Possible glueball production in relativistic heavy–ion collisions

I.N. Mishustin,1,2 L.M. Satarov,1,2 and W. Greiner1

1Frankfurt Institute for Advanced Studies, J.W. Goethe Universität, D–60438 Frankfurt am Main, Germany
2The Kurchatov Institute, Russian Research Center, 123182 Moscow, Russia

Abstract

Within a thermal model we estimate possible multiplicities of scalar glueballs in central Au+Au collisions at AGS, SPS, RHIC and LHC energies. For the glueball mass in the region 1.5–1.7 GeV, the model predicts on average (per event) 0.5–1.5 glueballs at RHIC and 1.5–4 glueballs at LHC energies. Possible enhancement mechanisms are discussed.

Glueballs are probably the most unusual particles predicted by the QCD but not found experimentally yet. It is believed that they can be produced in "gluon–rich" processes, like the $J/\psi$ radiative decay or $p\bar{p}$ collisions. The lowest glueball states with quantum numbers $J^{PC} = 0^{++}, 2^{++}, 0^{-+}$ predicted by the lattice calculations lie in the range 1.4–2.4 GeV:

$$m(0^{++}) = 1.6 \pm 0.2 \text{ GeV}, \ m(2^{++}) = 2.2 \pm 0.1 \text{ GeV}, \ m(0^{-+}) = 2.4 \pm 0.05 \text{ GeV}. \ (1)$$

The uncertainty in masses is mainly introduced by the mixing with the $q\bar{q}$ states. For example, it is expected that the $f_0(1500)$ meson has a very large glueball component (see recent discussion in Ref. [4]). We think that relativistic heavy–ion collisions might be a right tool to produce and study these exotic particles. If the quark–gluon plasma is indeed produced in such collisions, a significant fraction, more than 30%, of its entropy should be represented by thermal gluons. If these gluons survive until the hadronization stage, they will inevitably form glueballs as two–gluon bound states.

It is well established now [5, 6, 7] that ratios of hadron multiplicities, observed in central heavy–ion collisions in a broad range of bombarding energies, can be well reproduced within a simple thermal model. This model assumes that all hadrons are formed in a common equilibrated system characterized by the temperature $T$, the chemical potential $\mu_B$ and the volume $V$. The number density $N/V$ of bosons in a baryon–free system is given by the formula ($\hbar = c = 1$)

$$\frac{N}{V} = \frac{(2J + 1)}{(2\pi)^3} \gamma_s^{n_s} \int d^3p \left[ \exp \left( \sqrt{\frac{m^2 + p^2}{T}} \right) - 1 \right]^{-1}, \ (2)$$

where $m$ and $J$ are, respectively, the boson mass and spin. Following Refs. [3, 8] we take into account possible deviations from chemical equilibrium for hadrons, containing nonzero number ($n_s$) of strange quarks and antiquarks, by introducing a strangeness suppression factor $\gamma_s$.

In our previous paper [9] we have used this model to predict possible yields of exotic baryonia. In this letter we apply the same model with the same parameters to estimate multiplicities of glueballs, assuming that they are in thermal and chemical equilibrium with other hadrons. In order to eliminate unknown volume we consider the ratio of the glueball multiplicity to the multiplicity of $\phi(1020)$ mesons ($n_s = 2$). Assuming further that the
glueball is a flavor–neutral particle we get for this ratio:

\[ \frac{N_G}{N_\phi} \simeq \frac{2J + 1}{3} \gamma_s^2 \left( \frac{m_G}{m_\phi} \right)^{3/2} e^{(m_\phi - m_G)/T}, \]  

(3)

where \( m_G(m_\phi) \) is the glueball (\( \phi \)-meson) mass. The r.h.s. of Eq. (3) is obtained in the Boltzmann approximation and in the lowest order in \( T/m \). Below we consider only the scalar glueballs (\( J = 0 \)).

TABLE I: Parameters of thermal model for central Au+Au and Pb+Pb collisions at different c.m. energies and the observed multiplicities of \( \phi \)-mesons.

<table>
<thead>
<tr>
<th>reaction</th>
<th>( \sqrt{s_{NN}} ) (GeV)</th>
<th>( T ) (MeV)</th>
<th>( \gamma_s )</th>
<th>( N_\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td>4.87</td>
<td>119.1</td>
<td>0.763</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>8.87</td>
<td>145.5</td>
<td>0.807</td>
<td>2.57 ± 0.1</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>12.4</td>
<td>151.9</td>
<td>0.766</td>
<td>4.37 ± 0.14</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>17.3</td>
<td>154.8</td>
<td>0.938</td>
<td>7.6 ± 1.1</td>
</tr>
<tr>
<td>Au+Au</td>
<td>130</td>
<td>176</td>
<td>1.0</td>
<td>34 ± 5</td>
</tr>
<tr>
<td>Au+Au</td>
<td>200</td>
<td>177</td>
<td>1.0</td>
<td>38 ± 3</td>
</tr>
<tr>
<td>Au+Au</td>
<td>5.5 \cdot 10^3</td>
<td>177</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

We use the parameters of thermal model obtained in Refs. 5 (fit B) and 6 by fitting the hadron ratios observed in central Au+Au and Pb+Pb collisions at various energies. These parameters as well as experimental values of the \( \phi \)-meson multiplicities in these reactions are given in Table I. In the case of Au+Au collisions at the AGS and RHIC energies the total \( \phi \) multiplicities are not yet available. For these reactions we use the \( \phi/\pi \) ratios observed at midrapidity 10, 12, 13 and estimate \( N_\phi \) multiplying these ratios by charged pion multiplicities 14, 15 extrapolated to the whole rapidity space. At the LHC energy \( \sqrt{s_{NN}} = 5.5 \text{ TeV} \) we take the same \( T \) and \( \gamma_s \) as for central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) and use the value \( N_\phi = 100 \), obtained by extrapolating the RHIC data. In this extrapolation we assume that the ratio of \( \phi \) multiplicities at the LHC and RHIC energies equals the corresponding ratio of charged particle multiplicities, \( N_{ch} \). The phenomenological formula for the energy dependence of \( N_{ch} \) is taken from Ref. 16.

By using Eq. (3) with the parameters from Table I we calculate \( N_G/N_\phi \) for the case of most central Au+Au collisions at different bombarding energies. The results for two values
FIG. 1: Ratio of mean multiplicities of glueballs and \( \phi \)-mesons in central Au+Au collisions at different c.m. bombarding energies calculated within the thermal model. Solid and dashed lines show results for glueballs with masses \( m_G = 1.5 \) and 1.7 GeV, respectively.

of the glueball mass, \( m_G = 1.5 \) and 1.7 GeV, are shown in Fig. II. A nontrivial behavior of the \( N_G/N_\phi \)-ratio is explained by the nonmonotonic energy dependence of \( \gamma_s \). One can see that for the most central Au+Au collisions at \( \sqrt{s_{NN}} \gtrsim 200 \) GeV this ratio is predicted in the range of 1.5–4%.

Figure II shows the excitation functions of the absolute glueball multiplicity \( N_G \) in the central Au+Au collisions. At higher RHIC energy the predicted glueball yields are in the range of 0.6–1.5 (per event) for \( m_G = 1.5–1.7 \) GeV. At the future LHC facility we predict, respectively, 1.5–4 glueballs per central Au+Au collision.

It is instructive to compare these predictions with glueball multiplicities obtained for superposition of independent nucleon–nucleon collisions. In order to estimate glueball yields in a single NN-collision we use the thermal model of \( pp \) and \( p\bar{p} \) reactions, suggested in
FIG. 2: Mean multiplicities of glueballs in central Au+Au collisions for different values of mass $m_G$.

Ref. [17]. Within this model, the hadron multiplicities observed in $p\bar{p}$ interactions at $\sqrt{s} = 200$ GeV can be reproduced with the effective temperature $T \simeq 175 \pm 11$ MeV and the particle emitting volume $V \simeq 35 \pm 14$ fm$^3$. Using Eq. (2), we get the following estimate for average multiplicity of glueballs in a single $p\bar{p}$-collision at $\sqrt{s} = 200$ GeV:

$$N_G(p\bar{p}) \simeq (3.4 - 9.0) \cdot 10^{-3}. \quad (4)$$

The two values in the r.h.s. correspond to $m_G = 1.5$ and 1.7 GeV. We further assume that probabilities of the glueball production in the $p\bar{p}$- and the NN-collisions are the same at high energies. Multiplying Eq. (1) by $N_{\text{part}}/2 \simeq 178$ [18], the average number of NN-pairs participating in most central Au+Au collisions, we obtain 0.6-1.6 glueballs per central Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV. From Fig. 2 one can see that these values are rather close to the glueball multiplicities, predicted by the thermal model for the highest RHIC energy.

We think, that the estimates presented above should be regarded as a lower bound for
the glueball yield in high–energy heavy–ion collisions. As follows from the QCD–based calculations [19, 20] and also from some effective models [21, 22], the gluon–like excitations acquire a temperature–dependent mass, \( m_g \simeq 0.8 \text{ GeV} \) just before the hadronization transition. Such quasiparticles may form glueball–like bound states already in the plasma phase [23]. Applying the same formula (2) for gluonic quasiparticles and replacing \( 2J + 1 \) by the effective statistical weight of massive gluons, \( \nu_g \sim 10 \), one gets the ratio of the scalar glueball multiplicity to the gluon multiplicity at \( T = T_c \):

\[
N_G \simeq \nu_g^{-1} \left( \frac{m_G}{m_g} \right)^{3/2} e^{(m_g - m_G)/T_c} \sim 0.3\% ,
\]

where the numerical value is obtained assuming \( T_c = 170 \text{ MeV} \) and \( m_G = 2m_g \).

However, in a rapidly expanding system the abundances of different species will be determined not only by the temperature, but also by the corresponding reaction rates. In this case the \( N_G/N_g \)–ratio may significantly overshoot the ”equilibrium” value (5). Indeed, during the hadronization, the massive gluons may decay into \( q\bar{q} \)–pairs or recombine into the \( gg \)–bound states forming, respectively, mesons or glueballs. Using simple kinetic equations for glueball and gluon abundances with the recombination term, proportional to the \( gg \rightarrow G \) cross section, \( \sigma_{gg} \), and the \( g \rightarrow q\bar{q} \) decay term, characterized by the width \( \Gamma_g \), we obtain the estimate

\[
\frac{N_G}{N_g} \sim \frac{n_g \sigma_{gg} v_{rel}}{\Gamma_g} \sim 5\% .
\]

Here we have used the typical values \( \sigma_{gg} \sim 10 \text{ mb} \), \( \Gamma_g \sim 100 \text{ MeV} \), \( v_{rel} \sim \sqrt{T_c/m_g} \simeq 0.5 \) and the equilibrium gluon density \( n_g = n_g(T_c) \simeq 0.05 \text{ fm}^{-3} \). The ratio (6) exceeds the thermal estimate (5) by more than one order of magnitude. Therefore, much more favorable conditions for the glueball production may be realized in the explosive hadronization scenario [24].

For the experimental identification of glueballs one can use the decay mode \( G \rightarrow K\bar{K} \) with predicted partial width in the range 10–40 MeV. For typical conditions, when glueballs are slow in the c.m. frame, one should look for the back–to–back correlated kaons with individual momenta of about 0.6–0.7 GeV/c. The \( G \rightarrow \gamma\gamma \) channel with the partial width of about 1-10 keV [4] can also be used for the glueball identification.

In conclusion, we have used a simple thermal model to predict possible yields of scalar glueballs in central Au+Au collisions at different energies, from AGS to LHC. Their maximal multiplicities are predicted in the range of 1.5–4\% of the \( \phi \)–meson multiplicity. Even larger
yields are expected in the case of explosive hadronization of the quark–gluon plasma. We believe that such yields are in the reach of experimental observations.

Acknowledgments

This work has been partly supported by the GSI (Germany), the DFG Grant 436 RUS 113/711/0-2, the RFBR Grant 05–02–04013, and the MIS Grant NSH–8756.2006.2.

[25] Analogous mechanism leading to the overpopulation of $q\bar{q}$-pairs was proposed in Ref. [8].