally polarized electron target.

PROTON SCATTERING FOR POLARIZED TARGET

In ref./4/ the electron polarized target (Supermendur in a weak magnetic field with H = 90 Gauss) was used to measure the longitudinal polarization of 10 GeV electrons due to elastic e-e scattering. The similar method may be suggested to measure proton polarization.

Note that the analyzing power of p-e polarimeters may be enhanced using oriented ferromagnetic crystal target placed in external magnetic field. The mean polarization degree for magnetized ferromagnetic target may be estimated with the equation:

$$\bar{P}_e \approx \frac{\mu}{\mu_o Z} \qquad (1)$$

where μ denotes atomic magnetic moment, Z - the atomic number, μ_o - the Bohr magneton (for Fe one gets $P_e \approx 0.084$). The sign of electron polarization can be easily changed by reversing the external magnetic field.

Another result may be obtained using the oriented crystal.

When the energetic proton is incident at small angle $\theta < \theta_c$ (θ_c is critical angle /5/) to crystal planes, the proton undergoes steering by the crystal planes (channeling) /5/. The channeling proton moves far from nuclei in space regions with low electron density ρ but enhanced polarized d -electron density ρ_B. Thus the effective electron polarization degree $P_e \sim \rho_B/\rho_e$ increases.

Fig.4 shows the electron polarization degree dependence on proton incident angle θ in Fe crystal oriented with (110) plane along the beam. The dashed line corresponds to random incident. Thus for narrow beam $\Delta\theta < \theta_c$ ($\Delta\theta$ is the beam divergence) one gets $\approx$ 60 % enhancement of the electron target polarization.

The polarimeter analyzing power may be evaluated as follows:

$$\bar{R}_{p-e} = A\,\bar{P}_e$$

where A is the asymmetry ratio.

Let us estimate of the polarization measurements accuracy for following parameters:

proton energy $E = 250$ GeV,

electron scattering angle $\theta_e = 3$ mrad,

scattering cross section $d\sigma/d\Omega = 170$ mBarn/sterad,

detector angular aperture $\Delta\Omega = 10^{-2}$ sterad,

extracted beam intensity $J_{ext} = 10^{9}$ protons/sec,

target electron density $n = 10^{23}$ electrons/cm^2.

The rate of the detected electrons is approximately $N = 3\cdot10^{5}$ events per sec. For 1 minute measurement with effective analyzing power $A = 0.24$ and 12% polarized electrons one gets $\Delta P/P = 0.7$ % accuracy.

For polarization measurements in the storage ring we suggest to use polarized hydrogen jet. To estimate the accuracy of polarization measurements consider 100 % polarized hydrogen jet with density $n \approx 2\cdot 10^{11}$ atoms/cm^2 interacting with collider beam. For electron recoil angle $\theta_e = 3$ mrad with detector aperture 10^{-4} sterad and for 1 hour measurement with proton current in ring j = 0.1 A one gets statistics $N = 2\cdot 10^4$. Thus the polarization measurement accuracy is defined by the relation:

$$\Delta P/P = 1/(NR^2_{pe})^{1/2} = 3\ \%.$$

At last it is worth to mention that there is another possibility to create a polarized electron target, that may be good enough to measure polarization of high-energy protons. An intensive e^--beam with the energy E_e > 10 keV and polarization $P_e \approx 50\%$ can be produced by acceleration of photoelectrons created by circularly polarized laser beam. This electron beam may be used as an electron target instead of polarized hydrogen jet.

References

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3. J. R. Dunning, K. W. Chen et al, Phys. Rev., v. 141, p. 1286, 1966
4. P. S. Cooper et al, Phys. Rev. Lett., v. 34, p. 1589, 1975
5. D. S. Gemmel, Rev. Mod. Phys., v. 46, p. 129, 1974

Figure Captions

Fig. 1 Effective analyzing power $A^2 d\sigma/d\Omega$ (dashed curve) for Coulomb-nuclear interference (above) and p-e scattering (below). Solid curve-analyzing power.

Figs.2,3 Cross-section (dashed curve) and analyzing power A_T for elastic scattering of longitudinally polarized protons with E_p = 250 GeV (Fig. 2) and 1 TeV (Fig. 3).

Fig.4 The mean polarization degree of electron for aligned crystal of Fe (solid curve) and for amorphous Fe (dashed curve).

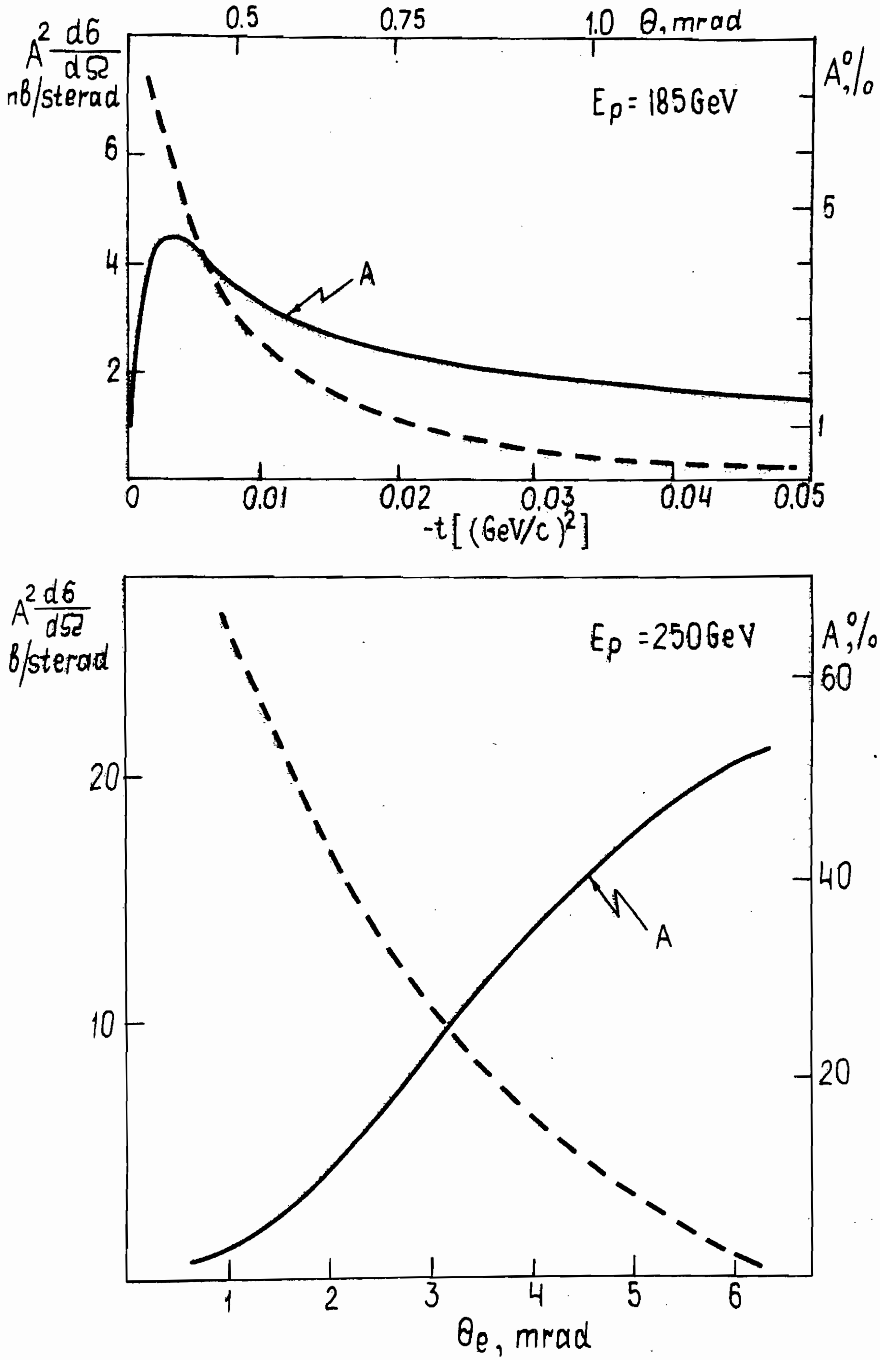
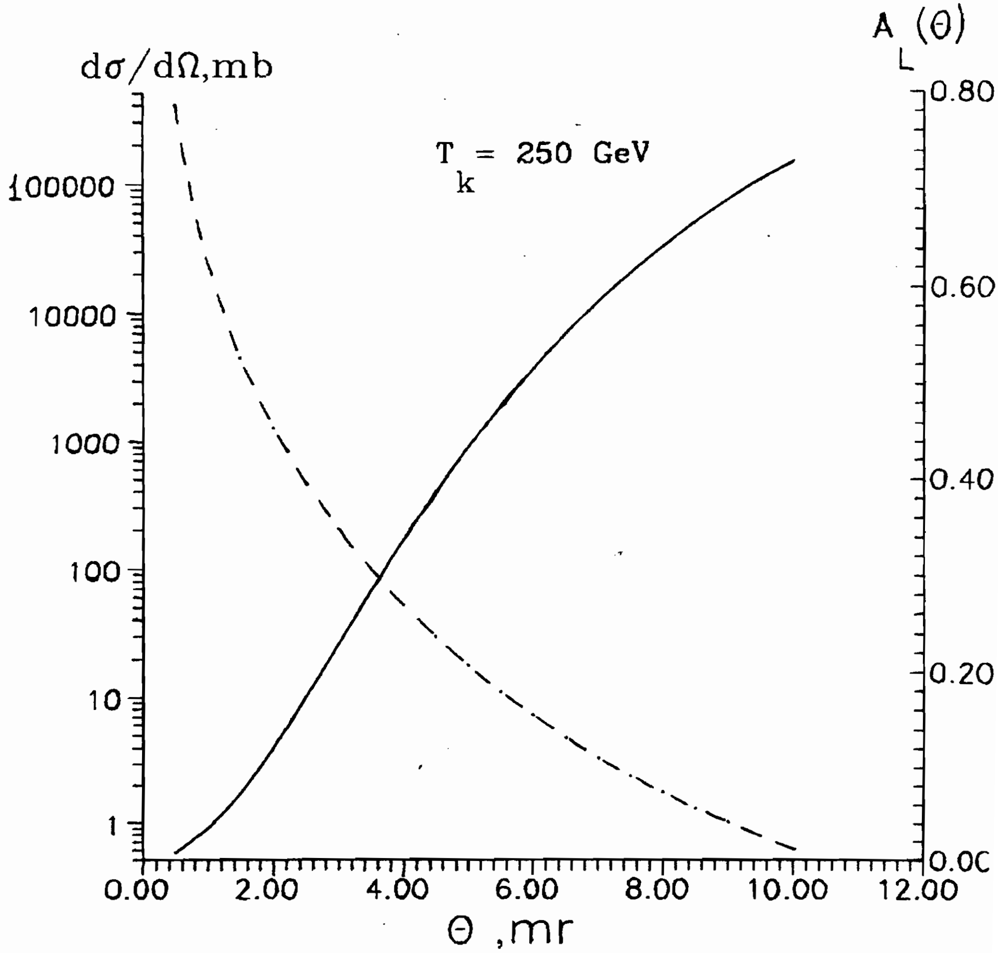

$A^2 \frac{d\sigma}{d\Omega}$
nb/sterad
0.5
0.75
1.0 θ, mrad
$A, \%$
E_p = 185 GeV
6
4
2
5
1
A
0
0.01
0.02
0.03
0.04
0.05
$-t\,[(GeV/c)^2]$
$A^2 \frac{d\sigma}{d\Omega}$
b/sterad
E_p = 250 GeV
$A, \%$
60
20
10
40
20
A
1
2
3
4
5
6
θ_e, mrad

Fig.1



dσ/dΩ,mb
A_L (Θ)
T_k = 250 GeV
100000
10000
1000
100
10
1
0.80
0.60
0.40
0.20
0.0C
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Θ ,mr

Fig. 2

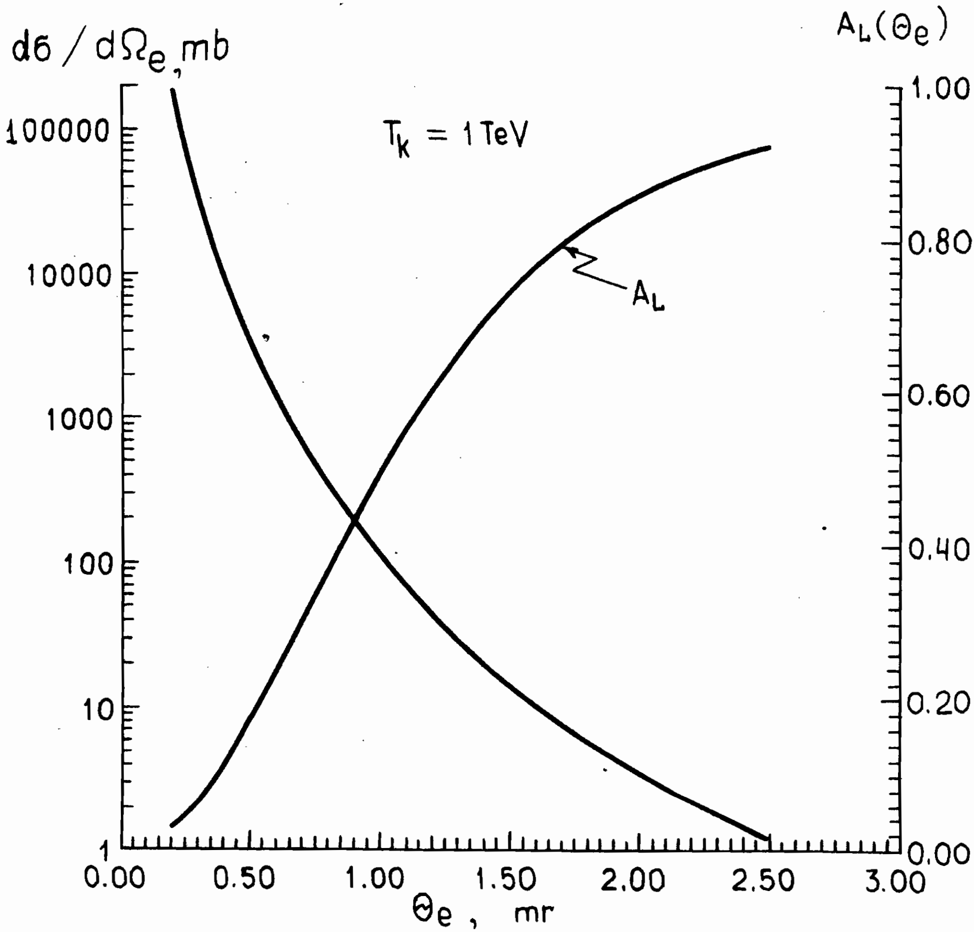

dσ / dΩe, mb
A_L(Θe)
Tk = 1 TeV
A_L
100000
10000
1000
100
10
1
1.00
0.80
0.60
0.40
0.20
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
Θe , mr

Fig.3

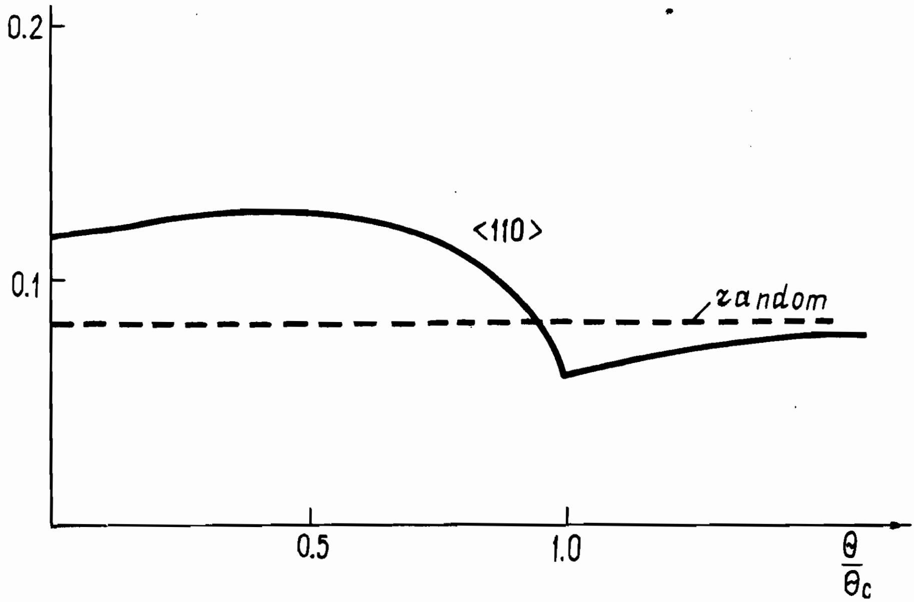


Fig.4