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# POLARIZATION EXPERIMENTS AT FERMILAB (E-581/704)[§]

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We describe the Fermilab polarized beam and antiproton beams in the MP beam line. We present the Fermilab polarized-beam program using this facility.

## I) INTRODUCTION

The physics objectives for the Fermilab polarized beam facility are in part based upon the facts that there are already several experimental indications that spin effects are significant at high energy. They are:

- Measurements of $\pi^0$ production at high $p_\perp$ in proton-proton and $\pi^-$-proton collisions have revealed sizeable asymmetries at 24 GeV/c and 40 GeV/c, respectively.
- Hyperons produced inclusively off nuclei and hydrogen, particularly at large $x_F$, are observed to have high polarizations.
- Inelastic scattering of longitudinally polarized electrons on longitudinally polarized protons yielded a large asymmetry, implying that proton helicity orientation is communicated to the constituent

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quarks. Thus, spin dependence in quark-quark collisions can be inferred from measurements of spin dependence in proton-proton collisions in appropriate kinematic regions.

## II) FERMILAB POLARIZED-BEAM (protons and anti-protons) FACILITY AND COMMISSIONING OF THE POLARIZED BEAM (E-581)

During the last decade, construction of a high-energy (above 100 GeV/c) polarized beam has been attempted. In order to avoid possible complications involving depolarization at high energies, polarized protons can be produced from decaying hyperons, lambdas or sigmas. The Fermilab polarized-beam facility has been constructed and is expected to be operational this fall.

### Design and Construction of Polarized Beam

We review the earlier design of the polarized-proton beam at CERN.[1] The idea then was to select high-momentum protons which were forward decaying, around $\theta_{c.m.} = 0°$, from lambdas near the highest momentum point of the lambda production spectrum. These protons were longitudinally polarized and therefore would have many rotations of the spin prior to reaching a final focal point. We note that this method could not be applied to either low-momentum protons (below 600 GeV) produced using 1-TeV incident protons or antiprotons since antilambdas are produced at much lower momenta than the incident momentum of protons striking a production target.

It has been shown that we can select protons or antiprotons at all momenta which are decaying around $\theta_{c.m.} = 90°$ from lambdas.[2] We show how this scheme works.

The polarization of protons and antiprotons comes from parity violating decays of lambdas and antilambdas respectively, and the measured polarization

was 64%.[3] The spin direction in the lambda center-of-mass frame (decay frame) is shown in Fig. 1.

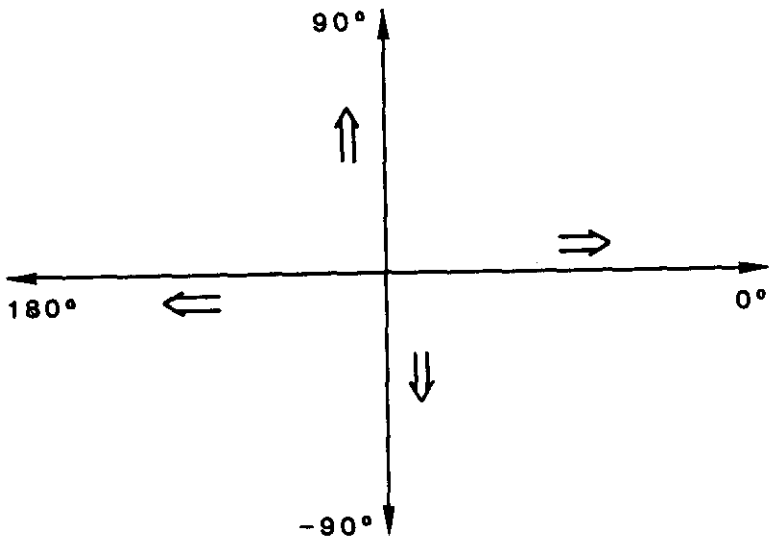


Figure 1 Spin direction of protons vs. decay angles. The spin direction is indicated by ⇒ and ⇑ symbols.

We note that spin direction is almost unchanged in transforming from the lambda-decay frame to the laboratory. Therefore protons and antiprotons decaying around $\theta_{c.m.} = 0°$ and 180° are longitudinally polarized ($\vec{L}$) while those with $\theta_{c.m.} = 90°$ are transversely polarized ($\vec{N}$, up and down, or $\vec{S} = \vec{N} \times \vec{L}$) in the laboratory. Since protons and antiprotons with $\theta_{c.m.} = 0°$ move in the same direction (lab decay angle = 0°) in the laboratory, there are no longitudinally polarized beams at momenta which are much less than the incident proton momentum.

Protons with $\theta_{c.m.} = 90°$ and -90° have the opposite laboratory decay angles which are not zero. They can be distinguished from those decaying at $\theta_{c.m.} = 0°$ from lambda with the production target as the source of the beam. Virtual sources for $|\theta_{c.m.}| = 90°$ particles are illustrated in Fig. 2. The spin direction, $\vec{N}$ or $\vec{S}$, should be chosen using the field direction of the sweeping magnets and bending magnets for the momentum selection, so that the spin direction is parallel to the field. The polarized beam line (up to 200 GeV/c) at Fermilab is shown in Fig. 3. Here we produce the $\vec{S}$ type beam before

reaching the snake magnets which make fast reversal of the spin direction.[4] The snake magnets consisting of twelve dipoles with 45° precessions as shown in Fig. 4 can also change the spin direction from $\vec{S}$ to $\vec{N}$ or $\vec{S}$ to $\vec{L}$ with constant beam direction and constant phase space. These magnets are expected to control systematic errors by periodic reversal.

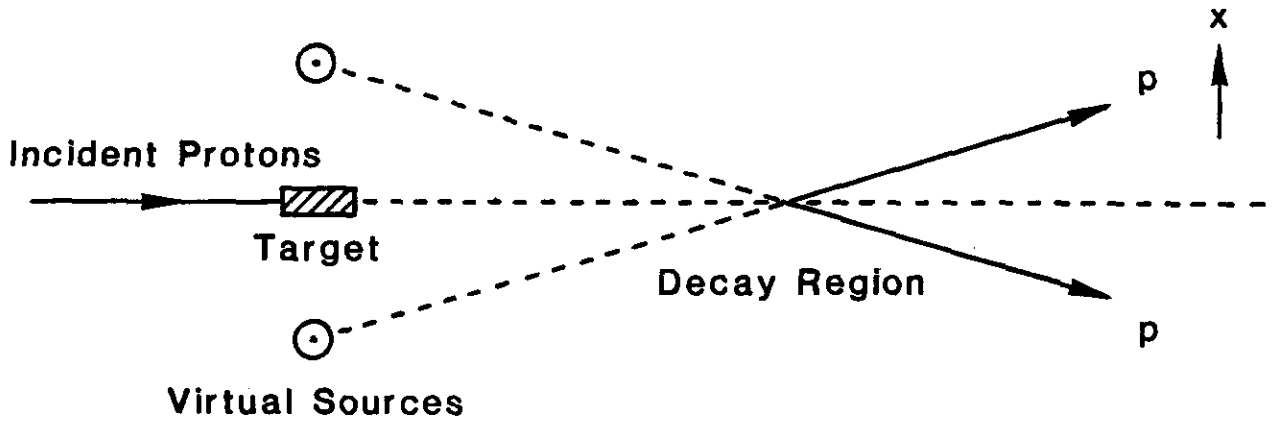


Figure 2 Virtual Sources (Top View)

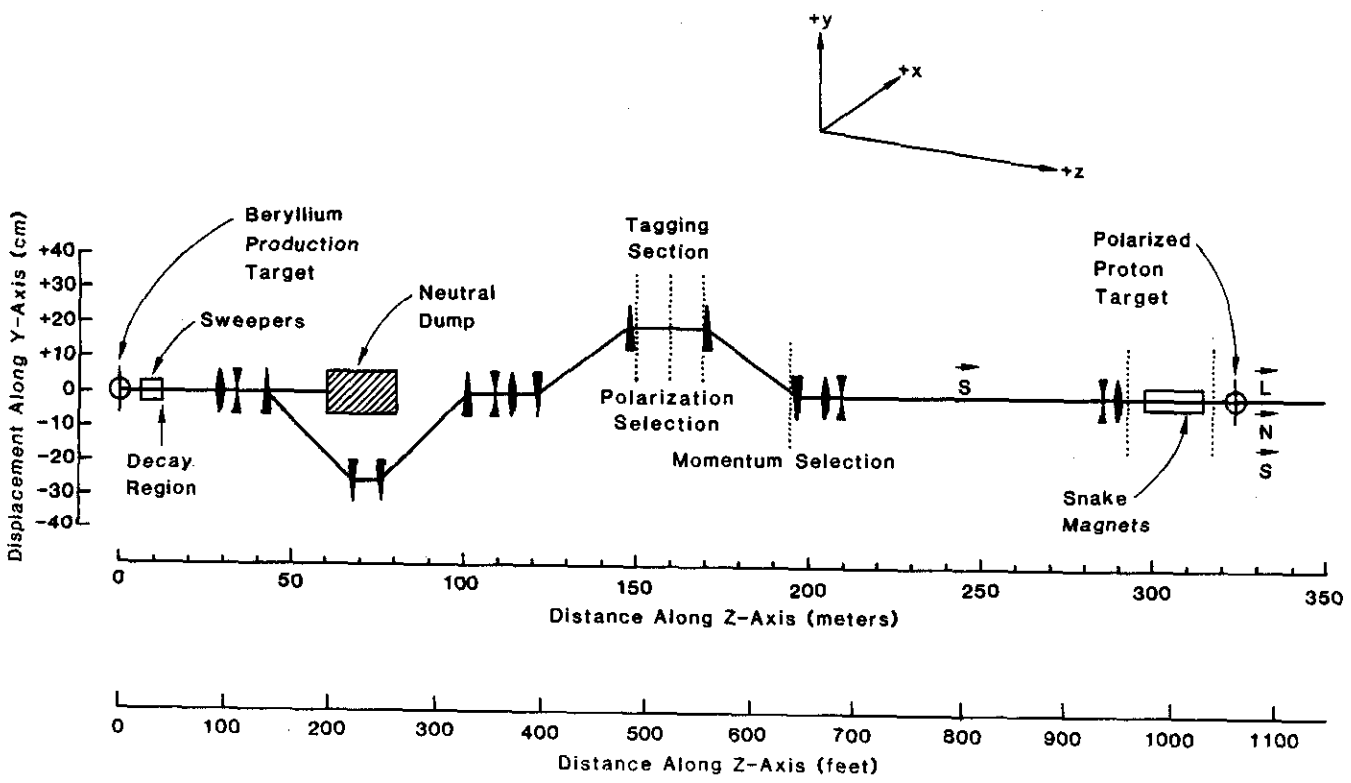


Figure 3 Side View of the Fermilab Polarized Beam
MP Secondary Beam (Side View)

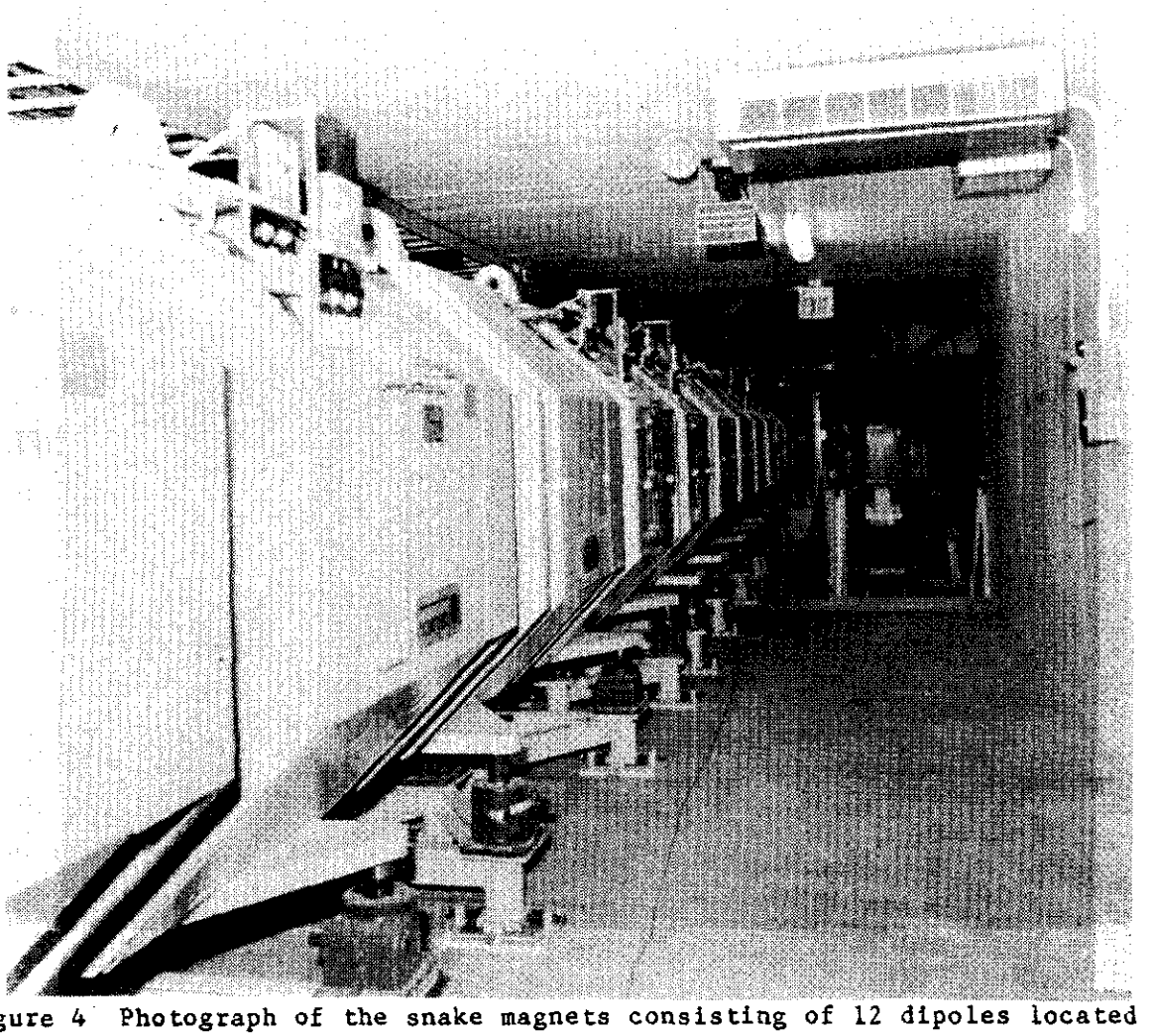

Figure 4 Photograph of the snake magnets consisting of 12 dipoles located at the entrance to the experimental hall.

Polarized protons from the virtual sources as shown in Fig. 2 are focused in the tagging section, where both the momentum and polarization are selected (see Fig. 3). The polarization is strongly related to the x position at the tagging section, and the average polarization, $\langle P \rangle$ and $I\langle P \rangle^2$, with $\Delta p/p = \pm 1\%$ and $\pm 5\%$ are shown in Figs. 5 and 6 respectively with respect to x in mm. The estimated intensities of polarized beams with a beam polarization of 45% produced by 400-GeV/c and 1000-GeV/c incident protons are shown in Fig. 7.

The momentum and flux of the present polarized-beam line are limited by the quadrupole strength. We are proposing to upgrade the present conventional quads to 4" superconducting quads. The estimated flux are shown in Fig. 8.

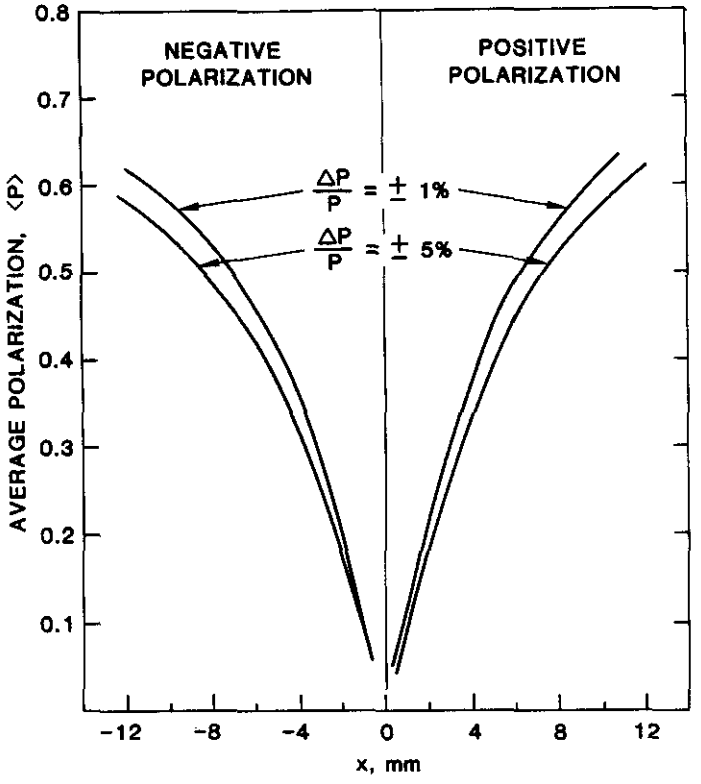


Figure 5

<P> vs x in the Tagging Section.

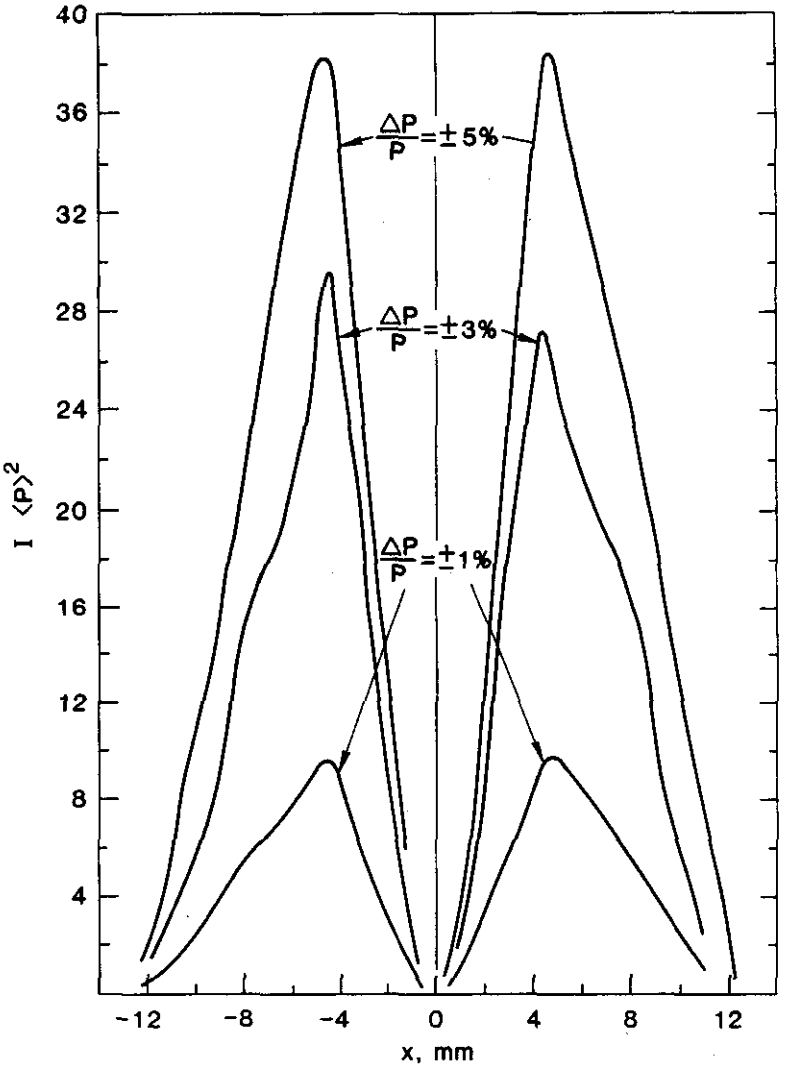


Figure 6

$I\langle P\rangle^2$ vs x in the Tagging Section.

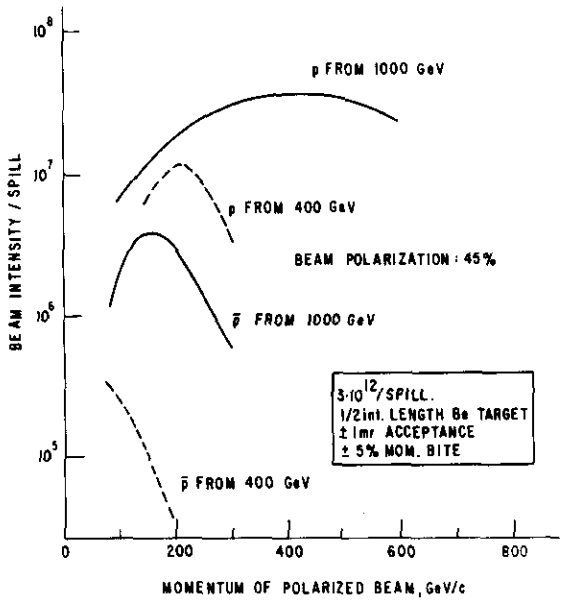


Figure 7

Polarized Beam Intensity

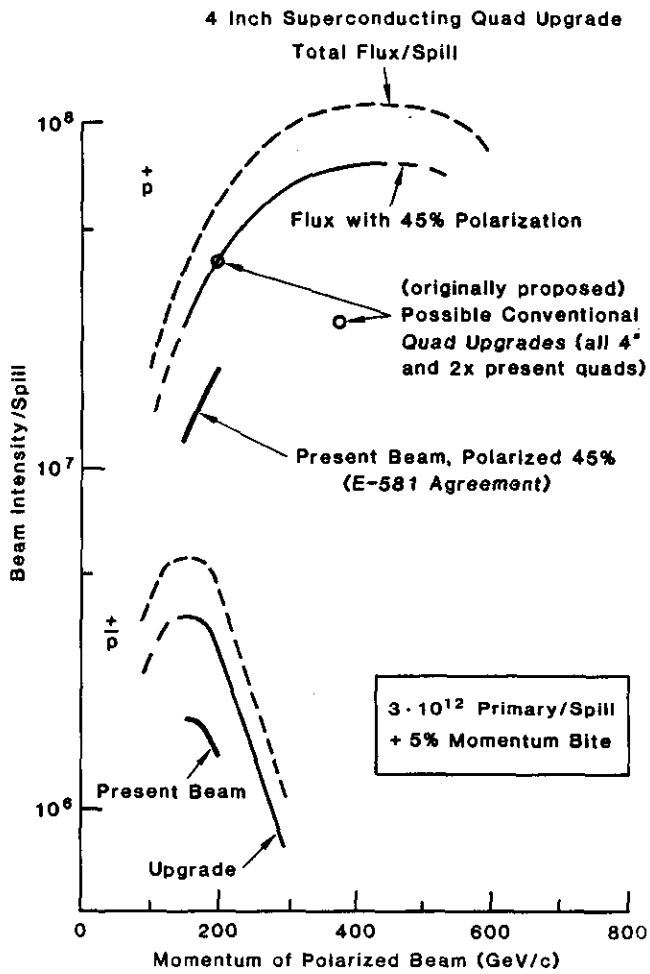


Figure 8 Proposed Polarized Beam Upgrade.

The very first measurement we need to carry out is to determine the polarization of the polarized beams. We describe two polarimeters currently installed in the experimental hall.

1) Coulomb-Nuclear Polarimeter

This is to measure the interference term of the non-flip amplitude and the electromagnetic spin-flip amplitude. The proton polarization arising from the interference is $P \approx 5\%$ at $|t| = 2 \cdot 10^{-3}$ $(GeV/c)^2$ and is energy independent.

For a beam momentum of 200 GeV/c, we operate the C-N polarimeter covering $0.1 < \theta_{lab} < 0.5$ mrad. Such scattering angles are smaller than the beam divergence (~ 1 mrad) so that kinematic overdetermination becomes imperative for adequate background suppression. We utilize a forward spectrometer consisting of the BM-109 magnet and MWPC's as shown in Fig. 9. The recoil protons with energies from 0.5 to 5 MeV will also be detected by scintillation targets.

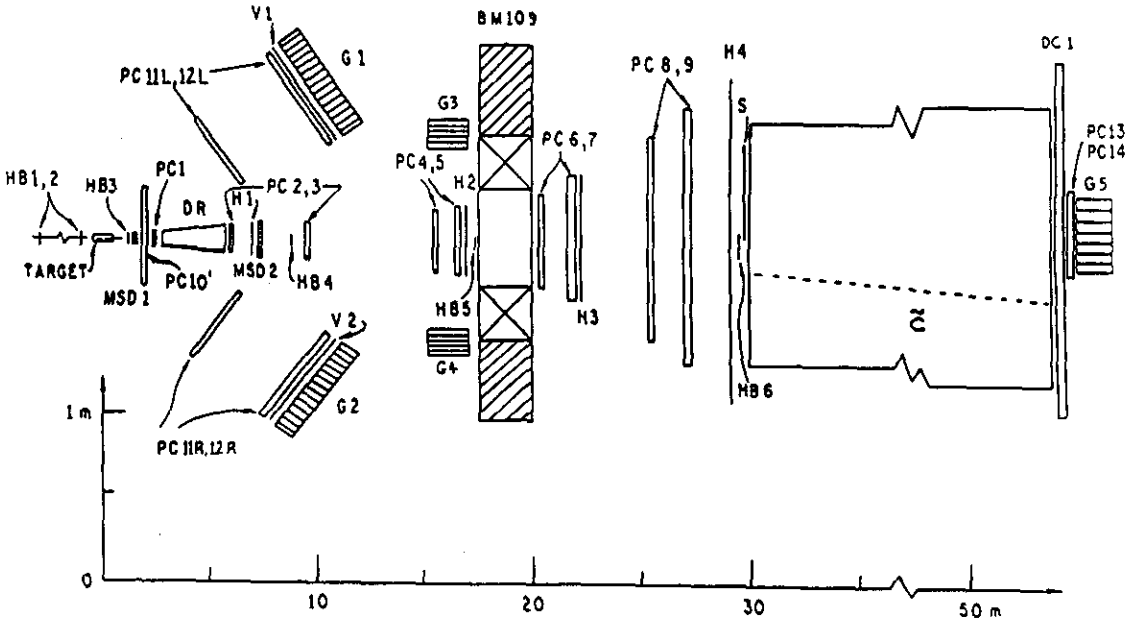


Figure 9 Detectors in the MP Experimental Hall (top view).

2) Primakoff-Effect Polarimeter

The diffractive dissociation of incoming high-energy proton into ($\pi N$) system by the Coulomb field of nuclei[5] is related to the low-energy photoproduction including the polarization effect. This fact can be applicable to a polarimeter for high-energy polarized beams.[6] The scheme of Primakoff-effect polarimeter is shown in Fig. 10. The process $pA \rightarrow pA\pi^{\circ}$ can be related via the Primakoff effect to low-energy photoproduction, i.e., $\gamma p \rightarrow \pi^{\circ} p$. The amplitude $\psi$ for diffractive production from a nucleus with charge Z and atomic number A can be written as:[7]

$$\int |\psi|^2 \, d\phi = \frac{Z^2 \alpha}{p_{\perp}^2} \left( \frac{2M_A}{s_{\pi p} - m_p^2} \right)^2 \left( A \cdot \frac{d\sigma}{d\Omega} \right)_{\gamma p \rightarrow \pi^0 p},$$

where A is the photoproduction asymmetry at the given value of $p_{\perp}$ and $s_{\pi p}$. Asymmetries at the $\gamma p$ kinetic energy of 600 MeV are as large as 90%.

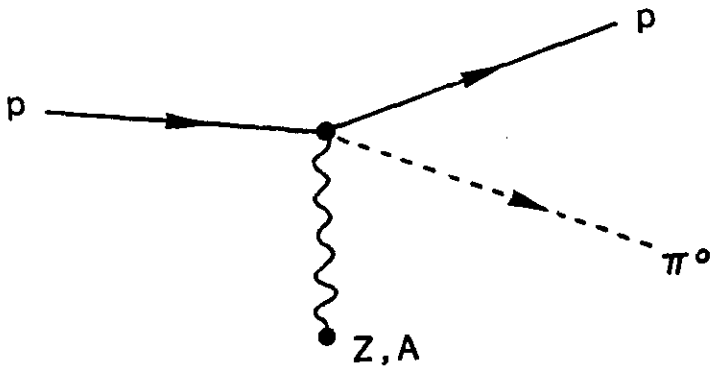


Fig. 10

Primakoff Effect

The detectors for the Primakoff polarimeter include the forward spectrometer mentioned above and a lead-glass hodoscope as shown in Fig. 11.

## II) First Round Experiments Using the Polarized-Beam Facility

Experiment 704, the Integrated Proposal on First Round Experiments with the Polarized Beam Facility, constitutes a proposal to simultaneously perform substantial parts of previously proposed Experiments 674 (Asymmetries in

Inclusive Pion and Kaon Production at Large x with a Polarized Beam), 676 (An Experiment to Measure $\Delta\sigma_L$ in p-p and $\bar{p}$-p Scattering Between 100 and 500 GeV), 677 (To Study the Spin Dependence in the Inclusive Production of Lambda Particles with the Polarized Beam), and 678 (Proposal to Study the Spin Effects in Inclusive $\pi^0$ and Direct Gamma Production at High-$p_\perp$ with the Polarized Beam Facility).

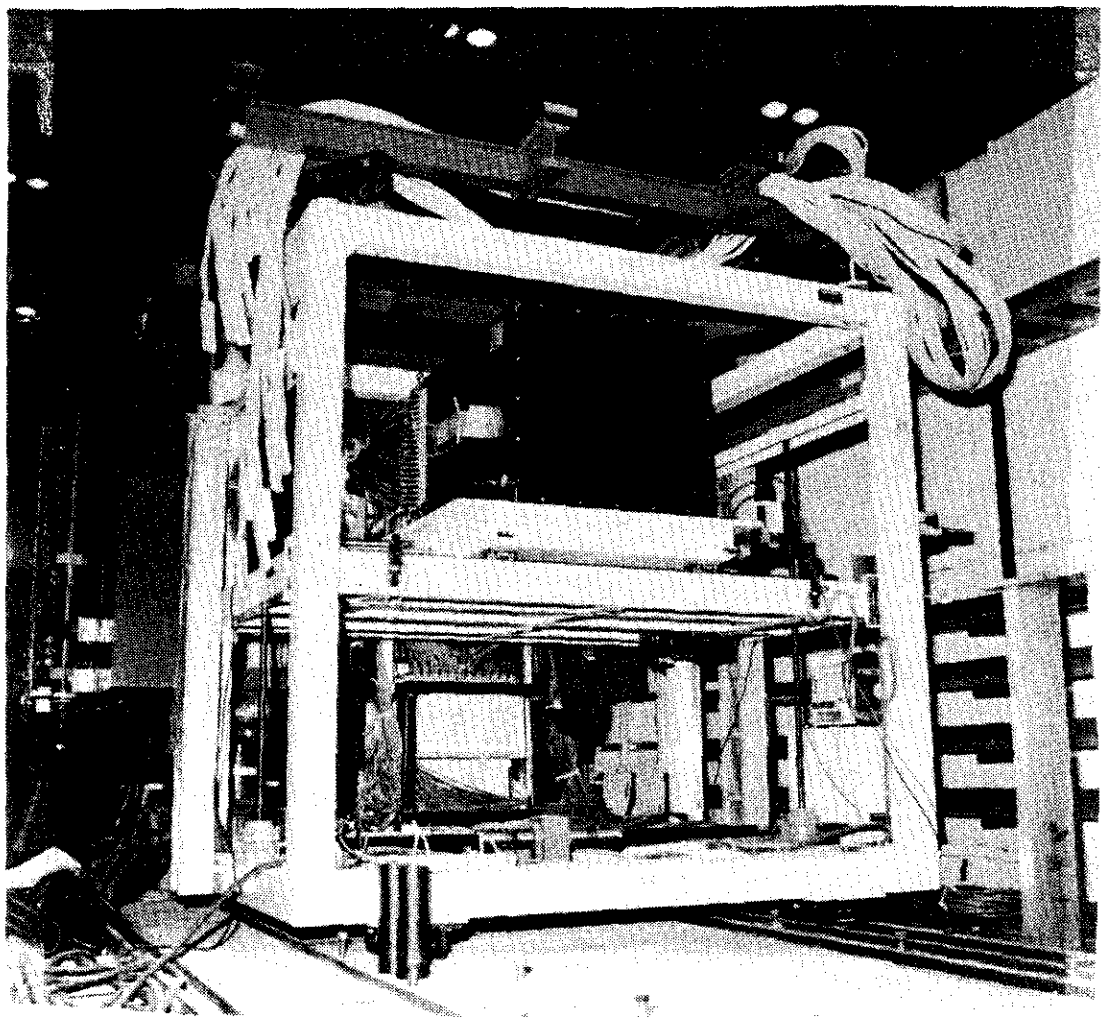

Figure 11 Photograph of the Primakoff polarimeter placed upstream of the analyzing magnet, BM-109.

Experimenters involved in these measurements are from Argonne National Laboratory, Fermi National Accelerator Laboratory, Kyoto University, Kyoto

Sangyo, Kyoto Education, KEK, Tsukuba (Japan), LAPP (Annecy, France), Los Alamos National Laboratory, Northwestern University, Rice University, CEN Saclay (France), IHEP-Serpukhov (USSR), University of Texas, and Trieste INFN (Italy).

The integrated proposal is for a 200-GeV/c conventional magnet beam line. We will carry out the following measurements:

A) $\Delta\sigma_L(pp)$ and $\Delta\sigma_L(\bar{p}p)$

We intend to explore the spin dependence of the interactions in a global way using a straightforward experiment which will measure the difference in pp and $\bar{p}p$ total cross sections between the states with helicities of target and beam parallel and antiparallel.

$$\Delta\sigma^{Tot} = \sigma^{Tot}(\uparrow\downarrow) - \sigma^{Tot}(\uparrow\uparrow).$$

Experience shows that accuracy of $\pm$ 100 microbarns can easily be achieved.

Helicity asymmetries were found to be unexpectedly large at low energies and we are led to expect that they may persist into the region of Fermilab energies.

In $\bar{p}p$ interactions there are also good reasons to expect polarization effects at the highest energies. In any process at relativistic energy involving the annihilation of spin -1/2 particles into vector intermediate states, a reaction with initial particles having like helicities is almost completely suppressed (by a factor $\gamma$) relative to the rate for the same reaction in a state of opposite helicities.

The hodoscopes in this experiment are expected to be used for the polarimeter which measures transverse beam polarization through elastic scattering in the Coulomb-interference region. With a longitudinally

polarized beam, the polarimeter cannot monitor the beam polarization directly during the actual experiment, and there is no conflict in using the same apparatus for both purposes. Beam polarization will be checked periodically by changing to transverse spin and inserting $H_2$ target or depolarizing the polarized target.

We will use a standard, longitudinally polarized proton target, in a superconducting solenoid target. A target mateial such as ethylene glycol or propanediol, 10% hydrogen by weight and with a free proton density of .07 gm/cm$^3$, can be used to reliably obtain polarizations above 80%.

Matrix logic will be used to reject multi-particle events, and other obviously inelastic or large-angle scattering events. For tracks that are nearly collinear, before and after the target, a hard-wired calculation of the scattering angle $\theta$ will be executed, and a corresponding scaler incremented. Additional scalers will record the number of incident tracks and other pertinent matrix outputs. All scalers will be read into an on-line computer after each spill. In addition, magnet currents, target polarization, and hodoscope hit-patterns will be sampled periodically to monitor the data.

Beam passing through the polarized-proton target is attenuated by the the free polarized protons and the rest of the material. The number of particles, $N_i$ (corrected for efficiency), transmitted through the target into the ith element of solid angle covered by segments of the transmission hodoscope is given by:

$$N_i^{\pm} = N_0^{\pm} \exp[-\alpha_i - \frac{1}{A} (\sigma_i \pm P_B P_T \frac{\Delta\sigma_{L,i}}{2})],$$

where $\pm$ refers to antiparallel (+) or parallel(-) beam and target polarizations, $N_0$ is the number of incident beam particles, $\alpha_i$ is the

attenuation constant for everything in the target except free hydrogen, $\sigma_i$ is the integrated differential cross section from the ith solid angle subtended, $A = (N_A \rho_F L)^{-1} = 2320$ mb is the target constant for free hydrogen, $N_A$ is Avogadro's number, $\rho_F = 0.0714$ g/cm$^3$ is the free-proton density, L = 10 cm is the target length, and $P_B = 0.45$ and $P_T = 0.8$ are the magnitude of the beam and target polarization, respectively.

The partial cross-section difference for each counter, $\Delta\sigma_{L,i}$, is calculated from these numbers by:

$$\tanh \frac{\Delta\sigma_{L,i} P_B P_T}{2A} = - \frac{N_i^+/N_0^+ - N_i^-/N_0^-}{N_i^+/N_0^+ + N_i^-/N_0^-} .$$

B) Hadron production on hydrogen target with polarized beam,

$p^\uparrow p \to (\pi^\circ, \pi^\pm, \Lambda^\circ, \Sigma^\circ) + X$

We will simultaneously study the inclusive production of neutral pions around $x_F \approx 0$ at large $p_\perp$, and of $\Lambda^\circ$, $\Sigma^\circ$ at large x. We will measure single-spin asymmetries in the hadron production,

$$A_N = \frac{E \frac{d^3\sigma}{dp^3}\uparrow - E \frac{d^3\sigma}{dp^3}\downarrow}{E \frac{d^3\sigma}{dp^3}\uparrow + E \frac{d^3\sigma}{dp^3}\downarrow} ,$$

where the arrows refer to the transversity of the incoming proton.

Interpretation of the polarization of hyperons ($\Lambda$, $\Sigma$, $\Xi$) produced inclusively ($pp \to \Lambda^{\circ\uparrow}x$, $Kp \to \Lambda^{\circ\uparrow}x$, etc.) has given rise to extensive discussion about the origin of this polarization. We expect that information of spin transfer from initial to final state in this reaction will enlighten the debate.

The major detectors for this experiment are: i) two gamma spectrometers (called CEMC, central electromagnetic calorimeter), G1 and G2 as shown in Fig. 9, with 500 lead-glass cells each will be used to detect $\gamma$'s from $\pi^{\circ}$ decay. Figure 12 shows the photograph of the CEMC in the experimental hall. ii) The magnetic spectrometer with proportional and drift-chamber systems (PC's and DC1 as shown in Fig. 9) and with a Cerenkov counter followed by lead-glass cells is to detect $\pi^{\pm}$, $\Lambda^{\circ}$, and $\Sigma^{\circ}$. Fast-electronics enclosures are placed along the various detectors as shown in Fig. 13.

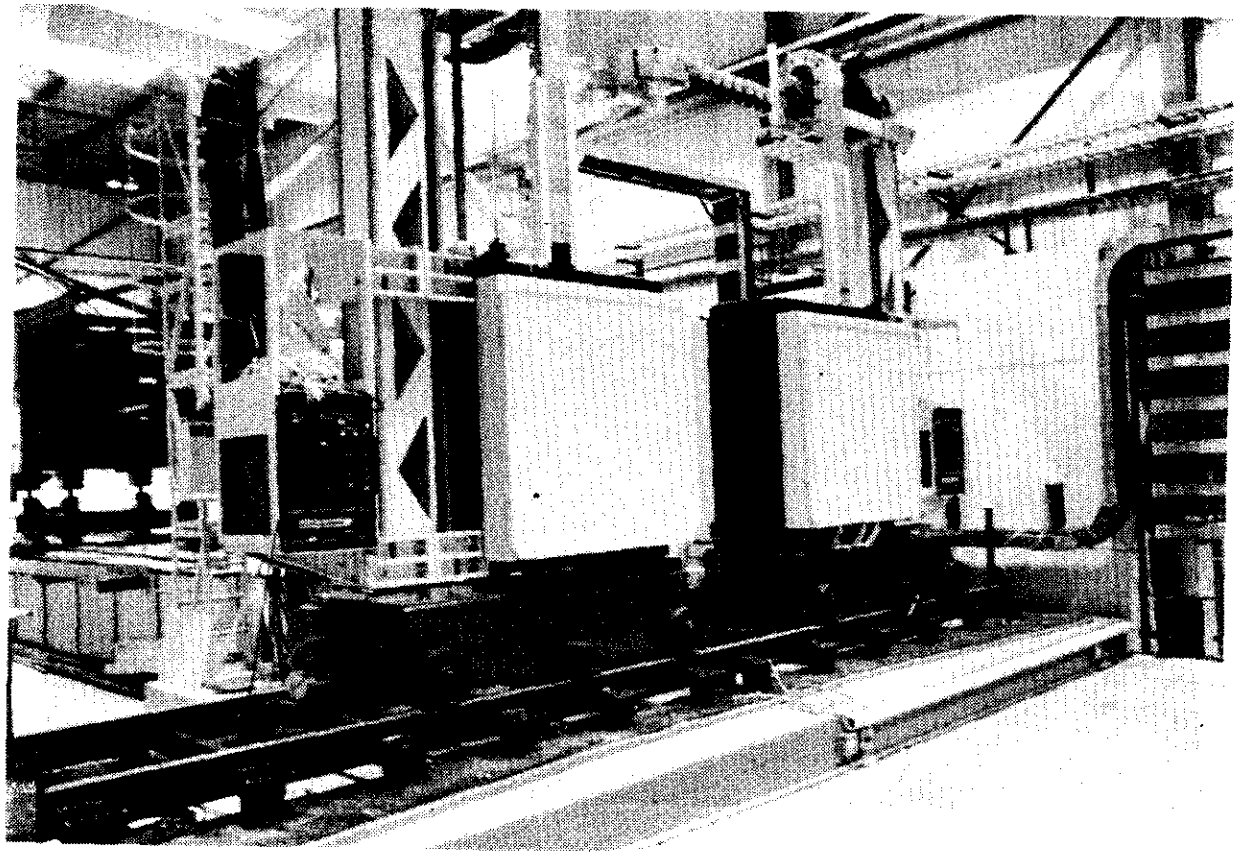

Figure 12 Photograph of the CEMC (Central Electromagnetic Calorimeter).

The technique for measuring single spin measurements in hadron production is considerably improved over the previous experiment since the polarized beam allows the use of a liquid hydrogen target.

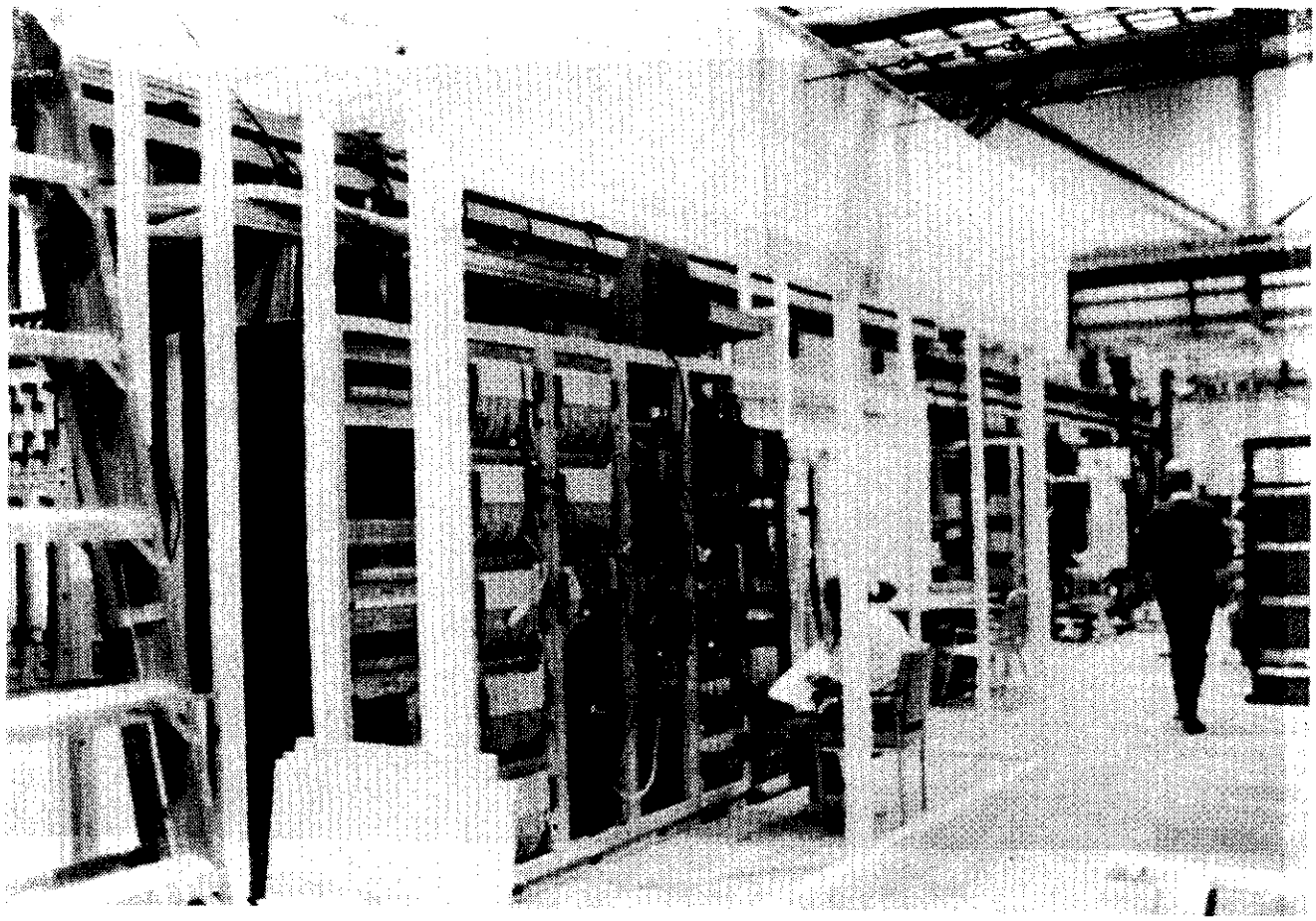

Figure 13 Photograph of the fast-electronic enclosures.

## III) Second Round Experiments

We intend to propose the hadron production using the Polarized-Beam Facility and the Polarized Target Facility. We will measure the difference in the hadron production cross sections between the status with helicities of beam and target parallel and antiparallel.

$$p^{\uparrow}p^{\uparrow} \rightarrow (\pi^0,\ \pi^{\pm},\ \Lambda^0,\ \Sigma^0) + X$$

While a perturbative QCD seems to have problems in predicting the polarization in the hadron production, it has a definite prediction for the hadron production at high $p_{\perp}$ in the pure helicity states.

For the spin-spin asymmetry measurements, we need to increase the angular acceptance of the detectors since the effective target polarization becomes much smaller than 80% mentioned above. For the pizero production measurement, we plan to double lead-glass cells in the CEMC.

Pending proposals using the polarized-beam facility are:

#682 Study of the $p_\perp$ Dependence of $\pi^\pm$ Inclusive Production with a Polarized Proton Beam and Target

#688 Nuclear-Size Dependence of Single-Spin Asymmetries in High-p⊥ Hadron Production

#699 Study of Spin-Dependent Asymmetries Using Calorimeter Triggered High-$p_\perp$ Events with Polarized Beam and Polarized Target.

## REFERENCES


1. P. Dalpiaz et al., CERN/ECFA/72/4, Vol. I, p. 284; CERN proposal SPSC/p. 87, July 1977.
2. D. Underwood et al., A Polarized Beam for the M-3 Line (Fermilab), ANL-HEP-PR-78-05.
3. J. W. Cronin and O. E. Overseth, Phys. Rev. 129, 1795 (1963); O. E. Overseth et al., Phys. Rev. Lett. 19, 391 (1967).
4. D. G. Underwood, Nucl. Inst. and Meth. 173, 351 (1980).
5. H. Primakoff, Phys. Rev. 81, 899 (1951).
6. D. G. Underwood, ANL-HEP-PR-77-56.
7. B. Margolis and G. H. Thomas, "High Energy Polarized Proton Beams", AIP Conference Proceedings, No. 42, p. 173.