Polarization Parameter in p-p Scattering from 1.7 to 6.1 BeV*

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The polarization parameter in proton-proton scattering has been measured at incident proton kinetic energies of 1.7, 2.85, 3.5, 4.0, 5.05, and 6.15 BeV and for four-momentum transfer squared between 0.1 and 1.0 $(\text{BeV}/c)^2$. The experiment was done with an unpolarized proton beam from the Bevatron striking a polarized proton target. Both final-state protons were detected in coincidence and the asymmetry in counting rate for target protons polarized parallel and antiparallel to the scattering normal was measured. The maximum polarization was observed to decrease from 0.4 at 1.7 BeV to 0.2 at 6.1 BeV. The maximum of the polarization at all energies studied occurs at a four-momentum transfer squared of 0.3 to 0.4 $(\text{BeV}/c)^2$.

I. INTRODUCTION

ONE of the central problems in high-energy physics is the study of the nucleon-nucleon interaction, owing to its importance in the understanding of the nuclear force and to the fact it is at least representative of the strong interaction in general. In particular the proton-proton interaction is easily studied experimentally since proton targets and beams are easily obtainable.

At low energies many of the parameters depending on expectation values and correlations of spins have been studied. However, measurements of the spin parameters in the multi-BeV range have been hampered by the lack of adequate polarized beams and the generally diminishing elastic differential cross section. This paper presents the results of an experiment to measure the polarization parameter $P(\theta)$ in elastic proton-proton scattering from 1.7 to 6.1 BeV. The method employed was to study the scattering of an unpolarized proton beam from the Bevatron on a target containing polarized protons. The advantages of this method are that relatively high polarizations in the target can be achieved (about 40–50% during this experiment) and that no second scattering is necessary. Furthermore, the polarization can be measured over a range of angles at the same time.

While the results of this experiment, coupled with previous measurements of the elastic differential proton-proton cross section and the total cross section, cannot completely determine the proton-proton scattering matrix, it is possible to discuss the data in terms of various dynamical models. In particular, our results tend to agree with the general predictions of a single Regge-pole model as applied to nucleon-nucleon scattering.

The complexity of the two-nucleon interaction stems to a large degree from the fact that both particles have spin $\frac{1}{2}$. The choice of the framework in which to discuss the spin complications depends on the type of analysis to be employed; for example, making a partial-wave expansion suggests the use of a representation which diagonalizes the total angular momentum J and the spin S, while tests of conservation laws or symmetry principles are made more transparent if a direct product representation in the two-particle spin space is used. Most of the theoretical work done on high-energy nucleon-nucleon scattering has made use of the helicity representation due to its relatively simple behavior under Lorentz transformations and crossing symmetry.[1]

The helicity representation requires the quantization of each particle's spin along its own direction of motion. A set of two-particle helicity states $\{\chi_\mu\}$, $\mu=1, \cdots, 4$ can be chosen, where $|\chi_1\rangle=|++\rangle$, $|\chi_2\rangle=|+-\rangle$, $|\chi_3\rangle=|-+\rangle$, and $|\chi_4\rangle=|--\rangle$ and, for example, $|+-\rangle$ means that particle 1 has helicity $+\frac{1}{2}$ and particle 2 has helicity $-\frac{1}{2}$.

Application of reflection invariance, time-reversal invariance, and particle-exchange symmetry to the scattering matrix for proton-proton scattering gives the usual result that only five amplitudes are independent. In terms of the helicity states above, these are the non-helicity-flip amplitudes $\varphi_1=\langle ++|M|++\rangle$ and $\varphi_3=\langle +-|M|+-\rangle$, the double-flip amplitudes $\varphi_2=\langle ++|M|--\rangle$ and $\varphi_4=\langle +-|M|-+\rangle$, and the single-flip amplitude $\varphi_5=\langle ++|M|+-\rangle$. Here M is the proton-proton scattering matrix.[2] One can then find the expression for the analyzing power $P'(t)$[3] (where t is the four-momentum transfer squared) in terms of these five amplitudes[4]:

$$I_0P'(t)=\mathrm{Im}[\varphi_5(\varphi_1+\varphi_2+\varphi_3-\varphi_4)^*]. \quad (1)$$

Here I_0 is the intensity for scattering two unpolarized

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protons

$$I_0=\tfrac{1}{2}[|\varphi_1|^2+|\varphi_2|^2+|\varphi_3|^2+|\varphi_4|^2+4|\varphi_5|^2]$$

and I, the intensity for scattering a proton of polarization P_T normal to the scattering plane from an unpolarized proton is

$$I=I_0[1+P_TP'(t)]. \tag{2}$$

As mentioned in the previous paper, the analyzing power $P'(t)$ and the polarization parameter $P(t)$ are equal if the proton-proton interaction is invariant under time reversal.

It should also be pointed out that for this experiment, in which the polarization of the target proton is perpendicular to the scattering plane, there is no rotation of the spins from relativistic effects.[4]

II. EXPERIMENT AND ANALYSIS

This experiment was performed in the external proton beam at the Bevatron; the energy of the incident particles was maintained constant over spill times ranging from 300 msec to 1 sec at proton kinetic energies of 1.7, 2.85, 3.5, 4.0, 5.05, and 6.15 BeV. No component of incident proton polarization perpendicular to the scattering plane utilized is expected. This is because the plane of the Bevatron is perpendicular to the plane of the scattering from the polarized target. Further, it is expected that the circulating beam should not be appreciably polarized. Typical proton fluxes were 10^8 protons/sec, instantaneous rate.

The polarized proton target and the nuclear-magnetic-resonance (NMR) detection system have been described elsewhere.[3,5,6] Elastic proton-proton scatters were detected by coincidence counting, using the same arrays described in the preceding paper. A monitor, sensitive primarily to pions, was constructed using an additional water Čerenkov counter beneath the lower array; the monitor counting rate was demonstrated to be independent of target polarization. The event-handling and analysis procedures have been discussed in the preceding paper. At all but the lowest energy, separate runs were made for the high- and low-momentum-transfer data. Range limitations required that the four-momentum transfer squared be above 0.1 $(\text{BeV}/c)^2$ and the diminishing cross section imposed an upper limit of 1.0 $(\text{BeV}/c)^2$.

One feature of the analysis of this experiment warrants some comments. A calibration experiment showed that the proton polarization in the target was not uniform over the volume of the crystals. This was demonstrated by directing a beam of approximately $\frac{1}{4}$-in. diam. on various portions of the target and measuring the asymmetry in counting rate for positive and negative target polarizations. A correction to the data was necessary since the intensity of the beam varied across the face of the target crystals and the sensitivity of the NMR detection system was also nonuniform. Combining the results of the small-beam experiment with photographs of the beam spot immediately behind the crystals taken during the run and the known detection efficiency allowed the calculation of a correction factor. The detected target polarization was higher than the polarization weighted by the beam intensity, since the NMR sensing efficiency was greatest near the periphery of the crystals where the polarization was large, while the beam intensity was greatest at the center of the crystals. Hence the values of the polarization parameters have been scaled upward by a factor which was typically about 1.25; the error in this scaling factor is estimated at 5% and has been included as a systematic error.

III. RESULTS

The results of the measurements are shown graphically in Figs. 1 through 6; the numbers are presented in Tables I through VI. Note that the errors indicated

TABLE I. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 1.7 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ_0^* $\pm 1°$	$-t[(\text{BeV}/c)^2]$ ± 0.01	$P(t)$	$\Delta P(t)$	α
23.3	0.129	0.431	0.021	1.235
29.0	0.161	0.389	0.014	
28.7	0.196	0.423	0.015	
31.4	0.233	0.404	0.016	
34.1	0.273	0.396	0.017	
36.7	0.315	0.362	0.020	1.235

TABLE II. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 2.85 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ_0^* $\pm 1°$	$-t[(\text{BeV}/c)^2]$ ± 0.15	$P(t)$	$\Delta P(t)$	α
16.6	0.111	0.151	0.085	1.245
19.0	0.146	0.188	0.020	
21.5	0.185	0.237	0.015	
23.9	0.228	0.245	0.015	
26.2	0.275	0.255	0.017	
28.6	0.326	0.260	0.020	
31.0	0.380	0.221	0.022	1.245
32.0	0.405	0.270	0.019	1.240
33.3	0.438	0.283	0.028	1.245
34.4	0.463	0.242	0.022	1.240
36.5	0.524	0.225	0.023	
38.8	0.588	0.196	0.027	
41.0	0.655	0.142	0.031	
43.2	0.724	0.218	0.036	
45.4	0.796	0.156	0.040	
47.0	0.869	0.130	0.042	
49.7	0.943	0.171	0.055	
51.8	1.02	0.104	0.092	1.240

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TABLE. III. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 3.5 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\,\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ^* $\pm 1°$	$-t[(\mathrm{BeV}/c)^2]$ ± 0.02	$P(t)$	$\Delta P(t)$	α
20.8	0.215	0.171	0.019	1.250
22.8	0.257	0.203	0.021	
24.8	0.304	0.203	0.024	
26.8	0.353	0.218	0.028	
28.8	0.405	0.207	0.030	
30.7	0.461	0.224	0.035	
32.6	0.519	0.131	0.046	
34.5	0.580	0.123	0.044	
36.4	0.643	0.083	0.054	
38.3	0.709	0.127	0.063	1.250

TABLE. IV. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 4.0 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ^* $\pm 1°$	$-t[(\mathrm{BeV}/c)^2]$ ± 0.02	$P(t)$	$\Delta P(t)$	α
15.6	0.138	0.144	0.025	1.260
17.6	0.176	0.191	0.016	
19.7	0.218	0.211	0.015	
21.7	0.264	0.193	0.017	
23.6	0.314	0.217	0.020	
25.6	0.368	0.181	0.022	
27.6	0.425	0.194	0.026	1.260

by the flags are statistical only; the systematic error arising from the thermal-equilibrium polarization measurement and the nonuniform polarization correction has been indicated in each figure. The numerical factor by which the data have been corrected for the nonuniformity in target polarization is listed in the

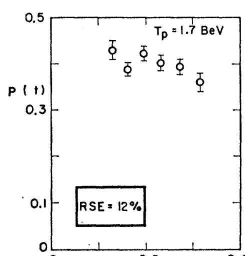

FIG. 1. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 1.7 BeV. R.S.E. is the relative systematic error.

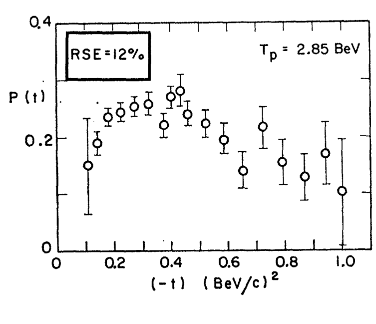

FIG. 2. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 2.85 BeV. R.S.E. is the relative systematic error.

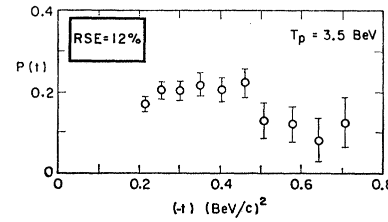

FIG. 3. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 3.5 BeV. R. S. E. is the relative systematic error.

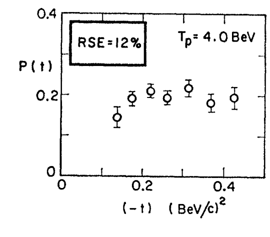

FIG. 4. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 4.0 BeV. R.S.E. is the relative systematic error.

tables. This factor is in general different for different energies and for the high and low momentum-transfer measurement. This comes about because the beam-spot

TABLE. V. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 5.05 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ^* $\pm 1°$	$-t[(\mathrm{BeV}/c)^2]$ ± 0.03	$P(t)$	$\Delta P(t)$	α
12.5	0.112	0.089	0.100	1.275
14.3	0.147	0.152	0.024	
16.1	0.186	0.166	0.019	
18.0	0.229	0.153	0.019	
19.7	0.277	0.178	0.022	
21.5	0.329	0.185	0.027	
23.3	0.384	0.136	0.030	1.275
23.7	0.398	0.226	0.054	1.260
25.0	0.444	0.138	0.034	1.275
25.4	0.459	0.201	0.059	1.260
27.2	0.523	0.145	0.055	
28.9	0.591	0.008	0.062	
30.7	0.662	0.231	0.087	
32.4	0.736	0.206	0.100	
34.1	0.814	0.100	0.121	
36.2	0.914	0.041	0.138	1.260

TABLE VI. Polarization parameter $P(t)$ in p-p scattering for incident lab kinetic energy of 6.15 BeV. α is the correction factor for nonuniform target polarization. $\Delta P(t)$ is the statistical error to which must be added a relative systematic error of $\pm 12\% \times P(t)$. θ^* is the scattering angle in the center-of-mass system.

θ^* $\pm 1°$	$-t[(\mathrm{BeV}/c)^2]$ ± 0.03	$P(t)$	$\Delta P(t)$	α
13.2	0.152	0.112	0.049	1.28
15.0	0.195	0.177	0.031	
16.7	0.242	0.196	0.028	
18.4	0.295	0.177	0.031	
20.1	0.352	0.262	0.037	
21.8	0.413	0.160	0.042	1.28
23.1	0.461	0.169	0.027	1.27
23.5	0.480	0.157	0.053	1.28
24.7	0.529	0.117	0.032	1.27
25.2	0.550	0.077	0.064	1.28
26.4	0.602	0.085	0.042	1.27
28.1	0.679	0.142	0.053	
29.7	0.759	0.002	0.074	1.27

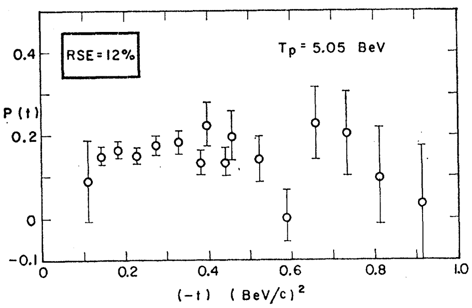

FIG. 5. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 5.05 BeV. R.S.E. is the relative systematic error.

diameter changed from one running period to the next.

As we can see from the data of this experiment, the polarization maximum at high energies is quite broad and is approximately stationary at a momentum transfer $t \approx -0.3$ (BeV/c)^2.

Figure 7 shows the present data in comparison with other measurements of polarization.[3,7–18] We have plotted the maximum polarization as a function of beam kinetic energy.

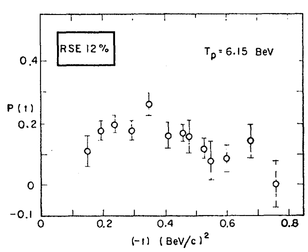

FIG. 6. Polarization parameter $P(t)$ as a function of the four-momentum transfer squared t at an incident proton kinetic energy of 6.15 BeV. R.S.E. is the relative systematic error.

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IV. DISCUSSION OF THE DATA

Several general comments may be given on the data presented in III. The polarization parameter $P(t)$ is seen to have relatively simple behavior both in its energy and angle dependences in the regions studied. We see that the polarization achieves a rather broad maximum in the vicinity of $t=-0.3$ to -0.4 (BeV/c)^2 for each of the energies studied; also the shape of the curve P versus t seems to be the same throughout the range of energies 1.7 to 6.1 BeV. The dependence of the maximum polarization on the energy variable also seems to be rather simple; at present we may note the maximum polarization decreases as energy increases. This point will be considered in more detail below.

A complete reconstruction of the amplitude for proton-proton scattering is one of the primary objectives of an experimental program. This reconstruction has been attempted at some of the lower energies through a determination of the relevant phase shifts. It is clear, however, that such a program is impractical at energies above 1 BeV due to the large number of partial waves expected to contribute. Furthermore, the present status of experimental work is that only two types of experiments have been performed—the differential cross section and the polarization, whereas a complete reconstruction of the p-p amplitude, without any *a priori* assumptions, requires in principle at least eleven experiments.[19] Thus any meaningful analysis done with the presently available data must make use of a reasonably restrictive dynamical model.

One model which has had reasonable success in explaining very high-energy proton-proton scattering data involves the assumption that the amplitudes are controlled by exchange of Regge poles. The applica-

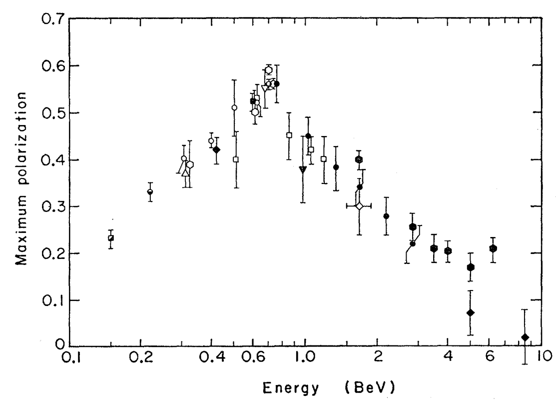

FIG. 7. Maximum polarization as a function of beam kinetic energy. The points below 600 MeV are representative. Solid hexagons, data from this experiment; ◪, data from Ref. 7; ◒, data from Ref. 8; ○, data from Ref. 9; △, data from Ref. 10; open hexagons, data from Ref. 3; open lozenges data from Ref. 11; □, data from Ref. 12; ■, data from Ref. 13; ▽, data from Ref. 14; solid lozenges, data from Ref. 18.

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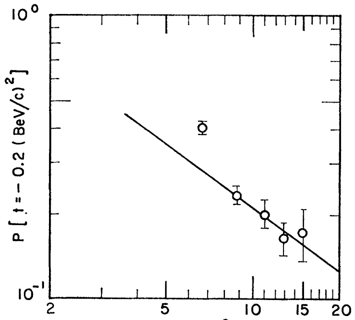

FIG. 8. Polarization parameter for fixed $t=-0.2$ $(\mathrm{BeV}/c)^2$ as a function of s. The straight line is a least-squares fit to the data with $s>8$ $(\mathrm{BeV})^2$ of the form $\log P=[\alpha_2-\alpha_1]\log s+\text{constant}$ and the fitted value is $[\alpha_2-\alpha_1]=-0.75\pm0.31$.

tion to nucleon-nucleon scattering has been made by several authors,[20] and we shall review only those points pertinent to the analysis of polarization.

Under the assumption that the high-energy proton-proton scattering amplitude is dominated by Regge poles in the crossed channel, each of the five independent amplitudes φ_i discussed in I can be shown to have the form

$$\varphi_i(s,t) \underset{s\to\infty}{\longrightarrow} \sum_n \beta_n{}^i(t)\zeta_n(t)s^{\alpha_n(t)}, \tag{3}$$

where s is the square of the total center-of-mass energy, t is the square of the four-momentum transfer, $\alpha_n(t)$ is the (real) position of the nth pole in angular momentum space, $\beta_n{}^i(t)$ is essentially the coupling of the nth pole to the crossed channel and is a real function of t, in general different for each of the five helicity amplitudes, and $\zeta_n(t)$ is a complex factor (the signature factor) which depends only on the position of the pole and is common to all five amplitudes. Thus, if the energy is so high that one pole dominates the amplitude [the one with largest $\alpha_n(t)$], no polarization results since polarization depends on the imaginary part of an interference between amplitudes [Eq. (1)]. The first-order contribution to the polarization at high energy in a Regge-pole model comes then from a two-pole approximation; in this case

$$P\frac{d\sigma}{d\Omega} \underset{s\to\infty}{\longrightarrow} f(t)s^{\alpha_1(t)+\alpha_2(t)-1},$$

where $f(t)$ is some function of momentum transfer only and α_1 and α_2 are the positions of the leading and secondary poles. The corresponding first-order contribution to the differential cross section is

$$\frac{d\sigma}{d\Omega} \underset{s\to\infty}{\longrightarrow} g(t)s^{2\alpha_1(t)-1},$$

where $g(t)$ is another function of momentum transfer. Thus the polarization parameter in a two-pole approximation would have an energy dependence for fixed momentum transfer[21]

$$P(\text{fixed } t)\sim s^{\alpha_2(t)-\alpha_1(t)}. \tag{4}$$

Analyses of differential and total cross sections for p-p scattering at high energies have shown that only three Regge poles need be included: the Pomeranchuk pole P, the second Pomeranchuk pole P', and the pole associated with the ω. However, these analysis suggest the the P' and ω follow essentially the same trajectory in angular momentum space[22] so that the above two-pole approximation should be reasonable.

To test these hypotheses we have fitted the data for each energy by a smooth curve of the form

$$P(t)=\sum_{n=1}^{4} a_n t^n.$$

The fitted values are plotted versus s for fixed momentum transfers of 0.2, 0.3, and 0.4 $(\mathrm{BeV}/c)^2$ in Figs. 8–10; the error bars include both statistical and fitting errors. Least-squares fits to the slopes $d(\ln P)/d(\ln s)$ were made using only the points with $s>8$ $(\mathrm{BeV})^2$; the slopes for all three values of t are essentially the same and have the value $d(\ln P)/d(\ln s)\approx-\frac{3}{4}$ with rather large errors.

It would seem that these data are not compelling in their confirmation of Regge behavior, though they certainly do not disagree with this hypothesis. The values for the slopes would indicate that the separation of the two leading poles, $(\alpha_1-\alpha_2)$, is about $\frac{3}{4}$ and is not varying rapidly as a function of t. If we assume that the leading pole with position α_1 is on the Pomeranchuk trajectory, then the trajectory interfering with it would be expected to have $\alpha_2(t=0)\approx0.25\pm0.35$. It is

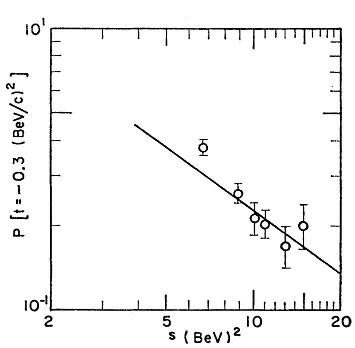

FIG. 9. Polarization parameter for fixed $t=-0.3(\mathrm{BeV}/c)^2$ as a function of s. The straight line is a least-squares fit to the data with $s>8$ $(\mathrm{BeV})^2$ of the form $\log P=[\alpha_2-\alpha_1]\log s+\text{constant}$ and the fitted value is $[\alpha_2-\alpha_1]=-0.73\pm0.31$.

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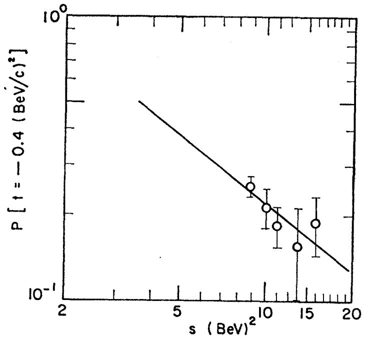

FIG. 10. Polarization parameter for fixed $t=-0.4$ (BeV/c)^2 as a function of s. The straight line is a least-squares fit to the data with $s>8$ (BeV)^2 of the form $\log P=[\alpha_2-\alpha_1] \log s+\text{constant}$ and the fitted value is $[\alpha_2-\alpha_1] = -0.81\pm0.42$.

known that the ω and P' trajectories couple strongly to the $p\bar{p}$ channel and have positions at $t=0$ of approximately 0.5.[22] Our polarization data are thus consistent with the assumption that the interference is between the "Pomeranchon" and P or ω, though we would favor a lower position at $t=0$ for the competing pole.

It should be borne in mind that the simple Regge-pole model outlined above is intended to apply to scattering in the "asymptotic" energy region, whereas the energy region of the present experiment may be significantly lower. A more complete study of nucleon-nucleon scattering, using a Regge pole approach, has been initiated by Phillips and Rarita which will include all the available high-energy data.[22]

We wish to emphasize that, with the Regge-pole hypothesis, the polarization parameter becomes small at high energy because the phases of all five helicity amplitudes become the same when just one pole is exchanged. In terms of the five helicity amplitudes in the limit of high energy (where the Pomeranchon dominates)[23]

$$\varphi_1=\varphi_3=|\varphi_1|^{i\psi}$$
$$\varphi_2=-\varphi_4=|\varphi_2|e^{i\psi}$$
$$\varphi_5=|\varphi_5|e^{i\psi}$$

and all five remain finite.

[23] Cf. I. J. Muzinich, Ref. 20.

It would be an interesting further check of the Regge hypothesis to see whether the decrease of polarization should indeed be interpreted as resulting from the amplitudes tending to the same phase or from the spin dependence of the interaction becoming small. The latter possibility might arise as the more natural explanation from an optical-type model. The natural method of testing this point is to measure a parameter which depends on the real part of an interference and hence does not vanish if all five amplitudes go to the same phase at high energy, yet does contain spin dependence in an essential way.

The parameters $C_{NN}=(NN;00)$ and $D_t=(N0;0N)$ have the correct form but can be shown to be zero for Pomeranchon exchange alone, due to the factorization of the residues[24]; a better choice would be to measure the parameters $(K0;K0)$, $(K0;P0)$, and $(P0;P0)$ (or equivalently, R, R', and A in Wolfenstein's notation[2]). We use here a notation introduced by Moravcsik[2]; $(\lambda\tau,\mu\nu)$ represents the measurable correlation parameter in which initial particles have spin components μ and ν and final-state particles have spin components λ and τ. Here (μ,ν,λ,τ) can be $(0,N,K,P)$, where N, K, and P are the orthogonal vectors $(\mathbf{k}_i\times\mathbf{k}_f)/|\mathbf{k}_i\times\mathbf{k}_f|$, $(\mathbf{k}_f-\mathbf{k}_i)/|\mathbf{k}_f-\mathbf{k}_i|$, and $(\mathbf{k}_f+\mathbf{k}_i)/|\mathbf{k}_f+\mathbf{k}_i|$ and $\mathbf{k}_i$ and $\mathbf{k}_f$ are the center-of-mass momenta of the beam particle and forward-scattered particle in the final state; 0 represents the state of no polarization. The parameter $(NN;00)$, for example, is the correlation between normal components of the two final-state spins, given that neither initial-state particle is polarized.

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