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The Meson Spectrum Between 1 and 2 GeV: Gluonic States and Other Exotica *

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Abstract

Present understanding of the meson spectrum is reviewed, with special attention on the search for gluonic states. Experimental progress has resulted in several paradoxes indicating states outside the $\bar{q}q$ spectrum of the nonrelativistic quark model.

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1. Introduction

During the last few years much effort has been devoted to the experimental study of the meson spectrum between 1 and 2 GeV, with impressive results. We have learned much more about the "ordinary" spectrum of $\bar{q}q$ mesons, increasing the number of complete nonets from just three only five years ago to eight today. Three additional nonets lack only one state for completion, so we are close to eleven. The results are interesting in themselves and they are crucial to enable us to recognize new physics, such as the gluonic states predicted by QCD. Perhaps the most important consequence of this data is a set of beautiful paradoxes pointing clearly to new physics beyond the $\bar{q}q$ spectrum of the nonrelativistic quark model. Clearly drawn paradoxes have traditionally preceded advances in the history of physics. The purpose of this talk is to review the experimental findings that have exposed the present paradoxes in the meson spectrum.

In section 2, I discuss "why" and "how" — why so much effort is focused on the gluonic states and how we expect to find them. Section 3 is a brief review of the status of the ordinary spectrum, including a little "Sound and Light" show borrowed from a beautiful talk by W. Dunwoodie[1] illustrating the value of high statistics data. Section 4 is the heart of the talk, reviewing four puzzles that have emerged clearly from the experimental data:

- $J^C = 1^+$
- $\eta/\iota(1460)$ *et al.*
- $f_2/\theta(1720)$
- Scalars

Section 5 concludes with a brief discussion of theoretical interpretations and of the prospects to solve these puzzles in the coming decade.

2. Why and How

First, why? Who cares? The answer is obvious to anyone familiar with the history of twentieth century physics: the spectrum is the traditional test of any quantum theory. Besides confinement, the principal qualitative feature of the QCD spectrum is the predicted existence of gluonic states. In leading approximation these are the purely gluonic states called glueballs and the mixed $\bar{q}qg$ states I call meiktons (pronounced *maketon*, from the classical Greek for a mixed thing).

The evidence for QCD is very strong though largely circumstantial. For experimentally attainable short distance scales, $L \ll 1$ fm, the running coupling constant $\alpha_S(L)$ is typically not small enough for truly precision tests. For large distances, $L \geq 1$ fm, the interaction is strong, and rich, unexpected dynamics may occur. This is the domain that controls the physics of the light quark and gluon spectrum. Since gluonic states reflect the most unique feature of QCD, they have the greatest potential to surprise us.

The search for gluonic states began seriously only ten years ago. The difficulties are formidable. On the theoretical side we face the familiar intractable problems of strong-coupling quantum field theory. On the experimental side there is a very complex spectrum of overlapping states above 1 GeV that is not easily resolved.

Though there are still no definitive theoretical results, we may be able to learn from today's crude models, provided they are used judiciously, without losing sight of their limitations. The MIT bag[2] is a model of confinement with the cosiderable virtue of being relativistic (light-quark mesons *are* relativistic bound states). But excited meson states have not been successfully treated (see section 5). Since it describes the ground state mesons and baryons reasonably well, the bag model may also give a reasonably good description of the ground state glueballs and meiktons; in that case, unless the gluon self energy is unexpectedly large, the lightest glueballs and meiktons lie below 2 GeV.[3,4)]

The flux tube model is a nonrelativistic, potential model of confinement, applicable to the ground state and excited meson spectrum.[5)] Predictions based on the flux tube model suggest that the scalar glueball may be the *only* gluonic state below 2 GeV,[6)] contrary to the bag model. Neither the bag nor flux tube models can provide a definitive, quantitative description of the QCD spectrum. Unless there is a real theoretical breakthrough, the only hope rests in the lattice simulations. With increased computing power they could produce reliable calculations of the spectrum during the coming decade.

For now we must rely on the safest, qualitative features of the theory:

- gluonic states are "extra"; in practice this requires thorough understanding of the "ordinary" spectrum.
- some gluonic states have exotic quantum numbers, *e.g.*, $J^{PC} = 1^{-+}$, which do not appear in the nonrelativistic quark model.
- unusual production or decay characteristics; this must be applied with the greatest caution, since it involves guesses about dynamics that could surprise us.

An example of unusual production marked the beginning of the experimental search for gluonic states: the discovery of a surprisingly large "E" signal in $\psi \to \gamma \overline{K} K \pi$ by the Mark II collaboration.[7)] $\psi \to \gamma X$ occurs in QCD perturbation theory in leading order via[8)] $\psi \to \gamma g g$, in reasonable agreement with the measured inclusive decay rate[9)]. Since the two gluons are in a net color singlet, it is an ideal glueball production channel. It was the last place to expect a large signal for the E meson, interpreted as a $J^{PC} = 1^{++}$ $\bar{s}s$ meson, since the Landau–Yang theorem implies that two on-shell gluons (corresponding to the absorptive part of the perturbative amplitude) cannot couple to a spin 1 state. For this and other reasons, having also to do with the original "E" signal in $\bar{p}p$ annihilation, it was quickly suggested[10)] that the observed resonance was not the axial-vector E(1420) but rather a pseudoscalar, $J^{PC} = 0^{-+}$, and perhaps a glueball. The first hypothesis was soon verified by the Crystal Ball collaboration,[11)] which used the name *iota* for the resonance. The second has been the subject of intense study and discussion ever since. I will describe some interesting new experimental results on $\psi \to \iota\gamma$ in section 4.

An example of an unusual decay characteristic follows from the electrical neutrality of gluons, implying that glueball decays to two photons are small. The stickiness[12)] S_X of a state X combines this unusual decay property with unusual production in $\psi \to \gamma X$, by considering the ratio

$$S_X = \frac{\Gamma(\psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)} \; \frac{PS(X \to \gamma\gamma)}{PS(\psi \to \gamma X)} \tag{2.1}$$

where PS is the phase space factor. It has the experimental advantage that unknown branching ratios (e.g., BR($\iota \to \overline{K} K \pi$)) cancel in the ratio, and the theoretical advantage that unknown dynamical properties of the gluon and photon matrix elements *tend* to cancel. Naively we expect glueballs to be very sticky. From perturbation theory we expect[12a)] $J^{PC} = 0^{-+}, 0^{++}$, and 2^{++} glueballs to be prominent in $\psi \to \gamma G$.

It has been suggested that glueballs might be favored in $\overline{p}p$ annihilation, in central production, and in Zweig-rule-violating reactions[13] and that they may decay to pairs of η and/or η' mesons,[14] whereas production of ordinary mesons is favored in peripheral pion and kaon scattering. These are plausible suggestions. However radiative ψ decay is unique among these in its accessibility to perturbative QCD, allowing semiquantitative control that is lacking in the other processes.

It is clear from this brief description of the theoretical tools that leadership today belongs to experiment. As discussed in the next section, experiments with ever greater statistics will be essential for further progress.

3. "Ordinary" Meson Spectrum

The efforts of many impressive experiments have yielded big gains in our understanding of the meson spectrum during the previous decade. Even higher statistics experiments will be needed in the future. As W. Dunwoodie showed at the SLAC Tau-Charm facility workshop [1], many mass histograms with little or no evident structure may in fact be dominated by overlapping resonances that can only be resolved by partial wave amplitude analysis. Since a general amplitude analysis has many free parameters and because the nonleading (lower spin) states are especially hard to resolve, very high statistics is needed. This is one of the principal lessons to be learned from the LASS experiment, which logged 140 million Kp scattering triggers. For instance, that level of statistics enabled LASS to resolve six resonances in the $\overline{K}^0\pi^+\pi^-$ channel below 2.3 GeV, where only two bumps are visible in the mass histogram. In fact 2/3 of the events in the histogram are attributed to resonances in the LASS analysis, though to the eye the histogram appears to be predominantly nonresonant.

To maintain sanity in the face of the complexity of the meson spectrum and the ambiguities of the data, it is useful to look at the LASS data in the $K\pi$ channel.[15] The trajectory of leading resonances falls on a beautiful linear Regge trajectory: $1^-(892)$, $2^+(1430)$, $3^-(1780)$, $4^+(2075)$, and $5^-(2380)$. These are presumably the highest angular momentum states of the $L = 0,1,2,3,4$ spin triplet ($S = 1$) $\overline{q}q$ states in the nonrelativistic quark model classification. In addition the following six nonleading states are seen in the $K\pi$ channel:

- Three vector states at 1400, 1700 and 2050 MeV (the last requiring confirmation). The 1400 may be the first radial excitation 2^3S_1 of the $K^*(892)$, the 1700 may be the 1^3D_1 orbital excitation, and the 2050 could be the second radial excitation, 3^3S_1.
- Two scalars at 1350 and 1950 MeV, the former the quark model p-wave spin-triplet, 1^3P_0, and the latter its radial excitation, i.e., $L = 1$ and $N = 2$.
- A tensor meson at 1970 MeV would be the radial excitation of the $K_2^*(1430)$, $L = 1$ and $N = 2$, i.e., 2^3P_2.

If peripheral scattering favors production of $\overline{q}q$ mesons, at the LASS level of statistics we can also learn from the absence of particular signals. Two notable examples discussed below are the E(1420) and the $\theta(1720)$.

A personal, nonauthoritative summary of the status of the $\overline{q}q$ spectrum is shown in figure 1 (see also Montanet's review[16] at HADRON '89). During the 1980's the number of complete nonets has gone from four to three (when the 1^{++} nonet became "disestablished" with the loss of the f_1/E as a plausible member) and now to eight. All six of the $L = 0$ and $L = 1$ nonets are filled, as is the leading 3^{--} $L = 2$ nonet and the $N = 2$ radially excited pseudoscalar nonet. Two excited vector meson nonets and the leading ($L = 3$) 4^{++} nonet lack only a single state for completion, which would bring the total to 11.

With these results we are at last really getting somewhere! In particular we can look for the states that do not fit in figure 1. I will next discuss four beautiful paradoxes that have emerged from this effort.

4. Four Paradoxes

Real progress occurs when nature gives us a well-defined puzzle, whose solution is sure to teach us something new. We are fortunate to have arrived at that situation in the study of the meson spectrum. I have selected four examples to review here.

#1 The $J^C = 1^+$ Channel: LASS[17)] has confirmed the $f_1(1530)$ but does not see the $f_1/E(1420)$. This suggests a 1^{++} nonet consisting of the $a_1(1260)$, $K_1(1270/1420)$, $f_1/D(1285)$ and $f_1(1530)$. The WA76 experiment[18)] in a partial wave analysis of $\overline{K}K\pi$ produced centrally in pp scattering, verifies the existence of a 1^{++} E(1420), decaying predominantly to KK^*. In addition, unambiguous evidence for a $J^C = 1^+$ $\overline{K}K\pi$ state at 1420 was found by the TPC in tagged two photon scattering, confirmed by four other experiments.[19)]. No signal is not seen in untagged two photon scattering (see discussion of iota below) but a sizeable signal is seen in tagged events, in which one of the two photons is significantly off-shell. By the Landau-Yang theorem, supported by quantitative analysis of the q^2 dependence, this is good evidence for a spin 1 state, hence $J^C = 1^+$. The mass and width are consistent with the classic E(1420). We therefore have incontrovertible evidence for too many $J^C = 1^+$ states.

I will refer to the state seen in $\gamma\gamma^*$ scattering as X(1420) since its parity is not yet measured. Besides its existence, the X has other puzzling properties. First, its sizeable two-photon coupling suggests an isoscalar with large u quark content ($\overline{u}u + \overline{d}d$), but the upper limit on its decay to $\eta\pi\pi$ (less than 60% of $\overline{K}K\pi$) suggests a large $\overline{s}s$ content. A similar puzzle is observed by the Mark III and DM2 in hadronic ψ decay to ω or ϕ plus $\overline{K}K\pi$: an ω"E" signal is seen, which is six times larger than the 90% upper limit on ϕ"E", also suggesting predominant $\overline{u}u + \overline{d}d$ content. Both signals share a common puzzle: production properties like $\overline{u}u + \overline{d}d$ but decays like $\overline{s}s$.

This puzzle could have a purely kinematical solution [20]. If the X were a negative parity isoscalar its decay to $\eta\pi\pi$ would be kinematically suppressed, since it would require either four units of angular momentum if the dipion is in an L eigenstate, or, if an $\eta\pi$ pair is in an L eigenstate, it would require the existence of an exotic $I = 1$, $J^{PC} = 1^{-+}$ resonance/enhancement below 1280 MeV (which decidedly does not exist).

Since there are two independent amplitudes a model independent parity determination has not been possible with the available statistics. The data fits the distribution predicted for a 1^{++} state in the nonrelativistic quark model[21)] but 1^{-+} is not excluded[19)].

There are two interesting developments concerning the negative-parity hypothesis. First, the combined Dalitz plot from four experiments shows clear KK^* dominance but lacks constructive interference where the K^* bands cross,[22)] contrary to isoscalar 1^{++} but consistent with isovector 1^{++} or isoscalar 1^{-+}. Second in a partial wave analysis by DM2 of radiative ψ decay to $\overline{K}K\pi$, presented at HADRON 89[23)], the third or fourth largest amplitude is the 1^{-+} KK^*, showing an enhancement of perhaps three or four sigma with mass and width compatible with X(1420). (For reasons I do not understand, the authors offer no comment on this possible exotic signal and discard it in their final four-channel fit to the iota region, retaining instead the much smaller 1^{++} $\delta\pi$ p-wave.)

GAMS[24] has reported a resonance in the $\eta\pi$ p-wave, the M(1405) with a width of about 200 MeV. The observed forward-backward decay asymmetry in the Gottfried-Jackson frame is strong evidence since it requires odd L, hence $J^{PC} = 1^{-+}, 3^{-+}, \ldots$ The M has not been confirmed in any other reaction. GAMS[25] has presented a 95% upper limit on the ratio of the $\eta'\pi$ decay relative to $\eta\pi$ of 0.8. M(1405) could be an isovector partner to an isoscalar 1^{-+} X(1420), interpreted as members of a $\bar{q}qg$ meikton nonet. However this interpretation could not be sustained if the ratio of $\eta'\pi$ decay relative to $\eta\pi$ is found to be much less than one, as predicted in a molecular interpretation[26].

#2 η/ι (1460) et al.

Although the spectrum of $I = 0$, $J^{PC} = 0^{-+}$ states above 1200 GeV remains somewhat confused, it is clear that there are too many states for the nonrelativistic quark model.

The $\eta(1290)$, first seen in $\pi p \to \eta\pi\pi n$ at the ZGS,[27] was confirmed in the same channel at KEK[28] and in $\pi p \to \overline{K}K\pi n$ at BNL.[29] Its width is about ~ 30 MeV. It does not appear strongly if at all in $\psi \to \gamma\eta\pi\pi$; a broad enhancement at ~ 1300 MeV is dominantly 1^{++},[30] though it is much broader than the $f_1(1285)$.

A hint of $\eta(1410)$ was first seen at the ZGS[27] but the first definite observation was at KEK, originally[28] in $\pi p \to \eta\pi\pi n$ and later also[31] in $\pi p \to \overline{K}K\pi n$. In both KEK experiments the width is rather narrow, $\Gamma \sim 35$ MeV. The Mark III collaboration recently reported[30] a partial wave analysis in $\psi \to \gamma\eta\pi\pi$ which also confirms the $\eta(1410)$, finding $M = 1401 \pm 6$ MeV , $\Gamma = 46 \pm 14$, and $B(\psi \to \gamma\eta(1410))B(\eta(1410) \to a_0\pi)B(a_0 \to \eta\pi) = (3.30 \pm 1.26 \pm 0.58) \cdot 10^{-4}$. The latter rate is small compared to $\psi \to \gamma\iota$ discussed below. The ASTERIX collaboration also reports an observation[32] in $\bar{p}p \to (\overline{K}K\pi)\pi\pi$ (H_2 gas target) compatible with $\eta(1410)$, i.e., $M = 1413 \pm 8$ and $\Gamma = 62 \pm 16$ MeV. In all the above experiments the dominant decay is reported to be $\eta(1410) \to a_0(980)\pi$. The near-unanimity is spoiled by the high statistics E 771 experiment at BNL which in $\pi p \to \overline{K}K\pi n$ reports[29] two resonant 0^{-+} amplitudes in the region of the $\eta(1410)$, one in $a_0\pi$ with $\Gamma \sim 75$ MeV and a second in K^*K with a width of ~ 135 MeV.

Notwithstanding the evidence from E771 of possible additional structure, it seems that $\eta(1290)$ and $\eta(1410)$ can both be regarded as established, and I assigned them to the radially excited 0^{-+} nonet in figure 1. However the rather stringent upper limits[33] on their production in $\gamma\gamma \to \eta\pi\pi$ are much less than would naively be expected, and I have speculated elsewhere on another interpretation.[34] The larger rate for $\psi \to \gamma\eta(1410)$ than $\eta(1290)$ suggests singlet–octet mixing, like $\eta'(958)$ and $\eta(549)$.

The "classic" iota is both heavier and broader than $\eta(1410)$ and is striking for the very large signal, $B(\psi \to \gamma\iota)B(\iota \to \overline{K}K\pi) \cong 5 \cdot 10^{-3}$. For instance, a Mark III fit of a few years ago[35] gave $M = 1461 \pm 5$, and $\Gamma = 101 \pm 10$. A resonance of very similar mass and width has been seen by E 769 at BNL in $\pi p \to K_S K_S \pi^0 n$.[36] This experiment differs from the BNL and KEK experiments discussed above, which saw only $\eta(1290)$ and $\eta(1410)$, by virtue of greater beam energy (21 GeV compared to 8 GeV) and the fact that $K_S K_S \pi^0$ is a pure $C = +$ channel. The event sample of E771 is however several times larger.

The "classic" iota is extremely sticky. Combining the branching ratio in radiative ψ decay with Feindt's compiled 95% upper limit,[22] $\Gamma(\iota \to \gamma\gamma)B(\iota \to \overline{K}K\pi) < 0.75$ keV, we find (with $S_\eta = 1$ as normalization),

$$S_\eta : S_{\eta'} : S_\iota = 1 : 4 :> 128 \tag{4.1}$$

It is also important to determine the stickiness of $\eta(1290)$ and $\eta(1410)$. With the above data from the Mark III[30] and using the 0.3 keV upper limit on $\eta_{1410} \to \gamma\gamma$ from the Crystal Ball, I find $S_{1410} > 16$ in the units of equation 4.1.

The classic iota may be developing schizophrenia. Amplitude analyses of Mark III[37] and DM2[23] data find three distinct components, although the two analyses are inconsistent as shown in table 1. The analysis of Mark III data could be interpreted as two or three states, since the 0^{-+} K^*K wave at 1476 MeV could be displaced upward by the effect of p-wave phase space and could therefore have the same origin as the lighter $a_0\pi$ s-wave. But no such effect can explain the DM2 results, also shown in the table, which surely require three states.

These analyses are interesting efforts. However unambiguous results will require larger data samples, as might be obtained from BEPC (Beijing Electron Positron Collider) now in operation or eventually at a tau-charm factory.

Two conclusions survive the iota's possible schizophrenia. First, there are too many states in the $I = 0$ $J^{PC} = 0^{-+}$ channel. Second, even the schizophrenic iota is very sticky. For instance, using the DM2 $0^{-+}a^0\pi$ s-wave or the combined 0^{-+} waves seen in the MARK III analysis, we would still have $S_\iota > 50$ in the units of equations (4.1).

#3 $f_2/\theta(1720)$

The $f_2/\theta(1720)$ was, like iota, discovered in radiative ψ decay. It decays predominantly to $\overline{K}K$, also to $\eta\eta$, and perhaps to $\pi\pi$ (no spin analysis yet in the $\pi\pi$ channel). Both the Crystal Ball, Mark III, and DM2 measure[38] $J = 2$. As always, it is much more difficult to determine whether there is also a $J = 0$ resonance beneath the θ — more about this in the next subsection. The branching ratio $B(\psi \to \gamma\theta) \gtrsim 1\frac{1}{2} \cdot 10^{-3}$ into channels *observed so far* is not very big, being of the same order as $\psi \to \gamma f_2(1270)$. The partial width $\Gamma_{\gamma\gamma}B(\overline{K}K) < 0.22$ keV at 95% CL implies a stickiness bound estimated by Feindt as[22]

$$S_f : S_{f'} : S_\theta \cong 1 : 13 : (> 28) \tag{4.2}$$

If $\theta \to \gamma\gamma$ is assumed to have the same dominant helicity-two amplitudes as $f_2(1270)$ and $f_2(1530)$, the upper limit on the $\gamma\gamma$ partial width improves to < 0.06 keV and the stickiness to > 100! (More recent[39] measurements of $\psi \to \gamma f'$ would roughly double $S_{f'}$ relative to equation 4.1.)

The θ has also been observed by WA76 in central production[40] with angular distributions best fit by $J = 2$ and by[41] MSS-ITEP in $\pi^- p \to K_S K_S n$. Significantly, it is not observed by LASS[17] in Kp scattering against Λ, though a large signal is seen for $f_2(1530)$. For this and other reasons it is a most implausible candidate for a $\overline{q}q$ radial excitation, 2^3P_2.

The θ would be a more plausible glueball if $B(\psi \to \gamma\theta)$ were a few times larger than the present lower limit, based on the three decay modes seen so far.. The LASS data provides a hint in this direction. If $Kp \to \theta\Lambda$ proceeds by K exchange, the amplitude for $Kp \to \theta\Lambda, \theta \to \overline{K}K$, is essentially $\overline{K}K \to \theta \to \overline{K}K$ with the incident $\overline{K}$ off-shell. Since $\Gamma_\theta = \sim 140$ MeV, if no other important decays occur $g_{\theta\overline{K}K}$ must be rather large, implying a contradiction with the LASS data. Longacre[42] has pursued this reasoning and finds in a coupled-channel fit that consistency requires $B(\theta \to \overline{K}K) < 0.2$, which in turn implies $B(\psi \to \gamma\theta) > 5 \cdot 10^{-3}$. The latter would be a very large rate, and would greatly increase the plausibility of θ as a glueball. To verify this hypothesis it is necessary to find the implied missing $\gtrsim 75\%$ of θ decays, which must be to 3 or 4 body final states and which may only be visible in a complete partial wave analysis. (For an alternate explanation see reference 43.)

I should also mention the three $2^{++}g_T$ states, seen[44)] in the OIZ violating channel $\pi p \rightarrow \phi\phi n$, but not [45)] in $\psi \rightarrow \gamma\phi\phi$ where a $J^P = 0^-$ structure is seen instead at ~ 2.22 GeV. The upper limit $B(\psi \rightarrow \gamma g_T)B(g_T \rightarrow \phi\phi) < 8.6 \cdot 10^{-5}$ is very strong, contrary to what is plausible for a tensor glueball. With limited statistics (~ 40 events), WA76 observes a $\phi\phi$ enhancement above threshold in central production,[46)] with decay angular distributions favoring 2^+ over 0^-.

Spin 2 quark model states, 1^3F_2 and 2^3P_2, are expected in the vicinity of the g_T states. They could explain the apparent OIZ violation in $\pi p \rightarrow \phi\phi n$ if they were not ideally mixed but contained substantial components of both $\bar{s}s$ and $\bar{u}u + \bar{d}d$.

#4 Scalars

This subject has a long history. Here I will focus on the most recent developments, which illustrate again how progress in the ordinary spectrum is inextricably tied to progress in the extraordinary.

There are many *qualitative* considerations suggesting that $f_0/S^*(975)$ and $a_0/\delta(980)$ should be interpreted as cryptoexotic $\bar{q}q\bar{s}s$ bag model states[47)] or as $\overline{K}K$ molecules[48)] in a nonrelativistic potential model. To confirm this assignment we must find the $I = 0$ and $I = 1$ states to complete the $^3P_0$ nonet. A candidate $a_0(1300)$ state was identified by Martin et al.[49)] in $\pi^- p \rightarrow K^- K_S p$ with $\Gamma \sim 250$ MeV. Its existence is now confirmed by GAMS[25)] in $\pi^- p \rightarrow \eta\pi^0 n$ with $M = 1322 \pm 30$ MeV though with a smaller width, $\Gamma = 130 \pm 30$ MeV. The $a_0(1300)$ agrees with the emerging evidence for small L-S splitting in the $^3P_{0,1,2}$ spin-triplet, as shown in table 2. Notice the remarkable degeneracy of the three $\bar{s}s$ states. In light of table 2 it seems even less likely that δ and S^* are $\bar{q}q$ states.

As in the cases of $\eta(1290)$ and $\eta(1410)$, there is a problem with the $\gamma\gamma$ partial widths of the $^3P_0$ candidates. The nonrelativistic quark model predicts the widths for scalar and tensor to be in the ratio $0^{++} : 2^{++} \sim 15 : 4(m_2/m_0)^n$ where $n = -\frac{1}{3}$ for a linear potential or $+3$ for a Coulomb potential. For the tensor mesons we have $\gamma\gamma$ widths of ~ 1 keV for $a_2(1320)$ and ~ 3 keV for $f_2(1270)$, which compare poorly with[19)] 0.19 keV for $f_0/S^*(975)$ and $0.19 - 0.29$ keV for $a_0/\delta(980)$, especially with the more plausible $n = -1/3$. However initial measurements of $\gamma\gamma \rightarrow \pi^+\pi^-$ seemed to leave little room for $f_0(1300)$ below the apparently dominant $f_2(1270)$, and Feindt[50)] finds using Crystal Ball data $\Gamma(a_0(1300) \rightarrow \gamma\gamma)B(a_0 \rightarrow \eta\pi) < 0.44$ keV at 95% CL. Though the nonrelativistic quark model prediction may be quantitatively unreliable, it would be surprising if the scalar widths are not at least as big as the tensors'. A recent coupled channel analysis of $\gamma\gamma \rightarrow f_0(1300) \rightarrow \pi^+\pi^-$ by Morgan and Pennington[51)] finds a larger range of values for the ratio: $\Gamma(f_0)/\Gamma(f_2) \sim 1.3 - 4$. Since these gentlemen have not to my knowledge taken any shifts, the Chanowitz Prize, announced at the 1988 Jerusalem Two Photon Workshop,[34] remains unclaimed: free lunch to the *experimenter* who proves (Chez Pannise, Berkeley) or disproves (Weizmann Institute cafeteria of the winner's [sic] choice) that ≥ 50 % of "f_2" $\rightarrow \gamma\gamma$ or "a_2" $\rightarrow \gamma\gamma$ are really $J = 0$.

I cannot leave the scalars without mentioning the $f_0/G(1590)$, discovered by GAMS[52)] decaying to $\eta\eta$ and $\eta\eta'$, as expected of a glueball decaying by the "discoloration" mechanism of Gershtein.[14)] The same reasoning suggests a sizeable rate for $\psi \rightarrow \gamma G$, so far unobserved. As for the $\gamma\gamma$ signals discussed above, it may be difficult to observe the scalar G below the tensor θ in their common $\eta\eta$ decay mode. W-G. Yan has argued that a sizeable G signal could be hiding in radiative ψ decays,[53)] and BEPC has developed the first all-neutral trigger for ψ decay studies to search in radiative ψ decay for the all-neutral modes that GAMS has studied so profitably in πp scattering. The Crystal Barrel detector has also developed an all-neutral trigger for use at LEAR.[54)]

5. Theoretical Alternatives and Experimental Prospects

The present crude theoretical models suggest two different pictures of the gluonic spectrum. The flux tube model — a nonrelativistic, potential model of confinement — views gluonic states as flux tube excitations. Estimates based on that picture suggest[6] that except for the scalar glueball, at $\sim 1\frac{1}{2}$ GeV, the spectrum of glueballs and meiktons begins at about 2 GeV.

In contrast the bag model treats gluonic states in complete analogy to quark states — in leading order, valence gluons are relativistic cavity modes of Maxwell's equations, just as valence quarks are cavity modes of the Dirac equation. Since the ground state quark cavity modes predict a spectrum roughly consistent with experiment, it is possible that the model also applies to the lowest gluonic modes. Then we would expect three glueballs $(0^{++}, 0^{-+}, 2^{++})$ and the ground- state meikton nonets $(0^{-+}, 1^{-+}, 1^{--}, 2^{-+})$ below 2 GeV.[4)] Gluonic states could however be heavier if the gluon self-energy is much bigger than expected, e.g., an order of magnitude larger than the quark self–energy.[55)]

Going beyond the fixed cavity approximation (which in practice has not been done), the bag model also has collective cavity excitations[56)], analogous to the flux tube excitations which in the flux tube model are identified with gluonic modes. In the bag model these cavity excitations are naively distinct from the Maxwellian cavity modes of the gluon field that populate the gluonic states below 2 GeV. Learned scholars have assured me that the distinction is not real but none have offered a proof. If the bag's collective cavity excitations are distinct from the "valence" Maxwellian gluon modes, than the flux tube estimate would apply to the former but not to the latter. To study the analogue of the gluon Maxwell modes in the flux tube model would require an ansatz more closely analogous to the treatment of quark constituents — i.e., constituent gluons connected by a flux tube. This approach has been tried by Cornwall and Soni[57], who find that the lightest glueballs may weigh less than 2 GeV.

In time lattice simulations should produce definitive results. Presently the most reliable results are for the scalar and tensor — the former at ~ 1.4 GeV and the latter 1.5 times heavier.[58)] No comparably reliable results are available for the pseudoscalar. It would be premature to draw any final conclusions from existing lattice studies. We must test the stability of the results against the next increases in L, a^{-1}, and N.[59)] And we also await the inclusion of quark loops which could produce large effects.

Eventually theory and experiment must come together to provide the answers. The present experimental evidence concerning $\iota(1460)$ and $\theta(1720)$ is suggestive but not decisive. To go forward experiments must approach and exceed the LASS level of statistics in all relevant experimental channels. This is a realistic goal at existing fixed target facilities, including LEAR and eventually TRIUMF II. It is a critical goal in J/ψ decay studies. The Beijing Election Positron Collider has come on line with $\sim 1.5 \cdot 10^6$ ψ's detected. Reproducible running at the ~ 60 nb/day rate already achieved on the best days would provide a sample of $\sim 25 \cdot 10^6$ ψ's in 200 days. Eventually running at design luminosity $(5 \cdot 10^{30} cm^{-2} s^{-1})$ would provide $\sim 10^8$ ψ's per 10^7 seconds. Even larger samples, requiring sophisticated on-line triggers and data acquisition, would be feasible at a Tau-Charm Factory, proposed for construction in Spain by mid-decade. The largest gap between desire and reality is in photon-photon scattering; high statistics studies could be performed at future B or Z factories operating at $10^{33}\ cm^{-2}s^{-1}$ or above.

By the end of the coming decade high statistics experiments and more powerful lattice simulations of QCD should answer the questions posed in the 1980's. Even better we hope to develop analytical tools for strongly-coupled field theories that will complement the numerical results obtained from the lattice computations.

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Table 1. Results of partial wave amplitude analyses of $\psi \to \gamma \overline{K} K \pi$ in the $\iota(1460)$ region.

		M	Γ	$BR^2(10^{-4})$
Mark III (J. Drinkard Ph.D. thesis)				
0^{-+}	$a_0\pi$	1424 ± 10	39 ± 7	$6.8 \pm 0.8 \pm 1.4$
	K^*K	1476 ± 11	77 ± 23	$11.0 \pm 1.7 \pm 2.2$
1^{++}	K^*K	1445 ± 7	90 ± 27	$9.5 \pm 1.2 \pm 1.9$
DM2 (G. Szklarz at HADRON 89)				
0^{-+}	K^*K	1421 ± 14	63 ± 18	$8.3 \pm 1.3 \pm 1.8$
	$a^0\pi$	1459 ± 5	75 ± 9	$18 \pm 2 \pm 3$
1^{++}	K^*K	1462 ± 20	129 ± 41	$7.6 \pm 1.5 \pm 2.1$

Table 2. Masses in MeV of $1^3P_{0,1,2}$ nonets taken from the 1990 review of particle properties,[58] updated with results from LASS[15,17] and GAMS.[25]

	$J=0$	$J=1$	$J=2$
I $=1$	1300	1260	1318
$=\frac{1}{2}$	1350-1430	1270/1402	1425
$=0$	1300-1400	1282	1274
$=0$	1530	1530	1525

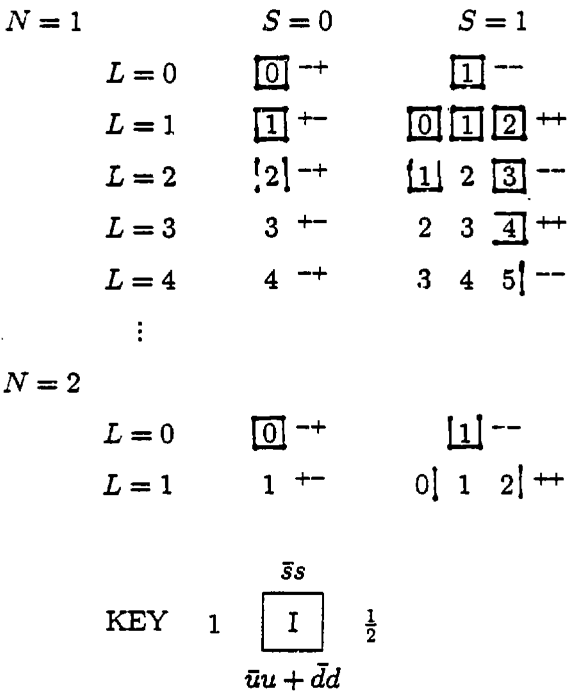

Figure 1. Non-authoritative summary of the meson spectrum.

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