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INCLUSIVE PRODUCTION OF ρ^0 IN νp CHARGED CURRENT INTERACTIONS

Aachen-Bonn-CERN-Munich-Oxford Collaboration

P. Allen, H. Grässler, D. Lanske and R. Schulte
III. Physikalisches Institut der Technischen Hochschule, Aachen

K. Böckmann, B. Eckart, C. Geich-Gimbel, B. Nellen and H. Saarikko
Physikalisches Institut der Universität Bonn, Bonn

P.C. Bosetti(*), V.T. Cocconi, A. Grant, H. Klein, D.R.O. Morrison,
P. Schmid and H. Wachsmuth
CERN, European Organization for Nuclear Research, Geneva

M. Aderholz, N. Schmitz, R. Settles and K.L. Wernhard
Max Planck Institut für Physik und Astrophysik, Munich

R. Batley and J. Wells
Department of Nuclear Physics, Oxford

ABSTRACT

Inclusive ρ^0 production in neutrino-proton charged-current interactions is studied, using a sample of 7831 events obtained in BEBC filled with hydrogen and exposed to the CERN wideband neutrino beam. An average multiplicity of 0.14 ± 0.02 ρ^0 per event is found, corresponding to a ratio $\langle \rho^0 \rangle / \langle \pi^- \rangle = 0.13 \pm 0.02$. The ρ^0 production characteristics are determined as functions of leptonic variables (W , Q^2 , x_B) and hadronic variables (x_F , z , p_t^2) and are found to be similar to those determined for hadron- and other lepton-induced reactions.

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(*) CERN Fellow from III. Physikalisches Institut der Technischen Hochschule, Aachen.

1. INTRODUCTION

Inclusive resonance production is a subject of great interest in studies of high energy hadronic interactions [1]. Comparatively large cross sections are obtained, e.g., for vector meson production, and it is realized increasingly that in high energy processes the majority of final state pions come from the decay of resonances. Furthermore, inclusive resonance production has been interpreted qualitatively in the quark-parton picture as being related to the dynamics of quark-quark collisions at low p_t [2].

Numerous studies of inclusive resonance production have been made in experiments of hadron-hadron collisions, covering the full available accelerator energy range, a variety of beam particles and a large number of mesonic and baryonic resonances produced. Only few studies exist in lepto-production reactions and they are usually based on small statistics experiments [3-6]. Experimental data on resonance production should reflect the basic processes in lepton-hadron interactions more closely than do the pion spectra, as these latter are smeared by the kinematics of resonance decays [7].

The purpose of this paper is to study the rate and characteristics of ρ^0 production by analyzing the reaction

$$\nu_\mu p + \mu^-(\pi^+\pi^-) + X \quad (1)$$

in a sample of 7831 charged current (CC) events of $\nu_\mu p$ interactions. In the quark-parton picture the dominant process in reaction (1) is the conversion of the valence d-quark of the target proton into a u-quark by absorption of the intermediate W^+ boson. The resulting u-quark and the two u-quarks of the target proton, usually considered as spectator quarks, then fragment into final state hadrons (current and target fragments, respectively) in a manner that is to be determined experimentally. Whenever possible, comparisons are made in the following with other lepton- and suitable hadron-induced reactions.

In sect. 2 experimental details are briefly discussed and in sect. 3 the fitting procedure to extract the ρ^0 signals is described. The rates for ρ^0 and f production in reaction (1) are reported in sect. 4, and in sect. 5 the ρ^0 production characteristics are studied as functions of the lepton and hadron variables commonly used to describe lepto-production processes. The conclusions are summarized in sect. 6.

2. EXPERIMENTAL DETAILS

This analysis is based on about 18 000 measured events obtained during a 285 000 picture exposure of the Big European Bubble Chamber (BEBC) filled with hydrogen to the SPS two-horn focused wideband neutrino beam. Muons with momentum greater than 3 GeV/c were identified by a two-plane External Muon Identifier (EMI) with detection efficiency varying from 40% at 3 GeV/c to 98.5% above 10 GeV/c. Furthermore the events were required to lie inside a fiducial volume of 19 m³ and to have a visible energy greater than 5 GeV. The final sample used for this work consisted of 7831 CC events.

The visible energy of each event was corrected for losses due to undetected neutrals [8]. The mean values of the neutrino energy, the hadronic invariant mass, and the four-momentum transfer squared in the sample used are $\langle E_\nu \rangle = 40$ GeV, $\langle W \rangle = 4.4$ GeV, and $\langle Q^2 \rangle = 6.4$ (GeV/c)², respectively.

All secondary hadrons were taken as pions unless otherwise identified by energy loss, range, ionization, interactions or decay.

3. FITTING PROCEDURE

The inclusive ρ^0 and f production rates were obtained by fitting the $(\pi^+\pi^-)$ invariant mass distribution of reaction (1) with the formula

$$\frac{dN}{dm(\pi^+\pi^-)} = BW.PS + BG, \quad (2)$$

where BW stands for a relativistic P-wave Breit-Wigner function [9] describing the selected resonance, BG for the background and PS for the phase space distribution which is assumed to have the same shape as the background. A background description of the form

$$BG = \alpha_1 (m - m_{th})^{\alpha_2} \exp(\alpha_3 m + \alpha_4 m^2) \quad (3)$$

was chosen (m_{th} = threshold mass), which takes into account threshold effects and the exponential fall-off at high values of the dipion mass.

The best fitting probabilities were obtained when extending the fit over the range 0.52 - 1.6 GeV and simultaneously fitting the ρ^0 and f meson enhancements, using the PDG table values [10] for the masses and the widths of ρ^0 and f

$$m(\rho^0) = 0.776 \text{ GeV} \quad m(f) = 1.273 \text{ GeV}$$

$$\Gamma(\rho^0) = 0.158 \text{ GeV} \quad \Gamma(f) = 0.178 \text{ GeV.}$$

When treating these quantities as free parameters, one obtains

$$m(\rho^0) = 0.771 \pm 0.008 \text{ GeV} \quad m(f) = 1.25 \pm 0.03 \text{ GeV}$$

$$\Gamma(\rho^0) = 0.13 \pm 0.04 \text{ GeV} \quad \Gamma(f) = 0.19 \pm 0.09 \text{ GeV.}$$

To determine the differential distributions with respect to a given variable (e.g. p_t^2), the data for the $(\pi^+\pi^-)$ system were subdivided into suitable bins in that variable and the resonance signal in the corresponding invariant mass distribution was fitted in each bin with the expression (2).

4. INCLUSIVE PRODUCTION RATES

Fig. 1(a) shows the $(\pi^+\pi^-)$ mass distribution for all events with hadronic multiplicity less than 10. In the events with hadronic multiplicities greater than or equal to 10, no ρ^0 signal was seen, and

the total rates obtained were not affected by application of this multiplicity cut. Such a cut is useful, however, as it reduces the large combinatorial background of high multiplicity events.

A good fit ($\chi^2/\text{NDF} = 0.97$) to the distribution in fig. 1(a) was obtained using the function (2), which yielded $1040 \pm 180 \rho^0$ mesons and $140 \pm 70 f$ mesons above background.

In order to check the reliability of these results, the partial production rates of various differential distributions were calculated and summed up. The results, presented in table 1, show good agreement. The average number of ρ^0 's is 1070 ± 160 . This corresponds to an average ρ^0 multiplicity per event $\langle \rho^0 \rangle = 0.14 \pm 0.02$. The ratio $\langle \rho^0 \rangle / \langle \pi^- \rangle = 0.13 \pm 0.02$ shows that 13% of all π^- are produced via ρ^0 decay.

The rate of f production, corrected for unseen decay-modes and for the branching ratio, is $\langle f \rangle = 0.04 \pm 0.02$ per event. This gives a ratio $\langle f \rangle / \langle \rho^0 \rangle = 0.26 \pm 0.13$, about the same value as observed in hadron-proton collisions [11].

These results are collected in table 2 and compared to those of other νp [3,12] and $\bar{\nu} p$ [4] experiments and of $\pi^+ p$ collisions at 16 GeV/c [11]. This comparison is in first approximation valid, but it is not exact, since especially the ν and $\bar{\nu}$ experiments differ in their overall W and Q^2 distributions and the analysis of the mass spectrum is in some cases done with other methods than described here. In νp and $\bar{\nu} p$ events of the lowest multiplicity, ρ^0 production is not allowed. Thus in the $\bar{\nu} p$ experiment, 1-prong events (final states containing no charged hadrons) were excluded. For a comparison, therefore, 3-prong events as well as a few other events containing no π^- , were excluded in the νp reactions.

The $\bar{\nu} p$ results [4] are in agreement with those of this experiment.

Figs 2(a)-2(d) show the mass spectra obtained separately for each charged hadronic multiplicity from 4 to 10. The ρ^0 rates obtained from fits of these mass distributions and the $\langle \rho^0 \rangle / \langle \pi^- \rangle$ ratios are collected in table 3.

The ρ^0 production rate per event is highest in 6- and 8-prong events, whereas the $\langle \rho^0 \rangle / \langle \pi^- \rangle$ ratio shows little variation with multiplicity. This agrees with the results of a νD experiment [12] shown in the same table. The multiplicity distribution obtained disagrees instead with the results of the νp experiment of ref. [3], where 4-prongs are claimed to contribute 3/4 of the total number of ρ^0 's.

5. DIFFERENTIAL DISTRIBUTIONS

5.1 Leptonic variables

Inclusive ρ^0 production has been studied as a function of the hadronic mass W defined as $W = (M^2 + 2M(E_\nu - E_\mu) - Q^2)^{1/2}$, where M is the mass of the target proton, E_ν the corrected neutrino energy, E_μ the energy of the final state muon, and Q^2 the squared four-momentum transfer between the neutrino and the muon. Fig. 3 shows that the ρ^0 rate increases with W^2 . Assuming a linear dependence on $\ln W^2$, one obtains values for the slope that are similar to πp and pp results [13] (see table 4).

The Q^2 dependence of ρ^0 production is illustrated in fig. 4. The ρ^0 rate does not seem to increase significantly with Q^2 , if one excludes the region $Q^2 < 2$ (GeV/c)². The low production rate in the lowest Q^2 bin is due to quasi-elastic events with hadronic multiplicity of 2 (dominated by Δ^{++} production), which are concentrated at low Q^2 but do not contribute to ρ^0 production. However, if the events in the first bin of the Q^2 distribution are normalized to the number of events containing at least one final state π^- , the ρ^0 rate as a function of Q^2 is constant within errors. Similar results have been found in antineutrino-proton [4] and inelastic muon-nucleon scattering [6].

Fig. 5 gives the rate of ρ^0 production as a function of Bjorken x , defined as $x_B = Q^2 / 2M(E_\nu - E_\mu)$. Again ρ^0 depends only weakly on this variable. When the dependence of the ρ^0 cross section on $\ln W^2$ is taken into account, the rate of ρ^0 production is essentially independent of Q^2 and x_B , i.e. the totality of the CC events and the subset of events containing a ρ^0 do not differ appreciably in their dependence on the leptonic variables.

5.2 Hadronic variables

In order to study the dynamics of ρ^0 production more closely and allow comparison with other leptonic and hadronic (especially π^+p) experiments, differential distributions in the Feynman variable x_F , in the z variable, and in the transverse momentum squared p_t^2 of the ρ^0 meson were studied.

The Feynman variable is taken as $x_F = p_L^*/p_{\max}^*$, p_L^* being the longitudinal momentum with respect to the current direction in the c.m. system of the final state hadrons. $p_{\max}^*$ is the maximum possible momentum in the c.m. system calculated for a given $\pi^+\pi^-$ mass. Fig. 6 gives the invariant Feynman x distribution of the ρ^0

$$F(\rho^0) = \frac{1}{N_{ev}} \cdot \frac{E^*}{\pi p_{\max}^*} \cdot \frac{dN(\rho^0)}{dx_F}$$

(E^* is the c.m. energy of the ρ^0).

The x_F distribution shows that the ρ^0 mesons are to a large extent produced in the forward (current) direction. The asymmetry parameter $(F-B)/(F+B)$ is 0.62 ± 0.14 , where F denotes the ρ^0 production rate in forward direction (defined as $x_F > 0$) and B in the backward direction ($x_F < 0$).

The results from a 16 GeV/c π^+p experiment [11] have also been plotted (multiplied by a scale factor which takes into account the different overall rates of ρ^0 production in the two experiments). The astonishingly good agreement of the two data sets shows that the two interaction processes must have underlying similarities in the ρ^0 production mechanism, both in the central and in the forward region (expect perhaps near $x_F = 1$, where diffraction dissociation may contribute more ρ^0 in π^+p interactions).

Fig. 7 shows the z distribution of the ρ^0 , where z is defined as the fraction of the hadronic energy in the laboratory frame carried by the ρ^0 , namely $z = E(\rho^0)/(E_\nu - E_\mu)$. The resulting curve is similar

to that obtained in inelastic muon nucleon scattering [6]. The discrepancy at high z is due to the absence of a large diffractive component in νp interactions. The $\langle \rho^0 \rangle / \langle \pi^- \rangle$ ratio is given in fig. 8 in terms of z . It may be noted that at large z there are more ρ^0 than π^- produced. The approximately exponential increase has also been observed in antineutrino [4] and muon [6] scattering. It suggests that the originally scattered u -quark to a large extent fragments directly into a ρ^0 -meson.

The transverse momentum p_t of the ρ^0 is defined with respect to the current direction. The p_t^2 distribution of the ρ^0 , given in fig. 9, shows the expected exponential fall-off towards high p_t^2 . In order to make a comparison with other experiments a fit with the function $1/N_{ev} \cdot dN(\rho^0)/dp_t^2 = A \exp(-B p_t^2)$ was made, yielding a slope $B = (3.8 \pm 1.0)(\text{GeV}/c)^{-2}$, which is in good agreement with hadron experiments [14]. This is also true for the average values $\langle p_t \rangle = (0.46 \pm 0.05)\text{GeV}/c$ and $\langle p_t^2 \rangle = (0.26 \pm 0.06)(\text{GeV}/c)^2$.

6. SUMMARY

The study of ~ 1000 ρ^0 mesons produced in charged current neutrino proton interactions allows the following conclusions:

- (a) The ρ^0 production rate in νp interactions is comparable to that found in $\bar{\nu}$ experiments. The average number of ρ^0 per event is $\langle \rho^0 \rangle = 0.14 \pm 0.02$, which becomes 0.21 ± 0.03 when normalizing to the number of CC events with more than two final state hadrons, i.e., containing at least one π^- . The average number of f -mesons in the same events is 0.04 ± 0.02 .
- (b) A significant amount of the negative pions in the final state, namely $\sim 13\%$, is produced indirectly via ρ^0 decay.
- (c) The ρ^0 rate increases with increasing hadronic mass W , but is fairly constant with increasing Q^2 and Bjorken x .

- (d) The Feynman x and the z distributions indicate that a large fraction of the ρ^0 mesons is produced in the current fragmentation region. The x_F distribution of the ρ^0 produced in neutrino induced reactions has the same shape as in π^+ induced reactions.
- (e) The p_t^2 distribution of the ρ^0 in νp interactions has the same slope as observed for ρ^0 production in hadron experiments.

Generally speaking, the characteristics of ρ^0 production in neutrino proton interactions exhibit the same features as found in hadron and other lepton induced reactions.

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TABLE CAPTIONS

- Table 1 The total number of ρ^0 and f mesons in the 7831 CC events of νp interactions.
- Table 2 Comparison of the total inclusive ρ^0 and f production rates in ν , $\bar{\nu}$, and π^+ induced reactions.
- Table 3 $\langle \rho^0 \rangle$ rates and $\langle \rho^0 \rangle / \langle \pi^- \rangle$ ratios in CC events with the charged hadronic multiplicity indicated.
- Table 4 Parameters obtained fitting the W^2 dependence of the inclusive ρ^0 production rate (fig. 3) with the function $A+B.\ln(W/\text{GeV})^2$ for ν , π^+ [13], and p [13] induced reactions.

TABLE 1

Distribution fitted	Total number of ρ^0	Total number of $f^{(a)}$
Inclusive ($\pi^+\pi^-$) mass spectrum	1040 ± 180	140 ± 70
Multiplicity bins	1140 ± 150	160 ± 70
W bins	1070 ± 170	190 ± 70
Q^2 bins	1110 ± 160	180 ± 70
x_{Bjorken} bins	890 ± 130	170 ± 60
x_{Feynman} bins	1180 ± 160	180 ± 60
x_{Feynman} (forward and backward region separately)	1020 ± 170	150 ± 70
z bins	1090 ± 160	160 ± 70
p_t^2 bins	1070 ± 180	120 ± 70
Weighted mean $\pm$ mean error	1070 ± 160	150 ± 70

- (a) The values given here for f are without correction for unseen decays and branching-ratio. The correction factor to be applied is 1.87, which gives as a weighted mean, 280 ± 130 f mesons.

TABLE 2

Experiment	$\langle \rho^0 \rangle$	$\langle f \rangle$	$\langle \rho^0 \rangle / \langle \pi^- \rangle$	$\langle f \rangle / \langle \rho^0 \rangle$
νp (this experiment) $\langle W \rangle = 4.4$ GeV	0.14 ± 0.02	0.04 ± 0.02	0.13 ± 0.02	0.26 ± 0.13
νp (this experiment) $\langle W \rangle = 4.4$ GeV	$0.21 \pm 0.03(a)$	-	-	-
νp [3] $\langle W \rangle \approx 5$ GeV	0.21 ± 0.04	-	-	-
νD [12] $\langle W \rangle \approx 5$ GeV	0.19 ± 0.04	-	0.15 ± 0.04	-
$\bar{\nu} p$ [4] $\langle W \rangle = 3.4$ GeV	0.21 ± 0.03	-	0.12 ± 0.02	-
$\pi^+ p$ [11] $\langle W \rangle = 5.56$ GeV	0.24 ± 0.02	0.050 ± 0.005	0.19 ± 0.02	0.21 ± 0.03

(a) This rate is normalized to the number of events containing at least one final state π^- .

TABLE 3

Charged hadron multiplicity	4	6	8	10
Number of events	2909	1472	486	155
Number of ρ^0 's	400 ± 80	540 ± 70	190 ± 90	0 ± 30
$\langle \rho^0 \rangle$ per event	0.14 ± 0.03	0.37 ± 0.05	0.39 ± 0.19	0.00 ± 0.19
$\langle \rho^0 \rangle / \langle \pi^- \rangle$	0.14 ± 0.03	0.18 ± 0.02	0.13 ± 0.06	0.00 ± 0.05
$\langle \rho^0 \rangle$ per event vD [12]	0.11 ± 0.01	0.38 ± 0.06	0.61 ± 0.23	-

TABLE 4

	A	B
v p (this experiment)	-0.08 ± 0.12	0.085 ± 0.045
π p [13]	-0.08 ± 0.01	0.09 ± 0.01
p p [13]	-0.23 ± 0.01	0.09 ± 0.01

FIGURE CAPTIONS

- Fig. 1 (a) Invariant mass spectrum of the $(\pi^+\pi^-)$ dipion system in the inclusive reaction $\nu p \rightarrow \mu^-(\pi^+\pi^-) + \text{anything}$, for events with < 10 prongs. The solid curve is the result of the fit described in sect. 3. The dashed curves represent the background, the ρ^0 signal and the f signal, as given by the fit.
- (b) The same mass spectrum as in fig. 1(a) in the range 0.5 to 1.6 GeV after the fitted background has been subtracted. The solid curve gives the sum of the ρ^0 and f resonance contributions as given by the fit.
- Fig. 2 The $(\pi^+\pi^-)$ invariant mass spectrum for different charged hadronic multiplicities. The curves are explained in the caption of fig. 1.
- Fig. 3 The rate of ρ^0 production as a function of W^2 , the mass squared of the hadronic system. The solid line is a fit to the νp data of the form $N(\rho^0)/\text{event} = A+B.\ln(W/\text{GeV})^2$.
- Fig. 4 The rate of ρ^0 production as a function of Q^2 , the square of the four-momentum transfer between the outgoing muon and the incoming neutrino, for νp and $\bar{\nu} p$ [4] reactions. The square indicates the νp result normalized to the number of events containing at least one final state π^- .
- Fig. 5 The rate of ρ^0 production in neutrino induced reactions as a function of the scaling variable Bjorken x .
- Fig. 6 The invariant differential distribution of the ρ^0 as a function of the Feynman variable x for νp and for 16 GeV/c $\pi^+ p$ [11] reactions (normalized to the same rate).

FIGURE CAPTIONS (Cont'd)

- Fig. 7 The z distribution of the ρ^0 for νp reactions and inelastic muon nucleon scattering [6].
- Fig. 8 The z dependence of the $\langle \rho^0 \rangle / \langle \pi^- \rangle$ ratio for ν and $\bar{\nu}$ [4] induced reactions.
- Fig. 9 The inclusive distribution of the transverse momentum squared for the ρ^0 . The solid line indicates a fit of the form $1/N_{ev} \cdot dN(\rho^0)/dp_t^2 = A \cdot \exp(-B \cdot p_t^2)$.

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