Measurements of the Asymmetries in the Differential Cross Sections for $\bar{p}p \to \bar{p}p$ and $\bar{p}p \to \pi^-\pi^+$ Using Polarized Protons*

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(Received 31 January 1972)

We report measured asymmetries as a function of polar scattering angle for the reactions $\bar{p}p \to \pi^-\pi^+$ and $\bar{p}p \to \bar{p}p$, using a polarized proton target. The annihilation data, obtained at a $\bar{p}$ momentum of 1.64 GeV/c, are the first asymmetry data to be collected for this channel. A fit of these data and published differential cross section data is made by a partial-wave expansion, and the results are compared with a previous analysis. The elastic scattering data, obtained at 1.64 and 2.55 GeV/c, are fitted with an eight-parameter strong-absorption model.

Using antiprotons incident on a lanthanum-magnesium-nitrate-type polarized proton target,[1] we have studied the reactions $\bar{p}p \to \pi^-\pi^+$ and $\bar{p}p \to \bar{p}p$. Specifically, we have measured the asymmetry in the differential cross sections for these reactions between proton polarization normal to, and antinormal to, the scattering plane,[2]

$$A = \frac{d\sigma/d\Omega_p - d\sigma/d\Omega_a}{d\sigma/d\Omega_p + d\sigma/d\Omega_a}.$$

Our annihilation data were obtained with an incident $\bar{p}$ momentum of 1.64 GeV/c and provide the first asymmetry measurements for this reaction. Previous studies of the reaction $\bar{p}p \to \pi^-\pi^+$ in this momentum range have been measurements of the differential cross sections in two low-statistics bubble-chamber experiments,[3] measurements of $d\sigma/d\Omega$ for $|\cos\theta_{\pi^-}{}^{\text{c.m.}}| \geq 0.96$ in a counter experiment,[4] and measurements of the folded differential cross sections in two counter experiments,[4,5] where only $|\cos\theta_{\pi^\pm}{}^{\text{c.m.}}|$ was determined. A partial-wave analysis,[4] performed using the counter data, showed a possible boson resonance with angular momentum $J = 5$ and mass $m_R = 2.29$ GeV ($P_{\text{lab}} = 1.60$ GeV/c). This analysis, which was limited by the lack of complete angular distributions, was dominated by resonant $J = 3$ and $J = 5$ partial waves while $J = 1$, 2, and 3 partial waves were included as background.

Our elastic-scattering data were obtained at beam momenta of 1.64 and 2.55 GeV/c and complement published results of asymmetry measurements.[6] In analyzing these data we have used a diffraction model[6] with eight parameters and, in contrast to earlier analyses, have included total-cross-section measurements[7] in the fits.

The experiment was performed at the Brookhaven National Laboratory alternating gradient synchrotron in conjunction with a previously reported K^+p elastic-scattering asymmetry measurement.[8] The experimental apparatus was essentially unchanged with the exception of the beam particle identification counters. A Cherenkov counter with a glycerin-water mixture as a

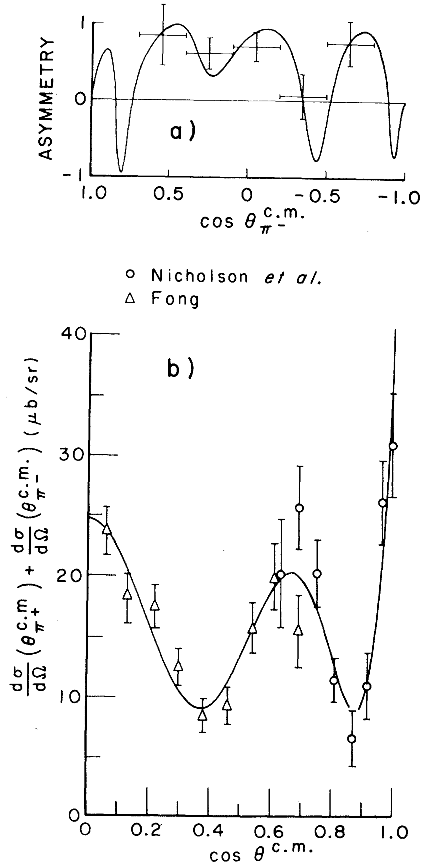

FIG. 1. Comparisons of measured data with the results of the fit described in the text for $\bar{p}p \to \pi^-\pi^+$ at 1.64 GeV/c. (a) Asymmetry measurements from this experiment. (b) Folded differential cross sections from Refs. 4 and 5.

radiator positively identified the antiprotons in the beam,[9] while a high-pressure ethylene-filled differential Cherenkov counter was used to veto residual pion contamination. Fluxes of antiprotons were 10^4 and 6.5×10^4 per 10^{12} protons incident on the production target at 1.64 and 2.55 GeV/c, respectively.

In extracting the signal events from the background, we calculated two quantities, $\Delta\theta_H$ and $\Delta\theta_V$, for each event. These quantities were the deviations of the measured horizontal and vertical scattering angles of the positively charged secondary particle from the values predicted from the measured angles for the negatively charged particle. The charges of the secondary particles were determined by the sense of bending of their trajectories in the polarized-proton-target magnet. The data were analyzed twice: once for the hypothesis of elastic scattering and again for annihilation into $\pi^-\pi^+$. Frequency distributions of events versus $\Delta\theta_H$ and $\Delta\theta_V$ were then examined to ascertain the numbers of signal events.[10]

Figure 1(a) shows the asymmetries as a function of $\cos\theta_{\pi^-}{}^{\text{c.m.}}$ for $\bar{p}p\to\pi^-\pi^+$ at a beam momentum of 1.64 GeV/c. A total of 350 events have been collected over the complete angular range. We could not collect annihilation data at 2.55 GeV/c because of the reduced cross sections. The errors shown in Fig. 1(a) are 1-standard-deviation statistical counting errors and do not include the following possible systematic errors: (1) background subtraction, approximately $\frac{1}{2}$ standard deviation for each point; (2) target polarization, approximately 5% of the quoted asymmetries; (3) beam normalization, approximately ± 0.03. We have also investigated possible polarization of the background and of the beam, and have found these effects to be consistent with zero.

Also shown in Fig. 1 are the results of a fit to these asymmetries and to the folded cross sections.[4,5] The fit was by a partial-wave expansion in which the differential cross section and asymmetry were parametrized by $d\sigma(\theta)/d\Omega=\{|f(\theta)|^2+|g(\theta)|^2\}$ and $A(\theta)=2\,\mathrm{Im}f^*g(d\sigma/d\Omega)^{-1}$, respectively, with

$$f(\theta)=\frac{1}{4k}\sum_{J=0}^{5}\{[J(2J+1)]^{1/2}S_J^- - [(J+1)(2J+1)]^{1/2}S_J^+\}P_J^0(\cos\theta_{\pi^-}{}^{\text{c.m.}}),$$

$$g(\theta)=\frac{1}{4k}\sum_{J=0}^{5}\left[\left(\frac{2J+1}{J+1}\right)^{1/2}S_J^+ + \left(\frac{2J+1}{J}\right)^{1/2}S_J^-\right]P_J^1(\cos\theta_{\pi^-}{}^{\text{c.m.}});$$

S_J^- and S_J^+ are the complex scattering matrix elements for initial states with orbital angular momentum of $l=J-1$ and $l=J+1$, respectively.

In fitting the above parametrization to the data, we chose initial values of $S_J^\pm$ to be those values found in the previous analysis of the folded cross sections.[4] The final results of our fit indicate the necessity of even partial-wave amplitudes comparable in magnitude to the odd amplitudes, and a lack of dominance by the $J=3$ and $J=5$ amplitudes. Thus we do not see supporting evidence in our energy-independent analysis for the possible $J=3$ and $J=5$ boson resonances suggested in Ref. 4.

In Fig. 2 the asymmetries for $\bar{p}p\to\bar{p}p$ at beam momenta of 1.64 and 2.55 GeV/c are shown. The data sample includes 10 000 and 26 000 events at the two momenta, respectively. The quoted errors are again only statistical, with the estimates of systematic effects as stated above.

We have attempted to fit these data with an eight-parameter model which is an extension of the five-parameter model used in Ref. 6. For simplicity the analysis is performed neglecting isospin decomposition, spin-spin interactions, and transitions in which orbital angular momentum l changes by 2. The assumptions of time reversal, parity, charge conjugation, and rotational invariance are also made. The resulting differential cross section and asymmetry are $d\sigma/d\Omega=|f(\theta)|^2+2|g(\theta)|^2$ and $A(\theta)=2\,\mathrm{Im}f^*g\times(d\sigma/d\Omega)^{-1}$. Since the spin-spin interaction and the $\Delta l=2$ transitions are neglected, only the triplet, $J=l\pm1$ elastic scattering matrix elements $S_{l\pm}{}^T$ are needed. The scattering amplitudes are then

$$f(\theta)=(i/2k)\textstyle\sum_l[(l+1)(1-S_{l+}{}^T)+l(1-S_{l-}{}^T)]P_l^0(\cos\theta_{\bar{p}}{}^{\text{c.m.}}),$$

$$g(\theta)=(i/4k)\textstyle\sum_l(S_{l+}{}^T-S_{l-}{}^T)P_l^1(\cos_{\bar{p}}{}^{\text{c.m.}}).$$

In the spirit of the phenomenological model of Frahn and Venter,[11] the parametrization of the S-matrix elements is as follows:

$$\mathrm{Re}S_{l\pm}{}^T=g_\pm(t)+\epsilon[1-g_\pm(t)],$$

$$\mathrm{Im}S_{l\pm}{}^T=\mu_\pm[1-(\mathrm{Re}S_{l\pm}{}^T)^2]^{1/2}(t/kR_\pm)^\alpha[1+(t/kR_\pm)^\alpha]^{-1},$$

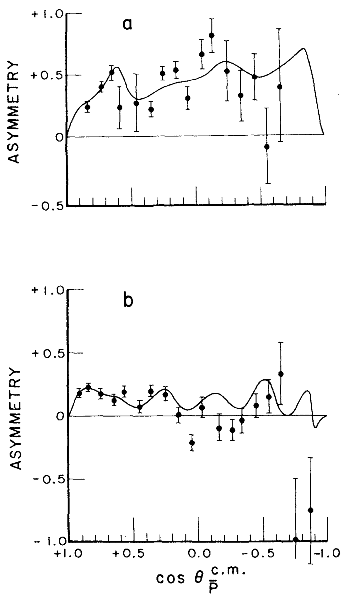

FIG. 2. Asymmetry measurements for $\bar{p}p \to \bar{p}p$ compared with fitted results. (a) Results for incident beam momentum of 1.64 GeV/c. (b) Results for incident beam momentum of 2.55 GeV/c.

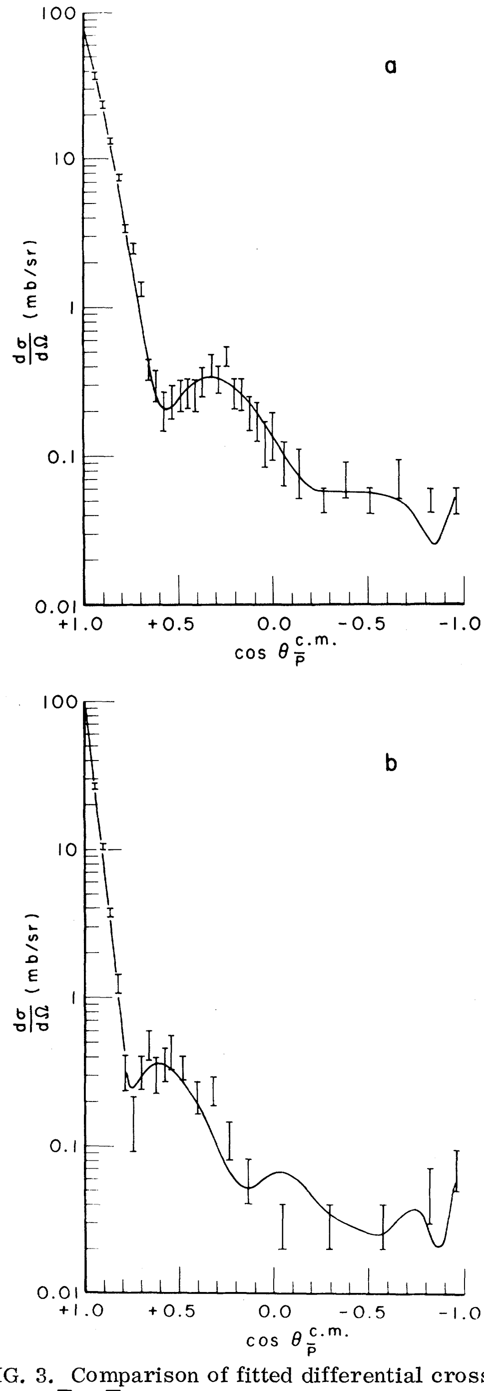

FIG. 3. Comparison of fitted differential cross sections for $\bar{p}p \to \bar{p}p$ with results of Ref. 12. (a) Incident beam momentum of 1.65 GeV/c; (b) incident beam momentum of 2.60 GeV/c.

with $t = l + \frac{1}{2}$, $g_\pm(t) = \{1 + \exp[(kR_\pm - t)/kd_\pm]\}^{-1}$, and k equal to the wave number of the particles in the center-of-mass system. The eight fitted parameters are as follows: $R_\pm$, the radius of interaction; $d_\pm$, the skin thickness or diffuseness of the edge of the interaction region; ϵ, the transparency of the interaction region for small l values; $\mu_\pm$, a parameter proportional to the real phase shift for partial waves participating in the interaction; and α, a parameter used to adjust the rate at which $\mathrm{Im}S_{l\pm}{}^T$ approaches zero as t approaches zero. The maximum value of l is 10.

The fits to polarizations and differential cross sections[12] are shown as solid lines in Figs. 2 and 3, respectively. The parameters used, and χ^2 values for the fits, are shown in Table I.

The above formulation, with its increased number of parameters over previous models, was necessary in order to fit total cross sections while maintaining reasonable fits to the backward differential cross sections. A disadvantage of such an extended parametrization is the increased number of solutions yielding comparable values of χ^2. The parameters shown are part of a family of values which vary smoothly with energy and yield fits which approximate the bulk of the existing data over the momentum range from 1.6 to 2.5 GeV/c.

The large values of χ^2 per number of degrees of freedom, especially at $P_{\mathrm{lab}} = 2.5$ GeV/c, indicate that this parametrization is inadequate to fit the totality of data. The fit is approximately correct for the low-energy point and for $d\sigma/d\Omega$ and A with $\cos\theta_{\bar{p}}{}^{c.m.} > 0$ for $P_{\mathrm{lab}} = 2.55$ GeV/c. Per-

TABLE I. Parameters for fits to $\bar{p}p$ elastic scattering data.

Parameter	Value at 1.6 GeV	Value at 2.5 GeV
R^+	1.26 ± 0.03 F	1.17 ± 0.03 F
d^+	0.28 ± 0.01 F	0.29 ± 0.01 F
R^-	1.03 ± 0.01 F	1.03 ± 0.02 F
d^-	0.04 ± 0.02 F	0.05 ± 0.01 F
μ^+	0.23 ± 0.09	0.16 ± 0.03
μ^-	-0.81 ± 0.05	-0.31 ± 0.03
ϵ	-0.05 ± 0.01	0.05 ± 0.01
α	2.0 ± 0.29	1.2 ± 0.17
χ^2	64	95
Degrees of freedom	41	33
σ_{tot} (Ref. 7)	97.81 ± 0.97 mb	81.12 ± 0.81 mb
σ_{tot} (fit)	97.50 mb	80.4 mb

haps the effects of the simplifying assumptions made above are being more strongly felt at large momentum transfers and higher energies, and the formulation of the amplitudes should thus be further expanded.

With respect to the stability of the radius of interaction as a function of energy, it is noted that R^- is constant while R^+ is not. The diffuseness of the interaction region, d, is greater for the $J = l+1$ waves, however; and we find that the rms value of the radius of the distribution function $g_+(t)$ is independent of energy.[13]

*Research supported in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)3075.

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$$R_{\text{rms}}{}^{\pm} = \frac{1}{k}\left[\frac{\int_0^\infty t^4[1-g_\pm(t)]\,dt}{\int_0^\infty t^2[1-g_\pm(t)]\,dt}\right]^{1/2}.$$

Tests for Heavy Lepton Production in Inclusive Neutrino Reactions*

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A phenomenological study is carried out for the production of heavy μ-type leptons in one-particle inclusive neutrino reactions. The muon spectrum is found to be distorted in a significant fashion from that expected with no heavy-lepton production, and sensitive tests are presented which serve to signal the fleeting presence of such excited leptons.

The existence of leptons heavier than the electron and muon is an intriguing possibility which awaits investigation at the new high-energy facilities. The question of their existence, obviously fundamental to the formulation of any complete theory of the weak interactions, was raised again several years ago by Ramm[1] (who suggested preliminary evidence for an anomalous $\pi^\pm\mu^\mp$ interaction) and, more recently, has been considered[2] as part of the solution to the $K_L \to \mu^+\mu^-$ puzzle.[3] The literature contains many weak-interaction schemes[4] which purport to involve heavy leptons