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LETTERS

Energy Dependence of the Parameter C_{NN} in pp Elastic Scattering between 2 and 6 GeV/c*

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We have measured the spin-spin correlation parameter C_{NN} at 2, 3, 4, and 6 GeV/c over the $|t|$ range of 0.1 to 2.0 (GeV/c)^2 and have observed a striking energy and $|t|$ dependence in C_{NN}. Polarization data were simultaneously collected and are compared to previous results.

The successful acceleration of polarized protons at Argonne National Laboratory has made it possible to do a detailed study of N-N scattering amplitudes at intermediate energies. As a first step in an experimental program to determine these amplitudes and their energy dependence, we have measured the spin-spin correlation parameter, C_{NN}, in proton-proton elastic scattering at 2, 3, 4, and 6 GeV/c.[1]

The parameter C_{NN} and polarization P, expressed in terms of t-channel helicity amplitudes, are[2]

$$I_0 P = -2 \operatorname{Im}(N_0 - N_2)N_1{}^*,$$

$$I_0 C_{NN} = 2 \operatorname{Re}(U_0 U_2{}^* - N_0 N_2{}^* + |N_1|^2),$$

where $I_0 = |N_0|^2 + 2|N_1|^2 + |N_2|^2 + |U_0|^2 + |U_2|^2$ is the unpolarized cross section, and N_0, N_1, and N_2 represent natural-parity exchange terms while U_0 and U_2 represent unnatural-parity terms.

The parameter C_{NN} has been previously measured at momenta of 1.0 to 1.9 and 6.0 GeV/c.[1,3,4] Although the lower-energy data have large statistical errors, they suggest a strong energy dependence. The 2–6-GeV/c region is thus of interest in explaining the striking difference between these energies. We note that phase-shift analy-

ses exist up to about 2 GeV/c and high-energy models typically only go as low as 6 GeV/c; the present data should then help to connect these two different theoretical approaches.

When both the beam and the target are polarized normal to the scattering plane, the differential cross section is

$$I(t) = I_0(t)[1 + P_B P(t) + P_T P(t) + P_B P_T C_{NN}(t)],$$

where P_B and P_T are the beam and target polarizations, respectively.

The target used was ethylene glycol doped with $K_2Cr_2O_7$. It was aligned in a 2.5-T magnetic field and maintained in a He^3 cryostat at ~0.4 K. Polarization was dynamically produced by microwave "spin pumping" and was continuously monitored via an NMR system. The average polarization was ~80% for the free protons in the target. Target polarization was reversed every 2–3 h to provide matched running conditions.

The proton beam at the target was ~1×2 cm^2 in cross section and had a beam divergence of ~10 mrad. Beam polarization was reversed each spill, thus providing well-matched running conditions between enhancements. The average beam polarization was $(65 \pm 5)\%$.
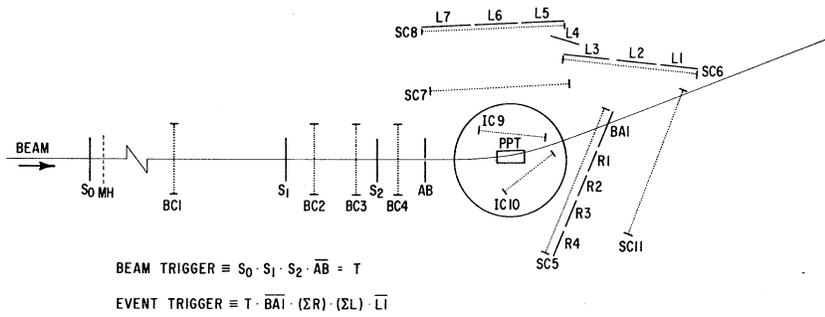
BEAM TRIGGER ≡ S₀ · S₁ · S₂ · ĀB ≡ T

EVENT TRIGGER ≡ T · B̄ĀI · (ΣR) · (ΣL) · L̄I

FIG. 1. Experimental apparatus. BC, IC, and SC are multiwire proportional chambers. The R, L and S counters are scintillation counters and MH is an array of scintillation counters used to determine upstream position of beam. PPT is the polarized proton target. The drawing is illustrative only and not to scale.

The experimental layout is shown in Fig. 1. The beam trigger was determined by a coincidence of S_0, S_1, and S_2 and anticoincidence with a hole counter AB. The event trigger was defined by the beam trigger, anti counters, and the L and R counters.

The beam and scattered particles were detected in an array of multiwire proportional chambers of ~3000 wires with a wire spacing of 2 mm. Four chambers were used to determine the beam trajectory; five large scattering chambers outside the magnetic field and two small chambers inside detected scattered and recoil protons. Each chamber consisted of a horizontal and a vertical wire plane.

The relevant kinematics were defined by the particle scattered into $SC5$ and $SC11$ (see Fig. 1). The polar angle, θ_S, and azimuthal angle, φ_S, after magnetic field corrections, define t and the production plane. Chamber resolution and vertex uncertainty yield an error of ~0.05 $(\text{GeV}/c)^2$ in t at $|t| = 1.0$ $(\text{GeV}/c)^2$ and a beam momentum of 6 GeV/c. By choosing suitable θ_S and φ_S bins a strong elastic peak is observed in the recoil-particle angular distribution, θ_R, for small $|\Delta\varphi|$, where

$$\Delta\varphi = \varphi_R - \varphi_S - 180°.$$

Signal-to-noise ratios varied from 3/1 to 8/1 depending on the $|t|$ region. Background, from quasi-elastic scattering off carbon and oxygen in the target, was subtracted using θ_R distributions for events with $|\Delta\varphi|$ values larger than the elastic events and then matching to the background on either side of the elastic peak.

Once the elastic events and their statistical errors were found they were used as input, along with P_B, ΔP_B, P_T, and beam normalization, into a χ^2 minimization program to determine simultaneously a best value for $P(t)$ and $C_{NN}(t)$ over

the entire $|t|$ range.

The data presented here include only events with $|\varphi_S| \lesssim 5°$. This sample ensures that possible contamination from the correlation term $(s, s; 0, 0)$ [5] is less than ± 8%. The analysis for the full aperture of $|\varphi_S| \lesssim 15°$ will be presented elsewhere.
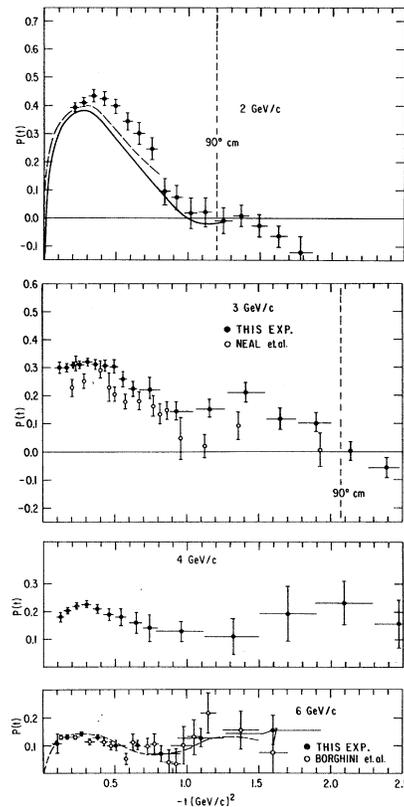
In Figs. 2 and 3 the results of $P(t)$ and $C_{NN}(t)$

FIG. 2. Polarization at 2, 3, 4, and 6 GeV/c. Comparisons with existing data are made at 3 and 6 GeV/c (Refs. 6 and 7). The solid curved for 2 GeV/c is a result of a phase-shift analysis. The dashed curves for 2 and 6 GeV/c are Regge fits.
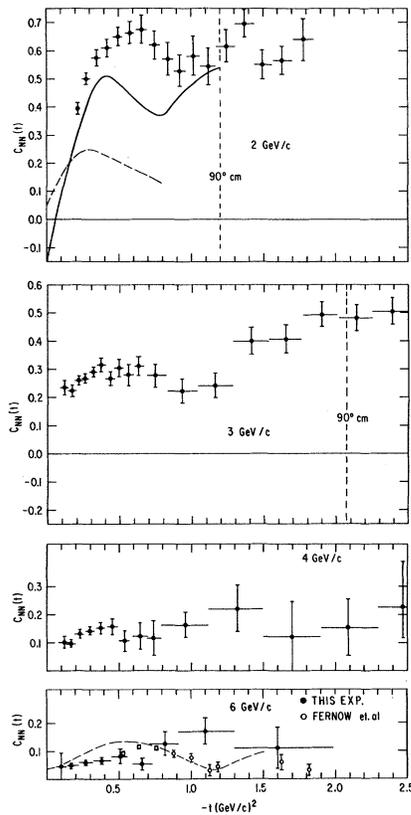
FIG. 3. C_{NN} at 2, 3, 4, and 6 GeV/c. Existing data are compared at 6 GeV/c (Ref.4). The solid curve for 2 GeV/c is a result of a phase-shift analysis. The dahsed curves for 2 and 6 GeV/c are Regge fits.

at 2, 3, 4, and 6 GeV/c are presented. The errors shown are purely statistical. Our data are compared to existing data[4,6,7] at 3 and 6 GeV/c. Systematic errors due to beam and target polarizations and to background subtraction are estimated to be less than 10% of the asymmetries shown.

We observe that C_{NN} has a stronger energy dependence than polarization does particularly at low $|t|$ ($\gtrsim 0.8$). This is not in agreement with Regge-type predictions. For example, the dashed curves at 6 and 2 GeV/c represent a parametrization[8] in terms of Regge poles, absorptive corrections, and possible lower-lying contributions; the fit was done utilizing previously available data on NN and $N\bar{N}$ scattering. While the results for polarization at 2 GeV/c are in reasonable agreement with experimental data, those for C_{NN} differ by a factor of 2–3.

Two points of interest at 2 and 3 GeV/c are the rapid increase of C_{NN} for small $|t|$ and the clearly defined dip at $|t| \sim 1.0$; these effects are less

pronounced at 4 and 6 GeV/c. It should be noted that C_{NN} at large $|t|$ with its slower falloff with energy is in qualitative agreement with an eikonal model.[9] Results of a phase-shift analysis at 2.14 GeV/c are compared with our 2-GeV/c data as shown in Figs. 2 and 3.[10]

At the present time, further experiments to measure correlation terms such as $(s, n; 0, s)$, $(s, 0; 0, s)$, $(n, 0; 0, n)$, and $(0, n; 0, n)$[5] are underway as part of a program to determine the pp scattering amplitudes uniquely.

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[1]For our earlier measuremnts, see G. Hicks et al., Phys. Rev. D 12, 2594 (1975), in which a 6-GeV/c measurement with scattering plane extending to $\varphi_S = \pm 15°$ was reported. We note here that the present data were collected with a lower accidental rate, more frequent reversal of beam polarization, and in general lower systematic errors than those reported in the above paper.

[2]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.)

[3]A. Beretvas et al., Rev. Mod. Phys. 39, 536 (1967), and Phys. Rev. 171, 1392 (1968); G. Cozzika et al., Phys. Rev. 164, 1962 (1967); Y. Ducros, Rev. Mod. Phys. 39, 531 (1967).

[4]6 GeV/c in the range of $|t| > 0.5$ (GeV/c)^2: R. C. Fernow et al., Phys. Lett. 52B, 243 (1974).

[5]For an explanation of this notation see Ref. 2.

[6]H. Neal et al., Phys. Rev. 161, 1374 (1967).

[7]M. Borghini et al., Phys. Lett 31B, 405 (1970).

[8]R. D. Field and P. Stevens, private communication, and California Institute of Technology Report No. CALT-68-534, 1976 (unpublished).

[9]C. Bourrely et al., ANL Report No. ANL-HEP-PR-75-41 (unpublished).

[10]N. Hoshizaki et al., Prog. Theor. Phys. 45, 1123 (1971); we are grateful to G. H. Thomas who has kindly supplied us with computed C_{NN} values using the results of these phase-shift analyses (solution A).