PHYSICAL REVIEW VOLUME 177, NUMBER 5 25 JANUARY 1969

Theory of High-Energy Polarizations*

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(Received 26 August 1968)

Using Regge poles with $SU(3)$ and exchange degeneracy, a theory of all experimentally accessible polarizations arising from pole-pole interferences is presented for pseudoscalar-baryon and baryon-baryon scattering and exchange reactions with all parameters (except for one sign) determined from differential cross-section data. All available data on πp, Kp, $\bar{p}p$, and pp elastic and $\pi^+p \to K^+\Sigma^+$ polarizations are compared with this theory at the highest available energies, and many predictions are presented.

I. INTRODUCTION

HIGH-ENERGY polarizations have been successfully fitted using Regge-pole models with many adjustable parameters.[1] However, this approach has a limited appeal to many physicists, since the predictive capacity is very small. We present here a theory of polarizations, arising from interfering poles, which has no adjustable parameters except for two signs, which we may determine from two elastic polarization reactions. The two pseudoscalar-meson–baryon (P-B) reactions which have only single-pole exchange, i.e., $\pi^-p \to \pi^0 n$ and $\pi^-p \to \eta n$, would have zero polarization in our theory, and these (relatively small) values must be calculated from a more sophisticated picture, presumably including an additional pole[2] or cuts.[3]

We treat the following four classes of reactions: P-B charge exchange and hypercharge exchange; P-B elastic scattering; B-B and $\bar{B}$-B charge and hypercharge exchange; and B-B and $\bar{B}$-B elastic scattering. In each case we include the poles whose intercept $\alpha(0)$ is above zero. In the elastic cases, the Pomeranchon is taken as a fixed singularity with purely imaginary contribution to the scattering amplitude.

The trajectory functions $\alpha(t)$ are taken as straight lines passing through known mesons. The residues of poles in the same $SU(3)$ multiplet are related by $SU(3)$ Clebsch-Gordan coefficients. We use pure F coupling for the t-channel helicity-nonflip ("charge") residues $b_1 = \alpha \hat{b}_1$, and a D/F ratio of $\frac{3}{2}$ for the helicity-flip ("magnetic") residues b_2. Residues and trajectories of corresponding poles with opposite signature are related by exchange degeneracy[4] (ED). We assume that $\hat{b}_1$ and b_2 have the same t dependence; the vector trajectories choose nonsense [i.e., b_1 proportional to $\alpha(t)$] to satisfy ED.[3] This leads to polarization predictions which do not depend specifically on the t dependence of the residues.

II. P-B EXCHANGE REACTIONS

For charge-exchange reactions, such as $K^-p \to \bar{K}^0 n$ and $K^+n \to K^0 p$, ρ and A_2 trajectories contribute, while for hypercharge-exchange reactions, such as $K^-p \to \pi\Sigma$, $K^-p \to \pi^0\Lambda$, $K^-p \to \eta\Lambda$, $\pi^+p \to K^+\Sigma^+$, and $\pi^-p \to K^0\Lambda$, trajectories passing through $K^*(890)$ and $K^*(1400)$ are appropriate. The residues are factored; $b_1 = \mu C_+$ and $b_2 = \mu C_-$ for each reaction, where μ depends on the mesons and $C_\pm$ depends on the baryons.[5]

The expression for polarization in these reactions has been derived previously.[4] At high energies and small angles we obtain (see end of Sec. III of Ref. 4)

$$P(\theta) = -\sin(\pi\alpha)\frac{2x\omega}{1+x^2\omega^2}\frac{2y}{y^2+1+(y^2-1)\cos\pi\alpha}, \quad (1)$$

where $\alpha(t)$ refers to $\alpha_\rho = \alpha_{A_2}$ for charge exchange and to $\alpha_{K^*(890)} = \alpha_{K^*(1400)}$ for hypercharge exchange; $\omega \equiv (-t)^{1/2}/2\bar{M}$, where $\bar{M}$ is the mean of the incoming

TABLE I. Values of y (for octet of P mesons).

Incoming meson Outgoing meson	K^- $\bar{K}^0, K^-$	K^- π^0, π^-	K^- η	π^- π^0	π^- η
y	$+1$	$+1$	$+\frac{1}{6}$	0	∞

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] W. Rarita, R. J. Riddell, Jr., Charles B. Chiu, and R. J. N. Phillips, Phys. Rev. **165**, 1615 (1968).
[2] T. J. Gadjicar, R. K. Logan, and J. W. Moffat, Phys. Rev. **170**, 1599 (1968).
[3] R. C. Arnold and M. L. Blackmon, Phys. Rev. **176**, 2082 (1968). This paper contains references to earlier literature. The factor of α in $b_1(t)$ is needed to eliminate ghosts. This would imply, in a pure pole model, a zero in the differential cross section for $\pi^-p \to \pi^0 n$ at $\alpha=0$. However, when cuts are taken into account (at the 10 or 20% level), this zero will not appear. In fact, it is found that, when an eikonal ansatz is used to generate cuts (see Arnold and Blackmon), this zero is responsible for the crossover effect around $-t=0.30$ GeV^2.
[4] R. C. Arnold, Phys. Rev. **153**, 1506 (1967). This paper contains references to the earlier literature.
[5] From ED (see Ref. 3), $\mu(t)$ must have a factor which vanishes like $\alpha^{1/2}$ near $\alpha=0$ in order that no ghost exist in KK scattering. This requires $C_+(t)$ to have a similar factor and $C_-(t)$ (in the simplest case) to have a factor $\alpha^{-1/2}$ near $\alpha=0$.

TABLE II. Values of x (for proton target).

Outgoing baryon	N	Σ	Λ
$x/x(pn)$	1	$-1/5$	$+8/5$

and outgoing baryon masses; $x=\hat{C}_-/\hat{C}_+$ and $y=\mu_T/\mu_V$, where T and V refer to tensor (even signature) and vector (odd signature), respectively; and $C_+\equiv\alpha^{1/2}\hat{C}_+$ and $C_-\equiv\hat{C}_-/\alpha^{1/2}$.[5] It is assumed here that $C_+{}^T=C_+{}^V$, while $C_-{}^T=-C_-{}^V$. If instead $C_-{}^T=C_-{}^V$, these polarizations will be zero.

In our calculation we use approximate ρ and K^* trajectories given by

$$\alpha_\rho(t)=0.5+t\,,\quad \alpha_{K^*}(t)=0.25+t\,,$$

with t in GeV^2. Note that our expression for $P(\theta)$ in Eq. (1) is a function of t only.

Table I, taken from material in Ref. 4, gives y for a complete octet of mesons; Table II similarly gives x in terms of the value $x(pn)$ in πp scattering. $|x(pn)|$ is determined to be about 8 by the shape of the π^-p charge-exchange cross section for $|t|<0.05$ GeV^2, but the sign of $x(pn)$, which turns out to be negative, can only be determined from a polarization datum. We choose the best-known polarization, which is the πp elastic; that determination is done in Sec. III.

To obtain y values for other reactions, e.g., $\pi^+p\to K^+\Sigma^+$, observe that under line reversal ($K^-,\pi^-\to\pi^+,K^+$) y changes sign, and the y values are the same within an isospin multiplet (e.g., K^+, K^0). Similarly, x values for neutron target are the same as the values tabulated for proton target, in allowed reactions; x is the same within an isospin multiplet.

Among reactions in this class with predicted nonzero polarization, data are available at present only on $\pi^+p\to K^+\Sigma^+$ at 3.25 GeV.[6]

In Fig. 1 we compare our prediction with these data.[6] This prediction will also hold at higher energies. The polarization for $K^-p\to\pi^-\Sigma^+$, on the other hand, is predicted to be just the opposite of this. In Figs. 2(a) and 2(b), we have shown our predictions for $\pi^-p\to K^0\Lambda$ and $K^-p\to\bar{K}^0n$, respectively. If $C_-{}^T=C_-{}^V$ (instead of $-C_-{}^V$), all these polarizations will be zero in pole approximation, and must be estimated by another model.[3]

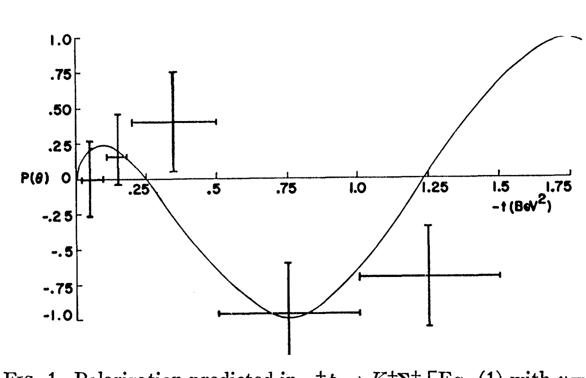

FIG. 1. Polarization predicted in $\pi^+p\to K^+\Sigma^+$ [Eq. (1) with $y=1$ and $x=-1.6$], with available data at 3.24 GeV/c from Ref. 6.

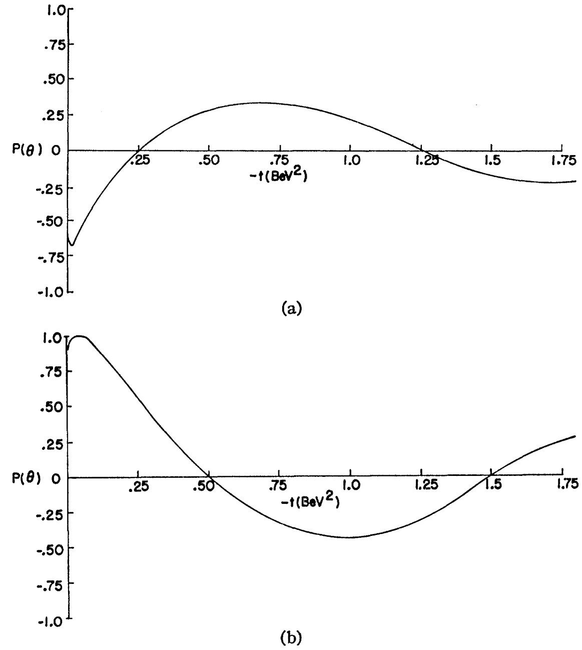

FIG. 2. (a) $\pi^-p\to K^0\Lambda$ predicted polarization. (b) $K^-p\to\bar{K}^0\,n$ predicted polarization.

III. *P-B* ELASTIC SCATTERING

Starting with the f (nonflip) and $\tilde{f}$ (flip) amplitudes of Frautschi *et al.*,[7] we define $\hat{f}=(w/m)f$; expressing these in terms of our poles, we have, in π^-p elastic scattering at high energies,

$$\hat{f}^\pi\cong i\beta_\pi(t)\,,$$

$$\tilde{f}^\pi=\frac{\alpha(\hat{b}_1{}^\rho-b_2{}^\rho)}{\sqrt{2}}\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1-e^{-i\pi\alpha}}{\sin\pi\alpha}\,,$$

where we have kept only the dominant (Pomeranchon) contribution to $\hat{f}$. We consistently assume that the exchanged $I=0$ poles have no helicity-flip contributions. The $\pi^-p\to\pi^0n$ amplitudes are

$$\hat{f}_{\text{c.e.}}{}^\pi=\alpha\hat{b}_1{}^\rho\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1-e^{-i\pi\alpha}}{\sin\pi\alpha}\,,$$

$$\tilde{f}_{\text{c.e.}}{}^\pi=\sqrt{2}\tilde{f}\,.$$

We define

$$R_\pi\equiv\frac{(d\sigma/dt)_{\text{c.e.}}{}^{1/2}}{(d\sigma/dt)_{\text{el}}{}^{1/2}}$$

[6] R. R. Kofler, R. W. Hartung, and D. D. Reeder, Phys. Rev. **163**, 1479 (1967).

[7] S. C. Frautschi, M. Gell-Mann, and F. Zachariasen, Phys. Rev. **126**, 2204 (1962).

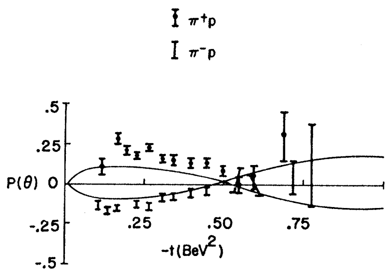

FIG. 3. Polarization in $\pi^\pm p$ elastic scattering at 6 GeV/c; asymptotic theory [Eq. (2)] and experiment (Ref. 8).

(which, for consistency, should be much less than unity). Then the elastic π^-p polarization can be expressed in terms of R using

$$P_{\pi^-}(\theta)=-2\omega\,\mathrm{Im}(\tilde{f}^*\hat{f})/(|\hat{f}|^2+\omega^2|\tilde{f}|^2),$$

which yields

$$P_{\pi^-}(\theta)=-\sqrt{2}\left(\frac{(\hat{b}_1-b_2)\omega}{[\hat{b}_1^2+\omega^2(\hat{b}_1-b_2)^2]^{1/2}}\right)R_\pi\sin(\tfrac{1}{2}\pi\alpha)$$

$$=-\sqrt{2}\sin(\tfrac{1}{2}\pi\alpha)R_\pi\left(\frac{(1-x)\omega}{[1+\omega^2(1-x)^2]^{1/2}}\right). \quad (2)$$

With $|t|\geq 0.05\ \mathrm{GeV}^2$, the magnitude of the expression in brackets is very close to unity. [Note also that $\sqrt{2}\sin(\frac{1}{2}\pi\alpha)\cong 1$ for small $|t|$.] The observation that the sign of the π^-p polarization is negative[8] leads to the conclusion that $x(pn)=b_2^\rho/\hat{b}_1^\rho$ is negative. [It is known that $\hat{b}_1^\rho$ is positive, since $\sigma_T(\pi^-p)>\sigma_T(\pi^+p)$.] The π^+p polarization is the negative of π^-, since the ρ contribution changes sign.

In Figs. 3 and 4 we compare this prediction with data at 6 and 10 GeV/c, taking R_π from experiment. The magnitude of our prediction is consistently less than that from experiment. This agreement can be improved by taking into account the fact that $\hat{f}^\pi$ has a small negative real part, presumably coming from P', which decreases with energy. Additional discrepancies could be due to effects[2,3] similar to those giving the nonzero πp charge-exchange polarization.

Turning to K^-p elastic scattering, including A_2 in the flip contribution, we have

$$\hat{f}^K\cong i\beta_K(t),$$

$$\tilde{f}^K=\alpha(\hat{b}_1^\rho-b_2^\rho)\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1-e^{-i\pi\alpha}}{\sin\pi\alpha}+\alpha(\hat{b}_1^A-b_2^A)\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1+e^{-i\pi\alpha}}{\sin\pi\alpha}.$$

Note that we do not assume $SU(3)$ for the Pomeranchon; $\beta_K\neq\beta_\pi$.

[8] M. Borghini *et al.*, Phys. Letters **24B**, 77 (1966).

For $K^-p\to\bar{K}^0n$ we have the same $\tilde{f}$, but the nonflip $\hat{f}$ is given by

$$\hat{f}_{\mathrm{c.e.}}{}^K=\alpha\hat{b}_1^\rho\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1-e^{-i\pi\alpha}}{\sin\pi\alpha}+\alpha\hat{b}_1^A\left(\frac{s}{s_0}\right)^{\alpha-1}\frac{1+e^{-i\pi\alpha}}{\sin\pi\alpha}.$$

We define R_K, analogous to R_π, by

$$R_K\equiv\left(\frac{(d\sigma/dt)_{K^-p\to\bar{K}^0n}}{(d\sigma/dt)_{K^-p\to K^-p}}\right)^{1/2}.$$

Using ED assumptions $b_1^A=-b_1^\rho$ and $b_2^A=+b_2^\rho$, the former appropriate to $\bar{K}N$, we obtain

$$P_{K^-}(\theta)=2R_K\frac{\omega(\cos\pi\alpha+x)}{[1+\omega^2(1+x^2+2x\cos\pi\alpha)]^{1/2}}. \quad (3)$$

For $|t|>0.05\ \mathrm{GeV}^2$, the denominator term proportional to the numerator dominates and $P_{K^-}\approx 2R_K$. The K^+p polarization is obtained similarly, but in that case $b_1^A=+b_1^\rho$ and $b_2^A=-b_2^\rho$ (line-reversed reaction). This yields

$$P_{K^+}(\theta)=2R_K\frac{\omega(1+x\cos\pi\alpha)}{[1+\omega^2(1+x^2+2x\cos\pi\alpha)]^{1/2}}. \quad (4)$$

Thus, for $|t|>0.05\ \mathrm{GeV}^2$, $P_{K^+}\cong\cos(\pi\alpha)P_{K^-}$.

These expressions, based on the choice of opposite signs for b_2^A/b_2^ρ compared to the b_1 ratio, were compared with K^- data[9] at 2.4 GeV/c, which is the highest momentum presently available. We found the wrong sign.

If we reverse this choice, i.e., choose $b_2^A\equiv-b_2^\rho$ in K^-p scattering, we obtain an interchange of formulas (3) and (4) together with an over-all change in sign, so $P_{K^-}\approx+2R_K$. We then obtain the agreement shown in Fig. 5. An extrapolation of R_K evaluated from experiment at higher energies is used. Since the available data is at low energy, both for this and for PB exchange-reaction polarizations, we are not yet able to conclude in favor of one of the sign choices; but one will be picked out when higher-energy data becomes available.

IV. B-B AND $\bar{B}$-B EXCHANGE REACTIONS

We take our formalism from Sharp and Wagner[10] (SW), with the altered notation $(\alpha^{1/2}C_+,\alpha^{-1/2}C_-)$ for the

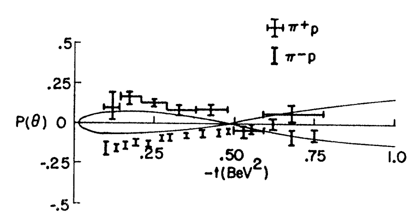

FIG. 4. Same as Fig. 3, at 10 GeV/c.

[9] C. Daum, F. Erné, J. P. Lagnaux, J. C. Sens, M. Steuer, and F. Udo, Nucl. Phys. **B6**, 273 (1968). See also Ref. 11.

[10] D. H. Sharp and W. G. Wagner, Phys. Rev. **131**, 2226 (1963).

factors[5] of the pole residues which are written (b_1,b_2) in their paper. Thus we have (for V and T separately, and for each baryon), for B-B processes,

$$\eta=(C_+ + \omega^2 C_-)\alpha^{1/2}$$

and

$$\phi=\omega(C_+ - C_-)\alpha^{1/2}.$$

The signature factors are

$$\zeta_{T,V}\equiv(1\pm e^{-i\pi\alpha})/2\sin\pi\alpha.$$

Then, for two-pole reactions [e.g., exchange reactions] where the poles are exchange-degenerate,

$$4\pi\frac{d\sigma}{dt}=[|\zeta_V|^2(\eta_V{}^2+\phi_V{}^2)^2+|\zeta_T|^2(\eta_T{}^2+\phi_T{}^2)^2]\times\left(\frac{s}{s_0}\right)^{2\alpha-2} \quad (5)$$

and

$$4\pi P\frac{d\sigma}{dt}=2\,\mathrm{Im}(\zeta_V{}^*\zeta_T)(\eta_V\eta_T+\phi_V\phi_T)(\phi_V\eta_T-\phi_T\eta_V)\times\left(\frac{s}{s_0}\right)^{2\alpha-2}. \quad (6)$$

These yield, after substituting $C_+{}^T=C_+{}^V$ and $C_-{}^T=-C_-{}^V$ (as in P-B reactions),

$$P_B(\theta)=\sin(\pi\alpha)\frac{2x\omega}{1+x^2\omega^2}\frac{1-x^2\omega^2}{1+x^2\omega^2}, \quad (7)$$

where x is the same as in the P-B reactions. Unfortunately, we do not yet have any data on such reactions, but we illustrate our prediction for n-p charge exchange in Fig. 6. This is the only experimentally accessible B-B exchange reaction allowed in our theory.

For $\bar{B}$-B exchange reactions, we change the sign of the vector terms in the polarization, yielding (at asymptotic energies where $R_{\bar{B}}=R_B$)

$$P_{\bar{B}}(\theta)=-P_B(\theta). \quad (8)$$

This refers to $\bar{p}p\to n\bar{n}$ and, with the appropriate x values, to $p\bar{p}\to\Lambda\bar{\Lambda}$ and $p\bar{p}\to\Sigma\bar{\Sigma}$.

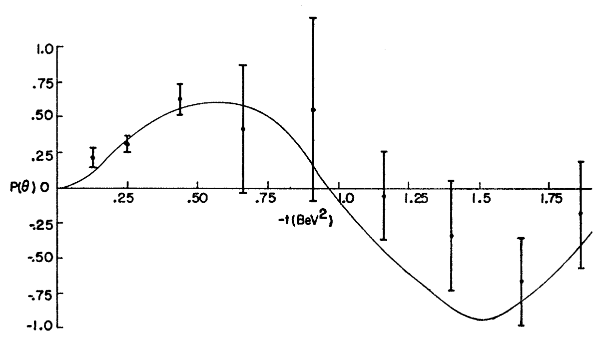

FIG. 5. Polarization in K^-p elastic scattering at 2.4 GeV/c; asymptotic theory versus experiment (Ref. 9).

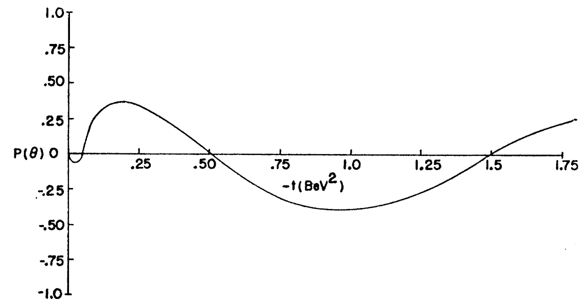

FIG. 6. Predicted polarization in np charge exchange [Eq. (7)].

With the other choice for $C_-{}^T/C_-{}^V$, polarizations vanish in pole approximation, as in P-B reactions.

V. B-B AND B-$\bar{B}$ ELASTIC SCATTERING

Again we use SW,[10] with the addition of a Pomeranchon pole P which has $b_{2p}=0$ and $\alpha_p=1$. (We emphasize again the feature that our theory should apply uniformly only to asymptotically high energy, since we ignore the effects of ω and P' relative to P.) Let $\beta_P=(b_{1p})^2$. Then

$$4\pi(d\sigma/dt)_{\rm el}\cong\tfrac{1}{4}\beta_p{}^2(t)(1+\omega^2)^2.$$

We examine the cross sections $pn\to np$ (or $\bar{p}p\to\bar{n}n$):

$$4\pi\left(\frac{d\sigma}{dt}\right)_{\rm c.e.}=\left(\frac{\alpha}{\sin\pi\alpha}\right)^2\left(\frac{s}{s_0}\right)^{2\alpha-2}\times(C_+{}^\rho)^4(1+\omega^2)^2(1+\omega^2x^2)^2, \quad (9)$$

and define

$$R_B\equiv\frac{(d\sigma/dt)_{\rm c.e.}{}^{1/2}}{(d\sigma/dt)_{\rm el}{}^{1/2}}.$$

Now from SW, keeping only terms linear in the Pomeranchon and using ED for p-p scattering as in Sec. IV, using $C_-{}^T=-C_-{}^V$,

$$4\pi P\left(\frac{d\sigma}{dt}\right)_{\rm el}\cong\cot(\pi\alpha)\left(\frac{s}{s_0}\right)^{\alpha-1}\omega\alpha\beta_p C_+{}^V C_-{}^V(1+\omega^2)^2,$$

whence, for pp scattering,

$$P_p=\cot(\pi\alpha)\frac{4\alpha C_+{}^V C_-{}^V\omega}{\beta_p}\left(\frac{s}{s_0}\right)^{\alpha-1}.$$

Utilizing the definition of R_B, we obtain, finally, with $x=x(pn)$,

$$P_p=-\cos(\pi\alpha)\frac{2x\omega}{1+\omega^2x^2}R_B. \quad (10)$$

Note that $x(pn)$ is negative; thus P_p is positive, for small $-t$.

This prediction holds for pp elastic polarization. For pn elastic polarization, the ρ and A_2 both change sign,

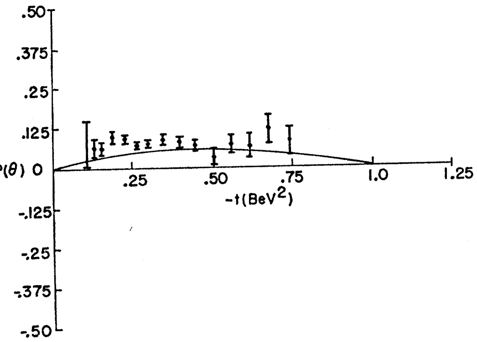

FIG. 7. Polarization in pp elastic scattering at 10 GeV/c; asymptotic theory [Eq. (10)] versus experiment (Ref. 8).

while the P does not; thus we obtain the negative of this.

Our results for pp polarization are compared in Fig. 7 with data[8] at 10 GeV/c.

Finally, we consider $\bar{B}B$ elastic scattering. The results can be obtained from BB by line reversal; the vector (ρ) terms change sign, but the tensor (A_2) and P do not. The result is

$$P_{\bar{B}}=\frac{-2\omega x}{1+\omega^2x^2}R_{\bar{B}} \tag{11}$$

for $\bar{p}p$ scattering, which has the *same* sign as pp, for small $-t$. (The x here refers to the baryon.) The only accessible scatterings are $\bar{p}p$ and $\bar{p}n$; the latter polarization is predicted to be the negative of $\bar{p}p$.

The available data[11] on $\bar{p}p$ polarization near 3 GeV are compared with our prediction in Fig. 8. The value of $R_{\bar{B}}$ here was R_B, taken from $pn\to np$ and $pp\to pp$; using data directly for $p\bar{p}\to n\bar{n}$ and $p\bar{p}\to p\bar{p}$ yields a polarization which is too large by a factor of 3–5. We interpret this as a stronger influence of nonasymptotic (absorptive) effects in the $p\bar{p}$ system; the poles are cleaner in pp and pn.

With the alternate choice for $C_-{}^T/C_-{}^V$, the formulas for pp and $\bar{p}p$ are interchanged; qualitative agreement remains.

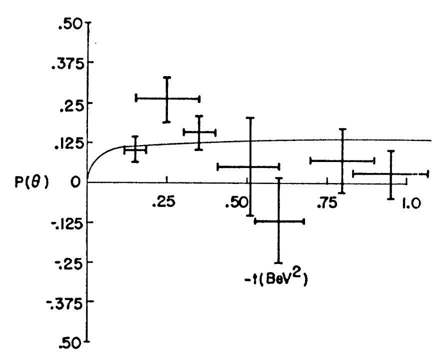

FIG. 8. Polarization in $\bar{p}p$ elastic scattering near 3 GeV/c; asymptotic theory [Eq. (11)] versus experiment (Ref. 11).

[11] C. Daum, F. Erné, J. P. Lagnaux, J. C. Sens, M. Steuer, and F. Udo, in *Proceedings of the Heidelberg International Conference on Elementary Particles*, edited by H. Filthuth (Wiley-Interscience Publishers, Inc., New York, 1968), pp. 169–170.

VI. CONCLUDING REMARKS

Several features should be remarked upon. The polarization in KN and NN processes in our theory is due mainly to the A_2 trajectory, not ω, as in other models.[1] This means, for example, that we predict the $\bar{p}p$ and pp polarizations to have the same sign, and similarly with K^+p and K^-p elastic scattering.

There should be a ratio between asymptotic elastic pp and $\bar{p}p$ polarizations given by $\cos(\pi\alpha)$ [or $\sec(\pi\alpha)$, if the alternate sign for $C_-{}^T/C_-{}^V$ is found]. Similarly, approximately such a ratio should connect asymptotic K^-p and K^+p elastic polarizations, for $|t|\gtrsim 0.05$ GeV^2.

In BB and $\bar{B}B$ reactions, we have ignored trajectories with intercepts below the K^*, which means that we do not take π exchange into account. We have assumed that this can be justified at nonasymptotic energies for $|t|\gtrsim 0.05$ GeV^2, since the pion contribution (together with possible conspiracy contributions) should drop off rapidly with increasing t. This assumption is supported, in BB processes, by the verification that the cross section given by (9), with constants $C_\pm$ and s_0 taken from π^-p charge exchange and ρ universality, gives a good fit to np data at 8 GeV/c expect for the region $|t|<0.05$ GeV^2. However, it does not work in $p\bar{p}\to n\bar{n}$ at 9 GeV/c; thus we would not suggest the reliability of our predictions for $B\bar{B}$ exchange reactions until a much higher energy is reached where $(d\sigma/dt)(p\bar{p}\to n\bar{n}) = (d\sigma/dt)(pn\to np)$ in some appreciably large region of momentum transfer.

In our simple-minded approach we have also ignored the possibility of the type of effect, whether it be due to cuts[3] or additional poles,[2] that causes nonzero π-p charge-exchange polarization. We are therefore not making *precise* predictions. We do feel, however, that high-energy polarizations should in general follow the structure that we have indicated.

ACKNOWLEDGMENT

One of the authors (R. K. L.) wishes to thank Professor K. C. Wali for his hospitality during the author's stay at Argonne National Laboratory.