Acceleration of Polarized Protons to
Multi-GeV Energies and Experiments
with Polarized Protons from 2-6 GeV/c *

Invited Talk Presented at the
Symposium on Hadron Physics
at High Energies
Liblice, Czechoslovakia

June 16-21, 1975

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* Work supported by the U. S. Energy Research and Development Administration

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Acceleration of Polarized Protons to Multi-GeV Energies and
Experiments with Polarized Protons from 2-6 GeV/c

I. Introduction

In July 1973 polarized protons were successfully accelerated to 6 GeV/c in the Zero Gradient Synchrotron (ZGS) at the Argonne National Laboratory.⁽¹⁾ Since then, there have been 26 weeks of accelerator operation with polarized protons for both experimental physics and machine improvements. Accelerated intensity has increased from 10^8 polarized protons per pulse (pppp) to 6×10^9 pppp during this time. The polarization of the extracted beam is $73\% \pm 8\%$ for an injected beam polarization of $73\% \pm 6\%$. During machine studies, polarized beam has been accelerated to 8.5 GeV/c and it is felt that there are no technical problems in accelerating to 12.0 GeV/c, which is presently scheduled for spring 1976. Some 12 experiments⁽²⁾ have taken data during this period and I will present most of the results to date. The layout of the experimental area is shown in figure 1. Four to five experiments have been able to take data simultaneously during most of the operating period.

The perfection of polarized target techniques and the operation of a high energy polarized beam makes accessible a rich new field of physics. Experiments which seemed almost impossible a few years ago are now being planned and done. It appears that within the next few years we will have a complete set of amplitudes for the P-P system in the few GeV energy range. This could lead to a much better understanding of one of the most fundamental problems of high energy physics, namely the P-P interaction.

Another puzzling feature of the P-P interaction is the breaks observed in the fixed angle cross section. As we will see later these also exist in the pure spin state cross sections and polarized beam polarized target experiments may lead to understanding this phenomenon. In addition, once the helicity amplitudes are known, parton type models can be put to rather stringent tests. It appears that the experiments

which are now underway will add a good deal of knowledge not only to the P-P interaction but to all of hadron physics.

II. Accelerator Operation

Protons are initially polarized in a ground state atomic beam source and emerge at 20 keV. They are then accelerated to 750 keV in a Cockcroft-Walton and then to 50 MeV in a linear accelerator. They are then injected into the synchrotron and accelerated to GeV energies. The major problem in accelerating polarized protons is the depolarization which can occur during the acceleration process.

When particles with a vertical polarization are injected into a synchrotron with a vertical guide field, the spin of the particles will precess about the vertical axis. Depolarization is caused by any horizontal field components that may be present. Since the ZGS is a weak focusing accelerator, it has no strong focusing quadrupoles with horizontal field components. Moreover, the field uniformity inside the 8 octant magnets is excellent, so they have no significant horizontal fields. The only significant horizontal fields are the fringe fields at the 16 edges of the octants and these can cause depolarization.

One can define two types of depolarization: nonresonant and resonant. Nonresonant depolarization occurs when a polarized particle sees a random horizontal field component once during the acceleration cycle and then never again. Fields too small to drive the beam vertically out of the ZGS will give a very small nonresonant depolarization. For each pass through a ZGS octant fringe field, the depolarization is estimated to be less than 10^{-9} .

Resonant depolarization occurs when particles circling a synchrotron see a similar horizontal field on many successive turns. This can be much more serious, since the depolarizing amplitudes from each turn can add coherently and quickly destroy the polarization. One type of depolarizing resonance comes from imperfections in the magnets. For the ZGS these are quite small but can be significant for some synchrotrons. ⁽³⁾ There are also "intrinsic" depolarizing resonances

which occur when the protons see periodically oscillating horizontal fields due to their vertical betatron oscillations. This vertical motion makes the protons periodically pass through the octant fringe fields at a vertical position where there is a significant horizontal field. When the frequency for passing through such a field becomes equal to the spin precessional frequency, the spin gets a similar depolarizing amplitude for many passes and there is a large depolarization.

For the ZGS these "intrinsic" depolarizing resonances can be quite serious. They occur at several values of γ during the acceleration cycle and if no corrective action is taken they will destroy most of the polarization before 5 GeV/c is reached.

In the ZGS there are 10 depolarizing resonances between injection and 12.0 GeV/c. Four of these are very strong and six are weak. To reduce the effect of these resonances, one can shift the vertical tune of the machine very rapidly just at the resonance. This is accomplished by using a pair of pulsed quadrupoles which operate at 2500 G-in/in with a 20 μ sec rise time. The effect of the quadrupoles is shown in Figure 2.

III. Experiments

A. Total Cross Section Experiment

The σ_{TOT} measurement was a standard "good geometry" attenuation experiment whose layout is shown in figure 3. The polarized beam from the ZGS first passes through a H_2 target. The left-right asymmetry from the elastic scattering is measured by the four-arm spectrometer. Left scattering for the forward particle in L1, 2, 3 and the left recoil particle in L4, 5 and 6. Right scattering is similarly measured in R1, 2, 3 and R4, 5 and 6. This measurement gives the beam polarization which was 70%. The beam continues downstream to a series of counters and the polarized target (PPT). This target was 86% polarized. The incident beam of $2 \cdot 10^5$ pppp was counted by the I counters

with an anticoincidence A counter to reduce accidentals. The A counter had a 3/4 in. diameter hole to allow the beam through. The attenuated beam after the PPT was counted by O counters which were respectively 10, 9, 6, 4 and 2 in. in diameter. At 6 GeV/c, 3×10^{10} events were accumulated. The beam polarization was flipped on a pulse-to-pulse basis and the target polarization about twice a day to remove systematic errors. The quantity measured was the difference $\Delta\sigma_{TOT} = \sigma_{TOT}(\uparrow\downarrow) - \sigma_{TOT}(\uparrow\uparrow)$, which is the difference in the total cross section for beam polarization up target polarization down and both beam and target polarization up. These are, of course, equivalent to the spin flipped condition by rotational invariance of space which insures that

$$\sigma_{TOT}(\uparrow\uparrow) = \sigma_{TOT}(\downarrow\downarrow) \text{ and } \sigma_{TOT}(\downarrow\uparrow) = \sigma_{TOT}(\uparrow\downarrow)$$

$$\Delta\sigma_{TOT} = - \frac{[I(O)/I]_{\uparrow\downarrow} - [I(O)/I]_{\uparrow\uparrow}}{I(O)/I > N_0 \rho t P_B P_T}$$

where the numerator contains the ratios of the transmitted event coincidences $I(O)$ to the number of protons I for the two different spin states which are perpendicular to the beam direction. $\langle I(O)/I \rangle$ is the spin average value of this ratio. N_0 is Avagadros number 6.02×10^{23} while $\rho = 0.073 \pm 0.005$ is the density of hydrogen protons in the polarized target and $t = 4.13$ cm is the length of the polarized proton target. P_B and P_T are the beam and target polarization which were $(70 \pm 5)\%$ and $(86 \pm 5)\%$.

The measured total cross-sections are clearly non-zero and positive. The anti-parallel cross-section $\sigma_{TOT}(\uparrow\downarrow)$

larger than the parallel cross section $\sigma_{TOT}(\uparrow\uparrow)$. There is also a very large value of $\Delta\sigma_{TOT}$ of almost 6 mb at 2 GeV/c compared to the 0.76 mb at 3 GeV/c.

B. Two and three spin proton elastic scattering measurements

1. The configuration of the preceding experiment was modified by adding a spectrometer after the polarized target and by removing the total cross-section counters. This is shown in figure 4. The elastic cross-section for the scattering of the polarized proton beam on the polarized proton target was measured using this two arm spectrometer containing magnets and scintillation counters (F1F2F3 B1 B2B3). The incident 6 GeV/c beam contained about 3×10^8 polarized protons with a beam polarization of $69 \pm 4\%$. The polarized target was $75 \pm 5\%$. The relative cross section for the four different initial spin states $\uparrow\uparrow, \downarrow\downarrow, \uparrow\downarrow, \downarrow\uparrow$ was measured. Since both the beam and target were only partially polarized (P_B and P_T) the relative cross sections were obtained from the equations shown in figure 4. $\langle d\sigma/d\Omega \rangle$ is the spin average cross-section and the N_{ij} is the normalized event rates in each state. The asymmetry parameter A is obtained by averaging over either the beam or target polarization. This gave a consistency check which typically held to within $\pm 1\%$. The values of A and C_{NN} are plotted against $P_{\perp}^2$, in figure 5. C_{NN} has a maximum around $P_{\perp}^2 = 0.7 \text{ (GeV/c)}^2$ which is where A has a minimum and is about where there is a break in the spin average cross section.

Next we turn to the measurement of the recoil proton spin using the B-polarimeter shown in figure 4. This observes the scattering of the $225 \pm 30 \text{ MeV}$ recoil proton at $P_{\perp}^2 = 0.5$

$(\text{GeV}/c)^2$ from a 5 in. long carbon block. Measuring the asymmetry in p-C elastic scattering to the left and to the right we obtain the recoil polarization. We estimated the effective analyzing power to be $A_{pC} = 0.50 \pm 0.05$ using the data of Chamberlain et al. at 289 MeV. ⁽⁴⁾

Thus for each of the 4 initial spin states ($\uparrow\uparrow$, $\downarrow\downarrow$, $\uparrow\downarrow$ and $\downarrow\uparrow$) we measure P_R and thus obtain the number of recoil protons in each state. Folding in the partial polarization of the beam and target (P_B and P_T) we then obtain the cross-sections for the 8 different spin states: $\sigma(\uparrow\uparrow \rightarrow 0\uparrow)$, $\sigma(\uparrow\uparrow \rightarrow 0\downarrow)$, $\sigma(\downarrow\downarrow \rightarrow 0\uparrow)$, $\sigma(\downarrow\downarrow \rightarrow 0\downarrow)$, $\sigma(\uparrow\downarrow \rightarrow 0\uparrow)$, $\sigma(\uparrow\downarrow \rightarrow 0\downarrow)$, $\sigma(\downarrow\uparrow \rightarrow 0\uparrow)$ and $\sigma(\downarrow\uparrow \rightarrow 0\downarrow)$. Our notation is $\sigma(\text{beam, target} \rightarrow \text{scattered, recoil})$ and 0 denotes unmeasured. If we assume parity invariance then all 8 single flip amplitudes must be zero (e. g., $\sigma(\uparrow\uparrow \rightarrow \uparrow\downarrow) = 0$). Then the 8 cross sections above are in fact the 8 pure spin state cross-sections: $\sigma(\uparrow\uparrow \rightarrow \uparrow\uparrow)$, $\sigma(\uparrow\uparrow \rightarrow \downarrow\downarrow)$, $\sigma(\downarrow\downarrow \rightarrow \uparrow\uparrow)$, $\sigma(\downarrow\downarrow \rightarrow \downarrow\downarrow)$, $\sigma(\uparrow\downarrow \rightarrow \uparrow\uparrow)$, $\sigma(\uparrow\downarrow \rightarrow \downarrow\downarrow)$, $\sigma(\downarrow\uparrow \rightarrow \uparrow\uparrow)$ and $\sigma(\downarrow\uparrow \rightarrow \downarrow\downarrow)$. Thus we have measured directly the square of the magnitude of the amplitudes for the 8 pure transversity states but have no information about their phases. Rotational invariance of space gives two relations between these

$$\begin{aligned}\sigma(\uparrow\downarrow \rightarrow \uparrow\downarrow) &= \sigma(\downarrow\uparrow \rightarrow \downarrow\uparrow) \text{ antiparallel non flip} \\ \sigma(\uparrow\downarrow \rightarrow \downarrow\uparrow) &= \sigma(\downarrow\uparrow \rightarrow \uparrow\downarrow) \text{ antiparallel double flip}\end{aligned}$$

and T invariance give another

$$\sigma(\uparrow\uparrow \rightarrow \downarrow\downarrow) = \sigma(\downarrow\downarrow \rightarrow \uparrow\uparrow) \text{ parallel double flip}$$

By assuming that P and T invariance hold one can average the cross-sections given above to obtain the $\sigma(\uparrow\downarrow\rightarrow\uparrow\downarrow)$, $\sigma(\uparrow\downarrow\rightarrow\downarrow\uparrow)$ and $\sigma(\uparrow\uparrow\rightarrow\downarrow\downarrow)$ shown in figure 6. Measurements of the other two of the 5 independent transversity cross sections $\sigma(\uparrow\uparrow\rightarrow\uparrow\uparrow)$ and $\sigma(\downarrow\downarrow\rightarrow\downarrow\downarrow)$ are also shown.

For the antiparallel non flip there is sufficient precision for a fair test of P invariance. One finds

$$\frac{\sigma(\uparrow\downarrow\rightarrow\downarrow\downarrow) - \sigma(\downarrow\uparrow\rightarrow\downarrow\uparrow)}{\sigma(\uparrow\downarrow\rightarrow\downarrow\downarrow) + \sigma(\downarrow\uparrow\rightarrow\downarrow\uparrow)} = -0.02 \pm 0.05.$$

This sets an upper limit on the single flip cross sections $\sigma(\uparrow\downarrow\rightarrow\uparrow\uparrow)$ and $\sigma(\downarrow\uparrow\rightarrow\uparrow\uparrow)$ or more precisely on any differences between these two P-violating cross sections. The other two tests involve smaller double flip amplitudes for which the precision is inadequate.

The most interesting feature seen in figure 6 is that the double flip cross sections are typically 10 times smaller than the non flip cross sections. The $\sigma(\uparrow\uparrow\rightarrow\downarrow\downarrow)$ cross-section is largest being some 80% larger than $\sigma(\uparrow\downarrow\rightarrow\uparrow\uparrow)$ and $\sigma(\downarrow\uparrow\rightarrow\uparrow\uparrow)$. Another way to present this data is in terms of the Wolfenstein parameters D_{nn} and K_{nn} . We find that $D_{nn} = 0.81 \pm 0.10$, $K_{nn} = 0.14 \pm 0.08$.

Finally in figure 7 is plotted the differential elastic cross sections themselves against $P_{\perp}^2$ rather than the cross section ratios. This more clearly demonstrates the relationship between the change in the spin dependence and the break in the cross section.

In the "diffraction peak" region of $P_{\perp}^2 < 1(\text{GeV}/c)^2$ the three cross sections are parallel and $\sigma(\uparrow\uparrow)$ is about 40% larger than $\sigma(\downarrow\downarrow)$ and $\sigma(\uparrow\downarrow)$ which are about equal. In the second region after the break $[P_{\perp}^2 > 1(\text{GeV}/c)^2]$ cross-sections are also parallel to each other but $\sigma(\uparrow\uparrow)$ is now about twice as big as $\sigma(\downarrow\downarrow)$; and $\sigma(\uparrow\downarrow)$ is about half-way between them.

The sharp breaks and the two cases of rather different but parallel behavior are quite striking. Further work will be done to measure the 2 and 3 spin cross-sections as a function of $P_{\perp}^2$.

2. C_{NN} Measurements

Measurements have been made at 2, 3, 4, 6 GeV/c over a $a(-t)$ range of 0.08 to 1.4 at 6 GeV/c and 0.1 to 2.5 at 3 GeV/c. The data at 2 and 4 GeV/c is very similar to 3 GeV/c when plotted against 0 . The analysis of the 2, 4 GeV/c is very preliminary. The data at 6 GeV/c represents about 1/5 of the total events and the data at 3 GeV/c is also preliminary. The group involved in this experiment is beginning a program to measure enough quantities of the type defined by Wolfenstein and Ashkin⁽⁵⁾ to be able to give a unique reconstruction of the nucleon-nucleon scattering data. Besides the C_{NN} data, they have collected some data using a spin rotating solenoid and recoil polarimeter. Their measurements are of (S, O; O, S), (S, N; O, S), (O, N; O, N) where the quantities in parenthesis represent (beam, target; scattered, recoil) spin. S is the polarization state transverse to the momentum in the scattering plane and N is the polarization state normal to the scattering plane. O is an unmeasured polarization state. Analysis of this data has just started. This group is also building a "R" and "A" magnet for the polarized target which will allow $P_T = \{S \text{ and } L\}$ where L is the polarization state along the particle momentum in the laboratory frame.

For the C_{NN} measurements shown in figure 8 and 9, data were then for the four possible combinations of up and down orientation of the beam and target polarizations. The polarized target was surrounded by proportional wire chamber hodoscopes and free proton events were separated from bound proton events by means of the angular correlation. The rates at a given angle can be expressed as

$$I(t) = I_0(t) \left\{ 1 + \left[(\pm P_B) + (\pm P_T) \right] A + (\pm P_B)(\pm P_T) C_{NN} \right\}$$

As can be seen in figure 8 there is a strong energy independence between the low energy data and the 6.0 GeV/c data. In figure 9, one can see a rise with increasing t . This however is still very preliminary. There appears to be some problem as evidenced by the non-symmetry about 90° cm.

3. D_{NN} Measurements

This experiment was done with an unpolarized beam on a polarized target and used a carbon analyzer for the recoil particle. It thus studies the change in the polarization of the initial state proton as a result of the scattering process and measured the Wolfenstein D parameter. The results are shown in figure 10. The principal feature to be noticed is that at small t , D is close to 1. Thus the spin of the polarized target proton is not appreciably changed by the

elastic P-P interaction. At large t and therefore larger momentum transfer D seems to deviate from 1.

Before we leave the subject of these correlation parameters, it might be useful to recall their relation to the scattering matrix. Using the notation of Schumacher and Bethe⁽⁶⁾ we have the contents of figure 11. M_T is the scattering matrix; σ_1, σ_2 the Pauli matrices and the coordinate system is defined by m, p, q vectors. We then see 1_0 the differential cross section, $D_{NN'}, K_{NN'}$ and $C_{NN'}$ in terms of the coefficients of the scattering matrix. The last quantities are $1_0 P$ where P is the polarization. This is the next set of experiments to be presented.

C. Polarization Measurements in PP Elastic Scattering

1. Small angle proton-proton elastic scattering, figure 12, shows the results of the measurements of the polarization parameter in small angle proton-proton elastic scattering at 6 GeV/c. The polarization rise like $\sqrt{-t}$ in the interval $0.02 < -t < 0.1 \text{ (GeV)}^2$. These measurements were done with polarized beam and used the Effective Mass Spectrometer Facility which will be described later. The beam was incident on a 50 cm liquid hydrogen target. The forward scattered particles were measured in five sets of magnetostrictive wire spark chambers placed before, within, and behind a large aperture magnet. The mean resolution in $-t$, was $\pm 0.006 \text{ (GeV)}^2$. These results combined with those of Borghini et al.⁽⁷⁾ are well fit by the empirical formula

$$P(t) = (0.506 \pm 0.021) \sqrt{-t} \exp [-(2.52 \pm 0.18) t]$$

over the interval $-t = 0.02$ to 0.5 (GeV)^2 . Using the notation of Halzen and Thomas ⁽⁸⁾ for t channel exchange we have

$$\frac{d\sigma}{dt} = |N_0|^2 + 2|N_1|^2 + |N_2|^2 + |A|^2 + |\pi|^2$$

$$P \frac{d\sigma}{dt} = 2 I_m (N_0 - N_2) * N_1$$

The polarization here depends only on the amplitudes N_0 , N_1 and N_2 , all with natural-parity exchange in the t channel; it does not depend on π and A , the unnatural-parity exchange amplitudes corresponding to π and A_1 quantum number exchange. The non-flip amplitude N_0 has a large diffractive component and is the dominant amplitude near the forward direction. Using results from a previous experiment with the same apparatus, ⁽⁹⁾

$$N_0 \approx \sqrt{d\sigma/dt} = 9 e^{3.8t} (\text{mb/GeV}^2)^{1/2}$$

Ignoring the double flip amplitude N_2 , one can use the polarization to estimate the component of the single-flip amplitude orthogonal to N_0 in the complex plane,

$$N_{1\perp} \approx 1/2 P \sqrt{d\sigma/dt} = 2.3 \sqrt{-t} e^{6.3t} (\text{mb/GeV}^2)^{1/2}.$$

The ratio of amplitudes $N_{1\perp} / |N_0| \approx P/2$, is approximately 6% over the region $-t = 0.06$ to 0.5 (GeV)^2 .

2. Comparison of PP and PN Polarization

This experiment was also done in the Effective Mass Spectrometer which consists basically of a large aperture magnet with spark chambers. The facility is very flexible and one can form triggers for many reactions. Figure 13 shows a sketch of the facility and also lists the data accumulated to date in polarized beam running. Over five million events have been collected and a great deal of this has been analyzed. I will only be able to cover a small portion of the available data today.

Figure 14 shows the results of the polarization measurements in PP and PN scattering at 2 and 6 GeV/c. The data at 3 and 4 GeV/c lie in between with 4 looking more like 6 and 3 more like 2 GeV/c. It is obvious that the NP system is not mirror symmetric like the $\pi^+ \pi^-$ system. In the t channel exchange language, the flip amplitude is mainly $I_t = 0$ or no ρ , A_2 exchange at 2 and 3 GeV/c. The $I_t = 1$ part falls more slowly with energy and becomes equal to $I_t = 0$ at 6 GeV/c depending on t. We also can see a dramatic change at $-t = 0.3 \text{ GeV}^2$ in the ratio of PP PN polarization. The ratio is 0.8 at 2 GeV/c and 0.2 at 6 GeV/c. This was not anticipated by any model. Using the Halzen-Thomas notation again; the $\text{Re } N_1$ is measured by the polarization. N_1 can be broken up into a part corresponding to $I = 0$ exchange in the t channel (ω , f , Pomeron), and an $I = 1$ part (ρ , A_2). If we compare the 2 and 6 GeV/c data, we find a large change in the ratio of the $\text{Re } N_1$ ($I = 0$) to $\text{Re } N_1$ ($I = 1$). This ratio changes by almost an order of magnitude. Figure 15 is a plot of the single-flip natural parity exchange amplitudes

and figure 16 is a power law fit to the single flip amplitude. We see that

$$a_{I=0} = -0.6 + 0.6 t$$

$$a_{I=1} = +0.1 - 0.1 t$$

D. Inelastic Interactions

1. N^* and Δ Production

The EMS looks at the decay products of fast forward N^* 's that are associated with the polarized beam proton. The present experiment uses the transversely polarized beam but longitudinal polarization experiments are also technically feasible and useful. For the present experiments the EMS was triggered on multi-particle events (≥ 2 forward tracks). To monitor the incident beam polarization elastic scatters were simultaneously recorded. A large aperture hodoscopic Cerenkov counter was used to differentiate fast pions and protons. With 6 GeV/c beam momentum, the geometric acceptance for a typical reaction, $P \uparrow P \rightarrow (P \pi^+) n$ is $\sim 40\%$. Figure 17 shows events as a function of $P\pi^-$ mass and the surprisingly large polarization in the Δ^{++} production.

Figure 18 shows the number of events in $P \uparrow P \rightarrow P \pi^- P$. and Figure 19 the events in $P \uparrow P \rightarrow P \pi^+ N$.

Figure 20 compares the natural and unnatural parity cross section for the Δ^{++} and $K^{*0}(890)$.

The quark model predicts that the natural parity cross section for Δ^{++} and $K^{*0}(890)$ should be equal.

They do have the same t dependence and it is different then for the $\bar{K}^{0*}$ (890).

One can study the spin-parity content of the $P\pi^+\pi^-$ system with the reactions $P\uparrow P \rightarrow P\pi^+\pi^-P$

$$P\uparrow N \rightarrow P\pi^+\pi^-N$$

$$P\uparrow d \rightarrow P\pi^+\pi^-d$$

Figure 21 shows some data for $P\uparrow P \rightarrow P\pi^+\pi^-P$ and one observes small peaks at masses of 1400, 1500, 1660 MeV. The 1400 peak is seen only at very small t .

E. Inclusive Λ Production

1. Effective mass spectrometer experiment

This experiment was done in the EMS and now has over 10^4 analyzed events with less than 2% background. The results are best discussed in terms of a straightforward generalization of the Wolfenstein parameters shown in Figure 22.

$$\sigma = \sigma_0 [1 + (P - P') \bar{e} \cdot \hat{n}]$$

$$\sigma \bar{f} \cdot \hat{n} = \sigma_0 [(P + P') + D \bar{e} \cdot \hat{n}]$$

where

$\bar{e}$ is the beam polarization and $\bar{f}$ is the Λ^0 polarization, and $\hat{n}$ is the production plane unit normal.

$(P - P')$ is the analyzing power or scattering asymmetry of the production process and $(P + P')$ is the polarization or polarizing power. These two are equal by time reversal in elastic processes, but do not have to be equal in inelastic

processes. The "depolarization" parameter D has the same meaning as in elastic scattering.

These parameters were looked at as a function of the Feynman scaling variable x . For $x > 0.75$ inequality of polarization and analyzing power as shown in figure 23. The natural parity exchange expectation that $D = 1$ near $x = 1$ is not borne out by the data as shown in figure 24. The data look nothing like R. D. Field's triple - Regge⁽¹⁰⁾ results. The value of $D \approx -0.4$ near $x = 1$ might be due to Λ^0 's from the decay of low-spin diffractively produced $N^{*1}S$.

2. 12 ft Bubble Chamber Exposure

W. J. Fickinger and D. K. Robinson of Case Western Reserve University and A. Engler and R. W. Kraemer have an exposure of 150,000 pictures with 6 GeV/c polarized protons. These have been scanned for V's. They have looked at Λ and K production and have a very preliminary indication, based on 260 events, that there seems to be a 60% asymmetry in K^0 production at a 4 standard deviation level. Λ production seems to show no asymmetry.

F. Coherent Polarized Proton⁴ He Interactions

This experiment has had a test run of 49,000 pictures at 6 GeV/c and the film is now being scanned to evaluate the effectiveness of the trigger and the number of pictures necessary for a good experiment. The experiment is planned for ~ 9 GeV/c. The 1.5 METER streamer chamber is filled with helium at one atmosphere. The

chamber gas is both target and detector. The trigger is simply an incoming proton, no outgoing beam, and a multiplicity ≥ 2 in a multi-wire proportional counter at the downstream end of the chamber. The recoil range and momentum is measured in the chamber gas. This is shown schematically in figure 25.

G. Parity Tests

The group involved in this experiment has previously published a result of $(1 \pm 4) \times 10^{-7}$ for the parity-nonconserving component in proton-proton scattering at 15 MeV. ⁽¹¹⁾ A similar experiment is being done at the ZGS at 6 GeV/c in p-nucleus interaction in order to obtain information on the energy dependence of the effect. The apparatus is shown in figure 26. The polarized beam was used to measure the dependence of the P-Be total-scattering cross section on the pseudoscalar quantity $\vec{S} \cdot \vec{P}$, where $\vec{S}$ is the spin of the incident proton and $\vec{P}$ its momentum. If parity is conserved in the interaction between nucleons, the cross section is independent of $\vec{S} \cdot \vec{P}$. Effects are expected to be of the order of 10^{-5} to 10^{-7} . Integral counting techniques were used with two independent systems, one consisting of ionization chambers and the other photomultipliers coupled to scintillators. The target was 20 cm of Be. The bending magnet has a horizontal field and bends the protons down by 7.75° which rotates the spin so that it is aligned with the momentum. In their first run they obtained $(-1.4 \pm 2.6) \times 10^{-5}$ from the ion chambers and $(5 \pm 9) \times 10^{-6}$ from the scintillator system.

In a run recently completed, new detectors were added to the system. These gave signals related to position and angle of the beam, beam spot size, and residual transverse polarization. Ion chambers and scintillator data were recorded on the same computer so that beam property corrections could more easily be made to both. The

results are still being analyzed but a preliminary value should be announced shortly.

Acknowledgements

I would like to thank the authors of all the experiments I have mentioned for their information, both published and unpublished.

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  - E-336 Measurement of Λ 's Produced by a Polarized Proton Beam - R. Winston, University of Chicago,
  - E-339 Study of Resonance Production with a Polarized Proton Beam Using the Effective Mass Spectrometer - A. B. Wicklund, Argonne National Laboratory.
  - E-351 Study of Coherent Polarized Proton ^4He Interactions - A. Fridman, Institut de Physique Nucleaire de Strasbourg.
  - E-354 Parity Violation in Proton Scattering Processes - D. E. Nagle, Los Alamos Scientific Laboratory.
  - E-364 Measurement of the Polarization Parameter of Small Angles in PP Elastic Scattering - D. R. Rust, University of Indiana.
  - E-366 Measurement of the Recoil Spin in PP Elastic Scattering with a Polarized Beam and Polarized Target -

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FIG. 1
LAYOUT OF ZGS EXPERIMENTAL AREA
BEAMS FOR POLARIZED PROTONS

NEW MEASUREMENT OF σ_{TOT} IN PROTON-PROTON SCATTERING IN PURE SPIN STATES

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LAYOUT OF EXPERIMENT

$\Delta\sigma_{TOT}$ PLOTTED AGAINST
INCIDENT BEAM MOMENTUM

$$\Delta\sigma_{TOT} = \sigma_{TOT}(p, p) - \sigma_{TOT}(p, p)$$

$$= - \frac{\{[I(\omega)/I]_{p, p} - [I(\omega)/I]_{p, p}\}}{\langle I(\omega)/I \rangle N_{opt} P_B P_T}$$

FIG. 3

SIMULTANEOUS MEASUREMENT OF 2 AND 3 SPINS IN PROTON PROTON ELASTIC SCATTERING AT 660V/C

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LAYOUT OF 2 ARM SPECTROMETER ADDED TO PREVIOUS EXPERIMENT

EQUATIONS FOR RELATIVE CROSS SECTIONS

$$\frac{d\sigma}{d\Omega}(\uparrow\uparrow) = \langle d\sigma/d\Omega \rangle \left[1 + \frac{4(N_{\uparrow\uparrow} - N_{\downarrow\downarrow})}{(P_B + P_T) \sum N_{ij}} + C_{NN} \right]$$

$$\frac{d\sigma}{d\Omega}(\downarrow\downarrow) = \langle d\sigma/d\Omega \rangle \left[1 - \frac{4(N_{\uparrow\uparrow} - N_{\downarrow\downarrow})}{(P_B + P_T) \sum N_{ij}} + C_{NN} \right]$$

$$\frac{d\sigma}{d\Omega}(\uparrow\downarrow) = \frac{d\sigma}{d\Omega}(\downarrow\uparrow) = \langle d\sigma/d\Omega \rangle [1 - C_{NN}]$$

where C_{NN} IS GIVEN BY

$$C_{NN} = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{P_B P_T \sum N_{ij}}$$

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{P_B \sum N_{ij}} = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{P_T \sum N_{ij}} = \frac{2(N_{\uparrow\uparrow} - N_{\downarrow\downarrow})}{(P_B + P_T) \sum N_{ij}}$$

FIG. 4

FIG. 5

FIG. 6

FIG.7

MEASUREMENT OF SPIN-SPIN CORRELATION PARAMETER C_{NN}
IN PROTON-PROTON SCATTERING AT 6 GeV/c

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FIG. 8

Fig. 9

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FIG. 10

Schumacher $\neq$ Bethe PHYS. REV. 121 1534( )

$$M_T = A_T + B_T \sigma_{1m} \sigma_{2m} + C_T (\sigma_{1m} + \sigma_{2m}) + D_T (\sigma_{1m} - \sigma_{2m}) \\ + E_T \sigma_{1s} \sigma_{2s} + F_T \sigma_{1p} \sigma_{2p}$$

σ_1, σ_2 Pauli matrices for incident and target nucleons

$\bar{m}, \bar{p}, \bar{q}$ 3 mutually perpendicular directions defined

$$\text{by } \bar{m} = \bar{k}_{in} \times \bar{k}_{out}$$

$$\bar{p} = \bar{k}_{in} + \bar{k}_{out}$$

$$\bar{q} = \bar{k}_{out} - \bar{k}_{in}$$

where $\bar{k}$ is the nucleon momentum in the CM system

Subscript T refers to the total isotopic spin of the system

Then

$$I_0 = |A|^2 + |B|^2 + 2|C|^2 + |E|^2 + |F|^2$$

$$I_0 D_{NN} = |A|^2 + |B|^2 + 2|C|^2 - |E|^2 - |F|^2$$

$$\frac{1}{2} I_0 C_{NN} = \text{Re } AB^* + |C|^2 - \text{Re } EF^*$$

$$\frac{1}{2} I_0 K_{NN} = \text{Re } AB^* + |C|^2 + \text{Re } EF^*$$

$$I_0 P = 2 \text{Re } C^* (A + B)$$

MEASUREMENT OF THE POLARIZATION PARAMETER IN SMALL
ANGLE PROTON-PROTON ELASTIC SCATTERING AT 6.6 GeV/c

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CURVE IS THE EMPIRICAL FORMULA

$$P(t) = (2.506 \pm 0.021) \sqrt{-t} \exp[(2.52 \pm 0.10)t]$$

FIG. 17

EFFECTIVE MASS SPECTROMETER EXPERIMENTS WITH POLARIZED PROTON BEAM

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I. $PAN \rightarrow PN$
 $PAP \rightarrow PP$ } FORWARD ELASTIC SCATTERING (10^7 triggers.
 $\sim 500,000$ events each at 2, 3, 4, and 6 GeV/c

II. N^* and Δ production (2.5×10^7 triggers)
 $\sim 3,200,000$ GOOD EVENTS, INCLUDING

$PAP \rightarrow P\pi^+N$ 600,000 at 3 GeV/c
600,000 " 4 GeV/c
1,300,000 " 6 GeV/c

$PAN \rightarrow P\pi^-P$ 200,000 " 6 GeV/c

$PAP \rightarrow P\pi^+\pi^-(p)$ 500,000 " 6 GeV/c

$PAD \rightarrow P\pi^+\pi^-(d)$
(NN)

$PAP \rightarrow P\pi^-\Delta^{++}$ 100,000 " 6 GeV/c

III. INCLUSIVE $PAP \rightarrow \Lambda X^{++}$ at 6 GeV/c

$\sim 10,000$ GOOD EVENTS

FIG. 13

FIG. 1

SINGLE-FLIP NATURAL-PARITY EXCH AMPS.

FIG. 15

POWER LAW FIT TO N_1 (3, 4 AND 6 GeV/c)

$$N_1 = a p_{\text{LAB}}^n = a p_{\text{LAB}}^{n-1}$$

FIG. 16

FIG. 1

FIG. 18

FIG. 19

FIG. 20

FIG. 21

INCLUSIVE PRODUCTION OF Λ^0 'S USING A POLARIZED PROTON BEAM

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$$\sigma = \sigma_0 [1 + (P-P') \bar{e} \cdot \hat{m}]$$

$$\sigma \bar{f} \cdot \hat{m} = \sigma_0 [(P+P') + D \bar{e} \cdot \hat{m}]$$

$\bar{e}$ BEAM POLARIZATION

$\bar{f}$ Λ^0 POLARIZATION

$\hat{m}$ PRODUCTION PLANE UNIT NORMAL

$(P-P')$ ANALYZING POWER OR SCATTERING ASYMMETRY
OF THE PRODUCTION PROCESS

$(P+P')$ POLARIZATION OR POLARIZING POWER

FIG. 29
~~FIG. 29~~

FIG. 23

FIG. 2

COHERENT P^4He INTERACTIONS in STREAMER CHAMBER

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FIG. 2

LIMIT ON PARTIAL NONCONSERVATION IN P-NUCLEUS SCATTERING AT 6 GeV/c

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