Gluonic Excitations of Mesons: Why They Are Missing and Where to Find Them

Nathan Isgur
Richard Kokoski

Department of Physics
University of Toronto
Toronto, Canada M5S 1A7

Jack Paton
Department of Theoretical Physics
University of Oxford
1 Keble Road, Oxford, England OX1 3NP

presented by Nathan Isgur

***

We have studied the decays of the low-lying gluonic excitations of mesons (hybrids) predicted by a flux tube model for chromodynamics. The probable reason for the absence to date of signals for such states is immediately explained: the lowest lying hybrids decay preferentially to final states with one excited meson (e.g., $B(1235)\pi$, $A_2(1320)\pi$, $K^*(1420)\bar{K}$, $\pi(1300)\pi$,...) rather than to two ground state mesons (e.g., $\pi\pi$, $\rho\pi$, $K^*\bar{K}$,...). We make specific predictions of decay channels which will contain J^{PC} exotic hybrid resonance signals and suggest some possibly fruitful production mechanisms.

***

Fundamental to quantum chromodynamics (QCD) is the existence of gluonic degrees of freedom in addition to the degrees of freedom associated with the quarks. Although evidence for glue has been found in jet studies and, circumstantially, in deep inelastic sum rules, there is still no direct evidence for its existence in hadron spectroscopy. Two of us have recently proposed a flux tube model for chromodynamics[1], based on strong coupling Hamiltonian lattice QCD, from which the quark model emerges as a natural low frequency limit.

but in which the gluonic degrees of freedom play an important role at masses above those where the quark model has been well tested. In this flux tube model, the degrees of freedom represented by perturbative gluon fields are replaced by the flux tube degrees of freedom appropriate to strong coupling (and thus to the physics of confinement). In those situations which may be approximated by quark motion in the adiabatic potential generated by the lowest gluon field (ie., flux tube) mode, one recovers the quark model. However, the flux tube may exist in excited states, and quark motion in the adiabatic potentials of such excited gluon field configurations generates states, called hybrids, which are not part of the usual quark model.[2)] It was argued in Ref. 1 that the low-lying hybrid meson states correspond to simple vibrational excitations of the flux tube; indeed, the lowest-lying states in this picture correspond to adding one phonon of transverse vibration in the lowest "string" mode. Since this phonon carries ±1 unit of angular momentum about the $q\bar{q}$ axis, two degenerate 36-plets of SU(3) quarks are made in this way. Among these states are three J^{PC} exotic nonets with nine neutral members having $J^{PC} = 2^{+-}, 1^{-+}$, and 0^{+-}.

It is clear that an unambiguous confirmation of the existence of hybrid mesons would constitute an important new qualitative test of QCD and a proof that the simple quark model classification scheme, which has been very successful up to now, has a limited range of validity. The observed properties of such states would in turn provide detailed checks of ideas on the character of QCD in the confinement region. There is in chromodynamics another class of states not contained in the quark model: those made of pure glue. However, according to the flux tube model the lowest of these states have non-exotic quantum numbers. It is our belief, therefore, that a search for J^{PC} exotic hybrid mesons is the most promising route to uncovering the gluonic degrees of freedom in hadron spectroscopy; to this end we present here a phenomenological guide to the terrain in which we believe they are buried. Our guide consists of a detailed discussion of the expected important partial widths of the exotic hybrids and some suggestions on how they might best be produced. As a by-product we shall come to understand why such states have not yet been found.

It has recently been shown [3)] that the decays of ordinary mesons can be quite well understood in the flux tube model in terms of a flux tube breaking mechanism suggested by strong coupling Hamiltonian lattice QCD[1)]. According to this mechanism, a flux tube has a uniform amplitude to break at any point along its length in a meson A, producing in the process a $q\bar{q}$ state in a relative $J^{PC} = 0^{++}$ state; the broken bits of "string" and the newly associated quark-antiquark pairs subsequently have amplitudes to find themselves in the string and quark wavefunctions of the final state mesons B and C. The 0^{++} ($^3P_0$) production of the new $q\bar{q}$ pair is reminiscent of the naive $^3P_0$ quark pair creation (QPC) model [4]; the main practical difference between the QPC model and the string breaking mechanism is that the latter includes the effects of flux tube dynamics. Since for ordinary meson decay the two $q\bar{q}$ wave functions localize the produced $q\bar{q}$ pair in the region between the original $q\bar{q}$ pair, for such decays the two pictures hardly differ at all. (Indeed, we consider this correspondence as placing the old and very successful QPC model on a more fundamental footing.)

The amplitude for a decay A→BC in the flux tube breaking picture takes the form[3]

$$M(A\to BC) = \gamma_0 \int d^3r \int d^3y \; \Psi_B^*\left(\tfrac{\vec{r}}{2}+\vec{y}\right) \Psi_C^*\left(\tfrac{\vec{r}}{2}-\vec{y}\right) \vec{\alpha}\cdot\left[i\overleftarrow{\nabla}_B + i\overleftarrow{\nabla}_C + \vec{q}\right] \cdot \Psi_A(\vec{r})\, e^{i\vec{q}\cdot\vec{r}/2} \langle \{y_B\}\{y_C\} | \{y_A\}\rangle \qquad (1)$$

Here the Ψ's are the quark (spinor) wavefunctions, $\vec{q}$ is the centre of mass momentum of B, γ_0 is an overall string breaking amplitude, $\vec{\alpha}$ are the Dirac matrices, and $\vec{r}$ and $\vec{y}$ are as defined in Figure 1. The last

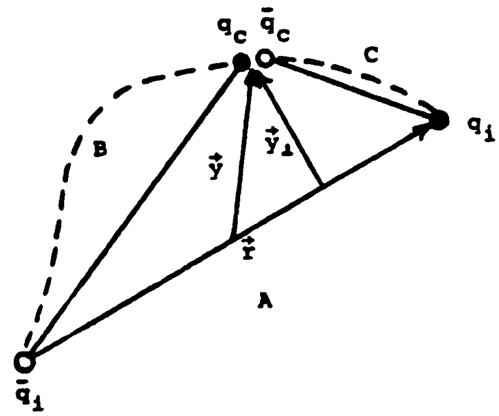

Figure 1: the geometry of string breaking showing the initial meson separation $\vec{r}=\vec{r}_{q_i}-\vec{r}_{\bar{q}_i}$ and the pair creation vector $\vec{y}=\frac{1}{2}(\vec{r}_{q_c}+\vec{r}_{\bar{q}_c}-\vec{r}_{q_i}-\vec{r}_{\bar{q}_i})$; the dashed line represents the (newly broken) string.

factor in the integrand in (1) is the string wavefunction overlap. This factor can be calculated by discretizing the string [3]; for ordinary meson decay one finds ($\{y_{I(0)}\}$ denotes a ground state string)

$$\langle\{y_{B(0)}\}\{y_{C(0)}\}|\{y_{A(0)}\}\rangle \sim \exp\left[-\tfrac{1}{2} f b y_\perp^2\right] \tag{2}$$

where f, which depends weakly on r and $\vec{y}.\vec{r}/r$ is of order unity when, as is appropriate, the string theory is cut off at a small scale $\lambda_0 \sim b^{-1/2}$. Phenomenologically f is not well determined for the same reason that the model tends to coincide with the QPC model: this string overlap factor is mimicked by quark wavefunction overlaps. For our calculations it is sufficient to simply set f=1.

This flux tube breaking model, unlike the QPC model, is easily extended to hybrid meson decays. One simply replaces the initial quark wavefunction by one appropriate to a hybrid meson

$$\Psi_{A(hybrid)}(\vec{r}) = \left(\frac{2L_A+1}{4\pi}\right)^{1/2} \mathcal{D}^{L_A}_{M_A\Lambda_A}(\phi,\theta,-\phi)\,\Psi_{A(hybrid)}(r) \tag{3}$$

and the ordinary string state by the appropriate excited string state with Λ_A units of angular momentum about the axis $\vec{r}$. In the case of one lowest mode (m=1) phonon (which has $\Lambda_A = \pm 1$) the string overlap factor in (1) is then changed to

$$\langle\{y_{B(0)}\}\{y_{C(0)}\}|\{y_{A(m=1,\Lambda_A=\pm1)}\}\rangle = K b^{1/2} y_\pm \langle\{y_{B(0)}\}\{y_{C(0)}\}|\{y_{A(0)}\}\rangle \tag{4}$$

where now $K \simeq 1$ is approximately independent of r and $\vec{y}.\vec{r}/r$ and where $y_\pm = y_1 \pm iy_2$ are spherical components of $\vec{y}$ with respect to axes rotated by Euler angles $(\phi,\theta,-\phi)$ with respect to the coordinate axes defining the components of $\vec{r}$. We can therefore predict hybrid decay rates in terms of the parameter γ_0 which controls ordinary meson decay.

The full results of our calculations for the decays of the lowest-lying meson hybrids will be published elsewhere[5]; in Table I

Table I: the dominant decays of the low-lying exotic meson hybrids

hybrid state*	J^{PG}	(decay mode)$_L$ of decay	partial width (MeV)
$x_2^{+-}(1900)$	2^{++}	$(\pi A_2)_P$	450
		$(\pi A_1)_P$	100
		$(\pi H)_P$	150
$y_2^{+-}(1900)$	2^{+-}	$(\pi B)_P$	500
$z_2^{+-}(2100)$	2^{+-}	$(\bar{K}K^*(1420)+c.c.)_P$	250
		$(\bar{K}Q_2+c.c.)_P$	200
$x_1^{-+}(1900)$	1^{--}	$(\pi B)_{S,D}$	100,30
		$(\pi D)_{S,D}$	30,20
$y_1^{-+}(1900)$	1^{-+}	$(\pi A_1)_{S,D}$	100,70
		$(\pi\pi(1300))_P$	100
		$(\bar{K}Q_2+c.c.)_S$	~100
$z_1^{-+}(2100)$		$(\bar{K}Q_1+c.c.)_D$	80
		$(\bar{K}Q_2+c.c.)_S$	250
		$(\bar{K}K(1400)+c.c.)_P$	30
$x_0^{+-}(1900)$	0^{++}	$(\pi A_1)_P$	800
		$(\pi H)_P$	100
		$(\pi\pi(1300))_S$	900
$y_0^{+-}(1900)$	0^{+-}	$(\pi B)_P$	250
$z_0^{+-}(2100)$	0^{+-}	$(\bar{K}Q_1+c.c.)_P$	800
		$(\bar{K}Q_2+c.c.)_P$	50
		$(\bar{K}K(1400)+c.c.)_S$	800

*x,y, and z denote the flavour states $\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})$, $\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$, and $s\bar{s}$. the subscript on a state is J, the superscripts are P and C_n.

we show the dominant decay modes of the definitive J^{PC} exotic states. (Table I also defines our nomenclature for these states). One reason these states (as well as their non-exotic counterparts) have not yet been seen is immediately apparent from our calculations: they have hardly any coupling strength to simple final states consisting of two ground state mesons (e.g., $\pi\pi$, $\pi\eta$, $\pi\rho$, $K\bar{K}$, $K^*\bar{K}$,...). There is a simple semiclassical explanation for this approximate selection rule which can be seen from the geometry of Figure 1: the relative coordinate of mesons B and C is parallel to $\vec{r}$ and so cannot absorb the unit of string angular momentum about the $\vec{r}$ axis. This selection rule is broken if mesons B and C have different spatial wavefunctions, but it is still nearly obeyed (i.e., widths of order 10 MeV result) in the cases of interest like $\rho\pi$.

There are other reasons why even the definitive exotic J^{PC} signals might have escaped detection so far. One is just their rather large masses. Another is that, of the nine candidate states, three are probably too broad to be seen with any clarity. When we turn to the six J^{PC} exotic hybrids which may be narrow enough to stand out as resonances [$y_2^{+-}(1900)$, $z_2^{+-}(2100)$, $x_1^{-+}(1900)$, $y_1^{-+}(1900)$, $z_1^{-+}(2100)$, and $y_0^{+-}(1900)$] , we encounter further reasons why they may have escaped detection so far. The $y_1^{-+}(1900)$ decays mainly to $[A_1(1275)\pi]_S$ and $[\pi(1300)\pi]_P$; considering the notorious difficulty of seeing the A_1 and the large width of the $\pi(1300)$ these channels would probably not be conducive to finding the y_1^{-+}. Similar difficulties would seem likely to obscure the $z_1^{-+}(2100)$. The remaining four states, while still presenting formidible challenges, should be easier to see : $y_2^{+-}(1900)$ and $y_0^{+-}(1900)$ both decay dominantly to $[B(1235)\pi]_P$, $z_2^{+-}(2100)$ will decay much of the time to $[K^*(1420)\bar{K}$ + c.c.$]_P$, and the $x_1^{-+}(1900)$ will be found most of the time in $[B(1235)\pi]_S$.

Neither the flux tube model masses nor the widths of Table I are at this time very precise: the predicted masses are uncertain by about 100 MeV and, even without the changes in phase space thereby induced, the predicted widths are uncertain by an overall strength factor of 1.5 from the flux tube overlap factor K and a further model error of about 1.2 (based on the mean errors found in the ordinary meson analysis of Ref. 3). Nevertheless, the main message of Table I is clear and compelling: exotic meson hybrids must be in these channels with the general characteristics we have detailed.

It remains to discuss how to produce these exotic states. In this case we can provide some suggestions, but no quantitative results. One of the implications of the flux tube model is that the hadronic spectrum becomes very dense with new non-quark model states for masses greater than about 2 GeV. These states are all strongly interacting and so, in particular, meson hybrids will be produced as copiously as ordinary mesons in hadronic collisions which probe such mass scales. We would suggest that high mass meson diffractive scattering will be particularly rich in hybrids. In the case where the beam flux tube is simply "plucked" by the target one will produce hybrids with the flavour and spin of the beam: a π beam would, for example, produce by this mechanism the non-exotic I=1 $J^{PC} = 1^{++}$ and 1^{--}

hybrids . More complicated spin flip and quantum number exchange mechanisms in which the hybrid is produced by quark scattering rather than pure glue scattering could produce the other hybrids, including the desirable exotic ones. Diffractive photoproduction, on the other hand, can produce "plucked" ρ, ω, and ϕ states and so could be a good source for all four of the desirable exotics y_2^{+-}, z_2^{+-}, x_1^{-+}, and y_0^{+-}. Traditional "gluon rich" channels may under certain circumstances also be a source of exotic hybrids. $\Psi\to\gamma X$, for example, might be a source for the $J^{PC} = 1^{-+}$ exotics if the perturbative argument against populating a vector channel by two vector gluons is faulty. The Ψ and Υ systems also decay directly via a "gluon rich" channel and since a $J^{PC} = 1^{--}$ virtual glue state can decay to a hybrid plus ordinary meson final state, one may expect some population of such channels as $[y_2^{+-}(1900)\eta]_D$, $[z_2^{+-}(2100)\eta]_D$, $[x_1^{-+}(1900)\rho]_P$, and $[y_0^{+-}(1900)f(1280)]_P$ in Ψ and Υ hadronic decays.

Exotic hybrids should also be readily produced in $\bar{p}p$ annihilation. Figure 2 illustrates an example of a mechanism that could be important in this process: after an initiating $\bar{q}q$ annihilation, one of the nascent mesons plucks the string of the other through the interaction of the section of the string they originally have in common. Consideration of the available quantum numbers indicates that the reactions produced could include $\bar{p}p \to y_2^{+-}\pi$, $x_1^{-+}\pi$, and $y_0^{+-}\pi$. These would seem to be much more favourable than the channels available in Υ and ψ decay.

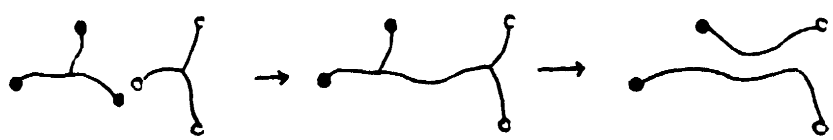

Figure 2: a mechanism by which $\bar{p}p$ can annihilate into one ordinary meson and one hybrid meson.

It is our belief that the guide to meson hybrids we have provided here, while imperfect, should be sufficient to lead to their discovery. The elusiveness of hybrids so far appears to us to be connected with their high masses and peculiar decay properties; in a thorough search for them in the right final states they should stand out clearly.

1. Nathan Isgur and Jack Paton, Phys. Lett. 124B, 247(1983); Phys. Rev. D31, 2910(1985).

2. F.E. Barnes, Caltech Ph.D. thesis (1977); Z. Phys. C10, 275 (1981); D. Horn and J. Mandula, Phys. Rev. D17, 898 (1978); P. Hasenfratz, R.R. Horgan, J. Kuti, and J. M. Richard, Phys. Lett. 95B, 299 (1980); F. E. Barnes, F. E. Close, and S. Monaghan, Nucl. Phys. B198, 380(1982); M. Chanowitz and S. Sharpe, Nucl. Phys. B222, 211 (1983); E. Golowich, E. Haqq, and G. Karl, Phys. Rev. D28, 160 (1983).

3. Richard Kokoski, "Meson Decay in the Quark Model", University of Toronto Ph.D. thesis, 1984; Richard Kokoski and Nathan Isgur, "Meson Decays by Flux Tube Breaking", University of Toronto preprint, September, 1984.

4. L. Micu, Nucl. Phys. B10, 521 (1961); A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Phys. Rev. D8, 2223 (1973) and Phys. Rev. D9, 1415 (1974).

5. Nathan Isgur, Richard Kokoski, and Jack Paton, in preparation.