Polarization Effects in ρ^0-Meson Production in Antiproton-Proton Interactions at 22.4, 12, and 5.7 GeV/c

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(Received 6 February 1985)

The ρ^0-meson spin alignment is studied in $\bar{p}p$ interactions at 22.4 and 12 GeV/c and in the reaction $\bar{p}p \to 2\pi^+ + 2\pi^- +$ neutrals at 5.7 GeV/c. An essential ρ^0-meson spin alignment is observed. The values of the ρ_{00}^T element of the ρ^0-meson spin-density matrix in the transversity frame are 0.56 ± 0.07, 0.53 ± 0.05, and 0.54 ± 0.04 for the above-mentioned interactions, respectively. An increase of ρ_{00}^T with ρ^0 transverse momentum is obtained.

PACS numbers: 13.85.Ni

Study of the spin dependence of multiparticle production is of considerable interest as a result of the observation of an unexpected strong polarization effect in many experiments at high energies.[1] We present results of an investigation of the spin effects in ρ^0-meson production in $\bar{p}p$ interactions at 22.4, 12, and 5.7 GeV/c. In a preliminary study[2] of the reaction $\bar{p}p \to \rho_0 + X$ at 22.4 GeV/c we have obtained an indication of ρ^0-meson spin alignment at the level of 2 standard deviations, and we confirmed this result later.[3] In this analysis we have used about 45 000 and 90 000 events (1.2 and 2.2 events per microbarn) of $\bar{p}p$ interactions at 22.4 and 12 GeV/c, respectively, and about 35 000 events (3.3 events per microbarn) of the reaction $\bar{p}p \to 2\pi^+ + 2\pi^- +$ neutrals at 5.7 GeV/c. Preliminary results have already been published.[4] The data are from the exposures of the 2-m hydrogen bubble chamber at CERN (5.7 and 12 GeV/c) and the Joint Institute for Nuclear Research 2-m hydrogen bubble chamber at Serpukhov (22.4-GeV/c data) by rf-separated antiproton beams. For the data at 12 and 22.4 GeV/c all charged particles, except the protons identified by ionization ($p_{\text{lab}} < 1.2$ GeV/c) and negative particles with the longitudinal variable $x > 0.6$, have been considered as pions. Other details of the experiments can be found elsewhere.[5-7]

The angular distributions of the pions from ρ^0-meson decays (i.e., the ρ^0-production cross sections in the intervals of the decay angles) have been obtained by fitting the $\pi^+\pi^-$ effective-mass distributions over a range 0.6–0.9 GeV/c^2 for separate angular intervals. The standard fitting formula accounting for contributions of ρ^0 meson and combinatorial background has been used:

$$d\sigma/dM = \sigma_\rho f_{\rho,\text{BW}}(M) f_{\text{bkg}}(M)/I_\rho + \sigma_{\text{bkg}}(M)/I_{\text{bkg}}, \quad (1)$$

where σ_i and I_i are the corresponding cross sections and normalization integrals,

$$f_{\rho,\text{BW}}(M) = \Gamma(M)(M/q)/[(M^2 - M_\rho^2)^2 + M_\rho^2\Gamma^2(M)]$$

is the relativistic p-wave Breit-Wigner function, $\Gamma(M) = \Gamma_\rho[q/q(M_\rho)]^3(M_\rho/M)$, and $q = q(M)$ is the decay momentum. The exponential background parametrization $f_{\text{bkg}}(M) = q\exp(-\beta M)$ has been used, where the factor q takes into account the phase space. Three free parameters have been fitted: the background slope β and the cross sections σ_i. The ρ^0 width Γ_ρ and mass M_ρ have been fixed at the values 155 and 770 MeV/c^2, respectively. In the case when the ρ^0 mass has been treated as a free parameter, the fits of the total $\pi^+\pi^-$ effective-mass spectra (Fig. 1) yield M_{ρ^0} values equal to 776 ± 3, 767 ± 4, and 764 ± 6 MeV/c^2 for 5.7-, 12-, and 22.4-GeV/c data, respectively. In Fig. 2 we present the cosine of the polar-

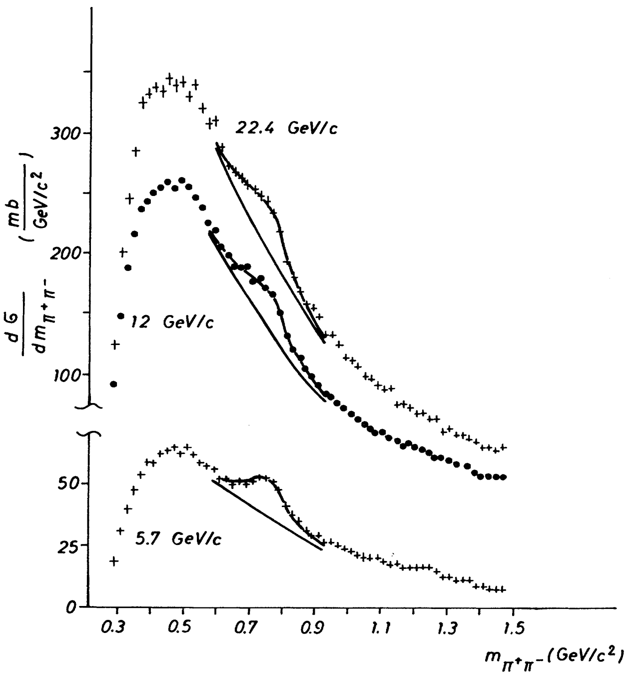

FIG. 1. Effective-mass distributions of $\pi^+\pi^-$ pairs produced in the reaction $\bar{p}p \rightarrow \pi^+\pi^- + X$ at 22.4 and 12 GeV/c and $\bar{p}p \rightarrow 2\pi^+ + 2\pi^- +$neutrals at 5.7 GeV/$c$. The curves represent the results of the fits by Eq. (1) in the mass interval 0.6–0.9 GeV/c^2.

angle θ_T distributions of the π^+ meson from the ρ^0-meson decay in the transversity frame; the z axis is directed along the normal $\mathbf{n} = \mathbf{p}_{\bar{p}} \times \mathbf{p}_\rho$ to the production plane. All the $\cos\theta_T$ distributions are essentially different from the uniform one, with minimum at $\cos\theta_T = 0$. See also Fig. 3, where the same effect is displayed in more detail for the reaction $\bar{p}p \rightarrow 2\pi^+ + 2\pi^- +$neutrals at 5.7 GeV/$c$. Since the $\cos\theta$ distribution in the decay $\rho \rightarrow \pi\pi$ has the form

$$\frac{d\sigma}{d\cos\theta} = \tfrac{1}{2}\sigma[1 + \tfrac{1}{2}(1 - 3\rho_{00})(1 - 3\cos^2\theta)], \quad (2)$$

this implies a large ($> \frac{1}{3}$) probability ρ_{00}^T of the zero ρ^0-meson spin projection on the normal to the reaction plane. As is seen from Table I, the deviation from the uniform $\cos\theta_T$ distribution ($\rho_{00}^T = \frac{1}{3}$) is about 3, 4, and 5 standard deviations for $\bar{p}p$ data at 22.4, 12, and 5.7 GeV/c, respectively. We have also analyzed the $\cos\theta$ distributions in several frames with the z axes lying in the reaction plane: In the Gottfried-Jackson frame the z axis is directed along the beam (target) momentum in the rest frame of ρ^0 produced in the forward (backward) c.m. system hemisphere, in the s-channel helicity frame, along the c.m. system ρ^0 momentum, and in the Adair frame, along the c.m. system reaction axis. All these distributions have been found opposite in character (maximum at $\cos\theta = 0$) as compared with the $\cos\theta_T$ distributions. This implies a small ($< \frac{1}{3}$) corresponding ρ_{00} value (see Table I). Note that the ρ_{00}^T can be expressed through the ρ^0 spin-density matrix elements in any frame with the z axis lying in the reaction plane in the form $\rho_{00}^T = \rho_{11} + \rho_{1,-1}$, where $|\rho_{1,-1}| \leq \rho_{11} \leq \frac{1}{2}$ (we assume parity conservation in the ρ^0-production process). It then follows that a large ρ_{00}^T value requires a small value of $\rho_{00} = 1 - 2\rho_{11}$; e.g.,

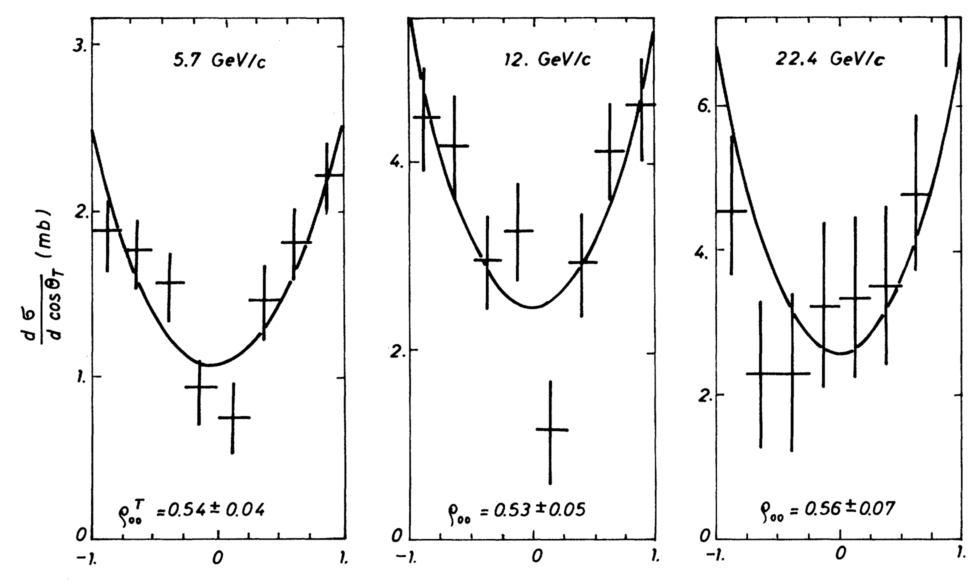

FIG. 2. ρ^0-decay angular distributions in the transversity frame ($\hat{\mathbf{z}} \parallel [\mathbf{p}_{\bar{p}} \times \mathbf{p}_\rho]$) for the reactions $\bar{p}p \rightarrow \rho^0 + X$ at 22.4 and 12 GeV/c and $\bar{p}p \rightarrow \rho^0\pi^+\pi^- +$neutrals at 5.7 GeV/$c$. The curves represent the results of the fits by Eq. (2).

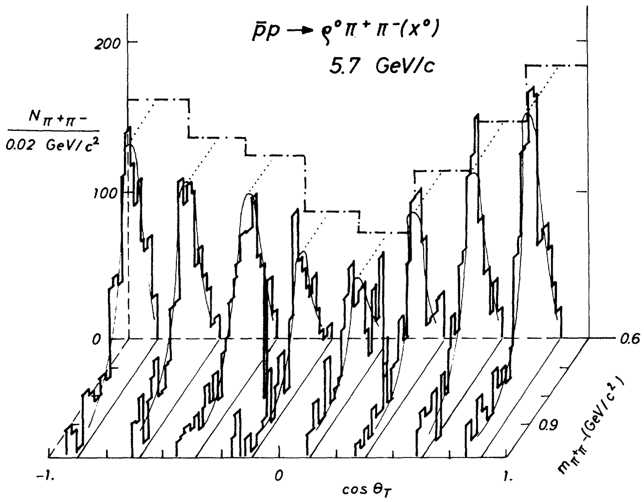

FIG. 3. ρ^0 signal in the effective-mass distributions of $\pi^+\pi^-$ pairs produced in various $\cos\theta_T$ intervals in the reaction $\bar{p}p \to 2\pi^+ + 2\pi^- +$ neutrals at 5.7 GeV/c after subtraction of the fitted background [the second term in Eq. (1)].

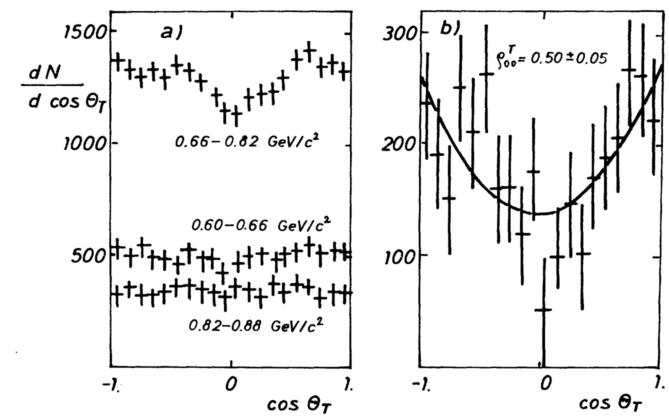

FIG. 4. Angular distribution of π^+ mesons in the transversity frame for $\pi^+\pi^-$ pairs in the reaction $\bar{p}p \to 2\pi^+ + 2\pi^- +$ neutrals at 5.7 GeV/c: (a) in different $\pi^+\pi^-$ effective-mass intervals; (b) in $\rho^0 \to \pi^+\pi^-$ decay, obtained by subtraction of the distributions in (a); the curve represents the result of the fit by Eq. (2).

$\rho^T_{00} = \frac{2}{3}$ requires $\rho_{00} \leq \frac{1}{3}$. The data of Table I satisfy this constraint. For checking the reliability of our inclusive analysis we have simulated Monte Carlo events according to the cylindrical phase space, taking into account the leading-particle effect and resonance production (assuming their isotropic decays). The simulation parameters have been chosen to achieve approximate description of the experimental one-particle characteristics as well as the $\pi^+\pi^-$ effective-mass spectra. Applying the same fitting procedure to the Monte Carlo events, we have reproduced the ρ^0 cross sections and the decay angular distributions. It should be pointed out that as a result of the cylindrical shape of the phase space the background $\cos\theta_T$ distribution behaves in an opposite way as compared with the observed effect (Fig. 2). The corresponding anisotropy is getting smaller with decreasing energy and $\pi^+\pi^-$ effective mass. Thus, at 5.7 GeV/c this distribution is only weakly changing in the mass region 0.6–0.9 GeV/c^2 (being close to the uniform one). This circumstance, as well as a relatively large signal-to-background ratio for the data at 5.7 GeV/c, make it possible in this case to obtain the $\cos\theta_T$ distribution in the $\rho^0 \to \pi^+\pi^-$ decay also by the simple subtraction method using the $\cos\theta_T$ distributions for $\pi^+\pi^-$ combinations in the ρ^0 mass region and in the adjacent regions (Fig. 4). The resulting value $\rho^T_{00} = 0.50 \pm 0.05$ agrees with the corresponding value in Table I. At higher primary momenta the background $\cos\theta$ distribution is rapidly changing with increasing mass and cannot be subtracted without detailed knowledge of its mass dependence. For the 12- and 22.4-GeV/c data we have checked the influence of $K^\pm$, $\bar{p}$, and p misidentification and reflections of K^{*0}, $\bar{K}^{*0}$, Δ^0, and $\bar{\Delta}^0$ decays, and it was found that the observed ρ^0-spin alignment could only be slightly weakened. For 22.4-GeV/c data the K^0_S mesons and identified protons were used for quantitative estimates as well. The resulting corrected value $\rho^T_{00} = 0.59 \pm 0.08$ is in agreement with the value given in Table I. It should be noted that the simple exponential background parametrization ensures a good description of the $\pi^+\pi^-$

TABLE I. Fitted values of ρ_{00} and (in parentheses) χ^2/d.o.f. for the reactions $\bar{p}p \to \rho^0 + X$ at 22.4 and 12 GeV/c and $\bar{p}p \to \rho^0\pi^+\pi^- +$ neutrals at 5.7 GeV/c.

p_{lab} (GeV/c)	Transversity frame	Gottfried-Jackson frame	Helicity frame	Adair frame
5.7	0.54 ± 0.04 ($\frac{8}{6}$)	0.21 ± 0.04 ($\frac{3}{6}$)	0.25 ± 0.04 ($\frac{7}{6}$)	0.24 ± 0.04 ($\frac{10}{6}$)
12	0.53 ± 0.05 ($\frac{10}{6}$)	0.15 ± 0.05 ($\frac{12}{6}$)	0.27 ± 0.05 ($\frac{3}{6}$)	0.15 ± 0.05 ($\frac{12}{6}$)
22.4	0.56 ± 0.07 ($\frac{9}{6}$)	0.19 ± 0.08 ($\frac{5}{6}$)	0.29 ± 0.08 ($\frac{7}{6}$)	0.33 ± 0.08 ($\frac{4}{6}$)

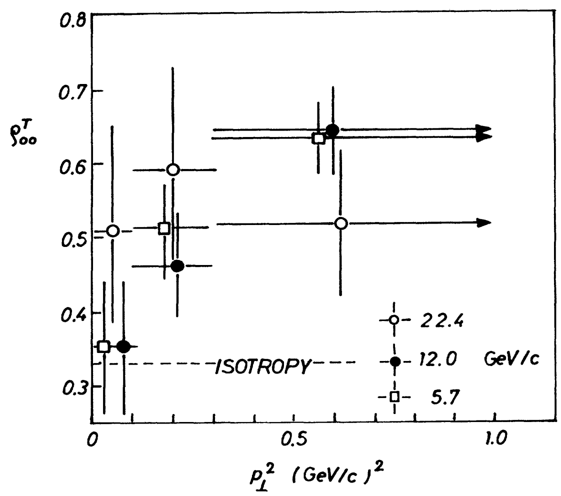

FIG. 5. $p_\perp^2$ dependence of ρ^T_{00} and ρ^0 meson produced in the same reactions as in Fig. 2.

effective-mass spectra in the narrow mass region quoted above. In wider mass intervals, however, a more complicated background parametrization, e.g., $f_{bkg} = q^\alpha \exp - (\beta M)$, could be required. Also, contributions of, e.g., f^0 and the reflection of the $\omega \to \pi^+\pi^-\pi^0$ decay should be taken into account. The uncertainty of the background form may cause systematical errors in ρ_{00} values. E.g., we have found systematically smaller ρ^T_{00} values in the case when the $\rho + f$ mass interval (0.55–1.5 GeV/c^2) was analyzed ($\Delta\rho^T_{00} \simeq -0.1$ at 22.4 GeV/c). This partly explains the small ρ^T_{00} value ($\rho^T_{00} = 0.26 \pm 0.04$) obtained in a similar analysis of $\bar{p}p$ data at 32 GeV/c.[8]

Note that the $\cos\theta$ distributions in the reaction $pp \to \rho^0 + X$ at 24 GeV/c practically coincide with the uniform one ($\rho^T_{00} \simeq \frac{1}{3}$).[9] This and the dominant contribution of annihilation channels in the reactions $\bar{p}p \to \rho^0\pi^+\pi^-$ + neutrals at 5.7 GeV/c ($\sim 100\%$) and $\bar{p}p \to \rho^0 + X$ at 12 GeV/c ($\sim 70\%$), as well as large annihilation contribution in the reaction $\bar{p}p \to \rho^0 + X$ at 22.4 GeV/c ($\sim 50\%$), make it possible to connect the observed ρ^0-spin alignment mainly with the annihilation mechanism. We should be careful, however, to attribute the difference of the ρ^0 yields in $\bar{p}p$ and pp interactions to annihilation reactions only. E.g., in the quark fusion model,[10] the difference $(\bar{p}p - pp) \to \rho$ corresponds to the fusion of valence quark and antiquark which can contribute to both $\bar{p}p$ annihilation and nonannihilation. A study of the spin-alignment effects in nonannihilation channels might be interesting in this context. With the assumption of no ρ^0-spin alignment in nonannihilation channels, a rough equality of the measured ρ^T_{00} elements for 5.7-, 12-, and 22.4-GeV/c data indicates an increase of ρ^T_{00} in annihilation channels with increasing energy (in annihilations at 22.4 GeV/c the estimated value of ρ^T_{00} would reach ~ 0.7). If such an increase saturates at ~ 20 GeV/c, we can predict a decrease of ρ^T_{00} for $\bar{p}p$ interactions at higher energies due to decreasing annihilation fraction (e.g., $\rho^T_{00} \sim 0.45$ at ~ 30 GeV/c). Models for polarization mechanism in $\bar{p}p$ interactions have been discussed elsewhere.[11–13]

For further understanding of the dynamical origin of the observed polarization effect we present in Fig. 5 the $p_\perp^2$ dependence of ρ^T_{00}. A significant increase of ρ^T_{00} with $p_\perp^2$ for 5.7- and 12-GeV/c data is observed. Similar behavior has been seen for hyperon polarization in nucleon-fragmentation reactions.[1]

We wish to thank the CERN–Prague Collaboration for their $\bar{p}p$ data at 5.7 GeV/c and the Amsterdam–Helsinki–Liverpool–Stockholm Collaboration for their 12-GeV/c $\bar{p}p$ data.

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