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EXPERIMENTS WITH POLARIZED PROTONS AND ANTIPROTONS AT FERMILAB

E-581/704-Collaboration
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Abstract - A Polarized Proton and Antiproton Facility will be built at Fermilab in 1985-86 for High Energy Spin Physics experiments starting in 1987. The project is defined in two Agreements concerning the Construction of the Facility (E-581) and the First Round Experiments (E-704). The objective, present status and schedule of both parts of the project are presented.

I - PROJECT STATUS AND SCHEDULE

Fermilab will build in 1985-86 a polarized proton and antiproton beam of 100 to 200 GeV obtained from A and A decay [1][2]. A first generation physics program comprising four experiments has been accepted and is scheduled to start in January 1987. The two Agreements between Fermilab and the Collaboration: "Construction of a Polarized Beam Facility in the Meson Area (E-581)" and "First Round Experiments with the Polarized Beam Facility (E-704)" were signed in 1983. Stage II Approval for E-704 was granted in July 1984. The Collaboration comprises 52 participants from 11 Laboratories in 5 countries. Preparation of beam equipment, polarimeters, polarized target, detectors and data acquisition for the first round experiments has already started.

For the participants this new experimental access to High Energy Spin Physics is an event of considerable importance. In the medium to long term perspective the decision by Fermilab to build the Polarized Beam Facility bears some analogy with the decision in the early 1970's by Argonne to equip the ZGS for acceleration of polarized protons. In both cases it was a choice to create, at the scale of a laboratory facility, the conditions for dedicated high energy experiments on the spin dependence of hadronic interactions using the special techniques of polarized beams and targets. The present Fermilab Polarized Beam energy of up to 200 GeV may appear low compared to the full Tevatron energy. In fact, it is about the highest energy where experiments with both protons and antiprotons are still possible under comparable conditions of beam intensity. The capability of comparing the spin dependence of interactions induced by protons and antiprotons, respectively, will be a distinctive feature of the Fermilab facility.

The location of the new beam line ("MP") and experimental hall ("Polarized Proton Lab.") is shown on Figure 1. According to the present schedule the beam line enclosures and the new experimental hall should be ready for installation of equipment by September 1985. Possibilities for first beam tests in 1986 are under discussion. The experiment is scheduled to start in January 1987.
II - THE BEAM

The beam uses the fact that parity violation in the weak decay of $\Lambda'$'s ($\bar{\Lambda}$'s) results in a longitudinal polarization $P_L = 0.64$ for the decay protons (antiprotons) in the decay c.m.system. The hyperons are produced by the extracted beam on a fixed target. At Tevatron energies the hyperons and their decay products are emitted in a narrow forward cone in the laboratory. An appropriate decay region is selected as the source of polarized protons or antiprotons for the beam transport line. The strong correlation between beam phase space and the direction of polarization in the laboratory frame allows the selection of regions with net transverse beam polarization. A sketch of the beam optics is shown on Figure 2. Immediately after the production target charged particles are swept away and dumped. Neutral particles emitted in the forward direction enter the decay region (Figure 2). Charged particles emerging from this region are carried around the neutral dump by a symmetric magnet system and are focussed at the intermediate image with momentum dispersion. The second part of the beam transport line produces the final image with momentum recombination at the experimental target. The subsection at the neutral dump and the general layout of the beam are symmetric in order to cancel out unwanted spin precessions in magnets and quadrupoles.

The intermediate focus can be considered as the real image of a virtual source in the plane of the production target (Figure 3). The decay protons due to hyperons in a given momentum bite of the production spectrum have a strong correlation between direction of polarization and position at the intermediate focus (Figure 4). Selected beams of net transverse polarizations can be defined either by slits or by tagging hodoscopes. The beam will be equipped for both techniques. The actual tagging system takes into account the chromaticity of the quadrupole focussing. It consists in three position tagging hodoscopes in the region of the intermediate focus, followed by three momentum tagging hodoscopes straddling the next bending magnet. The momentum tag decides which of the three focal plane hodoscopes is used to relate position and polarization.

At the end of the beam line a "Siberian Snake"-type string of 12 spin precessor dipole magnets allows the choice of any transverse or longitudinal direction of beam polarization at the experimental target, without change in beam direction or position.

The effective polarization of the selected or tagged beam is a compromise between polarization, intensity and tagging resolution. The design figures are a polarization of $|P_L| = 0.40$ to 0.50 with an intensity of $10^6$ protons or $10^5$ antiprotons for $3 \times 10^{12}$ incident protons. This is the expected primary beam intensity available on a given production target per burst approximately every 60 seconds. The Figure 5 shows an estimate of the intensity as a function of the beam momentum. The original proposal had been to use superconducting transport elements allowing 400 GeV/c beam momentum. The present project uses classical elements and is limited to 200 GeV/c. The superconducting version is an option for future developments.

III - THE FIRST ROUND EXPERIMENTAL PROGRAM

Eight Proposals had been submitted to the Physics Advisory Committee in 1981 illustrating the range of Physics that would become accessible with the new facility. Four of these proposals have been accepted for a first generation of experiments. The close contacts between the proposing groups permitted undertaking the four experiments not in series but in parallel. Simultaneous installation of the apparatus and, in some instances also simultaneous data taking seems possible. The four experiments are the following:

- "Total Cross Section Differences". Measurements of the pp and $\bar{p}p$ total cross section differences $\Delta \sigma$, with beam and target particles of definite helicities parallel and antiparallel, respectively.

- "Inclusive $\Lambda$ Production". Measurements of the $pp \to \Lambda^0 + X$ cross section differences with transversely polarized beam "up" and "down", respectively, with respect to the production plane, and measurements of the correlation between beam polarization and $\Lambda^0$ polarization.
"Inclusive π⁺ Production". Measurement of the pp → π⁺ + X cross section differences with transversely polarized beam "up" and "down", respectively, with respect to the production plane.

"Inclusive π⁰ Production in the Central Region". Measurements of the pp → π⁰ + X cross section differences at x_F = 0 with transversely polarized proton beam "up" and "down", respectively, with respect to the production plane.

1. "Total Cross Section Differences"

The experiment measures \( \Delta \sigma_{\text{TOT}} = \sigma_{\text{TOT}}^{(\uparrow)} - \sigma_{\text{TOT}}^{(\dagger)} \) for pp and \( \bar{p}p \) scattering in the region of 100 to 200 GeV. The symbols \((\uparrow)\) and \((\dagger)\) stand for beam and target helicities antiparallel and parallel, respectively. The three Nucleon-Nucleon forward scattering amplitudes are

\[
\begin{align*}
\langle +|++ \rangle &= \Phi_1 ; \\
\langle -|++ \rangle &= \Phi_2 ; \\
\langle +|+- \rangle &= \Phi_3 .
\end{align*}
\]

The relations between amplitudes and observables are usually written as

\[
\begin{align*}
\sigma_{\text{TOT}}^{(\uparrow)} &= (4\pi/k) \text{Im} \left[ \left( \Phi_1 + \Phi_3 \right) / 2 \right] \\
\Delta \sigma_L &= (4\pi/k) \text{Im} \left[ \Phi_1 - \Phi_3 \right].
\end{align*}
\]

In terms of total cross sections in definite helicity states the same relations read

\[
\begin{align*}
\sigma_{\text{TOT}}^{(\uparrow)} &= (4\pi/k) \text{Im} \Phi_1 \\
\sigma_{\text{TOT}}^{(\dagger)} &= (4\pi/k) \text{Im} \Phi_3
\end{align*}
\]

With antiparallel helicities of beam and target one measures \( \text{Im} \Phi_3 \), and with parallel helicities one measures \( \text{Im} \Phi_1 \). So far we know that in the region from 100 to 200 GeV the sum of the two terms (i.e., \( \sigma_{\text{TOT}}^{(\uparrow)} \)) is rising by about 2 percent in pp scattering, and that it is about constant in pp scattering. Nothing is known about \( \text{Im} \Phi_3 \) or \( \text{Im} \Phi_1 \) separably. In terms of crossed channel quantum numbers the difference \( \Phi_3 - \Phi_1 \) measures \( \Lambda \) exchange. The general expectation is that Pomeron exchange dominates at high energies. A model dependent extrapolation [3] of data on \( \Delta \sigma_L \) below 6 GeV/c predicts a difference of the order of 0.1 mb. The spin averaged total cross section is \( \approx 40 \) mb.

The measurements will be made with incident protons and antiprotons. The spin averaged total cross sections for pp and \( \bar{p}p \) scattering at 100 to 200 GeV/c still show different energy dependence and differ by about 7 percent. In terms of hadrons the difference is due to annihilation contributing to pp. In the naive parton model the hadronic total cross section represents the global effect of all possible parton subprocesses. What is known about parton scattering in definite helicity states? Leading order QCD cross sections for \((2 \leftrightarrow 2)\) parton scattering [4] fall into two groups (Figure 6). For the first group the cross sections for antiparallel (i.e., equal sign) "beam" and "target" parton helicities are in general larger than for parallel helicities, with the exception of exact forward scattering and in some cases also exact backward scattering where the two cross sections become equal. For the second group, to the contrary, the antiparallel cross sections vanish at all angles by angular momentum conservation in the limit of massless partons. A comparison of \( \Delta \sigma_{\text{L}}^{(\bar{p}p)} \) and \( \Delta \sigma_{\text{L}}^{(pp)} \) will give more specific information on the differences in the relative contributions from the parton subprocesses than a comparison of the unpolarized total cross sections alone.

2. "Inclusive Λ⁰ Production"

The experiment measures the single spin asymmetry

\[
\Lambda_y = [\sigma(\uparrow) - \sigma(\downarrow)]/[\sigma(\uparrow) + \sigma(\downarrow)]
\]
where $\sigma$ is the invariant cross section $E x d^3\sigma/dp^3 = f (x_F, p_L)$ for the inclusive process $pp \rightarrow A^0 + X$ and where the symbols $\uparrow$ and $\downarrow$ refer to the cross sections for incident protons with spin "up" and "down", respectively, with respect to the production plane. The target is unpolarized. From the decay angular distribution of the $A^0$ one determines the $A^0$ polarization. The experiment thus measures also the correlations between transverse beam polarization and $A^0$ polarization. It covers the kinematical range $x_F = 0.5 - 0.9$ and $p_L = 0.2 - 1.5$ GeV/c.

The study of hyperon polarization in inclusive production of hyperons with unpolarized beam and target has been for many years the most active field of High Energy Spin Physics. A large number of experiments has accumulated much data [5] revealing systematic structures of the polarization as a function of the kinematical variables $s$, $x_F$ and $p_L$ and of the quark contents of the projectile and the produced hyperons. Most features of these data can be explained by ad hoc models where the strange quarks produced in the interaction become polarized by specific mechanisms during the hadronization process leading to formation of the observed hyperon. These models do not attempt to describe also the mechanism by which the strange quark is produced in the interaction. Dependence of the production cross section on initial spins and correlations between initial and final spins are generally not within their scope.

Most useful for planning and interpreting hyperon production experiments with polarized beam is the development of a model independent formalism for inclusive helicity amplitudes [6]. The generalized optical theorem relates these amplitudes to $(3 \otimes 3)$ helicity amplitudes. The Mueller theorem plus angular momentum conservation introduces constraints leading for certain observables to kinematical suppressions which can be tested. Polarization experiments provide information about certain groups of amplitudes that do not contribute to unpolarized cross sections.

3. "Inclusive $\pi^\pm$ Production"

The experiment measures the single spin asymmetry

$$A_N = [\sigma(\uparrow) - \sigma(\downarrow)]/[\sigma(\uparrow) + \sigma(\downarrow)]$$

for the inclusive process $pp \rightarrow \pi^\pm + X$ with a beam polarized perpendicularly to the production plane incident on a liquid hydrogen target. The notations are the same as in Section III,2. The kinematical region is $x_F = 0.5 - 0.9$ and $p_L = 0.15 - 1.5$ GeV/c.

At 6 and 12 GeV/c incident momentum and within the same $x_F$ and $p_L$ region the asymmetry $A_N$ was found to be as large as 20 to 40 percent with strong dependence on transverse momentum and depending also on $x_F$ (Figure 7). Different possible interpretations have been discussed [7] but no conclusive explanation has been given so far. An asymmetry of the order of $|A_N| \geq 1/3$ means that the production from one of the beam spin states is twice as likely as from the other state. For interpretation of these data it is crucial to know if such large spin effects persist in the region of 100 to 200 GeV. The present high energy models for inclusive production at large $x_F$ predict only spin averaged observables. Should the difference for production from spin "up" and spin "down" states at 100 to 200 GeV/c turn out to be as large as at 12 GeV/c, only models able to correctly describe this spin dependence would survive. Calculations neglecting such large spin effects would not be considered satisfactory since they would ignore important aspects of the dynamics.

As stated already, the development of a model independent formalism for inclusive helicity amplitudes would be of great interest for this type of experiment. At present, not much effort is devoted to develop phenomenology or theory appropriate to this class of reactions which represents, by far, the majority of all events taking place in any of our experiments.

4. "Inclusive $\pi^0$ Production at $x_F = 0$"

This experiment measures the single spin asymmetry
for the reaction $pp \rightarrow \pi^0 + X$ in the central region with transversely polarized beam on an unpolarized target. The notation is the same as in Sections III.2 and III.3. The kinematical range is $|x_F| \leq 0.1$ and $p_{1\text{,max}} \leq 4 \text{ GeV/c}$. This is the only experiment in the central region. The upper limit in transverse momentum is given by beam intensity and cross section, not by the geometry of the apparatus.

The asymmetry $A_N$ has been measured at 24 GeV/c incident momentum [8] with unpolarized beam on a polarized proton target, for $\pi^0$'s produced at $|x_F| \leq 0.1$ with $p_1$ ranging from 1.0 to 2.5 GeV/c. The results (Figure 8) show a rapid rise of $|A_N|$ with increasing $p_1$ starting at $p_1 = 1.5 \text{ GeV/c}$. At $p_1 = 2.0 - 2.5 \text{ GeV/c}$ the asymmetry $|A_N|$ is very large. Its exact value depends on the estimate of the unpolarized target background. Performing the experiment with polarized beam instead of polarized target avoids the uncertainty due to target background subtraction.

For interpretation of this unexpected result it is important to know if the large asymmetry observed at 24 GeV/c is still present at 100 to 200 GeV. Lowest order perturbative QCD predicts zero single spin asymmetries. However, transverse momenta of $p_1 \leq 2.5 \text{ GeV/c}$ are generally considered too small to test predictions for parton hard scattering.

5. Comments on the E-704 Program and Apparatus.

The four experiments in E-704 will be the start-up of a new facility in a new energy range. The facility will remain unique for some time, particularly for its polarized antiproton capability.

The choice of the four subjects for a first generation of experiments was influenced by the existence of large, unexpected and in part still unexplained spin effects at the highest energies where polarization experiments have been performed.

The coexistence of four quasi-simultaneous experiments in the same beam is a particular aspect of the program. The aim is to make the most efficient use of the available beam time. Each experiment uses simple detectors in a dedicated lay-out corresponding to the particular reaction and kinematic region. In fact there are several instances where the same detector in the same position is used for more than one experiment. This requires specific solutions for data encoding and acquisition, with several front-end computers interconnected and linked to a larger computer for on-line treatment of data samples from different experiments. The detector configuration is shown schematically in Figure 9. The actual lay-out is shown in Figure 10. Not shown is the tagging station halfway along the beam line.

The same detector configuration could be used to measure the parameters corresponding to any other direction of beam or target polarization. Also, change from single spin measurements with unpolarized target to initial-initial spin correlations with polarized beam and polarized target is essentially a matter of running time and statistics only. For instance, with the detectors installed for measuring $A_N$ in inclusive $\pi^0$ production in the central region one could measure the initial helicity correlations $A_N^{\pi^0}(pp)$ and $A_L^{\pi^0}(EP)$ simply by using the same beam and target configuration as for the $\Delta_S$ experiment.

6. Other Subjects already studied

The other subjects submitted as proposals to the Physics Advisory Committee in 1981 were

- P-675 "Asymmetry Measurements for Dimuon Production in the J/Ψ Mass Region"
- P-678(part) "Proposal to Study the Spin Effects in ... Direct Gamma Production ..."
- P-682 "Study of the $p_1$ Dependence of $\pi^\pm$ Inclusive Production (at large $p_1$)"
P-688 "Nuclear Size Dependence of Single-Spin Asymmetries in High-p_t Hadron Production"

P-689 "Measurement of the Asymmetry in Calorimeter Triggered High-p_t Events"

The proposals at large p_t were motivated by the striking and fundamental spin effects in lowest order perturbative QCD. In the limit of massless quarks the constituent (2 → 2) scattering has zero single-spin asymmetries but, as a function of the parton c.m. scattering angle, there are in general large differences between cross sections for initial parton helicities parallel or antiparallel (Figure 6). These effects can be measured only if the parton helicities can be controlled experimentally by polarizing the parent hadrons. This is possible. The SLAC-Yale experiment [9] has shown that the u-quarks of x ≥ 0.4 in protons strongly remember the proton helicity. The same should hold for U-quarks in antiprotons and for d-quarks in neutrons. Extrapolation of the SLAC-Yale data to x = 1 suggests that u-quarks carrying the full momentum of the proton also carry its full helicity. A similar experiment on a polarized neutron target would determine the spin dependent structure function for d-quarks in protons. This important experiment has not yet been carried out. Lower bounds for the polarization of d-quarks in protons of definite helicity have been calculated [10] showing that at x = 1 the d-quarks should also strongly remember the proton helicity (Figure 11).

Independent of the details of the fragmentation model used to relate the parton polarization to the hadron polarization, the double-spin asymmetries of the parton subprocesses lead to measurable differences [4] in the cross sections for hard scattering events with beam and target polarized longitudinally either parallel or antiparallel. For the three models shown in Figure 12, inclusive \( \pi^0 \) production seems to be a test as good as jet production.

The proposals raised the usual question as to the energy and transverse momentum where QCD can be tested in a compelling way. In fact, the polarized beam intensity and the statistics required to measure cross section differences do not allow going to very large transverse momentum.

IV - POSSIBLE FUTURE PROGRAM

Possible second generation experiments using the Fermilab Polarized Beam Facility have been the subject of informal discussions only. A Workshop on this issue is now being considered for the not too distant future. Some of the technically trivial extensions of the E-704 program have been mentioned in Section III.5. They consist in changing from proton to antiproton beam, from unpolarized to polarized target and, for the target material, from protons to deuterons or to heavier nuclei. Any direction of beam polarization at the target can be realized. For the polarized target, the addition of a transverse holding field would be a minor modification. Should measurements in any of these other beam and target configurations become important, they could be performed with a minimum of additional effort.

Three of the experiments listed in Section III.6 [P-678(part), P-682 and P-688] could use the apparatus of E-704 without much modification whereas P-675 and P-689 would require new large detectors.

The existing data and the present theoretical ideas on High Energy Spin Physics together with these instrumental considerations are today our basis for discussing future experiments. However, it is likely that new ideas and new results, in particular those from the first generation of experiments at Fermilab will modify the situation and lead to new proposals for the second generation.

The physics potential of E-704 and of the Facility in general can be assessed by analogy with the recent evolution witnessed in a closely related field. Due to the self-analyzing power of weak decay, hyperon production reactions have been a first "natural" but narrow experimental window into High Energy Spin Physics. In the same kinematical region the new Fermilab Facility opens a larger window by using the special techniques of polarized beams and targets. This allows a more diversified approach and will give a broader view of the field. From the strong and systematic spin effects already visible through the present narrow window [5] it appears unlikely that the surrounding landscape is a desert.
REFERENCES


Fig. 1  Beam lines (a) at Fermilab and (b) at the Meson Area.
Fig. 2 Sketch of beam optics (schematic). The present project uses quadrupole doublets.

Fig. 3 The decay region is the source of the secondary beam.

Fig. 4 Transverse beam polarization at the intermediate focus.

Fig. 5 Beam intensities as a function of beam momentum.
Fig. 6 Leading order QCD cross sections for parton-parton scattering in definite initial helicity states summed over final spin states as a function of the parton c.m. scattering angles [4].

Fig. 7 Polarized proton beam asymmetry for inclusive \( \pi^+ \) production [7] as a function of the four-momentum transfer squared from the incoming proton to the observed pion at large longitudinal momentum \( x \) on (a) hydrogen and (b) deuterium. The deuteron is treated as a proton for the assignment of \( x \).

Fig. 8 Polarized proton target asymmetry for inclusive \( \pi^0 \) production by unpolarized protons [8] as a function of \( p_T \) at small \( x \).
Fig. 9  Schematic lay-out of the detectors.
Fig. 10 The Experimental Hall and Apparatus from the last beam quadrupoles (center of Fig. 10a) to the beam stop (right of Fig. 10c).
Fig.11. SLAC-Yale results [9] showing the probability for u-quarks to have the same helicity as the parent proton, as a function of the quark longitudinal momentum $x$. The dotted curves represent three alternate models used in ref.[4]: (a) "Conservative SU(6)"; (b) "Diquark" and (c) "Carlitz-Kaur". The other curves are calculated lower bounds for the polarization transfer from the proton to the d-quark ([10] and J.D.Bjorken, December 1980).

Fig.12 Leading order QCD predictions for $A_{2\ell}$ in $pp \rightarrow \pi^0 X$ at $90^\circ$ parton c.m. scattering angle as a function of the $\pi^0$ transverse momentum $x_L = 2 p_{\perp}/s$. Note that Fig.12c uses a different scale.