Dynamics of the $\pi^- p \to \pi^0\pi^0 n$ Reaction for $p_{\pi^-} < 750$ MeV/c

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Data are presented for the reaction $\pi^- p \to \pi^0\pi^0 n$ in the range from threshold to $p_{\pi^-} = 750$ MeV/c. The systematics of the data and multipole analyses are examined for sensitivity to a $f_0(600)$ ("σ") meson. A one-pion-exchange mechanism is found to be very weak, or absent. The reaction appears to become dominated by sequential π^0 decays through the $\Delta(1232)$ resonance as the beam momentum increases, along with substantial interference effects from several competing mechanisms.

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The $\pi\pi$ interaction is important for many nuclear processes and continues to have very high interest. The low-energy behavior is dominated by the $\rho(770)$ meson ($I, J^\pi = 1, 0^-$). A strong S-wave interaction is evident at lower masses, often suggested as manifesting a scalar-isoscalar $f_0(600)$ meson [also commonly known as the σ meson ($I, J^\pi = 0, 0^+$)] [1]. It was originally introduced in models to describe the breakdown of chiral symmetry [2,3], and its mass has been theoretically estimated to be near 600–800 MeV [4,5]. Some recent analyses of historical data have claimed firm evidence of its existence [6,7]. Recent direct experimental evidence for the f_0 meson from the $\pi^- p \to \pi^0\pi^0 n$ reaction at 9 GeV/c has also been claimed [8]. In nuclei, enhancements of the scalar $\pi\pi$ interaction near threshold have been suggested as a signature of the restoration of chiral symmetry in nuclear matter, an important step in the formation of a quark-gluon plasma [9]. The results from recent experiments are intriguing [10–13].

The isoscalar S-wave scattering length a_0^0 is a key item for comparison with chiral theories. The $\pi N \to \pi\pi N$ reaction is often used to get at this quantity. However, Chew-Low extrapolations from high energies to the unphysical pion pole are technically difficult and, when charged pions are in the final state, the sensitivity to a scalar state in the presence of a strong ρ-meson background is also challenging. Because of Bose statistics, the $\rho(770)$ cannot decay into two π^0's. Hence, the $\pi^0\pi^0$ channel should provide one of the best means for producing and observing the presence of a scalar meson.

Two π^0's can be produced in a $(\pi, 2\pi)$ reaction by a variety of processes, as illustrated in Fig. 1. A correlated pair such as the scalar f_0 meson can be produced either by one-pion exchange (OPE) from the nucleon or by decay of a N^* resonance formed in the s channel. An s-channel resonance such as the $N^*(1440)\frac{1}{2}^+$ or $N^*(1520)\frac{3}{2}^-$ can also have sequential π^0 emission through the $\Delta(1232)$. Finally, a (π^-, π^0) reaction process could lead via ρ exchange to the Δ or a N^* state, which decays to $\pi^0 n$.

As part of a program of studying the formation and decay of baryon resonances, we report on comprehensive measurements of the $\pi^- p \to \pi^0\pi^0 n$ reaction in the momentum range from threshold to $p_{\pi^-} \sim 750$ MeV/c. The data were obtained at the Alternating Gradient Synchrotron facility at the Brookhaven National Laboratory. Photons from the decay of the produced π^0's were detected in the Crystal Ball (CB) multiphoton spectrometer [14]. Neutrons can also be detected in the

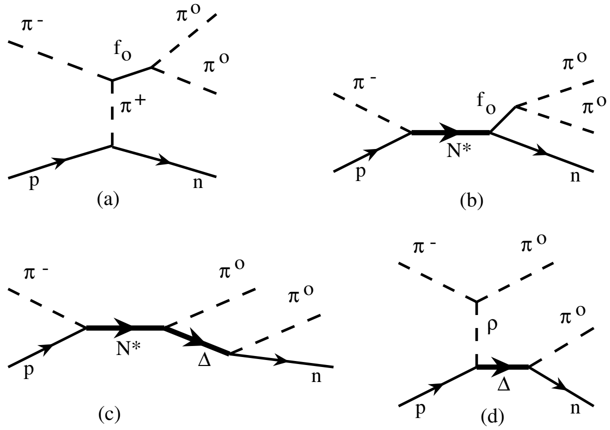

FIG. 1. Feynman diagrams leading to 2 π^0's: (a) one-pion exchange; (b) scalar-meson decay of a N^* resonance; (c) sequential π^0–π^0 decays through the $\Delta(1232)$; (d) π^0–Δ^0 production with π^0 decay.

CB, with detection efficiencies ranging up to 35%–40% [15].

The Crystal Ball consists of 672 NaI(Tl) crystals arranged in two hemispheres which cover about 93% of 4π steradians. Openings for a beam pipe span a polar angle of about 22° at each end. A 10-cm-long liquid hydrogen target was located at the center of the detector. A veto barrel composed of four scintillators surrounded the beam pipe and was used to reject events with charged particles in the final state, such as from elastic scattering. Full details of the setup are provided in recent publications [16,17].

The gains for the signals from the CB crystals were initially determined with a ^{137}Cs source. A final calibration was obtained from an extensive analysis of two-, three-, four-, and six-cluster events, where each cluster is a group of adjacent crystals which share the energy deposited by a photon or other particle. A kinematic fit method was used to associate the events with the $\pi^0 n$, ηn, $\pi^0\pi^0 n$, and $\eta n \rightarrow 3\pi^0 n$ final states from $\pi^- p$ interactions, simultaneously minimizing the deviations from the kinematics of these reactions.

Two methods were used to determine the actual beam momenta. The first used two-cluster data for the $\pi^- p \rightarrow \pi^0 n$ reaction and obtained the best simultaneous fit to the reconstructed π^0 invariant mass and the neutron missing mass. The other method was part of the procedure discussed above for the gain calibrations. The two methods almost always agreed to within 2–3 MeV/c.

Each photon from the decay of the π^0's, and sometimes also the neutron, deposits energy in a cluster of crystals. Both four-cluster (e.g., $\pi^0\pi^0$) and five-cluster ($\pi^0\pi^0 n$) events were selected for analysis. The events were then subjected to constrained kinematic fits to ensure that they arose from the $\pi^- p \rightarrow \pi^0\pi^0 n$ reaction. Backgrounds as determined from empty-target data were typically about 3%, and were subtracted from all data shown here. Acceptance corrections based on Monte Carlo calculations of three-body phase space of the reaction and the simulation of events in the CB, as determined by a GEANT 3.21 code, were also applied. The momentum resolution of the beam, and its transverse position and divergence in the target were provided by a sample of events from the beam triggers.

The large solid-angle coverage and the high segmentation of the angular coverage surpass those of all previous experiments of this type, and are essential for studies such as the one reported here. A common representation of the three-body final state is that provided by Dalitz plots, in which the density of events is proportional to the squared matrix element of the reaction process. A plot of the data at our highest beam momentum (out of 19 available) is shown in Fig. 2. Because the two π^0's cannot be distinguished, the plot has two entries per event, with equal $m^2(\pi^0\pi^0)$ values and $m^2(\pi^0 n)$ values symmetric to the dashed line in Fig. 2. There is enhanced strength along a vertical line for $m^2(\pi^0 n)$ values near (or just below) the Δ^0 mass of 1.232 GeV, as well as along the symmetric reflection of this line. The strong enhancement for $m^2(\pi^0\pi^0) > 0.25$ GeV occurs near the intersection of the two lines. However, there is very little indication of horizontal banding of this strength.

Many distributions can be formed from the data, and subsets are shown in Fig. 3. There are significant differences between the data and phase space at high beam momenta, but these largely disappear at low momenta. The shift in the peak of the $m(\pi^0 n)$ distribution to lower values is mainly due to kinematics, with the data representing population of the tail of the $\Delta(1232)$. The $\pi^0\pi^0$

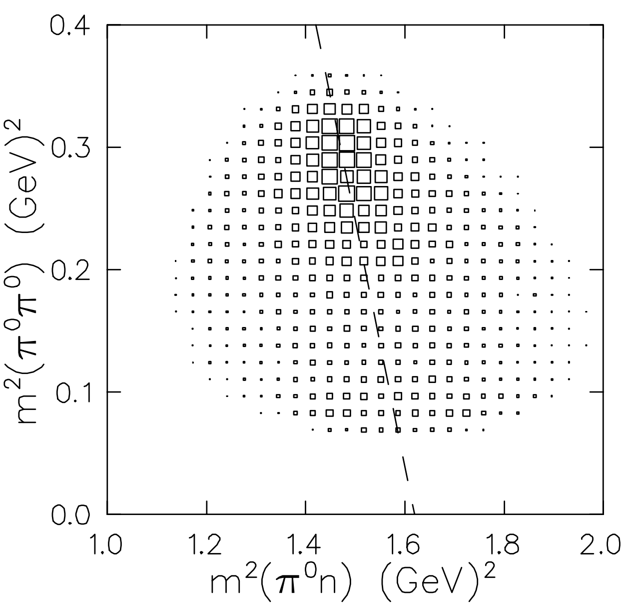

FIG. 2. Dalitz plot for the $\pi^- p \rightarrow \pi^0\pi^0 n$ reaction at a beam momentum of 0.748 GeV/c. The dashed line corresponds to $m^2(\pi^0_1 n) = m^2(\pi^0_2 n)$.

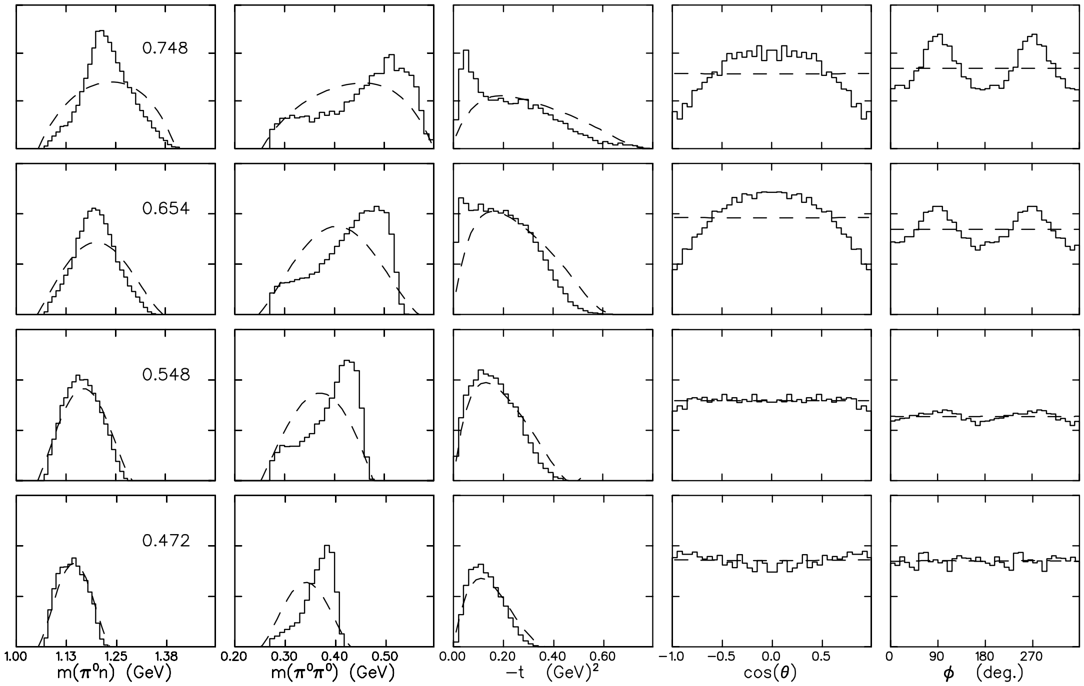

FIG. 3. Distributions for the π^0-n and $2\pi^0$ invariant masses, four-momentum-transfer $-t$ (proton to neutron), and polar and azimuthal decay angles for the π^0 decay in the rest frame of the $2\pi^0$ system (columns). The rows are labeled with the beam momenta (GeV/c) in the first column. The decay angles are given in the t-channel or Gottfried-Jackson frame. The dashed lines represent three-body phase space, normalized to equal events with the data. The vertical scales of acceptance-corrected yields are arbitrary. For scaling, the total cross sections from high to low beam momenta are 1.82 ± 0.16, 1.57 ± 0.16, 1.21 ± 0.11, and 0.66 ± 0.07 mb [17].

mass distributions show enhancements above phase space at the high ends even to very low beam momenta. We note that the θ and ϕ dependences in the last two columns and for the highest two beam momenta indicate that the two π^0's are predominantly emitted perpendicular to the reaction plane defined by the incoming π^- and outgoing di-pion (or neutron).

The enhancement above phase space for high $\pi^0\pi^0$ invariant masses might suggest the formation of a f_0 meson. An additional hint is seen in the $-t$ distributions. The proportionality of the yield to $-t/(t - m_\pi^2)^2$ implies that it should peak at $-t = 1m_\pi^2 = 0.02\ \mathrm{GeV}^2$ [18]. For high beam momenta, there is indeed a peak at that value, although the distribution falls off a little too rapidly. However, by selecting the data for $-t < 0.12\ \mathrm{GeV}^2$, it is found that these events correspond primarily to $m(\pi^0\pi^0)$ masses between 0.4 and 0.5 GeV, rather than the expected values above 0.5 GeV. The peaking at low $-t$ values disappears rapidly at lower beam momenta. In addition, if a f_0 meson were to be produced, its decay into two pions must be isotropic. The angular distributions in Fig. 3 for high beam momenta are definitely not so.

Dalitz plots provide only partial information about a three-body system. To get more specific information on the angular momentum properties of the data, a multipole decomposition into spherical harmonics was made on the di-pion decay angular distributions. The number of events N is related to the intensity $I(\theta, \phi)$ averaged over angles by $N = 4\pi\langle I\rangle$, and the normalized angular correlation function can be written as

$$W(\theta, \phi) = \frac{1}{N} I(\theta, \phi) = \sum_{L=0}^{\infty} \sum_{M=-L}^{L} a_{LM}\, Y_L^M(\theta, \phi). \quad (1)$$

Only the real parts of Y_L^M are needed, with real coefficients a_{LM}. It should be noted that the intensity will contain terms up to $L_{\max} = 2\ell_{\max}$, where ℓ is the orbital angular momentum in the amplitude. By construction in Eq. (1), $a_{00} = 1/\sqrt{4\pi}$.

The two π^0's were not distinguishable, and both are included in the decay distributions from the di-pion. The resulting symmetries restricted the sum to even values of L. It was found that terms up to $L = 4$ were significant, including all values of M. No additional cuts were imposed on the data for this analysis. To get a measure of the strength from each value of L, the sum

$$S_L = (2L + 1) \sum_{M=-L}^{L} \left(\frac{a_{LM}}{a_{00}}\right)^2 \quad (2)$$

was formed. The results are shown in Fig. 4. The $L = 4$ contributions are small, but cannot be ignored. The $L = 2$ contributions are relatively small at low momenta, but

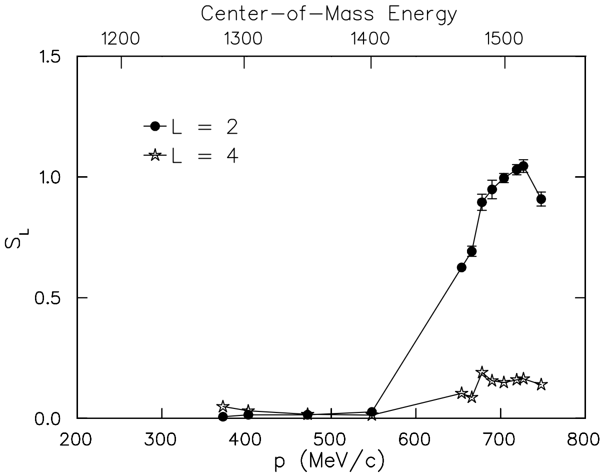

FIG. 4. Multipole strengths S_L for π^0 decay from a di-pion. The error bars reflect statistical errors. Systematic errors in the event selection are estimated to be of the order of 10% or ± 0.05, whichever is larger. The lines simply connect the data points.

begin to rise appreciably near the momentum where the π^0-Δ^0 production channel opens, and/or the kinematics allows population of $m(\pi^0\pi^0) > 0.45$ GeV. In fact, the S_L values are larger if the data are restricted to this higher mass region. Furthermore, they are also very strongly enhanced if the data are restricted to $-t < 0.12$ GeV^2. These behaviors are inconsistent with the formation of scalar f_0 mesons.

Mechanisms (c) and (d) in Fig. 1 cannot be distinguished on the basis of kinematics, and so one would need to consider other features such as angular distributions and correlations (see, e.g., Ref. [19]). At our beam momenta, the kinematics of the two π^0's are very similar and overlap substantially. Hence, in practice, it is very difficult to associate a specific π^0 with the one from a $\pi^- p \to \pi^0\Delta^0$ reaction, or the one from a Δ^0 decay. Moreover, the particle identity here also requires that interference effects must be taken into account. The threshold beam momentum for the $\pi^0\Delta^0$ channel, at the center of the Δ^0 resonance, is about 500 MeV/c, just below the point where the $L = 2$ multipole begins to rise in Fig. 4. Finally, if mechanism (c) is important, one must consider the patterns of sequential π^0 decay from, at least, the $N(1440)\frac{1}{2}^+$ and $N(1520)\frac{5}{2}^-$ resonances, which overlap considerably in this region.

In summary, the data for the $\pi^- p \to \pi^0\pi^0 n$ reaction in the baryon resonance region do not provide any substantive evidence for a low-mass scalar meson. Indeed, the signatures of the data are inconsistent with the expected properties of such mesons. Even at low momenta, the $-t$ distributions peak at values several times that expected for a OPE mechanism, which would be the most likely direct production process. The fact that the angular distributions from an assumed di-pion decay are nearly isotropic at low beam momenta is not particularly significant because there is not enough energy to provide angular momenta much beyond $L = 0$. To produce f_0 mesons with masses above 0.5 GeV, beam momenta greater than 0.6 GeV/c are needed. At this point, however, multipoles with $L > 0$ for the decay of a di-pion come in strongly. The $\pi^0\Delta^0$ reaction channel has opened up by this point, and the $m(\pi^0 n)$ projections in Fig. 3 show that Δ^0's are produced. Thus, treating the two π^0's as a correlated di-pion appears to be quite inaccurate. Interference effects can produce additional complexity. All of these features must be taken into account in efforts to unravel the properties of overlapping baryon resonances.

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