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Hadron Spectroscopy in 1987 and Beyond*

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1. INTRODUCTION

I would like to begin by expressing thanks on behalf of all the participants in *Hadron 87* to Professors R. Kajikawa, S. Ozaki, and K. Takamatsu and all members of the Program Committee, Organizing Committee, and the Conference Secretariat for a most enjoyable and lively conference. We are also grateful to KEK for extending its gracious hospitality and to the Research Institute for Fundamental Physics, Kyoto University and the Institute for Nuclear Studies, University of Tokyo, for their generous sponsorship.

This talk, though in part a summary and list of prospects for the future, cannot hope to do justice to the wide variety of topics presented here, and so there will necessarily be some selections made. I am helped in this regard by excellent rapporteur talks covering in detail subjects omitted or only treated superficially in the present lecture.

We will discuss in Section 2 hadrons without heavy quarks, including ordinary (quark-antiquark) mesons and gluonic bound states ("glueballs"), three-quark baryons, and exotic mesons and baryons. Section 3 is devoted to the physics of charmed quarks in charmonium and charmed particles, while Section 4 contains a corresponding treatment of b quarks. Some possibilities for the future, such as the t quark, a fourth generation, and spectroscopies beyond those governed by QCD, are noted in Section 5. Section 6 concludes.

2. NO HEAVY QUARKS

2.1. Overview of lightest meson states

In Figure 1 we reproduce a 1974 "box score" for the lightest quark-antiquark ($q\bar{q}$) mesons.[1] The $L=1$ mesons still were missing states. The spin-zero ($^3P_0$) $L=1$ candidates already gave hints of extra states beyond those anticipated on the basis of the quark model. Very little was known about radial excitations. Large gaps existed in the picture of the $L=2$ mesons.

More recent developments have led to the picture shown in Fig. 2. Aside from inconsequential changes of names,[2] a great deal has been learned over the years.

2.1.1. *Candidates for gluonic bound states* have been identified in the $J^{PC} = 0^{-+}$, 0^{++}, and 2^{++} channels. The $\iota(1460)$ is the best candidate for a 0^{-+} glueball.[3,4] The glue content of the η' is still an object of some controversy, as we shall see. The $I=0$ 0^{++} system appears considerably too rich for $q\bar{q}$ alone, with several claimed resonances below 1 *GeV*,[5] and resonant activity at 1.3, 1.59, and 1.75 *GeV*.[6,7] The $f_2/\theta(1720)$ is another very credible candidate for a glueball; its production and decay suggest that it is probably mixed with quarkonium. We shall discuss glueballs more thoroughly in Section 2.5.

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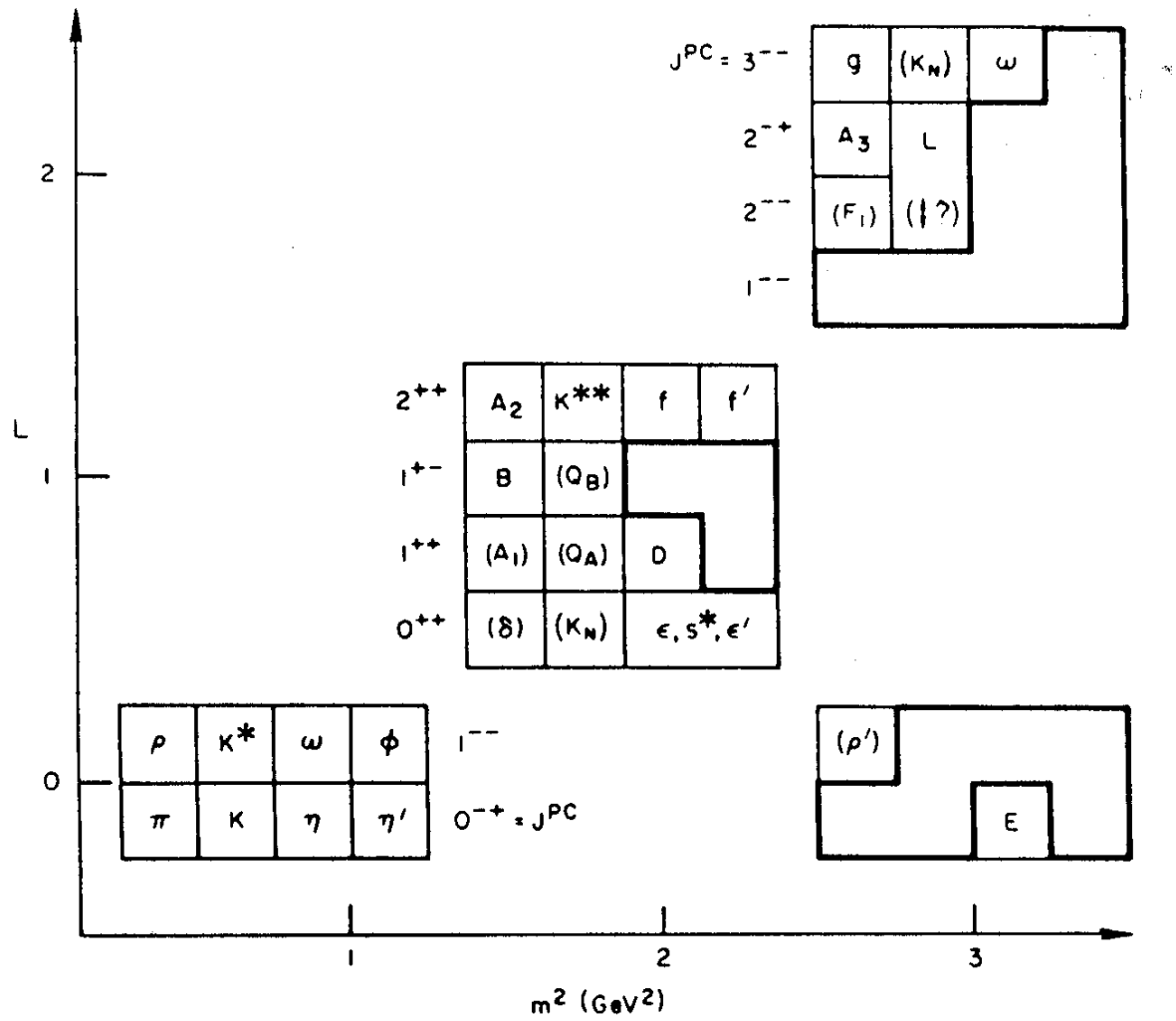

Figure 1. Lightest $q\bar{q}$ mesons as of 1974. From Ref. 1.

2.1.2. *Radial excitations* of all the S-wave mesons have been seen. The states π (1300), K_0 (1400) and K_1^*(1410) show up in phase shift analyses of the 3π, [2,8] $K\pi\pi$ and $K\pi$ [9] systems. The radially excited ρ is one of two states proposed[10] in order to explain ππ, ηππ and ωπ spectra in e^+e^- [11,12] and photoproduction reactions.[13,14] The η(1280) was first seen in $\pi^- p \to \eta\pi^+\pi^- n$.[15] It now appears a companion state, η'(~ 1400), is required to explain ηππ and $K\bar{K}\pi$ 0^{-+} spectra,[16,17] while the ι(1460) may in fact consist of η'(~ 1400) and a glueball candidate closer to 1500 *MeV*. We have taken the liberty of ascribing isoscalar states seen around 1.6 *GeV* in e^+e^- annihilations[18] and a φ' candidate seen in photoproduction[19] to radial excitations. It is likely that not all e^+e^- and photoproduction data [20] on isoscalar resonances can be explained by a single ω', so we arbitrarily assign the state seen in photoproduction of ηω to a $^3D_1$ level.

In a harmonic oscillator potential, popular for many years for describing light-quark spectroscopy, the first S-wave radial excitation ($2S$) is degenerate with the lowest L=2 level ($1D$). For a potential $V(r) \sim r^\alpha$ with $\alpha < 2$, the $2S$ level lies lower than the $1D$ one. This is a special case of more general theorems.[21] At the same time, when $\alpha > -1$, $E_{2S} > E_{1P}$. Indeed, the radial-excitation

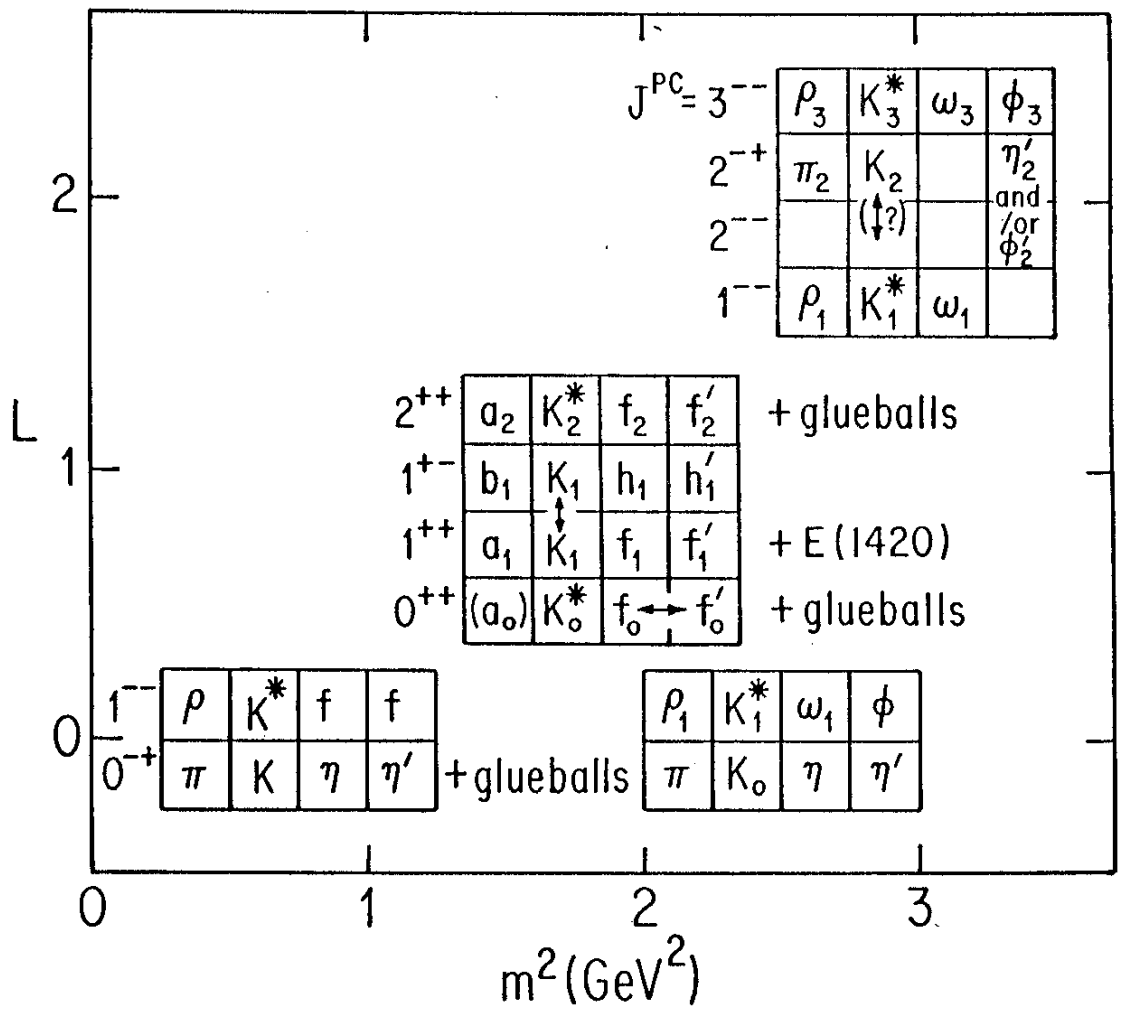

Figure 2. Lightest $q\bar{q}$ mesons as of 1987. The newest candidates are described in the text.

candidates in Figure 2 appear to satisfy $E_{1P} < E_{2S} < E_{1D}$, as one would expect for an effective power $-1 < \alpha_{eff} < 2$. For $\alpha_{eff} = (-1, 0, 1, 2)$ one expects the ratios $(E_{2S} - E_{1P})/(E_{1D} - E_{1P})$ to be 0, 0.55, 0.82, and 1, respectively.

2.1.3. *Progress in the identification of L=1 levels* now allows us to conclude that fine structure (L·S) splittings in the mesons seem less important than they did in 1974. The light-quark mesons then appear more like the corresponding baryons, for which spin-orbit forces appear to play a minor role.[22] The LASS group has obtained evidence for a $J^{PC} = 1^{++}$ $s\bar{s}$ candidate $f_1'(1530)$,[23] decaying to $K\bar{K}\pi$, confirming an earlier hint[24] of such a resonance. Data from the multi-particle spectrometer at Brookhaven[25] are also consistent with this state. The $f_1'(1530)$ would be almost exactly degenerate with the $f_2'(1525)$. Similarly, the a_2 and a_1 appear nearly degenerate, if one takes into account distortions in the a_1 spectrum due to interference with large $J^P = 1^+$ backgrounds.[26] The $a_0(980)$ does appear to be lower in mass than a_2 and a_1.[2] It has been suggested as a candidate for a four-quark state,[27] in which case a suitable alternative $q\bar{q}$ candidate still would remain to be seen around 1.3 GeV/c^2.

A $J^{PC} = 1^{+-}$ $s\bar{s}$ candidate h' also has appeared in the $K\bar{K}\pi$ system,[23,25] lying somewhat below 1.5 GeV. The presence of both 1^{++} and 1^{+-} states between 1.3 and 1.6 GeV is suggested by the unequal strength of $\bar{K}^*$ and K^* bands in the Dalitz plots (Figs. 3a and 3b).[23,28]

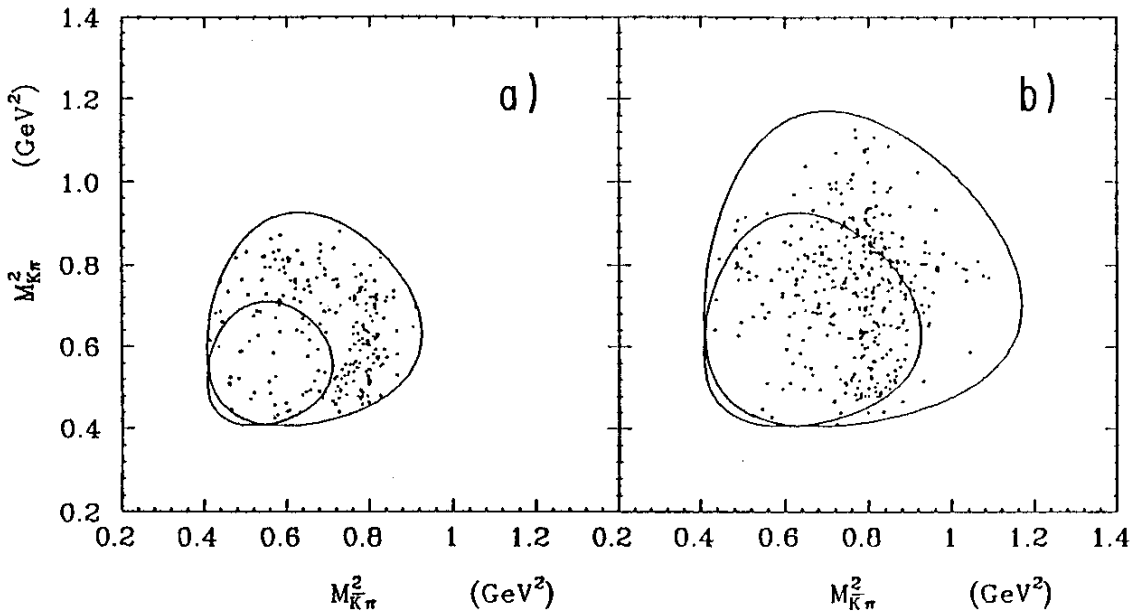

Figure 3. Dalitz plots for $K^{\pm}K^0_S\pi^{\mp}$ in the reaction $K^-p \rightarrow (K\bar{K}\pi)\Lambda$ at 11 GeV/c. From Ref. 23. a) $1.34 < M_{K\bar{K}\pi} < 1.46$ GeV; b) $1.46 < M_{K\bar{K}\pi} < 1.58$ GeV.

There is a hint of constructive interference in the overlap between $\bar{K}^*$ and K^* bands in the high-mass region (Fig. 3b), suggesting a $C = +1$ resonance, while at low mass (Fig. 3a), the interference is destructive if it occurs at all, suggesting that the lower-mass state has $C = -1$.

2.1.4. *An extra* $J^{PC} = 1^{++}$ *isoscalar state* is present if the $f_1(1285)$ [formerly D], $f_1(1420)$ [formerly E], and $f_1'(1530)$ [formerly D'] all are confirmed. Two possible explanations would be that a) the state at 1530 MeV is identical to that at 1420 MeV, but kinematically shifted as a result of the production process (as is the a_1 at times[26]), or b) the $K\bar{K}\pi$ system forms a "molecule", in which the $K\pi$, $\bar{K}\pi$, and $K\bar{K}$ systems simultaneously resonate to form a K^*, $\bar{K}^*$, and a_0 [formerly δ], as shown in Figure 4. Such a "molecule" naturally occurs when all three Dalitz plot bands overlap, or at

$$M = \{2m_{K^*}^2 + m_{a_0}^2 - 2m_K^2 - m_\pi^2\}^{1/2} \simeq 1435\ MeV \quad . \tag{2.1}$$

If the kaons are in an S-wave relative to one another and each in a P-wave with respect to the pion, the system will naturally have $J^{PC} = 1^{++}$. We shall return presently to the suggestion that other proposed hadron resonances may be "molecules".[29]

2.1.5. *The measurement of* $\eta\pi^+\pi^-$ *spectra* in e^+e^- annihilations[11] and in photoproduction[13] is relevant to the question of whether a substantial $\tau^{\pm} \rightarrow \eta\pi^{\pm}\pi^0\nu_\tau$ decay mode can proceed through the isovector weak current. A recent estimate[30] suggests $B(\tau^{\pm} \rightarrow \eta\pi^{\pm}\pi^0\nu_\tau) < 0.24\%$. We presented at this conference a somewhat more conservative bound obtained in the following manner. From e^+e^- annihilations[11] it is estimated that the peak in the cross section for $\eta\pi^+\pi^-$ production corresponds to a

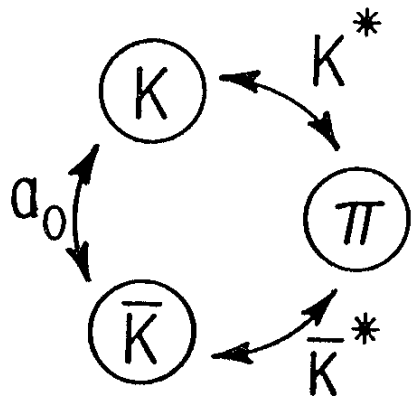

Figure 4. "Molecular" model of an $I=0$ $K\bar{K}\pi$ resonance at 1435 *MeV*.

ρ' with

$$B(\rho'^0 \to \rho^0\eta)/B(\rho'^0 \to \rho^0\pi^+\pi^-) = 0.123 \pm 0.027\ . \tag{2.2}$$

If the $\pi^+\pi^-$ system produced in $\rho'^0 \to \rho^0\pi^+\pi^-$ has $I=0$, a reasonable assumption since it appears to be in an S wave, then $B(\rho'^0 \to \rho^0\pi^+\pi^-) = B(\rho'^+ \to \rho^+\pi^+\pi^-)$. Then one expects

$$\begin{aligned} B(\tau^+ \to \rho^+\eta\nu_\tau) &= (10-15\%)B(\tau^+ \to \rho^+\pi^+\pi^-\nu_\tau) \\ &\lesssim (10-15\%)\ (5.3\pm0.8\%) \end{aligned} \tag{2.3}$$

or (conservatively)

$$B(\tau^\pm \to \rho^\pm\eta\nu_\tau) \lesssim 1\%\ . \tag{2.4}$$

The stronger bound found in Ref. 30 appears to stem in part from the fact that $e^+e^- \to \eta\pi^+\pi^-$ produces very few events below 1.4 *GeV*, while $\sigma(e^+e^- \to 2\pi^+2\pi^-)$ and particularly $\sigma(e^+e^- \to \pi^+\pi^-2\pi^0)$ are substantial there.

The question of $\tau^\pm \to \eta\pi^\pm\pi^0\nu_\tau$ decays is relevant to the general problem of missing 1-prong τ decays[31] and to the claim by the HRS collaboration[32] for a significant branching ratio for an experimentally related process:

$$HRS:\quad B(\tau^\pm \to \eta\pi^\pm\nu_\tau) = (5.1 \pm 1.0 \pm 1.2)\% \tag{2.5}$$

From (2.4) it is extremely unlikely that the HRS signal could have been due to events in which an extra π^0 is missing. More directly, however, the ARGUS collaboration can use data[33] obtained in observing the decay $\tau^\pm \to \omega\pi^\pm\nu_\tau$ to quote the upper bound[34]

$$ARGUS:\quad B(\tau^\pm \to \eta\pi^\pm\nu_\tau) \lesssim 1.5\%\ . \tag{2.6}$$

2.2. Families of orbitally excited mesons

2.2.1. Mesons made of nonstrange quarks exhibit an impressive sequence of orbital excitations, which may be understood on the basis of a rotating relativistic string of chromodynamic flux.[35] In Figure 5 we plot the spin J of isoscalar and isovector mesons with even and odd G-parity, on the basis of data quoted in Refs. 2 and 36-39.

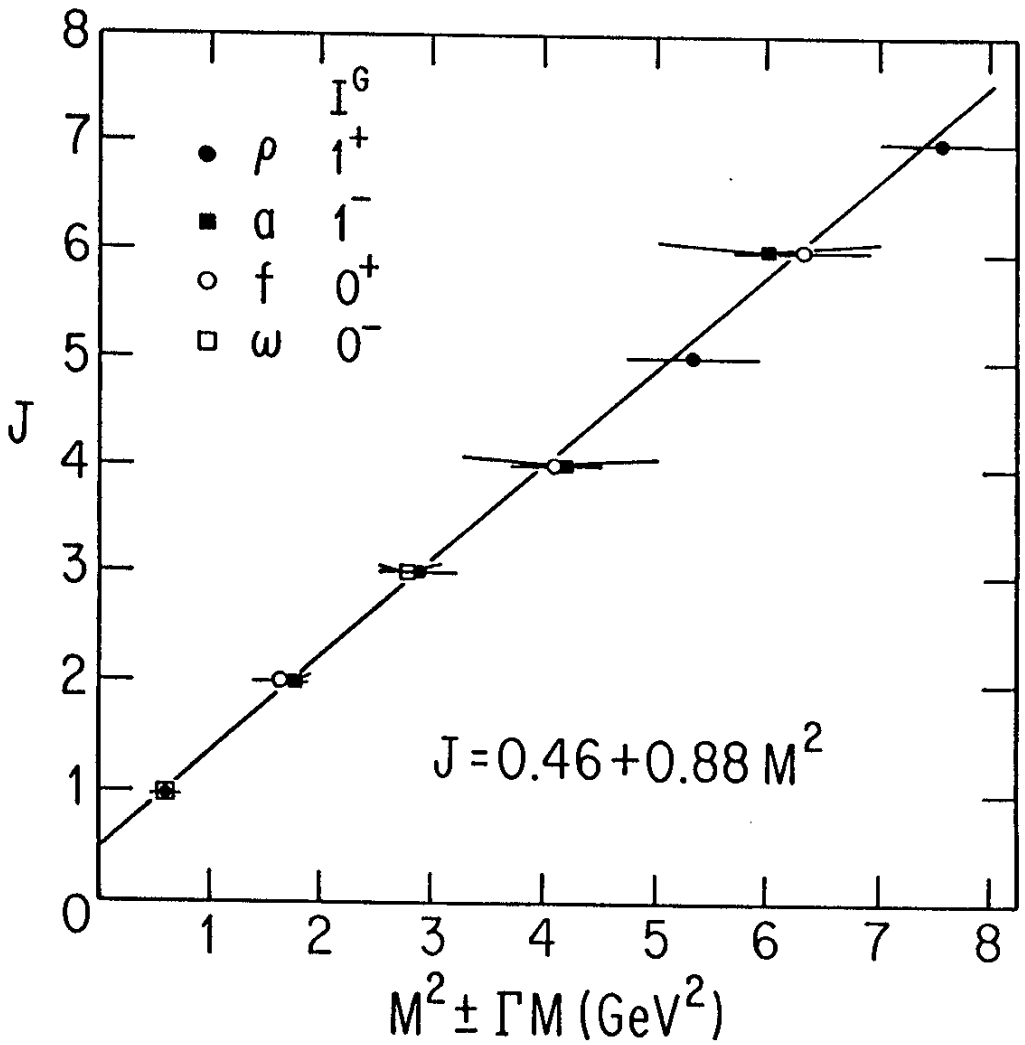

Figure 5. Linear Regge trajectory of mesons composed of nonstrange quarks.

A linear Regge trajectory

$$J = 0.46 + 0.88\ M^2 \tag{2.7}$$

describes states with $1 \leq J \leq 7$, corresponding to orbital excitations $0 \leq L \leq 6$ for spin-triplet quark-antiquark pairs. The slope $dJ/dM^2 = \alpha'$ corresponds to a string tension:

$$k = 1/(2\pi\alpha') = 0.18\ GeV^2\ , \tag{2.8}$$

a parameter of fundamental interest in lattice gauge theories and other nonperturbative approaches. Nearly the same value of α' characterizes several nonstrange baryon trajectories, for which evidence has existed for a number of years.[2]

2.2.2. *Strange mesons* lie on the linear Regge trajectory

$$J = 0.32 + 0.84\ M^2 \tag{2.9}$$

shown in Figure 6.[40]

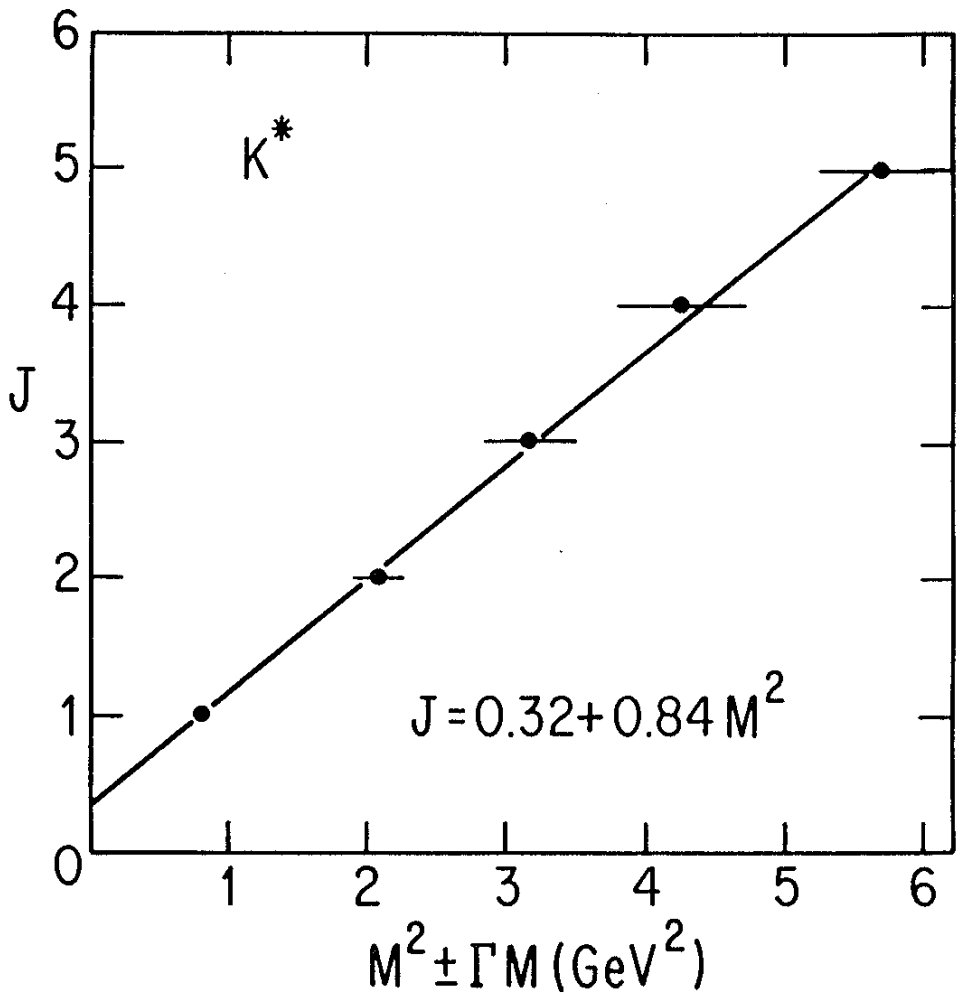

Figure 6. Linear Regge trajectory of strange mesons.

The LASS collaboration[41] has pointed out an interesting feature of $K\eta$ couplings of the states along this trajectory. The spin-2 state, $K_2^*(1420)$, does not appear to couple to $K\eta$, with a $K\eta/K\pi$ ratio less than 0.9%. An enormous $K\eta$ signal is seen for $K_3^*(1780)$, however, corresponding to

$$r_3 \equiv \frac{\Gamma[K_3^*(1780) \to K\eta]}{\Gamma[K_3^*(1780) \to K\pi]} = 0.40 \pm 0.15 \quad . \tag{2.10}$$

This is exactly as one expects in $SU(3)$. For an even-spin K^*, the contributions of the nonstrange and strange quarks in the η will be destructive, while they will be constructive for the odd-spin K^*. If we write

$$\eta = \eta_8 \cos\theta + \eta_1 \sin\theta \quad , \tag{2.11a}$$

$$\eta' = -\eta_8 \sin\theta + \eta_1 \cos\theta \quad , \tag{2.11b}$$

where $\eta_8 \equiv (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$, $\eta_1 \equiv (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, we expect

$$r_2 \equiv \frac{\Gamma[K_2^*(1420) \to K\eta]}{\Gamma[K_2^*(1420) \to K\pi]} = \frac{1}{9}\left[\frac{p_\eta^{(2)}}{p_\pi^{(2)}}\right]^5 (\cos\theta - 2\sqrt{2}\sin\theta)^2 = (0.033)\,(\cos\theta - 2\sqrt{2}\sin\theta)^2 \tag{2.12}$$

where $p_\eta^{(2)}$ and $p_\pi^{(2)}$ are the respective c.m. momenta for $K\eta$ and $K\pi$ decay of K_2^*. The experimental limit $r_2 \lesssim 0.9\%$ implies $\theta \gtrsim 10^0$, in accord with estimates[42,43] of $\theta \approx 19$–20^0 based on other decays involving η. At the same time, we expect $r_3 = (p_\eta^{(3)}/p_\pi^{(3)})^7 \cos^2\theta = 0.42\ \cos^2\theta$, in excellent accord with the result (2.10).

The decay of $K_4^*(2060)$ to $K\eta$ should be suppressed, by the same argument as that leading to Eq. (2.12). On the other hand, the $K_4^*(2060)$ should be visible in the $K\eta'$ final state. We predict

$$r_4' \equiv \frac{\Gamma[K_4^*(2060) \to K\eta']}{\Gamma[K_4^*(2060) \to K\pi]} = \frac{8}{9}\left[\frac{p_{\eta'}^{(4)}}{p_\pi^{(4)}}\right]^9 (\cos\theta + \frac{\sin\theta}{2\sqrt{2}})^2 \ , \qquad (2.13)$$

which should lead to an observable rate. There is also a spin-zero state $K_0^*(1950)$ reported by the LASS group, which may play a significant role in neutral D (charmed meson) decay. It has been pointed out that this state should have a significant $K\eta'$ decay mode, so one expects to see a large branching ratio (several percent) for $D^0 \to \bar{K}^0\eta'$.

The importance of final state interactions in charmed particle decays has been stressed[44] for a number of years, and will be noted in Section 3.2.4. The $\bar{K}^0\eta'$ mode was mentioned explicitly by Lipkin in the second of Refs. 44 and at this Conference.

2.2.3. Mesons composed of $s\bar{s}$ form an orbital excitation series shown in Figure 7.

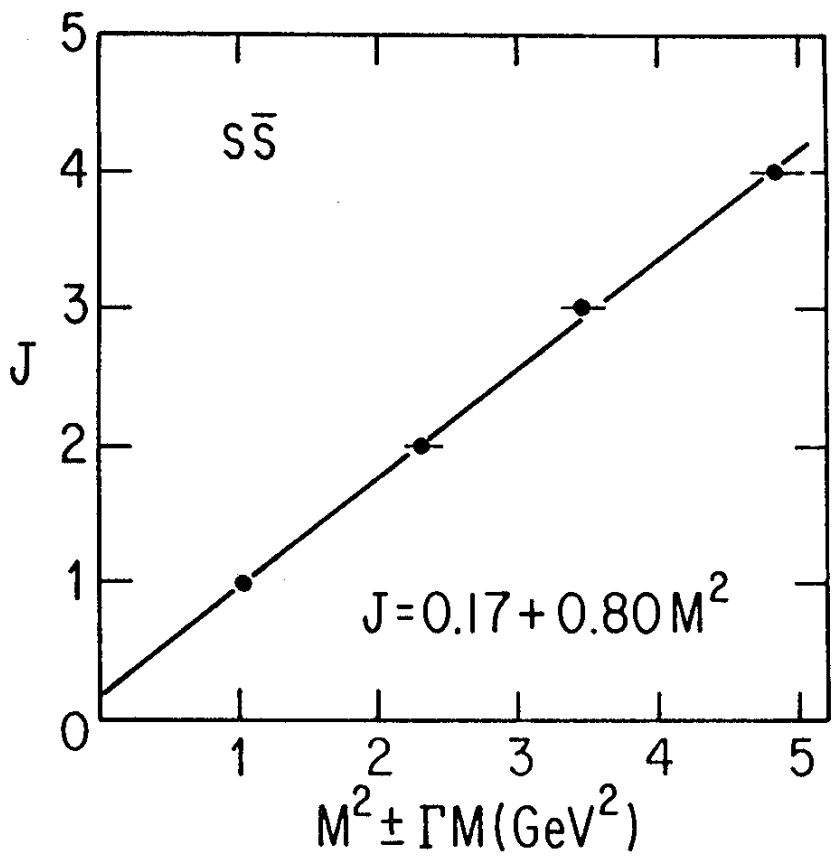

Figure 7. Linear Regge trajectory of $s\bar{s}$ mesons.

The highest level in this series is a recent candidate[41] for a $J^{PC} = 4^{++}$ state seen in the K^-K^+ spectrum of $K^-p \rightarrow K^-K^+\Lambda$, with $m(K^-K^+) = 2.2\ GeV/c^2$. This is the interesting region in which many other states have been observed, including a narrow peak ("$\xi(2.2)$") in K^-K^+ and K_SK_S seen by Mark III,[45] a broader enhancement in $K\overline{K}$ seen by both Mark III and DM2,[45,46] a resonance in $\eta\eta'$ seen by the GAMS collaboration,[6,47] and various $\phi\phi$ enhancements.[48–50] Some of these may be gluonic bound states or exotic particles; their interpretation is still uncertain.

2.3. Low-energy $\bar{p}p$ annihilations

2.3.1 Searches for narrow states in proton-antiproton annihilations have been performed, with negative results.[51,52]

2.3.2. Annihilation from a carefully controlled initial state is now possible at the ASTERIX experiment at LEAR.[52] A model for resonance decays proposed sometime ago[53] envisions a hadronic vertex as involving the creation or annihilation of a quark pair with the quantum numbers of the vacuum, or $^3P_0$. This model is illustrated for proton-antiproton annihilations[54] in Figure 8.

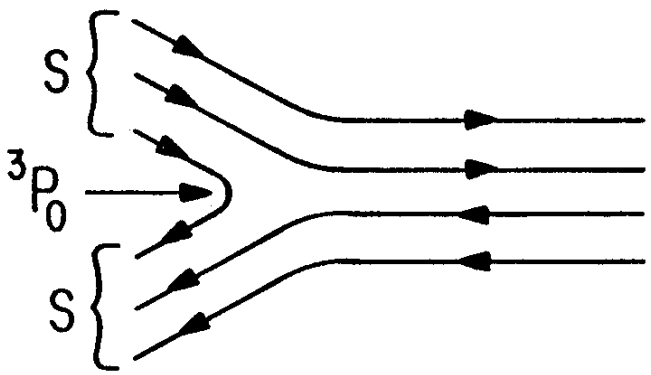

Figure 8. Diagram favoring P-state proton-antiproton annihilations at rest.

By utilizing a gas jet target, the ASTERIX Collaboration has managed to reduce the effect of Stark mixing, thereby enhancing P-state annihilation and the relative importance of the graph of Figure 8. Under such circumstances, the ratio of the rates $\Gamma(\bar{p}p \rightarrow K^+K^-)/\Gamma(\bar{p}p \rightarrow \pi^+\pi^-)$ is 17%. If in addition, one demands that an L X-ray be present (corresponding to the atomic transition $3D \rightarrow 2P$ preceding the annihilation), this ratio drops to 8%. The presence of an L X-ray is a good signal that a given $\bar{p}p$ atom has escaped Stark mixing. In liquid hydrogen, where Stark mixing is more important, the $K^+K^-/\pi^+\pi^-$ ratio is 26%. Now, the K^+K^- final state cannot occur via Figure 8, whereas $\pi^+\pi^-$ can. The suppression of the K^+K^- mode in cases where Stark mixing is unimportant thus is some evidence that the mechanism of Figure 8 plays an essential role in $\bar{p}p$ annihilation at rest.

The production of πf_2 and $\pi\rho$ can also be compared in S-state and P-state annihilation at rest. The ratio of $\bar{p}p \rightarrow \pi f_2$ to $\bar{p}p \rightarrow \pi\rho$ is higher when P-state annihilation is enhanced (as in a gas jet) than when S-waves dominate (as in liquid hydrogen). The I=0 πf_2 state has $J^P = 2^-$ and thus requires D-wave $\bar{p}p$ annihilation; states with $l(\pi f_2) = 1$ include ones accessible from $\bar{p}p$ P-waves. It requires $l(\pi f_2) \geq 2$ to produce any state accessible from S-wave $\bar{p}p$ annihilation. By contrast, the I=0 $\pi\rho$ state can be reached via the $\bar{p}p$ $^3P_1$ state, while $l(\pi\rho) = 1$ states include ones accessible from $\bar{p}p$ S-waves.

2.4. Two-photon processes

2.4.1. Measurements of $\gamma\gamma \to \pi^0, \eta, \eta'$ have been reviewed at this conference,[55] with the result[42,43,55] that the η and η' can be viewed as octet-singlet mixtures (2.11) with a mixing angle of $\theta \simeq 19^0$.

2.4.2. The processes $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$ have been measured.[55,56] Particularly interesting is the behavior of $\sigma(\gamma\gamma \to \pi^0\pi^0)$, which rises rapidly near threshold to an approximately energy-independent value of about 20 *nb* until the lower edge of the $f_2(1270)$ is reached a bit below $E_{\pi\pi} = 0.9\ GeV$. This process looks very promising for determining whether there is resonant behavior in the $I_{\pi\pi} = 0\ S$ wave below 1 *GeV*.[5,57–59]

2.4.3. Glueball tests can be made using $\gamma\gamma$ reactions. If a resonance X shows up strongly in other processes (particularly in $J/\psi \to \gamma X$) but not in $\gamma\gamma \to X$, it is a glueball candidate. At present in $K\bar{K}\pi$ and $\eta\pi\pi$ final states all resonances (aside from $f_2'(1525)$) above 1 *GeV* must then be considered as glueball candidates, since none of them shows up in $\gamma\gamma$ reactions. Specifically, for $\iota/\eta(1460)$,[60]

$$\Gamma[\iota \to \gamma\gamma]\ B(\iota \to K\bar{K}\pi) < 1.6\ keV. \tag{2.14}$$

For states at 1280 or 1400 *MeV* decaying to $\eta\pi\pi$, the corresponding upper limits are 0.3 *keV*.[61] At some level one should see the two photon couplings of quarkonium radial excitations of π^0, η, and η'; we do not yet know whether to be troubled by their absence.

2.4.4. Excitation of a state at 1420 MeV appears to proceed in two-photon processes if one of the photons is virtual.[62] Since two real photons cannot couple to a $J=1$ state[63] but no such selection rule forbids such a coupling if one photon is virtual, the state is assumed to have $J=1$. It could either be the $J^{PC} = 1^{++}$ meson mentioned earlier ("E") or a hybrid $J^{PC} = 1^{-+}$ state.[64,65] Estimates of its coupling to $\gamma\gamma^*$ are consistent with those expected for a quark-model 1^{++} state.[64]

2.5. Glueballs

2.5.1. The $\eta'(958)$ may contain a small gluonic component.[66] If we write

$$|\eta,\eta'\rangle = X_{\eta,\eta'}|(u\bar{u} + d\bar{d})/\sqrt{2}\rangle + Y_{\eta,\eta'}|s\bar{s}\rangle + Z_{\eta,\eta'}|G\rangle\ , \tag{2.15}$$

where G represents the "inert" or gluonic component, analysis of $J/\psi \to 0^-1^-$ decays[67] gives:

	Mark III:[68]	DM2:[69]	
$\lvert X_\eta \rvert =$	0.63 ± 0.06	0.61 ± 0.03	(2.16a)
$\lvert Y_\eta \rvert =$	0.83 ± 0.13	0.77 ± 0.12	(2.16b)
$\lvert X_{\eta'} \rvert =$	0.36 ± 0.05	0.39 ± 0.05	(2.16c)
$\lvert Y_{\eta'} \rvert =$	0.72 ± 0.12	0.69 ± 0.11	(2.16d)
$X_\eta^2 + Y_\eta^2 =$	1.09 ± 0.23	0.97 ± 0.19	(2.16e)
$X_{\eta'}^2 + Y_{\eta'}^2 =$	0.65 ± 0.18	0.63 ± 0.16	(2.16f)

The deviation of the numbers in (2.16f) from 1 could indicate the presence of glue in the η'.

Objections have been raised[43] to the above method, invoking the possibility of "double-OZI-violating" graphs in which the J/ψ, the 0^- meson, and the 1^- meson are connected to one another only via gluons. A free parameter is introduced in order to take account of this effect. Independently, one has some cause to doubt that the values of $|X_{\eta}'|$ are as low as shown in Eq. (2.16c), since $\eta' \to \rho\gamma$ and $\eta' \to \gamma\gamma$ decays lead to the conclusion [42,43,66] $X_{\eta'} \simeq 0.6$. The totality of radiative decays in fact leads us to suspect that *if* the η' is relatively free of glue, then

$$X_{\eta} = 0.8 \qquad Y_{\eta} = -0.6$$
$$X_{\eta'} = 0.6 \qquad Y_{\eta'} = 0.8 \ , \tag{2.17}$$

corresponding to the singlet-octet mixing angle of 19^0 mentioned earlier.

An independent test of the strange quark content of η' is needed, since radiative decays provide almost no constraints on $Y_{\eta'}$. It has been suggested[70] that the rare process $\phi \to \eta'\gamma$ could provide this test. We predict[66]

$$B(\phi \to \eta'\gamma) \simeq (7\times10^{-5})\, Y_{\eta'}^2/Y_{\eta}^2 \ , \tag{2.18}$$

or a branching ratio in excess of 10^{-4} for the values (2.17). Several million ϕ's, perhaps available in the future at Novosibirsk or at a dedicated ϕ factory, would be needed to observe the $\eta'\gamma$ decay mode. A ϕ factory would have independent value for CP violation studies.[71]

2.5.2. The $\iota(1460)$ is a good candidate for a $J^{PC} = 0^{-+}$ glueball.[4,72] It is copiously produced in radiative J/ψ decays and absent in $\gamma\gamma$ collisions. There appear to be too many isoscalar 0^{-+} states to be accommodated by a quark-antiquark picture. [For $1S$ $q\bar{q}$ levels we propose η and η'; for $2S$, $\eta(1280)$ and $\eta(\sim 1400)$.] On the other hand, it is true that there also appear to be too many 1^{++} I=0 levels for a $q\bar{q}$ picture. None of these [$f_1(1285)$, $E/f_1'(1420)$, $D'/f_1'(1530)$] is a good glueball candidate.

2.5.3. Candidates for scalar glueballs abound.[4–7,47,72,73] The GAMS collaboration has presented data at this Conference[6] and elsewhere[47,73] with respect to states at 1590 and 1750 *MeV* seen in $\pi^-p \to \eta\eta n$, $\pi^-p \to \eta\eta' n$, and $\pi^-p \to (4\pi^0)n$. It has been stresed (Yu. Prokoshkin, private communication) that modes such as $\eta\eta$, $\eta\eta'$, and $4\pi^0$ are particularly favorable for glueball searches, and indeed the spectra in these modes look somewhat different from those involving kaons or charged pions. Lattice gauge theories find the 0^{++} glueball the easiest to predict, with masses between 1 and 1.6 GeV/c^2 expected.[74]

The state at 1590 *MeV* is not seen in central hadron collisions.[75] One would expect a glueball to show up in such a reaction.

2.5.4. The $\theta/f_2(1720)$ passes most tests for a tensor (2^{++}) glueball, including its production in radiative J/ψ decays and in central hadron collisions.[75] Its suppressed $\pi\pi$ decay (in comparison with its $K\bar{K}$ and $\eta\eta$ modes) could be ascribed to a form-factor effect[76] which favors the emission of additional pions when a hadron materializes into nonstrange quarks. Perhaps such an effect is responsible for the curious ratio[77]

$$\Gamma(D^0 \to \pi^+\pi^-)/\Gamma(D^0 \to K^+K^-) = 0.27 \pm 0.11 \ . \tag{2.19}$$

Alternatively, the $\pi\pi$ decay of the θ/f_2 could be suppressed if it mixes primarily with nonstrange quarks[78,79] or with both strange and nonstrange quarks in certain combinations.[80] We will have to wait for lattice QCD results involving dynamical fermions to see if such mixing is plausible.

The properties of the $\theta/f_2(1720)$ can be said to have been anticipated well in advance of QCD. In fact, this state is a candidate for the first physical particle lying on the Pomeranchuk trajectory,[81]

or *Pomeron.*

The Pomeron was proposed in order to account for the approximate constancy of total cross sections σ_T at high energy. Accordingly, it must have intercept 1. It has been shown that a Pomeron slope half that of $q\bar{q}$ Regge trajectories (such as those illustrated in Figures 5-7) is expected.[82,83] If we then take a *linear* trajectory

$$J(M^2) = 1 + 0.44\, M^2 \ , \tag{2.20}$$

we expect a $J^P = 2^+$ particle lying on the Pomeron around 1.5 *GeV*. This particle probably mixes with the $f_2(1270)$,[78,83] thereby being raised in mass. The $\theta/f_2(1720)$ is a good candidate for it. Models of the Pomeron as a "glue-ring"[84] or as an effect due to two-gluon exchange[85] in fact have been proposed some time ago.

The Pomeron trajectory is expected to result only in even-spin physical particles. If a linear trajectory of the form (2.20) can be extended to $J^P = 4^+$, one expects such a particle at 2.6 *GeV*. [A linear Pomeron trajectory passing through zero mass at $J = 1$ and $\theta/f_2(1720)$ at $J=2$ would have a $J^P = 4^+$ particle at $M = \sqrt{3}(1720) = 2980\ MeV$.] It would be difficult to observe in J/ψ radiative decays but might show up in $\Upsilon \to \gamma +$ (hadrons).

The ratio of 2^{++} to 0^{++} glueball masses in lattice gauge theories and bag models is a subject of some discussion, with most estimates placing the 2^{++} higher.[86] The 2^{++} masses have not yet been estimated in the most recent calculations on large lattices reported at this Conference.[87]

2.6. Baryons

2.6.1. Ξ^* *resonances* are predicted in abundance by quark models,[1,88] with a recent set of expected masses and decay channels shown in Figure 9.

Until recently it has been difficult to study Ξ^*'s since no means of forming them in the direct channel has been available. States for which a fair amount of information has existed are denoted by an asterisk in Figure 9. These include the Ξ (1320, $1/2^+$), Ξ (1530, $3/2^+$), Ξ (1820, $3/2^-$[*?*]), and Ξ (2030) (J^P unknown, indicated by the solid arrow).

New data from the CERN hyperon beam[89] relate to the states shown by dashed arrows (J^P unknown) or shaded boxes (J^P known or assumed) in Figure 9. All of these appear to be diffractively produced. There is a $J^P = 1/2^+$ radial excitation candidate at 1690 *MeV*, and a $5/2^+$ candidate at 1960 *MeV*. The J^P of the state at 1820 *MeV* is confirmed to be $3/2^-$. States at 1783 and 2180 *MeV*, with unknown J^P, are also produced. The series $1/2^+$, $3/2^-$, $5/2^+$,... is what would be expected[90] if diffractive excitation gives quarks an orbital "kick".[91]

2.6.2. Ω^* *resonances* have now been identified by the CERN and LASS groups.[92,93] Predictions for masses and decay channels are shown in Figure 10. The new states are seen in the $\Xi^-\pi^+K^-$ decay mode.

The lower state (around 2250–2260 *MeV*) could be a radial excitation of the familiar $\Omega(1672)$, first observed in 1963. The model of Ref. 88 places the first radial excitation of the Ω only about 400 *MeV* above it, but other models[94] predict a larger spacing. The mass difference is just about the same as that between $1S$ and $2S$ levels in $c\bar{c}$ and $b\bar{b}$, as one might expect on the basis of phenomenological potentials.[95]

2.6.3. Skyrmions have been remarkably successful in describing relations among meson-baryon partial-wave scattering amplitudes in the resonance region.[96–98] Typical of these is the relation for pion-nucleon amplitudes denoted by L_{2I2J}:

$$F_{35} = \frac{1}{7}\, F_{15} + \frac{6}{7}\, F_{17} \tag{2.21a}$$

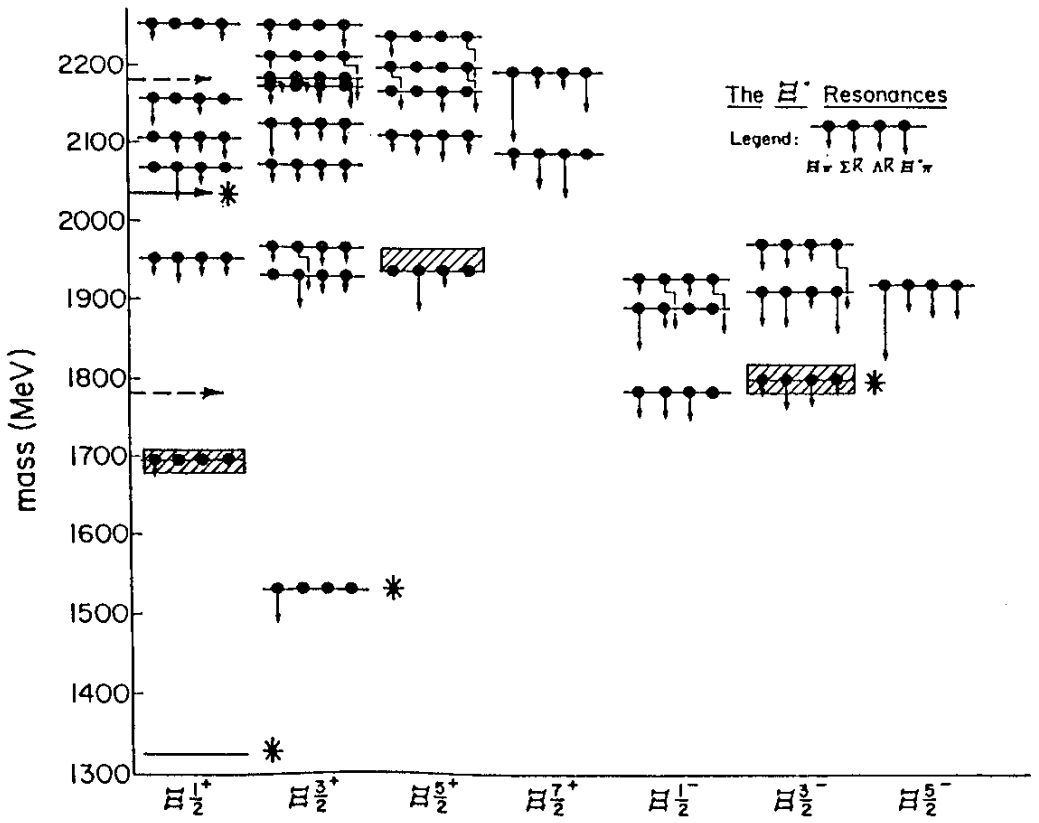

Figure 9. Masses and decay channels expected for the lowest-lying Ξ^* resonances. The abscissa denotes values of J^P. See text for symbols. From Ref. 88.

$$F_{37} = \frac{9}{14} F_{15} + \frac{5}{14} F_{17} \ , \tag{2.21b}$$

consistent with the observed experimental pattern. Relations of the type (2.21) appear to be best satisfied for the highest partial waves at a given energy. They reproduce an interesting "big-small-small-big" pattern illustrated in Table 1.

Table 1. Magnitudes of pion-nucleon partial wave amplitudes in the Skyrme model

Isospin	1/2	1/2	3/2	3/2
J	L - 1/2	L + 1/2	L - 1/2	L + 1/2
Magnitude	Big	Small	Small	Big
Examples	D_{13} F_{15} G_{17}	D_{15} F_{17} G_{19}	D_{33} F_{35} G_{37}	D_{35} F_{37} G_{39}

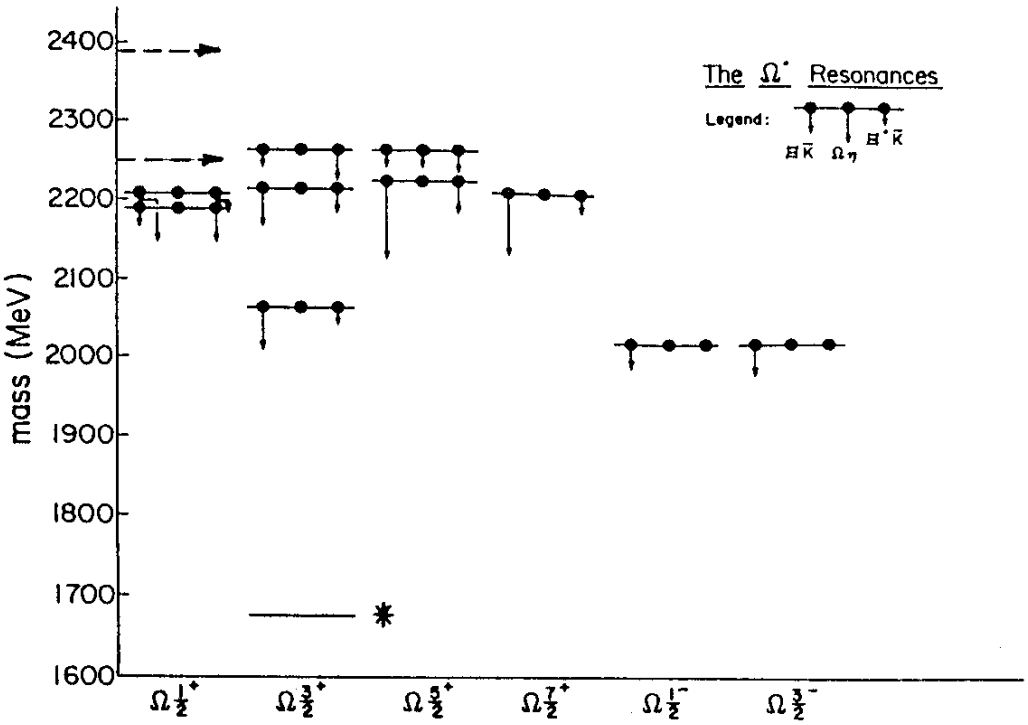

Figure 10. Predicted masses and decay channels (Ref. 88) for Ω^* resonances. Dashed arrows denote masses of states reported in Refs. 92 and 93. The asterisk denotes the previously known $\Omega(1672)$.

Quark models lead to a similar though not identical pattern. A low-mass D_{35} resonance is not expected in the quark model, but one does seem to be observed below 2 *GeV* in the c.m.[99] The presence of all four partial waves in Eq. (2.21) requires both 56- and 70-dimensional multiplets of $SU(6)$ with $L(qqq) = 2$. Now, $SU(6)$ alone only predicts relations among **56** and among **70** resonance couplings, but not between the two.[100] Relations between **56** and **70** $L(qqq) = 2$ couplings follow from a harmonic-oscillator quark model[101] and from duality between exchanged and direct-channel baryons in scattering processes.[102,103] The relations are identical. In Table 2 we show relative partial widths to πN (in arbitrary units) for various qqq states with L=2.

Table 2. Relative partial widths to πN of L=2 qqq states (arbitrary units)

Partial wave	$^{2S+1}SU(6)$ representation	$\Gamma_{\pi N}$	Partial wave	$^{2S+1}SU(6)$ representation	$\Gamma_{\pi N}$
F_{15}	^{2}56	175	F_{35}	^{4}56	16
	^{2}70	56		^{2}70	7
	^{4}70	2		^{2}70	7
F_{37}	^{4}56	72	F_{17}	^{4}70	9

The F_{15} and F_{37} resonances (except for ^{4}70) have large πN partial widths, while the F_{35} and F_{17}

states have small ones.

The Skyrme model has had many other impressive successes in describing scattering amplitudes, as in $\bar{K}N$ scattering, relations between πN and $\bar{K}N$ amplitudes, and resonant phases in $\pi N \to \pi\Delta$. In this last process, quark models have been able to correlate a wealth of data with one another,[104] but there has always remained some inconsistency[105] between resonance phases inferred from $\pi N \to \pi\Delta$ and those inferred from $\gamma N \to \pi N$. It would be interesting to examine Skyrme model predictions for photocouplings of nucleon resonances to see if this question is resolved in that model.

A decidedly "non-quark" prediction of the Skyrme model[98] is that there should be an exotic F_{05} resonance in KN scattering. Present phase shift analyses are mute on this point.

The beginnings of a description of hyperon radiative decays via the Skyrme model have been made.[106] Agreement with experiment is generally adequate except for the (best-measured) process $\Sigma^+ \to p\gamma$. We await further tests of the model through experiments at CERN and Fermilab.

2.7. Exotics and hybrids

While a number of claimed candidates exist for exotic (non-$q\bar{q}$ or qqq) and hybrid (e.g., $q\bar{q}$-gluon) resonances, none is firmly established. Relatively straightforward tests of the identity of these candidates are possible.

2.7.1. States $X(1480\ [0^{++}?])$, $X(1650\ [0^{++}, 2^{++}?])$ decaying to $\rho^0\rho^0$ have been proposed as possible admixtures of isospin 0 and 2.[107] If there are indeed well-defined $I = 2$ resonance states at such low masses they should be visible in the $\rho^\pm\rho^\pm$ mode in reactions such as $\pi^+p \to \rho^+\rho^+n$ and $\bar{p}n \to \rho^-\rho^-\pi^+$.

2.7.2. A narrow peak at 3.1 *GeV*, decaying to $\Lambda\bar{p}$ + (pions), was reported some time ago and discussed at this Conference.[108,109] The effect appears to have $I = 3/2$, making it a candidate for a $qq\bar{q}\bar{q}$ state.[110,111] Such objects, coupling to baryon-antibaryon pairs, were proposed some time ago,[112] but the mystery is why this particular resonance should be narrow when it lies so far above baryon-antibaryon threshold.

One suggestion recently resurrected[110] is that $qq\bar{q}\bar{q}$ states in which qq is coupled to a color sextet (and $\bar{q}\bar{q}$ to a 6^*) are somehow stabilized by high orbital angular momenta between the qq and $\bar{q}\bar{q}$ systems, so that rearrangement to $(qq)_3\cdot(\bar{q}\bar{q})_3$ is inhibited. It would be useful to see if dynamical theories (e.g., lattice gauge theories) are consistent with this suggestion. One would expect the chromodynamic force between two quarks in a sextet to be repulsive, for one thing.[111]

It has also been proposed[111] that the 3.1 *GeV* peak could involve a $(qq)_3\cdot(\bar{q}\bar{q})_3$ configuration whose decay to baryon pairs is inhibited by angular momentum considerations alone. An orbital series is proposed, with the mass of the state X_L with orbital angular momentum L between $(qq)_3$· and $(\bar{q}\bar{q})_3$ given by

$$M(X_L) \simeq \frac{3}{4}\, m_\rho + \frac{1}{4}\, m_\pi + M(K_L^*) \tag{2.22}$$

to ± 100 *MeV*. The $X(3.1)$ would be the $L = 4$ state, with predicted mass 2991 *MeV*. States with $L = (2, 3)$ at (2390, 2673) *MeV* would not have been observed because they are presumed broader. The difficulty with this interpretation is that the corresponding K^* states do *not* become markedly narrower at higher mass. The $L = (2, 3, 4)$ states depicted in Figure 6 (corresponding to $J = (3,4,5)$) have widths $\Gamma = (185.9 \pm 23.3 \pm 12.3,\ 221 \pm 48 \pm 27,\ 178 \pm 37 \pm 32)$ *MeV*.[40]

New experiments to confirm the state at 3.1 *GeV* will be mounted at CERN and perhaps Fermilab.[113] It may be prudent to await their results before speculating further on this curious effect.

2.7.3. $\phi\pi$ and $\eta\pi$ resonances[114,115] around 1.5 *GeV* have been proposed[111] as $qq\bar{q}\bar{q}$ states, specifically as $J^{PC} = 1^{--}$ and 1^{-+} members, respectively, of a $10 + 10^*$ multiplet of flavor $SU(3)$. If this suggestion is correct, one should observe $J^P = 1^-$ strangeness ± 2 resonances decaying to K^+K^0 or $K^-\bar{K}^0$, and $J^P = 1^-$ $I = 1/2$ and 3/2 states of strangeness ± 1.

2.7.4. The H (a proposed $\Lambda\Lambda$ bound state) has been a subject of controversy ever since the original suggestion[116] that one could gain chromomagnetic binding energy by recoupling quark spins in two Λ's. Preliminary results of new lattice calculations[87] suggest that the H is indeed bound, in contrast to an earlier result[117] based on a smaller lattice. At this point what is needed is not only reliable lattice calculations, but experiments designed to search for the H at the required level of sensitivity.[118] Earlier searches[119] have now been deemed inadequate.[120]

2.7.5. A $\bar{c}suud$ or $\bar{c}sudd$ baryon has been proposed[111] as a $\bar{D}_s N$ or $\bar{D}\Lambda$ bound state (thus lying below 2.9 *GeV*). The argument is based on color-spin, and gives as much binding as for the H in the $SU(3)$ limit. Such a particle should live (a few) $\times 10^{-13}s$ and have decay products typical of $\bar{D}_s N$ or $\bar{D}\Lambda$ final states.

2.7.6. Hybrids (candidates for $q\bar{q}g$ states) would include states with $J^{PC} = 1^{-+}$, which cannot be formed as $q\bar{q}$ composites. Candidates proposed at this Conference for such states include the $K\bar{K}\pi$ resonance at 1420 *MeV*, formed in $\gamma - \gamma^*$ collisions,[65] and the $\eta\pi$ state at 1410 *MeV*,[115] both mentioned earlier. There have been sensitive searches with negative results for such states up to about 1.5 *GeV*, in which the states are produced via the Primakoff effect by incident pions and detected in $\rho\pi$ and $\eta\pi$ modes.[121] It may be necessary to search at higher masses in modes such as $A_1\pi$ and $B\pi$, in which it will be harder to identify the unusual J^{PC} characteristic of a hybrid state.

2.7.7 Molecules of hadrons, as proposed above for a $K\bar{K}\pi$ resonance around 1435 *MeV*, could be widespread. Consider, for example, the prominent $\rho^0\rho^0$ resonance formed in $\gamma\gamma$ collisions just above threshold.[122] The pions in one ρ^0 could easily resonate with those in another, so that the "benzene-like" structure depicted in Figure 11 could result.

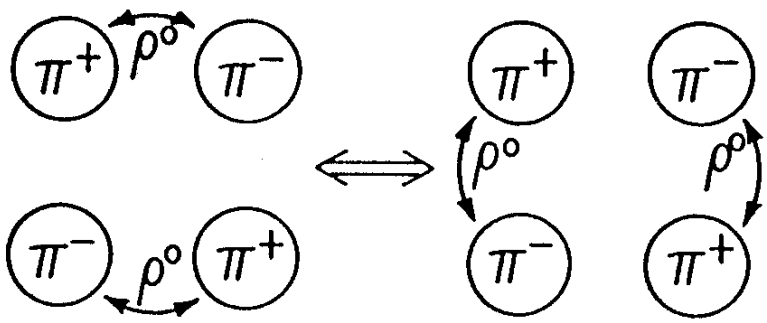

Figure 11. "Molecular" model for a $\rho^0\rho^0$ resonance near threshold.

We would like to know whether such configurations are stable, and what isospins, spins and parities are expected. Here, perhaps, is another challenge for lattice gauge theories.

3. CHARMED QUARKS

3.1. Charmonium levels

3.1.1. The η_c and J/ψ have been observed in their decays to ever more hadronic final states. In particular, the J/ψ has distinguished itself as a superb source of light-quark hadrons, useful particularly for glueball searches.[3,16,123,124]

For the first time, it has been possible to measure the two-photon width of the η_c, both via $\gamma\gamma$ collisions[125] and in $\bar{p}p \to \eta_c \to \gamma\gamma$.[126] The ratio of decay rates

$$\frac{\Gamma(\eta_c \to gg)}{\Gamma(\eta_c \to \gamma\gamma)} = \frac{9[\alpha_s(m_c)]^2}{8\alpha^2}\left[1 + 7.8\frac{\alpha_s}{\pi}\right] = \frac{(11.5 \pm 4.3\ MeV)}{(9 \pm 4\ keV)} = (1.28 \pm 0.74) \times 10^3 \quad (3.1)$$

implies $\alpha_s(m_c) = 0.20^{+0.05}_{-0.06}$, in reasonable accord with other determinations. The value of $\Gamma(\eta_c \to \gamma\gamma)$ itself is close to theoretical expectations.[125,127]

3.1.2. The $^1P_1$ *state of charmonium* may have been found in the last days of ISR running[128] at the expected ^3P_J center-of-gravity,

$$\bar{M}(^3P_J) \equiv [5M(^3P_2) + 3M(^3P_1) + M(^3P_0)]/9$$
$$\simeq 3525\ MeV\ . \quad (3.2)$$

One expects $M(^1P_1) \approx \bar{M}(^3P_J)$ since the spin-spin interaction in quarkonium is proportional to the Laplacian of the potential and hence to $\delta^3(r)$ for $V \sim \alpha_s/r$, as one expects for gluon exchange at short distances. Most potential models which account for logarithmic variations of α_s with r find $M(^1P_1)$ and $\bar{M}(^3P_J)$ to differ by no more than a few MeV in charmonium.[129] A recent prediction[130] that the lowest $^1P_1$ $c\bar{c}$ state lies below 3500 MeV thus is surprising, and will merit checking at a forthcoming Fermilab experiment[131] designed to study charmonium via direct-channel $\bar{p}p$ formation.

A recent thorough investigation of properties of $^1P_1$ quarkonium states was reported at this Conference.[132] It was found that the major decay mode of $c\bar{c}(^1P_1)$ should be $\gamma\eta_c$.

3.1.3. The $^3P_{2,1}$ *charmonium states* have been observed at the *ISR*[126] and more precise information obtained on their total widths. These values are in rough accord with QCD predictions,[133] aside from a χ_2 total width of $2.6^{+1.4}_{-1.0}$ MeV which would seem to imply a value of $\alpha_s(m_c) > 0.3$. This is uncomfortably high for other determinations,[134,135] which imply $\alpha_s(m_c) \lesssim 0.2$. The ISR collaboration has also measured $\Gamma(\chi_2 \to \gamma\gamma) = 2.9^{+1.3}_{-1.0} \pm 1.7\ keV$, leading via a relation similar to (3.1) to the expectation $\alpha_s(m_c) \simeq 0.2$. The present upper bound $\Gamma(\chi_1) < 1.3\ MeV$ lies well above the QCD expectation of $\Gamma(\chi_1) \simeq 1.7\ \alpha_s\Gamma(\chi_2) \simeq 0.32\ \Gamma(\chi_2)$ unless the χ_2 width itself is much too large for the QCD prediction.

3.1.4. The $\psi''(3770)$ is of renewed interest now that more precise branching ratios of D mesons to specific final states have been presented.[136] It is no longer so urgent to ask whether ψ'' can have substantial decay modes besides $D\bar{D}$.[137] Nonetheless, a study of these modes can prove useful. This state is mostly $^3D_1$, but can mix with the 2^3S_1 level. Since the $\psi'(3686)$ is predominantly 2^3S_1 and decays to $\psi\pi\pi$, $\gamma\chi$, and hadrons, one could expect similar decays for the ψ'' at a level which might probe the mixing. It has been suggested that the partial width for $^3D_1 \to \pi\pi^3S_1$ might be quite small,[138] so that $\psi'' \to \psi\pi\pi$ might be a particularly good measure of $^3D_1 - 2^3S_1$ mixing.

3.1.5. Prospects for physics at the ψ' include the more precise measurement of angular distributions in $\psi' \to \gamma\chi \to \gamma\gamma J/\psi$, in order to probe the small admixture of magnetic quadrupole ($M2$) amplitudes expected along with the dominant $E1$ amplitudes.[139] Such an experiment is one more way to measure the charmed quark magnetic moment. Others include the study of $M1$ transitions such as

$(J/\psi, \psi') \rightarrow \gamma\eta_c$ and $\psi' \rightarrow \eta_c'$, which seem to be somewhat suppressed in comparison with naive expectations,[140] and the direct measurement of the Λ_c magnetic moment, expected to be $\mu(\Lambda_c) \approx \mu(c)$, which poses an interesting experimental challenge.

3.2. Charmed particles

3.2.1. Hadronic cross sections for charm production appear to range from $\sigma_T(pp \rightarrow charm) = 20$ to 100 μb for $\sqrt{s} = 28$ to 63 GeV.[141]

3.2.2. Lifetimes of charmed hadrons are being measured with increasing precision, primarily as a result of sensitive vertex detection techniques.[142,143] It appears that[144]

$$\tau(\Lambda_c) \lesssim 0.2\ ps < \tau(D^0, D_s^+) \approx 0.4\ ps < \tau(D^+) \approx 1\ ps \quad . \tag{3.3}$$

This hierarchy of lifetimes can be understood in part as illustrated in Figure 12.

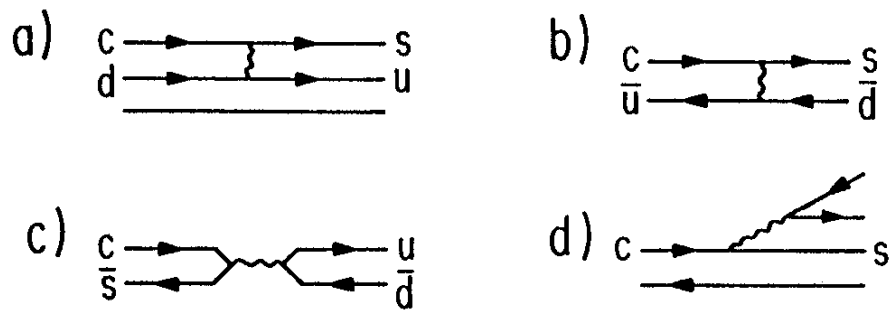

Figure 12. Diagrams illustrating possible contributions to weak decays of charmed particles. (a) Λ_c, (b) D^0, (c) D_s, (d) D^+.

The four-quark process has been estimated to lead to a satisfactorily short Λ_c lifetime (Figure 12a) when added to other contributions.[145] An open question is whether such processes are important in D^0 and D_s decays (Figures 12b, c). If so, one might expect 3π to be an important decay mode of D_s. On the other hand, the non-exotic nature of the D^0 and D_s final states may be sufficient reason for their shorter lifetime than D^+, whose Cabibbo-favored final states have isospin 3/2.[146] Only the "spectator" process illustrated in Figure 12d can contribute to D^+ decay, and the D^+ lifetime in fact agrees with a free-quark estimate.[127] Further mechanisms proposed to account for charmed particle lifetime differences have been reviewed in Refs. 127 and 147.

3.2.3. $D^0 - \bar{D}^0$ mixing has recently been studied with great precision in Fermilab E–691.[148] The rate for $D^0 \rightarrow \bar{D}^0$ transitions (and hence for appearance of wrong-sign kaons in decays) has been measured to be less than 1/2%. The small wrong-sign kaon signal that is observed in E–691 (and also by the Mark III collaboration at SPEAR[149]) can be ascribed unambiguously to double-Cabibbo-suppressed decays, since it is present immediately after D^0 production in the Fermilab experiment. (The identity of the produced D^0 or $\bar{D}^0$ is determined by whether it was associated with a π^+ or a π^- in a charged D^*.) By contrast, a wrong-sign kaon signal due to mixing would grow initially as t^2, where t is the time difference between production and decay.

3.2.4. Branching ratios of charmed particles as measured by the Mark III collaboration[136,147] have decreased by about 20% (for D^0) and 24% (for D^+) from values quoted earlier.[150] As a result, the possibility of a "charm deficit" in B decays[150] is much less likely.[147]

Detailed Dalitz-plot analyses of three-body charm decays were presented at this Conference.[151] While many of these processes appear to be dominated by quasi-two-body final states, others (such as $D^+ \to K^-\pi^+\pi^+$) clearly have large non-resonant contributions. Together with the new, lower Mark III branching ratios, this observation suggests that one pay more attention to multi-body charm decays.

Branching ratios for D_s decays may be expected soon, as a result of studies by the Mark III Collaboration of $D_s\bar{D}_s^* + D_s^*\bar{D}_s$ production in e^+e^- annihilation.[151a] New values of the $D_s^* - D_s$ mass difference,[147,151a]

$$M(D_s^*) - M(D_s) = \begin{cases} 144 \pm 9 \pm 7\ MeV (ARGUS) \\ 137.9 \pm 2.1 \pm 4.3\ MeV\ (Mark\ III) \end{cases} \tag{3.4}$$

are consistent with an empirical rule[152]

$$M^2(1^-) - M^2(0^-) \simeq 0.55 - 0.6\ GeV^2 \tag{3.5}$$

obeyed for systems containing at least one light (u, d, s) quark.[153]

Final state interactions appear to be crucial in the description of charmed particle decays. One can see, for example, by comparing $D^0 \to K^-K^+$, $D^0 \to \bar{K}^0\pi^0$, and $D^+ \to \bar{K}^0\pi^+$ rates that the amplitudes for $I = 1/2$ and 3/2 final states cannot be relatively real.[44] The presence of a $J^P = 0^+$ state in $K^-\pi^+$ phase shift analyses around 1950 MeV[41] is another reminder that individual resonance states can be important. Even in the limit of overlapping resonances, however, one expects the phases of $K\pi$ scattering amplitudes to differ in exotic and non-exotic channels,[154] and this phase difference is likely to persist in individual partial waves.

As mentioned in Section 2.2.2, if $D^0 \to K^-\pi^+$ decays are dominated by an $I = 1/2$ $J^P = 0^+$ resonance near the D^0 mass, one expects

$$\frac{\Gamma(D^0 \to \bar{K}^0\eta')}{\Gamma(D^0 \to \bar{K}\pi)} = \frac{8}{9}\left(\frac{p_{\eta'}}{p_\pi}\right) = \frac{8}{9}\left(\frac{564\ MeV}{859\ MeV}\right) = 0.58 \tag{3.6}$$

in the limit in which η' is an unmixed $q\bar{q}$ flavor singlet. Here

$$\Gamma(D^0 \to \bar{K}\pi) = \Gamma(D^0 \to K^-\pi^+) + \Gamma(D^0 \to \bar{K}^0\pi^0) \simeq (6\text{–}7\%)\Gamma(D^0)\ . \tag{3.7}$$

Thus we expect

$$B(D^0 \to \bar{K}^0\eta') = (3\text{–}4)\% \quad . \tag{3.8}$$

A corollary of $I = 1/2$ dominance is the relation $\Gamma(D^0 \to \bar{K}^0\pi^0) = \Gamma(D^0 \to K^-\pi^+)/2$, consistent with present data.

3.2.5. The P-wave D mesons (with $J^P = 0^+$, 1^+, and 2^+) should be showing up in new data from ARGUS, CLEO, and Fermilab E–691. The spectroscopy of these states[155] has not made much progress since a candidate was reported at 2420 MeV by the ARGUS group.[156]

3.2.6. The decays $D^* \to D\gamma$ are worthy of renewed study. At this Conference[157] the HRS Collaboration presented the value $B(D^{*0} \to D^0\gamma) = 0.47 \pm 0.23$, in accord with the published average[2] of 0.485 ± 0.076, and an upper limit $\Gamma(D^{*0}) < 1.5\ MeV$ (90% *c.l.*) based on the upper limit $\Gamma(D^{*0} \to D^+\pi^-) < 15\%$. [If the D^{*0} were broad enough, one would expect its $D^+\pi^-$ decay to be allowed.]

The tabulated value[2] $B(D^{*+} \to D^+\gamma) = 0.17 \pm 0.11$ is of little statistical significance except that it affects inferred branching ratios for $D^{*+} \to D\pi$, and hence indirectly influences quantitative estimates in much of charm (and even b) physics. On theoretical grounds[155,158,159] one expects

$1\% < B(D^{*+} \to D^+\gamma) < 5\%$. It is worth remeasuring this branching ratio!

4. THE b QUARK

4.1. $b\bar{b}$ Levels

A recent review of Υ spectroscopy[160] treats the subject in great detail. In what follows we discuss mainly the results reported at this Conference.

4.1.1. The 1S, 2S, and 3S levels of the Υ family have been seen with excellent mass resolution in hadronic production in Fermilab experiment E–605.[161] No other narrow peaks have been spotted in e^+e^- or $\mu^+\mu^-$ spectra up to $M \approx 16\ GeV$, at a level of a few percent of the Drell-Yan cross section. The copious observation of the $3S$ level suggests that if Υ levels are produced hadronically at least in part from electromagnetic decays of χ_b states, then the $\chi_b''(3P)$ level must be below flavor threshold, as is expected in potential models.

The CUSB group[162] has presented new values of $B_{\mu\mu}$ for the $\Upsilon(1S)$, $\Upsilon'(2S)$, and $\Upsilon''(3S)$, all compatible with $\alpha_s(m_b) = 0.17 - 0.18$ and $\Lambda_{\overline{MS}}$ in the range[147] of 120 to 200 MeV. Similar values are obtained[147] from ratios

$$R_\gamma \equiv \frac{\Gamma(\Upsilon \to \gamma gg)}{\Gamma(\Upsilon \to ggg)} = \begin{cases} (2.93 \pm 0.12 \pm 0.18)\%\ (ARGUS)^{147} \\ (2.54 \pm 0.18 \pm 0.14)\%\ (CLEO)^{163} \\ (2.99 \pm 0.59)\%\ (CUSB)^{164} \end{cases}$$

$$= \frac{4}{5}\,\frac{\alpha}{\alpha_s(m_b)}\,[1 - 2.8\,\frac{\alpha_s}{\pi}] \quad , \tag{4.1}$$

where the correction is evaluated in Ref. 135. Here it appears important to use the photon energy spectrum calculated by Field;[165] others[166] are not in accord with the data.

4.1.2. The $\chi_b'(2P)$ levels have been studied by the CUSB collaboration,[162] with more information expected soon from a new run of CESR at the $\Upsilon(3S)$. The preliminary value of

$$r \equiv \frac{M(\chi_2) - M(\chi_1)}{M(\chi_1) - M(\chi_0)} = 0.57 \pm 0.06 \tag{4.2}$$

is less than that (0.67 ± 0.06) observed for the $\chi_b(1P)$ levels,[2] which might suggest a greater role for scalar confinement in the (spatially larger) $2P$ states. The expected value for a vector interaction is $r = 0.8$.[167]

4.1.3. The 1^1P_1 state of $b\bar{b}$, for which preliminary evidence has been presented by the CLEO Collaboration,[168] has been discussed at this Conference.[132] The $\pi\pi$ mass spectrum in $\Upsilon(3S) \to \pi\pi\ 1^1P_1$ is predicted to peak at low $m_{\pi\pi}$. This is as one would expect if the $\pi\pi$ system is in a state with $J^P = 0^+$. The transition $\Upsilon(1^-) \to \pi\pi(0^+) + {}^1P_1(1^+)$ then must involve a P-wave between the dipion and the ${}^1P_1$ system, favoring large relative momenta between the dipion and the ${}^1P_1$ state, and hence low dipion masses. A *selection* of low dipion masses thus might well enhance the feeble 1^1P_1 signal.[168]

4.1.4. Prospects for observing $1^3D_{1,2,3}$ states depend on the ability of various detectors to see the decay chain

$$3S \xrightarrow[\gamma_1]{} 2P \xrightarrow[\gamma_2]{} 1D\ (10.16\ GeV)\ , \tag{4.3}$$

where each photon has about 100 *MeV* of energy, followed by the decay

$$1D \xrightarrow[\gamma_3]{} 1P \tag{4.4}$$

or

$$1D \xrightarrow[\pi\pi]{} \Upsilon \quad , \tag{4.5}$$

where the photon in (4.4) has $E_\gamma \simeq 250\ MeV$.

A strong centrifugal barrier is expected in the decays

$$^3D_{2,3} \rightarrow (\pi\pi)_{0^+} + \Upsilon \quad , \tag{4.6}$$

with $l = 2$ required between the dipion and the upsilon. Values of J^P other than 0^+ for the dipion are very unlikely in view of the restriction $m_{\pi\pi} < 0.7\ GeV$ for this decay. Thus, one expects at the very least the decays (4.6) to be characterized by extremely low $m_{\pi\pi}$. In fact, however, the rates themselves may be quite low. Billoire *et al.* have estimated[138] $\Gamma(1^3D_J \rightarrow \pi\pi\Upsilon) \simeq 0.07\ keV$ for the $J = 1$ level *as well as* for the $J = 2,3$ levels. The value for $J = 1$ is substantially lower than another that appears in the literature.[169] The combination of electromagnetic cascades (4.3) and (4.4) is then the favored method for finding the lowest D-wave $b\bar{b}$ states. These levels are important since (a) their center of gravity is predicted to within 10 *MeV* by potential models,[127] (b) their fine structure would tell us more about the long-range forces that confine quarks, and (c) the decay $1^3D_1 \rightarrow l^+l^-$ is expected to have a partial width of 1.5 *eV*,[170] making the observation of this state in lepton pairs just barely possible in the distant future. It will be important to distinguish this narrow state from a Higgs boson, though the property $\Gamma(1^3D_1 \rightarrow e^+e^-) = \Gamma(1^3D_1 \rightarrow \mu^+\mu^-)[\simeq \Gamma(1^3D_1 \rightarrow \tau^+\tau^-)]$ should allow this distinction to be made once the state is first seen.

4.2. B mesons: Evidence for $B_d - \bar{B}_d$ mixing

4.2.1. The ARGUS collaboration has presented evidence for $B_d - \bar{B}_d$ mixing[171] at a level far higher than originally estimated.[172–174] The B_d's were produced in pairs in the reaction

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d\bar{B}_d \quad . \tag{4.7}$$

Three methods were used to conclude that mixing was present. In the first, one B^0B^0 pair was fully reconstructed. This represents a *tour de force*, since both B^0's decayed semileptonically. In the second, the rates for same-sign and opposite-sign lepton pairs were compared with one another. The observed ratio

$$r_d \equiv \frac{\Gamma(B_d^0\bar{B}_d^0|_{t=0} \rightarrow l^\pm l^\pm + \ldots)}{\Gamma(B_d^0\bar{B}_d^0|_{t=0} \rightarrow l^+l^- + \ldots)} = 0.22 \pm 0.09 \pm 0.04 \tag{4.8}$$

is related to $x_d = (\Delta M/\Gamma)_{B_d}$ (in the limit when $|\Delta\Gamma| \ll |\Delta M|$) by[175]

$$r_d = x_d^2/(2 + x_d^2) \tag{4.9}$$

for $B_d\bar{B}_d$ pairs produced in a state with $J^{PC} = 1^{--}$.

A third method used to demonstrate mixing involves the reconstruction of one B and the observation of the semileptonic decay of the other. The signal of 4.1 ± 2.2 events (one additional event is ascribed to background) corresponds to $r_d = (20 \pm 12)\%$.

Combining the three methods, the ARGUS collaboration concludes $r_d = 0.21 \pm 0.08$ (> 0.09, 90% *c.l.*), or

$$(\Delta M/\Gamma)_{B_d} \geq 0.44 \ (90\% \ c.l.) \ . \tag{4.10}$$

The most "standard" explanation of the large $B_d - \bar{B}_d$ mixing rate is that the t quark is heavier than previously thought. Estimates presented at this conference[172,173] and elsewhere[176] range from $m_t > 30\ GeV$[173] to $m_t > 100\ GeV$[172] as minimum values able to accommodate the observed mixing via W loops. My own estimate is that one requires $m_t > 70\ GeV$. It is based on the following assumptions. (1) We take[174]

$$\left[\frac{\Delta M}{\Gamma}\right]_{B_d} = 0.035 \left[\frac{m_t}{40\ GeV}\right]^2 f(m_t^2/m_W^2) \left[\frac{f_B}{100\ MeV}\right]^2 \frac{\tau_B}{1.16\times10^{-12}s} \times [(1-\rho)^2 + \eta^2] \quad , \tag{4.11}$$

where $f(x)$ is a function which corrects for the finite W-mass,[177]

$$f(x) = \frac{1}{4} + \frac{9}{4(1-x)} - \frac{3}{2}\frac{1}{(1-x)^2} + \frac{3}{2}\frac{x^2 \log x}{(x-1)^3} \ , \tag{4.12}$$

and the KM element V_{td} has been taken as[178] $V_{td} = 0.011[(1-\rho) - i\eta]$; (2) We assume $f_B \leq 130\ MeV$,[179] $\tau_B \leq 1.3 \times 10^{-12}s$; (3) We take $\rho \geq -0.8$, and η negligibly small for the purposes of (4.11). This last constraint is compatible with the observed value of the CP-violating parameter ε in neutral K decays.[172] We then find $(\Delta M/\Gamma)_{B_d} \geq 0.5$ for $m_t \geq 70\ GeV$.

The above constraint on m_t would, of course, be relaxed if a fourth generation were found to exist, since less stringent bounds on $|V_{td}|$ would hold. A recent analysis of models with more than three generations may be found in Ref. 180.

At this Conference, Hagiwara[172] and Hara[173] have reminded us of other constraints on B mixing that follow from an observation of a signal by the UA1 Collaboration,[181] and upper bounds by Mark II and CLEO.[182] A large value of $(\Delta M/\Gamma)_{B_d}$ may imply too much mixing in the $B_s - \bar{B}_s$ system to be compatible with the Mark II limit, which involves some weighted average of B_d and B_s contributions. It will be interesting to see the value of x_d obtained by the CLEO Collaboration from their present run on the $\Upsilon(4S)$.

5. FUTURE SPECTROSCOPIES

5.1. The t quark

5.1.1. The $t\bar{t}$ system has been anticipated eagerly over the years as a source of information about the short-distance static quark-antiquark interaction.[183] More recently, the possibility that $t\bar{t}$ levels may mix with the Z has received attention.[184] It now appears that one may wish to wait for the discovery of the t quark before proceeding further. Initial reports of its observation between 30 and 50 GeV[185] have not been confirmed.[186] If the t quark is very heavy, $t\bar{t}$ spectroscopy will be difficult, as a result of the rapid beta-decay of individual t quarks in the system.

5.1.2. A heavy t quark may be related to the scale of W and other quark masses. Many programs, notably those based on supersymmetry,[187] have made use of this possibility. The t quark mass can set the scale for a negative value of μ^2 in the electroweak Lagrangian, thereby triggering electroweak symmetry breaking.

5.2. A fourth generation

5.2.1. Charged leptons L_4 of a fourth generation appear to be excluded up to a mass of 41 GeV,[188] but only if their corresponding neutrinos ν_4 are light. Bounds on a sequential charged

lepton that would follow from UA1 data if ν_4 is massive have been explored in Ref. 189.

5.2.2. Neutrinos of a fourth generation can be searched for in $e^+e^- \to Z_0^{virtual} \to \nu_4\bar{\nu}_4$, as the example of Ref. 190 shows, and in real Z decays.

5.2.3. A charge -1/3 quark b' could be responsible for some unusual events seen at the highest PETRA energies.[191] If so, it (and the structure of $b'\bar{b}'$ levels[174]) will be discovered at TRISTAN.

5.3. Fermions in superstring-E_6

The known generations of quarks and leptons would belong in E_6 grand unified models (such as suggested by superstrings) to a 27-dimensional representation, which contains several exotic species of quarks and leptons.[192]

5.3.1. Charged exotic leptons $E^{\pm}$ of both chiralities (left and right) belong to weak isodoublets. Consequently they do not exhibit forward-backward asymmetries in $e^+e^- \to E^+E^-$.

5.3.2. Neutral exotic leptons of both weak isodoublet and weak isosinglet types are expected. The weak isodoublets can be easily produced via a virtual Z in e^+e^- annihilations, or in real Z decays.

5.3.3. A weak isosinglet charge -1/3 quark h is expected in E_6. It could be the source of the unusual PETRA events[191] mentioned above. It would form $h\bar{h}$ levels.

5.4. Exotic quarks

5.4.1. Scalar quarks $\tilde{q}$ could form bound states[193] $\tilde{q}\bar{\tilde{q}}$ with a familiar potential but different level structure (since they are spinless). The lowest $\tilde{q}\bar{\tilde{q}}$ state is spinless and thus is not easily produced in e^+e^- annihilations. The P-wave $\tilde{q}\bar{\tilde{q}}$ states have very small leptonic widths.

5.4.2. Color sextet quarks are not expected in superstring theories. The negative results of axion searches may be used to exclude certain mass ranges of color sextet quarks.[194] Thus they are particularly interesting to look for directly, as in e^+e^- annihilations.

5.5. Spectroscopies beyond QCD

5.5.1. The electroweak scale may be a replay of QCD, but at about 2500 times the energy. Longitudinal W's and Z's and the Higgs boson may be analogous to the low-energy limit of hadron physics, involving pions and a σ (the old σ-model).[195] If that is so, there may be much more in store for us at the *TeV* scale than just a Higgs particle. We eagerly await the means to explore this new scale.

5.5.2. Quarks and leptons themselves possess a complex level structure every bit as rich as the hadrons of the early 1950's. We have no idea what it will take to probe this structure experimentally, but center-of-mass energies of at least a *TeV* seem a necessary, if not sufficient, condition, except in the study of certain rare processes like $K_L \to \mu e$.

6. SUMMARY

This conference has demonstrated that there is a bright future for hadron spectroscopy at laboratories around the world. KEK has already given us new insights into meson and baryon spectra, and we look forward to the successful operation of TRISTAN as a probe of new spectroscopies in the 50-70 GeV range. Results may be anticipated as well from SLC, LEP, CESR, the forthcoming Beijing e^+e^- collider, BNL, Fermilab, and machines that will begin operating in the 1990's. Detailed calculations in lattice QCD are just now beginning to confront experimental data on the hadron spectrum, but it is important to realize that older techniques have not lost their validity.

It has been a pleasure spending these three days among people who know what a hadron is. Questions that were asked as long as twenty or more years ago are actually being answered, thanks to the patient efforts of experimentalists and theorists. We need to be more bold in sharing these pleasures with students, for the study of new spectroscopies - just now beginning - builds on the old.

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