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Survey of Exotic Mesons

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A B S T R A C T

I review at an elementary level current discussions about exotic mesons, in particular gluonia and hadronic molecules.

1. Introduction

When Professor Guaraldo sent his invitation I was rather reluctant to talk on this topic, since I had not worked on exotic hadrons for some time. After accepting I had to spend several weeks to study what previous speakers had said in the last few years at such conferences, and try to read some of the literature¹⁻⁴). The point I wish to make is that there is very little original material in this article for experts. The intention is to survey material for experimenters in a simple fashion, and give you my impressions.

Exotic Hadrons are defined with respect to "ordinary" or "non exotic" hadrons, which are either mesons ($q\bar{q}$) or baryons (qqq), where q stands for a constituent quark. Since this conference is devoted to anti-proton annihilation which produce mesons, I will concentrate my attention on mesonic states. The ground state non-exotic mesons—pseudoscalar (1S_0 in the $q\bar{q}$ channel) and vector (3S_1) are well established and lie below 1GeV, with the ϕ -meson at 1.02 GeV.

The excited, P-wave mesons (3P_J and 1P_1) lie in the energy region of 1 – 2 GeV, and there is reasonable agreement even about these states. I shall take the assignments advocated at the last Lepton-Photon-Conference in 1991 by Landua¹), which agree with the quark model calculations⁵) of Godfrey and Isgur of 1985. The main charac—

teristic of these assignments is that there is rather little Spin orbit splitting between the 3P_J , which is similar to the situation in P-wave baryons.

Of these 3P_J states, the most interesting are the ones with $J = 0$, the scalar mesons, which have quantum numbers $J^{PC} = 0^{++}$, the quantum numbers of the vacuum. The $q\bar{q}$ states assigned to this sector are: $[I = 1, a_0(1320)]$, $[I = 1/2, K_0(1430)]$ $[I = 0, f_0(1400) \text{ and } f_0(1520)]$. The $I = 0$ states correspond respectively to $(u\bar{u} + d\bar{d})$ and $s\bar{s}$. But there are additional hadrons, listed in the particle data tables, with the same $J^{PC} = 0^{++}$ quantum numbers and in the same mass range. Let us call them supernumeraries. These are the $[I = 1, a_0(980)]$ and the $[I = 0, f_0(1590) = G, \text{ and } f_0(1710)]$. Now these three isoscalars are just too low in mass to be radial excitations of the nonexotic states, and so they are natural candidates for exotics. I will discuss these states in more detail below, but before doing so, I wish to tell you a little story, which is helpful to keep in mind as an analogy.

2. A little old story⁶⁾

In an ancient kingdom, people used camels for transportation. And there were two kinds of camels: with one hump and with two humps. As in all civilized societies, there were theoreticians in this kingdom, who studied everything, but especially socially important subjects, such as camels. So eventually the deepest theoreticians produced a satisfactory theory of camels, called Quantitative Camel Dynamics (or QCD), which was a wonderful theory. And it predicted, in particular Exotic Camels, with three humps. The abundance of such Exotic Camels was hard to predict, but the theory was firm that exotics must exist. Because it was clear that three humped camels may be very useful, searches were mounted to find them. These searches, first by looking at one thousand camels, then by looking at ten thousand camels. And no exotics were found. At first the theorists revised their estimates for the abundance of exotics, in favor of smaller numbers, but later they were baffled and depressed. Perhaps QCD was wrong. But eventually a bright young theorist explained that QCD was fine, but the whole puzzle arose from a mis-interpretation of the initial situation: There are no camels with one and two humps, there are only camels with one hump, but the sign of the hump can be positive or negative!

I think this story may also be helpful in the search for exotic hadrons.

3. Classes of Exotics

One can classify exotics by the number of quarks plus antiquarks they contain. At zero quarks these are gluonia or glueballs. At two quarks one has hybrid mesons, which are ordinary mesons with an excitation of the glue field inside. Similarly with three quarks one can have hybrid baryons. Four quark states have two quarks and two antiquarks. A special case which we discuss below are hadronic molecules $[(q\bar{q})(q\bar{q})]$. Then there are penta quarks P and hexa quarks H which have been proposed, so I could add here, for originality, hepta quarks, and perhaps even larger structures, which may be larger molecules.

As stated earlier, for this conference the main interest lies in the hadrons produced in antiproton proton reactions, which are in the mesonic sector. So we shall only talk about zero quark, two quark and four quark systems. And even among these systems we will just consider the sectors with $J^{PC} = 0^{++}$. This is both for limitations of space, time and for lack of expertise of the author.

4. Which are the important issues for experimenters?

Much of the theoretical literature discusses the spectrum of states which is expected, masses, quantum numbers etc. These results are rather model dependent, and at this stage is of little interest to experimenters, since it is not known which particular model or computing scheme is right. What is of very much more interest to experimentalists, is the pattern of couplings of the exotic hadrons to normal hadrons, which helps identify them. This is crucial and has to be sorted out first, so that we can be sure that we identify the exotic hadrons correctly.

I will give one example relating to dynamical issues. Most lattice gauge calculations compute the mass of the lowest scalar gluonium state in the so-called quenched approximation, which is found to be at about 1.5 GeV. This number is computed, in various schemes, to better than 10%. But, on the other hand, there is a theorem by J. Ellis and J. Lanik¹⁾ (and independently in different form by Schechter et. al.⁸⁾, based

on rather general assumptions, which asserts that for scalar gluonia of mass of 1 GeV or more the width for decay into two pions is as large as the mass: $\Gamma(0^{++}) \simeq M(0^{++})$ for $M \geq 1$ GeV. Therefore if this theorem holds, the lattice gauge computations for scalar gluonia are rather useless for the purposes of locating a scalar gluonium, which will not be a sharp state. I should add that I am not sufficiently familiar with the assumptions on which the Ellis—Janik—Schedter estimate is based to be certain whether it is realistic or not.

In any case it should be stressed that the Ellis—Janik—Schedter estimate only refers to scalar gluonia, and does not say any thing about other J^{PC} sectors. Therefore gluonia should be searched by experimentalists, since these states are expected in many models based on QCD. We will discuss next some gluonium properties, namely coupling to ordinary hadrons, to see how we can recognize gluonia experimentally.

5. Gluonium spotting⁹⁾

The main characteristic of gluonia is that they have no electric charge, strangeness and therefore are singlets under the flavor group SU_3 . Therefore we are interested in the SU_3 coupling of singlets. This is an old mathematical subject, more than a century old, called the construction of invariant forms under a group of transformations. To warm up, let's recall that if one has a vector $\vec{R}$ with components X, Y, Z then the formula to construct a scalar under the rotation group O_3 is:

$$R^2 = X^2 + Y^2 + Z^2 \quad (5.1)$$

Now in SU_3 we have unitary rotations, and instead of vectors we have octets, say a pseudoscalar octet $P = (\pi^+, \pi^-, \pi^0, K^+, K^-, \bar{K}^0, K^0, \eta_8)$. There are eight components, and these are so called "spherical" components, i. e. $\pi^\pm = (\pi_x \pm i \pi_y)/\sqrt{2}$, and so the prescription to construct an invariant 1 from the components of an octet is:

$$1 = \pi^+ \pi^- + \pi^0 \pi^0 + \pi^- \pi^+ + K^+ K^- + K^0 \bar{K}^0 + \bar{K}^0 K^0 + K^- K^+ + \eta_8 \eta_8 \quad (5.2)$$

We see right away from this expression that the amplitudes α for the decay of an SU_3 singlet satisfy

$$a(1 \rightarrow \pi^0 \pi^0) = a(1 \rightarrow \eta_8 \eta_8) \quad (5.3)$$

In other words, at this stage we conclude that gluonium decays with equal amplitude into two neutral pions, and also into two etas. But the physical hadron η is not entirely an octet component, there is some singlet admixture and may be the theorem is evaded. Let's investigate this possibility.

In the quark model, there are two quarkonium states η_8 and η_1 with the compositions:

$$\begin{aligned} \eta_1 &= (\sqrt{3})^{-1} (u\bar{u} + d\bar{d} + s\bar{s}) \\ \eta_8 &= (\sqrt{6})^{-1} (u\bar{u} + d\bar{d} - 2s\bar{s}) \end{aligned} \quad (5.4)$$

and the assumptions of the quark model correspond to so called nonet symmetry, in which the flavor group SU_3 is enlarged to U_3 . In this case, the octet plus singlet of SU_3 make a nonet of U_3 and

$$1 = \pi^+ \pi^- + \pi^0 \pi^0 + \dots + \eta_8 \eta_8 + \eta_1 \eta_1 \quad (5.5)$$

and this shows that even if there is mixing between η_1 and η_8 (i. e. the physical states η , η' are rotated):

$$\begin{aligned} \eta &= \cos \Theta \eta_8 - \sin \Theta \eta_1 \\ \eta' &= \sin \Theta \eta_8 + \cos \Theta \eta_1 \end{aligned} \quad (5.6)$$

we have as a consequence:

$$\eta_8 \eta_8 + \eta_1 \eta_1 = \eta \eta + \eta' \eta' \quad (5.7)$$

by invariance under O_2 rotations, if you wish. Therefore, in the quark model, or more abstractly with nonet symmetry, we still have the consequences:

$$a(1 \rightarrow \pi^0 \pi^0) = a(1 \rightarrow \eta \eta) = a(1 \rightarrow \eta' \eta') \quad (5.8)$$

and

$$a(1 \rightarrow \eta \eta') = 0 \quad (5.9)$$

and therefore this was widely forecast as a criterion for detecting gluonia, in the early eighties. However, it was pointed out by Gershtein and Prokoshkin¹⁰⁾ that this theo

rem can be evaded if the η and the η' themselves are not entirely built from quarkonia, but contain some (pseudoscalar) gluonium in their structure. This is an idea which has been debated in the literature for some time.

We shall assume, for simplicity¹¹⁾, that the quarkonium singlet η_1 mixes ("first") with some other singlet, denoted by R (for "remainder") to form an (SU_3) singlet α_1

$$|\alpha_1\rangle = \cos \alpha |\eta_1\rangle + \sin \alpha |R\rangle \quad (5.10)$$

and then α_1 mixes as before with the (quarkonium) η_8

$$\begin{aligned} \eta &= \cos \Theta |\eta_8\rangle - \sin \Theta |\alpha_1\rangle \\ \eta' &= +\sin \Theta |\eta_8\rangle + \cos \Theta |\alpha_1\rangle \end{aligned} \quad (5.11)$$

The η , η' are still orthogonal. The case $\alpha = 0$ corresponds to no mixing and U_3 symmetry. Now the coupling of the (gluonium) SU_3 singlet is no longer constrained by nonet symmetry, and if R couples directly to the singlet 1 we can have:

$$\begin{aligned} a(1 \rightarrow \eta\eta) &> a(1 \rightarrow \pi^0\pi^0) \\ a(1 \rightarrow \eta\eta') &> a(1 \rightarrow \eta\eta) \end{aligned} \quad (5.12)$$

All of this was partly triggered⁸⁾ by experiments done first at Serpukhov by the GAMS group¹²⁾, which observed multi-gamma events in pi-proton collisions, which were interpreted as resulting from the decay of an SU_3 singlet into two neutrals, $\eta\eta$ or $\eta\eta'$. We shall return to the experimental situation later; but at this stage we want to emphasize that the couplings (5.12) can be taken as a good diagnostic for glueballs.

Before we proceed we should at this point discuss briefly what are the constraints on the values of α and Θ in eqs (5.10) and (5.11). Much of the literature assumes that $\alpha = 0$, in other words, that the pseudoscalars η and η' are made entirely from quarkonium and there is no glue or other stuff in them. A good recent ('85) review, along these lines is given by Gilman and Kauffman¹³⁾. However as they note, this is an assumption, which they make, and there could well be some other components which are small. I have analyzed the data listed by the particle data group and find $\cos^2 \alpha \simeq \pm 24^\circ$. I will give details later, but note that there is a discussion by Bartelski and Tatur¹⁴⁾, using recent data, which also finds a small gluonic admixture in the η' .

The angle Θ is now rather generally found to be about minus 20° . This is in contrast to the earlier literature, in which minus 10° was the preferred value. We shall return to these questions later, but do not want to diverge too far from the main topic.

6. The G(1590) and $\Theta(1710)$ [or $f_0(1590)$ and $f_0(1710)$]

The GAMS group detected multigamma events in π_p collisions at Serpukhov, and observed ¹²⁾ a structure in $\eta\eta \rightarrow 4 \gamma$ at an invariant mass of about 1.59 GeV, which was claimed to be a meson G(1590) decaying into two eta mesons. At the same time the decay into $\pi^0\pi^0$ was not seen, and a limit was set for the decay rate into $2\pi^0$: $\Gamma(G \rightarrow \pi^0\pi^0)/\Gamma(G \rightarrow \eta\eta)$ is less than one third. As explained above this would fit well with a glueball interpretation for G, provided the eta has some gluonic component.

There is some evidence that the η couples strongly to channels which have a gluonic component, namely in the radiative decay of J/ψ , where the branching ratios of $J/\psi \rightarrow \gamma\eta$, $\gamma\eta'$ are enhanced relative to $\gamma\pi^0$.

$$\text{BR}[J/\psi \rightarrow \gamma\eta] \simeq 8.6 \times 10^{-4} \simeq 20 \text{ B.R.}[J/\psi \rightarrow \gamma\pi^0]$$

$$\text{BR}[J/\psi \rightarrow \gamma\eta'] \simeq 4 \times 10^{-3} \simeq 100 \text{ BR}[J/\psi \rightarrow \gamma\pi^0]$$

Gershtein et. al. based on these numbers predicted that

$$R = \frac{\Gamma(G \rightarrow \eta\eta')}{\Gamma(G \rightarrow \eta\eta)} \simeq 2 \times \frac{\Gamma(J/\psi \rightarrow \gamma\eta')}{\Gamma(J/\psi \rightarrow \gamma\eta)} \cdot \frac{\text{PS}(G \rightarrow \eta\eta')}{\text{PS}(G \rightarrow \eta\eta)} \simeq 4.3$$

where PS stands for phase space. Later reports from the GAMS collaboration gave as the observed value $R \simeq 2.1 \pm 0.5$. It is important to check these observations.

In the last year or so, experimenters of the Crystal Barrel detector at LEAR have reported¹⁵⁾ a $J^{PC} = 0^{++}$ resonance, with a mass of 1560 ± 25 MeV, and width 245 MeV decaying into the $\eta\eta$ channel. This may be taken to be the same state as the G(1590), since the precise position of the peak depends on the background in the production process. The main question is whether the additional features reported by the GAMS

group are confirmed by the Crystal Barrel collaboration. At this conference Augustin¹⁶⁾ reported the most recent (preliminary) Crystal Barrel data while they observe the decay $G \rightarrow \eta\eta$, they can put a limit on $R = \Gamma(G \rightarrow \eta\eta')/\Gamma(G \rightarrow \eta\eta) < 0.23$ which is in sharp contradiction (over a factor of ten) with the GAMX claim $R \simeq 3$. This result is unfavorable for a gluonium interpretation of G . The branching ratio for $G \rightarrow \pi^0\pi^0$ is claimed to be less than for the $\eta\eta$ mode, but a precise number is not yet available. A further issue affecting the state $G(1590)$, if it is a gluonium, or gluon enhanced, is its coupling in the radiative decay of the J/ψ . One would expect¹⁷⁾ that just as $J/\psi \rightarrow \gamma\eta'$ is enhanced, so would be the decay $J/\psi \rightarrow \gamma f_0(1590)$. Here the situation was rather confused by the fact that the decay which was reported from SLAC, namely $J/\psi \rightarrow \gamma\Theta(1710)$ also assigned the Θ spin two. Therefore the earlier literature claims that there is no scalar (O^{++}) in the radiative decay of the J/ψ . But now the spin two assignment for the $\Theta(1710)$ was withdrawn, as explained in detail at this conference by Dunwoodie¹⁸⁾. So now there is a scalar mode $J/\psi \rightarrow \gamma f_0(1710)$, but it seems that it is at a different mass than the $G(1590)$ [or 1560], and therefore the G does not couple to J/ψ radiative decays. It seems to me much more likely that the $f_0(1710)$ and $f_0(1590)$ are the same state, since they both decay to the $\eta\eta$ channel, and are both very broad, with a width larger than the 120 MeV separating them. A similar view was argued by Prokhoshkin¹⁹⁾ at the Singapore Conference in 1990, but before the Θ suffered the transition $\Delta J = -2$. I should perhaps spell out that it is unlikely on general grounds to have two resonances which have the same $J^{PC} = O^{++}$ which are degenerate (within their width) and have common decay channels. In such circumstances the two state system "reorients" into two states with different decay channels. A simple example is the $K^0-\bar{K}^0$ system, but this statement is much more general, not only for hadrons.

Therefore the situation with the $f_0(1600-1700)$ is still not clear, as the particle data book lists two states G and Θ , and it is likely that only one scalar state exists in this region. Perhaps we should also stress that other data in the hadron spectrum may also suffer from similar diseases, so we should be cautious in our interpretations. In any case, it is very likely that the scalar state(s) at 1600-1700 are exotic states, which do not belong to the quarkonium spectrum.

7. Four Quark Systems and Mesonic Molecular

With a quarkonium interpretation of low lying mesons, and simple estimates of the excitation energy ($\hbar\omega$) of the $q\bar{q}$ system, it is natural to consider simultaneously with the excited light quarkonia, the four quark system interact with each other, and we need to estimate their interaction, within some model.

The first serious estimation of the (hyperfine) interactions between quarks in a four quark system was done within the MIT bag model by Jaffe²⁰). He found that the scalar states O^{++} have lowest mass, and interpreted the $f_0(975)$ and $a_0(980)$ as four quark (hadronic) states. The bag model results were confirmed in a Nonrelativistic Quark Model variational calculation, (also using hyperfine interactions) by Weinstein and Isgur²¹). These authors found that the predominant component in the f_0 and the $a_0(980)$ wave functions was $K\bar{K}$, as a mesonic molecule. This conclusion is supported by the annihilation rates of these states into two photons, as studied by Barnes²²). These rates are slower for a $K\bar{K}$ molecule than for a $q\bar{q}$ state and are essentially the same for the f_0 and a_0 in the $K\bar{K}$ interpretation (where only K^+K^- annihilates), whereas they are in a ratio of 25/9 in the $q\bar{q}$ picture. The data on $\gamma\gamma$ widths supports the molecule interpretation²²).

Very interesting proposals were made in the last year separately by Tornqvist²³) and by Barnes et. al.²⁴), in suggesting the existence of vector meson molecules. Tornqvist proposed that vector mesons which contain light (up and down) quarks, will bind by pion exchange.

Tornqvist²³) then assigned a number of hadronic resonances to four quark-vector meson molecules. based on qualitative arguments about the relative binding strength in different channels. In this way a large number of states between 1 and 2 GeV were assigned (such as the $G(1590)$ and $\Theta(1710)$) to vector meson molecules, $K^*\bar{K}^*$ and K^*K^* . Barnes et. al.²⁴) generalized the model of Weinstein and Isgur to two vector mesons. The main force they consider is quark and gluon exchange, rather than pi exchange. As a result the bound states differ in the two models, for example, while Tornqvist has $K^*\bar{K}^*$ as a bound state, Barnes, Dooley and Swanson²⁴) have $(K^*\bar{K}^* + \omega\phi)$. The $\omega\phi$ is just a rearrangement of the quarks in $K^*\bar{K}^*$ so appears naturally under quark exchange. The bound states are found by Barnes et al. in the $I = 0$, $J = 0, 2$ channels. The results are not totally dissimilar. The proposal of Tornqvist to consider

pion exchange as the driving mechanism is very nice because of its universality, but on the other hand it is not clear that pi-exchange alone is strong enough to bind all the systems proposed by Tornqvist²⁵).

The nicest feature of the proposal of VMM (vector meson molecule) is that these systems have very distinct diagnostics, in their decay (and production) modes. In particular, because the systems are weakly bound, the two mesons (say K^* and $\bar{K}^*$) have the same properties as when free, and therefore the decay patterns can be obtained simply from the tables. For example, Barnes et. al. note that if the state $(K^* \bar{K}^* + \omega \phi)$ is bound the ω can decay via its mode $\omega \rightarrow \pi^0 \gamma$, so the system will decay to $(\pi^0 \gamma \phi) \rightarrow (\pi^0 \gamma K \bar{K})$ at a rate determined by $\omega \rightarrow \pi^0 \gamma$. This will make the identification of VMM rather simple, and these models therefore are easily put to the test. Barnes, Dooley and Swanson do provide tables of branching ratios expected.

Before ending the issue of hadronic molecules, I should add that this topic is not entirely uncontroversial. The proposal that the a_0 , f_0 are four quark states has been criticized by Morgan and Pennington on the basis of the analytic behaviour of amplitudes in the $\pi\pi$ - and $K\bar{K}$ -channel, in the region of the a_0 , f_0 . Also Tornqvist has an alternative interpretation since pion exchange is not a force in the $K\bar{K}$ -channel, because of parity constraints. Therefore Tornqvist does not accept the molecule interpretation for a_0 , f_0 .

It is clear that the notion of hadronic molecules is only at the start of its career, although a little more experimental confirmation would help unbelievers.

8. Hybrid Mesons and Conclusions

In addition to gluonia and four quark states, there are proposals for hybrid mesons, which have a quark and antiquark but the gluonic system is excited. This is analogous to electronically excited diatomic molecules, and in a string model — with quark and antiquark at the end of the string, it is the string which is excited. It is not obvious, however, whether these states will exist in light hadrons, where perhaps the distinction between motion of the light quark relative to the gluonic field (as in radially excited states) and the motion of the gluonic field about the fixed quarks appears to be the same thing. In other words, the adiabatic approximation is poor in light ha

drons, and as a result the notion of hybrid mesons would be inapplicable. However, in specific models, like the bag model or the string model this objection is not so clear, and in any case the existence of certain type of excitations is always a dynamical issue.

My prejudice is that with so many types of exotic hadrons, gluonia, four quark states and hybrid mesons – not all will be realized in nature, and I would further speculate that light hybrid mesons will be the ones missing. But experiment is the real arbiter of physics, so we have to learn by doing intelligent experiments.

To emphasize again my conclusion – exotic hadrons are an experimental subject. Experimenters should watch especially when theorists tell them the coupling pattern of exotic hadrons to normal ones – so that they can identify their findings. Clearly high statistics experiments are needed, with proper amplitude analyses. For high statistics one needs new, higher intensity machines, KAON, SUPERLEAR or their descendants.

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