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USING $\overline{p}p$ ANNIHILATION TO FIND EXOTIC MESONS*

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ABSTRACT

Present data suggests that a number of mesons have been found which cannot be accommodated in standard $\overline{q}q$ multiplets. Theory suggests that such exotic mesons should exist in the spectrum of Quantum Chromodynamics, but provides little guide to their properties. It is argued that a high luminosity, low energy $\overline{p}p$ machine would be a powerful tool with which to search for such exotics.

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1. INTRODUCTION

Meson spectroscopy is now at an exciting stage. Results which have accumulated over the last few years have shown that there are very likely a number of "exotic" meson states. I am here using "exotic" to refer to those states that do not fit, in any obvious way, into standard $\overline{q}q$ multiplets. I am not ruling out that some of these states might be squeezed into such multiplets, but I would be very surprised if all can be so accommodated.

The data which suggest these new states come from high statistics studies in hadron collisions and J/ψ decays. However, while the tip of the exotic iceberg has been exposed, it is still surrounded by an impenetrable fog of theoretical uncertainty. Exotic mesons are indeed expected in the spectrum of Quantum Chromodynamics (QCD) – glueballs, meiktons (a.k.a. hybrids, hermaphrodites), $\overline{q}^2q^2$ states – but so far there are no reliable theoretical predictions of their masses and properties. There is some rough theoretical guidance as to what quantum numbers to expect, and for the ordering of the different multiplets, but little else. Thus it is hard to try to fit the candidates into a scheme that has to made up as one goes along.

What this situation demands is further guidance from experiment. This it has been receiving in good measure, but more is needed. And here low energy $\overline{p}$-s can be of great help. Annihilation at rest provides a clear window on exotic states with masses up to ~ 1.7 GeV. Specific spin-parities can be selected by combining the constraints on the quantum numbers of initial and final states. The initial state quantum numbers are constrained because the annihilation occurs in certain atomic $\overline{p}p$ states. The final state quantum numbers can be restricted by looking at simple final states such as $\eta\eta\pi^0$. All the interesting channels can be looked at in this way. Annihilation in flight allows higher mass states to be studied. If a very low spread in the beam energy can be achieved, then a scan for states will be very interesting. Provided the luminosity is high enough, and the detectors can measure photons with good resolution, and have good K/π separation, a low energy $\overline{p}p$ machine will be an excellent laboratory for exotic mesons.

The remainder of this talk expands upon these claims. I first summarize the theoretical status. Then I enlarge upon why the present experimental situation is so interesting and intriguing. I comment upon some of the possible ideas for interpreting the data. Thirdly, I run through some case studies of final states that I think are particularly interesting for the search for exotics at a $\overline{p}p$ machine. I close with some conclusions.

I have benefitted greatly from the extant reviews of this subject[1]. I have tried to make this paper self contained, but of necessity details have been omitted, and can be found in these reviews, along with additional references.

2. THEORY

QCD is the only candidate for a theory of the strong interactions. Its stature is based upon a few, somewhat indirect, quantitative tests[2], and upon a large body of semi-quantitative evidence. A clear example of the latter is the appearance of quark and gluon jets at high energy colliders. Nevertheless, there are no tests which come close to those we have for QED. We cannot, to date, predict the spectrum of the theory from first principles. We cannot even prove that quarks are confined.

Our ignorance about QCD is almost exclusively in the low momentum, long distance regime of particle masses, form factors, reaction cross sections, etc.. Of course, we do know something about this region, based on the $SU(3)$ flavor symmetry, and upon the associated chiral symmetry. We understand why particles come in multiplets, and why the pions and kaons are light, and how the latter couple. What we do not understand is why the spectrum of states, and to some extent their decays, can be explained by relatively simple quark models[3]. This is worth stressing: though most of the existing mesons and baryons fit well into a scheme in which constituent quarks and anti-quarks interact by a confining potential, we cannot show from first principles why this should be so. In particular, the constituent quarks of these models are much heavier – $\sim$ 300 MeV – than the bare current quark masses which we put into the QCD Lagrangian. Constituent quarks must be thought of as blobs of glue and $\overline{q}q$ pairs surrounding the bare quark.

Given the success of the quark model many people have speculated that there should be particles in the spectrum other than normal mesons ($\overline{q}q$) and baryons (qqq). If there are constituent quarks, why not constituent gluons, and the glueballs composed of such constituents. There are two levels of objection to this extrapolation. The deepest objection is that gluons have already been accounted for in turning bare quarks into blobs: glueballs are not different from $\overline{q}q$ states. I think this is wrong for two reasons. First, one can make operators out of glue alone with quantum numbers not allowed for $\overline{q}q$ states – spin-parity exotics such as 0^{--}. However, these operators could simply couple to the continuum, rather than create resonances, so this is only suggestive. The second reason is that there are two limits of QCD in which glueballs are certainly distinct from $\overline{q}q$ states: the number of colors $\rightarrow \infty$, and the quark masses $\rightarrow \infty$. The limit of infinite quark masses is pure gauge theory – glue alone – and lattice simulations of this theory have shown fairly conclusively the existence of a spectrum of glueballs of non-zero mass. As one goes from these limiting cases back to QCD, the $\overline{q}q$ states can mix with these glueballs, but both should be present in the spectrum. The weaker objection allows the existence of glueballs, but not of the notion of constituent gluons. Neither of the limits just discussed tells us about the structure of glueballs. They may be hideously complicated entities, requiring numerical simulations to predict their properties. This seems quite possible to me, and though in the following I will often use the language of constituent gluons, this caveat should be borne in mind.

A different path to exotica is to add together more $\overline{q}q$ pairs. The simplest examples are $\overline{q}^2q^2$ states[4]. The question of whether such states exist gets to the core of the problem with constituent quarks. For if $\overline{q}^2q^2$ states do exist, then there should also be $\overline{q}^3q^3$ states, etc.. A neat answer was provided by

Jaffe[4] who found in the bag model that nearly all such states would be able to decay classically into two $\overline{q}q$ mesons. Only a few exceptions, most notably the $a_0(980)$ and $f_0(975)$, would be stable. A similar conclusion has been reached within the quark model by Isgur and collaborators[5], who think of such states as molecules of mesons. Most of these molecules are not bound, the exception being the $\overline{K}K$ system, giving rise to the a_0 and f_0 just below the $\overline{K}K$ threshold. I will discuss this interpretation in the next section. The point I want to make here is that two quite different approaches agree that $\overline{q}^2q^2$ resonances will not be abundant in the spectrum.

The same need not be true of $\overline{q}qg$ states, i.e. meiktons[6]. These take the notion of constituent gluons to its logical conclusion: if they exist they can combine with a color octet $\overline{q}q$ pair. There are no fall apart decays, and thus the possibility of a rich spectrum. Indeed, some of the meiktons have spin-parities not available to $\overline{q}q$ mesons. There is another way of thinking about meiktons, which does not depend upon the notion of constituent gluons, and so strengthens the case for the existence of meiktons. To the extent that mesons can be thought of as $\overline{q}q$ pairs bound by a string of color electric flux, one can imagine exciting the string. This gives rise to a meikton, with the string excitation energy playing the role of the constituent gluon mass. Such a picture makes sense in the limit of heavy quarks, and it is possible to do lattice calculations of the excitation energy. The best numbers so far are 1.3 GeV for b quarks and 0.9 GeV for c quarks[7]. An unfortunate corrolary of this result, not directly relevant here but worthy of mention, is that $\overline{b}bg$ and $\overline{c}cg$ states will be above their respective open flavor thresholds.

In summary, I would say that it is almost certain that there is a rich spectrum of exotic states out there waiting to be found. The questions are: Where are they? What do they look like? and How are we to find them? The most important issue is their mass, and this depends on the mass of the constituent gluon. Here, it seems to me, we must depend upon numerical calculations as our major guide. The bag model[8], the flux tube model[9], and the QCD sum rules[10], all purport to answer this question, but they do not agree. This is perhaps not surprising, since all these methods are being extended beyond the limits within which they are known to work. Lattice QCD allows a calculation from first principles, limited only by computer resources. In the pure gluon theory, methods have matured enough to give a prediction for the 0^{++} and 2^{++} glueball masses[11]. The 0^{++} is the lightest state, with mass about 1400 MeV, the 2^{++} being about 1.6 times heavier. Addition of dynamical quarks, a next generation calculation, may change these values somewhat, and will allow the states to mix and decay. So these numbers are only rough guides, but it looks to me like a constituent gluon mass of 800 MeV is reasonable. Here I have allowed spin splittings to lower the mass of the scalar glueball from twice the constituent gluon mass. This number is consistent with the extrapolation to light quarks of the string excitation energy discussed above. It should be compared to the 300 MeV constituent mass of light quarks.

Given the constituent gluon mass one can attempt to predict the spectrum of exotic mesons. I shall follow Jaffe *et al.*[12], who extract some general features common to all models, but be a little bolder (foolhardy?) and give some masses. All numbers are to be taken as uncertain by at least a few hundred MeV.

In addition to the glueballs mentioned above, glueballs with quantum numbers 0^{-+} and 2^{-+} should be among the lightest, with masses higher than their positive parity counterparts. This brings us to about 2 GeV, beyond which there may lie many states, including the exotic spin-parities 1^{-+} and 0^{--}.

The lightest meiktons should appear around 1300 MeV. This is the sum of the constituent masses, less a bit for hyperfine splitting. The quantum numbers of the lightest meiktons are less clear, but among the lightest should be those with $J^{PC} = 0^{-+}, 1^{-+}, 1^{--}, 2^{-+}$. In the bag model, the mass increases along this list, reaching close to 2 GeV at the end. All models find excited states coming in at around this mass, with more and more states appearing as the mass increases further. Each of these J^{PC}s is a nonet of states.

It seems to me, then, that there may be a window of opportunity in the mass range $\sim 1300 - \sim 2000$ MeV. Above this range, there will a growing number of exotics, as well as of $\overline{q}q$ mesons. Most will be broad and so states will be hard to identify and to disentangle. Within the window, on the other hand, there are a manageable number of states, both exotic and ordinary. Having fewer states in each channel also makes it more likely that some of the exotics will not be significantly mixed with ordinary mesons. It is in this region that a $\overline{p}p$ machine is particularly powerful, and it is here too that a growing number of experimental candidates for exotics have been collecting. To these I now turn.

3. THE PRESENT EXPERIMENTAL STATUS

Exotics must stand out against a background of filled $\overline{q}q$ nonets. Below 1 GeV there are the ground state 0^{-+} and 1^{--} nonets, both of which are filled and well understood. Above 1 GeV, there are the radially excited pseudoscalars and vectors, neither of which are filled, and the orbitally excited nonets with spin-parities $(0,1,2)^{++}$ and 1^{+-}. The 2^{++} has long been filled, and, thanks to the efforts of the last 18 months or so, both spin 1 nonets are complete too. Quite a number of higher spin states – higher orbital excitations – are also known, particularly the strange states. But the lightest exotics probably have low spin, and so I shall concentrate on $\overline{q}q$ states of low spin.

Now I come to my list of candidate exotics. This list is not meant to be complete, but rather to indicate that there are a growing number of well documented, though poorly understood, exotics. I use the new notation for particles throughout. First on my list is the $\eta(1460)$ (was iota). This isoscalar, pseudoscalar is very prominent in radiative J/ψ decays, decaying into $\overline{K}K\pi$ with a width $\Gamma \sim 100$ MeV. It appears not to decay into $\eta\pi\pi$ and $\rho\gamma$[13]. It has not been seen in the hadronic decays of the J/ψ, in $\gamma\gamma$ production, or in high energy πp, $\overline{p}p$, or Kp production. It may have been discovered in 1966 in $\overline{p}p$ annihilation at rest[14]. Thus is appears to be a quarkless state – a prime glueball candidate.

Close by, there is growing evidence for an additional pseudoscalar – the $\eta(1400)$ (known to some as $\eta(1420)$). It is produced in πp scattering, decaying into $\overline{K}K\pi$ and $\eta\pi\pi$[15]. Its status in Kp scattering is less clear. LASS sees no signal[16], while Lepton-F finds evidence for a state at around 1400 MeV[17]. They interpret this a 1^{++} state, but Caldwell[18] suggests that it may be the $\eta(1400)$. It is not seen in two photon production, but may explain part of the $\eta\pi\pi$ signal in radiative J/ψ decay.

All this is rather puzzling. The radially excited pseudoscalar nonet is expected in this mass region, and indeed there is the isovector $\pi(1300)$, and the isoscalar $\eta(1275)$. The $\overline{s}s$ isoscalar is thus expected at $\sim$ 1550 MeV[3]. There are two possibilities that I can see. (1) Lepton-F is seeing the $\eta(1400)$, which is the required $\overline{s}s$ state, explaining its weak production in two photon and radiative J/ψ decay. (2) LASS is right, and we have another exotic on our hands, leaving no candidate for an $\overline{s}s$ state. In either case, the $\eta(1460)$ remains a prime glueball candidate.

Actually, even the $\eta(1275)$ and $\pi(1300)$ are not completely understood. Crystal ball has looked for both in $\gamma\gamma$ production, the former in $\eta\pi\pi$, the latter in $\pi\pi\pi$. They see no sign of either, and quote the limit[19]

$$\Gamma(\gamma\gamma \rightarrow \eta(1390)) \times B(\eta(1390) \rightarrow \eta\pi\pi) < 0.27 KeV.$$

In fact they see nothing in $\eta\pi\pi$ above the η'. The 2 photon widths of radially excited $\overline{q}q$ states are expected to be of $\mathcal{O}$(KeV), so these limits are beginning to be worrisome for the entire nonet.

I should also mention that in some quark models the second radial excitation of the η also lies in this mass region. Lipkin has pointed out that the mixing of this state with the $\overline{s}s$ radial excitation could be large and obscure flavor tagging arguments[20]. Nevertheless, I find it hard to see how the present data, and in particular the very large production of the $\eta(1460)$ in radiative J/ψ production, can be explained solely with $\overline{q}q$ states. In any case, $\overline{p}p$ experiments can play a crucial role in resolving this confusion. Annihilation at rest should be a source of both $\overline{q}q$ and glue-rich states, and so may be a way of producing both $\eta(1460)$ and $\eta(1400)$ at once.

The second exotic is the 1^{++} $f_1(1420)$, a.k.a. the E. This has been centrally produced in $\overline{p}p$ and πp[21], though not seen in forward production. More recently, a spin 1 state has been seen in $\gamma\gamma^*$ collisions, where the * means off-shell[22]. Although the exotic negative parity is not ruled out in $\gamma\gamma^*$, positive parity is preferred, and the most economical explanation is that the new state is the 1^{++} state seen earlier.

This assignment leads to a very puzzling problem. The orbitally excited 1^{++} nonet appears now to be filled with the $a_1(1270)$ (was A_1), $K_1(1280/1400)$, $f_1(1285)$ (was D), and the newly added $f_1'(1530)$. This latter state has been seen in Kp production by LASS decaying into $K^*\overline{K}$. It is thus a strong candidate for the $\overline{s}s$ member of the nonet, though its mass is somewhat high. If it does complete the nonet, then the $f_1(1420)$ is an odd-meson-out sitting right in the middle of the nonet.

However, the experimental situation is by no means clear. In some ways the $f_1(1420)$ looks like a light quark state: it is produced in hadronic decays of the J/ψ in association with an ω but not a ϕ[23]; the rate of $\gamma^*\gamma$ production suggests considerable light quark content[22]; and LASS does not see it in Kp production[16]. However, Lepton-F does see structure in Kp production at the right mass[17]. This could be 0^{-+} and/or $1^{+\pm}$, as discussed above. So the flavor content of the $f_1(1420)$ is unclear. Furthermore, there is evidence that the $f_1(1285)$ has $\overline{s}s$ content: the decay $J/\psi \to \phi f_1(1285)$ has been seen[23], and $f_1(1285) \to \phi\gamma$ has been measured[24].

The bottom line here is that there appears to be an extra state, and that no such state is expected in the quark model. It is also hard to think of an explanation for this state even as an exotic – $\overline{q}^2q^2$ has been suggested[18], but the mass seems somewhat low. If it were a 1^{-+} state, on the other hand, then it would fit nicely into the exotic spin-parity meikton nonet[25]. Or there may be both positive and negative parity states, which would be even more interesting. Clearly, something is going on, but clarification is essential.

Next I turn to the only isovector on my list, the $\rho(1490)$ (was C). This has been seen by the Lepton-F collaboration in πp scattering, decaying into $\phi\pi^0$ in a p-wave. Such a decay should set alarms ringing, since it has long been argued that $\overline{q}^2q^2$ states with hidden strangeness should decay in this way. Similarly, $\overline{q}qg$ states may decay significantly into this final state. The $\rho(1490)$ sits close to the mass expected of the radially excited vector states. The Particle Data Tables show a $\rho(1600)$, and there may be a $\phi(1680)$. LASS has confirmed the $K_1^*(1790)$[16] which also fits into this nonet. So an second isovector, particularly with such a strange decay (recall that the $\rho(1600)$ decays into 4 π and $\pi\pi$ with a large width of $\Gamma \sim 250$ MeV), is probably an exotic.

LASS has also turned up another vector exotic – the $K_1^*(1410)$[16]. This seems too light to be part of the radially excited vector nonet. If the $\rho(1490)$ contains an $\overline{s}s$ pair, then the $K_1^*(1410)$ could be related to it by changing an s quark to a d quark. This is possible in either $\overline{q}^2q^2$ or $\overline{q}qg$ interpretations. Both would also predict other states nearby: the rest of a nonet if the $\rho(1490)$ is $\overline{q}qg$; the rest of two decuplets of opposite G-parity if it is $\overline{q}^2q^2$[26]. The $\overline{q}qg$ option seems more plausible to me, since a vector $\overline{q}^2q^2$ state is orbitally excited and would be expected to be heavier. In either case, it is clearly essential to confirm these new states and study their properties, and a $\overline{p}p$ machine can do this for the $\rho(1490)$.

Another possible exotic is the scalar $f_0(1590)$ (was G). In fact, I do not have very strong reasons to single out this state, as the scalar spectrum is very confused. The quark model predicts an L=1 $\overline{q}q$ nonet somewhat above 1 GeV. In addition, $\overline{q}^2q^2$ states are expected close to the $\overline{K}K$ threshold. Finally, there should be the elusive scalar glueball. The isoscalars, including the glueball, should be broad, given the enormous phase space for $\pi\pi$ decay. This is a theoretical recipe for a mess, and a mess we indeed have.

The only established isovector is the $a_0(980)$ (was δ), but this is right at the $\overline{K}K$ threshold, which makes it difficult to establish its parameters. Most likely it is a $\overline{K}K$ molecule, or $\overline{q}^2q^2$, state, but more study is needed. As for the strange states, there is the $K_0^*(1350)$. The $\overline{q}^2q^2$ hypothesis does not expect stable states above 1 GeV – there should be broad regions of attraction in $K\pi$ and $\pi\pi$ scattering below 1 GeV – so the $K_0^*(1350)$ is most likely a $\overline{q}q$ state. But now to the isoscalars. Two detailed K-matrix analyses have been done, one published[27], and one preliminary[28]. Both use essentially all available data pertaining to the scalar isoscalar channel. They agree on $f_0(988)$ (was S^*), and on $f_0(1300)$ (was ϵ). This $f_0(988)$ fits well with the $\overline{q}^2q^2$ hypothesis, and is the partner of the $a_0(980)$, since both contain a hidden $\overline{s}s$ pair. The $f_0(1300)$ is the broad $\pi\pi$ resonance that has been with us for a long time, and which could be the light quark isoscalar of a $\overline{q}q$ nonet. Ref. 27 find another narrow state close to the $\overline{K}K$ threshold: the $f_0(991)$, decaying into $\overline{K}K$ and $\pi\pi$, which they claim is a candidate for a glueball. On the other hand Ref. 28 find a broad state at around 900 MeV, the ancient ϵ resonance. This might be the remnant of a light quark $\overline{q}^2q^2$ state, a very broad scalar glueball, or be part of a much distorted $\overline{q}q$ nonet.

Extending their analysis higher up in mass Ref. 28 come to the $f_0(1590)$ (was G). This is a much cleaner state, seen in πp production decaying into $\eta\eta$, $\eta\eta'$ and $4\pi^0$[24]. It is definitely not seen in radiative or hadronic J/ψ decays, which suggests that it is not a glueball. Since it decays predominantly to the η and η', it might be an $\overline{s}s$ state, but then why does it not decay into $\overline{K}K$? Maybe it is an excited meikton, for which decays to s quarks may dominate, or a $\overline{q}^2q^2$ state with hidden strangeness, but then why does it not fall apart?

At even higher mass Ref. 28 find a possible $f_0(1650)$ and $f_0(1750)$, and they mention that their final fit may need an additional $f_0(1240)$. Altogether, a lot of isoscalars, but no coherent pattern into which to fit them. Any possible clarification would be very helpful.

Another possible scalar or tensor exotic is the X(1480),[29] seen in $\overline{p}p$ and $\overline{p}n$ annihilations, and decaying mainly into $\rho\rho$.

This completes the list of states that can be seen in $\overline{p}p$ annihilation at rest. There are more oddities at higher mass which would be accessible from annihilation in flight. The first is the $f_2'(1720)$ (was θ), which remains a prime candidate for a glueball. It has not been seen so far in hadronic production. It is quite broad, and to search for it the large $\eta\eta$ mode would probably be most effective.

Higher in mass, there are the three tensor states seen in $\pi p \to \phi\phi n$[30]. These are at masses 2.01, 2.30 and 2.34 GeV, and are all broad. One might expect radially excited L=1 tensors at this mass, but not three, and not with this decay. The OZI forbidden nature of the process suggests glueballs, but three states so close in mass seems hard to accomodate in any theoretical scheme. To search for these states in low energy $\overline{p}p$ annihilation will be tricky, since they are so broad, but it is very important to have confirmation of them. They are not seen in J/ψ decays, which goes against the glueball hypothesis.

Conversely, the $\xi(2200)$ is seen in radiative J/ψ decay, possibly in πp production, possibly in Kp production, but not so far in $\overline{p}p$ at LEAR or BNL[15–31]. It maybe either a 2^{++} or 4^{++} state, which allows me to use its colloquial name. It is very narrow, and thus well suited to a $\overline{p}p$ scan, as long as the momentum spread is small enough. This state may well be a orbitally excited $\overline{q}q$ state[32], though the meikton hypothesis, and even the Higgs hypothesis, are still possibilities.

4. CASE STUDIES IN $\overline{p}p$ ANNIHILATION AT REST

The particular strengths of $\overline{p}p$ annihilations are two. For annihilation at rest, one can select the spin-parity of particular final states by using information about the initial atomic state. This reduces backgrounds, but will require searching in channels with small branching ratios. The second advantage is that annihilation in flight can scan in mass with very high precision, and thus search for narrow states such as the $\xi(2220)$. Of course, at higher masses one can study the charmonium states, and in particular some states not previously reached[33]. Such scans are straightforward in principle, however, so I focus my attention on the annihilation at rest. This is also where I have argued that there is the best possibility for unravelling the exotic spectrum of QCD.

Let me begin with some general comments about final states. There seems to be a growing experimental trend to find new states in channels involving mesons containing s quarks: η-s, η'-s, and ϕ-s. This is also where one would expect theoretically that the signal to background for exotics would be best. The signal may be enhanced because most exotic states contain gluons, which may have at least equal coupling to u, d and s quarks. In contrast, $\overline{q}q$ states have to either overcome the OZI rule, if they are made of light quarks, or the difficulty of popping an $\overline{s}s$ pair out of the vacuum, if they are $\overline{s}s$ states, in order to reach final states containing these particles. I am not suggesting that other channels should not be looked in, but I think these channels should be concentrated on when planning detector capabilities.

The beauty of annihilations from rest is that they occur from atomic states with definite J^{PC}. In a liquid target, where there is substantial Stark mixing, nearly all annihilations are from the s-wave, with $J^{PC} = 0^{-+}, 1^{--}$. In a gas target, roughly half of the annihilations come from p-wave states, with $J^{PC} = (0,1,2)^{++}, 1^{+-}$. It may be practical to tag the p-wave annihilations by their associated X-rays, and thus separate them from s-wave decays on an event by event basis, with some loss of efficiency. Even if this is not possible, a comparison of gas and liquid target data should allow a partial extraction of the p-wave component.

Kinematics restricts the search for exotics to the reactions (1) $\overline{p}p \rightarrow \pi X$ and (2) $\overline{p}p \rightarrow \pi\pi X$. In reaction (1) the allowed quantum numbers of X are $0^{++}, 1^{+-}$ from the s-wave atomic states, and $(0,1,2)^{-+}, 1^{--}$ from the p-wave states. I am assuming here that lack of phase space restricts the decay to zero orbital angular momentum. Masses for X of up to 1700 MeV can be studied. Reaction (2) yields quantum numbers for X that are the same as those of the initial $\overline{p}p$ state, assuming that the $\pi\pi$ pair in the final state is in a relative s-wave. Here, only masses up to 1550 MeV can be probed. In all cases, the isospin of the initial $\overline{p}p$ can be either 0 or 1, and so the same is true of X.

These considerations mean that decays from atomic s-wave states can search for exotic scalars, pseudoscalars and vectors. Addition of decays from p-wave atomic states allows study of the $J^{PC} = 1^{-+}$, 1^{++} and 2^{++}, as well as pushing up the mass available in the pseudoscalar and vector channels. The $\overline{q}q$ exotic 1^{-+} is particularly interesting. Thus annihilation from rest allows study of all the spin-parities in which the lightest exotics are expected. For the rest of this section I discuss some final states that seem particularly promising.

$\underline{X \rightarrow \overline{K}K\pi}$ This decay is allowed for $J^{PC}{}_X = 0^{-+}, 1^{+\pm}$, and includes the two body decays $\overline{K}K^*$ and $a_0\pi$. One can use it to search for exotic pseudoscalars and axial vectors. If one produces X in association with $\pi\pi$ from an initial s-wave, reaction (2S), then X must be a pseudoscalar, as pointed out by Chanowitz[34]. Indeed this is the classic channel in which the old E was found. It would be very nice to have more data in this channel, to see if both the $\eta(1400)$ and $\eta(1460)$ are present.

Utilizing initial p-wave states, and reaction (1), one can extend the mass available. One can also, using reaction (2), study 1^{++} states. If the tagging of initial p-wave states is possible, one then has a very nice method of switching between 0^{-+} and 1^{++}. It is harder to make a 1^{-+}, for this requires two units of orbital angular momentum.

$\underline{X \to \eta\pi\pi}$ This is very similar to the previous decay. Since there is uncertainty in the present data on the branching ratios into $\overline{K}K\pi$ and $\eta\pi\pi$, it is very important to do an analysis of both final states.

$\underline{X \to \eta\eta,\ \eta\eta'}$ These final states can only come from scalars or tensors, or from 1^{-+} states for $\eta\eta'$. Unfortunately, the latter channel, which is a good one for meiktons, is very close to the kinematic limit. We can select only the scalars by considering reaction (1S), which is here $\overline{p}p \to \pi^0\eta\eta(')$. This is a particularly nice final state because all the conceivable backgrounds are of interest. These are $a_0\eta$, which allows one to study the a_0, and $f_2\pi^0$, which is interesting to confirm the $f_2 \to \eta\eta$ decay. It should be possible to separate f_0 states from f_2 states from the Dalitz plot of the final state.

$\underline{X \to \eta\pi^0}$ These decays select appear for isovector particles, with quantum numbers $0^{++}, 1^{-+}, \ldots$. By choosing reaction (1S) we again pick out the scalar. This allows one to study the a_0. To select the exotic quantum numbers one must use reaction (1P). The final state is $\eta\pi^0\pi^0$, which again has few backgrounds. The choice of neutral pions removes any ρ contamination. This leaves the only background as ηf_0. This may be quite large, but is of interest in its own right as a complementary view of the scalar channel as compared to the $\eta\eta$ decay discussed above.

$\underline{X \to \phi\pi^0}$ This is the channel in which the $\rho(1490)$ has been seen. It allows the quantum numbers $1^{+-}, (0,1,2)^{--}$. Reaction (1S) selects from these the 1^{+-}, which is of interest because the $h_1(1400)$ may decay to $\phi\pi$. Reactions (2S) and (1P), on the other hand, select out the vector channel. The final state is $\phi\pi^0\pi^0$ for the latter, and in this case the only background is from low mass $\pi\pi$ structure. This is a particularly clean channel. It would also be interesting to replace the ϕ by an ω, though this will be a harder channel to study.

All of these channels will have small branching ratios, perhaps in the range $10^{-4} - 10^{-5}$. Thus high statistics will be essential. It is worth remembering that both the DM2 and Mark III groups have studied over 5 million J/ψ decays, 10% of which are in the intensively studied radiative decay mode. This has allowed these groups to discover a lot of new physics, but is not enough for detailed analysis of all interesting channels. So at least this number of $\overline{p}p$ annihilations will be needed to extract comparable physics.

5. CONCLUSIONS

I hope I have made the case for detailed further study of this exciting mass region. It seems to me reasonable that such study would yield a handful of glueballs and maybe a few partial nonets of meiktons. This study should be carried on with as many different production mechanisms as possible. $\overline{p}p$ annihilations at low energy or at rest can play a central role in these studies.

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