found to be 0.80 ± 0.03 GeV^{-1} where the error reflects only experimental uncertainties. To summarize, (1) the differential cross section $M_x^2 d^2\sigma/dt\,dM_x^2$ is a function of t only above the resonance missing-mass region; (2) a pronounced enhancement centered at M_x^2 of 1660 MeV is observed for all projectile particles. Cross sections for this enhancement exhibit an exponential behavior with $|B|$ about 2 (GeV)$^{-2}$ larger than the corresponding values for $M_x^2 > 4$ GeV out to $|t| = 0.6$ GeV; and (3) factorization of the cross section [Eq. (3)] works well, and the value obtained for the triple-Pomeron coupling is 0.80 GeV^{-1} for all channels.

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[1]Fermilab Single Arm Spectrometer Group, Phys. Rev. Lett. 35, 1195 (1975). (This reference also includes examples of raw inelastic scattering spectra from which the results of this paper are derived.)

[2]M. Benot, J. Litt, and R. Meunier, Nuclear Instrum. Methods 105, 431 (1972).

[3]R. L. Anderson and J. A. Grant, to be published.

[4]C. E. Detar, C. E. Jones, F. Low, J. H. Weiss, J. E. Young, and C. I. Tan, Phys. Rev. Lett. 26, 679 (1971); A. B. Kaidalov *et al.*, Phys. Lett. 45B, 493 (1973).

[5]The ratios are determined directly by this experiment and are independent of any assumptions as to the elastic cross sections.

[6]Y. Akimov *et al.*, Phys. Rev. Lett. 35, 766 (1975).

[7]M. G. Albrow, "Inelastic Diffractive Scattering at the CERN ISR," 1976 (unpublished).

[8]It is estimated that the inclusion of terms associated with other exchanges and a Pomeron slope of ~0.2 GeV^{-2} can lead to a reduction of about 20% of the value of $\sigma_{tot}^{\,\pi p}$.

[9]H. D. I. Abarbanel, J. Bartels, J. B. Bronzan, and O. Sidhu, Phys. Rev. D 12, 2798 (1975).

[10]W. Frazer and M. Moshe, Phys. Rev. D 12, 2370 (1975).

Measurement of the Spin-Spin Correlation Parameter C_{ss} in pp Elastic Scattering at 6 GeV/c*

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We have made the first measurement of the spin-spin correlation parameter C_{SS} in pp elastic scattering at 6 GeV/c over the $|t|$ range from 0.05 to 1.5 (GeV/c)^2. The measured C_{SS} data points are all negative, and their absolute values increase with $|t|$. The results are compared with some existing attempts to describe the pp scattering process.

An intensive program to determine proton-proton elastic scattering amplitudes is underway at the Argonne National Laboratory's zero-gradient synchrotron (ZGS). Measurements carried out so far include the differential cross section, the polarization, the spin-spin correlation parameter C_{NN},[1,2] the depolarization parameter D_{NN},[2,3] and the polarization transfer parameter K_{NN}.[2] In these measurements the spin direction of the polarized beam and the polarized target was in the $\vec{N}$ direction, normal to the scattering plane.

As can be seen in Table I, these observables are dominated by the product of two of the natural-parity exchange amplitudes (N_0, N_1, and N_2) and give little information about the unnatural-parity exchange amplitudes (U_0 and U_2). To obtain information on the latter, it is necessary to align the spin direction of beam and/or target in the scattering plane (i.e., either in the $\vec{S}$ or the $\vec{L}$ direction, where $\vec{L}$ is the longitudinal direction and $\vec{S} = \vec{N} \times \vec{L}$).

We have measured the spin-spin correlation parameter, C_{SS}, in proton-proton elastic scattering at 6 GeV/c over the $|t|$ range from 0.05 to 1.5 (GeV/c)^2. This is the first measurement of C_{SS} in which both the beam and the target are po-

TABLE I. Observables and exchange amplitudes. The notation of the observables expresses the spin direction in the order of (beam, target; scattered proton, recoil proton). N_0, N_1, and N_2 represent natural-parity exchange terms; and U_0 and U_2 represent unnatural-parity terms. θ_R is the angle of recoil proton with respect to the incident proton in the laboratory frame. The exchange amplitudes are related to s-channel helicity amplitudes as $N_0=\frac{1}{2}(\varphi_1+\varphi_3)$, $N_1=\varphi_5$, $N_2=\frac{1}{2}(\varphi_4-\varphi_2)$, $U_0=\frac{1}{2}(\varphi_1-\varphi_3)$, and $U_2=\frac{1}{2}(\varphi_4+\varphi_2)$, where $\varphi_1=\langle++|\varphi|++\rangle$, $\varphi_2=\langle--|\varphi|++\rangle$, $\varphi_3=\langle+-|\varphi|+-\rangle$, $\varphi_4=\langle+-|\varphi|-+\rangle$, and $\varphi_5=\langle++|\varphi|+-\rangle$.

Observables	Exchange amplitudes[a]
$\sigma(=I_0)=(0,0;0,0)$	$\lvert N_0\rvert^2+2\lvert N_1\rvert^2+\lvert N_2\rvert^2+\lvert U_0\rvert^2+\lvert U_2\rvert^2$
$P=(0,N;0,0)$ $=(N,0;0,0)$	$-2\,\mathrm{Im}(N_0-N_2)N_1^*/\sigma$
$C_{NN}=(N,N;0,0)$	$2\,\mathrm{Re}(U_0U_2^*-N_0N_2^*+\lvert N_1\rvert^2)/\sigma$
$K_{NN}=(N,0;0,N)$	$-2\,\mathrm{Re}(U_0U_2^*+N_0N_2^*-\lvert N_1\rvert^2)/\sigma$
$D_{NN}=(0,N;0,N)$	$[\lvert N_0\rvert^2+2\lvert N_1\rvert^2+\lvert N_2\rvert^2-\lvert U_0\rvert^2-\lvert U_2\rvert^2]/\sigma$
$C_{SS}=(S,S;0,0)$	$2\,\mathrm{Re}(N_0U_2^*-N_2U_0^*)/\sigma$
$C_{SL}=(S,L;0,0)$	$2\,\mathrm{Re}(U_0+U_2)N_1^*/\sigma$
$D_{SS}=(0,S;0,S)$	$[-2\,\mathrm{Re}(N_0+N_2)N_1^*\sin\theta_R-(\lvert N_0\rvert^2-\lvert N_2\rvert^2+\lvert U_2\rvert^2-\lvert U_0\rvert^2)\cos\theta_R]/\sigma$
$H_{NSS}=(N,S;0,S)$	$[-2\,\mathrm{Im}(U_0U_2^*-N_0N_2^*)\sin\theta_R+2\,\mathrm{Im}(N_0+N_2)N_1^*\cos\theta_R]/\sigma$

[a]See Ref. 12.

larized in the plane of scattering but perpendicular to the incident momentum. (See Table I and Fig. 1 for the definition of C_{SS}.) There have only been a few measurements of spin-spin correlation parameters which involve spin states that are in the scattering plane.[5] These experiments require a simultaneous measurement of the spins of the scattered and recoil proton and hence have a low statistical accuracy.

The differential cross section for a particular spin direction of beam and target $I^{\pm\pm}$ is given by

$$I^{\pm\pm}(t)=I_0(t)[1\pm\alpha(t)P_BP(t)\pm\alpha(t)P_TP(t)+(\pm P_B)(\pm P_T)C_{SS}(t)],$$

where ±± refers to beam and target polarization parallel/antiparallel to the $\vec{S}$ direction, respectively; $I_0(t)$ is the unpolarized cross section at t, the square of the momentum transfer; P_B and P_T are the beam and target polarization, respectively; $P(t)$ is the polarization parameter at t; and

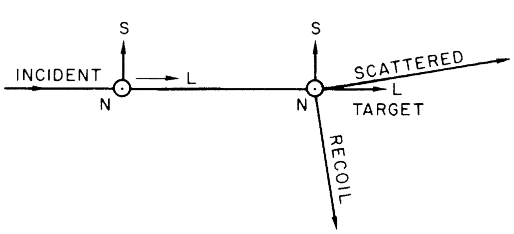

FIG. 1. Unit vectors $\vec{N}$, $\vec{L}$, and $\vec{S}$. $\vec{N}$ is normal to the scattering plane; $\vec{L}$ is in the longitudinal direction; and $\vec{S}=\vec{N}\times\vec{L}$ lies in the scattering plane.

$\alpha(t)P_B$ and $\alpha(t)P_T$ represent the $\vec{N}$ component of polarization when P_B and P_T are not exactly in the scattering plane.[6] We have assumed parity conservation which states that the terms $(S,0;0,0)$ and $(0,S;0,0)$ are zero. (See Table I for these notations.)

The above four measurements, $I^{\pm\pm}$, allow us to eliminate $I_0(t)$ and $\alpha P(t)$. Thus the parameter C_{SS} is found to be

$$C_{SS}=\frac{1}{P_BP_T}\frac{(I^{++}+I^{--})-(I^{+-}+I^{-+})}{(I^{++}+I^{--})+(I^{+-}+I^{-+})}.$$

We note that since the values of P_B and P_T for positive and negative spin directions are not the same, the expression for C_{SS} is more complicated.

The experimental layout is shown in Fig. 2. The spin of polarized protons emerging from the ZGS is in the $\vec{N}$ direction. A superconducting solenoid with a field of 12.0 T m has been constructed and placed downstream of the last quadrupole magnet. This solenoid was used to rotate the spin of the incident beam from the $\vec{N}$ to the $\vec{S}$ direction. The integral field required for a 90° rotation at $p=6$ GeV/c is

$$\int\vec{B}\cdot d\vec{l}=\frac{\pi/2}{(e/pc)g/2}=11.2\text{ T-m},$$

where $g/2=2.79$. The beam polarization was reversed each spill, thus providing well-matched running conditions for positive and negative polarization. The average beam polarization was

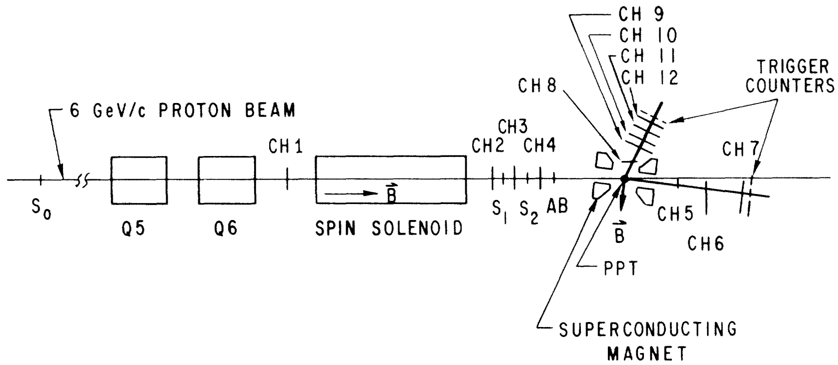

FIG. 2. Experimental apparatus. CH1 to CH12 are multiwire proportional chambers. The S_0, S_1, S_2, and AB are scintillation counters. The drawing is illustrative only and is not to scale.

$(71 \pm 5)\%$.

The proton beam at the target was 1×2 $(\text{cm})^2$ in cross section and had a divergence of $\sim\pm 5$ mrad. The beam intensity was $\sim 5\times 10^5$/pulse for small-$|t|$ $[0.05 \leq |t| \leq 0.6$ $(\text{GeV}/c)^2]$ and 1.5×10^6/pulse for large-$|t|$ measurements $[0.6 \leq |t| \leq 1.5$ $(\text{GeV}/c)^2]$.

A polarized-target magnet providing the direction of spins in the scattering plane has been constructed. The configuration of the superconducting magnet[7] used for this target is similar to the one constructed at Saclay.[8] The target was $2\times 2 \times 8$-$(\text{cm})^3$ ethylene glycol doped with $K_2Cr_2O_7$. It was aligned in a 2.5-T magnetic field and maintained in a ^{3}He cryostat at ~ 0.4 K. Polarization was dynamically produced by microwave "spin pumping" and was continuously monitored via an NMR system. For the free protons in the target, the average polarization was $(80\pm 2)\%$. Target polarization was reversed every 2–3 h to provide matched running conditions. The beam and scattered particles were detected in an array of multiwire proportional chambers of ~ 3000 wires with a 2-mm wire spacing. The experimental details and the data analyses to obtain elastic events are similar to our previous C_{NN} measurements which have been described in Ref. 1.

Figure 3 presents the result of $C_{SS}(t)$ up to $|t| = 1.5$ at 6 GeV/c. The errors shown are purely statistical. The systematic errors are estimated to be less than the statistical error. Since our measurements contain a small component of C_{SL} (see Ref. 6), the final value of C_{SS} is measured. The results of a Monte Carlo amplitude analysis using the existing 6-GeV/c data up to $|t| = 0.6$ show the value of C_{SL} to be less than 0.1.[8]

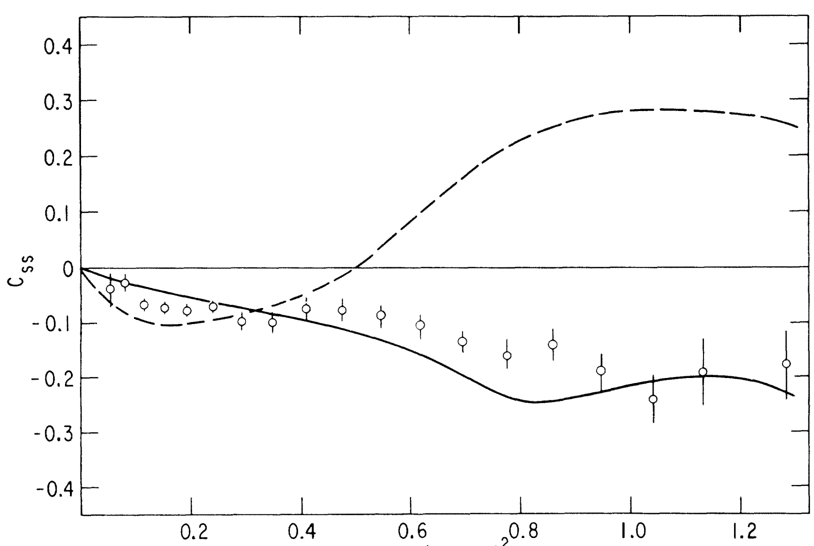

FIG. 3. C_{SS} at 6 GeV/c. The solid and dashed curves are Regge fits as described in the text.

According to Table I, the parameter C_{SS} is approximately expressed as the following:

$$I_0 C_{SS} \simeq 2\,\mathrm{Re}(N_0 U_2{}^*) = 2(\mathrm{Im}N_0)\cdot(\mathrm{Im}U_2),$$

where we assume $|N_0| \gg |N_2|$ following Field and Stevens,[10] and $|U_0| \approx |U_2|$. (N_0 is taken to be purely imaginary.) The data imply that the imaginary part of the U_2 term (corresponding to π exchange) is negative throughout the t-range measured. For comparison we show two existing attempts by Field and Stevens to describe the pp elastic-scattering process.[9] The dashed curve calculated by using the super-Regge model involves a large number of poles (P, f, ω, ρ, A_2, π, and B) and corrections due to absorption (Regge cuts). The solid curve, calculated by using the Kane model, involves the same Regge poles and absorption corrections calculated according to the Sopkovich prescription,[11] but does not require exchange degeneracy.[12] In addition, inelastic intermediate states play an important role in the Kane model. The difference of the two is primarily in the treatment of absorption correction π_c (B_c). The data clearly favor the Kane model.

During the same running period, we also measured parameters $D_{SS} = (0, S; 0, S)$ by analyzing the spin of recoil protons. The results of these measurements will be reported elsewhere.

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[1]D. Miller *et al.*, Phys. Rev. Lett. 36, 763 (1976).

[2]R. C. Fernow *et al.*, Phys. Lett. 52B, 243 (1974).

[3]G. W. Abshire *et al.*, Phys. Rev. D 12, 3393 (1975).

[4]F. Halzen and G. H. Thomas, Phys. Rev. D 10, 344 (1974). (In this paper we have used U_0 and U_2 in place of A and π.)

[5]E. Engels *et al.*, Phys. Rev. 129, 1858 (1963).

[6]The magnetic field of this target, $\vec{B}$, was aligned at $\beta = 97°$ to the beam line in the horizontal plane as shown in Fig. 2. This introduces a small $\vec{L}$ component of the target spin. The presence of the magnetic field produces an asymmetric azimuthal aperture in the detector system ($-17° < \varphi < 5°$). This and the finite azimuthal aperture of the detectors allow a nonzero polarization contribution given by $\alpha(t)P(t)$, where $\alpha(t) = \langle \sin\varphi \rangle$ and $0.08 < |\alpha(t)| < 0.10$ for $0.2 < |t| < 1.5$ $(\mathrm{GeV}/c)^2$, and allow a small C_{NN} contribution to our result. Thus C_{SS} in the equation is replaced by $\sin\beta\langle\cos^2\varphi\rangle C_{SS} + \langle\sin^2\varphi\rangle C_{NN} + \cos\beta\langle\cos\varphi\rangle C_{SL} = 0.98C_{SS} + 0.02C_{NN} - 0.12C_{SL}$.

[7]S. T. Wang *et al.*, IEEE Proceedings, 1976 Applied Superconductivity Conference, Stanford University, Stanford, California, August 1976 (IEEE Trans. Magn., to be published).

[8]P. Antones *et al.*, Nucl. Instrum. Methods 103, 211 (1972).

[9]We appreciate the consulatation of P. Johnson and G. H. Thomas in this analysis.

[10]R. Field and P. Stevens, ANL Report No. ANL/HEP CP75-73 (unpublished), p. 28.

[11]N. J. Sopkovich, Nuovo Cimento 26, 186 (1962).

[12]G. L. Kane and A. Seidl, Rev. Mod. Phys. 48, 309 (1976). (The whole amplitude rather than the pole term is approximately degenerate.)