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Gluonic Excitations' Millennial Finale

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We provide an overview of theoretical developments on hybrid mesons and glueballs in the last year at this turn of the millenium conference. Cracks in potential models of conventional mesons are developing. Hybrid meson adiabatic surfaces have been calculated and interpreted, experimental J^{PC} exotics have hybrid meson, four–quark state or non–resonant interpretations, and the strong decay mechanism of hybrids has been studied. All theoretical progress on hybrid mesons in the last year is mentioned. Overall features of glueballs are visited: decays and the successes of the large N_c limit. Two promising experimental areas are mentioned: charmonium hybrids at B–factories and $s\bar{s}$ hybrids at Jefferson Lab.

1. Cracks in Potential Models: Radial Excitations

There are three mass regions in which in which there are recent experimental indications for states at masses inconsistent with potential model predictions:

- Crystal Barrel, VES, ARGUS and L3 [1] have evidence for $a_2(1660)$ approximately 170 MeV lower than potential model expectations [2].
- DELPHI, but *not* CLEO and OPAL, observes a new resonance $D(2637)$ with a total width of less than 15 MeV [3]. The observed mass uniquely identifies the state as a radially excited D^* if mass predictions from potential models are used [2,4]. However, this interpretation has been found to be inconsistent with the narrow width [3]. Assuming that the DELPHI result is confirmed, this may signal a crisis for potential models.
- Numerous light quark meson states $\gtrsim 2$ GeV have been reported recently by E818, VES and A.V. Anisovich, D.V. Bugg, A.V. Sarantsev and B.-S. Zou [1], typically at appreciably lower masses than found by potential models [2].

At least some of these discrepancies with potential models should be related to the appearance of new degrees of freedom in the QCD spectrum: hybrid mesons and glueballs.

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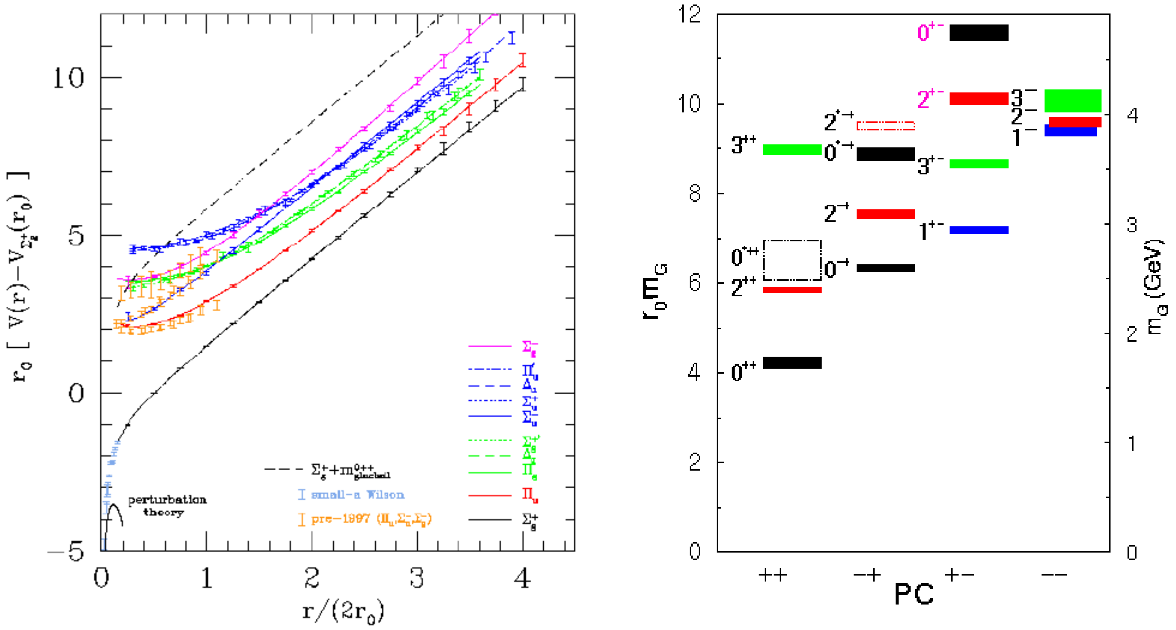

Figure 1. Lattice QCD adiabatic surfaces (left) and glueball spectrum (right).

2. Hybrid Mesons

2.1. Hybrid Adiabatic Surfaces

A careful lattice QCD calculation has been performed to map out the energy of a $q\bar{q}$ pair, with the quarks stationary, as a function of the distance r between them, called the *adiabatic surface* (see Figure 1) [5]. The lowest surface corresponds to conventional mesons, but the excited surfaces to various hybrid mesons. The interpretations of this result are consistent between various authors. At small r, the adiabatic bag model where quarks are stationary [6], or a glue–lump model where quarks are fixed at the centre of a bag [7], gives a reasonable description of the lattice data. At large r, a constituent gluon model (related to the bag model) is not applicable [8], but a Nambu–Goto string picture instead [9]. It has been argued that the string behaviour only sets on at r beyond that relevant for most of hadron spectroscopy [6].

2.2. J^{PC} Exotics and their Interpretations

Experimental isovector $J^{PC} = 1^{-+}$ exotic mesons have been reported at ~ 1.4 GeV in $\eta\pi$ by E852 and Crystal Barrel, and at ~ 1.6 GeV in $\rho\pi$, $\eta'\pi$ and $b_1\pi$ by E852 and VES [10]. An experimental search is currently underway at Jefferson Lab: for the $\eta\pi$ and $\eta'\pi$ channels the spin formalism for analysis is identical to that of a vector meson [11], which differs from the exotic by its C–parity.

The lowest state at ~ 1.4 GeV appears rather low in comparison to lattice QCD estimates for the lowest 1^{-+} state, which can be a hybrid or four–quark state. In the last year these are 2.0(1), 2.1(1) GeV [12] and 1.9(2) GeV [13]. The latter result incorporates some effects of unquenching, increasing the error bar. One has to remember that the lattice QCD predictions correspond to a strange quark, so that the light quark states should have even lower mass, taking experimental conventional meson masses as a guide. For a more comprehensive discussion of lattice QCD results, the reader is referred to ref. [14].

We shall now discuss three interpretations of the exotic states.

I. The 1.4 GeV state is a ground state hybrid, and the 1.6 GeV state an excited hybrid.

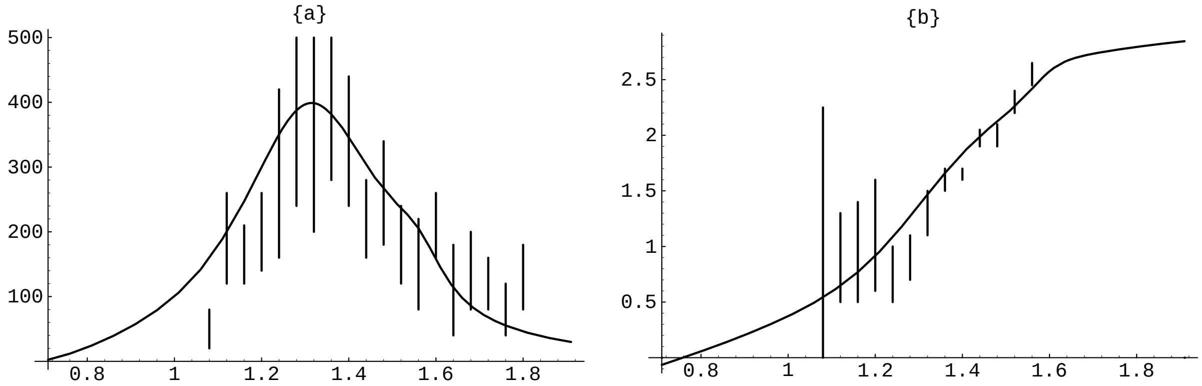

Figure 2. Results of the K–matrix analysis. (a) The events in $\eta\pi$ as compared to experiment; (b) The phase in $\eta\pi$ compared to experiment. The invariant mass is plotted on the horisontal axis in GeV.

This hypothesis is catastrophic [15]. The low mass of the 1.4 GeV state is a problem. The fact that the low mass state has only been seen in $\eta\pi$ is qualitatively in contradiction with symmetrization selection rules that suppress the decay of 1^{-+} hybrids to $\eta\pi$ [16]. Within the flux–tube model, the mass difference between the states is too small, the total width of the 1.4 GeV state too small and the ratio of widths of the two states opposite to experiment [15].

II. The 1.4 GeV state is a four–quark state (*or* molecule) and the 1.6 GeV state a ground state hybrid. First the 1.4 GeV state. The low mass is still a problem. It's observed decay to $\eta\pi$ is consistent with the symmetrization selection rules [16], and with a four–quark SU(3) selection rule that predicts $\Gamma(\eta\pi) > \Gamma(\eta^{'}\pi)$ [17]. A possible problem here is that no stable $J^{PC} = 1^{-+}$ four–quark state has been found in a quark model search [18]. For the 1.6 GeV state, its non–detection in $\eta\pi$ is consistent with the symmetrization selection rules [16], and $\Gamma(\eta\pi) < \Gamma(\eta^{'}\pi)$ with the hybrid SU(3) selection rule [17]. Moreover, the decay to $\rho\pi$ is also according to expectations [19].

III. The 1.4 GeV "state" is produced by the interference of a non–resonant Deck background peaking near 1.4 GeV with a hybrid meson resonance at 1.6 GeV. A K–matrix fit to the E852 event and phase data in $\eta\pi$ using this hypothesis in shown in Figure 2 [15]. A key feature is that the phase motion in the E852 $\eta\pi$ data at 1.4 GeV can arise from a 1.6 GeV resonance which does not couple strongly to $\eta\pi$, through coupled channel effects. The Deck process involves πp inelastic scattering into $\eta\pi p$ via ρ exchange. Deck processes are however only operative in πp experiments (E852 and VES), and not in $p\bar{p}$ annihilation at Crystal Barrel. Hence this explanation does not explain all the data.

2.3. Hybrid Strong Decay Mechanism

The mechanism of strong decay of hybrids to two mesons via pair creation is of significant interest, since it may be different from that of conventional mesons due to the structure of the glue. The first possibility is that hybrids decay similar to the phenomenologically successful way for mesons: $^3P_0$ pair creation by flux–tube breaking [20]. A second possibility, found in the heavy quark limit of QCD in Coulomb gauge, is $^3S_1$ pair creation by flux–tube breaking arising from the hamiltonian [21]

$$H_{int} = \int d^3x \; \Psi^+(\mathbf{x}) \; \boldsymbol{\sigma} \cdot (i\boldsymbol{\nabla} + g\mathbf{A}) \; \Psi(\mathbf{x}) \tag{1}$$

These two pictures lead to characteristic differences between the D– to S–wave width ratios of $1^{-+} \to b_1\pi,\ f_1\pi$: the ratios are much smaller in the $^3S_1$ than in the $^3P_0$ model [22]. One may soon be able to test these ratios with new data from E852 and VES.

2.4. Other new results for hybrids

The current status of light vector hybrids was discussed [23]. Also, there were various new QCD sum rule results. The first calculation of the width of a 1.6 GeV exotic to $f_1\pi$ yielded $\Gamma(1^{-+} \to \rho\pi,\ f_1\pi) = 40 \pm 20,\ 100 \pm 50$ MeV [24]. Non–exotic 0^{++} and 0^{-+} light hybrid masses were also investigated [25]. Also, heavy–light hybrid masses [26] and decays [27] were studied for this first time in any approach.

3. Glueballs

The high precision and almost complete glueball spectrum below ~ 4 GeV in Figure 1 was calculated in lattice QCD [28]. In order to connect this spectrum with experiment, mixing with and decay to conventional mesons need to be understood.

A first attempt at understanding the decay of the primitive (bare) scalar glueball to pseudoscalar mesons was made some time ago in lattice QCD [29]. An unusual decay pattern was found, where the coupling of the glueball to $\eta\eta$ was greater than its coupling to $K\bar{K}$, and the latter greater than its coupling to $\pi\pi$. Historically the expectation based on perturbative QCD was a "flavour democratic" decay pattern where each of these couplings are the same [30]. The first successful model to explain the lattice QCD decay pattern postulates that the glueball does not decay directly, but only via an intermediate scalar meson, which then subsequently decays to the two pseudoscalars via the familiar $^3P_0$ pair creation mechanism [31]. A perfect one–parameter fit to the three lattice points is obtained. It has paradoxically been found that perturbative QCD decay of glueballs with bag model gluon wave functions can also fit the lattice points [32], although the indirect decay through intermediate mesons is still present. The problem here is that perturbative QCD is not applicable for the scalar glueball [33].

The physical glueball does not necessarily decay flavour democratically or is narrow. This is already experimentally evident for the $f_0(1500)$ and $f_J(1770)$. It has also recently been found in an analysis of the tensor glueball [1], making a narrow flavour democratically decaying $f_J(2220)$ implausible. The only hope for finding narrow glueballs appears to be when they are unmixed with mesons. This is a possibility for glueballs beyond 3 GeV, since light mesons in this mass region may become unstable due to QCD pair creation, and charmonium have limited mixing [34]. For example, a "glue–rich" quark–gluon plasma can produce a narrow vector glueball which decays to readily detected e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$. Another tantilizing possibility is production of high–mass glueballs from the proposed GSI Darmstadt upgrade. The caveat is that even pure glueballs may not be narrow, as lattice QCD finds a scalar glueball width of 108 ± 28 MeV to pseudoscalars only, while models suggest that additional modes may increase the width to at least $250 - 390$ MeV [31].

Interesting new results were obtained in the large number of colours N_c limit of QCD. Teper noticed it to be an excellent guide to glueball masses even for $N_c = 3$ [35]. One can argue that the glueball mass follows the relation

$$\text{Glueball mass}_{N_c} = \text{Glueball mass}_{N_c=\infty} + \frac{constant}{{N_c}^2} \qquad (2)$$

so that corrections from the large N_c limit are of second order [35]. Simulations of the scalar and tensor glueball masses in SU(2), SU(3) and SU(4) are indicated in Table 1. The agreement between $N_c = 2-4$ is striking.

Table 1
Scalar and tensor glueball masses in string tension σ units ($a\sigma = 0.228 \pm 0.007$) [35].

	SU(2)	SU(3)	SU(4)
$M_{0^{++}}/\sqrt{\sigma}$	3.62 ± 0.07	3.22 ± 0.04	3.28 ± 0.30
$M_{2^{++}}/\sqrt{\sigma}$	5.58 ± 0.03	5.02 ± 0.04	5.31 ± 0.48

4. Experiment

4.1. Charmonium Hybrids at B–factories

The process $B \to (c\bar{c}$ hybrid$)$ X is an experimental frontier [36]. NRQCD estimates suggest a tiny decay branching ratio for the process [37], but the χ_{c2} has already been detected at this level [36]. Isgur recently argued that hybrid mesons should have similar production to conventional mesons in factorizable processes, which this one is not [38].

One of the issues critically determing the feasibility of detecting hybrid charmonium is the width of these states. Various arguments suggest that they should be narrow if they are below the $D^{**}D$ threshold, e.g. the 0^{+-} and 1^{-+} exotic hybrids should have total widths of order 5 and 20 MeV respectively [36]. Mass determinations for charmonium 1^{-+} hybrids in the last year are shown in Table 2, where the first four are lattice QCD results. The difference between the $D^{**}D$ threshold and the spin–averaged ground state charmonium mass is 1220 MeV, so that current 1^{-+} hybrid mass estimates straddle the $D^{**}D$ threshold.

It evident from Table 2 that the difference in mass between the $b\bar{b}$ hybrid and its spin–averaged ground state is *larger* than that for $c\bar{c}$. This is *opposite* to the behaviour of conventional radially and orbitally excited quarkonia.

4.2. $s\bar{s}$ hybrids at Jefferson Lab

We have performed a new study in the flux–tube model [20,22] of the decay of the $s\bar{s}$ 1^{-+} exotic hybrid meson, which differs from earlier work in that the $s\bar{s}$ hybrid is at different masses. The first mass chosen is 250 MeV above the experimental 1.6 GeV exotic state, i.e. 1840 MeV, making it the $s\bar{s}$ partner of the 1.6 GeV state; and the second is the mass of the exotic meson candidate $X(1920)$ [44]. The calculation is displayed in the narrow resonance approximation in Table 3.

Table 2
Difference between 1^{-+} hybrid and spin–averaged ground state quarkonium mass (MeV).

$c\bar{c}$	$b\bar{b}$	
1340^{+60}_{-150} + sys		MILC Collab. [39]
1323 ± 13	1542 ± 8	CP–PACS Collab. [40]
~ 1190	$1490 \pm 20 \pm 50$	[41]
	1680 ± 100	UKQCD Collab. [42]
~ 950	~ 1200	Constituent gluon model [43]
	1300 ± 100	QCD sum rules [26]

Table 3
Partial decay widths of an $s\bar{s}$ 1^{-+} hybrid (MeV) at 1840 and 1920 MeV in the $^3P_0$ decay model (IKP) [20] and the $^3S_1$ model (PSS) [22]. The $\eta'\eta$ partial width vanishes and $K^*(1410)K$ is tiny.

Decay Mode	1840 MeV		1920 MeV	
	PSS	IKP	PSS	IKP
K^*K	9	6	10	7
$K_1(1270)K$	7	17	10	24
$K_1(1400)K$			31	73
Total	16	22	52	104

The salient feature is that $K_1(1400)K$ is the would–be dominant mode, but that the $s\bar{s}$ hybrid mass straddles its threshold. Removing the narrow resonance approximation is expected to increase the width to $K_1(1400)K$. We obtain a surprisingly narrow state, whose simplest search channel is K^*K. A natural place to search for $s\bar{s}$ hybrids is at Jefferson Lab, where the photon has a sizable coupling to $s\bar{s}$. However, production may be complicated, as diffractive exchange is forbidden by C–parity conservation, and meson exchange involves OZI forbidden or evading processes.

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