Decay Distribution of High–Transverse-Momentum Rho Mesons

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The exclusive process $\pi^- p \to \rho^- p$ has been measured at 90° c.m. with an incident pion momentum of 9.9 GeV/c. We present data on the angular dependence of the decay $\rho^- \to \pi^- \pi^0$. We observe a strong azimuthal dependence in the decay in the c.m. helicity frame of the ρ. Such an azimuthal dependence is not compatible with SU(6) valence-quark perturbation calculations.

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Hadron elastic scattering at 90° in the center-of-mass (c.m.) system is characterized by an energy dependence strongly suggesting that for s (center-of-mass energy squared) greater than 10 GeV^2 the hadron scattering amplitude is built up from valence-quark subprocesses.[1,2] These results have motivated attempts to calculate exclusive hadron scattering by use of SU(6) wave functions and lowest-order perturbative QCD.[3,4] Such calculations, although still in progress, will give results of the normalization, the s dependence, and the spin dependence of these processes. From dimensional arguments, it is predicted that these results must agree with the observed s dependence of elastic scattering. Related calculations such as that of the pion and proton form factors also result in a correct functional dependence on t (invariant momentum transfer squared) but may give an unrealistic normalization.[5]

In these QCD-based models, since a few light quarks carry all of the hadron helicity, general constraints on the spin dependence of amplitudes may be inferred without explicit calculation. If the helicity of a hadron is the sum of the helicities of its valence quarks, whose masses (m) are much smaller than their subenergies (E), then the quark helicity-flip amplitude is suppressed relative to the nonflip amplitude by a factor of m/E. Since the quark spins cannot flip, the sum of the initial-state helicities must equal the sum of the final-state helicities.[6] This result may be contrasted with exclusive scattering via particle exchange. For example, the exchange of a meson in the natural-parity series would lead to violation of this helicity rule.

A spin-1 particle like the ρ, which is produced and decays in a parity-conserving process, will decay with a normalized angular distribution of the following form:

$$(4\pi/3)\, W(\theta,\phi) = r_{0,0}\cos^2(\theta) + r_{1,1}\sin^2(\theta) - r_{1,-1}\sin^2(\theta)\cos(2\phi) - \sqrt{2}\,\mathrm{Re}(r_{1,0})\sin(2\theta)\cos(\phi),$$

where θ and ϕ are the spherical polar angles measured in the c.m. helicity frame of the ρ. The coefficients $r_{m,n}$ are the final-state density-matrix elements of the ρ. This 3×3 matrix can be expressed in terms of the c.m.-helicity-frame amplitudes for the scattering process. For initial-state proton helicity m, final-state proton helicity n, and ρ helicity i, these are denoted $A^i_{n,m}(s,t)$. With a pion beam and unpolarized proton target, the unnormalized ρ density-matrix elements are given by

$$r_{i,i'} = \sum_{m,n} A^i_{m,n} A^{i'*}_{m,n}.$$

The consequence of a light-valence-quark perturbation calculation, that the sum of the initial-state particle helicities is conserved, requires the amplitudes $A^i_{n,m}$ to vanish unless

$$m = i + n.$$

It follows that $r_{1,0}$ and $r_{1,-1}$ must vanish and that the angular distribution reduces to a function of $\cos^2(\theta)$ only:

$$(4\pi/3)\, W(\theta,\phi) = r_{1,1} + (r_{0,0} - r_{1,1})\cos^2(\theta).$$

A clear test of the viability of such a model is the absence of ϕ dependence in the decay distribution of the ρ.

A corollary of this helicity-conservation rule is that if the scattering does not involve the exchange of quarks but only gluons, then the helicities of the initial two particles are individually conserved. Then only

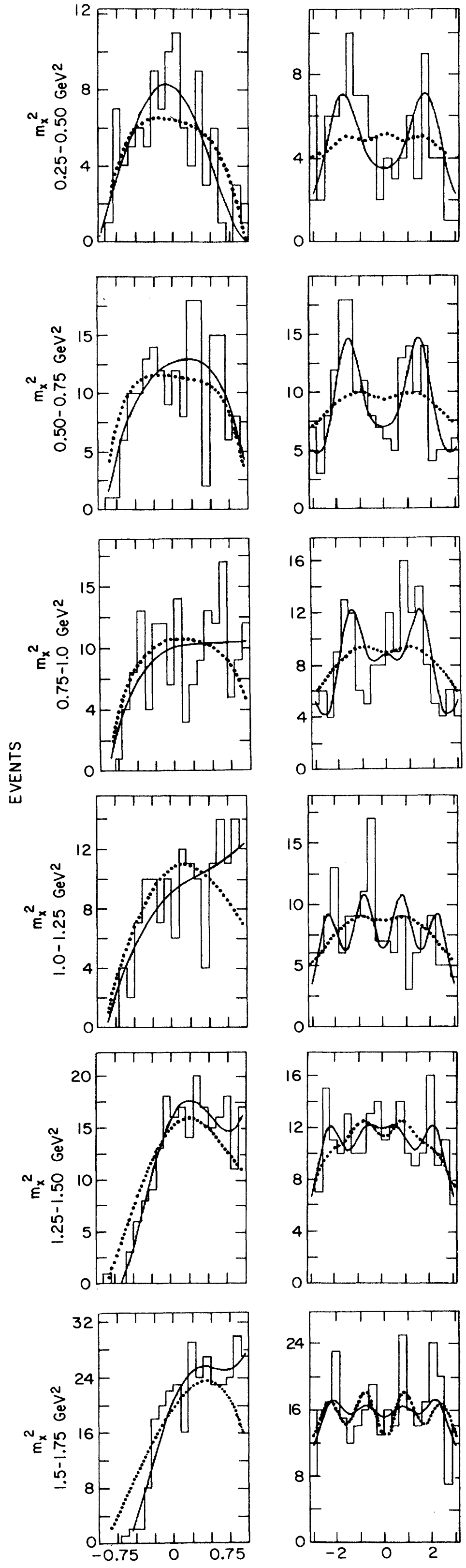

FIG. 1. cosθ and ϕ projections of the decay π^- for the reaction $\pi^- p \rightarrow p + X$, $X \rightarrow \pi^- \pi^0$. The angles are in the c.m. helicity frame of X. The projections are shown for six missing-mass bins (m_X^2). The dots superimposed over the data represent a Monte Carlo simulation of the acceptance and the solid lines are results from the maximum-likelihood fit described in the text.

$r_{0,0}$ can be nonzero.

The observation of $\pi^- p \rightarrow \rho^- p$ at 90° c.m. has been described in the preceding paper.[7] A magnetic spectrometer measured the momentum of the large-angle final-state proton. The resolution of the spectrometer was $\Delta p/p = 0.5\%$ and $\Delta\theta = 1$ mrad (FWHM). From this and the measurement of the incident-pion momentum and angle, it was possible to deduce the final-state-meson mass and the three-momentum. The uncertainty in the square of the missing mass was 0.23 GeV^2, the missing momentum was determined to within 2%, and the direction of this final-state meson was determined to within ± 3 mrad.

The particles produced in the decay of the final-state meson resonance were tracked in a side array consisting of seven planes of wire chambers. The side array measured only the direction of charged particles in the decay. Neutral particles were not observed. To deduce the c.m.-helicity-frame decay distribution of the $\rho^- \rightarrow \pi^- \pi^0$, the direction of the decay π^- was measured relative to the missing-momentum vector. This direction was then transformed to the ρ c.m. helicity frame, yielding angles θ and ϕ. The transformation of the angles has two solutions. The more forward solution was chosen in each case. At the mass of the ρ this was correct throughout 95% of the solid angle, but the problem is more severe at higher missing mass. The effect of choosing the forward solution was to deplete the distribution near $\cos(\theta) = -1$. In addition, the very forward decays [near $\cos(\theta) = 1$] were suppressed by a cut used to eliminate the resolution-smeared tail of the elastic-$\pi^- p$-scattering signal. Neither of these complications significantly biased our acceptance in ϕ.

We have fitted the angular distributions with a subset of the spherical harmonics representing all parity-conserving two-pion decays,

$$W(\theta,\phi) = \sum_{\substack{L,M \\ M \geq 0}} H_M^L D_M^L(\theta,\phi),$$

where

$$D_M^L(\theta,\phi) = [(2L+1)/(4\pi)]^{1/2}(2-\delta_{M,0})\mathrm{Re}[Y_M^L(\theta,\phi)],$$

with coefficients or moments given by the H_M^L's. The experimental acceptance was calculated with a Monte Carlo program as a function of missing mass, $\cos(\theta)$, and ϕ. The data, weighted for acceptance, were fitted by a maximum-likelihood method[8] with the first fifteen of these functions ($L=0$ to 4). The moments (H^L_M's) were determined for each of six missing-mass intervals ranging from 0.25 to 1.75 GeV^2. A bin width of 0.25 GeV^2 was chosen to achieve sufficient statistics for the polarization analysis.

In Fig. 1, the $\cos(\theta)$ and ϕ projections of the data are shown for each of the six mass bins. The acceptance and the results from the fits are superimposed over the data. The ϕ dependence is seen in the ρ mass region; this ϕ structure disappears at higher mass.

The allowed alignment for a spin-1 ρ decaying to two pions is completely described by $L=0$ and $L=2$ moments although other moments can be produced by interference between the ρ and nonresonant background. In general, quadrupole ($L=2$) moments are due to the ρ ($J=1$) decays and any higher-spin ($J>1$) decays. If the ρ were the only component present in a particular mass region, the observed moments would be related to c.m.-helicity-frame density-matrix elements:

$$H^0_0 \operatorname{Re}(r_{m,n}) = \sum_{\substack{L,M \\ L=0,2}} (-1)^k \frac{2L+1}{3} \frac{\langle LM|1m;1-n\rangle}{\langle L0|10;10\rangle} H^L_M,$$

where $k=n$ for $M>0$ and $k=m$ otherwise, and where the $\langle LM|Jm;J'm'\rangle$ are Clebsch-Gordan coefficients. We estimate that only 60% $\pm$10% of the events in the ρ mass region are from the ρ resonance.[7] If the remaining background does not contribute to the quadrupole moments, then the above relation is valid with H^0_0 (the total number of events) replaced by $0.6H^0_0$. In terms of the ratio $T^L_M = H^L_M/H^0_0$, the density-matrix elements become

$$r_{0,0} = \tfrac{1}{3} + \tfrac{5}{3} T^2_0/0.6,$$

$$r_{1,1} = \tfrac{1}{3} - \tfrac{5}{6} T^2_0/0.6,$$

$$r_{1,-1} = -(5/\sqrt{6}) T^2_2/0.6,$$

$$\operatorname{Re}(r_{1,0}) = -(5/\sqrt{12}) T^2_1/0.6.$$

In Figs. 2(a)–2(c) the ratios of quadrupole to scalar moments are shown for each of the six mass bins. Figure 2(d) shows the uncorrected mass distribution for data used in this analysis including a fit to the background.[7] The uncertainty in the measurement of moments was obtained by our generating Monte Carlo test distributions which contained numbers of events similar to the data sets. These distributions were then subjected to the fitting procedure to determine the errors. Since the experimental biases tend to affect the $\cos(\theta)$ distribution much more than the ϕ distribution, there are large errors on the determination of T^2_0.

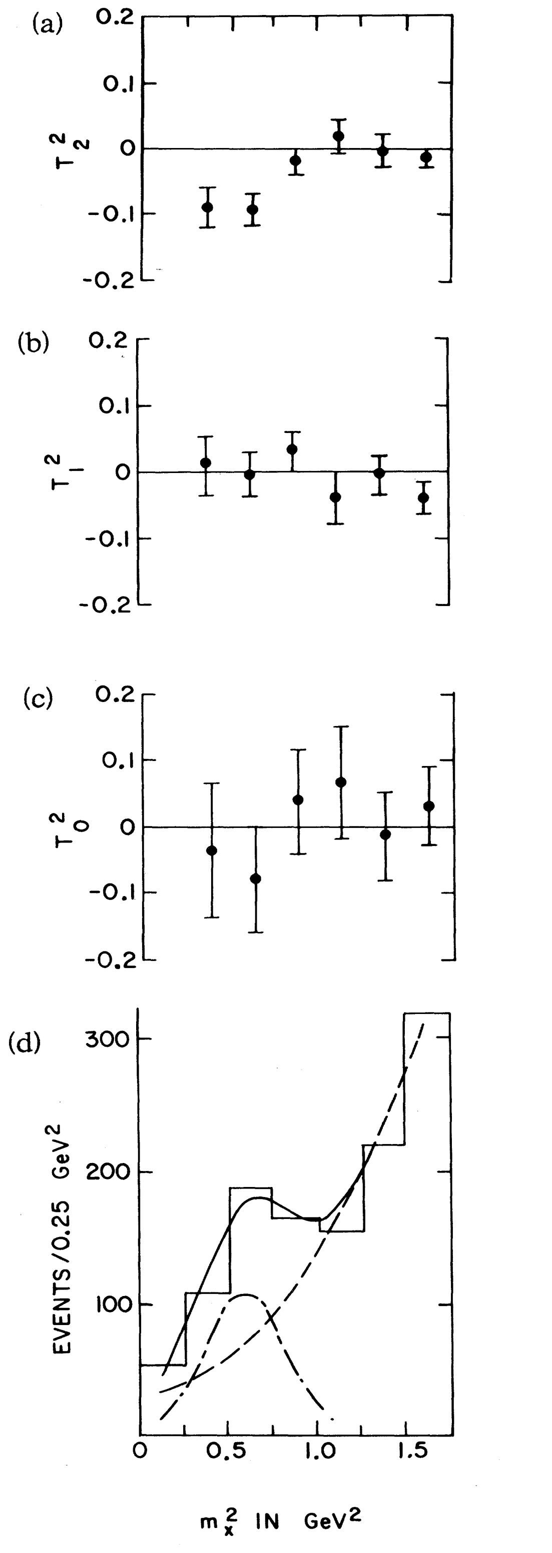

FIG. 2. (a)–(c) Ratios of quadrupole to scalar moments as a function of the square of the missing mass. (d) Missing-mass distribution for uncorrected events with a background fitted as described in Ref. 7.

T_1^2 and T_2^2 are well determined, however.

Within the ρ mass region (0.25–0.75 GeV^2), the measured quadrupole moments may be explained by ρ density-matrix elements:

$$r_{0,0}=0.12 \pm 0.30, \quad r_{1,1}=0.44 \pm 0.15,$$

$$r_{1,-1}=0.32 \pm 0.10, \quad \mathrm{Re}(r_{1,0})=-0.01 \pm 0.05.$$

The errors given here are statistical. The effect of background on the quadrupole structure has not been estimated. However, we observe that in the mass region above the ρ, the structure in ϕ is small.

Note in particular the large values for $r_{1,1}$ and $r_{1,-1}$. While acceptance biases reduce the sensitivity of our $\cos(\theta)$ measurement, our measurement of the ϕ distribution is relatively unbiased. At the ρ mass, we observe strong quadrupole structure in the ϕ distribution of the decay. This effect vanishes at higher missing mass. We can test for the significance of the ϕ dependence by comparing the fit to the acceptance in that projection. The probability that the distributions are uniform is 3.3×10^{-5}, while the probability of a fit with an expansion up to terms in $\cos(2\phi)$ is 3.6×10^{-2}. Folding the ϕ plot around 180° to remove a systematic asymmetry produces probabilities of 2.2×10^{-5} and 0.18.

The large value of $r_{1,-1}$ implies that the helicity amplitudes which violate the helicity-conservation rule are not small compared to the other amplitudes. It is difficult to see how any light-quark SU(6) calculation such as perturbative QCD could account for this result. The nonconservation of helicity may require that very-low-energy sea quarks, which may have large spin-flip amplitudes, must be considered in order to describe correctly the spin effects in large-angle exclusive scattering. Two phenomenological models can give an azimuthal dependence similar to the data. One model is based on a geometric description of quark confinement and is dominated by meson exchange[9]; in the other model a single quark scatters through a large angle, while the other valence quarks are spectators which recombine with the scattered quark.[10]

The only previous measurements of the ρ density-matrix elements have been for forward scattering ($|t| < 1.0\ \mathrm{GeV}^2/c^2$). In results previously reported, near $-t=1\ \mathrm{GeV}^2/c^2$, angular distributions have been observed which are very similar to those of this experiment.[11]

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