Glueball production in hadron and nucleus collisions

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Abstract

We elaborate on the hypothesis that in high energy hadron hadron and nucleus nucleus collisions the lowest mass glueballs are copiously produced from the gluon rich environment especially at high energy density. We discuss the particular glueball decay modes: $0^{++}, 2^{++} \rightarrow K\bar{K}$ and $0^{++} \rightarrow \pi^+ \pi^- \ell^+ \ell^-$. 

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1 Introduction

Early ideas on properties of gluonic mesons or glueballs as bound states of gauge bosons within QCD remained inconclusive at first because of an apparent lack of phenomenological evidence for such resonances beyond the prominent mesons \( q\bar{q} \), baryons \( qqq \) and antibaryons \( \overline{q\bar{q}} \).

An outline of expected scenarios for (mainly) binary glueballs, i.e. consisting predominantly of two gauge bosons, was presented in ref. [1]. Specifically a low mass and high mass scenario were distinguished in ref. [1], referring to the mass of the lowest lying glueball with quantum numbers \( J^{PC} = 0^{++} \). The latter is expected to be close to 1 GeV in the low mass scenario, whereas it is to be sought above or around 1.5 GeV in the high mass case. For an appraisal of these ideas we refer to ref. [2]. Lattice gauge theory, in particular without quark flavors indicates preference for the high mass scenario [3], [4], [5], [6]. In the presence of quarks lattice simulations are at the moment inconclusive [7], [8].

2 Reference production of glueballs

In a recent paper [9] the spectroscopic assignment of the three lowest lying binary gluonic mesons denoted \( gb \ (0^{++}) \), \( gb \ (0^{-+}) \), \( gb \ (2^{++}) \) shown in table 1 was proposed and discussed.

| name \( gb \) \( (0^{++}) \) | PDG \( f_0(400-1200) \) | mass (MeV) | \( \sim 1000 \) | \( \sim 1 \) | width (MeV) | \( 500-1000 \) |
|-----------------------------|---------------------|-------------|-------------|-------------|-------------|
| \( gb \ (0^{-+}) \)        | \( \eta(1440) \)    | 1400 - 1470 | 2.07        | 50 - 80     |
| \( gb \ (2^{++}) \)        | \( f_1(1710) \)     | 1712 ± 5    | 2.93        | 133 ± 14    |

Table 1: Properties of the basic triplet of binary glueballs.

Two main modes of production of \( gb(0^{++}) \) were elaborated on in ref. [9]:

a) two to two pseudoscalar meson scattering in the \( I = 0 \) channel:

The wide structure interrupted by two narrow width resonances, which manifest themselves as almost complete negative interference is referred to as ‘red dragon’ in ref. [9]. It is interpreted as \( gb \ (0^{++}) \) interfering with the two scalar, isoscalar \( q\bar{q} \) mesons, \( (f_0(980), f_0(1500)) \) forming the three flavor nonet.
\[
\pi\pi \rightarrow gb\ (0^{++}) \rightarrow \pi\pi \\
\rightarrow gb\ (0^{++}) \rightarrow K\overline{K} \\
\rightarrow gb\ (0^{++}) \rightarrow \eta\eta
\]

Table 2: Production and decay modes of gb 0++ in quasi-elastic ππ scattering.

This contrasts with the assignment proposed in ref. [10] where \( f_0\ (1500) \) is identified with \( gb\ (0^{++}) \) together with a nontrivial admixture of scalar \( q\overline{q} \) states.

The production characteristics is represented by the modulus square of the s wave scattering amplitude in the three channels in table 2, which we reproduce in figure 1 from ref. [9].

b) Production in the reaction \( pp \rightarrow pXp \) at central rapidity.

A most remarkable line shape over the whole region of \( gb\ (0^{++}) \) displaying a width of approximately 1 GeV is observed in the double pomeron dominated reaction

\[
p_1 + p_2 \rightarrow p'_1 + X + p'_2
\]

where the momentum transfers from \( p_1 \) to \( p'_1 \) and from \( p_2 \) to \( p'_2 \) are constrained to be quite small compared to the center of mass energy.

The line shape as observed by the Axial Field Spectrometer collaboration [11] is shown in figure 2. It represents the production of the 0++ glueball state (called red dragon) in ref. [9].

It is characterized by a different distribution over the two pion invariant mass than the two to two scattering cross sections in figure 1. The difference in shape is a manifestation of the chameleon nature of the leading scalar glueball as the unique genuinely wide resonance. The destructive interference pattern at the scalar resonances \( f_0\ (980) \) and \( f_0\ (1500) \) is clearly visible in both production line shapes.

The production of \( gb\ (0^{++}) \) in the decays

c) \( J/\Psi \rightarrow \gamma X\ ;\ X \rightarrow \pi\pi\ ;\ K\overline{K} \)
d) \( J/\Psi \rightarrow \omega X\ ;\ X \rightarrow \pi\pi\ ;\ K\overline{K} \)
e) \( J/\Psi \rightarrow \phi X\ ;\ X \rightarrow \pi\pi\ ;\ K\overline{K} \)

where it was systematically searched for, remains unresolved for the time being.

The Axial Field Spectrometer collaboration [11] performs a spin analysis of the ππ system up to an invariant mass of 2.3 GeV, involving s and d
waves. This analysis reveals a spin 2 resonance with the mass and width parameters $m = 1700$ MeV, $\Gamma = 120$ MeV. These parameters agree very well with those of $gb (2^{++})$ in table 1. There is a controversy over the spin of the $f_J (1700)$ ($J=0, 2$) [13, 14, 11]. We refer to the review of particle physics of the particle data group and to ref. [9] for more details. Further experiments and/or analysis are necessary to resolve this issue.

3 Modes of production and experimental signatures of glueballs

We consider hadron hadron and nucleus nucleus collisions at energies high enough to be dominated by Pomeron exchange. In this energy domain, multiplicities of produced particles, including heavy flavors such as strangeness and charm, could exhibit limiting behaviour in their ratios. In this regime we expect the glueball production to be dominant without imposing rapidity gaps.

We propose to study consequences of the hypothesis that correspondingly dominant particle production proceeds from a gluon rich environment. This then translates into a major component of $gb (0^{++})$ production. In this process the lower mass region $m (gb (0^{++})) \sim 400$ MeV is assumed to be dominant, similar to the shape of the 'red dragon' observed in central production in the reaction $pp \rightarrow p X p$ shown in figure 2. It is a general property of a wide resonance that its line shape is not universal but rather chameleon like. This is supported by the contrast between the line shapes in figures 1 and 2. The line shape in figure 2 shows an exponential dependence on the invariant mass, suggestive of a thermal distribution. We therefore deduce that the production of low masses of the $0^{++}$ glueball state is preferred in a high energy and high density hadronic environment.

Thus the two pion decay mode of $gb (0^{++})$ becomes dominant, giving rise to characteristic two pion s-wave correlations relative to directly produced pions, which in an approximately thermal and noninteracting model remain uncorrelated. The glueball associated s-wave component should dominate over direct production of vector mesons $\rho, \omega, \phi$, with the main two pion decay proceeding through the $\rho$.

The selection of central events, i.e. events with a small impact parameter enhances the gluon initiated production of $gb (0^{++})$.

We study the following production:

$$h + h' \rightarrow A + A' \rightarrow N \ gb (0^{++}) + n \pi + X \quad (2)$$

\[2\] Under rapidity gap we understand a cut excluding events with any particle within characteristic intervals of rapidity.
and the two decay channels:

1) \( gb \,(0^{++}) \rightarrow \pi \pi, K \overline{K} \)  

2) \( gb \,(0^{++}) \rightarrow \pi^+\pi^- \ell^+\ell^- \)  

In eq. (2) \( N \) denotes the number of scalar glueballs and \( n \) the number of pions emitted independently of glueballs.

The semileptonic glueball decay in eq. (4) proceeds as follows

\[ gb \,(0^{++}) \rightarrow \varrho_{\text{virtual}} \gamma_{\text{virtual}} , \varrho_{\text{virtual}} \rightarrow \pi^+\pi^- , \gamma_{\text{virtual}} \rightarrow \ell^+\ell^- \]  

The decay channel in equation (4) is not characteristic for a glueball. The gluonic Zweig rule suppresses the mixing of glueball and \( q\overline{q} \) states, but it does not apply to a low mass \( 0^{++} \) state because of the strong effective coupling. This is reflected by the large width (\( \sim 1 \) GeV) of the \( 0^{++} \) glueball [1, 9]. We estimate that the branching fraction for the decay in eq. (4) is of the order of \( 10^{-5} - 10^{-6} \). This branching fraction is of the same order as \( 0^{++} \rightarrow \gamma\gamma \). The latter is extracted from central \( e^+e^- \) production of hadrons [16].

The measurement of the \( 0^{++} \) glueball state in the high track density environment in the final state of heavy ion collisions could be pursued by searching for the typical interference pattern displayed in figures (1) and (2) in the invariant mass distributions of \( K_s^0K_s^0, K^+K^-, \pi^0\pi^0 \) and \( \pi^+\pi^- \). The decay channel to kaons is less affected by background, however it can reconstruct only the tail of the \( 0^{++} \) invariant mass distribution. Especially the \( K_s^0K_s^0 \) mode singles out natural spin parity (e.g. \( 0^{++}, 2^{++}, 4^{++}, \ldots \)). This fact compensates for the loss of statistics as compared to the \( K^+K^- \) channel. In particular the \( J^{PC} = 1^{--} \) channel is absent.

The characteristic interference pattern could be enhanced applying cuts on kinematic variables like the transverse momentum \( (p_T) \) and the opening angle of the decay products. Further we put forward the question, whether background subtraction differential in relative momentum of the decay products (e.g. \( K_s^0K_s^0 \)), renders possible an angular momentum analysis overcoming the serious combinatorial background. This analysis has been successfully performed in pp collisions [11, 17] albeit imposing severe rapidity gaps.

The measurement of the \( 2^{++} \) glueball state through e.g. the decay channel \( 2^{++} \rightarrow K\overline{K} \) may be possible. The associated production of the gb \( 2^{++} \) is suppressed compared to the \( 0^{++} \) state due to its mass. Nevertheless it could
be identified especially in the $K\bar{K}$ channels because of two things: first it would dominate the production of $2^{++}$ $q\bar{q}$ states of comparable mass and second it would decay through a normal decay width given in table 1 into $\pi\pi$ and $K\bar{K}$. Due to the well defined shape of the $2^{++}(1700)$ glueball and its small width it is possible to suppress the background in a more efficient way than for the $0^{++}$ glueball. This is achieved through cuts applied to the decay kinematics of the meson pairs (e.g. $2^{++}(1700) \rightarrow K\bar{K}$).

The production of the $0^{++}$ state could have important consequences for the invariant mass distribution of $\ell^+\ell^-$ pairs, through the decay channel $\pi^+\pi^- \ell^+\ell^-$. The invariant mass distribution of $e^+e^-$ pairs produced in S+Au and Pb+Au reactions at 200 and 158 GeV per nucleon respectively shows a significant excess over expectations based on known sources of $e^+e^-$ pair production [18] as shown in figure 3.

We emphasize that the contribution denoted 'known sources' in figure 3 represents the best knowledge as processed in Monte Carlo studies of $pp$ and $pA$ collisions at comparatively lower energy density than in central Pb Pb collisions at 158 GeV/c per nucleon. Figure 4 shows the invariant mass distribution of $e^+e^-$ pairs resulting from the decay $\rho \rightarrow e^+e^-$ and from the assumed copious production and decay of the $0^{++}$ glueball state : $gb$ ( $0^{++}$ ) $\rightarrow \pi^+\pi^-e^+e^-$. In this calculation it was assumed that the product of production cross section times branching fraction into $e^+e^-$ of the $\rho^0$ meson and the $0^{++}$ glueball state are in the ratio of $1 : 20$.

The branching ratio of the $\rho \rightarrow e^+e^-$ is $4.5 \times 10^{-5}$ and comparable with the one of $0^{++} \rightarrow \pi^+\pi^-e^+e^-$. Furthermore it was assumed that the $0^{++}$ glueball state is distributed in mass as shown in figure 2. The rapidity distribution is taken as gaussian with a width of 0.6 units. For the transverse mass distribution we choose an exponential shape with inverse slope of 150 MeV.

The $\rho$ meson was assumed to have the same rapidity distribution as the $0^{++}$ and its inverse slope in $m_T$ is taken as 200 MeV. Additionally in order to simulate the experimental response we introduced an error of $\Delta p/p = 5\%$ for the momenta of the decay products $e^+e^-$. In figure 4 the influence of the rejection of all dilepton transverse momenta below 0.2 GeV is shown. This cut follows the actual procedure applied to the experimental data of figure 3. The $e^+e^-$ pairs from the decay of the $0^{++}$ glueball state significantly populate the region of invariant mass where the excess is seen by the NA45 experiment.

The decay channel $0^{++} \rightarrow \pi^+\pi^-\gamma$ occurs with a branching ratio typically 100 times larger than for the decay in eq. (4). The resulting $\gamma$'s would have predominantly very low transverse momenta displayed in figure 4. An
abnormal production of $\gamma$’s from the above decay is negligible compared to Bremsstrahlung and $\pi^0$ decay.

4 Conclusions

We discussed consequences of dominant $0^{++}$ glueball production in high energy collisions of hadrons and nuclei. It is conceivable that the glueball production becomes a dominant part in central nuclear collisions. The existence of the QGP phase under thermodynamic conditions above a transition temperature of 150-200 MeV associates directly a gluon rich environment favoring the glueball production mechanism in the nuclear reaction case over hadronic collisions at the same energy. The characteristic interference pattern of the $0^{++}$ glueball with the $f_0$ (980) and $f_0$ (1500) could serve as the signature of this state decaying into a pair of mesons $K^0_sK^0_s$, $K^+K^-$, $\pi^0\pi^0$ and $\pi^+\pi^-$ without imposing large rapidity gaps. However the two meson channels suffer from combinatorial problems, which may be reduced for the $K\overline{K}$ channels.

A promising decay channel appears: \( gb\ (0^{++}) \rightarrow \pi^+\pi^- \ell^+\ell^- \). This is not a characteristic glueball decay channel but enhanced through $q\overline{q}$ mixing by the large width of glueball $0^{++}$. Because the branching fraction of this channel is of the order $10^{-5} - 10^{-6}$ the opposite sign dilepton signal becomes significant compared to the $\rho^0$ contribution. The expected signal is dominant in the dilepton mass region between 200 and 800 MeV. We conjecture that this enhancement is observed in S+Au and Pb+Au collisions at 200 and 158 GeV per nucleon respectively at low impact parameter and high energy density.

A dominant $0^{++}$ glueball component brings into focus an enhanced production of glueball $2^{++}(1700)$. Due to the well defined shape of the $2^{++}(1700)$ glueball and its small width it appears possible to suppress the background in a more efficient way than for the $0^{++}$ glueball.

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Figure 1: Isoscalar S-wave components of the mass spectra of pseudoscalar pairs produced in $\pi p$-collisions at small momentum transfers $t$, (a) $\pi^0\pi^0$ spectrum, the preferred solution for $m < 1.5$ GeV by the BNL-E852 experiment [19] (preliminary results) and an alternative solution for higher masses by GAMS [20]; (b) $K_0^0 K_0^0$ spectrum by Etkin et al. [21] which is similar to the results by Cohen et al. [22] below 1600 MeV and (c) $\eta\eta$ spectrum by Binon et al. [23].
Figure 2: The mass spectrum of the $\sqrt{s}=45$ GeV exclusive $\pi^{+}\pi^{-}$ events (data points). The solid line represents the $\sqrt{s}=63$ GeV data, normalised to the same total number of events. No acceptance has been applied to either distribution [11, 17].
Figure 3: Inclusive invariant $e^+e^-$ mass spectrum in 158 A GeV Pb+Au collisions normalised to the observed charge particle density [18]. The statistical errors of the data are shown as bars, the systematic errors are given independently as brackets. The full line represents the $e^+e^-$ yield from hadron decays scaled from p-induced collisions. The contributions of individual decay channels are also shown.
Figure 4: Invariant mass distribution of $e^+e^-$ pairs resulting from the decay $\rho \rightarrow e^+e^-$ and from the assumed decay of the $0^{++}$ glueball state $0^{++} \rightarrow \pi^+\pi^-e^+e^-$. In this calculation the products of production cross section times branching fraction into $e^+e^-$ of the $\rho^0$ meson and the $0^{++}$ glueball state are in the ratio of $1 : 20$. 
Figure 5: Invariant mass distribution of $e^+e^-$ pairs resulting from the decay $\rho \rightarrow e^+e^-$ and from the assumed decay of the $0^{++}$ glueball state $0^{++} \rightarrow \pi^+\pi^-e^+e^-$. A cut on the transverse momentum of the dipoleton pair of 0.2 GeV is imposed. In this calculation the products of production cross section times branching fraction into $e^+e^-$ of the $\rho^0$ meson and the $0^{++}$ glueball state are in the ratio of 1 : 20.
Figure 6: Transverse momentum distribution of photons and pions from the decay of the $0^{++}$ glueball state into $\pi^+ \pi^- \gamma$. 

\[ 0^{++} \rightarrow \pi^+ \pi^- \gamma \]