FUTURE REQUIREMENTS FOR GLUEBALL/MESON SPECTROSCOPY

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Summary

To discover and identify the glueball spectrum expected in Q.C.D. it is essential to understand in detail the very complicated spectrum of mesons between 1 and 2 1/2 GeV. To this end existing programs with fixed targets must be extended to even higher levels of statistics. Depending on the particular process, this may require more intense beams, faster detectors, on-line event selection, and more rapid data analysis. Radiative J/ψ decay plays a special role in the search because glueballs should appear there with enhanced rates and signal-to-noise ratios. Although we were lucky in the case of the glueball candidates i(1440) and θ(1640), it is likely that most of the new states will not be visible in mass histograms unaided by partial wave analysis. Progress requires increasing the statistical level in J/ψ decays by one or more orders of magnitude so that the methods of partial wave analysis can be applied. To achieve this a J/ψ factory is needed, which could be a new facility or an upgrade of an existing facility.

I. Introduction

The spectrum is the most fundamental test of any physical theory. In Q.C.D. the glueball sector is of special interest because it is a unique consequence of the nonabelian nature of the theory. It is a difficult and important experimental problem to find the low-lying levels of the glueball spectrum.[1]

Most estimates, based on lattice, bag, or potential models, imply that the low-lying glueballs are between 1 and 2 1/2 GeV. This is a very complicated region with a multitude of overlapping $\bar{q}q$ mesons: evidence exists for at least 17 $\bar{q}q$ nonets with $M \lesssim 2$ GeV. In the bag model the lightest glueballs have $J^{PC} = 0^{++}, 2^{++}, 0^{-+}, 2^{-+}$, and there are no known signatures that clearly and reliably distinguish them from $\bar{q}q$ states. Without resorting to very model-dependent theoretical ideas there are two properties of glueballs which can help identify them:

(A) They are not $\bar{q}q$ states and do not fit in $\bar{q}q$ nonets.
(B) They are copiously produced in channels where hard gluons can resonate into color singlet bound states.

(A) Glueballs are not $\bar{q}q$ mesons. This is a tautology, an unassailable proposition. It means that glueballs will not "fit" into $\bar{q}q$ nonets. Even if they mix strongly with $\bar{q}q$ states, there will be too many states to put in a nonet. For instance, the discovery of an I = 0 pseudoscalar meson in the 1450 - 1600 MeV region with the appropriate properties would fill the π' nonet and strengthen the glueball interpretation of i(1440).

(B) Glueballs may be produced prominently in hard gluon channels, such as $\psi \to \gamma X$ which in perturbation theory is dominated by $\psi \to \gamma gg$ where the digluon is in a color singlet and so may resonate to form glueballs. This is not quite a tautology. It is a simple consequence of quantum mechanics if we assume that glueballs are characterized by valence gluons just as mesons and baryons are characterized by valence quarks. In some theoretical approaches, such as the bag model, valence gluons are very natural. In others, such as the $1/N_{color}$ expansion, they are not; but even in the $1/N_{color}$ expansion we would expect to find glueballs in $\psi \to \gamma gg$, not because the gluons are hard but just because they form a purely gluonic color singlet configuration with invariant mass in the likely glueball mass region.

II. Fixed Target Experiments

Although property (A) is trivial conceptually it is very difficult to apply in practice. To use it we must understand the $\bar{q}q$ (and maybe the $\bar{q}qg$ and $\bar{q}\bar{q}qq$) spectrum below 2 GeV. very well indeed. In the last few years much progress has been made in high statistics partial wave analyses at fixed target machines. For instance, the ACCMOR collaboration at the CERN PS accumulated 600,000 events in $\pi^- p \to \pi^+\pi^-\pi^- p$ which enabled them to identify the A_1 away from the forward direction, to confirm the A_3 and to find evidence for π' and A_3'.[2] A ZGS experiment in $\pi p \to \eta\pi\pi n$ discovered (under the $J^P = 1^+ D(1285)$) another member of the π' nonet, the I = 0 ζ(1270).[3] And the LASS group at SLAC and ACCMOR have both seen the K'(1400).[4] These results block out 8/9 of the π' nonet. They and other recent results simply could not have been obtained by earlier lower statistics experiments.

Such work is important for the study of the glueball spectrum in two ways. First it establishes the matrix of known $\bar{q}q$ states against which a glueball can be recognized as "something else". Second, it may also lead directly to the discovery of glueball states. For instance the glueball candidate i(1440) was probably[5] first discovered (in 1965!) in a $\bar{p}p$ annihilation experiment.[6] Even if it turns out that most pure glueballs are not copiously produced in hadronic interactions, glueballs mixed with $\bar{q}q$ states may be copiously produced by virtue of their $\bar{q}q$ components.

New levels of statistics will be needed to analyze the 1-2 1/2 GeV region. As an example the ACCMOR experiment,[2] with 600,000 $\pi^- p \to \pi^-\pi^-\pi^+ p$ events, confirmed the existence of the $J^{PC} = 2^{-+}$ $A_3(1700)$ and obtained strong evidence for a second state, A_3', in the same channel. The full 600,000 events were needed to bring out the A_3' but were not sufficient to choose decisively between fits with $m_{A_3'} = 1850$ MeV and $m_{A_3'} = 2100$ MeV. The splitting $m_{A_3'} - m_{A_3}$ is rather small for a radial excitation (especially for $m_{A_3'} = 1850$ but even for $m_{A_3'} = 2100$). It has been proposed instead that A_3 and A_3' may be mixtures of the $\bar{q}q$ d-wave with the $\bar{q}qg$ s-wave.[7] Confirmation of A_3' and determination of its mass will require an effort surpassing the statistical level accumulated by ACCMOR.

III. Radiative ψ decay

Although i(1440) may have been discovered in $\bar{p}p$ annihilation in 1965, it was not recognized as a glueball candidate until its discovery in 1980 at SPEAR in $\psi \to \gamma X$.[8] This brings us to property(B), the need to explore hard gluon channels. Examples are radiative decay of quarkonium,

$$V \to \gamma X \sim V \to \gamma gg,$$

exclusive decay of quarkonium to two glueballs via five[9] gluons,

$$V \to ggggg \to GG',$$

and hadronization of gluon jets. The two glueball decays of upsilon are discussed elsewhere in these proceedings.[10]

The premier glueball production channel is J/ψ radiative decay, $\psi \to \gamma X$, which is dominated in perturbation theory by $\psi \to \gamma gg$. For the glueball spectrum in the expected 1 to 2 1/2 GeV. mass region no other source approaches $\psi \to \gamma X$ in rate or in ratio of signal to noise.

The true cross section at the peak

$$\sigma_\psi \cong 10^5 \text{ nb.} \cong 0.1 \text{ mb. !} \quad (1)$$

is degraded for a beam spread (as at SPEAR) $\Delta E = 10^{-3} E_{beam}$ to a still gargantuan

$$\bar{\sigma}_\psi \cong 2\cdot 10^3 \text{ nb.} \quad (2)$$

The corresponding R values are $R_\psi \cong 10^4$ and $\bar{R}_\psi \cong 240$. Thus the observed ψ signal is two orders of magnitude above the continuum background.

The Υ radiative decay suffers in comparison for four reasons:

1) Smaller observed cross section, $\bar{\sigma}_\Upsilon \cong 20$ nb., two orders of magnitude below $\bar{\sigma}_\psi$.
2) Smaller (by a factor 20) signal to noise, $\bar{R}_\Upsilon/R_{continuum} \cong 5$.
3) $\bar{b}b \to \gamma X$ is reduced by 1/4 relative to $\bar{c}c$ by the smaller charge of b.
4) The yield of $\Upsilon \to \gamma X$ for m_X between 1 and 2 GeV is reduced relative to $\psi \to \gamma X$ by approximately $M_\psi^2/M_\Upsilon^2 \cong 0.1$. This follows from the Ore-Powell spectrum of the photon in $\psi \to \gamma gg$, which is approximately linear in E_γ.

For heavier quankonia such as $\bar{t}t$ the prospects are as bad or worse than for Υ.

Something like 5% to 8% of ψ decays are in the radiative channel and a prominent glueball could capture 5% to 10% of all these radiative decays. For instance, the i(1440) is seen in the $\bar{K}K\pi$ channel alone with branching ratio $B(\psi \to \gamma(\bar{K}K\pi)_{1440}) \cong 4\cdot 10^{-3}$ corresponding to a cross section of

$$\bar{\sigma}(\bar{e}e \to \psi \to \gamma(\bar{K}K\pi)_{1440}) \cong 8 \text{ nb.} \quad (3)$$

Thus an experiment of 10^7 sec with an assumed luminosity of 10^{30} $cm^{-2}sec^{-1}$ would produce $8\cdot 10^4$ $G/i \to \bar{K}K\pi$ decays. Even with a combined detection efficiency of only $\sim 5\%$ this would leave 4000 decays in hand, a factor ~ 25 larger than the largest sample acquired to date (by the Crystal Ball).

The total number of radiative ψ decays in such a sample would be $\sim 10^6$. Careful analysis of this sample could bring out not only the glueball spectrum but would also provide an unparalleled view of the light $\bar{q}q$ meson spectrum in the glueball channel. The latter is interesting in and of itself but also because (property A) identification of the glueball states necessarily requires an understanding of the meson states of the same quantum numbers. For instance, at the present level of statistics the $\zeta(1280)$, which is purportedly[1] one of the two isoscalars in the π' nonet, has not been seen in $\psi \to \gamma\zeta$. If with greater statistics ζ and a second as yet undiscovered isoscalar, ζ', were seen at levels far below $\Gamma(\psi \to \gamma i)$, that would fill the π' nonet and help confirm the glueball interpretation of i. With this level of statistics one could also study dynamical issues, such as mixing between glueballs and $\bar{q}q$ mesons and the dynamics of glueball decays.

As a calibration point, the Crystal Ball study of i(1440) was based on a sample of about 150 observed $i \to K^+K^-\pi^0$ decays.[10] This was just barely enough to do the spin-parity analysis and establish $J^P(i) = 0^-$. Among glueball candidates i(1440) is a sitting duck: it appears with a large rate in a relatively background free setting in the $\bar{K}K\pi$ channel so that it could be discovered with the Mark II detector [8] in the $KK\pi$ mass histogram without partial wave analysis. $\theta(1640)$ is another similar example. Other glueball candidates may be much harder to find. In particular we may need to do partial wave analyses just to bring them out of the background. In this case we must surpass the statistical level of the Crystal Ball - $2\cdot 10^6$ J/ψ's - by at least an order of magnitude.

Neither SPEAR, DORIS nor ACO can now do this, but it is not hard to imagine a facility which could. With the rather unremarkable machine parameters of $\mathcal{L} = 10^{30}$ $cm^{-2}sec^{-1}$ and $\Delta E = 10^{-3} M_\psi$ an experiment of 10^7 seconds would yield $2\cdot 10^7$ J/ψ's and 10^6 radiative decays. It is not hard to imagine a facility which could go beyond this by another order of magnitude, say $\mathcal{L} = 3\cdot 10^{30} cm^{-2} sec^{-1}$ and $\Delta E/E = 3\cdot 10^{-4}$. At this level of statistics the problem of data analysis would be critical though not insuperable. More difficult problems are already being studied at fixed target machines: for instance, AGS experiment 766 has as its goal the development of hardware for precise on-line reconstruction of 10^5 complex events per second!

IV. Conclusion

We will not want to leave the study of Q.C.D. behind without having verified the existence of the expected spectrum of glueball states. We are therefore compelled to master in detail the very complicated meson spectrum between 1 and 2 1/2 GeV., where in addition to $\bar{q}q$ nonets and glueballs we may also find $\bar{q}qg$ nonets, $\bar{q}q$ bag/string excitations, and cryptoexotic $\bar{q}\bar{q}qq$ states.[1] This means that the highest statistics experiments, such as ACCMOR with 600,000 $\pi^-p \to \pi^-\pi^-\pi^+p$ events, must be matched in other channels. Indeed, as the discussion of A_3' illustrates, it will be necessary to go beyond the statistical level of ACCMOR.

High statistics studies of spectroscopy are being pursued, for instance, at the AGS, SLAC and KEK and will soon be initiated at the $\bar{p}p$ LEAR facility at CERN. New developments in beam intensities, fast detectors and analyzing power will be needed to reach the required statistical level. Major contributions could be made at LAMPF or TRIUMF, where energy upgrades are being discussed which would allow the study of the 1-2 GeV. mass region.

It will probably be impossible to achieve a definitive understanding of the glueball spectrum without accumulating more data from radiative J/ψ decay. The history of i(1440) illustrates this most clearly: although it may have been discovered in 1965 it could not be recognized as a possible glueball until it was seen at a large rate in $\psi \to \gamma i$.[5] Radiative J/ψ decay is crucial both because glueballs are produced there with large rate and signal-to-noise ratio and because their prominence in that channel is one of the few characteristics we can use to distinguish glueballs from other states.

As we know from fixed target studies, mass histograms alone will not often suffice to discover the new states in the 1.5 - 2.5 GeV. region. This means surpassing the present statisical level in radiative J/ψ decay by one or two orders of magnitude. The machine characteristics that would be required to achieve this seem well within reach. For instance with $\mathcal{L} = 3\cdot 10^{30}$ $cm^{-2}sec^{-1}$ and $\Delta E/E = 3\cdot 10^{-4}$ an experiment of 10^7 seconds would improve on the present statistics by a factor 100.

DORIS II, which is optimized at the Υ, will not have an improved luminosity at ψ. An improvement of the vacuum at SPEAR could reduce $\Delta E/E$ by a factor 3 and therefore increase the ψ production rate by the same factor, but there is at the moment no plan for such an upgrade.[12] I am not aware of any intention to improve the operating characteristics of ACO.

It is highly desirable that any new facility, such as the planned Beijing e^+e^- storage ring, have the luminosity and beam spread to provide the ψ production rates discussed here, and that it be equipped with detectors and analyzing power sufficient to exploit the increased event rate. We may also wish to consider the development of such a facility for the future U.S. high energy physics program. In addition to the spectroscopic studies which I have been comissioned to consider here, such a facility could also be used to study charmed mesons and their weak interaction decays.

References

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