

LIGHT HADRON SPECTROSCOPY

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Rapporteur talk at the Lepton-Photon Conference, Rome, July 2001: reviewing the evidence and strategies for understanding scalar mesons, glueballs and hybrids, the gluonic Pomeron and the interplay of heavy flavours and light hadron dynamics. Dedicated to the memory of Nathan Isgur, long-time collaborator and friend, whose original ideas in hadron spectroscopy formed the basis for much of the talk.

1 The Spectroscopy of Gluonic Excitations

What is the nature of confinement, in particular the role of gluonic degrees of freedom in the strong interaction limit of QCD? After decades of searches, a new generation of precision data has transformed this field in the last five years. In this talk I shall propose a potential solution to the problem of how glue is manifested and develop an experimental strategy to test it. The strategy involves a variety of complementary experiments, ranging from $\gamma\gamma$ to electromagnetic production at Jefferson Lab and other moderate energy dedicated machines, such as DAΦNE, to high energy innovative experiments at RHIC, Fermilab and possibly even the LHC, which should enable it to be refuted, refined or even substantially confirmed. The scope of my talk will be to discuss what theory expects, what the experimental situation is and what the new challenges for experiment are in light of these.

Our main intuition on the strong interaction limit of QCD derives from Lattice QCD which implies a linear potential for $q\bar{q}$ systems¹. This is well established for heavy flavours, where data confirm it. However, we are given a gift of Nature in that as one comes from heavy to light flavours, the linear potential continues phenomenologically to un-

derpin the data: the S-P-D gaps are similar for $b\bar{b}$, $c\bar{c}$, and even $u\bar{d}$ as can be verified by looking in the PDG tables^{2,3}. Even though we have no fundamental understanding of why this is, we can nonetheless accept the gift and be confident that we can assign light flavoured mesons of given J^{PC} to the required "slot" in the spectrum⁴. I shall not review here the current status of $q\bar{q}$ spectroscopy as I am not interested in stamp collecting; all I wish to note at this point is that the resulting pattern leads one to expect that the lightest $J^{PC} \ ^3P_0 \ q\bar{q}$ nonet should occur in the region above 1 GeV - of which more in a moment.

Not everything is independent of flavour. The $^3S_1 - ^1S_0$ mass gap grows as the flavours get lighter, a phenomenon that is understood, at least qualitatively, from the chromomagnetic effects of gluon exchange^{2,3}. Apart from this hint, gluonic effects have been all but absent - until now.

As the Coulomb potential of electrostatics implies that the electric fields tend to fill all three dimensions of space, so the linear potential implies that the analogous chromoelectric fields are highly collimated. This gave rise to the models where confinement arises from flux tubes^{5,6}. There are now hints from the lattice⁸ that such flux tubes indeed form, at least between static massive quarks. It is then almost model independent⁹ that

excitations of the flux tubes, analogous to phonons, will occur. The resulting new families are known as “hybrids”^{6,10}. I shall discuss the evidence in section 1.1

Lattice QCD predictions for the mass of the lightest (scalar) glueball are now mature. In the quenched approximation the mass is $\sim 1.6\text{GeV}$ ^{11,12,13,14,15}. Flux tube models imply that if there is a $q\bar{q}$ nonet nearby, with the same J^{PC} as the glueball, then $G - q\bar{q}$ mixing will dominate the decay¹⁶. This is found more generally¹⁷ and recent studies on coarse-grained lattices appear to confirm that there is indeed significant mixing between G and $q\bar{q}$ together with associated mass shifts, at least for the scalar sector¹⁸.

Precision data on scalar meson production and decay are consistent with this and the challenge now centres on clarifying the details and extent of such mixing. As there have been several developments here recently, I shall devote much of my talk to the question of scalar mesons, following the discussion of hybrids.

1.1 Hybrid Mesons

Qualitatively the energy for their excitation will be of order $\frac{\pi}{R}$ where R is the length scale between the quark coloured sources. This leads inexorably to the typical mass scale for light flavoured hybrids at or just below 2GeV , with hybrid charmonium at $\sim 4\text{ GeV}$. Hybrid D_g and B_g heavy flavours will also exist but are beyond the scope of this talk.

Hybrid states allow the existence of J^{PC} correlations, such as $0^{+-}, 1^{-+}, 2^{+-}$ that are forbidden for conventional mesons. The flux-tube model predicts that the lightest exotic hybrid, $J^{PC} = 1^{-+}$, lies just below 2GeV ^{19,7}; this is in accord with the heuristic argument above and, perhaps more significantly, with

lattice QCD^{20,21,22} for which $1^{-+} s\bar{s}$ has mass $2.0 \pm 0.2\text{ GeV}$ (and so the $n\bar{n}$ would be expected some 200 to 300 MeV lower). There should also be states that are gluonic excitations of the $\pi, \rho, 0^{-+}, 1^{-+}$ ^{23,10}. During the last two years evidence for exotic 1^{-+} has emerged from more than one experiment and in various channels.

Two experiments^{24,25} have evidence for $\pi_1(1600) \equiv 1^{-+}$ in the $\rho^0\pi^-$ channel in the reaction $\pi^- N \rightarrow (\pi^+\pi^-\pi^-)N$. At Serpukhov a $40\text{ GeV}/c$ π^- beam shows this resonant $\pi_1(1600)$ also in $\pi\eta'$ and $\pi b_1(1235)$, and at BNL the $\pi\eta'$ channel is also observed.

At BNL the channel $\pi f_1(1285)$ showed resonant 1^{-+} but nearer to 1800 MeV in mass¹⁰. Resonant 1^{-+} also shows up in two experiments in the $\pi\eta$ channel^{26,27} but around 1400 MeV .

It is the proliferation of evidence that leads to the consensus that a resonant exotic state has been found. One possibility is that the hybrid state is, in line with the lattice, $\sim 1.6 - 1.8\text{GeV}$ in mass and the $\pi f_1(1285)$ channel, which opens up in S-wave at 1420 MeV with 1^{-+} quantum numbers, is playing some role in disturbing the phase shifts in the various channels. These are details to be settled; the consensus is that an exotic 1^{-+} resonance is being manifested in different decay modes.

The question now is whether it is a true hybrid or more mundane, such as $qq\bar{q}\bar{q}$ or a molecular state of two mesons. To answer this question requires evidence in other channels - that is how we have historically determined the constituent nature of the “traditional” mesons (after all, you could ask of any meson, “how can I tell if it is $q\bar{q}$ or a molecular combination of other mesons?”). The answers come when it is seen to be produced in a variety of processes, with common s-

channel properties, and when the pattern of decays reveals its flavour content, in particular that it is not dominant in a single channel, as would be expected for a molecule. I shall return to this question later.

There are also tantalizing hints of $\pi_g, 0^{-+}$ at 1.8 GeV and $\rho_g, 1^{--}$ in the 1.45 - 1.7 GeV states. The former is seen prominently in unusual channels like $\pi f_0(980); \pi f_0(1500); KK_0^*; \pi\sigma$ and not in $\pi\rho; KK^*$; such patterns are as predicted for hybrids and contrast strongly with those expected of conventional mesons^{10,28}. Adding further support to the hypothesis that a hybrid 0^{-+} is being seen, is the evidence²⁹ for two isovector 0^{-+} states, $\pi(1600)$ and $\pi(1800)$ where the quark model predicts only one.

Whatever the $\pi(1800)$ is, its existence should concern anyone who is interested in D-decays. The D and π_g are degenerate and so the Cabibbo suppressed decays of the D may be affected³⁰. It is therefore important to determine the pattern of decays of the π_g and to compare with the Cabibbo suppressed modes of the D; e.g. the prominent $\pi\sigma$ in $D^+ \rightarrow \pi^-\pi^+\pi^+$ ⁴⁵. Similar remarks may apply to the D_s and the (as yet unseen) K_g strange partner.

The phenomenology of the vector mesons in the 1.45-1.7 GeV region seems to require hybrid content. One of the driving features is that a conventional 1^{--} has the $q\bar{q}$ with $S=1$, whereas for a hybrid it is the gluonic degrees of freedom that give the net $J=1$ while the $q\bar{q}$ are coupled to spin zero. This different internal structure gives rise to characteristic properties, which appear to be realized in the data^{31,10}. This should be a source of active future study for DAΦNE or VEPP. Conversely, the exotic 1^{-+} has $S_{q\bar{q}} = 1$ and so there is the possibility that photons can produce the $q\bar{q}$ conveniently in the spin triplet

state; ω or π exchange at low energies can be an entree into the hybrid sector. Thus photo and electroproduction at Jefferson Lab, in their 6 GeV programme and especially at a 12 GeV upgrade, will be exciting^{6,10,2}.

1.2 Glueballs

The third, and most well advertised, aspect of glue is the prediction that there exist glueballs (or in flux tube language, glue loops)³². The lattice has matured and converged on the following. The lightest glueball, in the quenched approximation, is predicted to be 0^{++} with a mass in the 1.4 - 1.7 GeV region; the next lightest being $2^{++}, 0^{-+}$ at around 2 GeV^{1,11,12,13,14}. There has been considerable progress in this area, especially as concerns the scalar glueball.

A problem is that the maturity of the $q\bar{q}$ spectrum, as already mentioned, tells us that we anticipate the $0^{++}, q\bar{q}$ nonet to occur in the 1.3 to 1.7 GeV region. Any such states will have widths and so will mix with a scalar glueball in the same mass range. It turns out that such mixing will lead to three physical isoscalar states with rather characteristic flavour content^{13,33}. Specifically; two will have the $n\bar{n}$ and $s\bar{s}$ in phase (“singlet tendency”), their mixings with the glueball having opposite relative phases; the third state will have the $n\bar{n}$ and $s\bar{s}$ out of phase (“octet tendency”) with the glueball tending to decouple in the limit of infinite mixing. There are now clear sightings of prominent scalar resonances $f_0(1500)$ and $f_0(1710)$ and, probably also, $f_0(1370)$. (Confirming the resonant status of the latter is one of the critical pieces needed to clinch the proof - see ref.³⁴ and later). The production and decays of these states is in remarkable agreement with this flavour scenario³³.

Were this the whole story on the scalar

sector there would be no doubt that the glueball has revealed itself. However, there are features of the scalars in the region from two pion threshold up to $O(1)\text{GeV}$ that have clouded the issue. There has been considerable recent progress here that enable a consistent picture to be proposed. I will now set the scene for this and return later to the experimental challenges.

2 Scalar Mesons: Above and Below 1 GeV

To understand the message of the $J = 0^{++}$ data one must distinguish the regions above and below 1 GeV, typified by the $K\bar{K}$ threshold.

The $q\bar{q} \ ^3P_0$ nonet is expected in the 1.3 - 1.7 GeV mass region. There is empirically a nonet (at least) and we shall return to this later. If that was the whole story then the scalar spectroscopy would be understood. But there are also the $f_0(980)$ and $a_0(980)$ mesons, and possibly a κ and σ below 1 GeV. (While the σ is claimed in recent data, there are conflicting conclusions about the κ ³⁵; a theoretical critique is in ref.³⁶). Various attempts have been made to describe them as a $q\bar{q}$ nonet shifted to low mass by some mechanism. While one cannot formally disprove such a picture, it ignores a fundamental aspect of QCD that appears to be realized in the data.

As pointed out by Jaffe³⁷ long ago, there is a strong QCD attraction among qq and $q\bar{q}$ in S-wave, 0^{++} , whereby a low lying nonet of scalars may be expected. As far as the quantum numbers are concerned these states will be like two $0^{-+} q\bar{q}$ mesons in S-wave. In the latter spirit, Isgur and Weinstein³⁸ had noticed that they could motivate an attraction among such mesons, to the extent that the $f_0(980)$ and $a_0(980)$ could be interpreted as

$K\bar{K}$ molecules.

The relationship between these is being debated^{39,40,41,42,43}, and I shall contribute to it here, but while the details may be argued about, there is a rather compelling message of the data as follows. Below 1 GeV the phenomena point clearly towards an S-wave attraction among two quarks and two antiquarks (either as $(qq)^3(\bar{q}\bar{q})^3$, or $(q\bar{q})^1(\bar{q}\bar{q})^1$ where superscripts denote their colour state), while above 1 GeV it is the P-wave $q\bar{q}$ that is manifested. There is a critical distinction between them: the “ideal” flavour pattern of a $q\bar{q}$ nonet on the one hand, and of a $qq\bar{q}\bar{q}$ or meson-meson, nonet on the other, are radically different; in effect they are flavoured inversions of one another. Thus whereas the former has a single $s\bar{s}$ heaviest, with strange in the middle and and I=0; I=1 set lightest (“ ϕ ; K ; ω , ρ -like”), the latter has the I=0; I=1 set heaviest ($K\bar{K}$; $\pi\eta$ or $s\bar{s}(u\bar{u} \pm d\bar{d})$) with strange in the middle and an isolated I=0 lightest ($\pi\pi$ or $u\bar{u}d\bar{d}$)^{37,38,44}.

The phenomenology of the 0^{++} sector appears to exhibit both of these patterns with $\sim 1\text{GeV}$ being the critical threshold. Below 1 GeV the inverted structure of the four quark dynamics in S-wave is revealed with $f_0(980)$; $a_0(980)$; κ and σ as the labels (for a recent observation of σ in charm decays see ref.⁴⁵, and conflicting claims for the κ are in ref.³⁵). One can debate whether these are truly resonant or instead are the effects of attractive long-range t -channel dynamics between the colour singlet $0^{-+} K\bar{K}$; $K\pi$; $\pi\pi$, but the systematics of the underlying dynamics seems clear. Above 1 GeV the $^3P_0 q\bar{q}$ nonet should be apparent: there are candidates in $a_0(\sim 1400)$; $f_0(1370)$; $K(1430)$; $f_0(1500)$ and $f_0(1710)$. One immediately notes that if all these states are real there is an excess, precisely as would be expected if the glueball predicted by the lattice is mixing in this re-

gion.

A major question is whether the effects of the glueball are localised in this region above 1 GeV, as discussed by ref^{46,33} or spread over a wide range, perhaps down to the $\pi\pi$ threshold⁴⁷. This is the phenomenology frontier. There are also two particular experimental issues that need to be settled: (i) confirm the existence of $a_0(1400)$ and determine its mass (ii) is the $f_0(1370)$ truly resonant or is it a t -channel exchange phenomenon associated with $\rho\rho$ ³⁴.

As concerns the region below 1GeV, the debate centres on whether the phenomena are truly resonant or driven by attractive t -channel exchanges, and if the former, whether they are molecules or $qq\bar{q}\bar{q}$. These are, in my opinion, secondary issues; each points to the strong attraction of QCD in the scalar S-wave nonet channels. The difference between molecules and compact $qq\bar{q}\bar{q}$ will be revealed in the tendency for the former to decay into a single dominant channel - the molecular constituents - while the latter will feed a range of channels driven by the flavour spin clebsch gordans. This is a general means to decide whether an exotic 1^{-+} is a hybrid or a molecule, for example, and for the light scalars has its analogue in the production characteristics.

The picture that is now emerging from both phenomenology^{48,49,50} and theory⁵¹ is that both components are present. As concerns the theory⁵¹, think for example of the two component picture as two channels. One, the quarkish channel (QQ) is somehow associated with the $(qq)^3\bar{q}\bar{q}^3$ coupling of a two quark-two antiquark system, and is where the attraction comes from. The other, the meson-meson channel (MM) could be completely passive (eg, no potential at all). There is some off diagonal potential which flips that system from the QQ channel to MM . The

way the object appears to experiment depends on the strength of the attraction in the QQ channel and the strength of the off-diagonal potential. The nearness of the f_0 and a_0 to $K\bar{K}$ threshold suggests that the QQ component cannot be too dominant, but the fact that there is an attraction at all means that the QQ component cannot be negligible. So in this line of argument, a_0 and f_0 must be four-quark states and $K\bar{K}$ molecules at the same time.

If one adopts this as a reference hypothesis, many data begin to make sense. I shall discuss this in section 4; first I shall concentrate on the glueball search, to decide if a scalar glueball is manifested above 1GeV.

3 Glueball production dynamics

The folklore has been that to enhance glueball signals one should concentrate on production mechanisms where quarks are disfavoured: thus $\psi \rightarrow \gamma G$ ⁵², $p\bar{p} \rightarrow \pi + G$ in annihilation at rest^{52,53}, and central production in diffractive (gluonic pomeron) processes, $pp \rightarrow pGp$ ^{54,53}. Contrasting this, $\gamma\gamma$ production should favour flavoured states such as $q\bar{q}$. Thus observing a state in the first three, which is absent in the latter, would be prima facie evidence.

Such ideas are simplistic. There has been progress in quantifying them and in the associated phenomenology. The central production has matured significantly in the last three years and inspires new experiments at RHIC, Fermilab and possibly even the LHC. Thus I shall concentrate on this, but first show how these complementary processes collectively are now painting a clearer picture.

First on the theoretical front, each of these has threats and opportunities. (i) In $\psi \rightarrow \gamma G$ the gluons are timelike and so it

is reasonable to suppose that glueball will be favoured over $q\bar{q}$ production. Quantification of this has been discussed in ref.⁵⁵ with some tantalising implications: (a) the $f_0(1500)$ and $f_0(1710)$ are produced with strengths consistent with them being $G-q\bar{q}$ mixtures, though there are some inconsistencies between data sets that need to be settled experimentally; (b) the $\xi(2200)$ is produced with a strength consistent with that for a glueball, with two provisos: - that it has spin 2 (which is probably the case), and that it really exists (which is debatable, see section 5).

(ii) In $p\bar{p}$ the q and \bar{q} can rearrange themselves to produce mesons without need for annihilation. So although a light glueball may be produced, it will be in competition with conventional mesons and any mixed state will be produced significantly by its $q\bar{q}$ components.

(iii) In central production the gluons are spacelike and so must rescatter in order to produce either a glueball or $q\bar{q}$. Thus here again one expects competition. However, a kinematic filter has been discovered⁵⁶, which appears able to suppress established $q\bar{q}$ states, when the $q\bar{q}$ are in P and higher waves.

Its essence was that the pattern of resonances produced in the central region of double tagged $pp \rightarrow pMp$ depends on the vector *difference* of the transverse momentum recoil of the final state protons (even at fixed four momentum transfers). When this quantity ($dP_T \equiv |k_{T1} - k_{T2}|$) is large, ($\geq O(\Lambda_{QCD})$), $q\bar{q}$ states are prominent whereas at small dP_T all well established $q\bar{q}$ are observed to be suppressed while the surviving resonances include the enigmatic $f_0(1500)$, $f_0(1710)$ and $f_0(980)$.

The data are consistent with the hypothesis that as $dP_T \rightarrow 0$ all bound states with internal $L > 0$ (e.g. ${}^3P_{0,2} q\bar{q}$) are suppressed while S-waves survive (e.g. 0^{++} or 2^{++} glue-

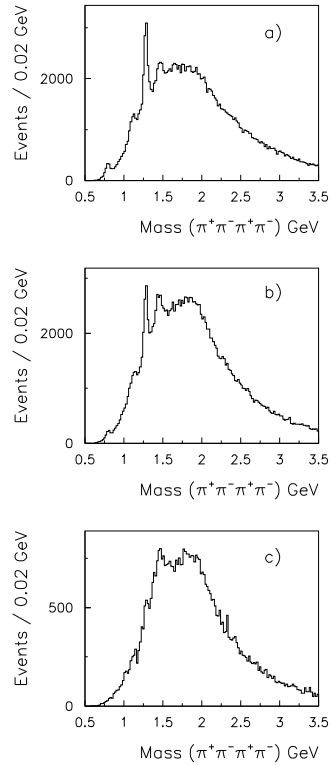


Figure 1. $pp \rightarrow pp + (2\pi^+ 2\pi^0)$. As dP_T decreases from (a) $> 0.5 \text{ GeV}$ to (b) $0.2 < dP_T < 0.5 \text{ GeV}$ and (c) $< 0.2 \text{ GeV}$ the ${}^3P_1(q\bar{q})f_1(1285)$ in (a) disappears while the $f_0(1500)$ and $f_2(1930)$ glueball candidates become prominent.

ball made of vector gluons and the $f_0(980)$ as any of glueball, or S-wave $qq\bar{q}\bar{q}$ or $K\bar{K}$ state). Models are needed to see if such a pattern is natural. As the states that survive this cut appear to have an affinity for S-wave, this may be evidence for $qq\bar{q}\bar{q}$ or $q\bar{q}q\bar{q}$ (as for example the $f_0(980)$) or for gg content (as perhaps in the case of $f_0(1500; 1710)$ and $f_2(1930)$). It would be interesting to study the production of known $q\bar{q}$ states in $e^+e^- \rightarrow e^+Me^-$ to see how they respond to this kinematic filter, and gain possible insights into its dynamics.

Following this discovery there has been an intensive experimental programme in the last three years by the WA102 collaboration at CERN, which has produced a large and

detailed set of data on both the dP_T ⁵⁶ and the azimuthal angle, ϕ , dependence of meson production (where ϕ is the angle between the transverse momentum vectors, p_T , of the two outgoing protons).

The azimuthal dependences as a function of J^{PC} and the momentum transferred at the proton vertices, t , are very striking. As seen in refs. ⁵⁷, and later in this talk, the ϕ distributions for mesons with $J^{PC} = 0^{-+}$ maximise around 90° , 1^{++} at 180° and 2^{-+} at 0° . This is not simply a J-dependent effect ⁵⁸ since 0^{++} production peaks at 0° for some states whereas others are more evenly spread ⁵⁹; 2^{++} established $q\bar{q}$ states peak at 180° whereas the $f_2(1950)$, whose mass may be consistent with the tensor glueball predicted in lattice QCD, peaks at 0° ⁵⁸. These data are all explained if the Pomeron transforms as a non-conserved vector current: specifically, having an intrinsic and important scalar component. The detailed calculations are described in ^{60,61}. Production of the $0^{-+}, 1^{++}, 2^{-+}$ sequence and the absence of a 0^{-+} glueball candidate in these data are now understood; the $0^{++}, 2^{++}$ states, where $q\bar{q}$ and glueballs are expected, are tantalizing. I shall now survey these J^{PC} states in turn.

$$J^{PC} = 0^{-+}$$

Here I shall concentrate on the η' meson whose production has been found to be consistent with double pomeron exchange ⁵⁷. The resulting behaviour of the cross section may be summarised as follows:

$$\frac{d\sigma}{dt_1 dt_2 d\phi} \sim t_1 t_2 G_E^{p2}(t_1) G_E^{p2}(t_2) \sin^2(\phi) \times F^2(t_1, t_2, M^2)$$

where ϕ is the angle between the two pp scattering planes in the P - P centre of mass. pp elastic scattering data and/or a Donnachie

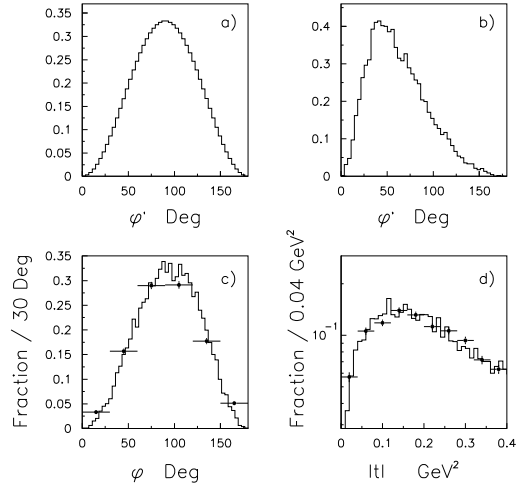


Figure 2. The predicted ϕ' distributions for $J^{PC} = 0^{-+}$ mesons a) naive distribution and b) taking into account the experimental kinematics. c) The ϕ and d) the $|t|$ distributions for the η' for the data (dots) and the model predictions from the Monte Carlo (histogram).

Landshoff type form factor ⁶² can be used as model of the proton- P form factor ($G_E^p(t)$). $F(t_1, t_2, M^2)$ is the P - P - η' form factor, parametrised as $exp^{-b_T(t_1+t_2)}$ where the sole parameter $b_T = 0.5 GeV^{-2}$ in order to describe the t dependence. Fig.(2) compare the final theoretical form for the ϕ distribution and the t dependence with the data for the η' .

Parity requires the vector pomeron to be transversely polarized, which gives rise to the $t_1 t_2$ factors in the cross section. For 0^{-+} states with $M \gg 1 GeV$, as expected for the lattice glueball or radial excitations of $q\bar{q}$, this dynamical $t_1 t_2$ factor will suppress the region where kinematics would favour the production. It would be interesting if glueball production dynamics involved a singular $(t_1 t_2)^{-1}$ that compensated for the transverse P factor, as in this case the cross section would be enhanced. However, we have no reason to ex-

pect such a fortunate accident, so observation of high mass 0^{-+} states is expected to be favourable only at higher energies, such as at RHIC, Fermilab or LHC.

$$J^{PC} = 1^{++}$$

Refs. ^{60,61,63} predicted that axial mesons are produced polarised, dominantly in helicity one, from one Pomeron that is polarized transversely and one longitudinally. This is verified by data ⁶⁴. Such spin dependence leads to a cross section structure

$$\frac{d\sigma}{dt_1 dt_2 d\phi} \sim [(\sqrt{t_1} - \sqrt{t_2})^2 + 4\sqrt{t_1 t_2} \sin^2(\phi/2)] \times a^2(t_1, t_2)$$

which implies a dominant $\sin^2(\phi/2)$ behaviour that tends to isotropy when suitable cuts on t_i are made. This is qualitatively realized.

Fig. (3) show the output of the model predictions from the Galuga Monte Carlo superimposed on the ϕ and t distributions for the $f_1(1285)$ from the WA102 experiment; the (parameter-free) prediction of the variation of the ϕ distribution as a function of $|t_1 - t_2|$ is shown in Fig. (3c and d). The agreement between the data and theory is excellent. Similar conclusions arise for the $f_1(1420)$.

In passing, the resulting analysis of axial meson production⁶⁵ implies that the $f_1(1285; 1420)$ are members of a nonet with

$$\begin{aligned} f_1(1285) &\sim |n\bar{n}\rangle - 0.5|s\bar{s}\rangle \\ f_1(1420) &\sim |s\bar{s}\rangle + 0.5|n\bar{n}\rangle \end{aligned}$$

($n\bar{n} \equiv (u\bar{u} + d\bar{d})/\sqrt{2}$). DELPHI⁶⁶ have measured the production rate $\langle n \rangle$ of these states per hadronic Z decay and find

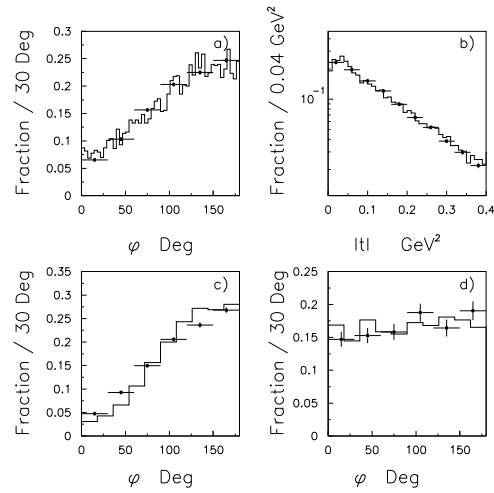


Figure 3. a) The ϕ and b) the $|t|$ distributions for the $f_1(1285)$ for the data (dots) and the Monte Carlo (histogram). c) and d) the ϕ distributions for $|t_1 - t_2| \leq 0.2$ and $|t_1 - t_2| \geq 0.4 \text{ GeV}^2$ respectively.

$\langle n(1285) \rangle = 0.13 \pm 0.03$; $\langle n(1420) \rangle = 0.05 \pm 0.01$. These are typical of the $\langle n \rangle$ for states with $n\bar{n}$ content, supporting the conclusion⁶⁵ that these mesons are partners in a nonet, each with non-negligible $n\bar{n}$ content. L3 also report at this conference⁸⁶ the $\gamma\gamma$ couplings to these states, in accord with these conclusions.

$$J^{PC} = 2^{-+}$$

The $J^{PC} = 2^{-+}$ states, the $\eta_2(1645)$ and $\eta_2(1870)$, are predicted to be produced polarised. Helicity 2 is suppressed by Bose symmetry⁶⁰ and has been found to be negligible experimentally⁶⁷. The structure of the cross section is then predicted to be dominantly in helicity-one. The helicity zero distribution is as for the 0^{-+} case,

$$\frac{d\sigma}{dt_1 dt_2 d\phi} \sim t_1 t_2 \sin^2(\phi)$$

and hence suppressed for $M \geq 1 \text{ GeV}$ as was the case for the 0^{-+} . The dominant helicity

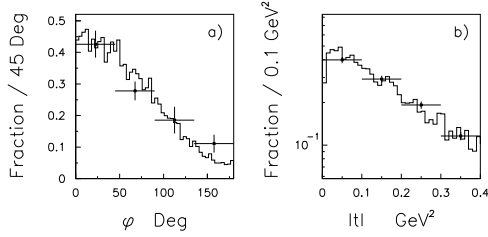


Figure 4. a) The ϕ and b) the $|t|$ distributions for the $\eta_2(1645)$ for the data (dots) and the Monte Carlo (histogram).

one: is as the 1^{++} case except for the important and significant change from $\sin^2(\phi'/2)$ to $\cos^2(\phi'/2)$.

The results of the WA102 collaboration for the $\eta_2(1645)$ ⁶⁷ are shown in fig. (4a and b). The distribution peaks as $\phi \rightarrow 0$, in marked contrast to the suppression in the 1^{++} case (fig. 3a); (the $\eta_2(1870)$ results are qualitatively similar).

Bearing in mind that there are no free parameters, the agreement is remarkable. Indeed, the successful description of the 0^{-+} , 1^{++} and 2^{-+} sectors, both qualitatively and in detail, sets the scene for our analysis of the 0^{++} and 2^{++} sectors where glueballs are predicted to be present together with established $q\bar{q}$ states.

$J^{PC} = 0^{++}$ and 2^{++}

Here we find that the production topologies do depend on the internal dynamics of the produced meson and as such may enable a distinction between $q\bar{q}$ and exotic, glueball,

states.

In contrast to the 0^{-+} case, where parity forbade the LL amplitude, in the 0^{++} case both TT and LL can occur. Hence there are two independent form factors ⁵⁵ $A_{TT}(t_1, t_2, M^2)$ and $A_{LL}(t_1, t_2, M^2)$. For 0^{++} and the helicity zero amplitude of 2^{++} (which experimentally is found to dominate ⁶⁸) the angular dependence of scalar meson production has the form ⁶¹

$$\frac{d\sigma}{d\phi} \sim \left[1 + \frac{\sqrt{t_1 t_2}}{\mu^2} a_T/a_L \cos(\phi)\right]^2$$

which successfully predicts that there should be significant changes in the ϕ distributions as t varies ⁵⁷.

The overall ϕ dependences for the $f_0(1370)$, $f_0(1500)$, $f_2(1270)$ and $f_2(1950)$ can be described by varying the quantity $\mu^2 a_L/a_T$. Results are shown in fig. 5. It is clear that these ϕ dependences discriminate two classes of meson in the 0^{++} sector and also in the 2^{++} . The $f_0(1370)$ can be described using $\mu^2 a_L/a_T = -0.5 \text{ GeV}^2$, for the $f_0(1500)$ it is $+0.7 \text{ GeV}^2$, for the $f_2(1270)$ it is -0.4 GeV^2 and for the $f_2(1950)$ it is $+0.7 \text{ GeV}^2$.

It is interesting to note that these ϕ distributions can be fitted with just one parameter and it is primarily the sign of this quantity that drives the ϕ dependences. Understanding the dynamical origin of this sign is now a central challenge in the quest to distinguish $q\bar{q}$ states from glueball or other exotic states.

4 Heavy Flavours and Light Scalars

The working hypothesis is that the $q\bar{q}$ nonet, mixed with a glueball, is realised above 1 GeV

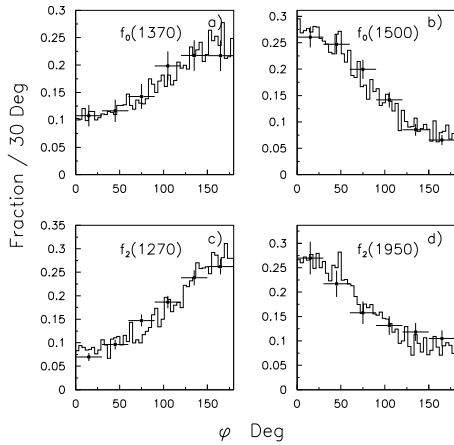


Figure 5. The ϕ distributions for the a) $f_0(1370)$, b) $f_0(1500)$, c) $f_2(1270)$ and d) $f_2(1950)$ for the data (dots) and the Monte Carlo (histogram).

and we now need to determine the flavour content of these states. In addition we need to confirm the picture of the $f_0(980)$ and light scalars below 1 GeV.

Novel probes are provided by the decays of heavy flavoured states. They can provide important information about the enigmatic 0^{-+} and 0^{++} light flavoured states in particular. The nature of the $\eta - \eta'$ system remains an important open question with an impact on heavy flavour decays. The D and B meson decays into final states containing η or η' continue to challenge theoretical predictions. Further experiments can test the nature of these 0^{-+} states, e.g. D^+ versus $D_s \rightarrow \eta(\eta')e^+\nu$ and B^0 versus $B_s \rightarrow J/\psi\eta(\eta')$ ⁶⁹.

$\psi \rightarrow \gamma\pi\pi$ compared with $D_s \rightarrow \pi\pi\pi$, and $\psi \rightarrow \gamma K\bar{K}$ compared with $D_s \rightarrow \pi K\bar{K}$ provide complementary entrees into the light flavoured 0^{++} mesons. Comparison with $D_d \rightarrow \pi K_0^*(1430)$ then enables us to “weigh” the flavour content of the nonets. In $\psi \rightarrow \gamma K\bar{K}$ Dunwoodie⁷⁰ finds the $f_0(1710)$ as

clear scalar, and this state could be sought in $D_s \rightarrow \pi K\bar{K}$ with enough statistics (in E687⁷² the $K^*\bar{K}$ band contaminates the 1710 region of the Dalitz plot). The momentum transfer in $D_s \rightarrow \pi f_0(1710)$ is small enough that a non-relativistic calculation of the transition amplitude $\langle c\bar{s}(^1S_0)|\pi(\vec{k})|s\bar{s}(^3P_0)\rangle$ may be reliable. In particular this could distinguish between the $f_0(1710)$ as a radially excited state, for which there is significant suppression, and a pure $s\bar{s}(^1P_0)$ for which the rate would maximise. Quantifying this rate could be a challenge for high statistics data e.g. with FOCUS. The major signal in the E687 data is the ϕ ; the $f_0(980)$ is just below threshold and it is not discussed whether any of the signal at threshold is due to this state. However, in the E791 data⁷³ on $D_s \rightarrow \pi\pi\pi$ the $f_0(980)$ is very prominent, together with the $f_0(1370)$ and a possible (though unclaimed) hint of a shoulder that could signal the $f_0(1500)$. Dunwoodie’s analysis of $\psi \rightarrow \gamma\pi\pi$ shows structure around 1400 MeV and with better statistics from BES and Cornell this should be verified and attempts to resolve it into $f_0(1370)$ and $f_0(1500)$ made. The strength of $f_0(1710)$ in these data should also be determined.

One clear message from the E791 data is that $f_0(980)$ has strong affinity for $s\bar{s}$ in its production; it decays into $\pi\pi$ as the $K\bar{K}$ channel is closed. This brings us naturally to new information, presented to this conference, which may at last help to solve the conundrum of the nature of the $f_0(980)$.

We argued earlier that the $f_0(980)$ and $a_0(980)$ have strong affinity for a four-quark composition, the question at issue being whether they are compact $qq\bar{q}\bar{q}$ or meson molecules. The emerging picture from phenomenology^{48,49,50} and theory⁵¹ is that both components are present.

There is a large amount of data on the

production of the $f_0(980)$ which require in some cases a strong affinity for $s\bar{s}$ (e.g. the D_s decays already), or for $n\bar{n}$ (the production in hadronic Z decays has all the characteristics associated with well established $n\bar{n}$ states^{66,71}) and also data that require both components to be present ($\psi \rightarrow \omega f_0$ versus $\psi \rightarrow \phi f_0$). There are new data that touch on the relationship between these states.

First I summarise arguments that the f_0 and a_0 are mixed. Then I shall review ideas on $\phi \rightarrow \gamma f_0/\gamma a_0$ and consider the implications of the mixing hypothesis on these data. Finally we shall see that the emerging data from DAΦNE, presented at this conference, are in remarkable agreement with these predictions and add weight to the idea that these scalar mesons are compact $qq\bar{q}\bar{q}$ states with an extended meson-meson cloud “molecular” tail.

4.1 f_0 a_0 mixing in central production

Fig 6c) and d) show the x_F distributions for the $a_0^0(980)$ and $a_2^0(1320)$ formed in $pp \rightarrow ppa_{0,2}$. The distribution for the $a_2^0(1320)$ is similar to that observed for the $a_2^-(1320)$ whereas that for the $a_0^0(980)$ is significantly different and peaks at $x_F = 0$. Indeed this is the only state with $I = 1$ that is observed to have a x_F distribution peaked at zero⁷⁴, and moreover the distribution for the $a_0^0(980)$ looks similar to the central production of states that are accessible to $\mathbf{P}\mathbf{P}$ fusion, in particular $\mathbf{P}\mathbf{P} \rightarrow f_0(980)$.

In the process $pp \rightarrow p(\eta\pi^0)p$, $\mathbf{P}\mathbf{P}$ fusion will feed only $I = 0$ channels, such as the $f_0(980)$ and $f_2(1270)$; one would not expect this to affect $a_{0,2}$ production unless isospin is broken. The $a_0(980)/a_2(1320)$ ratio in the WA102 data is relatively large and the x_F distribution of the $a_0(980)$ production is, within the errors, identical to that of the $f_0(980)$

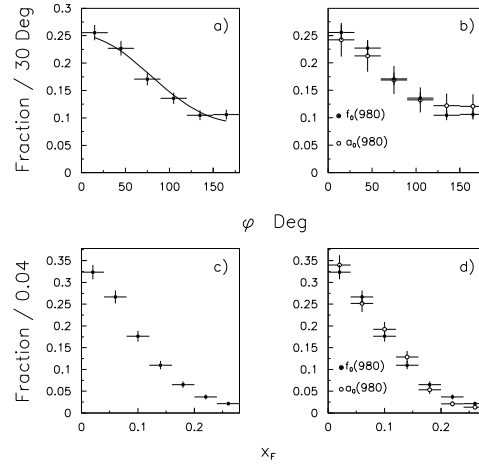


Figure 6. The ϕ distributions a) for the reaction $pp \rightarrow pp f_0(980)$ and b) for the $f_0(980)$ compared to the $a_0^0(980)$. The x_F distributions c) for the reaction $pp \rightarrow pp f_0(980)$ and d) for the $f_0(980)$ compared to the $a_0^0(980)$.

(see fig. 6d) and the ϕ distribution for the $a_0(980)$ also looks very similar to that observed for the $f_0(980)$ (fig. 6a and c). Qualitatively this is what would be expected if part of the centrally produced $a_0^0(980)$ is due to $\mathbf{P}\mathbf{P} \rightarrow f_0(980)$ followed by mixing between the $f_0(980)$ and the $a_0(980)$.

Ref⁴⁸ found that 80 ± 25 % of the $a_0^0(980)$ comes from the $f_0(980)$ and upon combining this result with the relative total cross sections for the production the $f_0(980)$ and $a_0^0(980)$ ⁷⁴ they found the $f_0(980) - a_0(980)$ mixing intensity to be 8 ± 3 %.

This adds weight to the hypothesis that the $f_0(980)$ and $a_0(980)$ are siblings that strongly mix, and that the $a_0(980)$ is not simply a ${}^3P_0 q\bar{q}$ partner of the $a_2(1320)$. This is consistent with the $0^{++} qq\bar{q}\bar{q}/MM$ picture of these states and a natural explanation of these results is that $K\bar{K}$ threshold plays an essential role in the existence and properties.

Other lines of study are now warranted. Experimentally to confirm these ideas requires measuring the production of the $\eta\pi$ channel at a much higher energy, for example, at LHC, Fermilab or RHIC where any residual Reggeon exchanges such as $\rho\omega$ would be effectively zero and hence any $a_0(980)$ production must come from isospin breaking effects. On the theory side, detailed predictions are needed in specific models in order to resolve precisely how the $K\bar{K}$ threshold relates to the $f_0(980)/a_0(980)$ states.

Other “pure” flavour channels should now be explored. Examples are D_s decays where the weak decay leads to a pure $I=1$ light hadron final state. Thus $\pi f_0(980)$ will be (and is⁷³) prominent, while the mixing results suggest that πa_0 should also be present at $8 \pm 3\%$ intensity. Studies with high statistics data sets now emerging from E791, Focus and BaBar are called for, and also studies of J/ψ decays at Beijing, in particular to the “forbidden” final states ωa_0 and ϕa_0 where ref⁴⁸ predicts branching ratios of $O(10^{-5})$.

4.2 $\phi \rightarrow \gamma f_0/\gamma a_0$

The radiative decays of the $\phi \rightarrow \gamma f_0(980)$ and $\gamma a_0(980)$ have long been recognised as a potential route towards disentangling their nature. In this section I note that isospin mixing effects could considerably alter some predictions in the literature for $\Gamma(\phi \rightarrow \gamma f_0(980))$ and $\Gamma(\phi \rightarrow \gamma a_0(980))$, and I show that new data from DAΦNE promise to reveal their nature.

The magnitudes of these widths are predicted to be rather sensitive to the fundamental structures of the f_0 and a_0 , and as such potentially discriminate amongst them. For example, if $f_0(980) \equiv s\bar{s}$ and the dominant dynamics is the “direct” quark transition $\phi(s\bar{s}) \rightarrow \gamma 0^{++}(s\bar{s})$, then the pre-

dicted $b.r.(\phi \rightarrow \gamma f_0) \sim 10^{-5}$, the rate to $\phi \rightarrow \gamma a_0(q\bar{q})$ being even smaller due to OZI suppression⁷⁵. For $K\bar{K}$ molecules the rate was predicted to be higher, $\sim (0.4 - 1) \times 10^{-475}$, while for tightly compact $qq\bar{q}\bar{q}$ states the rate is yet higher, $\sim 2 \times 10^{-476,75}$. Thus at first sight there seems to be a clear means to distinguish amongst them.

In the $K\bar{K}$ molecule and $qq\bar{q}\bar{q}$ scenarios it has uniformly been assumed that the radiative transition will be driven by an intermediate K^+K^- loop ($\phi \rightarrow K^+K^- \rightarrow \gamma K^+K^- \rightarrow \gamma 0^{++}$). Explicit calculations in the literature agree that this implies^{76,75,77,78}

$$b.r.(\phi \rightarrow f_0(980)\gamma) \sim 2 \pm 0.5(10^{-4}) \times F^2(R) \quad (1)$$

where $F^2(R) = 1$ in point-like effective field theory computations, such as refs.^{76,78}. (The range of predicted magnitudes for the branching ratios reflects the sensitivity to assumed parameters, such as masses and couplings that vary slightly among these references). By contrast, if the $f_0(980)$ and $a_0(980)$ are spatially extended $K\bar{K}$ molecules, (with r.m.s. radius $R > O(\Lambda_{QCD}^{-1})$), then the high momentum region of the integration in refs.^{75,77} is cut off, leading in effect to a form factor suppression, $F^2(R) < 1$ ^{75,79}. The differences in absolute rates are thus intimately linked to the model dependent magnitude of $F^2(R)$.

Precision data on both f_0 and a_0 production are now available from DAΦNE⁵⁰. Before discussing this, there are two particular items that I wish to address concerning the current predictions. One concerns the absolute branching ratios, and the second concerns the ratio of branching ratios where, if f_0 and a_0^0 have common constituents (and hence are “siblings”) and are eigenstates of isospin, then their affinity for K^+K^- should be the

same and so^{76,75,78}

$$\frac{\Gamma(\phi \rightarrow f_0\gamma)}{\Gamma(\phi \rightarrow a_0\gamma)} \sim 1. \quad (2)$$

There are reasons to be suspicious of the predictions in both eqs. (1) and (2). I frame these remarks in the context of the $K\bar{K}$ molecule, but they apply more generally.

If in the $K\bar{K}$ molecule one has

$$|f_0\rangle = \cos\theta|K^+K^- \rangle + \sin\theta|K^0\bar{K}^0\rangle \quad (3)$$

and

$$|a_0^0\rangle = \sin\theta|K^+K^- \rangle - \cos\theta|K^0\bar{K}^0\rangle \quad (4)$$

then the branching ratios $\phi \rightarrow \gamma f_0(\gamma a_0)$ as found in ref.⁷⁵ can be summarised as follows

$$\begin{aligned} b.r.(\phi \rightarrow \gamma f_0 : \gamma a_0) &= (4 \pm 1) \times 10^{-4} \\ &\times (\cos^2\theta : \sin^2\theta) \\ &\times \left(\frac{g_{SK^+K^-}^2/4\pi}{0.58\text{GeV}^2} \right) F^2(R) \end{aligned}$$

As shown in ref.⁷⁵, the analytical results of point-like effective field theory calculations (e.g. refs.^{76,78}) can be recovered as $R \rightarrow 0$, for which $F^2(R) \rightarrow 1$. In contrast to the compact hadronic four quark state, the $K\bar{K}$ molecule is spatially extended with r.m.s. $R \sim 1/\sqrt{m_K\epsilon}$, where ϵ is the binding energy and $F^2(R) < 1$, the precise magnitude depending on the $K\bar{K}$ molecular dynamics.

It is clear also that the absolute rate above is driven by (i) the assumed value for $\frac{g_{SK^+K^-}^2}{4\pi} = 0.58 \text{ GeV}^2$, and (ii) the further assumption that the f_0 and a_0 are $K\bar{K}$ states with $I = 0, 1$: hence $\theta = \pi/4$.

There is some uncertainty about the former, which needs to be experimentally studied further. In particular, an analysis of Fermilab E791⁷³ data, which studies the $f_0(980)$ produced in D_s decays, even suggests that $\frac{g_{fK^+K^-}^2}{4\pi} \sim 0.02 \pm 0.04 \pm 0.03 \text{ (GeV)}^2$, hence consistent with zero! However, it should be noted that only the $\pi\pi$ decay mode of the $f_0(980)$ has been studied in this experiment and hence the coupling to K^+K^- is only measured indirectly. With such uncertainties in the value of this coupling strength, predictions of absolute rates for $\phi \rightarrow \gamma f_0(980)$ or $\phi \rightarrow \gamma a_0(980)$ via an intermediate $K\bar{K}$ loop must be treated with some caution. By contrast, in the ratio of branching ratios this uncertainty is reduced, at least in the case of $K\bar{K}$ molecules for which⁷⁵ $\frac{\Gamma(\phi \rightarrow \gamma f_0)}{\Gamma(\phi \rightarrow \gamma a_0)} \sim 1$.

The central production, discussed above, suggested that there is a significant mixing. Specifically: in (isoscalar) P (Pomeron)-induced production in the central region at high energy, production of the $a_0^0(980)$ comes dominantly from mixing with the $f_0(980)$ such that the $f_0 - a_0$ are not good isospin eigenstates. In the language of the $K\bar{K}$ molecule, at least, this would translate into $\theta \neq \frac{\pi}{4}$ in eq. (6) and hence to a significant difference in behaviour for $\Gamma(\phi \rightarrow \gamma f_0)/\Gamma(\phi \rightarrow \gamma a_0)$.

With the basis as defined in eqs. (3) and (4), the ratio of production rates by P P (isoscalar) fusion in central production will be $\sigma(\mathbf{PP} \rightarrow a_0)/\sigma(\mathbf{PP} \rightarrow f_0) = \frac{1 - \sin 2\theta}{1 + \sin 2\theta}$

Ref.⁴⁸ found this to be $(8 \pm 3) \times 10^{-2}$. Hence if we assume that the production phase is the same for the two, then within this approximation the relative rates are predicted to be⁴⁹

$$\frac{\Gamma(\phi \rightarrow \gamma f_0)}{\Gamma(\phi \rightarrow \gamma a_0)} \equiv \cot^2\theta = 3.2 \pm 0.8 \quad (5)$$

This is far from the naive expectation of unity for ideal isospin states and is a rather direct

consequence of the isospin mixing obtained in ref. ⁴⁸. In order to use the data to abstract magnitudes of $F^2(R)$, and hence assess how compact the four-quark state is, a definitive accurate value for $g_{fKK}^2/4\pi$ will be required. If for orientation we adhere to the value used elsewhere, $g_{fKK}^2/4\pi \sim 0.6 \text{ GeV}^2$, and impose the preferred θ , then the results of ref. ⁷⁵ are revised to

$$b.r.(\phi \rightarrow \gamma f_0) + b.r.(\phi \rightarrow \gamma a_0) \leq (4 \pm 1)(10^{-4}) \quad (6)$$

and

$$b.r.(\phi \rightarrow \gamma f_0) = (3.0 \pm 0.6)10^{-4}F^2(R) \quad (7)$$

$$b.r.(\phi \rightarrow \gamma a_0) = (1.0 \pm 0.25)10^{-4}F^2(R) \quad (8)$$

Refs⁸⁰ and ⁷⁵ developed a simple potential picture of a $K\bar{K}$ molecule which led to $R \sim 1.2 \text{ fm}$, $F^2(R) \sim 0.25$. However, the predictions are rather sensitive to the assumed details and more sophisticated treatments, including mixing between $K\bar{K}$ and $qq\bar{q}\bar{q}$ are now warranted.

It is therefore most interesting that data presented here find ⁵⁰

$$\frac{\Gamma(\phi \rightarrow \gamma f_0)}{\Gamma(\phi \rightarrow \gamma a_0)} \equiv \cot^2\theta = 4.1 \pm 0.4 \quad (9)$$

consistent with the predicted ratio in eq. (6). The individual rates may therefore be used as a measure of $F^2(R)$. Branching ratios for which $F^2(R) \ll 1$ would imply that the $K^+K^-0^{++}$ interaction is spatially extended, $R > O(\Lambda_{QCD}^{-1})$. Conversely, for $F^2(R) \rightarrow 1$, the system would be spatially compact, as in $qq\bar{q}\bar{q}$.

The data from KLOE are ⁵⁰

$$b.r.(\phi \rightarrow \gamma f_0) = (2.4 \pm 0.1)10^{-4} \quad (10)$$

$$b.r.(\phi \rightarrow \gamma a_0) = (0.6 \pm 0.05)10^{-4} \quad (11)$$

which imply $F^2(R) \sim 0.7 \pm 0.2$, supporting the qualitative picture of a compact $qq\bar{q}\bar{q}$ structure that spends a sizeable part of its lifetime in a two meson state, such as $K\bar{K}$. An important feature of this also is that there is a significant isospin mixing at work, driven by the $K^+K^- - K^0\bar{K}^0$ mass difference. A subtle and unexplained violation of isospin has already been noted in the ratio $\phi \rightarrow K^+K^- / K^0\bar{K}^0$ ⁸¹, whose origin may also touch on these issues.

5 The $\xi(2.2)$

There is a tantalizing signal that has been claimed⁸² as evidence for a tensor glueball. I have severe doubts about this state, but first let me present the "case for the prosecution". It is narrow ($\sim 20 \text{ MeV}$) and seen in a glueball favoured production channel: $\psi \rightarrow \gamma\xi$ where $\xi \rightarrow K^+K^-; K^0\bar{K}^0, \pi^+\pi^-, p\bar{p}$, according to BES⁸². In each channel the effect is $\sim 4\sigma$ but the actual number of events is small. Support is claimed from old data by Mark3 at SPEAR⁸³ where a similar structure was seen in $K\bar{K}$. However, closer examination begins to reveal questions that merit further study.

First, DM2 ⁸⁴ see no evidence for a narrow state in either K^+K^- or $K_S^0\bar{K}_S^0$. Note also that Mark3 data⁸³ on the $p\bar{p}$ (marginally) and $\pi\pi$ (more significantly) do not add support for this state. But let's press on in hope. Two further pieces of data have been used to support the claim that ξ is a glueball. First, from LEAR one has no signal in $p\bar{p} \rightarrow \xi \rightarrow K\bar{K}$ ⁸⁵, which when combined with the signal for each of the individual $\xi \rightarrow K\bar{K}; \xi \rightarrow p\bar{p}$ from BES im-

plies a large intrinsic production: $br.(\psi \rightarrow \gamma\xi) > 10^{-3}$. Such a magnitude would be in line with expectations for a tensor glueball if $\Gamma_{tot} \sim 20\text{MeV}^{55}$, but at the price of having detected only a limited fraction of the decay channels. A further piece of evidence has been presented to this conference from L3. They find no signal in $\gamma\gamma$ and place an upper limit: $\Gamma(\xi \rightarrow \gamma\gamma)br.(\xi \rightarrow K_s K_s) < 1.4eV^{86}$.

So, we appear to have a large production in the glueball friendly ψ decay and a strong suppression in the “anti-glueball” $\gamma\gamma$ channel, which leads some to assert that the 2^{++} glueball is the ξ . The problem, in my opinion, is that the claims for glueball are based on what is **not** being seen! Furthermore, there is no convincing signal for ξ in any other experiment. There is another possible interpretation of the LEAR and L3 non-observations: the ξ does not exist!

If it does exist, another solution is that the $K\bar{K}$ decay is dominant (as in the Mark 3 data) and that, in particular, $p\bar{p}$ is suppressed. The LEAR limit would then be less restrictive, and allow $br.(\psi \rightarrow \gamma\xi) \sim 10^{-4}$. The true ξ could then be a broader state (as seen elsewhere, for example WA102⁸⁷, DM2⁸⁴ and ⁸⁸) and with $br.(\psi \rightarrow \gamma\xi) \sim 10^{-4}$ be compatible with a $q\bar{q}$ state⁵⁵. If this state has a significant $s\bar{s}$ content, an excited tensor with width $\sim 100\text{MeV}$, then it is probably compatible with the L3 $\gamma\gamma$ limit.

This is clearly a question that needs to be pursued with high priority at an upgraded BES and at a downgraded (in an energy sense!) CESR. High statistics and independent analyses should determine whether this state is real or not. If it is confirmed with the above properties then it will be rather compelling; however, at the present time I am of the opinion that absence of evidence may be evidence of absence. The challenge for the new facilities will be to settle this question.

6 Summary and Prospects

Establishing that gluonic degrees of freedom are being excited is now a real possibility and centres on understanding (a) the scalar mesons (b) being able to distinguish between hybrids and molecules or compact four-quark states for exotic $J^{PC} = 1^{-+}$.

A “pure” molecule would be produced and decay in the mesons that make it; a compact four quark or hybrid would show up in channels driven by the flavour spin clebsches. Furthermore, the latter configurations will be in nonets (any other representation would immediately eliminate hybrid) and the mass dependent pattern will in general be different for $q\bar{q}$ /hybrid and $(qq)^3(\bar{q}\bar{q})^3$. So, unless Nature is malicious, it will be possible to answer this puzzle definitively.

The scalars below 1 GeV are too light to enable a simple distinction between loose molecules and compact four-quarks states to be felt in decays (except perhaps for the $a_0(980)$ where the $K\bar{K}$ and $\eta\pi$ both couple strongly and point to a significant compact four-quark feature). However, the production dynamics and systematics of these states is interesting and full of enigmas, which may be soluble if one adopts the four-quark/molecule picture.

D_s decays into πf_0 clearly point to an $s\bar{s}$ presence in the f_0 . However, the production in Z decays is rather non-strange-like⁷¹. ψ to ωf_0 and ϕf_0 also do not equate easily with a simple $q\bar{q}$ description for f_0 and a_0 . The central production in pp shows that f_0 is strongly produced, akin to other $n\bar{n}$ states and much stronger than $s\bar{s}$ which appear to be suppressed in this mechanism. Furthermore, f_0 survives the $dk_T \rightarrow 0$ filter of ref.⁵⁶. The systematics of this filter I believe (and would like to prove) is driven by S-wave production: this would be fine for either a com-

compact four-quark or molecule. None of these phenomena fit easily with an intrinsic $3P_0 q\bar{q}$ as the dominant constituency.

Whenever S-wave dynamics can play a role it will override P-waves; so one expects $K\bar{K}$ S-wave production to drive the f_0/a_0 whenever allowed. This is indeed what happens in the $\phi \rightarrow \gamma f_0/\gamma a_0$; the “large” rate cries out for the K^+K^- loop to drive it. A question is whether the $s\bar{s}n\bar{n}$ constituents of the intermediate state “between” the initial ϕ and final f_0 are able to fluctuate spatially enough to be identified as two colour singlet K’s, which then couple to the f_0 , or whether they are a compact system in the sense of being confined within $\sim 1\text{fm}$. The former would have some form factor suppression of the rate; the latter would be more pointlike and larger rate. The emerging data are between these extremes, but nearer to the expectations for a compact configuration.

Knowledge on the $\gamma\gamma$ couplings is lacking and better data would be useful. We know that for the 2^{++} $\gamma\gamma$ reads the compact $q\bar{q}$ flavours; there is no 2-body S-wave competition in the imaginary part as $\rho\rho$ etc are too heavy. I would expect that for the 0^{++} the $K\bar{K}$ will dominate the $\gamma\gamma$ if there is a KK component in the wavefunction. At the other extreme; were the state a pure compact four quark, then higher intermediate states - KK, KK*, KK** etc - would all be present. Achasov⁷⁶ has discussed these and a precise calculation has many problems, but the RATIOS of $\gamma\gamma$ to f_0/a_0 would probably be sensitive and more reliable.

The theoretical frontier suggests that one can divide the phenomenology of scalars into those above and those below 1 GeV. I suspect that much of the confusion will begin to evaporate if one adopts such a strating point. Empirically, signs of gluonic excitation are appearing (i) in the form of hybrids with

the exotic $J^{PC} = 1^{-+}$ now seen in various channels and more than one experiment (ii) with 0^{-+} and 1^{--} signals in the 1.4 - 1.9 GeV region that do not fit well with conventional quarkonia and show features predicted for hybrids (iii) in the form of the scalar glueball mixed in with quarkonia in the 1.3 - 1.7 GeV mass range. Theoretical questions about the latter are concerned with whether its effects are localised above 1 GeV, or whether they are spread across a wider mass range, even down to threshold. Experimental questions that need to be resolved concern the existence and properties of the $f_0(1370)$ and $a_0(1400)$.

These questions in turn provoke my list of challenges for experiment.

(i) In e^+e^- , the region of hybrid charmonium promises to be $\sim 4\text{GeV}$. This would be an excellent area for study at an upgraded BES and the proposed CESR Tau-Charm-Factories. At lower energies, VEPP and DAΦNE can study the 1.4-1.7 GeV region where light flavour hybrid vectors may occur. High statistics studies of radiative decays of such states into the $f_0(980)$; $f_1(1285)$; $f_2(1270)$ could teach us much⁹⁰. HERA can also investigate the production mechanism, Q^2 dependence etc of the vectors in hope of distinguishing radial excited quarkonia from hybrids.

(ii) Photo and electroproduction of hybrids $\sim 2\text{GeV}$ mass can be studied at Jefferson Lab, via π and ω exchange. The vector nature of the photon, and its mixed isospin content, can access the exotic quantum numbered “golden” hybrids, such as 1^{-+} . In any event, the properties of the newly-sighted 1^{-+} around 1.4 - 1.6 GeV should be investigated. The moderate energies available here can actually be an aid.

(iii) $\gamma\gamma$ couplings give rather direct information on the flavour content of C=+ states.

Such information on the scalar mesons will be an essential part of interpreting these states.

(iv) Heavy flavour decays, in particular D_s and D into π and associated hadrons can access the scalar states. Precision data are needed to disentangle the contributions of the various diagrams, whereby the flavour content of the scalars can be inferred. There is also a tantalising degeneracy between the $\pi_g(1.8)$ and the D , which may radically affect the Cabibbo suppressed decays of the latter. Hence precision data on such charm decays is warranted.

(v) Central production need now to be studied at higher energies, at RHIC, Fermilab and possibly the LHC. The 0^{-+} glueball should be manifested once the $t_1 t_2 \rightarrow 0$ kinematic suppression is overcome. The systematics of scalar and tensor production, with their ϕ and dk_T dependences, need to be understood.

(vi) Tau Charm Factories may at last appear. Obtaining a well defined universally accepted data-set on ψ decays is needed; a problem for phenomenology is that data from different experiments do not always agree. Clarifying the status of $\xi(2.2)$ is needed from independent experiments, such as BES and CESR should provide. Finally, χ decays offer an entree into light flavoured states; the excitement about the scalar glueball mixing with the quarkonia nonet began when the precision data from $p\bar{p}$ annihilation at LEAR first emerged. Data at rest were beautiful and well analysed. Data in flight however tend to be more problematic, not least as one cannot so easily control knowledge of the incident partial wave. χ decays can access these phenomena, at c.m. energies up to 3.5GeV, and from well defined initial J^{PC} states. In particular, the 1^{++} decay into $\pi + X$ probes $X \equiv 1^{-+}$ in S-wave.

I hope that this talk has shown some

ways in which current and future experiments can impact on the physics of light flavours, and of glue. A TCF promises to be an important feature in this field; hopefully, together with BEPCII, That's Cornell's Future.

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