where $\delta \to K\bar{K}$ is assumed, is given by C. Dionisi *et al.*, Nucl. Phys. B169, 1 (1980).

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Have We Seen Our First Glueball?

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Evidence is presented that there are at least two states near 1.4 GeV which decay to $\bar{K}K\pi$. One is $E(1420)$, an axial vector, and the other is $G(1440)$, probably a pseudoscalar. The pseudoscalar is likely to be a glueball.

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The discovery of gluonium states would be dramatic confirmation of quantum chromodynamics (QCD). But their identification is an extremely challenging problem, because of the usual experimental difficulties of meson spectroscopy in the likely 1–2-GeV region, compounded by our inability to predict reliably the dynamical properties which might provide useful experimental signatures.[1] Lacking a reliable, detailed understanding of the gluonium spectrum and dynamics, the experimental search can rely only on the most generic features of the theoretical picture. One such property is that gluonium states do not fit into $\bar{q}q$ multiplets. Another is that their production is enhanced in channels which are rich in gluons.

Since the radiative decays $\psi \to \gamma X$ are dominated in perturbation theory[2] by $\psi \to \gamma + 2$ gluons, they provide an excellent channel for the search. The prominent appearance of a $\bar{K}K\pi$ enhancement at 1440 MeV is therefore very striking.[3-5] It is produced at a rate comparable to the other most prominent hadron in the channel, the $\eta'(958)$. In contrast, the $E(1420)$, with which we are tempted to identify the 1440, has been an obscure, difficult state to study in hadronic reactions. This contrast provides *prima facia* grounds for examining the 1440 as a gluonium candidate.

A first examination is not encouraging. First observed in $\bar{p}p$ annihilation at rest,[6] $E(1420)$ has been seen in recent high-statistics pion scattering experiments[7,8] with a clear preference[7] for $J^P=1^+$. $E(1420)$ and $D(1285)$ are then excellent candidates to be the $I=0$ members of the $J^{PC}=1^{++}$ nonet. In addition, if the $\bar{K}K\pi$ enhancement in $\psi\to\gamma X$ has $J^P=1^+$, then it cannot couple to two massless gluons,[9] which further undermines the rationale for regarding it as a gluonium candidate.

There is, however, an indication that the state observed in $\psi\to\gamma X$ is not the state seen in pion scattering. In $\psi\to\gamma X$, $(80\pm20)\%$ of the $(\bar{K}K\pi)_{1.44}$ signal is reportedly[5] due to $\delta\pi\to\bar{K}K\pi$, whereas in pion scattering[7] K^*K dominates, $B(1.4\to K^*K)/B(1.4\to K^*K+\delta\pi\to\bar{K}K\pi)=0.86\pm0.14$.

Motivated by these considerations, I have systematically reviewed the experimental literature on the $E(1420)$ meson. I have reached the following conclusions:

(1) There are at least two $I^C=0^+$ states near 1.4 GeV which decay to $\bar{K}K\pi$. The $E(1420)$ has $J^P=1^+$ and decays primarily to K^*K. The other state, which I call $G(1440)$,[10] decays to $\bar{K}K\pi$ and to $\eta\pi\pi$; both these decays have substantial $\delta\pi$ components.

(2) The $(\bar{K}K\pi)_{1.4}$ signals in $\psi\to\gamma X$ and in $\bar{p}p$ annihilation at rest are predominantly $G(1440)$, while those in π scattering (all with $p_{\rm lab}>4$ GeV) are predominantly $E(1420)$. In $\bar{p}p$ annihilation above threshold ($p_{\rm lab}>0.7$ GeV) there is substantial production of G and E.

(3) $E(1420)$ is the dominantly $\bar{s}s$ member of an ideally mixed nonet containing the A_1, D, E, and Q (appropriately mixed[11]).

(4) Although the spin and parity of G are not as clearly determined as that of E, all available evidence favors $J^P(G)=0^-$.

(5) $G(1440)$ is unlikely to be a $\bar{q}q$ meson. The most likely possibility is that it is predominantly a glueball, perhaps with an appreciable $\bar{q}q$ component.

These conclusions are based on an examination of the experimental literature, which is briefly summarized below and will be presented in detail elsewhere. The evidence for two states is based on four categories of experimental results:

(A) *$\eta\pi\pi$ decay.*—The $\bar{K}K\pi$ signal is seen in all processes [π (Refs. 7, 8, 12, and 13) and $\bar{p}$ (Refs. 6 and 14–19) scattering and $\psi\to\gamma X$ (Refs. 3–5)] but the $\eta\pi\pi$ signal is seen only in $\bar{p}p$ annihilation[20] and $\psi\to\gamma X$,[4,5] *not* in π scattering.[12,21] This is not an experimental artifact: The πp experiments which do not see an $(\eta\pi\pi)_{1.4}$ signal are exceedingly sensitive, far more sensitive than the $\bar{p}$ and $\psi\to\gamma X$ measurements which do. For instance, the most sensitive πp experiment[21] observes 3000 $\eta'\to\eta\pi^+\pi^-$ decays and no significant $(\eta\pi\pi)_{1.4}$ signal, while a $\bar{p}$ experiment[20] with only ~ 100 observed $\eta'\to\eta\pi^+\pi^-$ decays reports a signal in $\bar{p}p\to\pi^+\pi^-(\eta\pi^+\pi^-)_{1.4}$ with $\sigma=275\pm50$ μb. There is also an indication[4,5] of a signal in $\psi\to\gamma(\eta\pi^+\pi^-)_{1.4}$, largely in $\psi\to\gamma\delta\pi\to\gamma\eta\pi\pi$; the number of events is comparable to the 10–15 events observed for $\psi\to\gamma\eta'\to\gamma\eta\pi^+\pi^-$.

(B) *Dalitz plots.*—Because of kinematical overlaps the $\delta\pi$ and K^*K branching ratios cannot simply be extracted from $\bar{K}K$ and $K\pi$ mass histograms. An overall fit to the $\bar{K}K\pi$ Dalitz plot is essential. The Dalitz plot of Scharre *et al.*[3] is enhanced toward the δ region. There are events in the K^* region but they neither form uniform hands (as they would if the 1.44 had spin 1) nor bands which grow toward the boundaries from central nodes (as for spin 0). An analysis of these features yielded the result[5] that $(80\pm20)\%$ of the $\bar{K}K\pi$ signal is due to $\delta\pi$. In contrast, the Dalitz plot obtained from π scattering at $p_{\rm lab}=4$ GeV is dominated by uniform (except at the point of overlap) K^* bands, with the K^*K signal at least six times larger than $\delta\pi\to\bar{K}K\pi$.[7] The only other published Dalitz plot, from $\bar{p}p$ annihilation at rest,[19] resembles the plot of Scharre *et al.*[3]: a $\bar{K}K$ threshold enhancement and no complete K^* bands (no overall fit was made in this case).[22]

(C) *J^P determinations.*—The analysis[7,23] of the Dalitz plot obtained from πp scattering gives strong evidence for $J^P=1^+$. The high-statistics experiment[6] which first discovered the E/G in $\bar{p}p$ annihilation at rest favored $J^P=0^-$, based on analyses of the $\bar{K}K\pi$ Dalitz plot[24] and also on the angular distribution of δ with respect to $\pi^0\pi^0$ in $\bar{p}p\to\pi^0\pi^0(1.4)\to\pi^0\pi^0(\delta\pi)$. The latter evidence is very convincing if $J(\pi^0\pi^0)=0$ as assumed; this is very likely since $J=2$ is the next possibility and Q is only 170 MeV. Results from $\bar{p}p$ annihilation above threshold are inconclusive,[16–18] favoring $J^P=0^-$ and/or 1^+.

(D) *Production of $D(1280)$.*—A long-standing puzzle in the history of $E(1420)$ is the absence of a $D(1280)$ signal in $\bar{p}p$ annihilation at rest,[6,19] although D is typically produced (roughly five times[25,26]) more copiously than E in πp scattering[7,12,13] and in $\bar{p}p$ annihilation[14–17] with $p_{\rm lab}\geq0.7$ GeV. The greater cross section for D is consistent with the hypothesis that D and E are the nearly ideally mixed isoscalars of the $J^{PC}=1^{++}$ nonet, also supported by the small branching ratio[26] for $D \to \bar{K}K\pi$ (much of which may be $D \to \delta\pi \to \bar{K}K\pi$ and therefore not attributable to an $\bar{s}s$ component in D) and by the recent definitive high statistics, nondiffractive observation[27] of the A_1 with $m_{A_1} = m_D$ as expected for ideal mixing. The striking absence of a D signal in $\bar{p}p$ annihilation at rest[6,19] then suggests that the $(\bar{K}K\pi)_{1.4}$ signal which is observed there is not the E. Similarly there is no evidence for $\psi \to \gamma D$, though $\psi \to \gamma X$ is dominated by X in the SU(3) singlet,[28] so that with ideal mixing we expect $\Gamma(\psi \to \gamma D) \cong 2\Gamma(\psi \to \gamma E)$. This is just at the edge of being excluded by the upper bound[3] on $\psi \to \gamma(\bar{K}K\pi)_{1.28}$, but a still stronger constraint follows from the absence[4] of a D signal in $\psi \to \gamma\eta\pi\pi$ [since[26] $B(D \to \eta\pi\pi) = 0.5$].

This entire pattern of observations is compatible with hypotheses (1)–(3). In pion scattering, the absence of $(\eta\pi\pi)_{1.4}$, the dominance of K^*K in $(\bar{K}K\pi)_{1.4}$, the result $J^P = 1^+$, and the large D signal all indicate E production. But in $\psi \to \gamma X$, the indication of $(\eta\pi\pi)_{1.4}$ with a sizeable $\delta\pi$ component, the dominance of $\delta\pi$ in $(\bar{K}K\pi)_{1.4}$, and the absence of D (especially in $\eta\pi\pi$) all suggest G production. In $\bar{p}p$ annihilation at rest[29] the preference for $J^P = 0^-$, the striking absence of D, and the evidence for a sizable $\delta\pi \to \bar{K}K\pi$ component again suggest G production. Finally, in $\bar{p}p$ annihilation with $p_{\rm lab} \geq 0.7$ GeV, the presence of both D and $(\eta\pi\pi)_{1.4}$ and the inconclusive nature of the J^P analyses suggest that both E and G are substantially produced.

What is the spin of G? The most direct evidence is the result $J^P = 0^-$ in $\bar{p}p$ annihilation at rest.[6] This is also consistent with the following considerations:

(a) In lowest order QCD, the principal partial waves in $\psi \to \gamma X$ are[30] $J^P(X) = 0^-, 0^+, 2^+$. G has unnatural J^P since $G \to \delta\pi$, so only 0^- is possible.

(b) In $\bar{p}p$ annihilation at rest into $X\pi\pi$ with $I^C(X) = 0^+$ the final state may be pure s wave only if $J^P(X) = 0^-$. For $m_X = 1.42$ or 1.28 GeV, Q is very small and the relative inhibition of the p wave is appreciable. The assignments $J^P(G) = 0^-$ and $J^P(E) = J^P(D) = 1^+$ could then provide a kinematical explanation for the suppression of D and E.

(c) The $\delta\pi$ decay is favored if $J^P(G) = 0^-$ since it is then the only open two-body, s-wave channel (like K^*K for E if $J^P = 1^+$ for E).[31]

(d) If $J^P = 0^-$ for G, helicity conservation enhances the amplitude for $G \to \bar{s}s$ over $G \to \bar{u}u + \bar{d}d$. The $\bar{s}s$ quarks materialize as $\bar{K}K\pi$ in an s wave, which some fraction of the time appears as $\delta\pi$ by final-state interaction. This enhances the $\delta\pi$ yield and the nonresonant $\bar{K}K\pi$ final state.

If we suppose G is distinct from E and $J^P = 0^-$ for G, how can we decide if G is a glueball? If it is not a glueball, then it is most likely to be a radially excited $\bar{q}q$ meson. There are already two excellent candidates for an excited $J^{PC} = 0^{-+}$ nonet, $K'(1400)$ and $\zeta(1275)$ [the ζ was named in honor of the zero-gradient synchrotron at Brookhaven National Laboratory—it is called $\eta(1275)$ in the data card listings of Ref. 26]. The ζ was observed in a partial-wave analysis of $\pi^- p \to \zeta n \to \eta\pi^+\pi^- n$, in the very sensitive πp experiment[21] which did not see a significant $\eta\pi\pi$ signal near 1.4 GeV. We might hypothesize that G and ζ are the two isoscalars in the nonet.

However, this hypothesis is not tenable, regardless of the SU(3) mixing angle between G and ζ. The crucial facts have been presented above: (a) In πp scattering,[21] $\zeta \to \eta\pi\pi$ is strongly present but there is not significant signal for $G \to \eta\pi\pi$ while (b) in $\psi \to \gamma X$, G is strongly present in $\bar{K}K\pi$ and indicated in $\eta\pi\pi$ but there is no indication of ζ in $\bar{K}K\pi$, nor, most to the point, in $\eta\pi\pi$.[3,4] To explain $\Gamma(\psi \to \gamma G) \gg \Gamma(\psi \to \gamma\zeta)$ we need to assume[28] singlet-octet mixing, similar to that of η and η'. But then we expect

$$\frac{\sigma(\pi^- p \to nG)}{\sigma(\pi^- p \to n\zeta)} \cong \frac{\sigma(\pi^- p \to n\eta')}{\sigma(\pi^- p \to n\eta)},$$

which is badly violated. At $p_{\rm lab} = 8$ GeV the right side is $\sim \frac{1}{2}$ while the left side must be much smaller.[32] To accommodate a small value for the left-hand side we would need to invoke ideal mixing with $G \cong \bar{s}s$. But then we would expect[28] $\Gamma(\psi \to \gamma\zeta) \cong 2\Gamma(\psi \to \gamma G)$ and, even worse, $\Gamma(\psi \to \gamma\zeta \to \gamma\eta\pi\pi) \gg \Gamma(\psi \to \gamma G \to \gamma\eta\pi\pi)$, since $\eta\pi\pi$ would be an Okubo-Iizuka-Zweig–suppressed decay of G. G is unlikely to be the $I = 0$ partner of ζ.

There is a variety of additional information bearing on whether G is a $\bar{q}q$ state. The rates for $G \to \gamma\gamma$ and $G \to \rho\gamma$ would be rather large if G were a $\bar{q}q$ meson.[33] And, of course, if $\zeta(1275)$ were confirmed and an acceptable $I = 0$ partner found for it, that would exclude G from the nonet. There is a hint of a pseudoscalar near 1.4 GeV, seen in πp scattering.[21] Since the peak is below 1.4 GeV and appears not at all in $\delta\pi \to \eta\pi\pi$ but only in $\epsilon\eta$ ("ϵ" here denotes a parametrization of the $I = J = 0$ dipion phase shift), it is unlikely to be the G. The small magnitude of the signal would be explained if it were the predominantly $\bar{s}s$ member of the nonet. Like ζ it would appear much less strongly than G in $\psi \to \gamma X$, but it might be part of the $(\bar{K}K\pi)_{1.4}$ signal in $\bar{p}p$ annihilation at rest, where an anomalously large width was reported,[6] $\Gamma = 80 \pm 10$ MeV. This could be tested by comparing the $\eta\pi\pi$ and $\bar{K}K\pi$ decay channels. (It is clear from the proliferating $\bar{q}q$ spectrum alone, that the 1–2-GeV region may have many overlapping resonances.)

What about evidence that G *is* a glueball, as opposed to evidence that it is not a $\bar{q}q$ meson? If G were prominent in another, essentially different hard-gluon channel, the case would become quite convincing. Gluon jets are a good place to look. Just as the leading particle in a charmed-quark jet is a charmed hadron, glueballs may frequently appear among the leading particles of a gluon jet.[34,35] Quarkonium decays,[35] and low thrust e^+e^- annihilations in the continuum are good sources of gluon jets. It would be highly suggestive if there were again an enhanced G signal in this class of events.

In conclusion, it appears that there are at least two states in the 1.4-GeV region which decay to $\bar{K}K\pi$ and that one may be a glueball. These conclusions can be tested with increased statistics in $\psi \to \gamma X$; with higher-energy e^+e^- collisions at the Cornell Electron Storage Rings, the Deutsches Elektron-Synchrotron PETRA, the Stanford Linear Accelerator Center PEP, and the coming generation of Z factories; and with high-statistics $\bar{p}p$ studies at LEAR. A more complete presentation of this analysis and of the future experimental tests is in preparation.

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[22]Caution is required by the varying statistics and backgrounds of these three plots.

[23]The assignment $J^P = 1^+$ is also favored in Ref. 12.

[24]The Dalitz plot of Ref. 6 is unpublished and is not to be confused with the lower-statistics, published plot of Ref. 19. The fit of Ref. 6 yielded equal K^*K and $\delta\pi \to \bar{K}K\pi$ signals, unlike what is suggested by the appearance of the plot in Ref. 19.

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[32]From Ref. 21, the left-hand side is $\ll 1$ in the $\zeta, G \to \eta\pi\pi$ channel and using the Okubo-Iizuka-Zweig rule with the assumed mixing $B(G \to \eta\pi\pi) > B(\zeta \to \eta\pi\pi)$, which implies a large violation of the equation.

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