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Glueballs in Peripheral Heavy-Ion Collisions

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Abstract

We estimate the cross-section for glueball production in peripheral heavy-ion collisions through two-photon and double-Pomeron exchange, at energies that will be available at RHIC and LHC. Glueballs will be produced at large rates, opening the possibility to study decays with very small branching ratios. In particular, we discuss the possibility of observing the subprocess $\gamma\gamma(PP) \rightarrow G \rightarrow \gamma\gamma$.

The observation of gluon bound states, called gluonia or glueballs, is a crucial test of quantum chromodynamics. They are predicted in several theoretical models and expected to be in the range of 1 – 2 GeV. These states could be mainly observed in quarkonium decays, photon-photon collisions, and in diffractive hadron-hadron scattering through the double-Pomeron exchange [1].

There are some glueball candidates. For example, the $\eta(1440)$ which was observed in J/Ψ decays, and whose analyses by the different experimental groups are still contradictory [2]. There is also the case of the $f_2(1720)$ which also generated controversy between the experimental groups [3], and, among others, we can also quote the states $X(1450)$ and $X(1900)$ found recently in double-Pomeron exchange, and which have the correct quantum numbers for glueball candidates [4]. The status of the glueball observation will possibly become clear only with the combination of data from $p-p$ and e^+e^- machines with larger statistics. Unfortunately, since the glueball width into two-photons is small, their observation at large rates in photon-photon collisions will demand new high-luminosity e^+e^- colliders. In this work we would like to call attention to the fact that the already planned heavy-ion colliders, RHIC at Brookhaven [5] and LHC at CERN (operating in the heavy-ion mode) [6], may be a powerful source of glueball production through photon-photon collisions, as well as double-Pomeron exchange.

It is known that the main interest of relativistic heavy-ion colliders is in the search of a quark-gluon plasma in central nuclear reactions. On the other hand peripheral heavy-ion collisions may give rise to a huge luminosity of photons, opening possibilities of studying electromagnetic physics, as discussed at length by Bertulani and Baur [7], as well as the possible discovery of an intermediate-mass Higgs boson [8], or nonstandard $\gamma\gamma$ processes [9], which is a physics that requires very energetic photons. However, it is important to remember that most of the photons in heavy-ion collisions will carry only a small fraction of the ion momentum, favoring low mass final states, and recently we pointed out that hadronic resonances with $J^{PC} = 0^{\pm+}, 2^{\pm+}, \dots$ are copiously produced in peripheral heavy-ion collisions through $\gamma\gamma$ or double-Pomeron (PP) fusion [10]. In particular, we discussed how a particle as elusive as the σ meson, could be observed in the reaction $\gamma\gamma(PP) \rightarrow \sigma \rightarrow \gamma\gamma$, even considering the small width of the σ into photons. The same scenario will occur for glueballs, and we will give here estimates of glueball (G) production in peripheral collisions at RHIC and LHC, and

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consider its observation in the subprocess $\gamma\gamma(PP) \rightarrow G \rightarrow \gamma\gamma$.

We start our calculation remembering that the photon distribution in the heavy-ion collision can be determined through the equivalent photon or Weizsäcker-Williams approximation. Denoting by $F(x)dx$ the number of photons carrying a fraction between x and $x + dx$ of the total momentum of a nucleus of charge Ze , we can define the two-photon luminosity through

$$\frac{dL}{d\tau} = \int_{\tau}^1 \frac{dx}{x} F(x)F(\tau/x), \quad (1)$$

where $\tau = \hat{s}/s$, and $s(\hat{s})$ is the square of the c.m.-system (c.m.s) energy of the ion-ion (photon-photon) system. The total cross section $ZZ \rightarrow ZZ\gamma\gamma \rightarrow ZZG$ can be written as

$$\sigma(s) = \int d\tau \frac{dL}{d\tau} \hat{\sigma}(\hat{s}), \quad (2)$$

where $\hat{\sigma}(\hat{s})$ is the cross section of the subprocess $\gamma\gamma \rightarrow G$.

Taking into account a prescription for photon distribution in peripheral collisions proposed by Baur [11], we will use the most realistic photon distribution function determined by Cahn and Jackson [8], who obtained the following expression for the differential luminosity:

$$\frac{dL}{d\tau} = \left(\frac{Z^2\alpha}{\pi}\right)^2 \frac{16}{3\tau} \xi(z), \quad (3)$$

where $z = 2MR\sqrt{\tau}$, $M(R)$ is the nucleus mass(radius), and $\xi(z)$ is given by

$$\xi(z) = \sum_{i=1}^3 A_i e^{-b_i z}, \quad (4)$$

which is a fit resulting from the numerical integration of the photon distribution, accurate to 2% or better for $0.05 < z < 5.0$, and where $A_1 = 1.909$, $A_2 = 12.35$, $A_3 = 46.28$, $b_1 = 2.566$, $b_2 = 4.948$, and $b_3 = 15.21$. For $z < 0.05$ we use the expression (see Cahn and Jackson [8])

$$\frac{dL}{d\tau} = \left(\frac{Z^2\alpha}{\pi}\right)^2 \frac{16}{3\tau} \left(\ln\left(\frac{1.234}{z}\right)\right)^3. \quad (5)$$

To estimate the glueball production, we note that these states can be formed by photon-photon fusion with a coupling strength that is measured by their two-photon width

$$\hat{\sigma}_{\gamma\gamma \rightarrow G} = (2J+1) \frac{8\pi^2}{M_G s} \Gamma_{G \rightarrow \gamma\gamma} \delta\left(\tau - \frac{M_G^2}{s}\right), \quad (6)$$

where M_G is the glueball mass. There are several calculations for the two-photon widths of glueballs [12], and we will use the conservative result of Ref. [13]. In the case of the $\eta(1440)$ with $J^P = 0^-$ and $L = S = 1$, Ref. [13] gives the following result

$$\Gamma(\eta(1440) \rightarrow \gamma\gamma) = \frac{512}{9\pi^2} \alpha^2 \alpha_s^2 \frac{1}{M_G^4} |R'_1(0)|^2, \quad (7)$$

where $\alpha(\alpha_s)$ is the electromagnetic(strong) coupling constant, and $R_L(r)$ is the radial part of the wave function of the two-gluon system in configuration space. The calculation goes through the quark box diagram connecting two-photons to two-gluons and these will form the bound state. We are stressing this point because we shall return to it when discussing the double-Pomeron exchange. The unknown radial wave functions are eliminated in function of known partial decay widths involving these gluonium states, arriving at $\Gamma(\eta(1440) \rightarrow \gamma\gamma)B(\eta(1440) \rightarrow K\bar{K}\pi) = 90 eV$, for the $J = 0$ and $L = 1$ state. Partial widths for other states can also be found in Ref. [13].

We will compute the production rates only for $\eta(1440)$ and $f_2(1720)$, and with the average values of Ref. [14] we obtain $\Gamma(\eta(1440) \rightarrow \gamma\gamma) = 90 eV$, $\Gamma(f_2(1720) \rightarrow \gamma\gamma) = 223 eV$ for the $J = 2$ and $L = 2$ state, and $13 eV$ for the $J = 2$ and $L = 0$ state. To obtain these values we assumed $B(\eta(1440) \rightarrow K\bar{K}\pi) \sim 1$ and $B(f_2(1720) \rightarrow K\bar{K}) \sim 0.38$. It is important to notice that, for simplicity, we are assuming that $\eta(1440)$ and $f_2(1720)$ are still good glueball candidates, and, moreover, they are pure gluonium states, i.e., without any admixture of $q\bar{q}$ states. Among the many other candidates for glueballs they have been selected as typical examples, and the production rates that we will compute are going to be similar for other states. A full list of possible candidates, with their different denominations, can be found in Ref. [14].

In Table I we show the resulting cross-sections for the states we discussed above. We considered collisions of ^{238}U at RHIC, and ^{206}Pb at LHC. The

energies involved in these colliders will be $\sqrt{s} = 2.0 \times 10^2$ GeV/nucleon at RHIC, and $\sqrt{s} = 6.3 \times 10^3$ GeV/nucleon at LHC, operating with the luminosities $\mathcal{L}_{RHIC} \simeq 10^{27} \text{cm}^{-2}\text{s}^{-1}$ and $\mathcal{L}_{LHC} \simeq 10^{28} \text{cm}^{-2}\text{s}^{-1}$. From Table 1 we see, for instance, that we are going to have 4.4×10^5 and 2.1×10^8 events/yr of the $f_2(1720)$ state with $L = 2$, respectively at RHIC and LHC, assuming 100% efficiency for the peripheral collision separation and detection of the final state. The decays of the $f_2(1720)$ into two-photons will barely be observable at RHIC, and we shall have around 300 events/yr at LHC. Notice that we are discussing the two-photon decay because this will be the cleanest decay to confirm the existence of the glueball, as well as it gives the possibility to understand the underlying QCD calculation. As far as we know, we have used the smallest glueball partial widths into two-photons found in the literature, and we expect the result of Table I to be a conservative one. The total number of events is quite large, but, as we shall see, the situation will improve even more when we consider the strongly interacting peripheral collision.

We now turn to the case of double-Pomeron glueball production. The cross-section will be given by the convolution of the Pomeron distribution function in the nucleus, with the cross-section of the subprocess $PP \rightarrow G$, i.e.

$$\sigma_{ZZ}^{PP \rightarrow G} = \int dx_1 \int dx_2 F_P(x_1) F_P(x_2) \sigma_{PP}^G(\hat{s}). \quad (8)$$

The Pomeron distribution in a nucleus can be obtained folding the Pomeron distribution function of a Pomeron in the nucleon with the elastic nuclear form factor. This has been worked out in detail by Muller and Schramm [8], and is given by

$$F_P(x) = \left(\frac{3A\beta_0 Q_0^2}{2\pi} \right)^2 \frac{1}{x} \left(\frac{s'}{m^2} \right)^{2\epsilon} e^{-(\frac{xM}{Q_0})^2}, \quad (9)$$

where A is the atomic mass, β_0 is the quark-pomeron coupling, and is equal to $\beta_0^2 = 3.93 \text{GeV}^{-2}$. The factor $s'^{2\epsilon}$ in Eq.(9), where s' denotes the invariant mass of the subprocess with which the pomeron participates, comes from the Regge behavior of the pomeron, whose trajectory is given by $\alpha_P(t) = 1 + \epsilon + \alpha'_{PP}t$, with $\epsilon = 0.085$. In Eq.(9) $Q_0 \approx 60$ MeV determines the width of the nuclear gaussian form factor used to obtain the Pomeron distribution.

To compute the subprocess cross-section (σ_{PP}^G), on the basis of our present understanding of the QCD structure of the Pomeron is a very difficult task,

and we must make use of models for the Pomeron in order to do that. We will use the phenomenological fact that the pomeron couples to quarks like a isoscalar photon [15]. This will allow us to obtain the Pomeron-Pomeron \rightarrow glueball cross-section from the photon-photon one. However, it has also been found [16] that it is not always a good approximation to take the Pomeron-quark-quark vertex to be pointlike. In fact, when either or both of the two quark legs in this vertex goes far “off-shell”, the coupling must decrease. The simplest assumption that agrees with experiment is to take the Pomeron-quark coupling of the form [16]

$$\beta_0(Q^2) = \beta_0 \frac{\mu_0^2}{\mu_0^2 + Q^2}, \quad (10)$$

where we will simply assume $Q = \frac{1}{2}M_G$, and $\mu_0^2 = 1.2 \text{GeV}^2$ is a mass scale characteristic of the pomeron. According to this, it is easy to verify that we can obtain $\Gamma_{G \rightarrow PP}$ from $\Gamma_{G \rightarrow \gamma\gamma}$ as long as we substitute α^2 (see, for example, Eq.(7)) by $9\beta_0^2/16\pi^2$, where $\beta_0 = \beta_0(M_G/2)$.

The numerical results of glueball production through double-Pomeron exchange are presented in Table 2. The resulting cross-sections are at least one order of magnitude larger than the ones originated by photon-photon collisions. As a comparison, for the $f_2(1720)$ (with $L = 2$) we will have 2.1×10^8 and 1.9×10^9 events/year respectively at RHIC and LHC (again, assuming 100% efficiency). Since the branching ratio for two-photon decay of this state is approximately 1.6×10^{-6} , we can surely observe the subprocess $PP \rightarrow G \rightarrow \gamma\gamma$, as a clear signal for this glueball candidate.

Before discussing a little more about the two-photon signal, let us digress rapidly about the glueball production through double-Pomeron exchange. Since we are dealing with not well established objects in QCD, we can still make a very simple approximation to estimate σ_{PP}^G . We know that the geometrical factorization for hadronic elastic scattering seems to be a quite good approximation [17], i. e., the total cross-section for diffractive scattering of a hadron is proportional to the radius of this hadron, and we also know that the strong binding force between two gluons is even larger than the one between the triplet of colored quarks, therefore the interaction radius R_G of glueballs should be determined by the mass M_{G^0} of the lightest 0^{++} state (which we assume to be equal to the $\eta(1440)$ mass), these two facts together

allow us to expect that the cross-section for $PP \rightarrow G$ can be described by

$$\sigma_{PP}^G \sim \pi R_G^2, \quad R_G \sim \frac{1}{M_G^0}. \quad (11)$$

This may be a rough approximation, although we believe it to be enough to give an order of magnitude estimate. Notice that the first calculation is consistent with the Donnachie and Landshof [18] model for the Pomeron where it couples preferentially to quarks, whereas this last one can only be considered as an upper bound for our estimates. Eq.(11) gives a total cross-section that depends basically on the energy, for RHIC we obtain $\sigma_{ZZ}^{PP \rightarrow G} = 44 \text{ mb}$ and for LHC $\sigma_{ZZ}^{PP \rightarrow G} = 221 \text{ mb}$, which are indeed quite large rates. We recall again that this estimate is to be seen as an upper bound, and the values of Table 2 are more appropriate, however, it is valid in the sense that we still barely know how is the gluon coupling to the Pomeron, and are starting to collect more data about the Pomeron distribution in hadrons.

We can now make a few comments about the background to the reaction $ZZ \rightarrow ZZG \rightarrow ZZ\gamma\gamma$, where the glueball G is produced predominantly through double-Pomeron exchange. The main background for this process will come from the continuum subprocess of photon-photon scattering (or $PP \rightarrow \gamma\gamma$) through the box diagram. As discussed in Ref. [10] for the σ meson case, we can easily see that the resonant process is larger than the continuum one ². There is also the possibility of an accidental background originating, e.g. from the decay of the glueball into neutral mesons, and also possible decay of the last ones into 2γ , where the meson or the 2γ are identified as a unique fake γ . This is hardly going to happen because, due to the small glueball mass, the opening angle of the meson decay will be large enough to be detected with the calorimeters already in use. Finally, the detectors in these heavy-ion facilities will be prepared to detect photons of $O(1) \text{ GeV}$, because these are also a signal for the quark-gluon plasma formed in central collisions.

²The box diagram will be dominated by light quarks, and for these we can use the asymptotic expression of $\gamma\gamma$ scattering ($\sigma(s) \sim 20/s$), and integrate it in a bin centered at the glueball mass, and proportional to the glueball partial width into two-photons, obtaining a cross-section smaller than the resonant one with subsequent decay into two-photons. The $PP \rightarrow \gamma\gamma$ process is computed similarly, as discussed above. Notice that the interference between the box and resonant diagram is not important, because on resonance the two processes are out of phase.

In conclusion, we computed the cross-sections for glueball production in peripheral heavy-ion collisions. The subprocesses considered were photon-photon and double-Pomeron exchange. The rates for glueball production are very large, and will be dominated by the Pomeron-Pomeron scattering. Our estimates were conservative, in the sense that we used the smallest partial widths of glueballs into two-photons. We also used the Donnachie-Landshof model for the double-Pomeron calculation. A naive calculation using a geometrical model for Pomeron elastic scattering gives much larger rates. We have not considered mixture of the glueball with $q\bar{q}$ states, and if there is a mixing we can expect an increase of the total cross-section. We call attention to the fact that the subprocess $PP \rightarrow G \rightarrow \gamma\gamma$ can be observed, with more than 300 events/yr already at RHIC assuming 100% efficiency, and will provide a very clean signal for the glueball, as well as the possibility for studying the underlying QCD process.

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Tables

Glueball	$\sigma_{RHIC}(mb)$	$\sigma_{LHC}(mb)$
$\eta(1440)[J=0, L=1]$	3.0×10^{-3}	0.10
$f_2(1720)[J=2, L=2]$	1.4×10^{-2}	0.65
$f_2(1720)[J=2, L=0]$	8.3×10^{-4}	0.38×10^{-1}

Table 1: Cross-sections for glueball production through photon-photon fusion. The values are in mb. For RHIC ($\sqrt{s} = 0.2$ TeV/nucleon) we assumed collisions of ^{238}U , and for LHC ($\sqrt{s} = 6.3$ TeV/nucleon) the nucleus is ^{206}Pb .

Glueball	$\sigma_{RHIC}(mb)$	$\sigma_{LHC}(mb)$
$\eta(1440)[J=0, L=1]$	0.27	1.3
$f_2(1720)[J=2, L=2]$	1.2	6.1
$f_2(1720)[J=2, L=0]$	0.07	0.36

Table 2: Cross-sections for glueball production through double-Pomeron exchange. The values are in mb. The nuclei and energies are the same as in Table 1.

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