have done, it might be more consistent to use the number n_- of negative pions. However, since n_- is roughly proportional[6] to n we do not expect any large corrections to our results from using this variable. Nor would such modifications of the KNO scaling variable as those proposed[7] to get a more accurate fit to the multiplicity distribution affect the essence of our results.

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Comment on a Narrow Meson Resonance at 1932 MeV*

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A number of characteristics of a narrow resonance observed in $\bar{p}p$ scattering can be explained by assuming that it is a nucleon-antinucleon system, rather than quark-antiquark. This object, together with similar states in other baryon-antibaryon channels, could be instrumental in the saturation of duality constraints. Relations between our proposal and models for ψ and ψ' are discussed.

In addition to the now well-known ψ and ψ', at least one other very narrow meson resonance with mass greater than 1100 MeV seems reasonably well confirmed.[1] This object, which we will refer to as θ, appears as a bump in the total cross sections for $\bar{p}p$ and $\bar{p}d$ scattering and has a mass and width of

$$M_\theta = 1932 \pm 2 \text{ MeV}, \quad \Gamma = 9^{+4}_{-3} \text{ MeV}.$$

The mass of θ is sufficiently far above the masses of the lowest octet of 0^- mesons that we would expect the phase space available for multimeson decays to be extremely large, and therefore the value of Γ to be correspondingly large. For comparison, the widths[2] of $g(1680)$ and $\omega(1675)$ are 180 ± 30 MeV and 140 ± 20 MeV, respectively. Thus although θ seems perhaps less unusual than ψ and ψ', its narrow width is still surprising and needs explanation, particularly in relation to the various models offered for ψ and ψ'. In the present note, we will give semiquantitative arguments which suggest that the narrow width of θ can primarily be explained by the assumption that θ is a resonant $\bar{N}N$ (antinucleon-nucleon) system in much the same sense that deuterium is an NN bound state.[3] Thus part of our result is that θ appears to be exotic. We will also suggest that if there are a number of other $\bar{B}B$ (antibaryon-baryon) resonances and bound states, then these objects may be responsible for the saturation of duality in the 27, 10, and 10* $\bar{B}B$ channels. Finally we will show that an alternative interpretation of θ as a $\bar{q}_5 q_5$ system (where q_5 is a new fifth quark), similar to the many recent interpretations[4] of ψ and ψ' as $\bar{q}_4 q_4$, appears somewhat unlikely, while on the other hand, to the extent that a reasonable guess concerning magnetic form factors can be believed, it would seem that ψ and ψ' probably are not $\bar{B}B$ systems as some authors[5] have proposed.

The parameters of θ given by Carroll *et al.*[1] were obtained by fitting the observed bump in $\bar{p}p$ cross sections with a Breit-Wigner form. The maximum enhancement at the peak of the resonance is $\sigma_{max} = 18^{+6}_{-3}$ mb. Then if $\sqrt{s}$ is the c.m.-system energy of a $\bar{p}p$ scattering experiment, the quantity

$$\gamma = \int \sigma(\bar{p}p \to \theta)\, ds = \pi \Gamma M_\theta \sigma_{\max} \qquad (1)$$

is given by $\gamma \approx 2.5$. Using standard techniques,[4,6] we obtain

$$\Gamma(\theta \to \bar{p}p) = \frac{M_\theta \beta^2 \gamma}{4\pi^2(2J+1)} \approx \frac{7.1}{2J+1}\ \text{MeV}, \qquad (2)$$

where β is the c.m. velocity of the proton produced in $\theta \to \bar{p}p$ decay and J is the spin of θ. But we would expect θ to have definite isospin, either 1 or 0, since it couples to $\bar{p}p$. Therefore $\Gamma(\theta \to \bar{p}p) = \Gamma(\theta \to \bar{n}n)$ and since $\Gamma \geq \Gamma(\theta \to \bar{p}p) + \Gamma(\theta \to \bar{n}n)$, Eqs. (1) and (2) yield

$$2J + 1 \geq M_\theta^2 \beta^2 \sigma_{\max}/2\pi = 1.6^{+0.5}_{-0.3}. \qquad (3)$$

This inequality is violated by 2 standard deviations if $J = 0$, so that it appears likely that $J \geq 1$. In addition, Eq. (2) implies that unless J is extremely large, the branching ratio $\Gamma(\theta \to \bar{p}p)/\Gamma$ will be sizable. But since $M_\theta - 2M_N$ is only ≈ 56 MeV, the phase space available for $\bar{p}p$ decays is kinematically suppressed, especially for states of nonzero orbital angular momentum. This suggests that the underlying coupling strength of θ to $\bar{p}p$ may not be unusually small. If the decay of θ into $\bar{p}p$ states is described (in an obvious notation) by one of the phenomenological Lagrangians

$$\mathcal{L}_I = g_j \bar{p} Q_j p\, \theta \ \ (j = S, P),$$
$$\mathcal{L}_I = g_j \bar{p} Q_j^{\mu} p\, \theta_\mu \ \ (j = V, A), \qquad (4)$$

then the coupling constants g_j are given by

$$g_P^2 = \beta^2 g_S^2 = 2\beta^2 g_A^2 = (3 - \beta^2) g_V^2 = 2\beta\gamma/\pi, \qquad (5)$$

which implies $g_P^2 \approx 0.40$, $g_S^2 \approx 6.6$, $g_A^2 \approx 3.3$, and $g_V^2 \approx 0.13$. Therefore if the spin-cum-parity of θ is either 0^+ or 1^+, so that θ decays into $\bar{p}p$ states with orbital angular momentum $l = 1$, the underlying coupling constant for $\theta \to \bar{p}p$ will be of the usual order of magnitude[7] for strong interactions. The small value of $\Gamma(\theta \to \bar{p}p)$ will be a consequence of kinematics. A similar result holds for $J \geq 2$, since then we have $l \geq 1$.

If the coupling of θ to $\bar{p}p$ states actually is of normal strength, then to account for the narrow total width of θ we must find some mechanism which selectively represses the coupling of θ to mesons. We will show that this occurs if θ is a resonant $\bar{N}N$ system. The arguments we will give follow, in part, the results of Bogdanova, Dal'karov, and Shapiro.[3] The radius of the region in which $\bar{N}$ and N are held should be of the order of $1/k$, where $k \approx 230$ MeV is the magnitude of the c.m.-system momentum of the N produced when θ decays. On the other hand, the radius of the region in which $\bar{N}$ and N can annihilate into mesons is expected to be much smaller, of the order of $1/M_N$, since this process requires nucleon exchange. If the relative-position wave function of the resonant system is sufficiently small at the origin, annihilation will occur infrequently and often the nucleon and antinucleon will have tunneled through their potential barrier and escaped before annihilation can occur. More quantitatively, we can picture the annihilation region as the target of a scattering experiment occurring within the volume occupied by $\bar{N}$ and N. The flux at the target is approximately $2\beta\langle|\psi(0)|^2\rangle$, where $\langle|\psi(0)|^2\rangle$ is the effective probability density obtained by averaging the square of the magnitude of the Schrödinger wave function over the annihilation region. Then the rate at which annihilation events occur, which is equal to the width $\Gamma(\theta \to \text{mesons})$, is approximately

$$\Gamma(\theta \to \text{mesons}) \approx 2\beta\langle|\psi(0)|^2\rangle \sigma(\bar{N}N \to \text{mesons}). \qquad (6)$$

For $\beta \lesssim \frac{1}{2}$, $2\beta\sigma(\bar{N}N \to \text{mesons})$ is nearly independent of β and given[1] by ≈ 37 mb. To estimate $\langle|\psi(0)|^2\rangle$, let us assume that the resonance is the lowest radial excitation of a Schrödinger particle bound in a deep spherical potential well. Averaging over a region of radius $r_A = O(1/M_N) \ll 1/k$, we get

$$\langle|\psi(0)|^2\rangle \approx \frac{k^3 (r_A k)^{2l}}{2\pi^2[(2l+1)!!]^2} \ll \frac{k^3}{2\pi^2[(2l+1)!!]^2}, \qquad (7)$$

where l is the orbital angular momentum of the state. If $l = 0$ then $\Gamma(\theta \to \text{mesons}) \approx 60$ MeV, while for $l = 1$ this result is drastically reduced by the centrifugal barrier so that even if we use only the inequality in (7), we obtain $\Gamma(\theta \to \text{mesons}) \ll 7$ MeV. For higher l, $\Gamma(\theta \to \text{mesons})$ becomes progressively smaller. The precise numerical values we have gotten should not be taken too seriously since they depend on the behavior of the $\bar{N}N$ interaction at small distances and therefore may be sensitive to effects ignored in our calculation. Nonetheless it does appear that a width $\Gamma(\theta \to \text{mesons})$ of the order of a few MeV could be expected if $l \geq 1$.

Combining our results so far, we can conclude that if θ is an $\bar{N}N$ resonance, the most probable spin-cum-parity and charge-conjugation assignments are $J^{PC}=1^{+-}$ or 1^{++} with $l=1$ and $J^{PC}=1^{--}$ with $l=2$.

For the case $J^{PC}=1^{--}$, $l=2$, θ could, in principle, be produced in e^+e^- colliding-beam experiments. By a derivation similar to the argument leading to (6) we find

$$\Gamma(\theta\to e^+e^-)\approx 2\beta\langle|\psi(0)|^2\rangle\sigma(\bar{N}N\to e^+e^-). \qquad (8)$$

Combining (1), (2), (6) and (7), we obtain $\sigma_{\max}(e^+e^-\to\theta)\ll|G(M_\theta^2)|^2\times 0.3$ nb, where $G(M_\theta^2)$ is the proton's magnetic form factor evaluated at $s=M_\theta^2$. Under the assumption that the proton's electric and magnetic form factors are equal at $s=(2.1\text{ GeV})^2$, data obtained at Frascati[8] imply $|G((2.1\text{ GeV})^2)|=0.27\pm0.04$. But we would expect that $G(s)$ changes sufficiently slowly with s that $G((1.9\text{ GeV})^2)\approx G((2.1\text{ GeV})^2)$. We obtain $\sigma_{\max}(e^+e^-\to\theta)\ll 0.02$ nb. Thus for this particular model it appears that it would not be possible to observe θ in e^+e^- colliding beams.

The consistency of the interpretation of θ we have described depends critically, of course, on the large value of the radius of the $\bar{N}N$ system. If this number were of the order of $1/M_N$ or smaller, it would most likely be quite inaccurate to picture θ as composed of individual coherent nucleon and antinucleon. Even if the radius were of the order of $1/M_K$, where M_K is the kaon mass, we would at least have to consider the effect of K exchange, and therefore mixing between $\bar{N}N$ and other $\bar{B}B$ combinations. The overall probability of pairs aside from $\bar{N}N$, however, should be of the order

$$\delta=\int_{|x|\le r_K}|\psi(x)|^2\,d^3x \approx\frac{2(r_Kk)^{2l+3}}{3\pi[(2l+1)!!]^2}\ll\frac{2}{3\pi[(2l+1)!!]^2}, \qquad (9)$$

where $r_K=O(1/M_K)\ll k$ is the effective radius of K exchange. For the present model we get $\delta\approx0.02$ for $l=0$ and $\delta\ll0.02$ for $l=1$.

Next let us consider an SU(3) classification of θ. If the isospin of θ is 1, which seems favored by the data,[1] then θ will transform as a mixture of the representations $\underline{27}$, $\underline{10}$, $\underline{10}^*$, and two $\underline{8}$'s. If the isospin of θ is 0, then θ will be a mixture of $\underline{27}$, two $\underline{8}$'s, and $\underline{1}$. In either case, θ will contribute to the exotic $\underline{27}$ channel of $\bar{B}B$ scattering. It is possible, however, that as a consequence of SU(3) breaking, some or all of the states in $\underline{27}$ orthogonal to θ are really not resonances but continuum states instead. Nonetheless, we would assume that this is not the case and that all the states in $\underline{27}$, $\underline{10}$, $\underline{10}^*$, both $\underline{8}$'s, and $\underline{1}$ occur in some mixed combination as bound states or resonances. The likelihood of such a possibility could be tested by calculating $\bar{B}B$ potentials arising from known meson exchanges and then looking for resonances and bound states in a corresponding nonrelativistic potential model. For $\bar{N}N$ interactions, this is approximately what has been done by Bogdanova, Dal'karov, and Shapiro[3] and $\approx$20 near-threshold resonances and bound states were found. If a similar spectrum were actually realized in the other $\bar{B}B$ channels as well, then these objects might provide the contributions which, as pointed out by Rosner,[9] seem to be required by duality in the $\underline{27}$, $\underline{10}$, and $\underline{10}^*$ channels. An argument which supports this hypothesis is that all the near-threshold bound states and resonances found in Ref. 3 had $l\ge1$, and therefore, as expected of the exotic states proposed by Rosner, would couple weakly to channels containing only mesons (for the same reason, the coupling of θ to mesons is suppressed).

Let us now consider an alternative interpretation of θ. Just as the narrow widths of ψ and ψ' can be accounted for by assuming that these resonances are $\bar{q}_4q_4$ quark systems,[4] we might try to account for the relatively narrow width of θ by assuming it consists of $\bar{q}_5q_5$, where q_5 is yet an additional quark. If this were the case, however, there would be no reason for θ to couple more strongly to $\bar{p}p$ states than to meson states. Therefore θ would probably have $J^{PC}=1^{--}$ since the axial-vector coupling constant $g_A^2\approx3.3$ would lead to too large a width $\Gamma(\theta\to\text{mesons})$. But then by applying the first Weinberg spectral sum rule for SU(4) or SU(5) symmetry, the coupling of θ to a virtual photon could be determined in the same way[4] as the couplings of ψ and ψ' to photons have been determined. We would arrive at the conclusion that θ should produce a large narrow peak in e^+e^- colliding-beam experiments. This seems to conflict with existing data[10] and therefore the assumption that θ is a $\bar{q}_5q_5$ bound state is perhaps ruled out.

Finally, let us examine the suggestion[5] that ψ and ψ' themselves might be a $\bar{B}B$ resonance and bound state, respectively, with $B=\Omega^-$. The value of J^{PC} is assumed to be 1^{--} for both ψ and ψ' so that coupling to e^+e^- states is possible through a virtual photon. If this proposal is correct, then we can derive estimates for $\Gamma(\psi\to e^+e^-)$ and $\Gamma(\psi'\to e^+e^-)$ by using appropriate versions of Eq. (8). The largest value which can be obtained in this way for either width is $\Gamma(\psi\to e^+e^-)$, $\Gamma(\psi'\to e^+e^-)$ $\approx |G'(M_\psi^2)|\times 1$ keV for the choice $l=0$, where $G'(M_\psi^2)$ is the Ω^- magnetic form factor evaluated at $s=M_\psi^2$. The observed results[4,6] are $\Gamma(\psi\to e^+e^-)$ ≈ 5 keV and $\Gamma(\psi'\to e^+e^-)\approx 3$ keV. Thus it seems to us that with a reasonable guess for $G'(M_\psi^2)$, the predicted values of $\Gamma(\psi\to e^+e^-)$ and $\Gamma(\psi'\to e^+e^-)$ will become too small. For example, the quark model predicts that the Ω^- magnetic form factor and the proton's form factor will be equal at $s=0$. We would therefore expect $|G'(M_\psi^2)|$ to be no larger than the Frascati result[8] $|G((2.1\text{ GeV}^2)|$ $=0.27\pm0.04$ mentioned earlier. For this value we obtain $\Gamma(\psi\to e^+e^-)$, $\Gamma(\psi'\to e^+e^-)\lesssim 0.07$ keV, which is small by two orders of magnitude. If ψ or ψ' are orbital excitations[5] with $l\geq 2$, the predicted widths should become even smaller. Of course if for some reason $|G'(M_\psi^2)|$ were larger than our estimate by a factor of 10, results consistent with experiment could be derived. But it seems to us that this is an unlikely possibility and we therefore conclude that ψ and ψ' probably are not composed of $\overline{\Omega}^+$ and Ω^- nor any other $\overline{B}B$ combination (by a direct extension of our argument).

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