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RECENT RESULTS ON POLARIZATION PHENOMENA

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RECENT RESULTS ON POLARIZATION PHENOMENA

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INTRODUCTION

Today I would like to discuss several topics relating to polarization phenomena. First, the structure in certain pp spin observables measured at Argonne will be described, and a number of new results presented. These data may indicate the existence of a dibaryon resonance. Next, there are some recent results from the Indiana group on high energy inclusive proton polarization from Fermilab. The values are sizeable and they will be compared to the inclusive Λ polarization data at high energies. Finally, there are some new measurements of pp elastic scattering polarization at high energy from CERN and Fermilab. Some general features of these data will be discussed. Polarization phenomena at large P_T^2 will be covered in the talk by A. Krisch and will not be reviewed here.

A. LOW ENERGY pp DATA

There are some new results on pp spin parameters from several experimental groups at Argonne. I would like to concentrate on the significance of the structure observed in the total cross-section difference for longitudinally-polarized beam and target.

First, consider the helicity amplitudes used to describe the experimental data. There are three nonzero amplitudes at $t = 0$, namely ϕ_1 , ϕ_2 and ϕ_3 :

$$\begin{aligned}\phi_1 &= \langle ++ | ++ \rangle \\ \phi_2 &= \langle -- | ++ \rangle \\ \phi_3 &= \langle +- | +- \rangle\end{aligned}\tag{1}$$

and there are three total cross sections which have been measured,

$$\begin{aligned}\sigma_{\text{Tot}} &= \frac{2\pi}{k_{\text{cm}}} \text{Im} \{ \phi_1(0) + \phi_3(0) \} = \frac{1}{2} \{ \sigma_{\text{Tot}}(\vec{\uparrow}) + \sigma_{\text{Tot}}(\vec{\downarrow}) \} \\ \Delta\sigma_L &= \frac{4\pi}{k_{\text{cm}}} \text{Im} \{ \phi_1(0) - \phi_3(0) \} = \sigma_{\text{Tot}}(\vec{\uparrow}) - \sigma_{\text{Tot}}(\vec{\downarrow}) \\ \Delta\sigma_T &= -\frac{4\pi}{k_{\text{cm}}} \text{Im} \{ \phi_2(0) \} = \sigma_{\text{Tot}}(\uparrow\uparrow) - \sigma_{\text{Tot}}(\uparrow\downarrow)\end{aligned}\tag{2}$$

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where the arrows denote the beam and target spin directions in the laboratory frame. The first is the ordinary spin-averaged cross section σ_{TOT} . The other two are cross-section differences for longitudinal ($\Delta\sigma_L$) and transverse ($\Delta\sigma_T$) protons.

The data are shown in Fig. 1. The open triangles and open circles correspond to preliminary results. All cross-section measurements (σ_{TOT} , $\Delta\sigma_L$, $\Delta\sigma_T$) were performed as standard transmission experiments. The data are all plotted on the same scale to show that spin effects are quite sizeable at these energies. The $\Delta\sigma_T$ measurements were performed by two groups; one was a Michigan, Argonne, St. Louis collaboration¹ and the other was a Rice, Michigan, Houston group². There appears to be some sort of structure near 2 GeV/c. Additional measurements are planned to clarify the variation of $\Delta\sigma_T$ with energy.

Fig. 1 Total cross sections for pp interactions. The upper curve is the spin-averaged cross section, the middle curve is the cross-section difference for transversely-polarized beam and target, and the lower curve is the total cross-section difference for longitudinally-polarized beam and target. The open triangles² and open circles⁵ are preliminary results. The curves are drawn to guide the eye.

The $\Delta\sigma_L$ data, measured by the Argonne in-house polarization group,³⁻⁵ exhibit rather striking structure as a function of energy. Combining the $\Delta\sigma_L$ and total cross-section data, then the imaginary parts of the helicity amplitudes ϕ_1 and ϕ_3 can be separated,

$$\begin{aligned}\text{Im } \phi_1(0) &= \frac{k_{\text{cm}}}{4\pi} (\sigma_{\text{Tot}} + \Delta\sigma_L/2) \\ \text{Im } \phi_3(0) &= \frac{k_{\text{cm}}}{4\pi} (\sigma_{\text{Tot}} - \Delta\sigma_L/2) \quad . \quad (3)\end{aligned}$$

Fig. 2 Total cross sections for pure longitudinal spin states. The triangles correspond to preliminary data and the circles to data from references 3 and 4. Note that the structure appears only in $\phi_3(0)$.

The results are shown in Fig. 2. The spin-averaged cross section is the average of these two curves. It can be seen that the structure is present in ϕ_3 but not in ϕ_1 .

Decomposing the helicity amplitudes into partial waves, then

$$\begin{aligned}\phi_1 &= \text{singlet} + \text{triplet } (J = L \pm 1, \text{ even}) \\ \phi_2 &= -\text{singlet} + \text{triplet } (J = L \pm 1, \text{ even}) \\ \phi_3 &= \text{triplet } (J = L \pm 1, \text{ even}) + \\ &\quad \text{triplet } (J = L, \text{ odd}),\end{aligned}\quad (4)$$

where singlet refers to spin-singlet contributions and triplet to spin-triplet contributions. The fact that the structure in $\Delta\sigma_L$ appears in ϕ_3 but not in ϕ_1 indicates that the structure is caused by spin-triplet, $J = L = \text{odd}$ partial waves.

Grein and Kroll⁶ have applied fixed-t dispersion relations to the $\Delta\sigma_L$ results. In terms of the amplitude A_3 ,

$$A_3 = \frac{P_{\text{lab}}}{k_{\text{cm}}} (\phi_1 - \phi_3) \quad (5)$$

then

$$\text{Im}(A_3) = \frac{P_{\text{lab}}}{4\pi} \Delta\sigma_L. \quad (6)$$

Grein and Kroll used phase-shift results for $\Delta\sigma_L$ at low energies, the measured values of $\Delta\sigma_L$ between 1 and 6 GeV/c^{3,4} and some assumptions about the high energy behavior of $\Delta\sigma_L$, to obtain the imaginary part of A_3 as a function of energy as shown in Fig. 3. Then the real part of A_3 was computed from dispersion relations. (This is similar to the calculation of the real part of the forward scattering amplitude from the total cross section (σ_{Tot}) measurements in the spin-averaged case).

The amplitude A_3 is displayed in an Argand diagram in Fig. 4. Since the structure in $\Delta\sigma_L$ and A_3 arises from the helicity amplitude ϕ_3 , and since $A_3 \sim (\phi_1 - \phi_3)$, the amplitude ($-A_3$) is actually plotted. It exhibits a clear resonance-like behavior corresponding to a dibaryon resonance at $P_{\text{lab}} = 1.5$ GeV/c in the pp system.

Fig. 3 The real and imaginary parts of the amplitude A_3 from Grein and Kroll.⁶ The imaginary part was obtained from phase-shift results below 1 GeV/c and from $\Delta\sigma_L$ data (filled circles) between 1 and 6 GeV/c. For comparison, the preliminary $\Delta\sigma_L$ values (open circles) are also shown. The real part of A_3 was calculated from the imaginary part of A_3 using dispersion relations.

Fig. 4 Argand diagram of the amplitude $(-A_3) - (\phi_3 - \phi_1)$ from reference 6. The structure in $\Delta\sigma_T$ corresponds to resonance-like behavior in A_3 at $P_{\text{lab}} \approx 1.5 \text{ GeV/c}$.

Additional evidence for this dibaryon resonance comes from a number of pp elastic scattering measurements. The total elastic cross section, shown in Fig. 5, seems to exhibit a peak at about 1.5 GeV/c , though some improvement in these data would be desirable.

Fig. 5 Total cross section for pp elastic scattering.

Next, consider two elastic scattering spin-spin correlation measurements at $\theta_{cm} = 90^\circ$. The first, $C_{NN}(90^\circ)$, has both the beam and the target polarized transverse to the scattering plane. The other, $C_{LL}(90^\circ)$, has both polarized longitudinally. The results are shown in Fig. 6. Over the past 20 years, many groups have measured $C_{NN}(90^\circ)$, as indicated by the numerous points at momenta below 1.5 GeV/c. These were either double or triple scattering experiments, and consequently often of poor statistical accuracy. With the combination of a polarized beam and a polarized

target, higher precision measurements are possible. The statistical accuracy of some recent data from Argonne by the Michigan group⁷ is quite good, as indicated in Fig. 7. They plan measurements of $C_{NN}(90^\circ)$ up to 12 GeV/c, where their present $C_{NN}(\theta)$ results seem to be 0.2 to 0.3 and increasing with θ at the largest angles measured so far. Additional high-precision $C_{NN}(90^\circ)$ measurements in the range $P_{lab} \sim 1$ to 2 GeV/c would be quite helpful.

The $C_{LL}(90^\circ)$ data in Fig. 6 are preliminary. Values at additional energies will be available soon. (The $\Delta\sigma_L$ and $C_{LL}(90^\circ)$ measurements were performed simultaneously by the Argonne in-house polarization group.)

Fig. 6 The spin-spin correlation parameters C_{NN} and C_{LL} at $\theta_{cm} = 90^\circ$. The solid squares and triangles are preliminary data from references 5 and 7.

Fig. 7 The spin-spin correlation parameter $C_{NN}(90^\circ)$ as measured at Argonne.^{7,8}

The value of $C_{NN}(90^\circ)$ is given by the spin-triplet cross section at 90° minus the spin-singlet cross section, divided by the sum. The expression for $C_{LL}(90^\circ)$ is similar except that the spin-triplet term in the numerator is an interference of various triplet contributions:

$$C_{NN}(90^\circ) = \frac{\text{triplet} - \text{singlet}}{\text{triplet} + \text{singlet}}$$

$$C_{LL}(90^\circ) = \frac{\text{triplet}'(\text{mixture}) - \text{singlet}}{\text{triplet} + \text{singlet}} \quad . \quad (7)$$

There is a peak in $C_{LL}(90^\circ)$ and an indication of a peak in $C_{NN}(90^\circ)$ near 1.5 GeV/c seen in Fig. 6. Therefore, the spin-triplet contribution is sizeable in both the total cross sections and in the elastic channel at $\theta_{cm} = 90^\circ$.

One final bit of evidence from the elastic channel comes from the polarization parameter measured as a function of energy, shown in Fig. 8. The values have been averaged over the t -range of 0.1 to 0.2, and all data shown were collected by one group in order to minimize systematic differences between the points. The polarization times the differential cross section contains only spin-triplet terms, and it shows a significant peak near 1.5 GeV/c. Therefore, measurements of $C_{NN}(90^\circ)$, $C_{LL}(90^\circ)$ and polarization in pp elastic scattering are all consistent with structure in the spin-triplet partial waves near 1.5 GeV/c.

Fig. 8. The polarization parameter for pp elastic scattering averaged over $0.1 \leq |t| \leq 0.2$ (GeV/c)² from reference 9.

A Legendre coefficient analysis was performed by Hidaka et al. at Argonne¹⁰. The elastic angular distribution and the polarization as a function of angle are fit by the expressions:

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \sum_N A_N P_N(\cos \theta)$$

$$P = \frac{d\sigma}{d\Omega} = \frac{1}{k^2} \sum_N B_N P_N^1(\cos \theta) \quad (8)$$

The coefficients A_N and B_N are related to the individual partial waves. The variation of the coefficients as a function of energy indicates that the partial wave 3F_3 is responsible for the structure seen in the polarization. A phase-shift analysis performed by Hoshizaki¹¹ comes to the same conclusion. Note that the 3F_3 partial wave is consistent with the $J = L = \text{odd}$ condition derived from the observation of structure in $\phi_3(0)$ but not in $\phi_1(0)$.

Therefore, assuming the structure corresponds to a resonance, then its properties would be

$$\begin{array}{ll} \text{Mass} & \sim 2250 \text{ MeV} \\ \text{Width} & \sim 200 \text{ MeV} \\ \text{Charge} & 2 \\ J^P & 3^- \end{array} \quad (9)$$

A dibaryon with these quantum numbers has not been predicted to my knowledge. In order to fit such a resonance into the six quark bag model of Jaffe,¹² where all quarks are in an S-state, orbital excitation of the quarks would have to be included.

An argument could also be made that the structure observed in $\Delta\sigma_T$ near 2 GeV/c might be a resonance. However, at this time the evidence is much weaker than for the structure near 1.5 GeV/c in $\Delta\sigma_L$. For example, the structure in $\Delta\sigma_T$ probably corresponds to spin-singlet partial waves. In this case, the numerous pp polarization data give no information since only spin-triplet partial waves contribute.

B. HIGH-ENERGY INCLUSIVE POLARIZATION DATA

The Indiana University Group has recently performed an experiment at Fermilab to measure inclusive proton polarizations.¹³ Accelerating protons in the Fermilab main ring struck an internal carbon target. The inclusively-produced protons were detected in a superconducting spectrometer at $\theta_{lab} = 52^\circ$, which was set to record particles with $p_T = 1.1$ GeV/c. The proton polarization was measured in a carbon polarimeter, and pions were rejected by time

of flight requirements. The missing masses detected ranged from $M^2 = 30$ to 100 GeV^2 at 100 GeV and from 80 to 140 GeV^2 at 400-GeV incident protons, and $x \approx 0.89$.

Fig. 9 Inclusive polarization data at high energies and $P_T = 1.1 \text{ GeV/c}$. The circles are preliminary inclusive proton data for $p + C$ interactions,¹³ and the triangles are inclusive Λ polarizations for $p + \text{Be}$ (∇ , reference 14) and for $p + \text{Pt}$ (Δ , reference 15) interactions.

The results are shown in Fig. 9. The sizeable polarizations (6 - 10%) are essentially independent of energy within the error bars, and they are much larger in magnitude than expected from any simple Regge model. These inclusive-proton polarizations are reminiscent of the large Λ polarizations seen in another experiment at Fermilab. The Wisconsin, Michigan, Rutgers' Group^{14,15} measured a large inclusive Λ polarization at 300 GeV which seems independent

of energy down to 24 GeV/c at $P_T \geq 1.0$ GeV/c, as shown in Fig. 9. If the Λ and proton inclusive polarizations are related, there may be an increase in the inclusive proton polarization at higher P_T , which is seen in the Λ case. The Indiana group plans to investigate this possibility in the near future.

C. HIGH ENERGY pp POLARIZATION RESULTS

There are several new measurements of the polarization parameter in pp elastic scattering at high energy (see Figs. 10, 11, and 12). The CERN data at 24 GeV/c¹⁶ and the Serpukhov data at 45 GeV/c¹⁷ have both been published, except for the high- t points at 24 GeV/c. In addition, there are some other results at these energies recently obtained using a hydrogen jet target at Fermilab by the Indiana group.¹⁸ They measured the polarization of the recoil proton as a function of energy at $-t = 0.3, 0.6, 0.8$ and 1.0 GeV/c². Their data agree well with the results from the other groups who used polarized-proton targets. The Fermilab E-61 collaboration of Argonne, Berkeley, Fermilab, Harvard, Suffolk and Yale obtained polarization data at 100 and 300 GeV/c^{19,20} with a double-arm magnetic spectrometer. A similar experimental setup was used at the CERN-SPS by the CERN, Padova, Trieste, Vienna collaboration to measure the polarization at 150 GeV/c.²¹

These results have several features in common. The absolute value of the polarization is quite small (less than .05) out to $-t = 0.8$ (GeV/c)² at all energies shown in Figs. 10 and 11. The polarization is positive at small- t and seems consistently negative at $-t \approx 1.0$. The polarization data at 45 and 150 GeV/c are indistinguishable. However, the t -dependence of the 100 and 300 GeV/c results beyond $-t = 0.5$ is somewhat different from the 45 GeV/c data. The differences are probably within the quoted statistical uncertainties, though a sizeable energy dependence of the data at $|t| > 0.5$ (GeV/c)² is not excluded. Finally, at $|t| > 1$ there may be rapid changes in the polarization with t and with maximum asymmetries of $\pm .20$.

Predictions from two Regge models are given on the plots of the 100 and 300-GeV/c data in Figs. 10 and 11. The solid curves are from the model of Field and Stevens²² with a pure non-flip Pomeron. Their 100-GeV/c curve is somewhat high at small- t , and their 300 GeV/c-prediction agrees fairly well with the data. The dashed curve is from a model of Pomplin and Kane.²³ Their model has a spin-flip component of the Pomeron, which leads to polarizations on the order of -0.10 even at ISR energies. Figure 12 shows the data plotted at fixed- t as a function of energy. The Pomplin-Kane prediction is roughly -0.10 at $-t \approx 1$ (GeV/c)², which agrees with the high-energy measurements. Their prediction at $-t = 0.3$ is shown in Fig. 12, and the data are consistently smaller than the theoretical value at most energies shown.

Fig. 10 Polarization for pp elastic scattering at 24, 45 and 100 GeV/c.

Fig. 11 Polarization for pp elastic scattering at 150 and 300 GeV/c.

Fig. 12 Polarization in pp elastic scattering at fixed- t . The measurements are from the Indiana group ($\bullet$, Reference 18), CERN ($\circ$, Reference 16), Serpukhov ($\square$, Reference 17), the Fermilab E-61 collaboration (Δ , Reference 19, and 20) and the CERN-SPS group (∇ , Reference 21). The prediction of the Pumplin-Kane model at $-t = 0.3$ is also shown.

Polarization effects at larger $-t$ will be studied by the Fermilab E-61 collaboration and the CERN-SPS group. We can look forward to quite interesting results from these experiments, especially in the region of the dip in the pp elastic cross section, where there are already hints of sizeable structure in the polarization at 300 GeV/c.

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