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Production of $\rho^{+,-,0}(770)$, $\eta(550)$, $\omega(783)$
and $f_2(1270)$ Mesons in $\bar{\nu}$ Neon and ν Neon
Charged Current Interactions

BEBC WA59 Collaboration

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Abstract

The production of the meson resonances $\rho(770)$ (all three charge states), $\eta(550)$, $\omega(783)$ and $f_2(1270)$ in $\bar{\nu}Ne$ and νNe charged current interactions is investigated in a bubble chamber experiment with BEBC at CERN. Except for the f_2 , the main features of resonance production are reasonably well described by the *Lund* model, although the average resonance multiplicities are overestimated by the model by $(67 \pm 30)\%$. The average multiplicities of all resonances, including the f_2 , are well reproduced by a semi-empirical model, whose parameters were determined from hadron interaction data.

1. Introduction

It is known that the pions and kaons occurring in high energy interactions are to a large extent the decay products of resonances [1]. Resonance production characteristics are therefore expected to reflect the dynamics of the interactions more closely than the pion and kaon spectra and to provide a better ground for comparisons with theoretical models.

The present paper reports on the inclusive production of the non-strange meson resonances $\rho(770)$ (in all three charge states), $\eta(550)$, $\omega(783)$ and $f_2(1270)$ in $\bar{\nu}Ne$ and νNe charged current interactions. These interactions are unique in selecting particular types of quarks in the target : in $\bar{\nu}$ interactions the dominant process is the conversion of a u quark into a d quark, and in ν interactions the conversion of a d quark into a u quark. Thus the data provide information on the fragmentation of these quarks into meson resonances. They also serve as a test for the influence of nuclear reinteractions on the production of these resonances.

The outline of the paper is as follows. Section 2 deals with the experimental details and describes the procedure used to obtain the average multiplicities of the produced resonances from mass distributions. In Section 3 the production of resonances is studied as a function of W , x_F , z , and p_T and comparisons are made with predictions of the *Lund* model and of a semi-empirical model for high-energy inclusive reactions. A summary is given in Section 4.

2. Experimental Details

a) The Experiment

The data come from an experiment in which the bubble chamber BEBC was exposed to the $\bar{\nu}$ and ν wide band beams from the SPS at CERN. BEBC was filled with a 75 mole % Ne-H₂ mixture, whose radiation and hadronic collision lengths are 42 cm and 92 cm respectively.

Muons are identified with good efficiency ($> 85\%$ for momenta above 5 GeV/c) by an external muon identifier and most of the protons with momenta below 800 MeV/c are identified on the basis of ionization and range in Ne-H₂. Most of the remaining charged particles cannot be identified and thus are called pions.

For the present analysis only events with a muon momentum above 5 GeV/c and a total hadronic mass W between 1.5 and 10 GeV are accepted. The available statistics and the mean values of the quantities E_ν (energy of the incident (anti-) neutrino), W (effective mass of the total hadronic system), and Q^2 (squared four-momentum transfer between the incoming and outgoing lepton) are listed in Table 1.

The experimental procedure followed in this paper is identical to the one described in Ref. 2. Additional details about the ν energy estimation, the method of π^0 reconstruction, the treatment of low momentum protons (stubs) and the Monte Carlo calculations are also given in Ref. 2.

b) Reconstruction of π^0 Mesons

Neutral pions are reconstructed by combining photons (γ) that converted into electron-positron pairs within the bubble chamber. A special procedure is applied to select from all $\gamma\gamma$ pairs within an event those which very likely result from a π^0 decay. In this paper all selected $\gamma\gamma$ pairs are called π^0 . Monte Carlo calculations show that 80 % of the π^0 's obtained in this way are correctly combined $\gamma\gamma$ pairs. These 80 % correspond to 30 % of all produced π^0 . For further details of the π^0 reconstruction see Ref. 2.

c) Extraction of the Resonance Signals

The numbers of produced ρ^0, ρ^+, ρ^- and f_2 mesons are obtained by fitting the following expression to the respective $\pi\pi$ invariant mass distribution (see Table 2) :

$$\frac{dN}{dm} = a_1 \cdot BG + a_2 \cdot BG \cdot BW_\rho + a_3 \cdot BG \cdot BW_f \quad (1)$$

$$\text{with } BG = (m - 2m_\pi)^\alpha \cdot \exp(\beta m + \gamma m^2) \quad , \quad (2)$$

$$BW_\rho = \frac{m}{q} \cdot \Gamma'_\rho \cdot \frac{1}{(m^2 - m_\rho^2)^2 + (m_\rho \Gamma'_\rho)^2} \quad (3)$$

$$\Gamma'_\rho = \Gamma_\rho \cdot \left(\frac{q}{q_\rho}\right)^3 \cdot \frac{m_\rho}{m} \quad ,$$

$$BW_f = \frac{m}{q} \cdot \Gamma'_f \cdot \frac{1}{(m^2 - m_f^2)^2 + (m_f \Gamma'_f)^2} \quad (4)$$

$$\Gamma'_f = \Gamma_f \cdot \left(\frac{q}{q_f}\right)^5 \cdot \frac{m_f}{m} \quad .$$

BG represents the background parametrization and BW_ρ, BW_f are relativistic Breit-Wigner functions with mass dependent widths corresponding to a p-wave and a d-wave respectively [3]. m_ρ, m_f are the central mass values and Γ_ρ, Γ_f the widths of the ρ and f meson, m_π is the pion mass, m is the mass of the two-pion system, and q is the pion momentum in the two-pion rest frame. In the fits, which are performed in the mass region $2m_\pi < m < 1.7$ GeV, $a_1, a_2, a_3, \alpha, \beta$ and γ are free parameters, whereas m_ρ and m_f are fixed at the PDG values [4]. Γ_ρ and Γ_f are set to the values listed in Table 2, which were obtained from the PDG values by folding in the finite mass resolution. The resonance terms have been multiplied by BG in order to impose the kinematic constraints (which primarily determine the shape of the background) on the resonance contributions.

To determine the numbers of produced η and ω mesons the distribution of the $\pi^+\pi^-\pi^0$ mass M is fitted with the expression

$$\frac{dN}{dM} = a_1 \cdot BG + a_2 \cdot G_\eta + a_3 \cdot G_\omega \quad (5)$$

$$\text{with } BG = 1 + \sum_{i=1}^5 \alpha_i \cdot M^i \quad , \quad (6)$$

$$G_\eta = \exp\left(-\frac{(M - M_\eta)^2}{2\sigma_\eta^2}\right) \quad , \quad G_\omega = \exp\left(-\frac{(M - M_\omega)^2}{2\sigma_\omega^2}\right) \quad . \quad (7)$$

Since the experimental widths of the η and ω are dominated by the experimental mass resolution, their contributions are parametrized as Gaussians G_η, G_ω , with values for σ_η and σ_ω corresponding to the experimental mass resolution (see Table 3). M_η and M_ω are the central mass values of η and ω . The fits are performed in the mass range $3m_\pi < M < 1.3$ GeV with $a_1, a_2, a_3, \alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5 as free parameters. Unlike the case of the two-pion resonances ρ and f_2 , it is not necessary to multiply the η and

ω resonance terms by the background shape because the true widths of these resonances are small.

To measure the differential distribution of a resonance in a given variable (e.g. W, x_F, z, p_T) the data for the two-pion or three-pion system are subdivided into suitable bins in that variable. In each such bin, the resonance signal in the corresponding invariant mass distribution is then fitted with the expression (1) or (5).

As a check of the reliability of the fits, the number of resonance particles found in a given set of events was compared with the sum of the numbers found in its subsamples. In all cases good agreement was found.

d) Correction of the Data

The data have been corrected for effects of scanning and measuring inefficiencies, measurement errors, misidentification of charged hadrons, errors in the estimation of the ν energy and inefficiencies of the π^0 reconstruction. To this end, for each experimental distribution of a resonance (e.g. z distribution of the ρ^0) two corresponding distributions are produced for Monte Carlo (MC) events [5]: One distribution for *initial* MC events, i.e. for events generated assuming an ideal detector with 100 % reconstruction and identification efficiency for all secondary particles, and one distribution for *final* MC events, in which the experimental resolutions and inefficiencies are simulated. By dividing the *initial* and *final* distributions bin by bin, correction factors are obtained which are then applied to the experimental distributions.

The average correction factors, which also include the branching ratio for the relevant decay mode, are listed in Table 4. In calculating them it has been assumed that a resonance is detected if all observed decay particles are well measured (π^+, π^-) or correctly reconstructed (π^0).

The correction factors and their errors in Table 4 do not contain the uncertainties and systematic errors that arise in fitting the mass distributions. These were studied by fitting the mass distributions of MC events (for which the resonance content is known) as well as of the real data

- using different parametrizations of the background,
- choosing different mass ranges for the fit,
- varying the central mass values and the widths of the resonances, and
- varying the binning of the mass distribution.

The *statistical* error on the number of resonance particles is given by the fit, and is approximately $\sqrt{N_R}$, where N_R is the number of particle combinations in the resonance

region. The main source of the *systematic* error for the two-pion resonances is the uncertainty in the background shape. As can be seen from the MC calculations, the shape of the background is strongly influenced by the reflections from the decay of the resonances η, ω, K^* and Δ . Since the production rates of these resonances are not well known no attempt has been made to include 'reflection' terms in the fits. The parametrizations chosen are supposed to be flexible enough to describe the complicated background shapes expected. One reason for keeping the central masses and resonance widths constant in the fits was to prevent the fits from interpreting part of the background as resonance contribution, by shifting the resonance position or by choosing a larger width. A *systematic* error is estimated for the two-pion resonances by comparing the results of fits in which different parametrizations of the background (eq. (1), or eq. (1) multiplied by $(1 + \delta \cdot m)$, with δ as a free parameter) or different mass ranges ($m < 1.1$ GeV or $m < 1.7$ GeV) were chosen.

For the three-pion resonances the main source of the *systematic* error is the poor knowledge of the experimental width of the resonances. In this case a systematic error is estimated by comparing fits with different experimental widths of the resonances.

It should be emphasized that the average multiplicities presented in this paper are for the interaction on the neon nucleus. No attempt has been made to correct for nuclear effects or to determine the average multiplicities for the interaction on a free nucleon.

e) The Predictions of Theoretical Models

In the subsequent section experimental results for the average multiplicities $\langle n \rangle$ of produced resonances are compared with predictions of two theoretical models : the *Lund* model [6] and a semi-empirical model for high energy inclusive reactions (*Wells* model) [7]. The predictions of the two models are calculated for $\bar{\nu}$ and ν scattering off an isoscalar nucleon I according to

$$\langle n \rangle_{\bar{\nu}I} = [r_{\bar{\nu}} \cdot \langle n \rangle_{\bar{\nu}p} + \langle n \rangle_{\bar{\nu}n}] / (1 + r_{\bar{\nu}}) \quad \langle n \rangle_{\nu I} = [\langle n \rangle_{\nu p} + r_{\nu} \cdot \langle n \rangle_{\nu n}] / (1 + r_{\nu}) \quad (8)$$

$$\text{with} \quad r_{\bar{\nu}} = \sigma(\bar{\nu}p) / \sigma(\bar{\nu}n) \quad r_{\nu} = \sigma(\nu n) / \sigma(\nu p) , \quad (9)$$

where $r_{\bar{\nu}}$ and r_{ν} are taken as 2. No nuclear effects are included.

The *Lund* predictions are calculated using the version *LEPTO 4.3* [8] , *JETSET 5.2* [9] of the *Lund* Monte Carlo program. For the parameters $P(s)/P(u)$ (= suppression of s quark pair production compared to u or d pair production) and E_{min} (= remaining energy above the quark masses below which the fragmentation of a jet system is stopped)

the values 0.21 and 0.2 GeV [10] are chosen respectively, and all other parameters are set to their default values. In particular the parameter $V/(V + P)$ (= probability that a meson has spin 1) has a value of 0.5. Spin 2 mesons are not generated.

The semi-empirical model gives absolute predictions for particle and resonance multiplicities, including those for tensor mesons [7]. In the model the inclusive cross section is divided into a 'beam (or target) residue' and a 'central component', where in (anti-)neutrino-induced reactions the beam residue is defined as that part of the inclusive cross section which is due to the meson containing the struck quark. The central component is a function of W only, whereas the beam (or target) residue is independent of W . Besides the mesons of the $J^P = 0^-$ and 1^- multiplets ($l = 0$), the model includes the production of mesons of the $J^P = 0^+, 1_{a_1}^+, 2^+, 1_{b_1}^+$ multiplets, for which the orbital angular momentum (l) between the quark and the antiquark forming the meson is 1. The parameters of the model are a strangeness suppression factor (λ) in meson production, the coefficients a and b in the central component expression $\langle \text{primordial multiplicity} \rangle = a \cdot \ln(W/b)$, and a high- l meson excitation cutoff l_{max} . The parameters ($\lambda = 0.3, a = 1.34, b = 4 \text{ GeV}$ and $l_{max} = 1$) were determined from hadron interaction data. It should be noted, that the model has neither a free pseudoscalar/vector (P/V) ratio nor a free η/π ratio. They are set to 1/3 and 1/1 respectively, as expected from spin-statistics.

3. Results

All experimental results given below are fully corrected, as described above. Data points which are based on less than 10 events, or less than 10 particles, are not shown. The errors drawn in Figs. 3 to 7 and quoted in Tables 5 to 9 include the statistical error, the error of the correction factor and the systematic error. The different errors were added in quadrature.

The total numbers of resonances obtained from fits to the total data sample are given in Table 4. The two-pion and three-pion mass distributions for the forward region and the full W range are shown in Figs. 1 and 2 together with the fitted shapes of the background and of the resonances. The average value of χ^2 per degree of freedom is around 1.0.

There is evidence for the production of $\rho^0, \rho^+, \rho^-, \eta, \omega$ and f_2 both in $\bar{\nu}Ne$ and νNe scattering. In order to test the significance of the f_2 contribution, fits were performed with and without the f_2 . In most cases a significant fall in χ^2 is observed when the f_2 is included, and the falls are most significant in the forward region at large W (~ 6 with a

decrease of 1 for the number of degrees of freedom).

a) Average Multiplicities

The average multiplicities of the pions and of the resonances, for $4 \text{ GeV} < W < 10 \text{ GeV}$, are compared with each other in Fig. 3. The ρ^0, η and ω have similar average multiplicities. They are approximately equal in ν and $\bar{\nu}$ scattering, except that the η multiplicity seems to be higher in ν than in $\bar{\nu}$ scattering. The f_2 production is suppressed relative to the other neutral resonances by about a factor of 2.

Within the errors the total multiplicities for ρ^0, ρ^+, ρ^- in $\bar{\nu}Ne$ scattering agree with those for ρ^0, ρ^-, ρ^+ , respectively, in νNe scattering. A striking feature is the abundant production of ρ^- in $\bar{\nu}Ne$ and of ρ^+ in νNe scattering and the strong suppression of the opposite charge states of the ρ . The same hierarchy is seen for pions, but less pronounced, probably because the pions are mostly decay products of other particles (i.e. resonances).

The average multiplicities of the pions and of the different resonances are listed in Tables 5 and 6 for the full W range, for two subintervals of W , and for the backward, forward and total regions of the $W^\pm$ -nucleon system separately. The forward hemisphere is defined by the $W^\pm$ -direction in the $W^\pm$ -nucleon rest system, assuming zero Fermi momentum for the target nucleon. The forward and total multiplicities clearly increase with W , and in general the forward multiplicities exceed the backward ones.

The multiplicity predictions of the two theoretical models, for $4 \text{ GeV} < W < 10 \text{ GeV}$, are also listed in Tables 5 and 6. It should be noted that neither model includes nuclear reinteractions, which are known to increase the pion multiplicities in the backward hemisphere, and to have only little effect on the forward pion multiplicities [2]. Nuclear effects of similar size on the resonance multiplicities are below the sensitivity of this experiment (see also section c).

The *Lund* model reproduces reasonably well the pion multiplicities, in particular the charge separations, in the forward region. The excess of positive pions in the backward region is mainly due to nuclear reinteractions. Only predictions for the forward component are given in the *Wells* model, because the backward component requires an l_{max} for the baryons which is not well determined from hadron data. Putting $l_{max,baryon} = 0$ significantly underestimates the backward pion rates, implying substantial $l_{max,baryon} \geq 1$ (i.e. N^*, Δ^* etc.) production.

For the ρ and ω the *Wells* predictions are systematically lower than the *Lund* values and agree better with the data than the *Lund* values. The *Lund* predictions are by a factor of 1.67 ± 0.30 larger than the measurements. In an $\bar{\nu}D$ experiment [11] the ρ^0 multiplicity was found to be overestimated by the *Lund* model by $\sim 50 \%$. The above

mentioned hierarchy of ρ^0, ρ^+, ρ^- multiplicities and the symmetry of ρ multiplicities between $\bar{\nu}Ne$ and νNe scattering are reproduced by both models. They can be interpreted as consequences of the underlying quark production and fragmentation processes.

Only the semi-empirical model gives a prediction for the average f_2 multiplicity. It agrees well with the measurements.

The P/V ratio, which is defined as the ratio of directly produced 0^- (=P) and directly produced 1^- mesons (=V), warrants further comment. Most experiments are insensitive to $l = 1$ (i.e. $0^+, 1_{a_1}^+, 2^+$ and $1_{b_1}^+$) meson production, and thus only correct their pseudoscalar rates for pseudoscalars coming from vector meson decays. A value of P/V of about 1/1 is usually obtained, in disagreement with the naive spin-statistics ratio of 1/3. However, if one assumes (as in the semi-empirical model) that $l = 1$ as well as $l = 0$ mesons are produced (in the ratio $0^- : 1^- : 0^+ : 1_{a_1}^+ : 2^+ : 1_{b_1}^+ = 1 : 3 : 1 : 3 : 5 : 3$), and that they decay as given in the PDG tables [4], then the resultant mixture of P and V mesons would give an apparent P/V of about 1/1. The apparent pseudoscalar rate is enhanced because natural-spin-parity mesons usually decay to a pair of pseudoscalars whereas unnatural-spin-parity mesons usually decay to a vector and a pseudoscalar meson.

As the semi-empirical model gives an $l = 1$ multiplicity prediction in reasonable agreement with the measured f_2 multiplicity, one can conclude that

- $l = 1$ meson production is not strongly suppressed compared with P and V production,
- the bulk of the vector mesons (as well as of the pseudoscalars) are decay products, and
- there is no evidence contradicting the naive 1/3 ratio for P/V; however, Monte-Carlo generators should include unsuppressed $l = 1$ meson production.

In Table 7 the global resonance multiplicities from this experiment are compared with those from other experiments [11-18]. The differences seen between the average multiplicities for a given resonance are partly due to a W dependence. No conclusion can be drawn from Table 7 on an A dependence.

b) Inclusive Distributions of x_F, z and p_T

The hadronic variables x_F, z and p_T are defined as follows : $x_F = 2p_L^*/W$ (Feynman-x), where p_L^* is the component of the hadron momentum in the current direction, evaluated in the overall hadronic rest system; $z = E^h/\nu$ (fractional energy), where E^h is the energy of the hadron and ν the leptonic energy transfer ($\nu = E_\nu - E_\mu$) in the laboratory system; p_T (usually called $p_{T,out}$) is the modulus of the component of the

hadron momentum perpendicular to the lepton plane (defined by the incoming ' $\bar{\nu}$ ' and the outgoing muon), evaluated in the laboratory system. For the ρ^0, ρ^- and ω in $\bar{\nu}Ne$ scattering the average multiplicities are shown as a function of x_F in Fig. 4, and for the forward-going particles ($x_F > 0$) as a function of z in Fig. 5 and of p_T in Fig. 6. The prediction of the *Lund* model for scattering off an isoscalar nucleon are drawn as solid curves. All plots are for the region $4 \text{ GeV} < W < 10 \text{ GeV}$.

The x_F distributions show that both in the data and in the model forward production is stronger than backward production. The shapes of the x_F, z and p_T spectra in the forward region are in reasonable agreement with the model. Due to the large number of background combinations the average multiplicities cannot be determined accurately at low $|x_F|, z$ and p_T .

The average multiplicities at high z for ρ^0 and ρ^- relative to those of the π^0, π^+ and π^- are listed in Table 8. The data are in good agreement with the *Lund* values, which were calculated with a vector meson to pseudoscalar ratio of $V/P = 1$. From Fig. 7 it is seen that the dependence of these ratios on z is also well described by the model.

c) Nuclear effects

The total charge of an event (Q_T) is defined as the sum of the charges of all observed secondary particles, excluding particles likely to be spectators to the ' $\bar{\nu}$ ' interaction or to be nuclear fragments. For scattering off a proton or neutron target Q_T would have a value of 1 or 0 respectively, and $Q_T > 1$ can only result if at least one rescatter has occurred on a proton of the neon nucleus. The selection $Q_T > 1$ thus defines a pure reinteraction sample.

The average multiplicities of ρ^0, ρ^- and ω in $\bar{\nu}Ne$ scattering are given in Table 9 for the three samples $Q_T \leq 1, Q_T > 1$ and *all* Q_T . No significant trend is seen in the data when comparing the $Q_T \leq 1$ and $Q_T > 1$ samples. Thus, with the given experimental resolution, nuclear effects on resonance multiplicities are not observed, neither in the forward nor in the backward hemisphere.

4. Summary

The production of the meson resonances $\rho^0, \rho^+, \rho^-, \eta, \omega$ and f_2 in $\bar{\nu}Ne$ and νNe charged current interactions has been studied. The results can be summarized as follows :

- There is clear evidence for the production of all of these resonances both in $\bar{\nu}Ne$ and νNe scattering.

- The hierarchy of the average ρ^0, ρ^+, ρ^- multiplicities is the same as that of the π^0, π^+, π^- multiplicities and corresponds qualitatively to the expectations of the quark parton model.
- The average ρ^0, η and ω multiplicities are of approximately similar size.
- Within the errors the average multiplicities of $\rho^0, \rho^+, \rho^-, \omega$ and f_2 in $\bar{\nu}Ne$ scattering agree with those of $\rho^0, \rho^-, \rho^+, \omega$ and f_2 , respectively, in νNe scattering. η production seems to be stronger in νNe than in $\bar{\nu}Ne$ scattering.
- The resonance multiplicities increase with increasing W , and forward production is stronger than backward production.
- The main features of resonance production are qualitatively reproduced by the *Lund* model. The predicted average multiplicities are by a factor of 1.67 ± 0.30 larger than the measurements.
- The ρ/π ratios for $z > 0.6, x_F > 0, 4 \text{ GeV} < W < 10 \text{ GeV}$ agree with the *Lund* prediction, assuming a value for P/V of 1.
- The resonance multiplicities, in particular those of the f_2 , are in reasonable agreement with the predictions of a semi-empirical model, whose parameters were determined by hadron interaction data. From the comparison of this model with the experimental data it can be concluded that there is no evidence for a deviation of the P/V ratio from $1/3$, if in the theoretical model the production of $l = 1$ mesons, i.e. of mesons from the $0^+, 1_{a_1}^+, 2^+, 1_{b_1}^+$ multiplets, is included. An apparent P/V of about $1/1$ is obtained if the 0^- and 1^- mesons from the decay of the $l = 1$ mesons are included in P and V respectively.
- With the given experimental resolution, there is no evidence for nuclear effects on the resonance multiplicities.

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Tab. 1: Experimental samples used ($p_\mu > 5$ GeV/c, $1.5 \text{ GeV} < W < 10 \text{ GeV}$) and average values of E_ν , W and Q^2 for the total event sample.

	$\bar{\nu}\text{Ne}$	νNe
no. of events for		
$1.5 \text{ GeV} < W < 4.0 \text{ GeV}$	8336	3438
$4.0 \text{ GeV} < W < 10 \text{ GeV}$	5723	4906
$1.5 \text{ GeV} < W < 10 \text{ GeV}$	14059	8344
$\langle E_\nu \rangle$	39 GeV	50 GeV
$\langle W \rangle$	3.9 GeV	4.8 GeV
$\langle Q^2 \rangle$	4.0 GeV ²	6.2 GeV ²

Tab. 2: Resonance parameters of two-pion resonances

resonance	mass distribution	mass resolution at resonance (MeV)	PDG value of central mass (MeV)	PDG value of width (MeV)	Γ_ρ, Γ_f used in fit (MeV)
ρ^0	$\pi^+\pi^-$	28	770	153	166
ρ^+	$\pi^+\pi^0$	38	770	153	177
ρ^-	$\pi^-\pi^0$	38	770	153	177
f_2	$\pi^+\pi^-$	36	1274	185	201

Tab. 3: Resonance parameters of three-pion resonances

resonance	mass distribution	mass resolution at resonance (MeV)	PDG value of central mass (MeV)	PDG value of width (MeV)	$\sigma_\eta, \sigma_\omega$ used in fit (MeV)
η	$\pi^+\pi^-\pi^0$	12	549	0	12
ω	$\pi^+\pi^-\pi^0$	22	782	8.5	22

Tab. 4: Total number of observed mesons and average correction factors for the number of ρ, η, ω and f_2 mesons. The errors for the total number of observed mesons include the statistical and systematic error.

	branching ratio	$\bar{\nu}Ne$		νNe	
		no.of observed mesons	correction factor	no.of observed mesons	correction factor
$\rho^0 \rightarrow \pi^+ \pi^-$	1.00	1289 ± 197	1.26 ± 0.02	1152 ± 267	1.24 ± 0.02
$\rho^+ \rightarrow \pi^+ \pi^0$	1.00	184 ± 146	2.73 ± 0.10	763 ± 133	2.93 ± 0.09
$\rho^- \rightarrow \pi^- \pi^0$	1.00	845 ± 183	2.93 ± 0.08	83 ± 99	2.83 ± 0.09
$\eta \rightarrow \pi^+ \pi^- \pi^0$	0.237 ± 0.005	50 ± 25	17.05 ± 0.96	83 ± 23	19.64 ± 1.08
$\omega \rightarrow \pi^+ \pi^- \pi^0$	0.896 ± 0.005	456 ± 80	4.45 ± 0.15	241 ± 57	4.49 ± 0.13
$f_2 \rightarrow \pi^+ \pi^-$	$(0.86 \pm 0.02) \cdot 2/3$	319 ± 97	2.25 ± 0.08	197 ± 90	2.34 ± 0.07

Tab. 5: Average backward (B), forward (F) and total (T) multiplicities in $\bar{\nu}Ne$ scattering, for three regions of W . Values with a significance of less than 1 standard deviation are put in brackets. For $W > 4$ GeV also the predictions of the *Lund* and the *Wells* model are given. In general $\langle n_B \rangle + \langle n_F \rangle$ differs slightly from $\langle n_T \rangle$, since the corrections and, in the case of the resonances, the fits to the mass distributions are performed independently for B, F and T.

		$W < 4$ GeV	$W > 4$ GeV			all W
		data	data	<i>Lund</i>	<i>Wells</i>	data
π^0	<i>B</i>	0.54 ± 0.05	0.76 ± 0.06	0.87	—	0.62 ± 0.05
	<i>F</i>	0.51 ± 0.02	1.04 ± 0.04	1.17	1.00	0.73 ± 0.03
	<i>T</i>	1.01 ± 0.06	1.84 ± 0.10	2.05	—	1.35 ± 0.07
π^+	<i>B</i>	0.43 ± 0.07	0.81 ± 0.12	0.67	—	0.58 ± 0.09
	<i>F</i>	0.39 ± 0.06	0.78 ± 0.12	0.81	0.86	0.54 ± 0.08
	<i>T</i>	0.81 ± 0.12	1.59 ± 0.24	1.48	—	1.12 ± 0.17
π^-	<i>B</i>	0.63 ± 0.02	0.96 ± 0.03	0.88	—	0.76 ± 0.02
	<i>F</i>	0.62 ± 0.02	1.27 ± 0.03	1.22	1.08	0.89 ± 0.02
	<i>T</i>	1.25 ± 0.03	2.23 ± 0.05	2.10	—	1.64 ± 0.04
ρ^0	<i>B</i>	0.017 ± 0.014	0.033 ± 0.026	0.13	0.03	0.023 ± 0.013
	<i>F</i>	0.056 ± 0.012	0.144 ± 0.024	0.20	0.16	0.097 ± 0.012
	<i>T</i>	0.072 ± 0.018	0.175 ± 0.043	0.32	0.19	0.115 ± 0.018
ρ^+	<i>B</i>	(0.016 ± 0.024)	(0.021 ± 0.033)	0.10	0.03	(0.011 ± 0.017)
	<i>F</i>	0.018 ± 0.013	(0.035 ± 0.040)	0.11	0.08	0.024 ± 0.021
	<i>T</i>	0.032 ± 0.022	0.059 ± 0.040	0.21	0.11	0.036 ± 0.029
ρ^-	<i>B</i>	0.054 ± 0.036	0.079 ± 0.037	0.12	0.03	0.070 ± 0.018
	<i>F</i>	0.104 ± 0.032	0.098 ± 0.032	0.26	0.24	0.095 ± 0.017
	<i>T</i>	0.160 ± 0.023	0.220 ± 0.078	0.38	0.27	0.176 ± 0.039
η	<i>B</i>	(0.000 ± 0.087)	(0.031 ± 0.048)	0.11	0.02	(0.004 ± 0.042)
	<i>F</i>	0.068 ± 0.018	(0.027 ± 0.030)	0.18	0.12	0.047 ± 0.019
	<i>T</i>	0.077 ± 0.029	0.060 ± 0.052	0.28	0.14	0.061 ± 0.031
ω	<i>B</i>	0.041 ± 0.016	0.097 ± 0.034	0.11	0.04	0.066 ± 0.018
	<i>F</i>	0.053 ± 0.013	0.104 ± 0.027	0.18	0.19	0.080 ± 0.016
	<i>T</i>	0.098 ± 0.023	0.205 ± 0.045	0.29	0.22	0.145 ± 0.026
f_2	<i>B</i>	(0.001 ± 0.032)	0.055 ± 0.026	—	0.013	0.019 ± 0.011
	<i>F</i>	(0.015 ± 0.015)	0.067 ± 0.024	—	0.069	0.032 ± 0.011
	<i>T</i>	0.014 ± 0.012	0.122 ± 0.036	—	0.082	0.051 ± 0.016

Tab. 6: Average backward (B), forward (F) and total (T) multiplicities in νNe scattering, for three regions of W . Values with a significance of less than 1 standard deviation are put in brackets. For $W > 4$ GeV also the predictions of the *Lund* and the *Wells* model are given. In general $\langle n_B \rangle + \langle n_F \rangle$ differs slightly from $\langle n_T \rangle$, since the corrections and, in the case of the resonances, the fits to the mass distributions are performed independently for B, F and T.

		$W < 4$ GeV data	$W > 4$ GeV data <i>Lund</i> <i>Wells</i>			all W data
π^0	B	0.61 ± 0.05	0.97 ± 0.07	0.80	—	0.80 ± 0.06
	F	0.52 ± 0.03	1.14 ± 0.04	1.24	1.04	0.88 ± 0.03
	T	1.10 ± 0.07	2.13 ± 0.11	2.04	—	1.68 ± 0.09
π^+	B	0.75 ± 0.11	1.20 ± 0.18	0.83	—	1.00 ± 0.15
	F	0.81 ± 0.12	1.36 ± 0.20	1.29	1.13	1.12 ± 0.17
	T	1.56 ± 0.23	2.55 ± 0.38	2.12	—	2.12 ± 0.32
π^-	B	0.43 ± 0.02	0.89 ± 0.03	0.59	—	0.69 ± 0.02
	F	0.31 ± 0.01	0.91 ± 0.03	0.87	0.91	0.65 ± 0.02
	T	0.75 ± 0.03	1.80 ± 0.04	1.45	—	1.34 ± 0.03
ρ^0	B	0.029 ± 0.021	0.053 ± 0.039	0.10	0.04	0.045 ± 0.024
	F	0.057 ± 0.027	0.181 ± 0.043	0.22	0.17	0.132 ± 0.023
	T	0.088 ± 0.032	0.227 ± 0.073	0.32	0.21	0.171 ± 0.040
ρ^+	B	0.072 ± 0.037	0.128 ± 0.053	0.11	0.04	0.106 ± 0.041
	F	0.109 ± 0.035	0.149 ± 0.078	0.29	0.26	0.137 ± 0.044
	T	0.206 ± 0.053	0.269 ± 0.084	0.40	0.29	0.268 ± 0.047
ρ^-	B	(0.000 ± 0.074)	(0.000 ± 0.024)	0.08	0.04	(0.000 ± 0.018)
	F	(0.009 ± 0.026)	0.078 ± 0.034	0.12	0.09	0.051 ± 0.026
	T	(0.000 ± 0.134)	0.051 ± 0.046	0.20	0.13	(0.028 ± 0.033)
η	B	0.099 ± 0.059	(0.064 ± 0.085)	0.09	0.03	0.071 ± 0.055
	F	0.055 ± 0.030	0.128 ± 0.048	0.18	0.13	0.106 ± 0.033
	T	0.121 ± 0.057	0.227 ± 0.086	0.27	0.15	0.196 ± 0.056
ω	B	(0.025 ± 0.027)	0.059 ± 0.041	0.09	0.04	0.046 ± 0.026
	F	0.063 ± 0.019	0.096 ± 0.029	0.19	0.21	0.081 ± 0.020
	T	0.096 ± 0.031	0.153 ± 0.047	0.29	0.25	0.130 ± 0.031
f_2	B	(0.009 ± 0.016)	(0.017 ± 0.031)	—	0.016	(0.008 ± 0.018)
	F	(0.006 ± 0.016)	0.076 ± 0.032	—	0.076	0.046 ± 0.019
	T	(0.021 ± 0.023)	0.094 ± 0.042	—	0.093	0.055 ± 0.025

Tab. 7: Average multiplicities of resonances from different ' $\bar{\nu}$ ' experiments.

	target	W range (GeV)	$\langle W \rangle$ (GeV)	average multiplicity	reference
$\bar{\nu}$ experiments					
ρ^0	p		3.4	0.21 ± 0.03	[13]
	p	2 – 12	4.2	0.11 ± 0.02	[12]
	D	2 – 12		$0.19 \pm 0.02 \pm 0.03$	[11]
	Ne	1.5 – 10	3.9	0.12 ± 0.02	this exp.
ρ^+	Ne	1.5 – 10	3.9	0.04 ± 0.03	this exp.
ρ^-	Ne	1.5 – 10	3.9	0.18 ± 0.04	this exp.
η	Ne	1.5 – 10	3.9	0.06 ± 0.03	this exp.
ω	Ne	1.5 – 10	3.9	0.15 ± 0.03	this exp.
f_2	p	2 – 12	4.2	0.026 ± 0.016	[12]
	D	2 – 12		< 0.03 (90 % C.L.)	[11]
	Ne	1.5 – 10	3.9	0.051 ± 0.016	this exp.
ν experiments					
ρ^0	p	2 – 15	4.9	0.16 ± 0.02	[14, 12]
	p		5.0	0.21 ± 0.04	[15]
	D	2 – 15		$0.21 \pm 0.02 \pm 0.03$	[11]
	D	< 15	5.0	0.18 ± 0.03	[16]
	Freon	2 – 6	3.1	0.09 ± 0.02	[17]
	Ne			0.21 ± 0.03	[18]
	Ne	1.5 – 10	4.8	0.17 ± 0.04	this exp.
ρ^+	Ne			0.26 ± 0.07	[18]
	Ne	1.5 – 10	4.8	0.27 ± 0.05	this exp.
ρ^-	Ne	1.5 – 10	4.8	0.03 ± 0.04	this exp.
η	Ne			0.08 ± 0.04	[18]
	Ne	1.5 – 10	4.8	0.20 ± 0.06	this exp.
ω	D	< 15	5.0	0.39 ± 0.19	[16]
	Ne			0.08 ± 0.04	[18]
	Ne	1.5 – 10	4.8	0.13 ± 0.03	this exp.
f_2	p	2 – 15	4.9	0.04 ± 0.02	[14]
	D	2 – 15		< 0.03 (90 % C.L.)	[11]
	Ne	1.5 – 10	4.8	0.055 ± 0.025	this exp.

Tab. 8: Ratios of average multiplicities at high z ($z > 0.6, x_F > 0, 4 \text{ GeV} < W < 10 \text{ GeV}$).

meson ratio	data	Lund
	$\bar{\nu}Ne$	
ρ^0/π^0	1.08 ± 0.35	0.9
ρ^0/π^+	2.48 ± 0.79	2.0
ρ^0/π^-	0.47 ± 0.14	0.6
ρ^-/π^0	1.44 ± 1.10	1.2
ρ^-/π^+	3.31 ± 2.51	3.0
ρ^-/π^-	0.63 ± 0.47	0.9
	νNe	
ρ^0/π^0	1.04 ± 0.32	0.9
ρ^0/π^+	0.51 ± 0.14	0.6
ρ^0/π^-	6.49 ± 2.48	2.0

Tab. 9: Average backward (B), forward (F) and total (T) multiplicities of ρ^0, ρ^- and ω mesons in $\bar{\nu}Ne$ scattering ($1.5 \text{ GeV} < W < 10 \text{ GeV}$) for the three event samples $Q_T \leq 1$ (9782 events), $Q_T > 1$ (4277 events) and all Q_T (14059 events).

		$Q_T \leq 1$	$Q_T > 1$	all Q_T
ρ^0	B	0.017 ± 0.014	0.041 ± 0.031	0.023 ± 0.013
	F	0.105 ± 0.015	0.073 ± 0.023	0.097 ± 0.012
	T	0.123 ± 0.020	0.104 ± 0.049	0.115 ± 0.018
ρ^-	B	0.066 ± 0.021	0.034 ± 0.089	0.070 ± 0.018
	F	0.127 ± 0.025	0.077 ± 0.036	0.095 ± 0.017
	T	0.204 ± 0.038	0.127 ± 0.065	0.176 ± 0.039
ω	B	0.038 ± 0.015	0.150 ± 0.053	0.066 ± 0.018
	F	0.076 ± 0.018	0.093 ± 0.029	0.080 ± 0.016
	T	0.114 ± 0.026	0.236 ± 0.064	0.145 ± 0.026

FIGURE CAPTIONS

1. Two-pion and three-pion invariant mass distributions in $\bar{\nu}Ne$ scattering for the forward region and the full W range. The solid lines represent the result of fitting expression (1) or (5) to the distributions. The dashed lines show the contribution of the background and of the resonances separately. a) $\pi^+\pi^-$, b) $\pi^+\pi^0$, c) $\pi^-\pi^0$ and d) $\pi^+\pi^-\pi^0$ mass.
2. Two-pion and three-pion invariant mass distributions in νNe scattering for the forward region and the full W range. The solid lines represent the result of fitting expression (1) or (5) to the distributions. The dashed lines show the contribution of the background and of the resonances separately. a) $\pi^+\pi^-$, b) $\pi^+\pi^0$, c) $\pi^-\pi^0$ and d) $\pi^+\pi^-\pi^0$ mass.
3. Average multiplicities of pions and of the $\rho^0, \rho^+, \rho^-, \eta, \omega$ and f_2 resonances for the range $4 \text{ GeV} < W < 10 \text{ GeV}$.
4. Normalized x_F distributions $\frac{1}{N_{ev}} \cdot \frac{dN}{dx_F}$ of a) ρ^0 , b) ρ^- and c) ω in $\bar{\nu}Ne$ scattering for $4 \text{ GeV} < W < 10 \text{ GeV}$. The curves represent the predictions of the *Lund* model for $\bar{\nu}$ scattering off an isoscalar nucleon.
5. Normalized z distributions $\frac{1}{N_{ev}} \cdot \frac{dN}{dz}$ of a) ρ^0 , b) ρ^- and c) ω in $\bar{\nu}Ne$ scattering for $x_F > 0$ and $4 \text{ GeV} < W < 10 \text{ GeV}$. The curves represent the predictions of the *Lund* model for $\bar{\nu}$ scattering off an isoscalar nucleon.
6. Normalized p_T distributions $\frac{1}{N_{ev}} \cdot \frac{dN}{dp_T}$ of a) ρ^0 , b) ρ^- and c) ω in $\bar{\nu}Ne$ scattering for $x_F > 0$ and $4 \text{ GeV} < W < 10 \text{ GeV}$. The curves represent the predictions of the *Lund* model for $\bar{\nu}$ scattering off an isoscalar nucleon.
7. Ratios of average multiplicities as a function of z for $x_F > 0$ and $4 \text{ GeV} < W < 10 \text{ GeV}$. The curves represent the predictions of the *Lund* model for ' $\bar{\nu}$ ' scattering off an isoscalar nucleon. a) ρ^0/π^0 in $\bar{\nu}Ne$, b) ρ^-/π^- in $\bar{\nu}Ne$, and c) ρ^0/π^0 in νNe scattering.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7