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Study of Inclusive Vector-Meson Production in $\pi^- p$ Interactions at 15 GeV/c

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We examine the polarization properties exhibited by ρ^0's and ω^0's in the reactions $\pi^- + p \rightarrow \rho^0 + X^0$ and $\pi^- + p \rightarrow \omega^0 +$ charged particles at 15 GeV/c. ρ^0 production is analyzed in the framework of the triple Regge model. The trajectory coupled to the π^- ρ^0 is $\alpha(t) = (-0.12 \pm 0.07) + (0.78 \pm 0.21)t$ in good agreement with the π trajectory. The properties of the system recoiling against the ρ^0 (off-shell "π^-"p reaction) are very similar to those of the final states of on-shell $\pi^- p$ reactions at the same center-of-mass energy.

Extensive studies have been published in the last few years on the inclusive production of stable particles. Fewer studies have been made of the inclusive production of resonances. These analyses, especially at high energies, suffer from limited statistics and particle identification problems. However, they are badly needed not only to understand problems like direct pion production, clustering phenomena, or correlations among secondaries[1] but also to understand the nature of the reaction mechanisms involved.[2] Although inclusive cross sections for ρ^0 production and semi-inclusive ω^0 production have been reported previously, this is the first study that has investigated the polarization properties of these resonances.

The data come from an exposure of the Stanford Linear Accelerator Center 82-in. hydrogen bubble chamber to a π^- beam of 15 GeV/c nominal incident momentum. About 450 000 pictures were taken, measured by the Massachusetts Institute of Technology precision encoding and pattern recognition (PEPR) system, and processed through the GEOMAT-SQUAW chain. All negative particles were assumed to be pions while for positive tracks with momentum less than 1.2 GeV/c unambiguous identification of protons and pions was achieved. For higher momentum, all positive particles were considered to be pions. Further details about event selection criteria and related topics are given elsewhere.[3]

In this Letter we present data on the reactions

$$\pi^- + p \rightarrow \rho^0 + X^0, \tag{1}$$

$$\pi^- + p \rightarrow \omega^0 + \text{charged particles}, \tag{2}$$

and we concentrate on the different polarization properties exhibited by ρ^0's and ω^0's.

The cross sections of 4.72 ± 0.37 mb and 325 ± 40 μb for Reactions (1) and (2), respectively, have been obtained by fitting the inclusive $\pi^+\pi^-$ and semi-inclusive $\pi^+\pi^-\pi^0$ effective-mass distributions by Breit-Wigner forms plus additional polynomial background terms. The invariant cross sections

$$\sigma(x) = \int \frac{E^*}{p_{\parallel \max}^*} \frac{d^2\sigma}{dx\, dp_T^{\,a}}\, dp_T^{\,2} \tag{3}$$

have been obtained by repeating the fits in the appropriate x bins.

It has been shown[2] that if we define

$$\sigma_0(x) = \int \frac{E^*}{p_{\parallel \max}^*} \rho_{00} \frac{d^2\sigma}{dx\, dp_T^2} dp_T^2, \tag{4}$$

$$\sigma_\pm(x) = \int \frac{E^*}{p_{\parallel \max}^*} (\rho_{11} \pm \rho_{1-1}) \frac{d^2\sigma}{dx\, dp_T^2} dp_T^2, \tag{5}$$

where $\rho_{mm'}$ denotes the s-channel helicity vector-meson density matrix, these terms can be given the same interpretation that applies in quasi two-body phenomenology, provided the appropriate kinematic limit is taken (i.e., small t and large x).

We have measured the helicity-0, unnatural-parity-exchange contribution (4) and helicity-1 projection due to natural/unnatural parity exchange (5) (according to the +/− sign) by applying the S-P interference formalism described by Aguilar-Benitez *et al.*[4] In Fig. 1 we show these quantities for both Reactions (1) and (2); the solid lines represent the integrated invariant cross section.[5] The following two observations can be made: (a) σ_0 represents a major contribution to Reaction (1), and although σ_0 is comparable to σ_+ and σ_- in the central region, it represents the dominant contribution in the beam fragmentation region; (b) for Reaction (2) the contributions σ_0 and $\sigma_\pm$ are equally important.

This is an indication that both mechanisms known to be responsible for vector-meson production, namely, vector-meson production in the central and in the beam fragmentation regions, have very different properties; the former could be described by a thermodynamic model, and the latter has properties similar to quasi two-body reactions. Furthermore, it can be shown[5] that the increase in σ_0 for Reaction (1) takes place preferentially in the very low-P_T^2 [$P_T^2 \leq 0.2$ (GeV/c)^2] region, while no significant P_T^2 structure is observed for the different contributions responsible for ω^0 production.

The main conclusion that one is tempted to draw from this analysis is that ρ^0 production in the beam fragmentation region is due to π exchange. The extraction of the π trajectory from ρ^0 production data in quasi two-body charge-exchange reactions is well known to be a complex issue.[6] Therefore, to gain further insight into the reaction mechanisms responsible for ρ^0 production in the beam fragmentation region, we have attempted to describe the invariant cross section in the context of the triple Regge model,

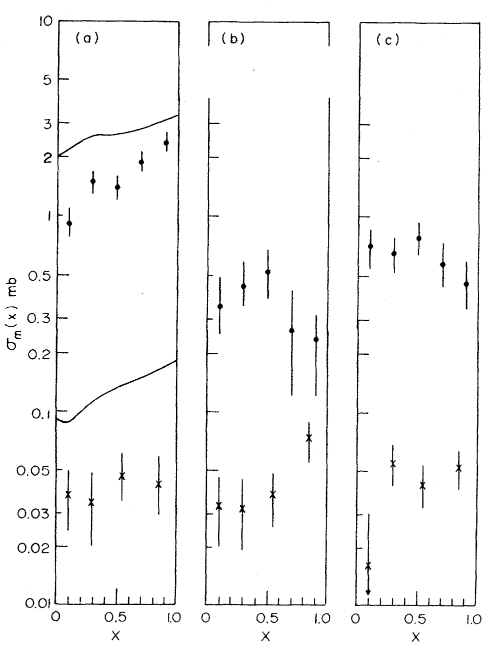

FIG. 1. Comparison of the reactions $\pi^- + p \rightarrow \rho^0 +$ anything (●) and $\pi^- + p \rightarrow \omega^0 +$ charged particles (×): (a) $\sigma_0(x)$, (b) $\sigma_+(x)$, (c) $\sigma_-(x)$ (see text for definitions). The solid curves in (a) represent an eye guide line to the corresponding invariant cross sections $\sigma(x)$.

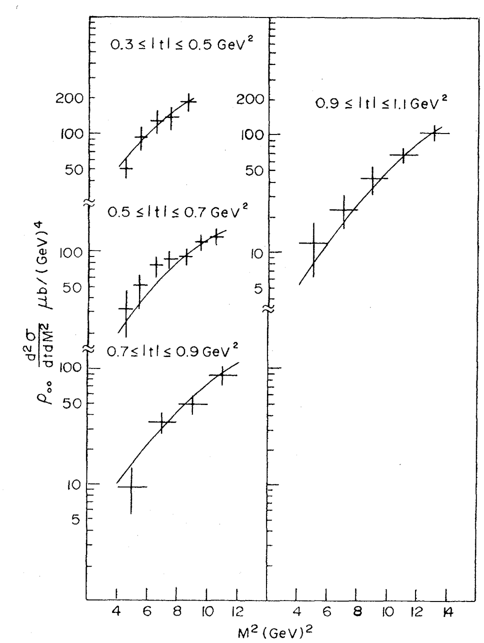

FIG. 2. Double-differential cross section $\rho_{00} d^2\sigma/dt\, dM^2$ for $\pi^- + p \rightarrow \rho^0 + X^0$. The solid lines represent the results of triple-Regge analysis.

using the following expression[7]:

$$\frac{d^2\sigma}{dt\,dM^2}=\sum_{ijk}\frac{1}{s^2}G_{ijk}(t)\left(\frac{s}{M^2}\right)^{\alpha_i(t)+\alpha_j(t)}(M^2)^{\alpha_k(0)}, \tag{6}$$

where t is the momentum transfer from the incident π^- to the outgoing ρ^0, M^2 is the square of the mass of the system of particles recoiling against the ρ^0, α_i and α_j stand for the trajectories coupled to the π^--ρ^0 vertex, α_k is the exchange responsible for $ip\to jp$ scattering, and $G_{ijk}(t)$ denotes the corresponding triple Regge coupling.

The above expression can be simplified if we take its projection due to spin-0 unnatural parity exchange (π exchange), namely,

$$\rho_{00}\frac{d^2\sigma}{dt\,dM^2}=s^{2\alpha_\pi(t)-2}\left[G_{\pi\pi\mathrm{P}}{}^{(t)}(M^2)^{1-2\alpha_\pi(t)}+G_{\pi\pi\mathrm{R}}{}^{(t)}(M^2)^{0.5-2\alpha_\pi(t)}\right], \tag{7}$$

where we have assumed the Pomeron and Reggeon intercepts to be 1 and 0.5, respectively, and we have written the triple Regge couplings in the following way:

$$G_{\pi\pi\mathrm{P}}{}^{(t)}=\frac{1}{4\pi}\frac{g_{\rho^0\pi\pi}{}^2}{4\pi}K(t)\frac{\exp[b_\pi(t-\mu^2)]}{(t-\mu^2)^2}\sigma_T{}^{\mathrm{P}}(\pi^-p),$$
$$G_{\pi\pi\mathrm{R}}(t)=\frac{1}{4\pi}\frac{g_{\rho^0\pi\pi}{}^2}{4\pi}K(t)\frac{\exp[b_\pi(t-\mu^2)]}{(t-\mu^2)^2}\sigma_T{}^{\mathrm{R}}(\pi^-p). \tag{8}$$

Here $g_{\rho^0\pi\pi}{}^2/4\pi$ is the $\rho^0\pi\pi$ coupling constant given by Nielsen and Oades,[8] μ is the mass of the pion, $K(t)$ is a kinematical factor $K(t)=[(m_{\rho^0}+\mu)^2-t]\times[(m_{\rho^0}-\mu)^2-t]/m_{\rho^0}{}^2$ as in Pumplin,[9] and finally $\sigma_T{}^{\mathrm{P}}$ and $\sigma_T{}^{\mathrm{R}}$ (20 mb and 26 mb GeV, respectively) are parameters giving a good description of the π^-p total cross sections parametrized as $\sigma_T{}^{\mathrm{P}}+\sigma_T{}^{\mathrm{R}}/\sqrt{s}$.

The experimental distribution for $\rho_{00}\,d^2\sigma/dt\,dM^2$ restricted to $|t|\leq 1.1$ (GeV/c)^2 and 4 (GeV/c)^2, shown in Fig. 2, was fitted by expression (7). The results obtained are $\alpha_\pi(t)=(-0.12\pm0.07)+(0.78\pm0.21)t$ and $b_\pi(t)=-0.34\pm0.32$, which agree with the expectations for a π trajectory given by a universal Regge slope and an intercept near zero. In Fig. 2 the results of this fit are also displayed.

In order to check the consistency of these results, we proceeded to make some phenomenological tests. If the reaction $\pi^-+p\to\rho^0+X^0$ is in fact due to π exchange, we could compare our data on $\pi^-+p\to\pi^-+X^+$ at 3.9-GeV/c incident-beam momentum[10] with data for "π^-"$+p\to\pi^-+X'^+$ obtained from analysis of the X^0 system (where $X^0\to X'^++\pi^-$) recoiling against the ρ^0 in the present experiment. However, the ρ^0 sample must be correctly defined, requiring not only a cut on the $\pi^+\pi^-$ effective-mass distribution $[0.62\leq m(\pi^+\pi^-)\leq 0.92]$ but also an appropriate cut in x (0.65–0.70) which will ensure that M^2 is centered approximately around the s value corresponding to π^-p interactions at 3.9 GeV/c. Figure 3(a) shows the invariant cross sections for $\pi^-+p\to\pi^-+X^+$ at 3.9 GeV/c and what we observe in "π^-"$+p\to\pi^-+X'^+$, where $X^0=\pi^-+X'^+$ is defined as discussed above. The distributions agree well not only in shape but in magnitude. In Fig. 3(b) we compare the multiplicity distributions for $\pi^-+p\to$anything at 3.9 GeV/c and "π^-"$+p\to X^0$. Again, agreement between both distributions is observed. Finally in Fig. 3(c) we show the differential cross section for "π^-"$+p\to\pi^-+p$ obtained by looking at the reaction $\pi^-+p\to\rho^0+\pi^-+p$. The distribution shows an exponential be-

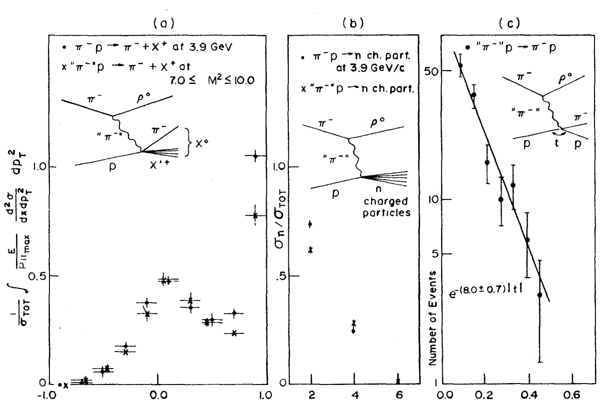

FIG. 3. Comparison between on- and off-mass-shell π^--induced reactions. (a) Invariant cross sections for outgoing π^-, (b) topological cross sections, (c) differential cross sections $d\sigma/dt$ for elastic scattering. The cuts on the off-shell reactions are described in the text.

havior in t with a slope of 8.0 ± 0.7 $(\mathrm{GeV}/c)^{-2}$ in excellent agreement with the value 7.36 ± 0.14 $(\mathrm{GeV}/c)^{-2}$ found in the literature for π^-p elastic scattering at 4.16 GeV/c [11] and 9.0 ± 0.6 $(\mathrm{GeV}/c)^{-2}$ found at 3.9 GeV/c in our data.[10] The solid line has a slope of 8.0 $(\mathrm{GeV}/c)^{-2}$.

In conclusion, from examining the helicity-0, unnatural parity exchange in both the ρ^0 and ω^0 inclusive production, we find that ρ^0 production in the beam fragmentation region seems to proceed by pion exchange, while in the central region other mechanisms are dominant. For the ω^0, all exchange contributions are equally important in all kinematic regions. A triple-Regge analysis of the ρ^0 inclusive production in the appropriate kinematic region confirms that pion exchange is dominant and we extract the π trajectory. We also find that off-mass-shell corrections are small.

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Hadronic Transitions between Quark-Antiquark Bound States

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A multipole expansion of the color gauge field is shown to yield selection rules and rate estimates for hadronic transitions between nonrelativistic quark-antiquark bound states. The non-Abelian character of the field is of critical importance in determining the selection rules for the leading ("allowed") transition.

One positronium-like hadronic system, the ψ family, is now well established,[1] and another, the Υ family, appears to be in the offing.[2] Transitions within these families occur via photon and/or hadron emission, as in $\psi'\to\psi\gamma\gamma$ and $\psi'\to\psi\pi\pi$. The former can be described with some success by the concepts of atomic spectroscopy,[3] but there is no comparable theory of the hadronic transitions. I address this problem by drawing on an analogy to another spectroscopic phenomenon, the emission of atomic electrons (internal conversion) and e^+e^- pairs by nuclei.[4,5]

In the nuclear process lepton emission is caused by the changing electromagnetic field of the nucleus. As nuclear velocities are low, and as nuclei are small compared to the wavelength of the emitted leptons, a multipole expansion of the nuclear field converges rapidly and thereby provides selection rules and rate estimates. If hadrons are really composed of quarks interact-