EXOTIC HADRONS AND HADRON DYNAMICS AT A TAU-CHARM FACTORY

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Prospects for identifying hybrids and glueballs in ψ decays are summarized.

The success of the nonrelativistic quark model in 1969 was that in the meson spectrum, a single quark and antiquark ($q\bar{q}$) gave the following satisfactory features:

1) No meson exotics with charge 2, strangeness -2

2) States cannot exist with $J^{PC} = 0^{--}$; 0^{+-}, 1^{-+}, 2^{+-}, etc.

These unobserved and undesired states were known as exotics of the first and second kinds, respectively.

With the advent of color as the charge responsible for hadron binding $q^2\bar{q}^2$ states were predicted (which include type I exotics in the ground state) and following the advent of QCD, glueballs were predicted including type II exotics. The former have been argued to be broad and invisible; the latter above 2 GeV and awaiting detection.

Hybrid states, where both quarks and gluons are dynamical degrees of freedom, are predicted to contain type II exotics in their ground state. If we are going to search for these in ψ decays, we have to face the question: why haven't they been seen in 25 years of hadron physics?

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Possibly they don't exist! This is important if true, and we should push the limits on their production down. An order of magnitude improvement in statistics for ψ decay — a favorite glue hunting ground — could be significant. However, theorists should guide experimentalists by coming to a concensus on the level at which failure to see gluonic degrees of freedom would become worrying.

Possibly they exist and have already been seen. The iota, theta, $\zeta(2200)$ have all been claimed as examples. Bear in mind Dunwoodie's example[1] of how primitive hadroproduction data were in the iota region in the days when events per bin were similar in quantity to the present situation for ψ data. With modern data samples LASS have identified[1] a detailed J^P structure in several partial waves out of what previously appeared as a single bump. An order of magnitude increase in statistics for ψ decay will surely reveal how naive we are treating the theta, say, as a simple 2^+ state. Discussions in the parallel sessions[2] convince me that there is 0^+ present and make me wonder if the $\eta\eta$ and the $K\bar{K}$ final states are due to a single resonance state or not.

Gluonic states are probably lost in the crowd. The meson spectrum is very rich in the 1 to 2 GeV region and gluonic degrees of freedom are probably mixed into the wavefunctions of what we have deemed $q\bar{q}$ states. If so, there will be an excess of states relative to that predicted in the $q\bar{q}$ model. LASS, in particular, have begun to clarify the details of the latter, and we are now glimpsing the radial excitations. As insights into the spectroscopy of $q\bar{q}$ develop, so can the presence of "extra" states be accessed.

Another example where statistics can be seminal is if hybrids, for example, decay into excited $q\bar{q}$ states. Rather than constructing resonances from combinations in the final state π and K, one may have to work back along the chain to the "grandparents" or earlier; e.g., suppose that

$$\begin{tikzcd}[column sep=small] \mathscr{H}(1^{-+}) \rightarrow \pi + d(1285) \arrow[d, ""] \\ \pi\ a_0(980) \end{tikzcd}$$

The d(1285) is useful because it is narrow and fairly easy to reconstruct.

We may have missed them in detection, e.g., if they decay to neutrals, η and η'. GAMS[3] may be finding examples of previously unknown states decaying into neutrals. Have they discovered a rich lode?

Finally, we may have been prejudicing ourselves in favor of $q\bar{q}$ states by our concentration on hadron beams. The novel feature of the ψ is that the $c\bar{c}$ content is destroyed in the decay, and we access all degrees of freedom without prejudice.

To reinforce this importance of the ψ, recall that, independent of theoretical prejudice, experiment has revealed in the decays of ψ at least three states, iota, theta, and $\zeta(2200)$, that were not previously clearly identified. There is an untapped resource in that the χ states have decay channels that have hardly been studied. The $\chi \rightarrow \gamma G^{(-)}$ could access c = − glueballs, but the branching ratio will be $O(\alpha)$ — there is no enhancement due to the "replacement of a gluon by a photon" as in $\psi \rightarrow \gamma G^{(+)}$.

Weinstein, in the parallel sessions,[2] reported how $\psi \rightarrow \omega(\pi\pi)$ probes $\pi\pi$ dynamics. This relates to the important question of whether pairs of mesons form "molecular" bound states — analogs of the deuteron but in the meson sector.[4] (These are, in my opinion, "nonexotic", and their dynamics essentially different to $q^2\bar{q}^2$ systems, e.g., "the deuteron is not a six-quark bag"). This probes the final-state interaction dynamics between mesons in a rather clean way and may provide essential insights into their effects upon the $\Delta I = 1/2$ rule. As a test of these new dynamical ideas, we need the χ decays, e.g., the spectra in

$$\chi_{0,2} \rightarrow \pi\pi(\pi\pi);\ \pi\pi(K\bar{K});\ (\pi\pi)K\bar{K}.$$

The idea that mesons can form molecules in S-waves is beginning to clarify some of the confusions in spectroscopy. If the $K\bar{K}$ system forms 0^{++} bound states with $I = 0,1$, then does $\Delta\bar{\Delta}$ do likewise? If there is an $I=1$ $\Delta\bar{\Delta}$ bound state "molecule", then it could be accessed by triggering[5] on the ψ at the ψ' or ψ''

$$e^+e^- \rightarrow \psi'' \rightarrow \gamma(\Delta\bar{\Delta})_{0^+} \rightarrow \gamma(\psi\pi)$$

Other open questions are whether ΔK, πK form bound states or have strong enhancements above threshold. There is also the question whether KK^* form an S-wave enhancement in 1^{++}. There now appears to be an excess of 1^{++} states (or even more exotic, as Chanowitz has argued,[6] that there is 1^{-+} at 1450 MeV in $\gamma\gamma^*$). Is the old E(1420) a KK^* "unbound molecule", and, if so, how good is the evidence against an $I=1$ partner? (Note $\psi \rightarrow \gamma X$ accesses $I = 0$ dominantly, and so is not a good probe for this.)

No individual model can claim to be a good guide for glueball hunters. However, the common features in models of glueball spectroscopy[7] are that $c = +$ states are lightest (reinforcing one's optimism for $\psi \rightarrow \gamma G^{(+)}$), that 0^{++} are the lightest of these with 0^{-+}, 2^{++} next, and that 1^{+-} may be the lightest state with $c = -$. The absence of 0^{++} signals in the favored gluon channel $\psi \rightarrow \gamma X$ is tantalizing. Here again, an order of magnitude increase in statistics should be able to isolate the scalar partial wave.

Another general feature appears to be that if the glueball sector weights in at above 1.5 GeV, then it is hybrids that are likely to be the lightest gluonic states. An heuristic reason underlying this is that the $q\bar{q}$ sector "costs" 700 MeV before hyperfine splittings. If confined gluons cost too much energy, it may be more economical to form the hybrid $Gq\bar{q}$ than the glueball GG.

Thus, if glueballs are in $\psi \to \gamma X$ data, then it is likely that hybrids are also. The partial wave analysis is likely to be very rich. This will require careful analysis of high statistics data. There is no short cut.

Statistics and painstaking analysis; the former requires the machine, the latter the manpower. When utopia has arrived, how will we be able to disentangle the constitution of this overpopulation?

The quark model was established not by discovery of a single state (though some were more seminal than others), but by the pattern of J^{PC} running throughout the spectroscopy. Above 1 GeV, one finds[7]

$Q\bar{Q}$: $0^{++}2^{++}$, $(0^{-+})^*$
$Q^2\bar{Q}^2$: $0^{++}2^{++}$, 0^{-+} some 500 MeV higher (P-wave)
GG: $0^{++}2^{++}$, 0^{-+}
$(Gq\bar{q})$: $0^{-+}1^{-+}$; higher in mass are $0^{++}2^{++}$
KK molecule: 0^{++}

Notice that 0^{++} and 2^{++} tend to be associated in all models apart from the KK molecule (though the vector-vector sector of this dynamics has not yet been studied in any detail). The 0^{-+} sector also offers promise. A radial excitation is predicted in the $q\bar{q}$ sector just above 1 GeV, but another 0^{-+} in this region would be hard to explain in the $q^2\bar{q}^2$ sector, which requires a P-wave excitation above the 0^+2^+ S-wave states. The 0^- $q^2\bar{q}^2$ will presumably be not far from the 1^{--} including the exotic state accessible in $e^+e^- \to \phi\pi^\circ$ (hidden strangeness with I = 1). Thus, an excess of 0^{-+} states would indicate the need to go beyond quark degrees of freedom.

The presence of a 1^{-+} would be clearly beyond the nonrelativistic $q\bar{q}$ picture. Whether $q^2\bar{q}^2$ or hybrid would require further study (e.g., of decays where $\mathcal{H} \to \eta'\pi > \eta\pi$ is predicted).[8]

In the hybrid sector the most detailed studies have been made within the MIT bag model.[9,10] The mass splittings are agreed upon; mixings with $\bar{q}q$, $q^2\bar{q}^2$, and gg are included at $O(\alpha)$. In reality, these mixings may shift masses around by several MeV. So within the spirit of Refs. 10 and 11, I shift masses slightly and compare with several experimental states of varying degrees of validity. One might have the beginning of a hybrid spectroscopy here! More realistically, I suggest this as a scenario to be eliminated.

0^{-+}:	$\pi(1300)$	$\eta(1440)$	$K(1400)$	$\eta_s(1600)$
1^{-+}:	$\pi(1405) \rightarrow \eta\pi$	$\eta(1420) \rightarrow \gamma\gamma^*$	$K(1400)$	$\eta_s(1600)$
1^{--}:	$\rho/\omega(1400\text{-}1600?)$		$K^*(1430)$ (LASS)	$\phi(1700)$
2^{-+}:	$\pi(\sim 2\text{ GeV})$	$K(\sim 2\text{ GeV})$	$\eta(\sim 2\text{ GeV})$	

The 0^{-+} states are usually candidates for radials. The 1^{--} states could also be radials, but the $K^*(1430)$ of LASS is anomalously light compared to the ρ states even after Donnachie's recent study[12] hinting that the ρ may be lighter than hitherto thought. The 2^{-+} were discussed in the original paper of Chanowitz and Sharpe.[10] The 1^{-+} are interesting in view of the GAMS data;[3] see also Chanowitz's argument that $\gamma\gamma^* \rightarrow 1420$ does not rule out 1^{-+} for that state.[6]

Finally, I have some comments on the decay products of glueballs. There is a folklore that gluons being flavorless cause glueballs to have flavor-independent decays. This is not true if there is momentum in the quark-gluon vertex, scaled by a mass, as for example in magnetic interactions (e.g., the successful hyperfine splitting mass dependences). If one allows gluon-strange quark coupling to differ from that for the n,d flavors, there is still an "anti-selection rule" relating $\eta\eta$ and $K\bar{K}$ partial widths.[13]

In the ideal case where η and η' are 50:50 mixtures of $s\bar{s}$ and $n\bar{n}$, the $\eta\eta$

and $K\bar{K}$ final states in $G \to MM$ contain equal weights of strange and nonstrange, albeit distributed in different ways. These symmetry-breaking effects at the $g \to q\bar{q}$ vertices are common. Suppose one flavor is preferred, say $g \to s\bar{s}$. The $K\bar{K}$ feels this once in the amplitude. As the η require flavors to match ($s\bar{s}$ or $d\bar{d}$, not $d\bar{s}$, since that would be K), the $g \to s\bar{s}$ enhancement comes in squared but suppressed by two, due to the $g \to \Lambda\bar{\Lambda}$ contribution which is also present.

If R is the enhancement factor, then one has

$$K\bar{K}:2\eta\eta = R : \frac{1+R^2}{2}$$

where $R \geq 1$. (If $g \to s\bar{s}$ is suppressed, then the argument still goes through by letting R refer to $g \to n\bar{n}$ instead.) Thus, one has $2\eta\eta \geq K\bar{K}$ for a glueball. With more realistic η,η' mixing angles, one has

$$\frac{G \to 2\eta\eta}{G \to K\bar{K}} \geq 0.84.$$

Finding data consistent with this inequality do not confirm a glueball, but its violation would argue against a glueball — hence an "anti-selection rule".

The $f_2(1720)$ is consistent with this

$$\frac{2\ B[f_2 \to \eta\eta]}{B[f_2 \to K\bar{K}]} = \frac{36\ {}^{+6}_{-26}}{38\ {}^{+9}_{-19}}$$

However, if f_2 is more than one state, then the $K\bar{K}$ channel will not be glueball, and the $\eta\eta$ state will be glueball-favored.

The anti-selection rule may be relevant in connection with the $\zeta(2240)$ in that $K\bar{K}$ is seen whereas $\eta\eta$ is not yet seen. This is, at present, as much a question of statistics and efficiency as it is of physics. Here we have another example of the need for detecting neutrals.

To determine the internal constitution of mesons, I cannot overstress the utility of the photon as a probe. The electromagnetic interaction "proved the quark model". It revealed the flavor-spin correlations in the nucleon (magnetic moment ratios) and in $\gamma p \to N^*$. The leptonic widths of vector mesons reveal the quark charges within the meson; recall that the $b\bar{b}$ and $c\bar{c}$ nature of T and ψ were, in part, indicated by this. The $V \to p\gamma$ transitions probe the mixings of η and η'.

These ideas can be applied[14] to $\psi \to \gamma M \to \gamma[\gamma V]$. The ideal flavor content of $V = \rho$, ω, and ϕ yields

$$M(n\bar{n}) \to \gamma\rho,\ \gamma\omega$$

$$M(s\bar{s}) \to \gamma\phi.$$

If $M \equiv G$ or a flavor singlet, then there is a single peak for which

$$B[g \to \gamma\rho{:}\gamma\omega{:}\gamma\phi] = 9{:}1{:}2$$

However, if M has $I = 0(q\bar{q})$ or $\mathcal{K}(q\bar{q}g)$, then there are two bumps. The dominantly $n\bar{n}$ state $\to \gamma\rho{:}\gamma\omega$ in the ratio 9:1. The dominantly $s\bar{s}$ will be at a higher mass and $\to \gamma\phi$ at a rate 2/9 of the $n\bar{n}$ coupling to $\gamma\rho$.

Thus, by finding $\gamma\phi$ (and even $\gamma\omega$), one can disentangle whether the structure seen in $\gamma\rho$ is a single state or a member of a multiplet. In the latter, one can eventually determine the flavor content. This may be how we will determine the constitution of the iota.

We have here great opportunity. The 0^{++} sector is beginning to clarify, and with this the $q\bar{q}$ spectroscopy begins to fit in with the quark model expectations. We may soon be able to compare masses of candidates against the model to determine which states refuse to fit in. The excess of 1^{++} states, a possible proliferation of 0^{-+}, and a candidate exotic 1^{-+} pose clear questions which ψ decays can answer. To stop at the present level of statistics would be an irresponsible use of the last decade's investment. Do not forget Dunwoodie's lesson[1] on what we have to do in order to determine the full details of the spectroscopy. Proceeding in the naive belief that the theta is one and only one state with $J = 2^{++}$ is likely to distort model building. The need for an order of magnitude increase in data is manifest.

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