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Evidence for a $\pi\pi$ isoscalar resonance degenerate with the f' produced in $\bar{p}N$ annihilations at rest

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Evidence for a new resonance $f_2' \to \pi\pi$ produced in $\bar{p}N \to \pi f_2'$ at rest is presented. The resonance parameters are $M = 1527 \pm 5$ MeV, $\Gamma = 101 \pm 13$ MeV, which are consistent with those of the f'. The absence of f' production in $\bar{p}N \to \pi f'(\to \bar{K}K)$ rules out the hypothesis that the f_2' is the same as the f'. $J=0$ is cautiously suggested for the f_2'.

We report on a new state, the $f_2' \to 2\pi$, observed in

$$\bar{p}+p \to \pi^0 + f_2'(\to 2\pi^0) \quad (1)$$

and

$$\bar{p}+\text{"}n\text{"} \to \pi^- + f_2'(\to \pi^+\pi^-) \quad (2)$$

annihilations at rest, where "n" is a spectator neutron in deuterium. The mass and width are consistent with those of the $f' \to \bar{K}K$. Using known limits on $f' \to 2\pi$ decay and the cascade branching ratios for

$$\bar{p}+p \to \pi^0 + f'(\to K_S K_S) \ , \quad (3)$$

$$\bar{p}+\text{"}n\text{"} \to \pi^- + f'(\to K^- K^+) \ , \quad (4a)$$

and

$$\bar{p}+\text{"}n\text{"} \to \pi^- + f'(\to K_S K_S) \ , \quad (4b)$$

we conclude that the f' and f_2' are not the same. Due to uncertainties in $\bar{p}$ capture and parametrization of 3π amplitudes, the f_2' spin cannot be determined with certainty. The nature of this state is unclear. As a $J^{PC}=0^{++}, 2^{++}, \ldots$ state it can be a candidate for a glueball (gg), or baryonium ($\overline{qq}qq$), or bound $\bar{N}N$ state. The degeneracy in mass and width with the f' is intriguing and reminiscent of the E-ι puzzle.[1] Another similar degeneracy has been suggested to exist[2] of a 2^{++} glueball with the f.

The data on reactions (1), (2), and (3) have been published previously.[3-6] The structure at the f' mass has been pointed out[3,5] but no attempt was made to identify it as a new state. It was considered that it might be the result of the 3π dynamics. Recently, a refined analysis[7] has been made of the $3\pi^0$, $2\pi^-\pi^+$ annihilations at rest which, in general, describes them well in terms of the known $\pi\pi$ phase shifts with P-state $\bar{p}N$ captures in addition to S-state captures. This analysis, however, singularly fails to fit the f'-mass region. In view of the current interest in the (1–2)-GeV/c^2 mass region,[8] we would like to discuss the f_2' effects and suggest them as evidence for a new $\pi\pi$ resonance.

Figures 1 and 2 show the $2\pi^0$, $\pi^+\pi^-$ mass distributions from the data of Refs. 3 and 5. In order to reduce the combinatorial background, one sextant (upper right one) of the $3\pi^0$ Dalitz plot (Fig. 2, Ref. 3) has been projected on the M_{23} axis. The band

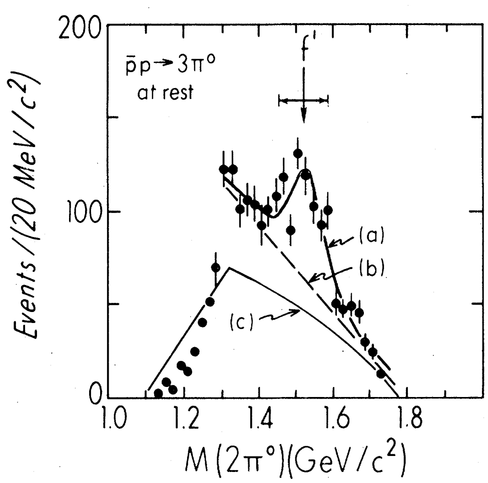

FIG. 1. Invariant-mass distribution of the least energetic two π^0's in $\bar{p}p \to 3\pi^0$ annihilations at rest from the data of Ref. 3. (a) is a fit with a Breit-Wigner resonance form and a quadratic background indicated by (b). (c) is unnormalized phase space.

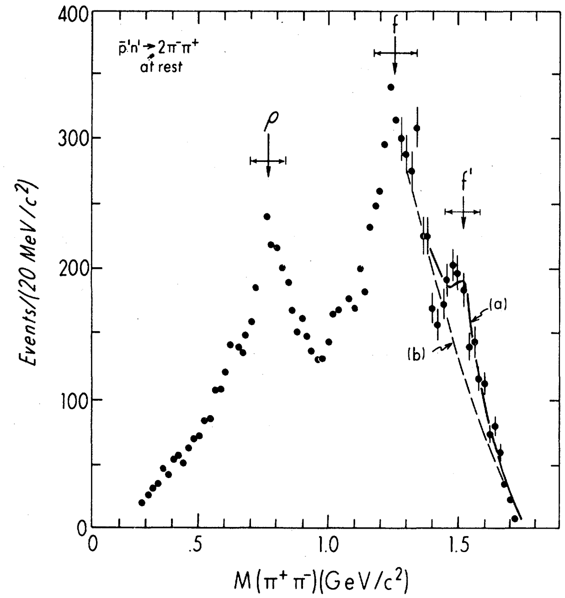

FIG. 2. Invariant-mass distribution of the $\pi^-\pi^+$ pairs in $\bar{p}$ "n"$\to 2\pi^-\pi^+$ annihilations at rest from the data of Ref. 4. (a) is a fit with a Breit-Wigner resonance form and a quadratic background indicated by (b). Fit has been done over the data with error bars.

seen on the Dalitz plot and indicated as f' shows well as a resonance peak in Fig. 1. In Fig. 2, apart from the dominant ρ and f peaks, a third one at the f' mass is present. This peak, identified as "tower B" in Ref. 5, is produced when the second π^- forms an invariant mass with the π^+ equal to the ρ.

Fits to the data of Figs. 1 and 2 were performed around the f' peak (shown by the solid curves) using a quadratic background and a Breit-Wigner resonance form. The results are presented in Table I and compared with the data. The optimized masses and widths are in excellent agreement with those of the f'. Using the optimized number of resonance events and the $3\pi^0$ ($2\pi^-\pi^+$) branching ratios from Ref. 3 (5), the following cascade branching ratios are obtained by assuming $I=0$ for the f_2':

$$B(\bar{p}p \to \pi^0 f_2')B(f_2' \to 2\pi) = (4.7 \pm 1.4)\times 10^{-3} \ , \tag{5a}$$

$$B(\bar{p}'n' \to \pi^- f_2')B(f_2' \to 2\pi) = (3.9 \pm 0.5)\times 10^{-3} \ , \tag{5b}$$

and

$$\frac{B(\bar{p}p \to \pi^0 f_2')}{B(\bar{p}'n' \to \pi^- f_2')} = 1.2 \pm 0.4 \ . \tag{5c}$$

Assuming that $f_2' \to 2\pi$ is dominant, the branching ratios $\bar{p}N \to \pi f_2'$ are typical[9] of two-body annihilations [e.g., $B(\bar{p}p \to 2\pi) \simeq 3\times 10^{-3}$]. From i-spin we would expect that (5c) should be approximately $\frac{1}{2}$. Considering the experimental difficulties associated with the $3\pi^0$ branching ratio, result (5c) compares favorably with expectations if the f_2' is an $I=0$ $\pi\pi$ resonance.

The branching ratio[10] for $f' \to 2\pi$ is $< 10\%$ and probably close to 1% as suggested by $\pi\pi$, $\bar{K}K$ phase-shift analyses.[11] Assuming that the $f_2' \to 2\pi$ is indeed the $f' \to \bar{K}K$ then (5a) and (5b) imply that

$$0.05 \lesssim B(\bar{p}N \to \pi f_2') < 0.5 \ . \tag{6}$$

Such a branching ratio for two-body f' production in annihilations is indeed extraordinarily large. In any case, we have looked for the $f' \to \bar{K}K$ in reactions (3) and (4).

Figures 3 and 4 show new data[12] on $\bar{p}$ "n" $\to K^+K^-\pi^-$, $K_SK_S\pi^-$ from annihilations at rest in deuterium. They have been collected during an analysis of $\bar{p}d$ film from the 30-in. BNL bubble chamber. Except for abundant $K^*(880)$ and ϕ production there is no evidence for any other state and, in particular, for the $f' \to \bar{K}K$. Figure 5 shows $\bar{K}K$ invariant-mass distributions obtained from Figs. 3 and 4 and Ref. 6. The following limits ($\sim 2\sigma$ level) for f' production have been obtained:

$$B(\bar{p}p \to \pi^0 f')B(f' \to \bar{K}K) < 3.4\times 10^{-4}\ (K_SK_S\pi^0) \ , \tag{6a}$$

$$B(\bar{p}n \to \pi^- f')B(f' \to \bar{K}K) < 2.1\times 10^{-4}\ (K^+K^-\pi^-) \tag{6b}$$

$$< 1.5\times 10^{-4}\ (K_SK_S\pi^-) \ . \tag{6c}$$

Assuming that the f_2' is the same as the f' then (5) and (6) yield the results

$$\frac{B(f' \to 2\pi)}{B(f' \to \bar{K}K)} > 14 \ [\text{from}(5a),(6a)]$$
$$> 16 \ [\text{from}(5b),(6b)]$$
$$> 26 \ [\text{from}(5c),(6c)] \ ,$$

to be compared with < 0.1 *as given in other observations of* f'. These f_2' effects *cannot therefore be associated with the* f'.

TABLE I. Mass, width, and number of f_2' events obtained by fitting the $2\pi^0$ ($\pi^+\pi^-$) invariant-mass distributions in $\bar{p}p \to 3\pi^0$ ($\bar{p}$ "n" $\to 2\pi^-\pi^+$) annihilations at rest (Figs. 1 and 2). The f' mass and width are presented for comparison.

	f_2'			f'
	$3\pi^0$	$2\pi^-\pi^+$	Combined	
M (MeV)	1529 ±6	1525 ±8	1525 ±5	1516 ±12
Γ (MeV)	106 ±18	96 ±20	101 ±13	67 ±10
Events	435 ±45	421 ±50		

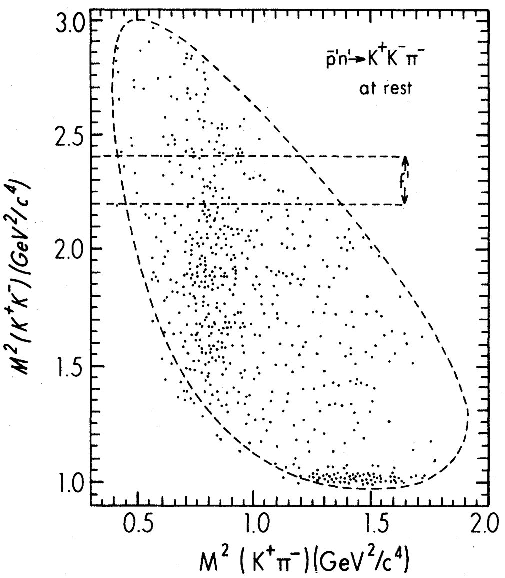

FIG. 3. Dalitz plot of the $K^+K^-\pi^-$ events collected from annihilations at rest in deuterium. The boundary has been calculated assuming zero proton recoil momentum. The band over which the f' should be expected is indicated. Copious ϕ and K^{*0} production is present but no evidence of f'. Upper limit of f' production is much less than the $\phi(\rightarrow K^+K^-)$ production which is $(3.5 \pm 0.6) \times 10^{-4}$.

Is the f_2' an artifact of 3π dynamics? Since the dynamics of strong interactions are uncertain there is no way to exclude this possibility. However, if one insists on a total understanding the same question should be raised in regard to other states as well

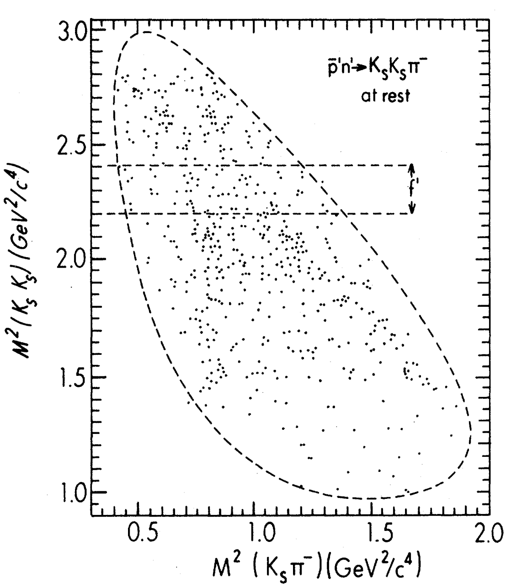

FIG. 4. Dalitz plot of the $K_SK_S\pi^-$ events (two points/event) collected from $\bar{p}d$ annihilations at rest. The boundary has been calculated assuming zero proton recoil momentum. The band over which the f' should be expected is indicated. Copious K^{*-} production is present but no evidence of f'.

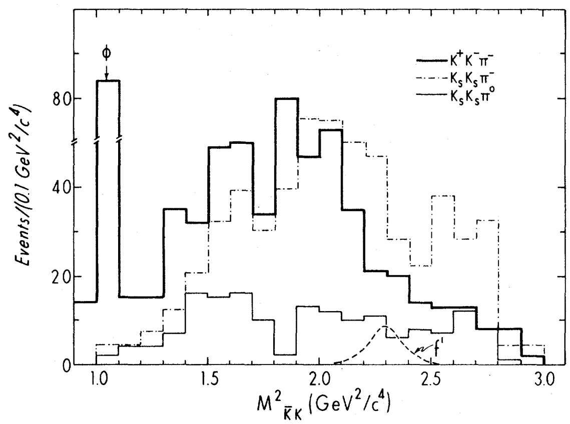

FIG. 5. $\bar{K}K$ invariant-mass-squared distributions from Figs. 3 and 4 and Ref. 6 produced in $\bar{p}N \rightarrow \pi K\bar{K}$ at-rest annihilations. The f' "signal" (arbitrary normalization) is indicated. No evidence of f' production is present in any of these channels.

(e.g., E, ι, θ). It is a matter of experience that resonances are preserved in direct projections while internal dynamics average out and produce phase-space-like backgrounds. As an example the $2\pi^-\pi^+$ annihilation at rest, in spite of strong internal structures, shows in the $\pi^+\pi^-$ invariant-mass distribution well-known (ρ,f) resonances while the $\pi^-\pi^-$ distribution is smooth.[4,5] If, nevertheless, one insists in attributing the f_2' effect to $2\pi^-\pi^+$ internal dynamics its presence in $3\pi^0$ with the expected magnitude is indeed surprising when one considers the large differences in internal wave structure.

Figure 6 shows the results of Kasper *et al.*[7] based on a fit of the $2\pi^-\pi^+$ (and $3\pi^0$) data in terms of $\pi\pi$ phase shifts. They use standard three-body final-state interaction parametrizations and allowing $\bar{p}$ capture from S and P states. The fits are reasonable but they fail to account for the f_2' peak. On the other hand, dual models[5,13] have not been as successful in describing the 3π data and also do not produce peaks at the f_2'.

Why has the f_2' not been seen elsewhere? Again this question cannot be answered at present. It is necessary, however, that it should be present in $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ at rest. Using the product branching ratio (5b) we expect that

$$B(\bar{p}p \rightarrow \pi^0 f_2')B(f_2' \rightarrow \pi^+\pi^-) \simeq (1.3 \pm 0.2) \times 10^{-3} \ .$$

Foster *et al.*[14] have analyzed this reaction but do not introduce a contribution from $\bar{p}p \rightarrow \pi^0 f'(\rightarrow \pi^+\pi^-)$. They do obtain, however, a branching ratio for

$$B(\bar{p}p \rightarrow f\pi^0)B(f \rightarrow \pi^+\pi^-) \simeq (2.4 \pm 0.7) \times 10^{-3} \ .$$

Considering that the f is hardly evident in Fig. 5 of Ref. 14 we conclude that the present $\pi^+\pi^-\pi^0$ data are not statistically significant to provide evidence for or against the f_2'. It is clearly of great interest in this

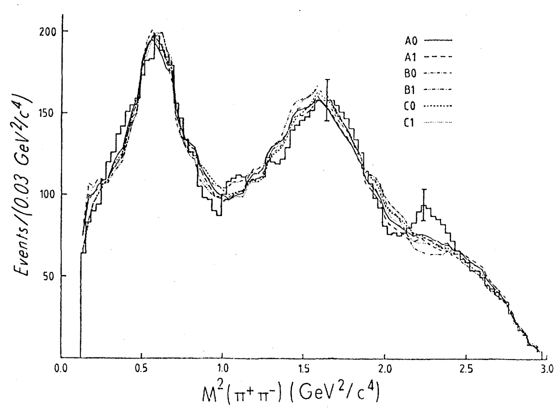

FIG. 6. Fits of the $2\pi^-\pi^+$ data obtained by Kasper *et al.* The various fits correspond to the available $\pi\pi$ phase shifts. The f_2' effect is not accounted for by any of the $\pi\pi$ phase-shift solutions. Similar results have been obtained for the $3\pi^0$.

context to increase the $\bar{p}p \to \pi^+\pi^-\pi^0$ statistics and look for the f_2'. If observed at the appropriate level, it will further enhance the interpretation that the f_2' effects are due to a resonance.

Quantum numbers. Since it decays into $2\pi^0$ and $I=2$ is excluded [no evidence of a peak in $M(\pi^-\pi^-)$, Ref. 5, Fig. 5], $I=0$ and consequently $J^{PC}=0^{++}, 2^{++}, \cdots$. The angular distribution of the $f_2' \to 2\pi^0$ in its c.m. system with respect to the third π^0 is isotropic (isotropic band, Ref. 1, Fig. 2). On the other hand, in $2\pi^-\pi^+$ it shows as highly anisotropic being produced in association[5] with the ρ. It is known[4] that in $2\pi^-\pi^+$ both the ρ and f angular distributions are not reliable measures of their spins. If the spin is $J=2$ and further one assumes capture from S states the $\pi f_2'$ relative momentum will be $J=2$. In this case one expects that centrifugal-barrier effects may suppress the production of $\pi f_2'$ much more than πf due to the fact that the relative momentum in $\pi f_2'$ is smaller than in πf. On the basis of these general observations one may tend to favor $J=0$.

Can the f_2' be the θ ($\to\eta\eta$)? The θ (Ref. 15) and f_2' masses and widths are certainly inconsistent. However, centrifugal-barrier effects may account for the difference.[16] For example, assuming $\bar{p}N$ captures come from low-relative-angular-momentum states, the relative π-θ angular momentum for S capture is $l=2$. Consequently the transition $\bar{p}p \to \pi\theta$ will be

$$\propto k\frac{(kR)^4}{(kR)^4+3(kR)^2+9}F_{\mathrm{BW}}(M_\theta,\Gamma_\theta) ,$$

where k is the π-θ c.m. momentum and R the radius of interaction. It is possible to shift the maximum of this function to coincide with the maximum of the f_2' with reasonable R but the width is much larger (more than a factor of 2) and asymmetric around the maximum, exhibiting a long tail at low masses.

In summary, there is an $f_2' \to \pi\pi$ $I=0$ resonance degenerate in mass and width with the $f' \to \bar{K}K$. It is being produced copiously in $\bar{p}N$ annihilations at rest. The spin is uncertain but we cautiously suggest that it is zero. In this case it is another $J^{PC}=0^{++}$ state in a mass region where many others have already been reported by Etkin *et al.*[17] They have observed also a state (ϵ) by studying K_SK_S phase shifts at 1470 $\pm$10 MeV with a width 140 $\pm$10 MeV. They fit this state to a $q\bar{q}$ nonet. The f_2' can be a $\bar{q}q$ candidate. Donoghue *et al.*[2], using the bag model, predict a three-gluon 0^{++} state with this mass. As a $\overline{qq}qq$ candidate[18] it is probably too narrow and it should decay strongly into two vector mesons. As an $\bar{N}N$ bound state it would be a ${}^{1,3}P_0$ (${}^{2I+1,2S+1}L_J$). Dover[19] predicts on the basis of NN potentials such a state at 1826 MeV and Shapiro[20] predicts one at 1289 MeV.

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