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HIGH ENERGY POLARIZATION EXPERIMENTS
AND REGGE POLES

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Please make the following corrections on subject report.

Abstract page reads: "William Rarita." It should read "William Rarita‡".

Page 16, line 10 from bottom reads: ". . . ρ and A_z . . ." It should read ". . . ρ and A_2 . . ."

Page 17, line 2 reads: "ρ, A_z . . ." It should read "ρ, A_2 . . ."

Page 18, line 4 reads: ". . useful for measing. . ." It should read ". . useful for measuring. . ."

Research and Development

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HIGH ENERGY POLARIZATION EXPERIMENTS AND REGGE POLES

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June 10, 1965

HIGH ENERGY POLARIZATION EXPERIMENTS AND REGGE POLES*

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June 10, 1965

ABSTRACT

This report reviews various types of high-energy polarization measurement, and their relation to Regge pole models. Illustrations are given.

I. INTRODUCTION

This is a review of various types of polarization experiment at high energy, that may be performed, now or in the future, and the types of prediction that Regge pole models make. We hope it will focus attention on certain properties of these models and stimulate experiments.

Specifically we consider πN, KN, $\bar{K}N$, NN and $\bar{N}N$ scattering, and polarization tensors of the first and second ranks only. The experiments may not all be feasible in the near future, but at least they are not unthinkable.

The polarization formalism is given in §2. General qualitative properties of Regge pole models and their experimental implications are described in §3. Illustrations are given. § 4 contains some conclusions.

2. POLARIZATION FORMALISM

We shall be concerned with spin-0 and spin-$\frac{1}{2}$ particles only.[1]

The spin state of a spin-$\frac{1}{2}$ particle is conveniently described by going to its rest-frame, where a two-dimensional spinor is sufficient. This approach leads to a formalism that looks non-relativistic, in the sense that no γ-matrices appear; however, Stapp[2] has shown that it is completely general. Relativistic effects enter explicitly at two points; in the relations between lab and c.m. angles, and in a rotation of spin co-ordinates when the appropriate rest frame is redefined between two scatterings.[2]

The c.m. scattering amplitude M is a matrix in spin space. For πN, KN or $\bar{K}N$ scattering with given isospin, M is a 2×2 matrix ; the most general form consistent with parity conservation is

$$M = g + i\, h\, \underset{\sim}{\sigma} \cdot \underset{\sim}{N} \tag{1}$$

where $\underset{\sim}{N}$ is a unit vector normal to the scattering plane; $\underset{\sim}{\sigma}$ is the Pauli spin operator for the nucleon; g and h are scalar coefficients depending on energy and scattering angle (but not on azimuth). It is implied that g is multiplied by the unit operator in spin space.

For NN or $\bar{N}N$ scattering with given isospin, M is a 4×4 matrix. The most general form consistent with parity

conservation, charge conjugation and time-reversal invariance, and charge independence, may be written.

$$M = a + i\, c(\underset{\sim}{\sigma}^{(1)} + \underset{\sim}{\sigma}^{(2)})\cdot\underset{\sim}{N} + m\, \underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{N}\underset{\sim}{\sigma}^{(2)}\cdot\underset{\sim}{N} + (g+h)\, \underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{P}\underset{\sim}{\sigma}^{(2)}\cdot\underset{\sim}{P} + (g-h)\, \underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{K}\, \underset{\sim}{\sigma}^{(2)}\cdot\underset{\sim}{K} \tag{2}$$

Here $\underset{\sim}{\sigma}^{(1)}$ and $\underset{\sim}{\sigma}^{(2)}$ are the Pauli spin operators for the two particles ; a, c, m, g and h are scalar functions of energy and scattering angle; $\underset{\sim}{N}, \underset{\sim}{P}$ and $\underset{\sim}{K}$ are a right-handed triad of unit vectors, defined in the directions $\underset{\sim}{p}_i \times \underset{\sim}{p}_f$, $\underset{\sim}{p}_i + \underset{\sim}{p}_f$, $\underset{\sim}{p}_f - \underset{\sim}{p}_i$, where $\underset{\sim}{p}_i$ and $\underset{\sim}{p}_f$ are the initial and final c.m. momenta of particle 1.

In what follows it will be convenient to use $\underset{\sim}{N}, \underset{\sim}{P}$ and $\underset{\sim}{K}$ as axes of reference, and denote components with respect to these axes by subscripts: $\underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{N} = \sigma_N^{(1)}$, etc

Consider a monoenergetic beam incident upon a target, and let the initial polarization of the system be described by a density matrix ρ_i . After scattering through some angle the final density matrix ρ_f depends on M and is given by

$$\rho_f = M\rho_i M^+ \quad . \tag{3}$$

If intensity alone is measured after scattering, we have the differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_f = \text{trace } \rho_f/\text{trace } \rho_i = \text{trace } M\rho_i M^+/\text{trace } \rho_i \,. \tag{4}$$

If the expectation value of some spin variable ξ is measured, we have

$$\langle\xi\rangle_f = \text{trace } \rho_f \xi/\text{trace } \rho_f \,, \tag{5}$$

$$\therefore \langle\xi\rangle_f \left(\frac{d\sigma}{d\Omega}\right)_f = \text{trace } M\rho_i M^+ \xi/\text{trace } \rho_i \,. \tag{6}$$

Thus experiments essentially measure quantities of the form

$$\text{trace } M\, x\, M^+ y \,, \tag{7}$$

where x and y are spin operators (including the unit operator) referring to some aspect of initial polarization and final analysis, respectively.

Let us take some practical examples.

i) No initial polarization, final intensity measured; $\rho_i = 1$, $\xi = 1$. This gives the unpolarized cross section which we shall denote by I_o :

$$I_o = \left(\frac{d\sigma}{d\Omega}\right)_o = \text{trace } MM^+/\text{trace } 1 \tag{8}$$

(ii) No initial polarization, final polarization of particle 1 measured; $\rho_i = 1$, $\xi = \underset{\sim}{\sigma}^{(1)}$.

$$I_o\langle \underset{\sim}{\sigma}^{(1)}\rangle_f = \text{trace } MM^+\underset{\sim}{\sigma}^{(1)}/\text{ trace } 1 \quad . \tag{9}$$

Parity conservation, incorporated in M, constrains $\langle \underset{\sim}{\sigma}^{(1)}\rangle$ to be normal to the scattering plane: $\langle \underset{\sim}{\sigma}^{(1)}\rangle_f = P(\theta)\,\underset{\sim}{N}$. $P(\theta)$ is known as the polarization parameter; it can also be measured in an experiment where one particle is initially polarized and an asymmetry in the cross section is measured, essentially the time-reverse of the present case.

iii) Particle 1 has initial polarization $\underset{\sim}{\mathcal{P}}$, and its final polarization is measured in some direction $j; \rho_i = 1 + \underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{\mathcal{P}}$, $\xi = \sigma_j^{(1)}$. The final polarization contains a term depending on the initial polarization through the "depolarization tensor" $D_{kj}(\theta)$:

$$\langle \sigma_j^{(1)}\rangle_f \left(\frac{d\sigma}{d\Omega}\right)_f = \text{trace } M(1+\underset{\sim}{\sigma}^{(1)}\cdot\underset{\sim}{\mathcal{P}})\, M^+\sigma_j^{(1)}/\text{trace } 1 \tag{10}$$

$$= I_o \left\{ P(\theta)N_j + D_{kj}(\theta)\mathcal{P}_k \right\} \quad . \tag{11}$$

With respect to the axes $\underset{\sim}{N}, \underset{\sim}{P}$ and $\underset{\sim}{K}$ the tensor D_{kj} simplifies: $D_{NK} = D_{KN} = D_{NP} = D_{PN} = 0$ and $D_{PK} = -D_{KP}$. The component D_{NN} is the so-called "depolarization parameter" $D(\theta)$; the other components appear in various combinations in the so-called "rotation parameters" $R(\theta)$, $A(\theta)$, $R'(\theta)$, $A'(\theta)$.

For the "R" experiment, the incident beam is polarized transversely and in the plane of scattering, while the scattered beam is also analyzed transversely in the scattering plane. For the "A" experiment, the incident beam is polarized longitudinally, but is analyzed as before. Thus the initial polarizations are in the directions $\underset{\sim}{P} \sin\frac{\theta}{2} + \underset{\sim}{K} \cos\frac{\theta}{2}$ and $\underset{\sim}{P} \cos\frac{\theta}{2} - \underset{\sim}{K} \sin\frac{\theta}{2}$, respectively, where θ is the c.m. scattering angle, (See Fig. 1). However, because of the two relativistic effects mentioned earlier,[2] the effective direction of analysis is not $\underset{\sim}{K}$ but rather $\underset{\sim}{K} \cos\left(\frac{\theta}{2} - \theta_L\right) - \underset{\sim}{P} \sin\left(\frac{\theta}{2} - \theta_L\right)$, where θ_L is the Lab scattering angle. Hence

$$R = \tfrac{1}{2}(D_{KK} + D_{PP})\cos(\theta-\theta_L) + \tfrac{1}{2}(D_{KK} - D_{PP}) \cos\theta_L + D_{PK} \sin(\theta-\theta_L) \qquad (12)$$

$$A = -\tfrac{1}{2}(D_{KK} + D_{PP}) \sin(\theta-\theta_L) - \tfrac{1}{2}(D_{KK} - D_{PP}) \sin\theta_L + D_{PK} \cos(\theta-\theta_L) \qquad (13)$$

For these experiments it may be more practical to polarize the target rather than the beam, and to analyze the recoil polarization. Let $\underset{\sim}{p}_i, \underset{\sim}{p}_f, \underset{\sim}{P}, \underset{\sim}{K}$ and θ be defined relative to the fast particle, and label the c.m. and Lab recoil angles by ϕ and ϕ_L, as shown in Figure 2. Then analogous R and A experiments can be defined, with initial polarizations in the directions $-\underset{\sim}{K} \sin\frac{\phi}{2} - \underset{\sim}{P} \cos\frac{\phi}{2}$ and $\underset{\sim}{K} \cos\frac{\phi}{2} - \underset{\sim}{P} \sin\frac{\phi}{2}$ respectively. With the geometry shown in Fig. 2, the effective direction of polarization analysis is $\underset{\sim}{K} \sin\left(\frac{\phi}{2} - \phi_L\right) - \underset{\sim}{P} \cos\left(\frac{\phi}{2} - \phi_L\right)$. Hence

$$R_{recoil} = \tfrac{1}{2}(D_{KK} + D_{PP})\cos(\phi - \phi_L) + \tfrac{1}{2}(D_{PP} - D_{KK})\cos\phi_L - D_{PK}\sin(\phi - \phi_L) \qquad (14)$$

$$A_{recoil} = \tfrac{1}{2}(D_{KK} + D_{PP})\sin(\phi - \phi_L) + \tfrac{1}{2}(D_{PP} - D_{KK})\sin\phi_L + D_{PK}\cos(\phi - \phi_L) \qquad (15)$$

Experiments to find R' and A' require the measurement of longitudinal polarization: we shall not discuss them here.

iv) Suppose particle 1 has initial polarization $\underset{\sim}{\mathcal{P}}$, and the final polarization of the <u>other</u> particle is measured in some direction j. This is like case (iii) above, except that D_{kj} is now replaced by a "polarization transfer" tensor K_{kj} :

$$\langle \sigma_j^{(1)} \rangle_f \left(\frac{d\sigma}{d\Omega}\right)_f = \text{trace } M\left(1 + \underset{\sim}{\sigma}^{(1)} \cdot \underset{\sim}{\mathcal{P}}\right) M^{+} \sigma_j^{(2)} / \text{trace } 1 \ , \qquad (16)$$

$$= I_o \left\{ P(\theta) N_j + K_{kj}(\theta)\, \mathcal{P}_k \right\} . \qquad (17)$$

The tensor K_{kj} simplifies, just like D_{kj}, with respect to the axes $\underset{\sim}{N}$, $\underset{\sim}{P}$ and $\underset{\sim}{K}$. The component K_{NN} is directly measureable by polarizing and analyzing normal to the scattering plane. The other components appear in various analogues of the R, A, R' and A' experiments that may be defined. We shall not discuss them in detail, however, since they prove to have no interest in the present context.

v) Suppose there is no initial polarization, and the polarization of particles 1 and 2 are analyzed in <u>coincidence</u> in directions k and j ; $p_i = 1$, $\xi = \sigma_k^{(1)} \sigma_j^{(2)}$. This experiment measures the spin correlation tensor C_{kj} :

$$I_o \langle \sigma_k^{(1)} \sigma_j^{(2)} \rangle = \text{trace } MM^{+} \sigma_k^{(1)} \sigma_j^{(2)} / \text{trace } 1 \tag{18}$$

$$= I_o \; C_{kj}(\theta) \tag{19}$$

With respect to the axes $\underset{\sim}{N}, \underset{\sim}{P}$ and $\underset{\sim}{K}$, C_{kj} simplifies ; $C_{NP} = C_{PN} = C_{NK} = C_{KN} = 0$; $C_{KP} = C_{PK}$. The component C_{NN} is immediately measureable. The others normally occur in various combinations; however, they prove to have no interest in the present context. The spin-correlation tensor can also be found by polarizing both particles initially and measuring the final intensity--essentially the time reverse of case (v).

The experiments described above are these in which at most two polarizations occur (either initially or finally). We shall not discuss more complicated possibilities.

For spin-0 scattering on spin-$\frac{1}{2}$ particles, the experimental quantities can be written in terms of the M-matrix coefficients as follows (see Eq. (1)):

$$\begin{aligned}
I_o(\theta) &= |g|^2 + |h|^2 \;, \\
I_o P(\theta) &= 2 \, \mathrm{Im}(h^* g) \;, \\
I_o D_{KK}(\theta) &= I_o D_{PP}(\theta) = |g|^2 - |h|^2 \;, \\
I_o D_{KP}(\theta) &= -I_o D_{PK}(\theta) = 2 \, \mathrm{Re}(g^* h) \;, \\
D_{NN}(\theta) &= 1 \;,
\end{aligned} \tag{20}$$

All other components vanish. The tensors K_{kj} and C_{kj} are of course not defined when only one particle has spin.

The corresponding relations for two spin-$\frac{1}{2}$ particles are more complicated. However, it turns out that Regge pole models based on the leading trajectories give a simpler form for the M-matrix than Eq.(2): in fact, only the coefficients a, c and m remain. Using this special form, the expressions for physical quantities simplify enormously, and we find

$$
\begin{aligned}
I_o(\theta) &= |a|^2 + 2|c|^2 + |m|^2 \\
I_o P(\theta) &= 2\ \mathrm{Im}\ c^*(a + m) \\
D_{NN}(\theta) &= 1 \\
I_o D_{KK}(\theta) &= I_o D_{PP}(\theta) = |a|^2 - |m|^2 \\
I_o D_{KP}(\theta) &= -I_o D_{PK}(\theta) = 2\ \mathrm{Re}\ c^*(a-m) \\
I_o K_{NN}(\theta) &= I_o C_{NN}(\theta) = 2\ \mathrm{Re}\ am^* + 2\ |c|^2
\end{aligned}
\tag{21}
$$

All other components vanish. In particular, notice that the tensors K_{kj} and C_{kj} have only one non-trivial component, which is the same for both.

III. REGGE POLE MODELS

For the scattering of two spinless particles, a Regge pole in the crossed channel gives asymptotically a contribution to the scattering amplitude of the form,[3]

$$M = -\sqrt{s}\ \beta(t)\left[\frac{1 \pm \exp(-i\pi\alpha(t))}{2\sin\pi\alpha(t)}\right]\left(\frac{s}{s_o}\right)^{\alpha(t)-1} \tag{22}$$

Here s is the invariant square of total energy, t is the invariant square of momentum transfer, s_o is a scale constant, $\alpha(t)$ is the trajectory of the Regge pole and $\beta(t)$ is related to the residue at the pole. Both α and β are supposed to be real in the scattering region; thus the phase of the amplitude comes from the "signature factor" (in square braces). The signature $\pm$ determines whether the particles associated with the trajectory have even (+) or odd (-) spin. Contributions like Eq. (22) are additive.

For forward πN scattering (and for spin-0 on spin-$\frac{1}{2}$ in general) there are similar contributions to both the scalar amplitudes g and h which appear in M. In the high-energy approximation of Wagner,[4] and using his notation, we find the following contribution from a Regge pole labelled i :

$$M^i = -\frac{\sqrt{s}}{4\pi}\ \zeta_i\left(\frac{s}{s_{oi}}\right)^{\alpha_i-1}\ \eta_{\pi i}(\eta_{Ni} - i\ \underset{\sim}{\sigma}\cdot\underset{\sim}{N}\ \phi_{Ni})\ . \tag{23}$$

Here ζ_i is an abbreviation for the signature factor. The residue function is explicitly factored into a part $\eta_{\pi i}$ referring to the pion and a part, η_{Ni} or ϕ_{Ni}, referring to the nucleon. We have normalized M to correspond to the formulae in § 2.

For forward N-N scattering (and for spin-$\frac{1}{2}$ on spin-$\frac{1}{2}$ in general), the form of the contribution depends on the quantum numbers of the Regge pole. However, for the trajectories which correspond to 0^+, 2^+... and 1^-, 3^-,... particles (which appear to include all the leading trajectories of most physical importance), each contribution to M has the form

$$M^i = -\frac{\sqrt{s}}{4\pi}\, \zeta_i \left(\frac{s}{s_{oi}}\right)^{\alpha_i - 1} \left[\eta_{Ni} - i\, \underset{\sim}{\sigma}\cdot\underset{\sim}{N}\, \phi_{Ni}\right]^2 . \qquad (24)$$

Here again the residue function factors into two parts (in this case equal). Note that only the coefficients a, c and m appear, so that the simplified expressions in Eq. (21) are relevant.

Strictly speaking, Eqs. (23) and (24) describe the contributions of a Regge pole with vacuum quantum numbers. In general, there is a $\pm$ sign and sometimes a Clebsch-Gordon coefficient, depending on the particular process in question, the isospins of the particles, and the quantum numbers of the Regge pole. These details do not affect the present discussion. The Wagner formulae are asymptotic, in the sense that they retain only terms with the leading energy dependence. Thus it may be that in the 10-20 GeV region some of the terms omitted are not completely negligible.

However, we only require them as a qualitative guide, and as such they should not be misleading.

It is a simple matter to derive expressions for physical quantities in terms of Wagner's parameters, using the formulae above. We shall not write them out. (Incidentally, it seems that reference 4 uses the opposite sign convention for P).

The Regge pole contributions (23) and (24) have two important properties:[5] (i) the spin-dependent and spin-independent terms from a given pole have the same energy dependence; (ii) these terms also have the same phase.

Let us discuss some consequences for various processes.

<u>πN, KN and $\overline{K}N$ elastic scattering.</u>

Point (i) implies that there may exist non-trivial spin dependence even in the asymptotic region. In contrast, one does not expect such behavior in a diffraction picture of scattering.[6]

We must be careful, however, what we mean by the absence of spin dependence. In the formalism we have been using, the natural definition seems to be the absence of σ-matrices in M. This definition, which we label (a), is equivalent to

$$\phi_{Ni} = 0 \tag{25a}$$

On the other hand, if we consider the relativistic T-matrix referred to Dirac spinors, the natural definition is the absence of

γ-matrices; we label this (b); it is equivalent to

$$\phi_{Ni} = -\sqrt{-t/4m_N^2}\ \eta_{Ni} \tag{25b}$$

where m_N is the nucleon mass. The latter form introduces a certain kinematic spin-dependence for the rest-frame spinors. We do not need to decide here whether (a) or (b) is more appropriate for a diffraction model: the point is that Regge pole models are not restricted in such a way.

Now asymptotically, where the Pomeranchuk pole alone is significant, the polarization parameter $P(\theta)$ vanishes because of point (ii) and the form of its definition. To detect an asymptotic spin-dependence, therefore, we are driven to second-rank polarization tensors. In the present case only $D_{kj}(\theta)$ is available, and the measurements have to be made on a polarized target.

To illustrate the effects that may be found, Figure 3 shows predictions of R_{recoil} and A_{recoil} for π^+p scattering at 5, 40 and 320 GeV/c for a particular Regge pole model, number 1 in reference 7. (For the sake of illustration, we have extrapolated this model beyond the range in s and t where it was fitted to data). For comparision, Figure 4 shows the predictions at 20 GeV/c only, for the definitions (a) and (b) of spin-independence above, which lead respectively to

$$\left.\begin{aligned} D_{KK} &= D_{PP} = 1 \\ D_{KP} &= D_{PK} = 0 \end{aligned}\right\} \qquad (26a)$$

$$\left.\begin{aligned} D_{KK} &= D_{PP} = (1 - x^2)/(1 + x^2) \\ D_{KP} &= -D_{PK} = 2x/(1 + x^2) \end{aligned}\right\} \qquad (26b)$$

where $x = p^2 \sin\theta/((E_N + m_N)^2 - p^2\cos\theta)$, and $E_N = \sqrt{p^2 + m_N^2}$ is the c.m. nucleon energy.

The polarization parameter $P(\theta)$, on the other hand, depends on interference between at least two Regge poles, and behaves asymptotically as $s^{\alpha_2 - \alpha_1}$, where α_1 and α_2 are the highest and second-highest trajectories. For the particular example used above (π^+p scattering according to solution 1 of ref. 7), the maximum value of $|P|$ is about 0.12, 0.04 and 0.014 at 5, 40 and 320 GeV/c, respectively.

NN and $\bar{N}N$ elastic scattering.

The general remarks above about asymptotic spin dependence apply here also. There is nothing new to add about $P(\theta)$ or $D_{kj}(\theta)$, except that a polarized beam may now be considered, but there are two new second-rank tensors $K_{kj}(\theta)$ and $C_{kj}(\theta)$ available. However, the property of the leading Regge poles that $g = h = 0$ in Eq. (2) effectively reduces these two tensors to a

single component, as we have already seen. Furthermore, the factorized form of Eq.(24) causes this remaining component to vanish for a single Regge pole.[9] Thus C_{NN} and K_{NN}, like P, depend on interference between poles.

To exhibit asymptotic spin dependence, we are therefore left with the depolarization tensor as before. To illustrate the effects that may plausibly occur, we take an unpublished Regge pole model[8] which approximately reproduces pp and $\bar{p}p$ data for cross sections and $P(\theta)$. Figure 5 shows the predictions for A_{recoil} and R_{recoil} in pp scattering at 5,20 and 200 GeV/c.

The two definitions of spin independence described above carry over to the present case; Eqs. (25 a,b) and (26,a,b) apply equally to the NN and $\bar{N}N$ case, and so does Figure 4 (ignoring the tiny effect of different particle masses).

Charge-exchange scattering.

These cross sections are much smaller than elastic scattering, at high energy. In a Regge pole model, the integrated cross section tends to zero asymptotically like $s^{2\alpha_o-2}/\ln s$, where α_o is the intercept at $t = 0$ of the leading trajectory; for elastic scattering α_o is 1, but for charge exchange it is around 0.5 or less. We therefore limit our discussion to $P(\theta)$ at non-asymptotic energies.

Consider first $\bar{\pi} + p \rightarrow \pi^o + n$. The present data are compatible with the dominance of the ρ Regge pole alone.

If this is true, $P = 0$. However, other contributions may be present, and a measurement of P can detect them. Even if these other terms give only 20% of the amplitude at some energy and angle, they can still make P as large as 0.4 under favorable circumstances.

Consider next $\pi^- + p \rightarrow \eta^0 + n$. The only known Regge pole that can contribute here is the one associated with the A_2 meson. Once more, a measurement of P would be a sensitive test of other contributions.

In the case of $K^- + p \rightarrow \bar{K}^0 + n$ and $K^+ + n \rightarrow K^0 + p$, the ρ and A_2 Regge poles are believed to dominate.[7] Since these trajectories lie close together, the polarization resulting from interference falls rather slowly with increasing energy. Since these trajectories have opposite signatures, the relative phase of their contributions is extremely favorable for P. The fits to data that have been made require large spin-dependences for both the ρ and A_z terms, leading to big polarization effects which ought to be measured. As an illustration, Figure 6 shows $P(\theta)$ for $K^- + p \rightarrow \bar{K}^0 + n$ at 5 and 40 GeV/c, according to solution 1 of reference 7. This illustrates dramatically how in such favorable circumstances, P can be very large and show no sign of tending to zero. Note that P appears to be increasing with energy in some regions. It turns out that even at 400 GeV/c the asymptotic region where a single pole dominates has not been reached, and P still comes close to 1 at some angles, with the model in question.

For $p + n \to n + p$ and $\bar{p} + p \to \bar{n} + n$, we expect contributions from ρ, A_z and π Regge poles at least. No really satisfactory explanation of the differential cross section has yet been given (either with or without Regge poles), but there is still a shortage of data. There seems to be every chance that P may be substantial in the present accelerator range.

Relation between asymptotic spin-dependences

When the Pomeranchuk pole alone dominates, the depolarization tensor D_{kj} becomes the same for all the elastic scatterings we have considered (πN, KN, $\bar{K}N$, NN, $\bar{N}N$). This is because of factorization, and the trivial connection between N and $\bar{N}$ vertices.[9] We then have [illegible]

$$D_{NN} = 0$$

$$D_{KK} = D_{PP} = (\eta_N^2 - \phi_N^2)/(\eta_N^2 + \phi_N^2) \tag{27}$$

$$D_{KP} = -D_{PK} = -2\,\eta_N\phi_N/(\eta_N^2 + \phi_N^2)$$

Incidentally, a comparison of Figures 3 and 5 shows that the two corresponding Regge pole models are not strictly compatible.

IV. CONCLUSIONS

Regge pole models allow an asymptotic spin dependence, which cannot be measured by $P(\theta)$ because of the phase relations. It can however be measured through second-rank polarization tensors.

The parameter $P(\theta)$ is useful for measing the spacing between two leading trajectories, and for shedding light on their combined spin dependence. In favorable circumstances, such as $K^- p$ charge exchange, it may have large values up to surprisingly high energies. P is also a good test for secondary contribitions, when a single Regge pole is believed to dominate.

For NN and $\bar{N}N$ scattering, Regge pole models introduce some further special restrictions. The quantum numbers of the leading trajectories are such that the M-matrix simplifies. As a result, the polarization transfer tensor $K_{kj}(\theta)$ and spin correlation tensor $C_{kj}(\theta)$ have only one non-trivial component between them ($K_{NN} = C_{NN}$). The depolarization tensor $D_{kj}(\theta)$ retains two independent components, measurable through R and A.

The factored form of a single pole contribution is such that the single remaining element of K_{kj} and C_{kj} vanishes asymptotically. Only D_{kj} is suitable for detecting the asymptotic spin dependence that is predicted.

$C_{NN}(K_{NN})$ depends on interference between different Regge poles, like P, but is harder to measure. Perhaps the first interest in C_{NN} and K_{NN} is to see if they tend to zero asymptotically, as predicted by factorization.

It would also be interesting to check the relation $C_{NN} = K_{NN}$, and some of the others (such as $D_{NN} = 1$, $D_{PP} = D_{KK}$, $K_{PP} = K_{KK} = 0$, etc) which follow from the property $g = h = 0$ of the leading terms of the leading trajectories. This could give some measure of the importance of other contributions, such as those of the π and A_1 Regge poles, which do not have this restriction.

The relation $I_o P = 2 \text{ Im } c^*(a+m)$ continues to hold even when g and h are present in Eq.(2), so we do not expect P to be sensitive to these terms.

The predicted asymptotic equality of the depolarization tensors, for all the processes considered, offers an important check on factorization.

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FOOTNOTES AND REFERENCES

* This work was done under the auspices of the United States Atomic Energy Commission

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‡ Visiting scientist

1. Systematic discussions of polarization effects have been given by many authors, for example the following:
L.Wolfenstein, Phys. Rev. 96, 1654 (1954) ; Ann. Rev. Nucl. Sci. 6 43 (1956)
L.D. Puzikov, R. Ryndin and Ia. Smorodinsky, Nucl. Phys. 3, 436 (1957)
R.J.N. Phillips, Harwell report AERE-R3141 (1960), unpublished.
H. P. Stapp, M. H. MacGregor and M.J. Moravcsik, Ann. Rev. Nucl. Sci. 10, 291 (1960)
C. R. Schumacher and H. A. Bethe, Phys. Rev. 121, 1534 (1961)
2. H. P. Stapp, Phys. Rev. 103 , 425 (1956).
3. See for example S. Frautschi, M. Gell-Mann and F. Zachariasen, Phys. Rev. 126, 2204 (1962) .
4. W.G. Wagner, Phys. Rev. Letters 10 202 (1963); D. H. Sharp and W. G. Wagner, Phys. Rev. 131, 2226 (1963).
5. These two properties are related, as shown by dispersion relations.
6. This remark was made to us by G.F. Chew.
7. R. J. N. Phillips and W. Rarita, "Regge pole models for high-energy πN, KN and $\bar{K}N$ scattering," UCRL-16033 (1965), submitted to the Physical Review. This work includes several terms that would be neglected in the Wagner approximation. The calculations

of R and A have been made directly, without going through Eq. (23).

8. This model, constructed by W. Rarita, uses the P , P' and ω Regge poles and the Wagner approximation.

9. This result was first noticed by V. N. Gribov and I. Ya. Pomeranchuk, Phys. Rev. Letters 8, 412 (1962).

FIGURE CAPTIONS

Figure 1. Geometry for R and A experiments on the beam particle.

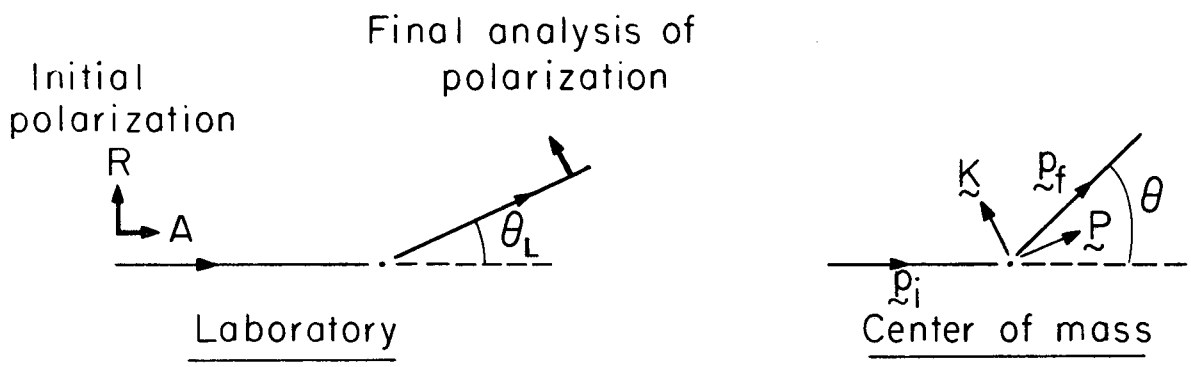
Figure 2. Geometry for R and A experiments on the target particle.

Figure 3. R_{recoil} and A_{recoil}, for π^+p scattering at 5, 40 and 320 GeV/c, according to solution 1 of reference 7.

Figure 4. R_{recoil} and A_{recoil}, for meson-baryon and baryon-baryon scattering at 20 GeV/c, according to the two alternative definitions of spin-independent scattering defined in the text. Case (a) is denoted by dotted lines, case (b) by solid lines.

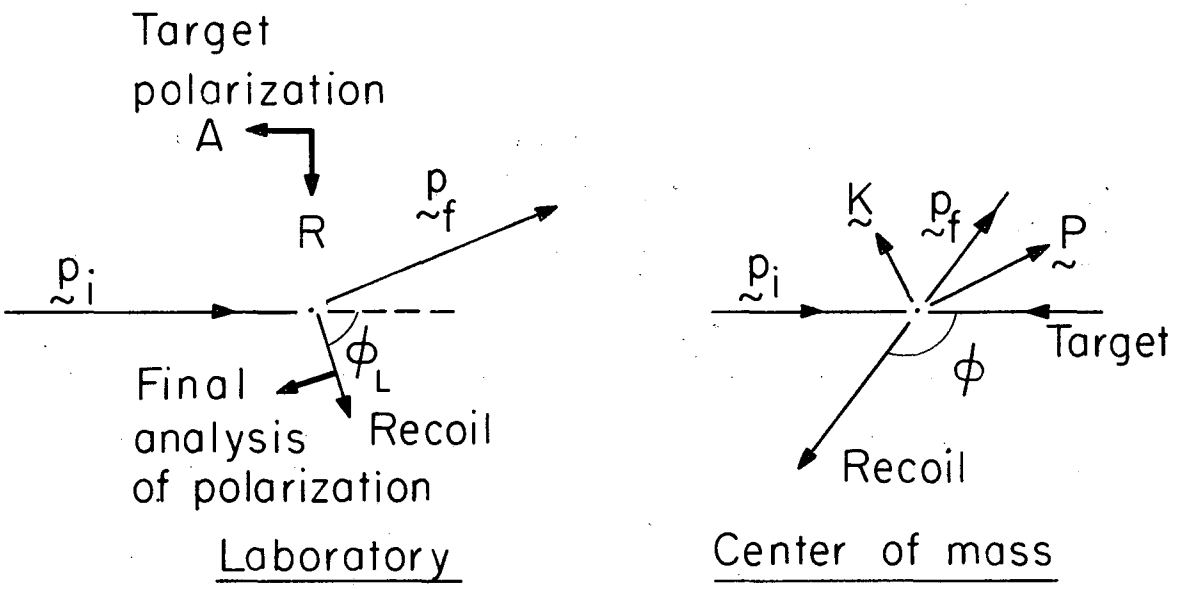
Figure 5. R_{recoil} and A_{recoil} for pp scattering at 5, 20 and 200 GeV/c, according to the model of Ref. 8.

Figure 6. P for $K^- + p \rightarrow \bar{K}^0 + n$ at 5 and 40 GeV/c, according to solution 1 of reference 7.



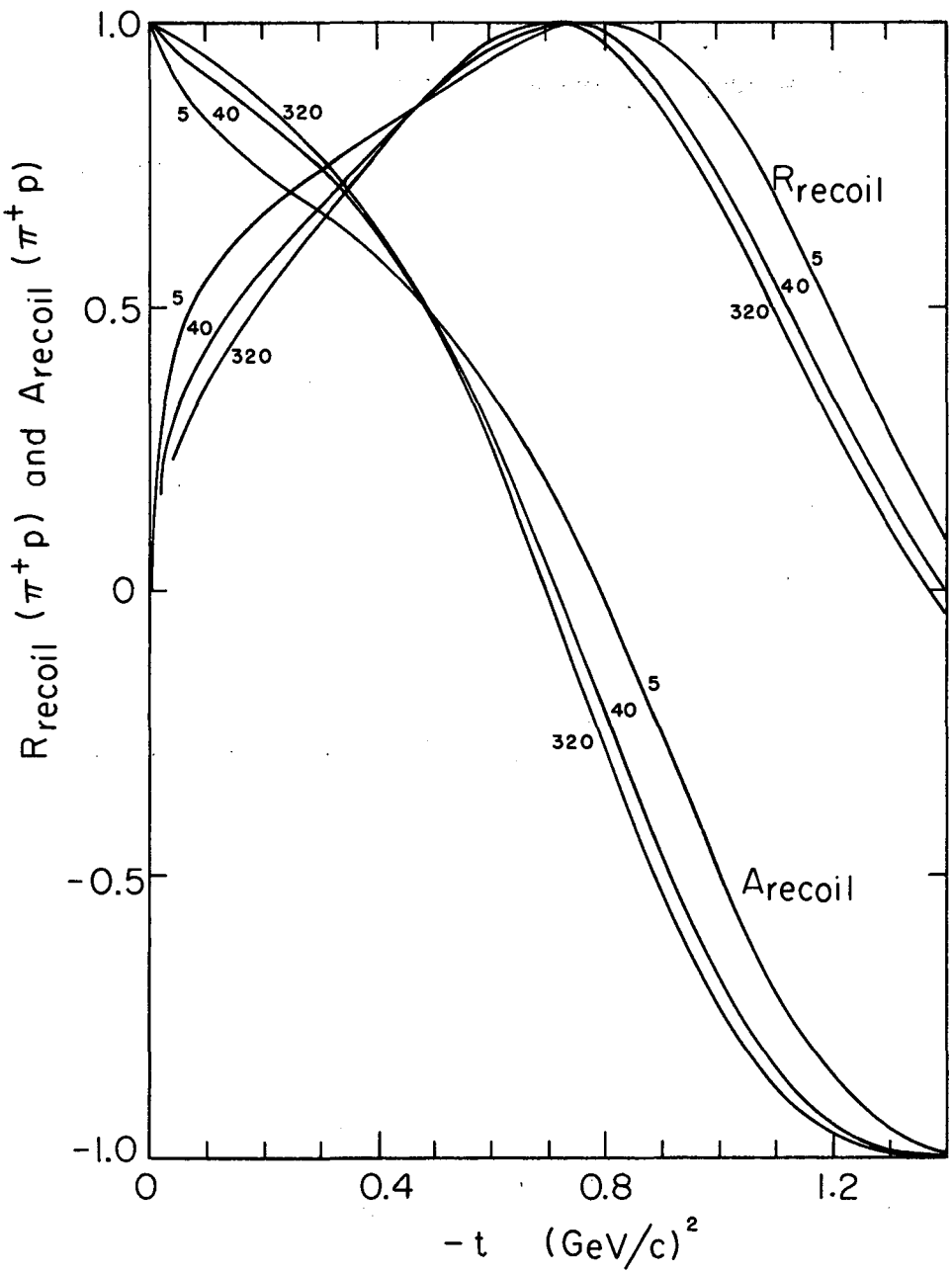
MUB-6575

Fig. 1



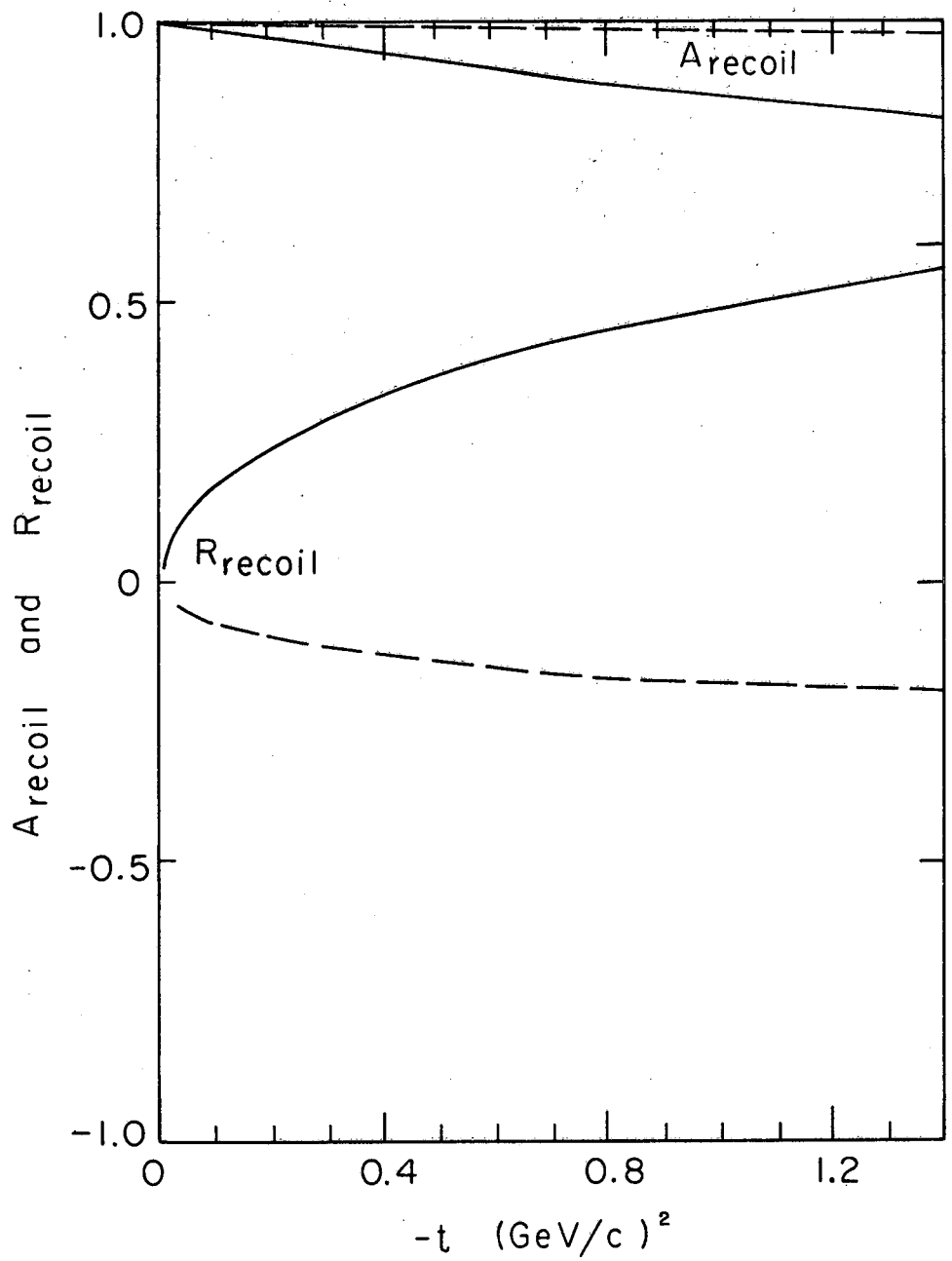
MUB-6576

Fig. 2



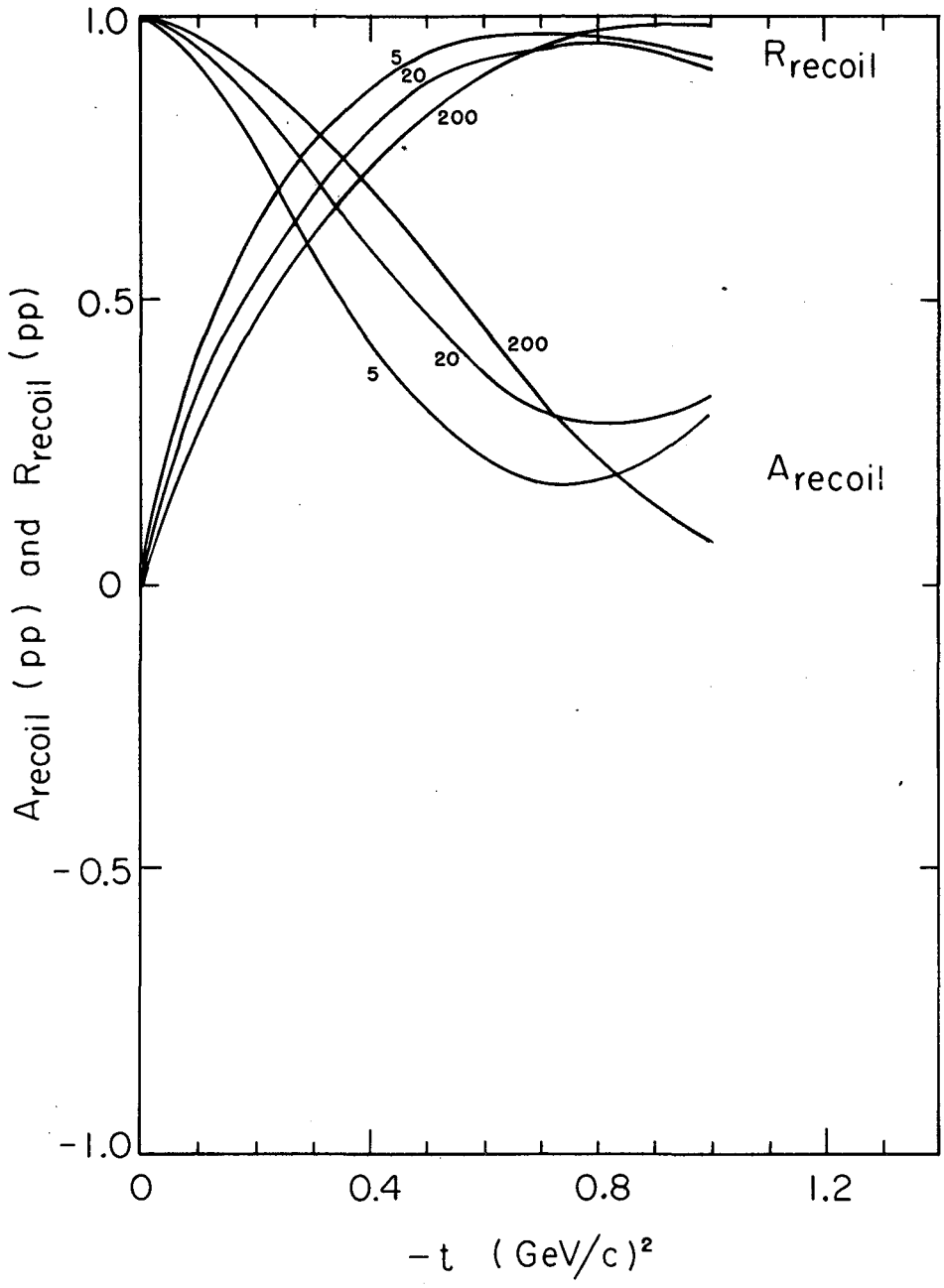
MUB-6577

Fig. 3



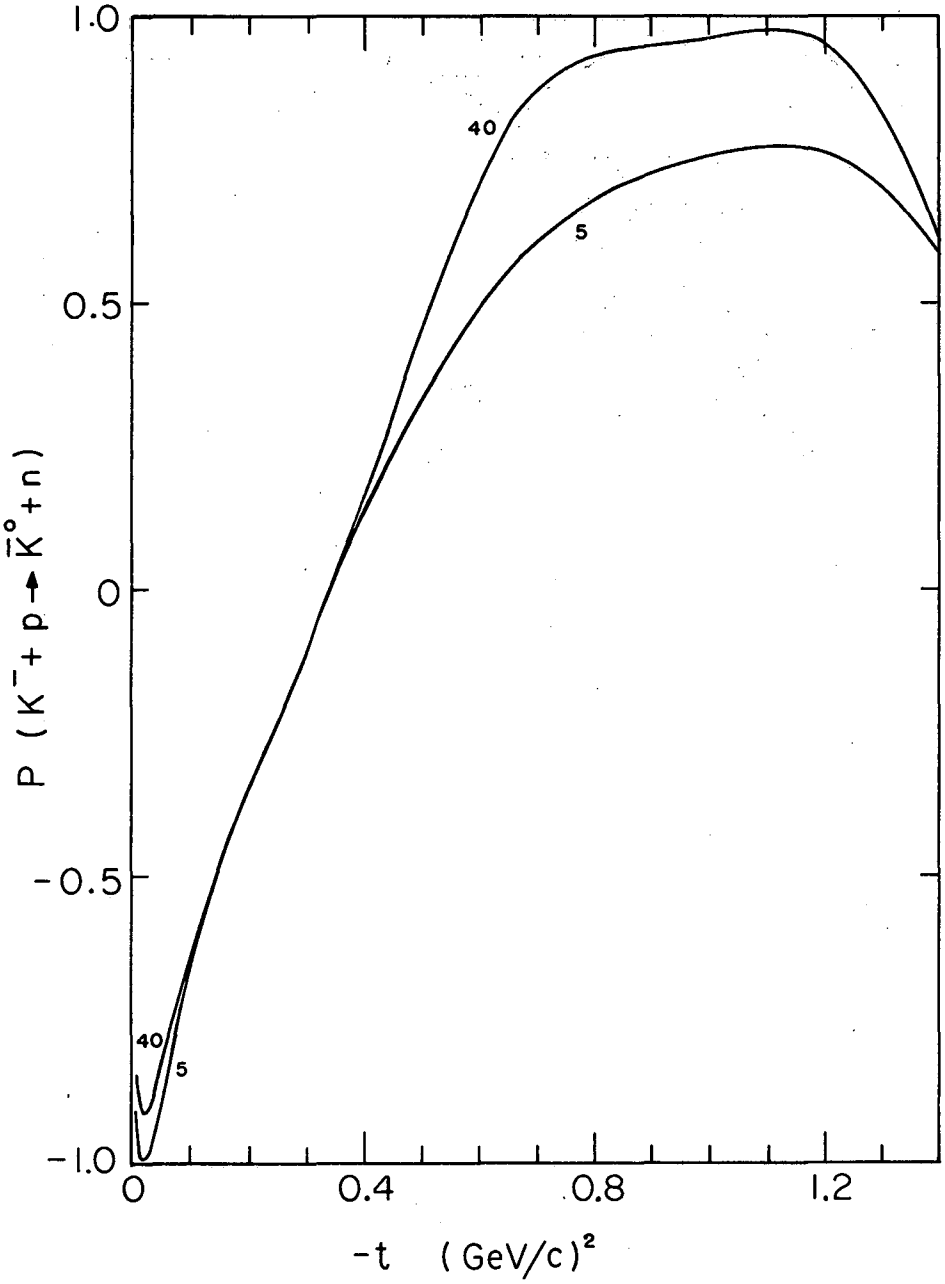
MUB-6578

Fig. 4



MUB-6579

Fig. 5



MUB-6580

Fig. 6

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