# Properties of the $\zeta(1480)$

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A novel analysis technique of $\bar{p}n$ annihilations at rest has recently brought strong evidence for a new state, called here $\zeta$, of mass $1477 \pm 5$ and width $116 \pm 9$ MeV/$c^2$, which contributes dominantly to the $3\pi^-2\pi^+$ final state. An analysis has been made of the $3\pi^-2\pi^+$ considering all known intermediate states. It is found that only the cascade $\bar{p}n \rightarrow \pi^-\zeta$ and $\zeta \rightarrow 2\rho^0$ with $\zeta$ quantum numbers $0^+,2^{++}$ ($I^G,J^{PC}$) describes $3\pi^-2\pi^+$. The product branching ratio $B(\bar{p}n \rightarrow \pi^-\zeta)B(\zeta \rightarrow 2\rho)$ is large, equal to $(11.1 \pm 0.8)$%. The $\zeta$ is a good candidate as a quasinuclear $\bar{N}N$ bound state or as a $\bar{Q}^2Q^2$ state or, perhaps, as a glueball.

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The discovery and application of the difference spectrum in $\bar{p}n$ annihilations at rest has brought strong evidence[1,2] for the existence of a new state of mass 1480 MeV/$c^2$. Because of the novelty of the technique and the rather surprising results, it is important to confirm by "standard" analysis the conclusions reached from the difference spectra and elucidate the nature of this dominant effect. Specifically, and relevant to this work, the difference technique revealed that[2] $\bar{p}n \rightarrow \pi^- + X(1480)$ $(\rightarrow 2\pi^-2\pi^+)$ contributes about 80% to the $3\pi^-2\pi^+$ final state where $X$ is a resonancelike structure of width 115 MeV/$c^2$.

The reactions $\bar{p}n \rightarrow 3\pi^-2\pi^+$ and $\bar{p}p \rightarrow 2\pi^-2\pi^+\pi^0$, with pion multiplicity equal to the average for antiproton annihilations at rest, have been studied in bubble chambers.[3-5] Using the usual final-state-interaction parametrization, Bettini *et al.*[3] introduced a state of mass 1410 MeV/$c^2$ and width 90 MeV/$c^2$ decaying into $2\rho^0$ with quantum numbers $I^G,J^{PC} = 0^+,0^{++}$ in order to describe $3\pi^-2\pi^+$. Similarly, Hagerty[4] attempted unsuccessfully to achieve fits to $3\pi^-2\pi^+$ without introducing new states. Defoix and Espigat[5], in an analysis of $2\pi^-2\pi^+\pi^0$, obtained "reasonable" fits by introducing the Bettini *et al.* $2\rho^0$ state with a mass 1435 MeV/$c^2$, but better fits were obtained with the addition of a $2\rho^0$ state at 1500 MeV/$c^2$ with $I^G,J^P = 0^+,2^+$. There has thus been general agreement that these five-pion annihilations, particularly $3\pi^-2\pi^+$, are dominated by double $\rho$ production which are perhaps the decay products of one or more broad states with mass 1400–1500 MeV/$c^2$, width about 100 MeV/$c^2$, and possibly zero spin. However, the absence of a clear signal in the $2\pi^-2\pi^+$ mass distribution (which only recently became clear from the difference spectrum), the complexity of the analyses, the resulting unsatisfactory "fits," and the absence of evidence in other reactions have kept these works in relative obscurity.

We present here the results of a new, and perhaps simpler, analysis of the $\bar{p}n \rightarrow 3\pi^-2\pi^+$ using the data[6] of Ref. 4. The following intermediate states involving all known mesons which lead to $3\pi^-2\pi^+$ have been considered:

$$\bar{p}n \rightarrow 3\pi^-2\pi^+,\ 2\pi^-\pi^+\rho^0,\ \pi^+\pi^-A_2^-,\ \pi^-2\rho^0, \tag{1}$$

$$\bar{p}n(^1S_0) \rightarrow \pi^- + X(J^P)\ \ (\rightarrow 2\rho^0), \tag{2}$$

where $X$ is the state reported in Ref. 2 with spin and parity $J^P$. The annihilation is assumed to proceed via $^1S_0$ atomic states. (The $^3S_1$, by $G$-parity conservation, do not contribute to $5\pi$.) The results of our analysis are found to be insensitive to this commonly used assumption.

All available distributions from Ref. 4 are shown in Figs. 1–4. They come from $\bar{p}n$ antiproton annihila-

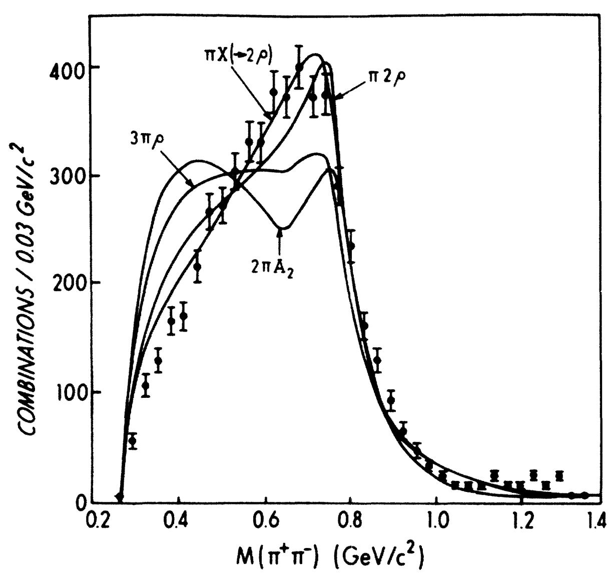


FIG. 1. The $\pi^+\pi^-$ (six combinations per event) invariant-mass distribution in $\bar{p}n \rightarrow 3\pi^-2\pi^+$. It shows that the channel is dominated by double $\rho$ production and that if their mass is restricted to the $\chi(1480)$ mass the best "fit" is achieved. The $\chi^2$ for 22 bins are 88 and 130 for $\pi\chi$ and $\pi 2\rho$, respectively.

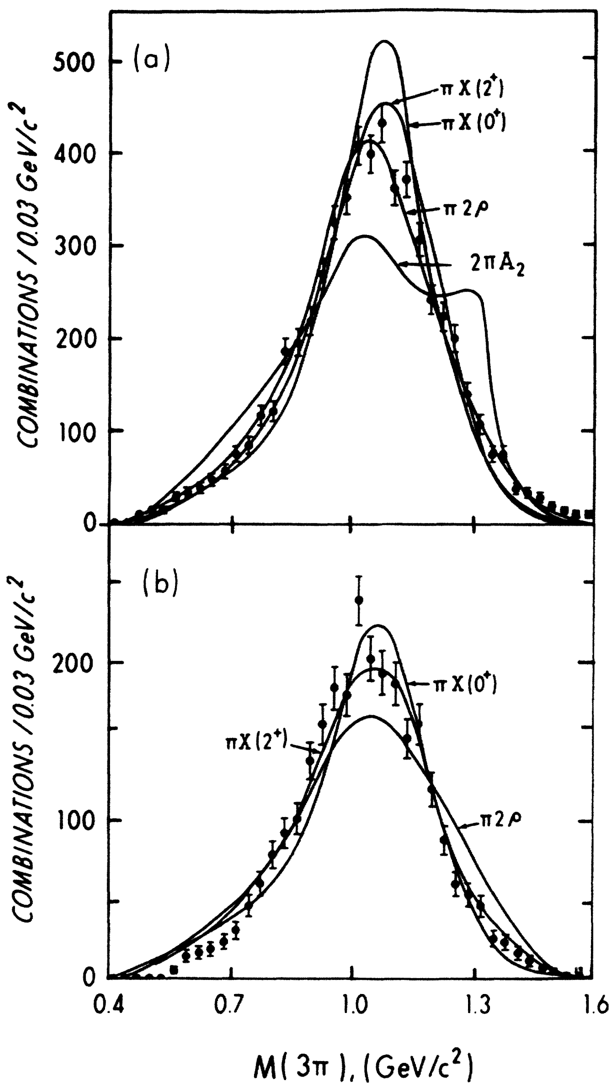


FIG. 2. (a) The $2\pi^-\pi^+$ and (b) the $2\pi^+\pi^-$ invariant-mass distributions in $\bar{p}n \to 3\pi^-2\pi^+$. They show that $A_2$ does not contribute, and $2^+$ is preferred over the $0^+$ or nonresonant $\rho$'s. The $\chi^2$ over 29 bins of the $\pi X(0^+)$, $\pi X(2^+)$, $\pi 2\rho$ hypotheses for (a) are 84, 32, 20 and for (b) 96, 66, 216, respectively.

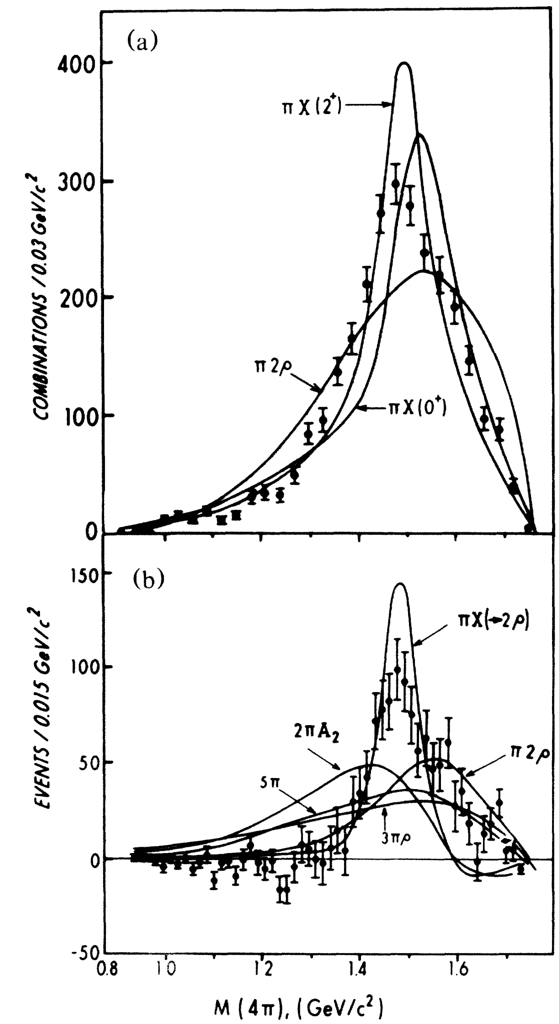


FIG. 3. (a) The $2\pi^+2\pi^-$ invariant-mass distribution and (b) the difference spectrum in $\bar{p}n \to 3\pi^-2\pi^+$. The difference spectrum clearly shows dominance ($\sim 80\%$) of $X \to 2\rho$. The tail at higher mass may be due to $\pi 2\rho$ or other states.

tions at rest in liquid deuterium into five charged pions associated with proton spectators of momentum $< 200$ MeV/$c$. The data are compared with predictions of Monte Carlo simulations of reactions (1) and (2). The program generates $3\pi^-2\pi^+$ according to phase space and the physics is represented by a product of weighting factors: (i) Bose-Einstein (BE) $2\pi^+$ and $3\pi^-$ symmetry factors[7] are used; (ii) the $\rho$ and $A_2$ in $3\pi\rho$ and $2\pi A_2$ are represented with the square of a coherent sum of Breit-Wigner amplitudes with the sum carried over all possible pion combinations; (iii) in $\pi^-2\rho^0$ and reaction (2) centrifugal barriers between the $\rho$'s and between the recoil $\pi^-$ and the $2\rho^0$ system are also included. Specifically this factor is the square of the following symmetrized "amplitude":

$$\sum_{ij}\{B(X_{ij})p^L[B(\rho_i)q^l S_{ij} B(\rho_j)]\},$$

where $B(X_{ij})$ are Breit-Wigner amplitudes, $1/[(M-M_0)+i\Gamma/2]$, for $X_{ij} \to \rho_i + \rho_j$, $B(\rho_i), B(\rho_j)$ are the $\rho_{i,j}$ Breit-Wigner amplitudes, $L$ is the relative angular momentum between the $\pi^-$ and $X$, $l$ is that between $\rho_i$ and $\rho_j$, and $S_{ij}$ is a $\rho_i\rho_j$ spin factor. The spin factor is a scalar for the singlet and tensor for the quintuplet $\rho_i\rho_j$ spin states, the two cases of interest. For example the scalar factor is $(\mathbf{p}_1 - \mathbf{p}_2)\cdot(\mathbf{p}_3 - \mathbf{p}_4)$ where the $\mathbf{p}_i$ are the momenta to which the two $\rho$'s decay: $\rho_i \to \pi_1^+ + \pi_2^-$, $\rho_j \to \pi_3^+ + \pi_4^-$. The amplitude has been fully symmetrized as a coherent sum of all possible combinations. $\pi^-2\rho^0$ has been simulated by the

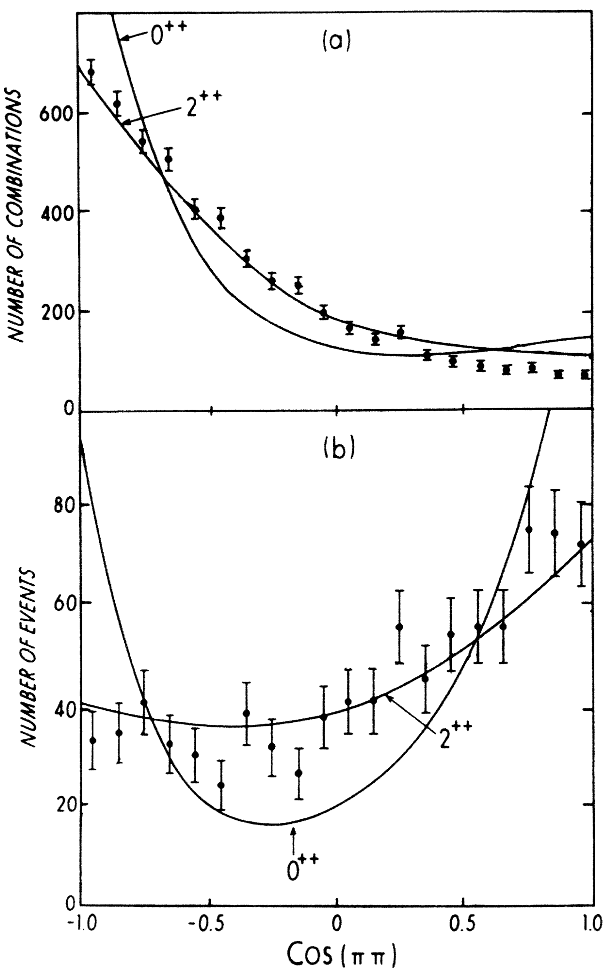


FIG. 4. (a) The $\pi^-\pi^+$ and (b) the $\pi^+\pi^+$ angular distributions in the laboratory system for the reaction $\bar{p}n \to 3\pi^-2\pi^+$. Notice their large difference, one being "backward" while the other is "forward." These distributions are sensitive to the quantum numbers of the $X \to 2\rho$; the $2^{++}$ ($J^{PC}$) assignment is clearly preferred over the $0^{++}$.

setting of the $X$ width to a very large number but otherwise this and (2) have been treated identically. We simulated all distributions expected on the basis of reactions (1) but for clarity only a few are shown. As seen by inspection of the figures, reaction (2) with $J^P = 2^+$ provides by far the best description[8] of the data.

All factors in the matrix element for $\pi X(\to 2\rho)$ have been investigated and found to improve the fits. The effect of the BE symmetry factors is most noticeable in the $\pi^+\pi^+$ angular distribution which turns out to be a most critical distribution. The centrifugal barrier between $\pi$ and $X$ shows a maximum effect in the $M(2\pi^+2\pi^-)$ distribution [Fig. 3(a)] as it directly relates to the momentum of the recoiling pion against the $2\pi^+2\pi^-$. With an $X$ spin and parity $2^+$ and $S$ capture the $\pi X$ relative angular momentum is $L = 2$. On the other hand, if the capture is from a $P$ state[9] then $L = 1$. In either case the conclusions of this paper are unaffected.

The difference spectrum in Fig. 3(b) (which directly relates[2] to $\pi^- X$ formation by elimination of the combinatorial background) with the predictions based on the intermediate states considered here gives a sensitive overview. Clearly none of the intermediate states, except $\pi X$, produces a peak at 1480 MeV/$c^2$. Apart from the 20% tail at higher mass, which may be due to $\pi 2\rho$ or other states, $\pi^- X$ describes it well. The $4\pi$ mass spectra are not sensitive to the spin assignment because the $\pi X$ centrifugal barrier can be compensated by a change in the mass. The angular distributions of Fig. 4 are most sensitive to $J^P$ through the $S_{ij}$ spin factor and they clearly favor $J^P = 2^+$. The $M(3\pi)$ spectra of Fig. 2, which are influenced indirectly by the quantum numbers, do again favor $J^P = 2^+$ as the $\chi^2$, quoted in the caption, indicate.

The decay into $4\pi$ implies positive $G$ parity while the decay into $2\rho^0$ implies $I = 0$ or 2 and positive $C$ parity. The positive $C$ parity allows only $J^{PC} = 0^{++}$, $2^{++}$, etc., nonexotic[10] states which are realizable with the $2\rho^0$ in an $S$ state ($l = 0$). The simulations favor (particularly the angular distributions in Fig. 4) that the $X$ is a $2^{++}$ state which decays into $2\rho$ in zero relative angular momentum. Using[11] the $B(\bar{p}n \to 3\pi^-2\pi^+) = (4.5 \pm 0.2)\%$ and the channel branching ratio[2] of $0.82 \pm 0.05$ we obtain the product branching ratio $B(\bar{p}n \to \pi^-\zeta)B(\zeta \to 2\rho^0) = (3.7 \pm 0.3)\%$. If the $\zeta$ is an $I = 0$ state then $B(\bar{p}n \to \pi^-\zeta)B(\zeta \to 2\rho) = (11.1 \pm 0.8)\%$ which is reasonable if the $\zeta$ is a quasinuclear state[12] and an order of magnitude higher than typical two-body annihilation frequencies.[13] If, on the other hand, $I = 2$, then the relation

$$14B(\bar{p}n \to \pi\zeta \to 3\pi^-2\pi^+) = B(\bar{p}n \to \pi\zeta \to 2\pi^-\pi^+2\pi^0)$$

must be satisfied. The left-hand side is $(51.8 \pm 4.2)\%$ and the right[14] $\leq B(\bar{p}n \to 3\text{ prong}) - B(\bar{p}n \to 2\pi^-\pi^+\pi^0) = (41.3 \pm 3.7)\%$. Furthermore, $B(\bar{p}n \to \pi\zeta \to 2\rho) = (55.5 \pm 4.5)\%$, which is too large when one considers other contributions to annihilation. For example, the known[15] frequencies of $\pi^-$ + neutrals, $2\pi^-\pi^+$, $2\pi^-\pi^+\pi^0$ account for $(39.0 \pm 0.8)\%$ of the annihilation. We thus conclude that $I = 2$ is unlikely.

Our results are in agreement with Refs. 3 and 5 on the following points: (a) $3\pi^-2\pi^+$ and $2\pi^+2\pi^-\pi^0$ are dominated by $\pi 2\rho$ and (b) the $2\rho$ are products of at least one isoscalar state with mass 1400–1500 MeV/$c^2$ and width $\sim 100$ MeV/$c^2$. They disagree on the mass value and more importantly on spin. The low (1410 MeV/$c^2$) mass obtained in Ref. 3 cannot be reconciled with that observed directly from the difference spectrum. Bettini *et al.* "optimized" mass, among many other variables, and since the "fits" are qualitative[8] their lower mass value is not necessarily in contradiction to that obtained directly from the difference spectra.[1,2] The most serious contradiction is created by their choice of $0^+$ over $2^+$ in Ref. 3. Considering the exploratory nature of Ref. 3, the poor overall "fits" with either $0^+$ or $2^+$, their choice of $0^+$ may be questionable. Defoix *et al.*, although constrained by the results of Ref. 3, obtained a higher mass (1435 MeV/$c^2$) but their data required another $2^+$ state at 1500 MeV/$c^2$ which, by association to the $f'$, they did not like. Perhaps they could have obtained equally satisfactory fits if they used our mass, width, and $2^+$.

A prominent structure in the $2\rho$ invariant-mass distribution between 1.4 and 1.8 GeV/$c^2$ has been seen[16] in $\psi \to \gamma + 2\rho$ and in photon-photon collisions.[17] The width of the structure is by about a factor of 2–3 larger than the $\zeta$. Althoff *et al.*[16] favor spin $0^+$ while Baltrusaitis *et al.*[17] $0^-$, both of which are inconsistent with our $2^+$. The nature of the $2\rho$ enhancements in $e^+e^-$ experiments is, however, much in debate.[18]

The $\zeta$ cannot fit to a $\bar{Q}Q$ sequence.[19] On the other hand, its strong coupling to $\bar{N}N$ makes it a good candidate as an $\bar{N}N$ quasinuclear or a $\bar{Q}^2Q^2$ "baryonium" state.[12] Of course, other interpretations based on gluon-quark composites cannot be excluded including the interesting case of glueballs. As a quasinuclear state it is a candidate for the $^{13}P_2$-$^{13}F_2$ $\bar{N}N$ bound states in the standard $^{2I+1,2S+1}L_J$ notation. Mass, width, decay branching ratios, and coupling to $\bar{N}N$ are all in good agreement[12] with potential-model predictions.

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[2]D. Bridges *et al.*, Phys. Rev. Lett. **56**, 215 (1986).

[3]A. Bettini *et al.*, Nuovo Cimento **62**, 695 (1966).

[4]P. Hagerty, Ph.D. dissertation, Syracuse University, 1969 (unpublished); T. E. Kalogeropoulos, Argonne National Laboratory Report No. ANL/HEP 6812, 1968 (unpublished).

[5]C. Defoix and P. Espigat, in *Proceedings of the Symposium on Antinucleon-Nucleon Interactions, Liblice-Prague, Czechoslovakia, 25–28 June 1974* (CERN, Geneva, Switzerland, 1974), pp. 28–36.

[6]The only available data up to now on this channel at rest are those from the Padova-Pisa collaboration (Ref. 3) and the ones used here from the Rome-Syracuse collaboration (Ref 4). They are statistically equivalent and in agreement in their main features. They have been selected by measurement of the five-charged-pion $\bar{p}n$ annihilations associated with invisible and visible protons. The $3\pi^-2\pi^+p_s$ have been selected by use of $\chi^2$ and missing-mass cuts. The kinematics of this reaction allow excellent separation from $3\pi^-2\pi^+\pi^0$ and suppression of in-flight annihilations. There is estimated (Ref. 4) a $(6.3 \pm 2.3)\%$ in-flight contamination while in Ref. 3 this is $< 13\%$, and a $(2.1 \pm 0.4)\%$ contamination from $3\pi^-2\pi^+\pi^0$. The Padova-Pisa collaboration defines as spectator events those with protons of $< 250$ MeV/$c$ while the Rome-Syracuse collaboration uses a lower limit ($< 200$ MeV/$c$). From these considerations and comparing the $2\pi^-\pi^+$ Dalitz plots from the same groups [A. Bettini *et al.*, Nuovo Cimento **63A**, 770 (1967); P. Anninos *et al.*, Phys. Rev. Lett. **20**, 402 (1968)] we conclude that the data on $3\pi^-2\pi^+$ from Ref. 4 have less contamination from in-flight, $1\pi^0$, and nonspectator events. The technical details of the selection of the $3\pi^-2\pi^+$ events are given in Hagerty, Ref. 4.

[7]G. Goldhaber, S. Goldhaber, W. Lee, and A. Pais, Phys. Rev. **120**, 300 (1960). The $3\pi^-$ symmetrization factor has been expanded in terms of the $2\pi^-$ symmetrization factors. The two-pion symmetrization factor $1 + [3j_1 + (qR)/qR]^2$ has been used where $q$ is the relative momentum of the pions, $R$ the radius of interaction, and $j_i$ the first-order spherical Bessel function.

[8]"Description" does not imply, strictly speaking, good $\chi^2$. "Goodness of fit" can only be useful if the nature of the 20% excess at mass beyond the $\zeta$ [see Fig. 3(b) and Ref. 2] is identified and properly included. Even then, the "amplitude" used here is only an approximation of the true five-body amplitude.

[9]L. Gray *et al.*, Phys. Rev. Lett. **30**, 1091 (1973).

[10]We do not consider the case of exotics, $J^{PC} = 1^{-+}$, which requires a $\rho^0\rho^0$ in a $P$ state. We considered also $2\rho^0$ in the triplet state which is required for $1^{-+}$ by use of the vector spin factor $(\mathbf{p}_1 - \mathbf{p}_2) \times (\mathbf{p}_3 - \mathbf{p}_4)$. This also does not fit the angular distributions.

[11]This is the weighted average of Ref. 3, $(5.2 \pm 0.5)\%$, and Ref. 4, $(4.2 \pm 0.2)\%$.

[12]C. B. Dover, Phys. Rev. Lett. **57**, 1207 (1986).

[13]See, e.g., C. Baltay *et al.*, Phys. Rev. Lett. **15**, 533 (1965).

[14]We have averaged the measurements of Bettini *et al.*, (Ref. 3) and L. Gray, Ph.D. dissertation, Syracuse University, 1969 (unpublished). Bettini (Gray) give three-prong and $2\pi^-\pi^+\pi^0$ frequencies $0.597 \pm 0.017$ $(0.595 \pm 0.014)$ and $0.218 \pm 0.022$ $(0.137 \pm 0.02)$, respectively.

[15]A. Bettini *et al.*, Nuovo Cimento **67**, 770 (1967).

[16]R. Brandelik *et al.*, Phys. Lett. **97B**, 448 (1980); D. L. Burke *et al.*, Phys. Lett. **103B**, 153 (1981); M. Althoff *et al.*, Z. Phys. C **16**, 13 (1982); H. J. Behrend, Z. Phys. C **21**, 205 (1984).

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