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#### POLARIZATION IN ELASTIC SCATTERING AT HIGH ENERGY

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### 1. πp SCATTERING

First I want to remind you briefly that in terms of the non-spinflip and the spin-flip amplitudes f and g, the  $\pi p$  scattering amplitude is

$$T = f + ig\vec{\sigma} \cdot \vec{n} .$$
 (1)

The differential cross-section for scattering on unpolarized protons

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto \left( \left| \mathbf{f} \right|^2 + \left| \mathbf{g} \right|^2 \right) , \qquad (2)$$

and the recoil proton polarization is

$$P_{0} = \frac{2 \operatorname{Im} (f g^{*})}{|f|^{2} + |g|^{2}}$$
(3)

Angular momentum conservation ensures that  $P_0 = 0$ , at  $\theta = 0$ , and  $\theta = \pi$ .

 $P_0$  is currently measured in scattering experiments on a target containing hydrogen with a known polarization  $P_T$ . When the target polarization is reversed from up (†) to down (+), the asymmetry A in the counting rate ( $N_{\uparrow}$  or  $N_{\downarrow}$ ) of elastic events on the polarized target protons is related to  $P_0$  as follows

$$A(\theta, k) = \frac{N_{\downarrow} - N_{\uparrow}}{N_{\uparrow} + N_{\downarrow}} = P_0 P_T . \qquad (4)$$

A polarized target of composition  $CH_2$ , is now in operation at CERN; this target is  $\sim$  5 cm long and 14 mm in diameter. At the beginning of 1970, the polarization  $P_T$  was raised from  $\sim$  35% to  $\sim$  65%, by means of <sup>3</sup>He refrigeration (down to  $\sim$  0.5°K).

A compilation of representative  $P_0$  data [taken from Andersson et al.<sup>1)</sup>, Esterling et al.<sup>2)</sup>, Borghini et al.<sup>3,5)</sup>, and the CERN-Orsay-Pisa Collaboration<sup>4)</sup>] for  $\pi$  p forward scattering is shown in Fig. 1. The 10 GeV/c data are preliminary. New data by the CERN-Orsay-Pisa Group will soon be available at 14.0 GeV/c.

The following features should be observed:

- a) the first minimum occurs consistently at  $|t| \sim 0.6$  (GeV/c)<sup>2</sup> at all energies;
- b) below  $|t| \sim 2 (\text{GeV/c})^2$  the polarization pattern varies only slightly with energy. Above  $|t| \sim 2.0 (\text{GeV/c})^2$  there is an indication that P<sub>0</sub> remains negative at the highest energies (in contrast with the 2.74 GeV/c data);
- c) the energy variation of P<sub>0</sub> at  $|t| \sim 1.5 (\text{GeV/c})^{\hat{2}}$  appears to be weaker than that expected if the polarization is due to the  $\rho$ -exchange amplitude interfering with a flat Pomeranchuk. A rough estimate of the variation of log P<sub>0</sub> at  $|t| \sim 1.5 (\text{GeV/c})^2$  versus log S is shown in Fig. 2. If, as in the  $\rho$  + P interference model,

$$P_0 \propto \text{Im} (f g^*) \propto f_P \cdot \text{Re} g_0 \propto S^{\alpha} \rho^{-1}$$

and  $\alpha_{\rho} \sim 0.5 + t [t in (GeV/c)^2]$ , one expects at t  $\sim -1.5$  (GeV/c)  $\alpha_{\rho}^{-1} \sim -2.0$  The data of Fig. 2 would favour an energy dependence like  $S^{-1}$  (or even weaker than this).

Representative  $\pi^+ p$  polarization data<sup>1-3,5,6)</sup> are shown in Fig. 3. Additional new data by the CERN-Orsay-Pisa Group at 10.0, 14.0, and 17.5 GeV/c will soon be available. Backward scattering polarization data between 2.75 GeV/c and 3.75 GeV/c, obtained by the Chicago-Argonne Group, are also available; these data will be discussed in the seminar on backward scattering. The 2.75 GeV/c data by this group are shown in Fig. 3 together with the data by Andersson et al.<sup>1)</sup>

The following observations should be made:

- a) At |t| below  $\sim 1.5$  (GeV/c)<sup>2</sup>, the data are roughly mirror-symmetric of the  $\pi^{-}p$  data. However, at  $|t| \leq 0.6$  (GeV/c)<sup>2</sup>, P<sub>0</sub> shows a faster decrease with increasing energy than in the  $\pi^{-}p$  case.
- b) The 6 GeV/c data show that  $P_0$  might change sign at  $|t| \sim 2.0$  (GeV/c) in contrast to the  $\pi^- p$  data. However, this phenomenon needs better data in order to be firmly established.

To illustrate the possible relationships between structures in the differential cross-section and structures in  $P_0$  the  $\pi^{\pm}p$  differential cross-sections at 2.74 GeV/c is shown in Fig. 4 and the corresponding

polarizations in Fig. 5. One sees that in both distributions the first structure in  $P_0$  corresponds to the first structure in  $d\sigma/dt$ , while at larger |t| the relationship between the strong structures in  $d\sigma/dt$  and in  $P_0$  is less clear.

A comparison of the 6 GeV/c  $\pi$  p and  $\pi$  p polarization data by the CERN-Orsay-Pisa Group is shown in Fig. 6. One observes that there is some indication for a non-mirror-symmetric behaviour at large |t|.

To fully determine the amplitudes f and g (Eq. 1), one measures two other polarization parameters A and R, according to the scheme illustrated in Fig. 7 [Amblard et al.<sup>7)</sup>]. In both cases, the transverse component u of the recoil proton polarization on the scattering plane is measured. If the target polarization  $P_i$  is opposite to the incident beam momentum, as in part A of Fig. 7, one has

$$u = A|P_{i}| = \begin{cases} \frac{|f|^{2} - |g|^{2}}{|f|^{2} + |g|^{2}} \sin (\theta_{p}^{*} - \theta_{p}^{L}) - \frac{2 \operatorname{Re}(f g^{*})}{|f|^{2} + |g|^{2}} \cos (\theta_{p}^{*} - \theta_{p}^{L}) \end{cases} P_{i} \\ \approx \frac{|f|^{2} - |g|^{2}}{|f|^{2} + |g|^{2}} \cdot P_{i}$$
(5)

at small  $\theta_{\pi}$ , since  $\theta_{p}^{*} - \theta_{p}^{L} \sim \pi/2$ .  $\theta_{p}^{*}$  and  $\theta_{p}^{L}$  are the recoil proton angles in the centre of mass and in the laboratory system, respectively. If the target polarization is oriented as in R, one has

$$u = R|P_{i}| = \left\{ \frac{|f| - |g|^{2}}{|f|^{2} + |g|^{2}} \cos (\theta_{p}^{*} - \theta_{p}^{L}) + \frac{2 \operatorname{Re} (f g^{*})}{|f|^{2} + |g|^{2}} \sin (\theta_{p}^{*} - \theta_{p}^{L}) \right\} P_{i}$$

$$\simeq \frac{2 \operatorname{Re} (f g^{*})}{|f|^{2} + |g|^{2}} \cdot P_{i}$$
(6)

at small  $\theta_{\pi}$ .

Since in general the spin-flip amplitude g is small with respect to f, the A-measurement is not very sensitive to the spin-flip amplitude (A  $\approx$  1 at small |t|'s). On the other hand, R measures an interference term between f and g, as P<sub>0</sub> does. Preliminary results on A and R at 6 GeV were presented by the Saclay Group at the 1969 Lund Conference<sup>7)</sup>, and are shown in Fig. 8. The model predictions are from Cohen-Tannoudji et al.<sup>8)</sup> (free curves), and Barger and Phillips<sup>9)</sup> (dotted curves).

The qualitative features of the  $\pi^{\pm}p$  polarization data can be interpreted in the framework of the Regge-pole model by assuming that the non-spin-flip amplitude f is essentially imaginary and due to the exchange of a flat Pomeranchuk, and that the spin-flip amplitude g is due to  $\rho$ -exchange.

Thus, from formulas (3) and (6):

$$P_{0}(\pi^{-}p) \approx \sin \theta_{\pi} \cdot (1 - \cos \pi \alpha_{\rho}) \cdot s^{\alpha} \rho^{-1}$$

$$P_{0}(\pi^{+}p) \approx -\sin \theta_{\pi} \cdot (1 - \cos \pi \alpha_{\rho}) \cdot s^{\alpha} \rho^{-1}$$

$$R(\pi^{+}p) \approx \sin \theta_{\pi} \cdot \sin \pi \alpha_{\rho} \cdot s^{\alpha} \rho^{-1}$$
(7)

According to formula (7),  $P_0(\pi^-p)$  and  $P_0(\pi^+p)$  are (roughly) mirror-symmetric and have a quadratic zero at  $\alpha_{\rho} \sim 0$ ; namely at  $|t| \sim 0.6$  (GeV/c)<sup>2</sup>.  $R(\pi^-p)$  has a linear zero at  $\alpha_{\rho} \sim 0$  (compare with Fig. 8). The energy dependence is  $\sim S^{\alpha\rho^{-1}}$  (compare with Fig. 2). Detailed fits take into account absorptive corrections<sup>8</sup>, or contributions from additional poles<sup>9</sup>.

An optical model has been proposed by Berlad, Dar and Eilam<sup>10)</sup> in which the no-spin-flip amplitude is generated by absorption and is proportional to the Bessel function  $J_1(x)$ :

$$f \propto \frac{J_1(x)}{x}$$
,  $x = R\sqrt{|t|}$ .

The spin-flip amplitude is also proportional to  $J_1(x)$ , because contributions to it are assumed to come only from the edge of the nucleon . Therefore one gets the prediction

$$P_0 \propto J_1^2(x)/x$$

which repoduces the main features of the experimental data. A change in sign of P<sub>0</sub> from  $\pi^- p$  to  $\pi^+ p$  scattering is obtained by assuming that the spin-flip amplitude is associated with  $\rho$ -exchange. In this way one accommodates also for the energy dependence P<sub>0</sub>  $\propto$  S<sup> $\alpha \rho^{-1}$ </sup>.

### 2. Kp SCATTERING

The formalism [formulas (1) to (6)] is the same as for  $\pi p$  scattering. The experimental information is still limited to the parameter P<sub>0</sub> only. In the Regge-pole model one can exchange more poles than in  $\pi p$  scattering. Typically one would consider two I = 0 poles, the P' (or f<sub>0</sub>) and the  $\omega$ , and two J = 1 poles, the  $\rho$  and the A<sub>2</sub>. Thus (disregarding the contribution of the cuts):

$$T(K^{-}p) = T_{P}^{K} + T_{f}^{K} + T_{\omega}^{K} + T_{\rho}^{K} + T_{A}^{K}$$

$$T(K^{+}p) = T_{P}^{K} + T_{f}^{K} - T_{\omega}^{K} - T_{\rho}^{K} + T_{A}^{K}.$$
(8)

As it appears that there are no resonances in the K<sup>+</sup>p channel, one can assume exchange degeneracy between  $T_f^K$  and  $T_{\omega}^K$ , and between  $T_{\rho}^K$  and  $T_A^K$ , such that<sup>11,12</sup>

$$f(K^{-}p) \approx |i ~\tilde{\gamma}_{P}^{K} - \left(\tilde{\gamma}_{\omega K}^{nf} + \tilde{\gamma}_{\rho K}^{nf}\right) e^{-i\pi\alpha} s^{\alpha-1}$$

$$g(K^{-}p) \approx \sin \theta_{K} \left(\tilde{\gamma}_{\omega K}^{f} + \tilde{\gamma}_{\rho K}^{f}\right) e^{-i\pi\alpha} s^{\alpha-1}$$

$$f(K^{+}p) \approx i ~\tilde{\gamma}_{P}^{K} - \left(\tilde{\gamma}_{\omega K}^{nf} + \tilde{\gamma}_{\rho K}^{nf}\right) s^{\alpha-1}$$

$$g(K^{+}p) \approx \sin \theta_{K} \left(\tilde{\gamma}_{\omega K}^{f} + \tilde{\gamma}_{\rho K}^{f}\right) s^{\alpha-1},$$
(9)

where  $\alpha = \alpha_f = \alpha_{\omega} = \alpha_{\rho} = \alpha_A$ , and the symbols f and nf stand for spin-flip and no-spin-flip, respectively. The functions  $\tilde{\gamma}$  do not have zeros or singularities for t  $\leq 0$ . From Eq. (9) one gets the following predictions for the polarization parameter P<sub>0</sub>:

$$P_{0}(K^{-}p) \approx \sin \theta_{K} \cdot \cos \pi \alpha \cdot S^{\alpha-1}$$

$$P_{0}(K^{+}p) \approx \sin \theta_{K} \cdot S^{\alpha-1} .$$
(10)

Thus  $P_0(K^+p)$  is zero at  $\theta_K = 0$ , and rises smoothly as  $\sin \theta_K$  away from  $\theta_K = 0$ .  $P_0(K^-p)$  is also zero at  $\theta_K = 0$ , is maximum [and equal to  $P_0(K^+p)$ ]

at cos  $\pi\alpha = 1$ , namely at  $|t| = 0.5 (GeV/c)^2$ , and goes to zero and changes sign at cos  $\pi\alpha = 0$ , namely at  $|t| \sim 1 (GeV/c)^2$ . Blackmon and Goldstein<sup>13)</sup> have made a model of this type, in which they also took into account (in the eikonal formalism) the (Pomeranchuk + Regge-pole) cut contribution. Their predictions for P (K<sup>+</sup>p) and P (K<sup>-</sup>p) are shown in Figs. 9 and 10, respectively.

A compilation of existing  $(K^+p)$  polarization data<sup>14,1,3,6)</sup> is shown in Fig. 11. The significant information is limited to  $|t| \sim 1$  (GeV/c)<sup>2</sup>, when P<sub>0</sub> is a smooth function of t and decreases with increasing energy. The (K<sup>-</sup>p) data are shown in Fig. 12. The 10 GeV/c data by the CERN-Orsay-Pisa Group are preliminary. One can conclude that the polarization pattern at  $|t| \leq 1.5$  (GeV/c) does not change much between 2.74 GeV/c and 10 GeV/c, and is consistent with the exchange degenerate Regge-pole picture discussed above (see Figs. 10 and 11). Similar predictions for the Kp polarization were obtained by Arnold and Logan<sup>11)</sup>, and from Dass, Michael and Phillips<sup>15)</sup>, who supplemented the high-energy data with information from FESR. Figure 13, taken from Ref. (1), shows a comparison of the 2.74 GeV/c data on both dG/dt and P<sub>0</sub> for K<sup>+</sup>p and K<sup>-</sup>p scattering with predictions derived from the model of Dass et al.<sup>15)</sup>.

## 3. pp AND pp SCATTERING

In the Regge-pole model with exchange degeneracy (assuming that no resonances exist in the pp channel) this case is similar to the Kp one, even if there are some formal complications because of the possibility of spin-flip induced by the exchanged pole at the two nucleon-nucleonpole vertices. We write as in Eq. (8):

$$T(\bar{p}p) = T_{P}^{N} + T_{f}^{N} + T_{\omega}^{N} + T_{\rho}^{N} + T_{A}^{N}$$
$$T(pp) = T_{P}^{N} + T_{f}^{N} - T_{\omega}^{N} - T_{\rho}^{N} + T_{A}^{N},$$

and again assume  $f_{\omega}$  and  $\rho A$  degeneracy, in such a way as to give a real contribution to T(pp). Thus, in a simple-minded Pauli-type formalism

$$T(\bar{p}p) \approx i \tilde{\gamma}_{p}^{N} + \left(\tilde{\gamma}_{\omega N}^{nf} + i \tilde{\gamma}_{\omega N}^{f} \vec{\sigma}_{1} \cdot \vec{n}\right) e^{-i\pi\alpha} \left(\tilde{\gamma}_{\omega N}^{nf} + \tilde{\gamma}_{\omega N}^{f} + \vec{\sigma}_{2} \cdot \vec{n}\right) s^{\alpha-1} + \rho, A \text{ contribution as for } f, \omega.$$

# For pp scattering the formula is similar but without the $e^{-i\pi\alpha}$ factor. Thus one can write

$$T(\bar{p}p) = i \tilde{\gamma}_{p}^{N} + e^{-i\pi\alpha} \left\{ \eta_{a} + i \eta_{c} (\vec{\sigma}_{1} + \vec{\sigma}_{2}) \cdot \vec{n} + \eta_{m} (\vec{\sigma}_{1} \cdot \vec{n}) (\vec{\sigma}_{2} \cdot \vec{n}) \right\} s^{\alpha-1}$$

$$T(pp) \approx i \tilde{\gamma}_{p}^{N} + \left\{ \eta_{a} + i \eta_{c} (\vec{\sigma}_{1} + \vec{\sigma}_{2}) \cdot \vec{n} + \eta_{m} (\vec{\sigma}_{1} \cdot \vec{n}) (\vec{\sigma}_{2} \cdot \vec{n}) \right\} s^{\alpha-1}$$

$$(11)$$

If the NN scattering matrix is written as

$$T(NN) = a + i c(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{n} + m(\vec{\sigma}_1 \cdot \vec{n})(\vec{\sigma}_2 \cdot \vec{n})$$
(12)

the polarization parameter is

$$P_{0} = \frac{\operatorname{Im} \left[ (a + m)c^{*} \right]}{|a|^{2} + 2|c|^{2} + |m|^{2}}$$
(13)

In our case, assuming that the (a + m) term is dominated by  $T_P^N$  and consequently mostly imaginary, one gets

$$P_{0}(\bar{p}p) \propto \sin \theta_{\bar{p}} \cdot \cos \pi \alpha \cdot S^{\alpha-1}$$

$$P_{0}(pp) \propto \sin \theta \cdot S^{\alpha-1}$$
(14)

which are similar to Eq. (10). Thus the two polarizations should have the same sign at small |t|, and  $P_0(\bar{p}p)$  should exhibit a cos  $\pi\alpha$  behaviour. A compilation of pp data<sup>16,3,4,6)</sup> is shown in Fig. 14. The 17.5 GeV/c data by the CERN-Orsay-Pisa Group are very preliminary. At  $|t| \leq 1 (\text{GeV/c})^2 P_0$  is a smooth function of t and decreases with energy, being  $\sim 4.5\%$  at 17.5 Gev/c. Something interesting might happen at  $|t| \approx 1$  GeV/c, but one needs better data (which are at the moment on the magnetic tape) to really say something about it.

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The proton-antiproton polarization data are shown in Fig. 15. The 10 GeV/c data by the CERN-Orsay-Pisa Group are preliminary. The 2.74 GeV/c data are consistent with the exchange-degenerate Regge-pole model discussed above, but at 10 GeV/c, the picture looks rather different. Thus the pp and pp polarization might provide us with some surprises, but at the moment no firm conclusion should be drawn. To clarify this situation, further data will be collected by the CERN-Orsay-Pisa Group in the near future.

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## Figure captions

- Fig. 1 : Comparison of representative  $P_0(\pi^-p)$  data at several energies between 2.74 GeV/c and 12.0 GeV/c. (Data at 2.74, 5.15, 6.0, 10.0, and 12.0 GeV/c: Refs. 1, 2, 3, 4 and 5 respectively.)
- Fig. 2 : Estimate of the variation of log P<sub>0</sub> as a function of log S (S = c.m. energy squared) at  $|t| \sim 1.5$  (GeV/c)<sup>2</sup>, from data of Fig. 1. A line with energy dependence S<sup>-1</sup> is shown for comparison.
- Fig. 3 : Comparison of representative P<sub>0</sub>(π<sup>+</sup>p) data at several energies between 2.74 GeV/c and 14.0 GeV/c. (Data at 2.74, 5.15, 6.0, 10.0, and 14.0 GeV/c: Refs. 1, 2, 3, 5, and 6 respectively.)
- Fig. 4 :  $d\sigma/dt$  for  $\pi^+ p$  and  $\pi^- p$  at 2.7 GeV/c (from Ref. 1).

Fig. 5 :  $P_0(\pi^+ p)$  and  $P_0(\pi^- p)$  at 2.74 GeV/c (from Ref. 1).

Fig. 6 :  $P_0(\pi^+ p)$  and  $P_0(\pi^- p)$  at 6.0 GeV/c (from Ref. 3).

- Fig. 7 : The target polarization orientations to measure the polarization parameters A and R by means of a measurement of the u-component of the recoil proton polarization (from Ref. 7).
- Fig. 8 : The polarization parameters A and R for  $\pi^{-}$  p scattering at 6.0 GeV/c<sup>7</sup>.
- Fig. 9 : Polarization in K<sup>+</sup>p elastic scattering (from Ref. 13), for complete exchange degeneracy.
- Fig. 10 : Polarization in K p elastic scattering (from Ref. 13), for complete exchange degeneracy.

- Fig. 11 : Representative polarization data in K<sup>+</sup>p elastic scattering at high energies. (Data at 2.74, 4.40, 6.0, and 14.0 GeV/c: Refs. 1, 14, 3, and 6, respectively.)
- Fig. 12 : Representative polarization data in K<sup>-</sup>p elastic scattering at high energies. (Data at 2.74, 6.0, and 10.0 GeV/c: Refs. 1, 3, and 4, respectively.)
- Fig. 13 :  $K^{\pm}p$  elastic scattering and polarization data at 2.74 GeV/c (from Ref. 1). The curves are predictions obtained in the model by Dass et al.<sup>15</sup>) (free curve:  $K^{\pm}p$ , dotted curve:  $K^{-}p$ ).
- Fig. 14 : Representative polarization data in pp elastic scattering at several energies between 2.74 GeV/c and 17.5 GeV/c. (Data at 2.74, 5.15, 6.0, 14.0, and 17.5 GeV/c: Refs. 1, 16, 3, 6, and 4, respectively.)
- Fig. 15 : Polarization data in pp elastic scattering at high energies. (Data at 2.74, 6.0, and 10.0 GeV/c: Refs. 1, 3, and 4, respectively.)





 $\Pi^+ - P$ POLARIZATION





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K<sup>+</sup>-P POLARIZATION





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p-p POLARIZATION







