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Inclusive Production of ρ^0 in Inelastic Muon-Nucleon Scattering

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We measured the inclusive production of ρ^0 mesons in virtual-photon–nucleon collisions. The extracted structure functions are Q^2 independent and approximately equal to those observed in photoproduction, if one excludes the diffractive (elastic) region where a large decrease is observed. A significant fraction of the inclusive $\pi^\pm$ distribution results from the decay of these ρ^0's.

In this Letter, we present first data on the inclusive production of ρ^0 mesons in deeply inelastic muon-nucleon scattering. This process, usually interpreted in terms of the exchange of one virtual photon of four-momentum q ($Q^2 \equiv -q^2$),

$$\gamma_v N \to \rho^0 + \dots ,$$

is of considerable interest in a number of model interpretations of this process:

(1) In elastic ρ^0 production, this meson is seen as a faithful probe of the incoming photon's hadronic content.[1] Does it do similarly as a leading particle in the beam fragmentation region of the inelastic process?

(2) The photoproduction ($Q^2 = 0$) total cross section is known to contain a much larger fraction of elastic ρ events than the deeply virtual-photon interaction.[2] Does this difference extend into inclusive nonleading ρ^0 production? Are there Q^2 trends?

(3) There has long been the question of to what extent π production in inelastic collisions is "direct" and to what extent due to the decay of heavier mesons ("resonances"). The ρ^0 is the most easily traceable of these "resonances."

(4) In a simple-minded quark-parton model[3] for leading particles, the virtual photon interacting with one of the valence quarks will lead to easily predicted ρ^0/π ratios; i.e., there might be a π (direct) to π (from ρ^0 decay) ratio of 1/3 due to spin factors, in the leading-particle spectrum. Are such ratios in fact observed?

With these points in mind, we have measured ρ^0 cross sections in muon-nucleon scattering, where the muon serves as a source of virtual photons of variable mass. We compare our results to those measured in photoproduction. The experiment from which our data are taken is described in detail by del Papa *et al.*[5] The data sample contains 7750 events on hydrogen and deuterium targets.

Inclusive distributions for the production of a given type of hadron are typically displayed in terms of the Feynman scaling variable[6] x_F, defined to be the longitudinal momentum of the hadron divided by its maximum possible value, in the appropriate center-of-mass system. For the ρ^0, we define a structure function

$$F^{\rho^0}(x_F) = \frac{E^*}{\pi p_{max}^*}\frac{1}{\sigma_{tot}}\frac{d\sigma^{\rho^0}}{dx_F}, \quad (1)$$

where x_F is the fractional ρ^0 momentum along the virtual-photon direction; p_{max}^* is calculated for a given $\pi^+\pi^-$ mass by assuming that this mass recoils against a nucleon; and the cross sections are integrated over given bins in W and Q^2 for the virtual-photon–nucleon system.

In lepton-induced reactions, a related variable z,[3] equal to a hadron's laboratory energy divided by the energy of the incident virtual photon, provides an alternative way to display inclusive distributions. In this variable, we get a distribution often called a structure function:

$$F_{\mu N}^{\rho^0}(z_{\rho^0}) = \frac{z_{\rho^0}}{\sigma_{tot}}\frac{d\sigma_{\rho^0}}{dz_{\rho^0}}. \quad (2)$$

This function particularly emphasizes the fragmentation region of the virtual photon for a target nucleon of type N (proton or neutron).

To calculate the functions discussed above for given W and Q^2 ranges, we chose bands of x_F or z_{ρ^0} and fitted the di-pion mass distributions by a Breit-Wigner ρ^0 signal, plus a smooth background for all pairs falling into the given band. To extract $F^{\rho^0}(x_F)$ and $F_{\mu N}^{\rho^0}(z_{\rho^0})$ directly, all pairs are weighted by $E^*/\pi P_{max}^*$ or z_{ρ^0}, respectively, before fitting. The calculated distributions are equal within statistics for both our proton and our deuteron experiments; we have therefore summed all of our data to improve the statistical significance of the results. We note that both diffractive and quark fragmentation models predict that yields in the photon-fragmentation region should be nearly equal for proton and neutron targets. Because of a lack of particle identification, all particles other than the trigger muon are assumed to be pions.

In Fig. 1, we show the mass distributions in bands of x_F, for our full data sample ($2.8 \leq W \leq 4.7$ GeV, $0.3 \leq Q^2 \leq 4.5$ GeV^2; $\langle W\rangle = 3.5$ GeV, $\langle Q^2\rangle = 1.0$ GeV^2). We fitted the mass distribution for $500 \leq M_{\pi\pi} \leq 1100$ MeV by assuming an exponential background shape to which we add a relativistic P-wave Breit-Wigner form,[7] without a skewing parameter, centered at $m_{\rho^0} = 770$ MeV, and with a width $\Gamma_{\rho^0} = 150$ MeV. The $\pi\pi$ mass distribution is binned in 20-MeV bins, and a χ^2 value for the fit is calculated by comparing the predicted bin population for the fit to the binned data. Resulting fits are good, yielding typically a χ^2 of 1 per degree of freedom.

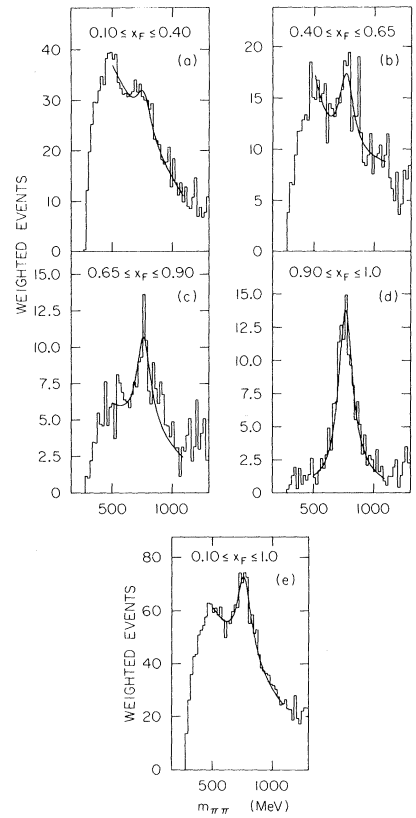

FIG. 1. Mass distributions for $\pi^+\pi^-$ in bands of the fractional longitudinal momentum, x_F. Each event is weighted by $E^*/\pi p_{max}^*$ and so the bin populations do not reflect the true number of events. Curves are the best fits in terms of an exponential background and a Breit-Wigner form.

To test our procedure, we checked that the distributions do not change by more than the calculated errors if (1) bin edges are moved by half a bin width; (2) a second-order polynomial instead of an exponential is used to parametrize the background; (3) fits for a band covering several bins are compared with the sum of individually extracted ρ^0 signals; and (4) exponential fits to $\pi^+\pi^+$ and $\pi^-\pi^-$ distributions have good χ^2 values.

Figure 2(a) shows the function $F^{\rho^0}(x_F)$ for our full data sample, as well as the analogous distribution in photoproduction. Our data are only shown for $x_F > 0.1$, where we feel we can reliably extract the ρ^0 cross section. For backward ρ^0's, the signal-to-background ratio is small, and nucleon resonances give reflections (for misidentified protons) which distort the ρ^0 mass region.

Figure 2(b) gives the strucutre function in terms of the variable z_{ρ^0}, on a linear scale, for comparison with structure functions[8] from other processes. As expected asymptotically, $F_{\mu N}^{\rho^0}(z_{\rho^0})$

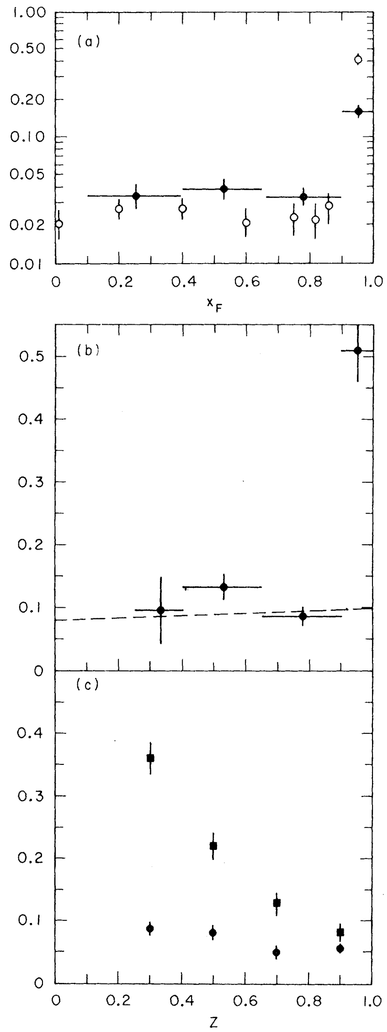

FIG. 2. (a) Distribution $F^{\rho^0}(x_F)$ for virtual-photon–nucleon scattering (solid circles) and real-photon–proton scattering (open circles). (b) Structure function $F_{\mu N}{}^{\rho^0}(z_{\rho^0})$ for full data sample. (c) Analogous function, $F_{\mu N}{}^{\pi^-}(z_{\pi^-})$, for all negative hadrons (solid squares). Also shown is the contribution of ρ^0-decay π^-'s to this function (solid circles).

$\simeq \pi F^{\rho^0}(x_F)$ in the photon-fragmentation region. The dashed curve shown is a prediction of a specific parton model[9] under the assumption that only nonstrange quarks are found in the proton at our values of Q^2 and W. Both the shape and the normalization of the prediction are in reasonable agreement with the data. Figure 2(c) shows the analogous structure function calculated from our data[10] for negative hadrons, assumed to be pions, and a measurement of the contribution of π^- from ρ^0 decay to this distribution.

In Fig. 3, the quantity $F^{\rho^0}(x_F)$ is presented as a function of Q^2, for three x_F bands. Analogous

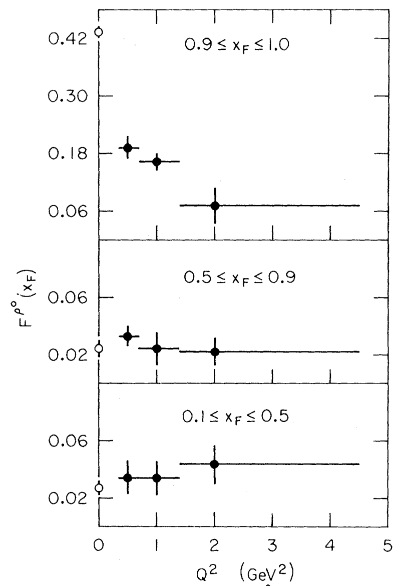

FIG. 3. Distribution funtion $F^{\rho^0}(x_F)$ for incident virtual photons of various Q^2. Photoproduction values are shown at $Q^2=0$.

photoproduction data are again shown.

The structure functions for the ρ^0 shown in Figs. 2 and 3 lead to the following conclusions:

(1) For x_F or $z_{\rho^0} > 0.9$, we see strong Q^2 change in the distribution. This region is populated almost entirely (> 90% for our hydrogen data, where we use a four-constraint fit to constrain the $\mu p \to \mu p \pi^+\pi^-$ final state explicitly) by the elastic ρ^0 final state, which decreases by almost a factor of 3 when compared to photoproduction.[2]

(2) In the inelastic region ($0.1 \leq x_F \leq 0.9$), the inclusive distribution is very flat in x_F. Furthermore, we see almost no Q^2 dependence. Using our four-constraint fits to the hydrogen data, we find that this region contains essentially no contribution from the elastic ρ^0 final state, and it does not mirror its Q^2 dependence. The photoproduction distribution is, if anything, a little below the high-Q^2 distribution.

(3) The ρ^0 contributes a substantial number of π^- to the structure function for these particles. For $0.8 \leq z_{\pi^-} \leq 1.0$, $(70 \pm 15)\%$ of the π^- come from ρ^0 (almost all from elastic ρ^0); for $0.2 \leq z_{\pi^-} \leq 0.4$, $(24 \pm 5)\%$ come from ρ^0 (mostly inelastic ρ^0). Since the structure function for large z for positive hadrons is about twice as large as for negative hadrons,[10] a smaller percentage of these come from ρ^0 decay. If other vector and heavier pseudoscalar mesons are as copiously produced as inelastic ρ^0's, they can account for a very substantial number of the detected pions.

(4) The ρ^0 contribution is large in magnitude: In terms of the model of Ref. 9, which gives a reasonable prediction of our measured functions, there is as much direct production of ρ^0 as there is of π^0.

Clearly, it would be desirable to have analogous results from e^+e^- annihilation and neutrino scattering to compare with our data: There are parton-model relations between all of these processes.

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Evidence against Copious Threshold Pion Production in Heavy-Ion Collisions

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In a recent publication, McNulty *et al.* reported a very high pion multiplicity in relatively low-energy heavy-ion interactions in nuclear emulsion. Using an emulsion stack virtually identical to theirs we find a pion multiplicity at least a factor of 30 smaller. We show here that the previously reported multiplicity was based on an erroneous identification of high-energy protons as pions.

In a recent publication, McNulty *et al.*[1] reported a charged-pion multiplicity of 2.1 pions/interaction (2.8 pions/pion-producing event) in the reactions of 280–100-MeV/nucleon ^{20}Ne in Ilford G.5 nuclear emulsion. Bertsch[2] has made a theoretical calculation of the charged-pion multiplicity expected in nucleus-nucleus collisions based on an independent-particle model, which includes the effects of Fermi motion; his model predicts a pion multiplicity less than 2% of that claimed by McNulty *et al.* Thus, if the multiplicity of 2.1 pions/interaction were true, it would represent strong evidence for the existence of a new cooperative effect in nuclear interactions. We have attempted to verify this result, but find that in the region we scanned, the stopping pion multiplicity, at the 95% confidence level, is less than 0.06 of that claimed by McNulty *et al.* We shall show in this Letter that the discrepancy can be resolved since the results of Ref. 1 were based on a misidentification of fast protons as pions.

We are able to check their experimental results directly since we have on hand a stack of Ilford G.5 nuclear emulsion which had been exposed to 230-MeV/nucleon ^{20}Ne at the Bevalac. Our stack consists of fifty pellicles, each pellicle being 12.0 cm × 7.0 cm × 670 μm. As we show below, our processing was virtually identical to theirs. That our exposure was at 230 MeV/nucleon, instead of at 280 MeV/nucleon, does not affect our comparison because, according to McNulty *et al.*, approximately 70% of their pions were produced below 230 MeV/nucleon.

We checked the results of McNulty *et al.* by area scanning for stopping charged pions. On the basis of the pion production frequency as a function of