SEARCH FOR GLUONIC MESONS IN GLUON JETS

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We present a short survey of the theoretical expectations on glueballs and hybrids as well as of the present phenomenological status. The possibility to obtain new information on gluonic mesons from the study of gluon jets in comparison to quark jets is discussed.

1 Introduction

The existence of glueballs, the bound states of two or more gluons, are an early expectation of QCD\(^1\). Calculations on a space time lattice have confirmed this expectation in the quantitative analysis. Their existence though is still in doubt despite continued efforts over the years. The identification of the glueballs requires the analysis of production and decay properties of the candidate mesons and has to be performed together with the identification of the lowest \(q \bar{q}\) multiplets. Glueballs are searched for in particular in the “gluon rich environment” of central production in hadron hadron collisions (double Pomeron exchange), in radiative \(J/\psi\) decays (hadrons from two intermediate gluons in the perturbative picture) or baryon antibaryon annihilation into mesons near threshold. On the other hand, the production of glueballs is expected to be suppressed in two photon processes.

An alternative possibility is the study of glueballs in gluon jets, which – although emphasized already long ago\(^2\) – has not been systematically explored until now. Recent discussions\(^3,\,4,\,5\) emphasize the interest in studying the fragmentation region of the gluon jet. We will discuss here especially our considerations how the detailed comparison of the fragmentation regions of quark and gluon jets could provide new clues on the existence of gluonic mesons.

2 Theoretical Expectations

There is general agreement in the theoretical analysis that the lightest glueball should be the bound state of two valence gluons with antiparallel spins in a relative S-wave with quantum numbers \(J^{PC} = 0^{++}\). The computation of its mass in lattice QCD has been carried out with increasing accuracy in recent years in the quenched approximation (without light sea quark-antiquark pairs) and a recent summary\(^6\) quotes the result \(m(0^{++}) = 1611\) MeV with a systematic error of about 10%. First results from unquenched calculations, i.e. including mixing effects with \(q \bar{q}\) mesons, would shift the mass down by \(\sim 20\%\) and so would lead to a mass of \(\sim 1300\) MeV but these results may still be affected by large systematic errors.

For the hybrids the state of lowest mass is the \((q \bar{q}g)\) bound state with exotic
quantum numbers $J^{PC} = 1^{-+}$ and the mass is expected at $\sim 1900$ MeV.

An alternative approach to hadron spectroscopy is provided by the QCD sum rules. Recent calculations (see review) for the $0^{++}$ glueball yield an estimated mass consistent with the quenched lattice result (with upper bound $2.16 \pm 0.22$ GeV), but in addition require a gluonic state near 1 GeV called $\sigma$ with strong mixing to $q\bar{q}$ and a large width of 0.8 GeV.

These results suggest that the lightest glueball should be searched for in the mass region 1.0 - 1.7 GeV, say.

3 Phenomenological Studies

The lightest glueball should be found among the light scalar particles or be mixed with them. The Particle Data Group (PDG) lists the following $0^{++}$ states

$$f_0(400 - 1200) \text{ (or } \sigma) \quad f_0(980) \quad f_0(1370) \quad f_0(1500) \quad f_0(1710) \quad (J = 0) \quad (1)$$

Numerous suggestions on the interpretation of these states have been proposed. We note two strategies

I) One starts from the quenched lattice result with a mass around 1600 MeV. Then the $f_0(1500)$ is the natural candidate for the lightest glueball or for the state with a strong admixture of gluonic component whereas the nearby states $f_0(1370)$ and $f_0(1710)$ should have a small gluonic admixture as in an early proposal. However, rather different mixing schemes have been suggested, depending in particular on the data included in the consideration (recent review), for example, one with the largest gluon component in $f_0(1710)$ and small one in $f_0(1500)$. In these schemes the $f_0(980)$ and $a_0(980)$ are often superfluous, they are taken as $K\bar{K}$ molecules and in this way removed from $q\bar{q}$ spectroscopy.

II) Alternatively, one can try to determine the scalar $q\bar{q}$ nonet first considering the scalar particles below $\sim 1700$ MeV. Theoretical considerations as well as the phenomenological analysis suggested $f_0(1500)$ to be a member of the $q\bar{q}$ nonet with flavor mixing close to the octet. Especially the negative relative sign of the decay amplitudes into $K\bar{K}$ and $\eta\eta$ determined in this analysis is not compatible with a dominant glueball component of $f_0(1500)$. The nonet can then be argued to be

$$q\bar{q} (0^{++}) : \quad f_0(980) \quad a_0(980) \quad K^*(1430) \quad f_0(1500) \quad (2)$$

which is also in good agreement with the Gell Mann Okubo mass formula.

The remaining light scalars in (1), $f_0(400 - 1200)$ and $f_0(1370)$ are then interpreted as non-$q\bar{q}$ effects. One possibility considered is their origin from $t$-channel Regge exchanges; in our view these two states are reflections of a single broad resonance, the lightest binary glueball $gb(1000)$. The arguments in favour of the glueball hypothesis include: the strong central production in $pp$ collisions and the suppression in $\gamma\gamma$ collisions against the glueball interpretation it has been put forward the lack of strong production in $J/\psi$ decay and certain inconsistencies in the decay ratios of $f_0(1370)$ into $\sigma\sigma$ and $\rho\rho$ in different processes.

In the sector of hybrids there is now good evidence for states with the spin exotic quantum numbers $J^{PC} = 1^{-+}$ and masses of 1.4 and 1.6 GeV. These
masses are again lower than expected from lattice calculations and one might discuss alternative interpretations of these states, for example, four quark states.

To summarize the phenomenology, there are interesting candidates for gluonic mesons but there is not yet a general consensus. It seems therefore important to find further ways to identify the gluonic components of scalar mesons and in the remaining part of this outline we will discuss such a proposal.

4 New Search Program for Gluonic Mesons

Let us compare the production of hadrons in quark and gluon jets. A fast hadron in a quark jet will likely carry the primary quark which initialized the jet as a valence quark and this likelihood will increase with increasing momentum fraction $x$ of the hadron in the jet. This leads to the well established phenomenology of quark fragmentation functions, for example, the $u$-quark will produce more $\pi^+$ than $\pi^-$ of large momentum fraction $x$. A natural extension of this phenomenology consists in supposing a similar process for a gluon jet: particles with large momentum fraction $x$ should carry the initial gluon as valence gluon so the leading particles should be glueballs or hybrids (see Fig. 1). So far, there is not yet a systematic investigation of the gluon fragmentation beyond the study of single inclusive spectra. We therefore propose investigating the gluon fragmentation in greater detail and we discuss first the possible production mechanisms.

![Figure 1](attachment:image.png)

Figure 1. Fragmentation of a quark into a $q\bar{q}$ meson and of a gluon into a glueball in the fragmentation region.

4.1 Hadron Production and Colour Neutralization

An energetic quark or gluon emerging from a hard collision process will generate a parton cascade by subsequent gluon bremsstrahlung and quark pair production. The extension of such a cascade for a 100 GeV jet in space can be rather large and exceed 100 f (see, for example [17, 18]). The formation of colour singlet systems should proceed during the evolution whenever the separation of colour charges exceeds the confinement length $R_c \sim 1f$. Two types of neutralization processes are possible (see Fig. 2).

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*A negative result from a search for heavy glueballs has been reported from a high statistics analysis of the $K^0_L K^0_L$ mass spectra but no restriction to the fragmentation region was applied.*
a) Colour triplet neutralization.
Consider first the production of a $q\bar{q}$ pair in a colour singlet state corresponding to separating colour triplet charges (possibly accompanied by secondary partons from bremsstrahlung). The colour field between the primary quarks can be neutralized eventually by the (nonperturbative) production of a soft quark antiquark pair. This process of triplet neutralization may repeat itself for the various branchings inside the quark gluon cascade until the total energy is carried by $q\bar{q}$ hadrons. Also possible is the formation of hybrid mesons from the gluons at the end of the perturbative cascade and the soft $q\bar{q}$. 

b) Colour octet neutralization.
In case of a primary colour singlet $gg$ pair the field between the separating colour octet charges can be neutralized at the confinement distance either by the production of a gluon pair or by the sequential production of two quark pairs. Only the mechanism with gluon pair production could yield pure gluonic bound states at the end.

It is not obvious to what extent the two types of neutralization mechanisms are realized in a given process. The octet neutralization could be an overall rare process enhanced for particular kinematic configurations. An experimental test has been proposed which does not rely on the existence of glueballs.

Consider the production of a hard gluon which travels without gluon radiation for a while forming a jet with a large rapidity gap empty of hadrons. In this case the hard isolated gluon builds up an octet field to the remaining partons, then the octet neutralization mechanism will become clearly visible if it exists. Namely, the total charge of the leading particles beyond the gap should have total charge $Q = 0$; on the other hand, the charge distribution in case of double triplet neutralization should have in addition a component with charges $Q = \pm 1$. With increasing rapidity gap the charge distribution should approach a limiting behaviour. An illustrative example of the limiting charge distribution of the leading cluster in a jet is discussed elsewhere.

If the enhanced neutral component from octet neutralization is not observed we would not expect a preferred source of glueballs in gluon jets either. In this case glueballs would be produced through their mixing with quarkonium states in any collision process and not preferentially through their valence glue component.
4.2 Search for Glueballs and Hybrids: Comparison of Quark and Gluon Jets

The following further study to identify the gluonic component of hadrons is suggested. One measures the mass distribution of the leading clusters with zero charge \((Q = 0)\), either clusters beyond a rapidity gap or clusters with large momentum fraction \(x\) in the jet. We would expect a smaller background under a resonance in the first case because of small contributions from soft particles in the jet. In any case the direct comparison of these mass spectra in quark and gluon jets should reveal the possibly dominant component – either gluonic or quarkonic. The ratio of these spectra should reflect the global differences of both types of jets (different inclusive spectra, phase space . . .) and the local differences due to resonances of different intrinsic composition. Alternatively, one may also first normalize the cross section of a state to a well known \(q\bar{q}\) resonance nearby in mass and compare these ratios in quark and gluon jets.

5 Summary

We propose studying the fragmentation region of quark and gluon jets with a selection of a rapidity gap or with large momentum fraction \(x\) of a particle cluster. The charge distribution of the leading cluster should reveal the relevance of the color octet neutralization mechanism. The relative production rates of the candidate gluonic mesons, in particular of the scalar mesons in (1), in the fragmentation region of quark and gluon jets should reveal their gluonic component.

An advantage of this method we consider the well established gluonic nature of jets in certain configurations emerging from high energy collisions; the gluonic nature of alternative processes like radiative decays of Quarkonium or double Pomeron production is not yet established at the same level of confidence.

References

1. H. Fritzsch and P. Minkowski, Nuovo Cimento 30, 393 (1975).
2. C. Peterson and T.F. Walsh, Phys. Lett. B 91, 455 (1980).
3. P. Roy, K. Sridhar, JHEP 9907, 013 (1999).
4. P. Minkowski and W. Ochs, Phys. Lett. B 485, 139 (2000).
5. Spiessberger and P. Zerwas Phys. Lett. B 481, 236 (2000).
6. C. Michael, “Glueballs, hybrids and exotic mesons and string breaking”, 4th Int. Conf. on Quark Confinement and the Hadron Spectrum, Vienna, Austria, July 2000, hep-ph/0009115.
7. S. Narison, “On the quark and gluon substructure of the \(\sigma\) and other scalar mesons”, Montpellier Conference (QCD 2000), Montpellier, France, July 2000, hep-ph/0009108.
8. Particle Data Group, D.E. Groom et al., Eur. Phys. J. C 15, 1 (2000).
9. C. Amsler and F.E. Close, Phys. Rev. D 53, 295 (1996).
10. E. Klempt, “Meson Spectroscopy: Glueballs, Hybrids and \(Q\bar{Q}\) Mesons”, PSI Zuoz Summer School: Phenomenology of Gauge Interactions, August 2000, hep-ex/0101031.
11. J. Sexton, A. Vaccarino and D. Weingarten, *Nucl. Phys.* B 47, 128 (1996).
12. P. Minkowski and W. Ochs, *Eur. Phys. J.* C 9, 283 (1999).
13. E. Klempt, B.C. Metsch, C.R. Munz and H.R. Petry, *Phys. Lett.* B 361, 160 (1995).
14. P. Minkowski and W. Ochs, in *Proc. Workshop on Hadron Spectroscopy*, Frascati, March 1999, Italy, Eds. T. Bressani et al. (Frascati Physics Series XV, 1999) p.245.
15. D. Thompson et al., *Phys. Rev. Lett.* 79, 1630 (1997); S.U. Chung et al., *Phys. Rev. D* 60, 092001 (1999); D. Adams et al., *Phys. Rev. Lett.* 81, 5760 (1998), A. Abele et al., *Phys. Lett.* B 423, 175 (1998).
16. OPAL Physics Note PN357, “A Search for the Tensor Glueball Candidate $f_{2}(2220)$ in hadronic $Z^{0}$ Decays ”, subm. ICHEP 98 conference Vancouver, 22-30 July 1998.
17. Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller and S.I. Troyan, “Basics of Perturbative QCD ” (Editions Frontière, Gif-sur-Yvette, France, 1991).
18. W. Ochs and T. Shimada, in *QCD and Multiparticle Production*, Proc. ISMD99, Providence RI, USA, August 1999, Eds. I. Sarcevic and Chung-I Tan (World Scientific, Singapore, 2000) p.64, hep-ph/9911240.