Evidence of $Q^2\bar{Q}^2$ Mesons in $\bar{p}n$ Annihilations and $\gamma\gamma$ Reactions

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A new resonance at 1480 MeV with a width of 110 MeV is found in $\bar{p}n$ annihilations in the channel $\bar{p}n \to \pi^- X_0(1480) \to \pi^-\rho^0\rho^0$. Its mass, width, spin, and parity are shown to be consistent with the $\rho^0\rho^0$ enhancement observed in $\gamma\gamma$ reactions. Together with the suppression in the $\gamma\gamma \to \rho^+\rho^-$ data which requires the admixture of an isotensor structure, this $\rho^0\rho^0$ resonance in $\bar{p}n$ annihilation and $\gamma\gamma$ reactions and their small $\pi\pi$ branching ratios represent the best evidence yet for $Q^2\bar{Q}^2$ states. A $\rho^-\rho^-$ resonance in $\bar{p}n$ annihilations which would betray the exotic isotensor nature of the resonance is predicted.

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Recent experimental studies of $\bar{p}n$ annihilations at rest[1,2] have revealed new resonances in the difference spectra between π^- and π^+. A resonance at ≈ 1480 MeV is found to dominate the channel $\bar{p}n \to \pi^- X_0(1480) \to 3\pi^- 2\pi^+$ where $X_0(1480)$ decays to 4π mainly through $\rho^0\rho^0$ (see Fig. 1).[2] Another prominent state is possibly found to be present in the channel $\bar{p}n \to \pi^- X_1(1470) \to 2\pi^-\pi^+\pi^0$ (see Fig. 2). Notwithstanding the fact that the fitted mass and width of $X_1(1470)$ at $\simeq 1470$ MeV and $\simeq 90$ MeV are very close to those of the first state $X_0(1480)$, they are believed to be distinct states because of their different G parities.

The dominant $\rho^0\rho^0$ decay of $X_0(1480)$ is reminiscent of the $\rho^0\rho^0$ enhancement observed in $\gamma\gamma$ reactions (see Fig. 3)[4-8] in this mass region. It is natural to question whether these $\rho^0\rho^0$ decays have the same origin. First, we note the apparent difference between the two data. The $\rho^0\rho^0$ enhancement in $\gamma\gamma$ reactions appears to have a much wider distribution than $X_0(1480)$. It starts from below the $\rho^0\rho^0$ threshold where $X_0(1480)$ is located and extends to fairly far above the threshold (see Fig. 3) where $X_0(1480)$ has little contribution. This difference in width can be resolved. According to the spin and parity analysis of the $\rho^0\rho^0$ events in $\gamma\gamma$ reactions by Althoff *et al.*,[5] there is a sizable 0^{++} contribution below and near the $\rho\rho$ threshold, whereas above 1.7 GeV, the main contribution comes from 2^{++}. Apparently, in the $\bar{p}n$ annihilation, the 0^{++} is seen and identified with $X_0(1480)$ and the 2^{++}, which we denote by $X_2(1650)$, is not. This can be understood in terms of the kinematics involved. The $\bar{p}n$ annihilation experiment was done at rest. Hence, the most probable J^P for the 5π decay channel is 0^- $({}^1S_0)$. In order for us to see the 2^{++} $X_2(1650)$ in $\bar{p}n \to \pi^- X_2(1650)$, the outgoing π^- and $X_2(1650)$ must be in a relative D wave. This possibility is suppressed as a result of the fact that the combined mass of $X_2(1650)$ and the recoiling π^- is so close to the $\bar{p}n$ threshold that there is not enough phase space for them to exit in a D

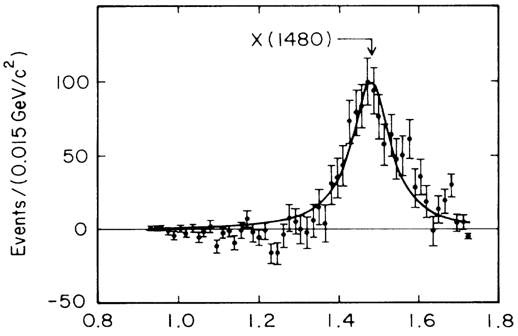

FIG. 1. The resonance $X_0(1480)$ with a width of ~ 110 MeV observed in $\bar{p}n \to \pi^- X_0(1480) \to \pi^-\rho^0\rho^0$ in the difference spectrum between π^- and π^+. The fit is made with $\pi^- X^0(1480)$. This is taken from Ref. 2.

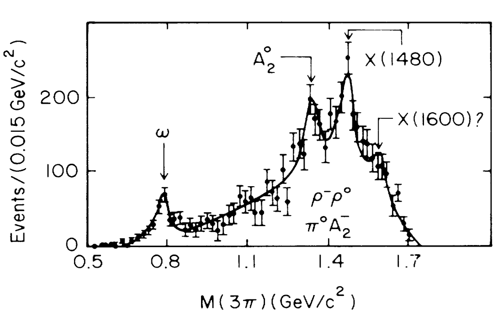

FIG. 2. The difference spectrum of the mass of three pions recoiling against the π^+ and π^- in the $2\pi^-\pi^+\pi^0$ channel of $\bar{p}n$ annihilations. The fit is made with $\pi^-\omega$, $\pi^- A_2^0(\to \rho\pi)$, $\pi^- X_1(1470)$, $\pi^- X(1600)$, and the "background" from $\rho^-\rho^0$, $\pi^0 A_2^-$. This is taken from Ref. 2.

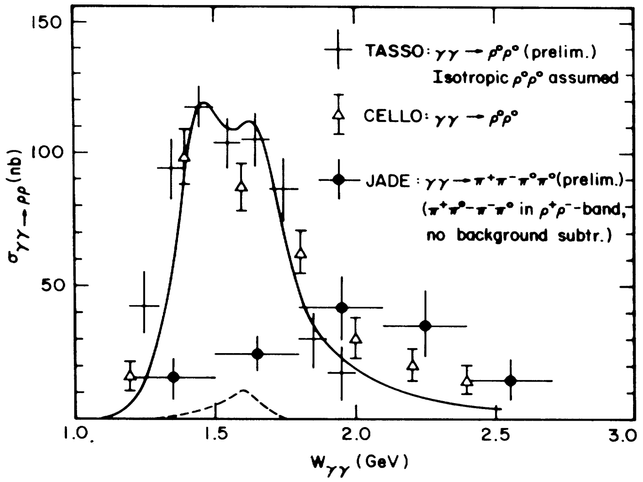

FIG. 3. The calculated $X_0(1480)$ and $X_2(1650)$ mesonia contribution to the $\gamma\gamma\to\rho^0\rho^0$ cross section (solid line) and the $\gamma\gamma\to\rho^+\rho^-$ cross section (dashed line) in comparison with the experimental data. This is taken from Ref. 3.

wave. To illustrate this, let us take the nucleon size to be ~1 fm; then the maximum allowed classical angular momentum between the π^- and $X_2(1650)$ in the exit channel is ~1.7, which is less than 2 for the D wave. On the other hand, there is no centrifugal suppression for the 0^{++} $X_0(1480)$. Hence, the latter is observable in $\bar{p}n$ annihilation at rest. As the center-of-mass energy of the $\bar{p}n$ annihilation increases, we expect the signal for $X_2(1650)$ to grow, which can be verified experimentally. Although the $\rho^0\rho^0$ width difference in $\gamma\gamma$ reactions and $\bar{p}n$ annihilations is resolved, there is still a controversy over the spin and parity assignment of $X_0(1480)$. As mentioned above, the $\rho^0\rho^0$ events below the threshold are attributed to a 0^{++} state in the $\gamma\gamma$ reaction analysis.[5] The same spin and parity assignment is also favored over 2^+ and 1^- in an earlier analysis[9] of the reaction $\bar{p}n\to\pi^+\pi^+\pi^-\pi^-\pi^-$ at rest where a $\rho^0\rho^0$ resonance was seen with $m=1.410$ GeV and $\Gamma=0.090$ GeV. On the other hand, a recent angular analysis[10] of the $\rho^0\rho^0$ decay of the resonance $X_0(1480)$ observed in the difference spectrum in $\bar{p}n$ annihilations at rest[1,2] indicates that a 2^{++} assignment is preferred over the 0^{++}. Despite the fact that a 0^{++} $X_0(1480)$ is favored from the theoretical point of view as will be discussed later, a 2^{++} $\rho\rho$ resonance at 1480 MeV, unlike the 2^{++} $X_2(1650)$, cannot be ruled out *a priori* from angular momentum considerations. This apparent discrepancy in spin and parity assignment must be settled experimentally before we have a better understanding of the nature of the resonance. It is our speculation that perhaps a 0^{++} at 1480 MeV and a 2^{++} at ~1650 MeV will produce a better fit of the angular distributions than a 0^{++} or a 2^{++} separately.

The $X_0(1480)$ and $X_2(1650)$ in the $\gamma\gamma$ reactions were interpreted[3,11-13] as states which are composed of two quarks and two antiquarks ($Q^2\bar{Q}^2$) and decay mainly through meson pairs, and which we can call mesonia. The spectroscopy of the s-wave $Q^2\bar{Q}^2$ mesons has been studied both in the Massachusetts Institute of Technology (MIT) bag model[14,15] and the potential model.[16] It is learned that there are several 2^{++} $Q^2\bar{Q}^2$ mesons [$C^0(\mathbf{9})$, $C^0(\mathbf{36})$, $E_{\pi\pi}(\mathbf{36})$, and $C_\pi(\mathbf{36})$ in Jaffe's notation[15]] predicted[15] to be at 1650 MeV—exactly where $X_2(1650)$ is. There is also a 0^{++} $C^0(\mathbf{9^*})$ predicted[15] at 1450 MeV, which coincides with $X_0(1480)$. In general, the mesonia are "superallowed" by the Okubo-Zweig-Iizuka rule: Most of the $Q^2\bar{Q}^2$ mesons can "fall apart" into two constituent $Q\bar{Q}$ mesons; hence they are too broad to be observed. However, there are exceptions. For those which are sitting close to the threshold of their respective main decay modes, they are possibly narrow enough to be detected as a result of the limited phase space. Both the above-mentioned 2^{++} and 0^{++} $Q^2\bar{Q}^2$ fall into this category. They are located within 100 MeV of their predominant decay modes of $\rho\rho$ and $\omega\omega$. Therefore, they are the best mesonium candidates to be observed. In comparison with the experimental data, we find that the calculated $\gamma\gamma\to\rho^0\rho^0$ cross section at the 2^{++} mass of 1650 MeV is essentially model independent (it depends only on the vector-dominance-model constants and the color-spin and flavor structure of these mesonia) and it agrees well with experiment.[3,11,12]

Besides the mass, the spin and parity, and the $\rho^0\rho^0$ cross section, a crucial piece of information comes from $\gamma\gamma\to\rho^+\rho^-$. It was predicted[3,11,13] that the $\rho^+\rho^-$ cross section is suppressed compared to that of $\rho^0\rho^0$, which was confirmed by the JADE data.[17] This suppression is the result of a selection rule: Under the condition that meson exchange is negligible, no flavor exchange between the scattering mesons is allowed with gluon dynamics if all the allowed flavor multiplets of the mesonia with specific spin and parity are degenerate or nearly degenerate. Therefore, the experimental suppression of $\rho^+\rho^-$ requires the presence of the exotic isotensor ($I=2$) state in addition to the isoscalar ($I=0$) states for both the $X_0(1480)$ and $X_2(1650)$. This rules out the $Q\bar{Q}$, glueball, and $Q\bar{Q}g$ interpretations of the resonance which would predict the $\rho^+\rho^-$ cross section to be twice that of $\rho^0\rho^0$. Hence, the suppression of $\rho^+\rho^-$ has been taken[3,12,13] as strong evidence for the mesonium structure and it simply reflects the $Q^2\bar{Q}^2$ flavor classification and its dynamics.[15,16]

It is found[3,12] in the fitting of the $\gamma\gamma\to\rho^0\rho^0$ cross section that 0^{++} $C^0(\mathbf{9^*})$, $C^0(\mathbf{36^*})$, and $E_{\pi\pi}(\mathbf{36^*})$ with a total width of ~130 MeV are needed to describe the $\rho^0\rho^0$ and $\rho^+\rho^-$ data below the threshold (Fig. 3). This width is quite in accord with the width of $X_0(1480)$, which is ~110 MeV. It has been stressed[3,11,12] that the pseudoscalar pair (e.g., $\pi\pi$) decay from the 0^{++} $X_0(1480)$ is small mainly because the corresponding color-spin recoupling coefficients are small.[18] With the calculated recoupling coefficients,[18] we predict the branching ratio for $\pi^+\pi^-$ to be an order of magnitude smaller than that of $\rho^0\rho^0$. A $\pi\pi$ resonance with $M=1527\pm5$ MeV and $\Gamma=101\pm12$ MeV is found in the following annihilations[2,19]:

$$\bar{p}p \to \pi^0 f_2'(\to 2\pi^0), \quad \bar{p}n \to \pi^- f_2'(\to \pi^+\pi^-). \qquad (1)$$

By comparison with data from $\bar{p}p \to \pi^0 K\bar{K}$ and $\bar{p}n \to \pi^- K\bar{K}$, it is concluded that f_2' is not associated with f'. On the basis of their similar masses and widths, it would be natural to interpret f_2' as the 2π decay mode of $X_0(1480)$. In this case, the experimental ratio of the branching ratios is

$$\frac{B(\bar{p}n \to \pi^- X_0(1480) \to \pi^-\pi^+\pi^-)}{B(\bar{p}n \to \pi^- X_0(1480) \to \pi^-\rho^0\rho^0)} \simeq 5\%. \qquad (2)$$

This agrees well with our prediction based on the mesonium structure. To unravel the situation further, we predict the ratio for the $\rho^+\rho^-$ and $\rho^-\rho^-$ production relative to $\rho^0\rho^0$ in the quark-fusion picture for $\bar{p}n \to \pi^-\rho\rho$. In this case, the cross section is proportional to

$$\sigma(\pi^-\rho\rho) \simeq \left| \sum_i \frac{\langle \rho\rho\pi^- | T | M_i\pi^- \rangle \langle M_i\pi^- | T | \bar{p}n \rangle}{W - E_i + i\Gamma_i/2} \right|^2, \qquad (3)$$

where

$$\langle M_i\pi^- | T | \bar{p}n \rangle \propto \textstyle\sum_j a_j^i f_j^i c_j, \qquad (4)$$

and where a_j^i is the color-spin recoupling coefficient for the jth meson-pair component ($j=PP$, VV, $\mathbf{P}\cdot\mathbf{P}$, $\mathbf{V}\cdot\mathbf{V}$, where P and V are the color-singlet pseudoscalar and vector $Q\bar{Q}$ mesons, and $\mathbf{P}$ and $\mathbf{V}$ are the color-octet representations of the same) in the mesonium M_i [$i=C^0(\mathbf{9}^*)$, $C^0(\mathbf{36}^*)$, and $E_{\pi\pi}(\mathbf{36}^*)$]. f_j^i is the overlap coefficient between $M_i\pi^-$ and $\bar{p}n(^1S_0)$. c_j is the color factor which is $\sqrt{\frac{1}{3}}$ for PP and VV and $-\sqrt{\frac{2}{3}}$ for $\mathbf{P}\cdot\mathbf{P}$ and $\mathbf{V}\cdot\mathbf{V}$. Furthermore,

$$\langle \rho\rho\pi^- | T | M_i\pi^- \rangle \propto a_{vv}^i b^i(\rho\rho), \qquad (5)$$

where a_{vv} is the color-spin recoupling coefficient for the decaying VV pair in M_i and $b^i(\rho\rho)$ is the Clebsch-Gordon coefficient for $\rho\rho$, be it $\rho^0\rho^0$, $\rho^+\rho^-$, or $\rho^-\rho^-$, in the VV part of M_i. Our predictions for the ratios of the branching ratios $B(\rho^+\rho^-\pi^-)/B(\rho^0\rho^0\pi^-)$ and $B(\rho^-\rho^-\pi)/B(\rho^0\rho^0\pi^-)$ are presented in Table I. We note that the ratio between $\rho^+\rho^-$ and $\rho^0\rho^0$ is expected to be 2 if $X_0(1480)$ is an $I=0$ resonance. The fact that the predicted ratio is roughly half of that is the result of the presence of an $I=2$ state in addition to two $I=0$ states, much like the suppression evidenced in $\gamma\gamma \to \rho^+\rho^-$. It is also interesting to note that the predicted branching ratio for $\rho^-\rho^-$ production is reasonably large. If detected, it would reveal the exotic isotensor structure of the mesonium explicitly and thereby establish the existence of the $Q^2\bar{Q}^2$ mesons beyond doubt.

TABLE I. The predicted ratios of different $\rho\rho$ decay modes for the 0^{++} $X_0(1480)$ in $\bar{p}n$ annihilations.

$B(\rho^+\rho^-\pi^-)/B(\rho^0\rho^0\pi^-)$	$\simeq 1.0$
$B(\rho^-\rho^-\pi^+)/B(\rho^0\rho^0\pi^-)$	$\simeq 0.2$

Regarding the structure $X_1(1470)$ seen in the $\pi^+\pi^-\pi^0$ channel (see Fig. 2), we contemplate that it could be the $\rho\pi$ decay mode of 1^{+-} $E_{\rho\pi}$ and $C^0(\mathbf{36})$ which were calculated in the Massachusetts Institute of Technology bag model[15] to be roughly degenerate with 0^{++} $C^0(\mathbf{9}^*)$ [$X_0(1480)$]. If this assignment turns out to be correct, then we are beginning to see the systematics of the mesonia of u and d quarks—i.e., 0^{++}, 1^{+-}, and 2^{++} states—all at the expected masses.

To conclude, we show that the apparent difference in the invariant-mass distributions between the $\rho^0\rho^0$ resonance $X_0(1480)$ observed in $\bar{p}n$ annihilations and the $\rho^0\rho^0$ enhancement in $\gamma\gamma$ reactions can be reconciled in view of the spin and parity analysis in $\gamma\gamma$ reactions[5] and $\bar{p}n$ annihilations,[9,10] namely, a 0^{++} or 2^{++} resonance $X_0(1480)$ at 1480 MeV and a 2^{++} resonance $X_2(1650)$ at a higher mass. Both are observable and observed in $\gamma\gamma$ reactions, while only $X_0(1480)$ is seen in $\bar{p}n$ annihilations at rest because the 2^{++} $X_2(1650)$ is suppressed by the centrifugal effect. If we identify f_2' observed in $\bar{p}n$ annihilations as the $\pi\pi$ decay mode of $X_0(1480)$, its small branching ratio is understandable in terms of the corresponding small recoupling coefficients in the $Q^2\bar{Q}^2$ color-spin wave functions. When this is combined with the JADE data[17] on the suppression of $\gamma\gamma \to \rho^+\rho^-$ in the same region, which requires the admixture of an isotensor structure, we believe that the $Q^2\bar{Q}^2$ nature of $X_0(1480)$ is on the verge of being established. Branching ratios for the $\rho^+\rho^-$ and $\rho^-\rho^-$ decays are predicted to be large enough to be measurable in $\bar{p}n$ annihilations. Experimental detection of the $\rho^-\rho^-$ decay of $X_0(1480)$, which would unveil the exotic isotensor nature of the mesonium, is called for.

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[1]D. Bridges *et al.*, Phys. Rev. Lett. **56**, 211 (1986).

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

[3]B. A. Li and K. F. Liu, Phys. Rev. Lett. **51**, 1510 (1983).

[4]R. Brandelik *et al.* (TASSO Collaboration), Phys. Lett. **97B**, 448 (1980).

[5]M. Althoff *et al.* (TASSO Collaboration), Z. Phys. C **16**, 13 (1982).

[6]D. L. Burke *et al.*, Phys. Lett. **103B**, 153 (1981).

[7]H. J. Behrend *et al.* (CELLO Collaboration), Z. Phys. C **21**, 205 (1984).

[8]W. Ko (PEP4-PEP9 Collaboration), in *Proceedings of the Twenty-Second International Conference on High Energy Physics, Leipzig, East Germany, 1984,* edited by A. Meyer and E. Wieczorek (Akademie der Wissenschaften der Deutsche Demokratische Republik, Zeuth, East Germany, 1984).

[9]A. Bettini *et al.*, Nuovo Cimento A **42**, 695 (1986).

[10]D. Bridges, I. Daftari, and T. E. Kalogeropoulos, Phys. Rev. Lett. **57**, 1534 (1986).

[11]B. A. Li and K. F. Liu, Phys. Lett. **118B**, 435 (1982), and **124B**, 550(E) (1983).

[12]B. A. Li and K. F. Liu, Phys. Rev. D **30**, 613 (1984).

[13]N. N. Achasov, S. A. Devyanin, and G. N. Shestakov, Phys. Lett. **108B**, 134 (1982).

[14]R. L. Jaffe and K. Johnson, Phys. Lett. **60B**, 201 (1976).

[15]R. L. Jaffe, Phys. Rev. D **15**, 267 (1977).

[16]K. F. Liu and C. W. Wong, Phys. Lett. **107B**, 391 (1981); H. Lipkin, Phys. Lett. **70B**, 113 (1977); J. Weinstein and N. Isgur, Phys. Rev. D **27**, 588 (1983).

[17]J. Dainton, in *Proceedings of the International Europhysics Conference on High Energy Physics, Brighton, England, 1983,* edited by J. Guy and C. Costain (Rutherford-Appleton Laboratory, Chilton, Didcot, Oxfordshire, England, 1984).

[18]C. W. Wong and K. F. Liu, Phys. Rev. D **21**, 2039 (1980).

[19]L. Gray *et al.*, Phys. Rev. D **27**, 307 (1983).