COHERENT PRODUCTION OF $\pi^+\pi^+\pi^-$ IN DEUTERIUM BY 8-GeV/c π^+

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A diffractively produced 3π enhancement is observed with mass ~1.1 GeV and width ~0.35 GeV. There is no structure observed in the peak in either the mass or angular distributions. The system is predominantly s-wave $\pi\rho$ with a 3π 0^- admixture which is essentially constant in percentage and relative phase across the peak.

An analysis of 45 000 three- and four-prong events originating in an exposure of the 80-in. deuterium bubble chamber to a beam of 8-GeV/c π^+ particles yielded 792 events identified[1] as

$$\pi^+d \to \pi^+\pi^+\pi^-d. \qquad (1)$$

The measurements were made using the Brookhaven National Laboratory flying spot digitizer and analyzed with the Brookhaven National Laboratory versions of the TVGP-SQUAW programs. The effective-mass distributions for channel (1) are shown in Fig. 1. From the figures it may be seen that (a) the 3π mass spectrum consists mainly of a 350-MeV wide structureless peak similar to that observed in other coherent interactions[2]; (b) the $\pi^+\pi^-$ mass spectrum is dominated by ρ formation, with 80 % of events in the 3π mass region 0.850-1.450 GeV having a $\pi^+\pi^-$ combination in the mass interval 0.660-0.860 GeV; (c) there is ~10% D^{*++} formation[2] but little evidence for D^{*0} production (not shown).

For the remainder of this Letter we discuss the 607 events forming the 3π peak lying in the mass region 0.850-1.450 GeV.

As stated above, no structure is evident in the mass spectrum with the statistics available. A moments analysis of the angular distribution of the normal to the plane of the 3π's relative to the beam direction and of the ρ^0 decay angles relative to the beam, as a function of the 3π mass, have confirmed this lack of structure by showing

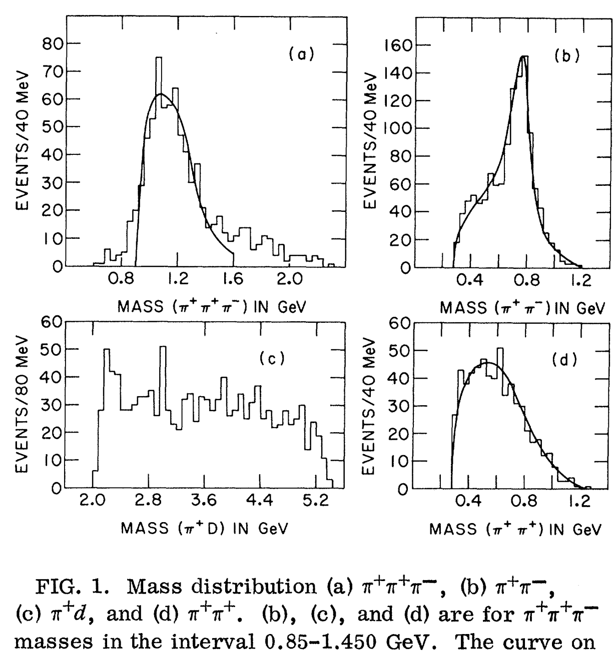

FIG. 1. Mass distribution (a) $\pi^+\pi^+\pi^-$, (b) $\pi^+\pi^-$, (c) π^+d, and (d) $\pi^+\pi^+$. (b), (c), and (d) are for $\pi^+\pi^+\pi^-$ masses in the interval 0.85-1.450 GeV. The curve on (a) is from the Reggeized Deck calculation normalized to the average height of the distribution in the interval 1.0-1.2 GeV. The curves on (b) and (d) are from the maximum-likelihood Dalitz-plot fit.

only a smooth variation across the peak. We conclude, therefore, that there is no evidence in these data for the production of narrow resonances.

The overall angular-distribution characteristics of the mass region 0.850-1.450 GeV are shown in Fig. 2. The predominantly $\sin^2\theta$ distribution of the normal to the 3π plane as shown in Fig. 2(a) could originate from the production of a 1^+ or 2^- state.[3] A maximum-likelihood fit assuming 1^+ production gives a 3π density-matrix element ρ_{00} of 0.95 ± 0.04 while a similar fit to 2^- yields a ρ_{00} of 0.45 ± 0.09. Figure 2(b) shows that the ρ is produced strongly aligned with a ρ_{00} of 0.79 ± 0.025; the ρ decay is asymmetric indicating that there is interference with a background of opposite parity.[4] The strong alignment of the ρ indicates that the produced 3π state is predominantly s-wave 1^+. The interfering state giving rise to the ρ decay asymmetry has to be of opposite parity to 1^+ and hence could be due to some admixture of either 0^- or 2^-. The value

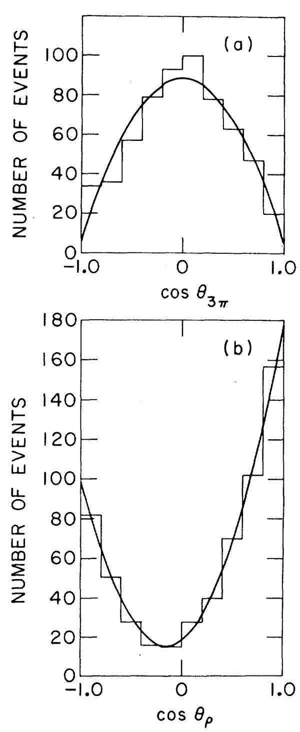

FIG. 2. (a) Polar angular distribution of the normal to the 3π plane. The curve is a fit assuming a pure 1^+ state. (b) Polar angular distribution of the π^+ from ρ^0 decay. The curve is from the maximum-likelihood Dalitz-plot fit. For (a) and (b) the z axis is defined as the beam direction in the 3π and 2π rest systems, respectively.

of ρ_{00} obtained assuming that the 3π's are in a 1^+ state permits an admixture fraction of 0.1 ± 0.06 0^- in conjunction with a completely aligned 1^+ state. No exact estimate has been made of the fraction of 2^- since it leads to the same distribution of the normal to the decay plane as does the 1^+ state; however, the ρ alignment shows that the fraction cannot be large.

From the above analysis it may be concluded that the 0.850- to 1.450-GeV peak consists predominantly of a strongly aligned 1^+ state with some admixture of opposite parity. The simplest explanation of the strong alignment is that we are observing a diffractively produced 3π system.

In order to study the 3π state further we have attempted to find an amplitude describing channel (1) which fits the mass distribution in the 3π Dalitz plot for six 0.1-GeV-wide 3π mass intervals. The analysis follows the procedures used in the study of $\bar{p}p$ annihilations[5] with the additional assumption that $\rho_{00} = 1.0$ for the 3π system.

If q is the relative momentum of two pions in their rest system and p is the momentum of the remaining pion in the 3π rest system, the transition amplitude may be written as

$$A = \sum_{lt} F_{lt}(p,q) S_l(p,q),$$

where S is in a spin-parity function constructed according to the procedure of Zemach[6] and $F_{lt} = m \exp(i\delta_l^t)\sin\delta_l^t(q^{2l+1})^{-1}$. δ_l^t is the $\pi\pi$ scattering phase shift for the appropriate angular momentum l and isospin t, and m is the 2π effective mass. Two $\pi\pi$ phase shifts $\delta_1{}^1$ and $\delta_0{}^0$ are known to be large in the mass region under study. $\delta_1{}^1$ has been parametrized[7] as $\tan^{-1}[\Gamma m_0/(m_0^2 - m^2)]$ with $\Gamma = \Gamma_0(m_0/m)(q/q_0)^3$, where $\Gamma_0 = 0.140$ GeV, $m_0 = 0.780$ GeV, and $q_0 = (\frac{1}{4}m_0^2 - m_\pi^2)^{1/2}$. It is not unreasonable to believe that $\delta_0{}^0$ resonates close to 0.7 GeV,[8] and so a linear parametrization in m of $\delta_0{}^0$ has been used with this characteristic.

The amplitude A giving the highest value of the likelihood function for the fit to the Dalitz plots has the form

$$|A|^2 = |aA(1^+) + be^{i\varphi}A(0^-)|^2 + c^2D^2,$$

where $A(1^+)$ is the symmetrized amplitude for a 1^+ s-wave $\pi\rho$ state and $A(0^-)$ is the symmetrized amplitude for a 0^- state with three pions in an s wave with respect to each other. The normalization used is such that $a^2 + b^2 + c^2 = 1$, and that the integral over the Dalitz plot of $A(1^+)$, $A(0^-)$, and the constant D, representing a uniform background, are each equal to unity. b^2 and c^2 represent the fraction of 0^- and background, respectively, and φ is the phase angle between the 0^- and 1^+ state; these parameters were varied in the fit.

Other amplitudes with coherent 0^- and 2^- $\pi\rho$ admixtures were tried. Both amplitudes gave likelihood functions lower by two orders of magnitude than the preferred fit over the lower 3π mass interval, but in the higher 3π mass range (greater than 1.250 GeV) the 2^- background gave an equally satisfactory fit to the data.

Figure 3 shows the results of the Dalitz-plot fit as a function of the three-pion mass. It may be seen that apart from the peak at 1.3 GeV in the fraction of uniform background, the 3π characteristics are essentially constant across the peak. In particular the phase angle between 0^- and 1^+ is consistent with zero across the peak and the fraction of 0^- does not show any strong variation. The results from the six mass interval fits have been used to determine[9] the form of the 2π mass spectrum and the ρ decay angular distribution; the curves on Figs. 1(b), 1(d), and 2(b) show the results of the fits. Evidently the amplitude gives a good description of the distributions.

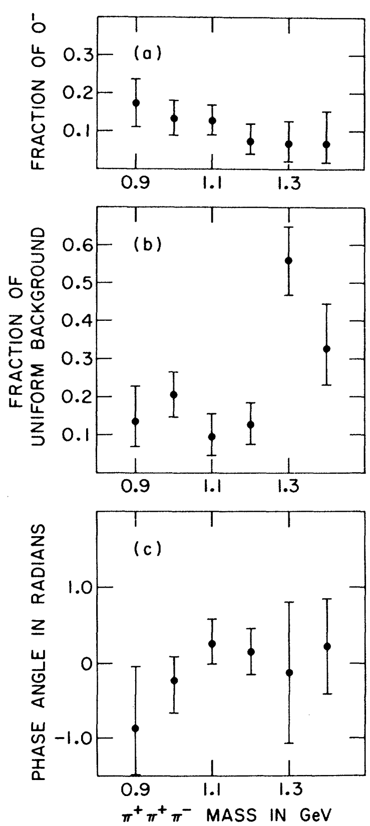

FIG. 3. (a) The fraction of 0^-, (b) the fraction of uniform background, and (c) the relative phase of 0^- and 1^+ amplitudes as a function of the 3π mass.

The origin of the uniform distribution D is not known. However, it may be noted that a direct 3π production was needed in antiproton annihilation at rest[5]; also we have not taken into account D^* production or $T=2$ $\pi\pi$ interactions[5] and have used only the simplest form of amplitude. The non-ρ events, which are mainly the uniform background events, show some evidence of having 1^+ characteristics. The D term could also be due to the presence of a d-wave $\pi\rho$ 1^+ state. Fits with d wave in place of the D term give, within errors, the same percentage and phase of 0^- across the peak and the fitted percentage of d wave is equal to that of the uniform D term. The likelihood function is slightly lower for this amplitude at low 3π masses but is larger for the higher masses. Hence, while this analysis does not require a d-wave $\pi\rho$ 1^+ state, about 15 % may be present in the central region of the peak.

Figure 1(a) shows the 3π mass distribution calculated from a Reggeized Deck model[10]; the distribution agrees well with the data. Other aspects of the data such as the s-wave form of the 0^- background and the phase angle and percentage of 0^- have not been investigated theoretically in the framework of this model. However, the characteristics of the ρ produced in the Deck model should be similar to the ρ produced in the πN interactions; hence a 0^- admixture of constant percentage and zero relative phase would be expected to be associated with an s-wave $\pi\rho$ system. It may be concluded that, with the exception of the predicted cross section, the Reggeized Deck model agrees well with the data.

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[1]All three- and four-prong events were fitted as $\pi^+d \rightarrow \pi^+\pi^+\pi^- np$. The np mass spectrum showed a sharp peak at the np mass threshold of width 8 and 3 MeV for the three- and four-prong events, respectively. Coherent deuteron events were defined as the events in these low-mass np peaks with a kinematic-fit probability greater than 10%. Coherent events occurred approximately equally in the three- and four-prong topologies. We estimate that there may be a 10% contamination of incoherent events in the three-prong sample while the contamination is negligible for the four-prong events. The exposure yields 2.3 ± 0.2 events/μb.

[2]M. A. Abolins, D. D. Carmony, R. L. Lander, and N.-h. Xuong, Phys. Rev. Letters 15, 125 (1965); L. Seidlitz, O. I. Dahl, and D. H. Miller, in Proceedings of the Athens Second Topical Conference on Resonant Particles, 10-12 June 1965, edited by B. A. Munir (Ohio University Press, Athens, Ohio, 1965), p. 162; A. Forino et al., Phys. Letters 19, 68 (1965); G. Vegni, H. Winzeler, and P. Zaniol, Phys. Letters 19, 526 (1965); J. F. Allard et al., Nuovo Cimento 46A, 737 (1966).

[3]We consider states 1^+ and 2^- only since the polar distribution relative to the beam of the normal to the 3π plane, defined in the 3π rest system, has no significant moments higher than Y_2^0 and the spin and parity series 1^-, 2^+, $\cdots$ are inconsistent with the $\pi^+\pi^+$ mass distribution. 1^- is not considered as a background since the state is not produced in a diffractive production process.

[4]The fit was made assuming an s- and p-wave mixture, hence the density-matrix element $\rho_{00} = \rho_{00}^{11} + \frac{1}{3}\rho_{00}^{00}$.

[5]P. Anninos et al., Phys. Rev. Letters 20, 402 (1968); M. Foster et al., Nucl. Phys. B6, 107 (1968).

[6]C. Zemach, Phys. Rev. 133, B1201 (1954). For 1^+ we use $S = \vec{B} \cdot \vec{q}$ where $\vec{B}$ is the beam direction in the ρ rest frame; for 0^-, $S =$ const for three pions in a relative s wave.

[7]The results of the analysis are not sensitive to the ρ mass and width; the numbers used here are from a fit to the Dalitz plot in the 3π mass interval 1.05-1.35 GeV.

[8]L. J. Gutay et al., Purdue University Report No. COO-1428-65 (unpublished); C. Lovelace, in Proceedings of the International Conference on Elementary Particles, Heidelberg, Germany, 1967, edited by H. Filthuth (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p. 79; S. Marateck et al., this issue [Phys. Rev. Letters 21, 1613 (1968)]. The report of Gutay et al. gives references to earlier work. The form used is $\delta_0^0 = 4.9 = 4.9(m-0.4)$ for $m > 0.4$ plus a term corresponding to a scattering length of $0.2 m_\pi^{-1}$.

[9]The Monte Carlo program FOWL by F. James was used extensively in this analysis.

[10]E. L. Berger, private communication. The calculation is similar to that in E. L. Berger, Phys. Rev. 166, 1525 (1968). The πd elastic differential cross section was assumed to have the form e^{-30t}. The predicted $\pi\rho$ cross section is about 60% of that observed experimentally. In Fig. 1(a) the peak height of the theoretical distribution has been normalized to the average height of the experimental 3π mass distribution in the interval 1.0-1.2 GeV. Two other parameters may be compared with the data, namely the momentum transfer to the deuteron and the momentum transfer t between the incoming π^+ and the ρ^0. Both agree reasonably well with the data; a form factor of the form e^{-t} would improve the agreement with the ρ momentum-transfer distribution and also reduce the width of the $\rho\pi$ mass distribution.