tions imposed by the single-particle nature of the Lane model. The good agreement achieved by the microscopic method indicates that structure effects are important. We conclude that the microscopic approach is required to provide a reliable account of the experimental ratios. Since we have assumed throughout that the nuclear force is charge independent, we further conclude that the observed ratios can be satisfactorily understood without requiring explicit charge dependence of the nuclear interaction.

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Observation of the Decay $f^0 \to \pi^+\pi^+\pi^-\pi^-$

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We have observed the decay mode $f^0 \to \pi^+\pi^+\pi^-\pi^-$ and determined the branching ratio $\Gamma(f^0 \to \pi^+\pi^+\pi^-\pi^-)/\Gamma(f^0 \to \pi^+\pi^-) = (5.5 \pm 1.0)\times 10^{-2}$.

Information about the decay $f^0 \to \pi^+\pi^+\pi^-\pi^-$ is sparse. The only observation of this decay mode has been reported by Ascoli *et al.*,[1] who found 78 events in the region of the f^0 mass. Other experiments[2] have obtained upper limits for this decay mode.

We report here on a search for the four-pion decay of the f^0 from a study of the reaction

$$\pi^+ + d \to \pi^+ + \pi^+ + \pi^- + \pi^- + p + p_s, \quad (1)$$

where p_s denotes the spectator proton. Data were obtained from a 16-event/μb exposure of the 30-in. Argonne National Laboratory bubble chamber to a 6-GeV/c π^+ beam. The sample consists of 7271 events which fit Reaction (1) by kinematics and are consistent with the observed ionization. We have included events with invisible spectator protons and have applied a momentum cutoff of 250 MeV/c for visible spectator protons.

The four-pion mass spectrum is shown in Fig. 1(a). Note that we observe less than 15 events between the four-pion threshold and 1 GeV. In Fig. 1(b), we show part of the mass spectrum for events up to mass 1.57 GeV with $|t| \leq 0.3$ (GeV/c)^2 where t is the four-momentum transfer between the incident π^+ and the outgoing four-pion system. An enhancement around 1.28 GeV for these peripherally produced events is clearly visible.

Since the energy dependence of the width of a resonance decaying into four particles is not known, it is not clear what shape is appropriate to describe this enhancement. Fortunately, the results presented here are insensitive to the specific choice for the assumed resonance shape. If we assume a two-body D-wave Breit-Wigner shape plus a polynomial background,[3] we obtain the following results for events with $|t| \leq 0.3$ (GeV/c)^2:

$$M = 1.283 \pm 0.010 \text{ GeV},$$

$$\Gamma = 0.185 \pm 0.025 \text{ GeV}, \quad N = 154 \pm 22,$$

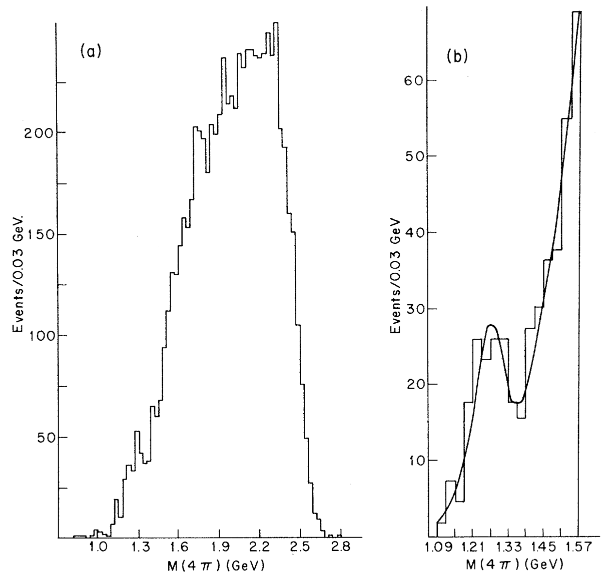

FIG. 1. (a) Four-pion mass spectrum for events fitting Reaction (1). (b) Four-pion mass spectrum up to 1.57 GeV for events fitting Reaction (1) with $|t| \leq 0.3$ $(\mathrm{GeV}/c)^2$. The curve represents the result of the fit described in the text.

where M is the mass, Γ the width of the resonance, and N the number of events above background. The curve in Fig. 1(b) represents these results; the observed enhancement corresponds to a 6-standard-deviation effect. The values for the mass and width of the four-pion enhancement are in good agreement with those observed in our data[4] for f^0 production via the reaction $\pi^+ + d \to \pi^+ + \pi^- + p + p_s$ ($M = 1.272 \pm 0.004$ GeV, $\Gamma = 0.192 \pm 0.016$ GeV).

In the analysis which follows we define the region of enhancement to be 1.1 GeV $\leq M(4\pi) \leq$ 1.38 GeV with $|t| \leq 0.3$ $(\mathrm{GeV}/c)^2$. There are 165 events which satisfy these criteria.

We have examined the differential cross section $d\sigma/dt$ for these events. Assuming $d\sigma/dt = Ae^{bt}$, we find $b = 8.2 \pm 3.9$ $(\mathrm{GeV}/c)^{-2}$. The differential cross section for events from $f^0 \to \pi^+\pi^-$ in the same t interval has an exponent $b = 10.3 \pm 0.3$ $(\mathrm{GeV}/c)^{-2}$. The exponents are in good agreement with each other.

In Fig. 2(a) we show the distribution in $x \equiv \cos\theta_{++} = \hat{p}_{\mathrm{in}} \cdot \hat{p}_{++}$ for the 165 events, where $\hat{p}_{\mathrm{in}}$ is a unit vector along the incident pion direction and $\hat{p}_{++}$ is a unit vector along the direction of the outgoing $\pi^+\pi^+$ system, both calculated in the four-pion rest frame. We note the distribution is anisotropic but has little forward-backward asymmetry. We have therefore fitted the folded distribution by a Legendre polynomial expansion in x and find the following coefficients[5]:

$$A_2 = 0.88 \pm 0.20, \quad A_4 = 0.59 \pm 0.25.$$

These coefficients are consistent with the decay of a spin-2 object.

All these observations lead to the conclusion that the enhancement around 1280 MeV is indeed due to the four-pion decay of the f^0 meson.[6] Using the 154 ± 22 four-pion events above background which we attribute to the f^0 and the 3253 ± 108 $f^0 \to \pi^+\pi^-$ events in the same mass and four-momentum transfer intervals, we obtain

$$R = \frac{\Gamma(f^0 \to \pi^+\pi^+\pi^-\pi^-)}{\Gamma(f^0 \to \pi^+\pi^-)} = (5.5 \pm 1.0) \times 10^{-2}$$

or

$$\frac{\Gamma(f^0 \to \pi^+\pi^+\pi^-\pi^-)}{\Gamma(f^0 \to \pi\pi)} = \tfrac{2}{3}R = (3.7 \pm 0.7) \times 10^{-2}.$$

This ratio contains a normalization correction of 1.18 to the four-pion sample,[7] and the error includes the systematic uncertainties which are mainly due to background subtraction.

We now turn to a discussion of dynamical models which attempt to explain the four-pion decay of the f^0 meson. A particularly simple model has been proposed by Ascoli *et al.* In this model the decay $f^0 \to \pi^+\pi^+\pi^-\pi^-$ is assumed to proceed via $f^0 \to \rho\rho$ with the ρ's being emitted in a relative s state. The only unknown in this model is the $f^0 \to \rho\rho$ form factor, and hence apart from overall normalization, various internal distributions can be predicted.[8] The distribution in x for a spin-2 object is given by

$$\begin{aligned} W(x) = {} & \rho_{00}[1 + \tfrac{10}{7}Q_2P_2(x) + \tfrac{18}{7}Q_4P_4(x)] \\ & + 2\rho_{11}[1 + \tfrac{5}{7}Q_2P_2(x) - \tfrac{12}{7}Q_4P_4(x)] \\ & + 2\rho_{22}[1 - \tfrac{10}{7}Q_2P_2(x) + \tfrac{3}{7}Q_4P_4(x)]. \end{aligned}$$

Here ρ_{ii} are the usual density-matrix elements, P_L are the Legendre polynomials, and Q_L are model-dependent coefficients. If the model of Ascoli *et al.* is assumed, the coefficients Q_2 and Q_4 are predicted[9] to have the values $Q_2 = 0.63$ and $Q_4 = 0.58$. Using the coefficients of the Legendre polynomial expansion previously determined, we can calculate Q_L by assuming $\rho_{00} = 1$, i.e., pure one-pion exchange. We find $Q_2 = 0.62 \pm 0.16$, $Q_4 = 0.23 \pm 0.10$. Alternately, using the density-matrix elements $\rho_{00} = 0.91 \pm 0.02$, $\rho_{11} = 0.26 \pm 0.01$, $\rho_{22} = -0.22 \pm 0.01$ as determined from the $f^0 \to \pi^+\pi^-$ data, we find $Q_2 = 0.39 \pm 0.09$, $Q_4 = 0.40 \pm 0.17$.

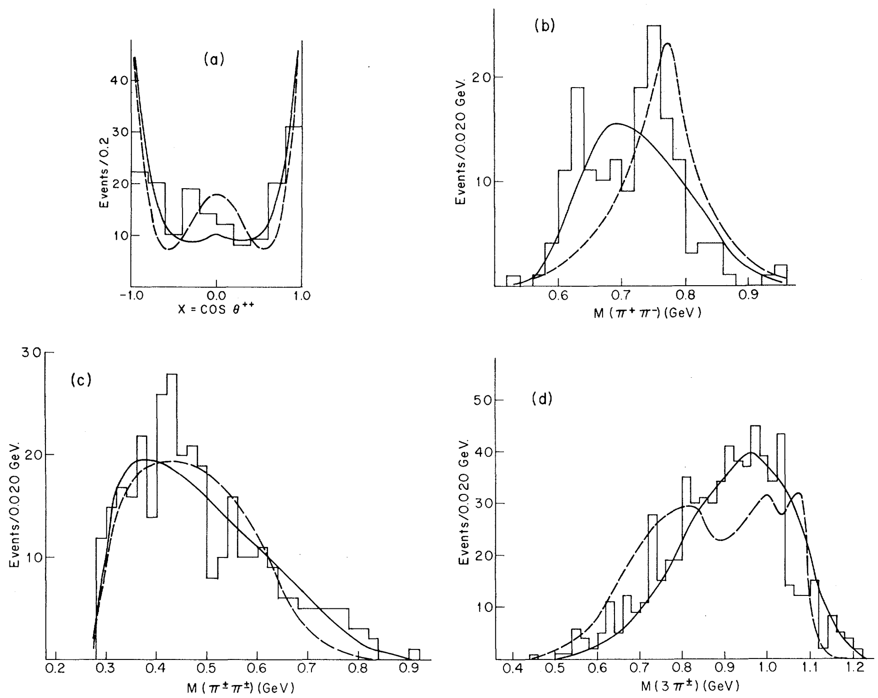

FIG. 2. Internal distributions for 165 events in the enhancement region defined in the text. Solid curves in (b), (c), and (d), predictions of the $\rho\rho$ model. Dashed curves, predictions of Banyai and Rittenberg. (a) Distribution in $x \equiv \cos\theta_{++}$. Solid curve, prediction of the $f \to \rho\rho$ model assuming $\rho_{00}=1$. Dashed curve, prediction of the same model using ρ_{ii} as determined from $\pi^+\pi^-$ data. (b) Distribution of the highest $\pi^+\pi^-$ mass combination. (c) Distribution of the like $\pi\pi$ mass combinations, i.e., $\pi^+\pi^+$ plus $\pi^-\pi^-$. (d) Distributions of the three-pion mass combinations.

Thirdly, we can assume Q_L to be given by the $f^0 \to \rho\rho$ model and calculate the f^0 density-matrix elements. The result is $\rho_{00}=0.52\pm0.11$, $\rho_{11}=0.27\pm0.12$, $\rho_{22}=-0.03\pm0.12$.

In Figs. 2(b)–2(d) we show mass distributions in (b) the highest-mass $\pi^+\pi^-$ combination, (c) the $\pi^+\pi^+$ plus $\pi^-\pi^-$ combinations, and (d) the three-pion combinations. The solid curves are the predictions of the $\rho\rho$ model. Given the limited statistics available this model seems to give an adequate description of the experimental data.

A model for $f^0 \to 4\pi$ based on chiral dynamics has been proposed by Banyai and Rittenberg.[10] Here the contributing graphs involve $f \to 4\pi$, $f \to \rho\pi\pi$, and $f \to A_1\pi$ but not $f \to \rho\rho$ vertices. This model predicts the branching ratio R to be 4.4%, which is in good agreement with our result. The dashed curves in Figs. 2(b)–2(d) represent the predictions of Banyai and Rittenberg. Agreement with the $\pi^+\pi^-$ and 3π mass distributions is poorer than in the $\rho\rho$ model.[11]

In conclusion, our experiment shows clear evidence for the decay $f^0 \to \pi^+\pi^+\pi^-\pi^-$ and establishes a branching ratio $R=(5.5\pm1.0)\times10^{-2}$. The various internal distributions appear consistent with the simple $f^0 \to \rho\rho$ model proposed by Ascoli *et al.*

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[3]The results for the mass and width vary by less than 10 MeV for other reasonable parametrizations of the resonance shape and background. Furthermore, the number of events above background changes by

less than 10% for different parametrizations.

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[5]If we allow one more term in the expansion, we find $A_2 = 0.83 \pm 0.24$, $A_4 = 0.48 \pm 0.31$, $A_6 = 0.47 \pm 0.75$, with A_0 set equal to 1.

[6]The width of the observed enhancement is much larger than that of the D meson; hence we attribute the enhancement entirely to the four-pion decay of the f^0 meson.

[7]Because of different scanning and measurement corrections for the two samples, a normalization is necessary.

[8]We have verified that the predictions of this model are insensitive to the assumed width of the ρ meson and the $f_{\rho\pi\pi}$ form factor. We wish to thank Professor Ascoli for his comments on this point.

[9]These coefficients have been obtained from a Monte Carlo sample of 10 000 $f^0 \to \pi^+\pi^+\pi^-\pi^-$ events. These events were generated according to the $\rho\rho$ model of Ascoli *et al.* For the f^0 mass distribution in the Monte Carlo model, the experimentally observed $f^0 \to \pi^+\pi^+\pi^-\pi^-$ mass distribution was assumed.

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[11]A comparison of predictions of the two models with the experimental distributions yields the following results. For the model of Banyai and Rittenberg the χ^2 per degree of freedom is 6.1, 2.6, and 5.2 for the distributions in Figs. 2(b), 2(c), and 2(d), respectively. For the $\rho\rho$ model we obtain a χ^2 per degree of freedom equal to 1.9, 1.2, and 2.2 for the same distributions.

Exploratory Study of High-Energy Neutrino Interactions*

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We report the results of an initial investigation of high-energy neutrino interactions using a dichromatic neutrino beam. Two bands of neutrinos, from pion decay ($\langle E_\nu \rangle \approx 50$ GeV) and kaon decay ($\langle E_\nu \rangle \approx 145$ GeV), were incident on a counter–spark-chamber detector. We discuss analysis of events of the type $\nu_\mu + N \to \mu^- +$ hadrons. Qualitative comparisons are made with lower-energy neutrino results and the deep-inelastic e-N scaling structure functions.

An exploratory study of high-energy neutrino interactions was carried out in a dichromatic beam at the National Accelerator Laboratory in January 1973.[1] The purposes of this brief preliminary run were to study our apparatus, investigate the qualitative features of high-energy neutrino interactions, and to look for possible anomalous effects. An improved lower bound on the W-boson mass and a preliminary search for a heavy muon have been reported from this run.[2]

We report here on the qualitative results obtained from neutrino interactions of the type

$$\nu_\mu + N \to \mu^- + \text{hadrons}. \tag{1}$$

In order to study all the relevant features of this reaction, we have constructed an experiment which measures the hadron energy E_h, the muon energy E', and muon lab angle θ'. This allows determination of the invariant kinematic variables: four-momentum transfer Q^2 and energy transfer ν to the hadron system.

It is beyond the purview of this paper to describe in detail the apparatus and beam. Briefly, a momentum and sign-selected secondary hadron beam is created from the interactions of primary protons from the accelerator, and is directed down a 345-m decay pipe in which kaon and pion decays yield neutrinos and muons. The muons and nondecaying hadrons are removed by 530 m of dirt and steel shielding. The resulting neutrino beam consists of low- and high-energy bands of muon neutrinos from the decays $\pi^+ \to \mu^+ + \nu_\mu$ and $K^+ \to \mu^+ + \nu_\mu$, respectively.

To investigate neutrino interactions, we have constructed a 160-ton steel target interspersed with liquid scintillation counters and wire spark