Photon-photon and pomeron-pomeron processes in peripheral heavy ion collisions

C. G. Roldão* and A. A. Natale†
Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona, 145, 01405-900, São Paulo, SP, Brazil
(Received 22 September 1999; published 19 May 2000)

We estimate the cross sections for the production of resonances, pion pairs, and a central cluster of hadrons in peripheral heavy-ion collisions through two-photon and double-pomeron exchange, at energies that will be available at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). The effect of the impact parameter in the diffractive reactions is introduced, and by imposing the condition for realistic peripheral collisions we verify that in the case of very heavy ions the pomeron-pomeron contribution is indeed smaller than the electromagnetic one. However, they give a non-negligible background in the collision of light ions. This diffractive background will be more important at RHIC than at LHC.

PACS number(s): 25.75.Dw, 13.40.−f

I. INTRODUCTION

Collisions at relativistic heavy ion colliders like the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) (operating in its heavy ion mode) are mainly devoted to the search of the quark gluon plasma. However, peripheral heavy ion collisions also open up a broad area of studies as advocated by Baur and collaborators [1,2]. Examples are the possible discovery of an intermediate-mass Higgs boson [3,4] or beyond standard model physics [5] using peripheral ion collisions, which have been discussed at length in the literature. More promising than these may be the study of hadronic physics, which will appear quite similarly to the two-photon hadronic physics at e^+e^- machines with the advantage of a huge photon luminosity peaked at small energies [1,2,6]. Due to this large photon luminosity it will become possible to discover resonances that couple weakly to the photons [7].

Double-pomeron exchange will also occur in peripheral heavy ion collisions and their contribution is similar to the two-photon one as discussed by Baur [1] and Klein [6]. A detailed calculation performed by Müller and Schramm of Higgs boson production has shown that the diffractive contribution is much smaller than the electromagnetic one [8]. We can easily understand this result remembering that the coupling between the Higgs boson and the pomerons is intermediated by quarks, and according to the pomeron model of Donnachie and Landshoff [9] when in the vertex pomeron-quark-quark any of the quark legs goes far ''off-shell'' the coupling with the pomeron decreases. Therefore, we do not need to worry about the pomeron-pomeron contribution in peripheral heavy ion collisions when heavy (or far ''off-shell'') quarks are present. However, this is not what happens in the case of light resonances [7], where double diffraction was claimed to be as important as photon initiated processes. In particular, Engel *et al.* [10] have shown that at the LHC the diffractive production of hadrons may be a background for the photonic one.

In Ref. [1] it was remarked that the effect of removing ''central collisions'' should also be performed in the double-pomeron calculation, implying a considerable reduction of the background calculated in Ref. [10]. This claim is the same presented by Baur [2] and Cahn and Jackson [4] in the case of early calculations of peripheral heavy ion collisions. Roughly speaking we must enforce that the minimum impact parameter ($b_{\min}$) should be larger than (R_1+R_2), where R_i is the nuclear radius of the ion ''i,'' in order to have both ions coming out intact after the interaction.

In this work we will compute the production of resonances, pion-pairs, and a hadron cluster with invariant mass M_X through photon-photon and pomeron-pomeron fusion in peripheral heavy ion collisions at the energies of RHIC and LHC. We will take into account the effect of the impact parameter as discussed in the preceding paragraph for photons as well as for pomerons. We also compare this approach to cut the central collisions with the use of an absorption factor in the Glauber approximation. The inclusion of pion-pairs production is important because they certainly will be studied at these colliders, and they also represent a background for glueball (and other hadrons) detection. The pomeron physics within the ion will be described by the Donnachie and Landshoff model [9,11]. We will focus on the values of the cross sections that shall be measured in the already quoted ion colliders, and point out when pomeron-pomeron processes can be considered competitive or not with photon-photon collisions. The arrangement of our paper is the following: Sec. II contains a discussion of the photon and pomeron distributions in the nuclei. In Sec. III we introduce the cross section for the elementary processes. Finally, Sec. IV contains the results and conclusions.

II. PHOTONS AND POMERONS DISTRIBUTION FUNCTIONS

A. Photons in the nuclei

The photon distribution in the nucleus can be described using the equivalent-photon or Weizsäcker-Williams approximation in the impact parameter space. Denoting by $F(x)dx$ the number of photons carrying a fraction between x

*Electronic address: roldao@ift.unesp.br
†Electronic address: natale@ift.unesp.br

and $x+dx$ of the total momentum of a nucleus of charge Ze, we can define the two-photon luminosity through

$$\frac{dL}{d\tau}=\int_{\tau}^{1}\frac{dx}{x}F(x)F(\tau/x), \tag{2.1}$$

where $\tau=\hat{s}/s$; $\hat{s}$ is the square of the center-of-mass system (c.m.s.) energy of the two photons and s of the ion-ion system. The total cross section $ZZ\to ZZ\gamma\gamma\to ZZX$, where X is the particle produced within the rapidity gap, is

$$\sigma(s)=\int d\tau\frac{dL}{d\tau}\hat{\sigma}(\hat{s}), \tag{2.2}$$

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

There remains only to determine $F(x)$. In the literature there are several approaches for doing so, and we choose the conservative and more realistic photon distribution of Ref. [4]. Cahn and Jackson [4], using a prescription proposed by Baur [1], obtained a photon distribution which is not factorizable. However, they were able to give a fit for the differential luminosity which is quite useful in practical calculations:

$$\frac{dL}{d\tau}=\left(\frac{Z^2\alpha}{\pi}\right)^2\frac{16}{3\tau}\xi(z), \tag{2.3}$$

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

$$\xi(z)=\sum_{i=1}^{3}A_i e^{-b_i z}, \tag{2.4}$$

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 Ref. [4])

$$\frac{dL}{d\tau}=\left(\frac{Z^2\alpha}{\pi}\right)^2\frac{16}{3\tau}\left[\ln\left(\frac{1.234}{z}\right)\right]^3. \tag{2.5}$$

The condition for realistic peripheral collisions ($b_{\min}>R_1+R_2$) is present in the photon distributions shown above, and the applications of Sec. IV are straightforward once we determine the cross sections for the elementary processes.

B. Pomerons in the nuclei

In the case where the intermediary particles exchanged in the nucleus-nucleus collisions are pomerons instead of photons, we can follow closely the work of Müller and Schramm [8] and make a generalization of the equivalent photon approximation method to this new situation. So the cross section for particle production via two pomerons exchange can be written as

$$\sigma_{AA}^{PP}=\int dx_1 dx_2 f_P(x_1)f_P(x_2)\sigma_{PP}(s_{PP}), \tag{2.6}$$

where $f_P(x)$ is the distribution function that describes the probability of finding a pomeron in the nucleus with energy fraction x and $\sigma_{PP}(s_{PP})$ is the subprocess cross section with energy squared s_{PP}. In the case of inclusive particle production we use the form given by Donnachie and Landshoff [12],

$$f_P(x)=\frac{1}{4\pi^2 x}\int_{-\infty}^{-(xM)^2}dt|\beta_{AP}(t)|^2|D_P(t;s')|^2, \tag{2.7}$$

where $D_P(t;s')$ is the pomeron propagator [11],

$$D_P(t;s)=\frac{(s/m^2)^{\alpha_P(t)-1}}{\sin(\frac{1}{2}\pi\alpha_P(t))}\exp\left(-\frac{1}{2}i\pi\alpha_P(t)\right),$$

with s the total squared c.m. energy. The Regge trajectory obeyed by the pomeron is $\alpha_P(t)=1+\varepsilon+\alpha'_P t$, where $\varepsilon=0.085$, $\alpha'_P=0.25$ GeV^{-2}, and t is a small exchanged four-momentum square, $t=k^2\ll 1$, so the pomeron behaves like a spin-one boson. The term in the denominator of the pomeron propagator, $[\sin(\frac{1}{2}\pi\alpha_P(t))]^{-1}$, is the signature factor that expresses the different properties of the pomeron under C and P conjugation. At very high c.m. energy this factor falls very rapidly with $\mathbf{k}^2$, whose exponential slope is given by $\alpha'_P\ln(s/m^2)$, m is the proton mass, and it is possible to neglect this $\mathbf{k}^2$ dependence,

$$\sin\frac{1}{2}\pi(1+\varepsilon-\alpha'_P\mathbf{k}^2)\approx\cos\left(\frac{1}{2}\pi\varepsilon\right)\approx 1.$$

If we define the pomeron range parameter r_0 as

$$r_0^2=\alpha'_P\ln(s/m^2), \tag{2.8}$$

the pomeron propagator can be written as

$$|D_P(t=-\mathbf{k}^2;s)|=(s/m^2)^{\varepsilon}e^{-r_0^2\mathbf{k}^2}. \tag{2.9}$$

Since we are interested in the spatial distribution of the virtual quanta in the nuclear rest frame, we are using $t=-\mathbf{k}^2$.

The nucleus-pomeron coupling has the form [12]

$$\beta_{AP}(t)=3A\beta_0 F_A(-t),$$

where $\beta_0=1.8$ GeV^{-1} is the pomeron-quark coupling, A is the atomic number of the colliding nucleus, and $F_A(-t)$ is the nuclear form factor for which there is usually assumed a Gaussian expression (see, e.g., Drees *et al.* in [3])

$$F_A(-t)=e^{t/2Q_0^2}, \tag{2.10}$$

where $Q_0=60$ MeV.

Performing the t integration of the distribution function in Eq. (2.7) we obtain

$$f_P(x)=\frac{(3A\beta_0)^2}{(2\pi)^2x}\left(\frac{s'}{m^2}\right)^{2\varepsilon}\int_{-\infty}^{-(xM)^2}dt\, e^{t/Q_0^2}$$
$$=\frac{(3A\beta_0Q_0)^2}{(2\pi)^2x}\left(\frac{s'}{m^2}\right)^{2\varepsilon}\exp\left[-\left(\frac{xM}{Q_0}\right)^2\right].$$

The total cross section for an inclusive particle production is obtained with the above distribution and also with the expression for the subprocess $PP\to X$ as prescribed in Eq. (2.6). However, in Eq. (2.6) the cases where the two nuclei overlap are not excluded. To enforce the realistic condition of a peripheral collision, it is necessary to perform the calculation taking into account the impact parameter dependence, b. It is straightforward to verify that in the collision of two identical nuclei the total cross section of Eq. (2.6) is modified to [8]

$$\frac{d^2\sigma_{AA}^{PP\to X}}{d^2b}=\frac{Q'^2}{2\pi}e^{-Q'^2\,b^2/2}\sigma_{AA}^{PP}, \tag{2.11}$$

where $(Q')^{-2}=(Q_0)^{-2}+2r_0^2$. The total cross section for inclusive processes is obtained after integration of Eq. (2.11) with the condition $b_{\min}>2R$ in the case of identical ions.

For exclusive particle production the determination of the pomeron distribution function in the nuclei is slightly modified, because in this case some specific assumption about the pomeron internal structure is necessary [13]. Following Ref. [8] the distribution function of pomerons is

$$f_P(x)=\frac{(3A\beta_0)^2}{(2\pi)^2x}\int_{-\infty}^{-(xM)^2}dt(-t-x^2M^2)F_A(-t)^2|D(t)|^2, \tag{2.12}$$

and the cross section for a resonance production as a function of the impact parameter is [14]

$$\frac{d^2\sigma_{AA}^{PP\to R}}{d^2b}=2\pi\left(\frac{3A\beta_0}{2\pi^2}\right)^4\int\frac{dx_1}{x_1}\frac{dx_2}{x_2}\times Q_1^4Q_2^4\tilde{Q}^2e^{-x_1^2M^2/Q_1^2}e^{-x_2^2M^2/Q_2^2}\times\left(\frac{x_1x_2s^2}{m^4}\right)^{2\varepsilon}\sigma_{AA}^{PP\to R}(x_1x_2s)b^2\tilde{Q}^2e^{-b^2\tilde{Q}^2/2},$$

with $\sigma_{AA}^{PP\to R}(x_1x_2s)$ indicating the subprocess cross section (double pomeron fusion producing a resonance), and where

$$\tilde{Q}^{-2}=\frac{1}{2}(Q_1^{-2}+Q_2^{-2}),$$

with $Q_i^{-2}\equiv Q_0^{-2}+2r_0^2$ for identical ions. In the calculations we are going to perform we noticed that the approximation $Q_i^{-2}\approx Q_0^{-2}$ is quite reasonable, because for the energies that we shall consider the pomeron range parameter [Eq. (2.8)] is smaller than the width of the Gaussian form factor and consequently $\tilde{Q}^2\approx Q_0^2$. Therefore, we obtain the final expression

$$\frac{d^2\sigma_{AA}^{PP\to R}}{d^2b}=2\pi\left(\frac{3A\beta_0Q_0^2}{2\pi^2}\right)^4\int\frac{dx_1}{x_1}\frac{dx_2}{x_2}e^{-x_1^2M^2/Q_0^2}e^{-x_2^2M^2/Q_0^2}\times\left(\frac{x_1x_2s^2}{m^4}\right)^{2\varepsilon}\sigma_{AA}^{PP\to R}(x_1x_2s)b^2Q_0^4e^{-b^2Q_0^2/2}. \tag{2.13}$$

As discussed previously, to enforce the condition of peripheral collisions we integrate Eq. (2.13) with the condition $b_{\min}>2R$.

Another way to exclude events due to inelastic central collisions is through the introduction of an absorption factor computed in the Glauber aproximation [15]. This factor modifies the cross section in the following form:

$$\frac{d\sigma_{AA}^{gl}}{d^2b}=\frac{d\sigma_{AA}^{PP\to R}}{d^2b}\exp\left[-A^2b\sigma_0\int\frac{dQ^2}{(2\pi)^2}F_A^2(Q^2)e^{iQb}\right]$$
$$=\frac{d\sigma_{AA}^{PP\to R}}{d^2b}\exp\left[-A^2b\sigma_0\frac{Q_0^2}{4\pi}e^{-Q_0^2b^2/4}\right], \tag{2.14}$$

where σ_0 is the nucleon-nucleon total cross section, whose value for the different energy domains that we shall consider is obtained directly from the fit of Ref. [16],

$$\sigma_0=Xs^{\epsilon}+Y_1s^{-\eta_1}+Y_2s^{-\eta_2},$$

with $X=18.256$, $Y_1=60.19$, $Y_2=33.43$, $\epsilon=0.34$, $\eta_1=0.34$, $\eta_2=0.55$, $F_A(Q^2)=e^{-Q^2/2Q_0^2}$, and we exemplified Eq. (2.14) for the case of resonance production, i.e., $\sigma_{AA}^{PP\to R}$ is the total cross section for the resonance production to be discussed in the next section. The integration in Eq. (2.14) is over all impact parameter space and in the final section we discuss the differences between the two approaches shown above for removing central collisions.

III. SUBPROCESSES INITIATED BY PHOTONS AND POMERONS

A. Resonances

The main motivation to study resonance production in peripheral heavy ion collisions is that the high photon luminosity will allow us to observe resonances that couple very weakly to photons. The simplicity of this calculation also enables us to test the methods for removing central collisions, as well as to check to which degree the double pomeron exchange is or is not a background for the two-photon physics.

To estimate the production of single spin-zero resonances, we note that these states can be formed by photon-photon fusion with a coupling strength that is measured by their photonic width,

$$\hat{\sigma}_{\gamma\gamma\to R}=\frac{8\pi^2}{M_R\hat{s}}\Gamma_{R\to\gamma\gamma}\delta\left(\tau-\frac{M_R^2}{\hat{s}}\right), \tag{3.1}$$

where M_R is the ressonance mass and $\Gamma_{R\to\gamma\gamma}$ its decay width in two photons. Using this expression in Eq. (2.2), we obtain the total cross section for the production of pseudoscalar mesons.

To compute the cross section of the subprocess $PP\to R$, we can use the pomeron model of Donnachie and Landshoff [11]. In this model it is assumed that the pomeron couples to the quarks like an isoscalar photon [11]. This means that the cross sections of $PP\to X$ subprocesses can be obtained from suitable modifications on the cross section for $\gamma\gamma\to X$. Another aspect to be considered is that the pomeron-quark-quark vertex is not pointlike, and when either or both of the two quark legs in this vertex goes far off shell, the coupling is known to decrease. So the quark-pomeron coupling β_0 must be replaced by

$$\tilde{\beta}_0(q^2)=\frac{\beta_0\mu_0^2}{\mu_0^2+Q^2}, \tag{3.2}$$

where $\mu_0^2=1.2\ \mathrm{GeV}^2$ is a mass scale characteristic of the pomeron; in the case of resonance production $Q=M_R/2$ measures how far one of the quark legs is off mass shell and M_R is the resonance mass. Therefore, the process $PP\to R$ is totally similar to the one initiated by photons unless from an appropriate change of factors. The cross section we are looking for is obtained changing the fine-structure constant α by $9\tilde{\beta}/16\pi^2$, where $\tilde{\beta}$ is given by Eq. (3.2) and $9=3^2$ is a color factor, leading to

$$\sigma_{PP}^R=\frac{9}{2}\frac{\tilde{\beta}^4}{\alpha^2}\frac{\Gamma(R\to\gamma\gamma)}{M_R}\delta(x_1x_2s-M_R^2).$$

Using this expression in Eq. (2.13), the total cross section is equal to

$$\sigma_{AA}^{PP\to R}=\frac{9\pi}{8}\frac{(\tilde{\beta}Q_0)^4}{\alpha^2}\left(\frac{3A\beta_0Q_0}{2\pi}\right)^4\frac{\Gamma(R\to\gamma\gamma)}{M_R}\left(\frac{M_R^2s}{m^4}\right)^{2\epsilon}\times\frac{Q_0^4}{M_R^2}\int\frac{dx}{x}\exp\left[\left(-\frac{M_R^2M}{sQ_0x}\right)^2-\frac{(xM)^2}{Q_0^2}\right]\times\int_{b_{\min}}^{\infty}db\,2\pi b^3e^{-Q_0^2b^2/2}, \tag{3.3}$$

where $b_{\min}=2R$.

B. Pion pair production

The continuous production of pion pairs ($\pi^+\pi^-$) is also an interesting signal to be observed in peripheral heavy ion collisions, mostly because they are a background for glueball and other resonance decays. Here we discuss the subprocess cross sections for two photons $ZZ\to\gamma\gamma\to ZZ\pi^+\pi^-$, and two pomerons exchange, $ZZ\to PP\to ZZ\pi^+\pi^-$.

The cross section for pion pair production by two photons can be calculated approximately by using a low-energy theorem derived from a partially-conserved-axial-vector-current hypothesis and current algebra and is equal to [17]

$$\sigma(\gamma\gamma\to\pi^+\pi^-)\cong\frac{2\pi\alpha^2}{s}\left(1-\frac{4m_\pi^2}{s}\right)^{(1/2)}\times\left[\frac{m_V^4}{\left(\frac{1}{2}s+m_V^2\right)\left(\frac{1}{4}s+m_V^2\right)}\right]^2, \tag{3.4}$$

where m_π is the pion mass, s its squared energy, and m_V is a free parameter, whose value that provides the best fit to the experimental data is $m_V\cong1.4$ GeV. This expression shows a nice agreement with the experimental data [18]. For large values of s it deviates from the Brodsky and Lepage formula [19]. However, since most of the photon distribution is concentrated in the small x region, i.e., the photons carry a small fraction of the momentum of the incoming ion, the difference is negligible.

Using Eqs. (3.4) and (2.2) we obtain

$$\sigma(s)=\frac{2\pi\alpha^2}{s}\int_{\tau_{\min}}^1\frac{d\tau}{\tau}\left(1-\frac{4m_\pi^2}{s\tau}\right)^{(1/2)}\times\left[\frac{m_V^4}{\left(\frac{1}{2}s\tau+m_V^2\right)\left(\frac{1}{4}s\tau+m_V^2\right)}\right]^2\frac{dL}{d\tau}.$$

In the case of double pomeron exchange producing a pion pair we use once again the Donnachie and Landshoff model for the pomeron, obtaining the cross section for $PP\to\pi^+\pi^-$ from the photonic one changing $\alpha^2\to9\tilde{\beta}_0^4/16\pi^2$ in $\sigma(\gamma\gamma\to\pi^+\pi^-)$, and the resulting expression replaces $\sigma_{AA}^{PP\to R}(x_1x_2s)$ in Eq. (2.13). The total cross section appears after we perform the integration in the parameter space representation of the following equation:

$$\frac{d^2\sigma_{AA}^{PP\to\pi^+\pi^-}}{db^2}=\left(\frac{\pi^2}{8}\right)\frac{9}{4}\frac{(\tilde{\beta}_0Q_0)^4}{s}\left(\frac{3A\beta_0Q_0}{2\pi^2}\right)^4\times\int\frac{dx_1}{x_1^2}\frac{dx_2}{x_2^2}e^{-(x_1M)^2/Q_0^2}e^{-(x_2M)^2/Q_0^2}\times\left(\frac{x_1x_2s^2}{m^4}\right)^{2\varepsilon}\left(1-\frac{4m_\pi^2}{x_1x_2s}\right)^{1/2}\times\left[\frac{m_V^4}{\left(\frac{x_1x_2s}{2}+m_V^2\right)\left(\frac{x_1x_2s}{4}+m_V^2\right)}\right]^2\times\int_{b_{\min}}^{\infty}db\,2\pi Q_0^4b^3e^{-b^2Q_0^2/2}.$$

C. Multiple particle production

The elementary cross section for multiple-particle production via two-photon fusion can be described by the parametrization [20]

$$\sigma_{\gamma\gamma\to\text{hadrons}}=C_1\left(\frac{s}{s_0}\right)^{\epsilon}+C_2\left(\frac{s}{s_0}\right)^{-\eta}, \tag{3.5}$$

where $C_1=173$ nbarn, $C_2=519$ nbarn, $s_0=1$ GeV^2, $\epsilon=0.079$, and $\eta=0.4678$. The total cross section comes out from Eq. (2.2).

Within the Donnachie and Landshoff model it is straightforward to see that with the above parametrization the differential cross section to produce a cluster of particles with mass M_X through double pomeron exchange is

$$\frac{d\sigma}{dM_X}=\frac{(3A\beta_0\tilde{\beta}_0\mu_0)^4}{(2\pi)^4R_N^4(16\pi^2\alpha^2)}\frac{1}{2M_X}\int\frac{ds'}{s'}\left[C_1\left(\frac{s'}{s_0}\right)^{\epsilon}+C_2\left(\frac{s'}{s_0}\right)^{-\eta}\right]\exp\left[-\left(\frac{s'MR_N}{s}\right)^2-\left(\frac{M_X^2MR_N}{s'}\right)^2\right]\int_{b_{\min}}^{\infty}db\, b\frac{e^{-b^2/2R_N^2}}{R_N^2}.$$

To obtain this expression we used the pomeron distribution function in the nucleus for an inclusive process [Eq. (2.7)].

To enable a comparison with the work of Engel *et al.* [10], we also make use of the Ter-Martirosyan [21] model for diffractive multiparticle production. In this model the subprocess $PP\to$hadrons is characterized by the cross section

$$\sigma_{PP}^{tot}(\ln(M_X^2/m^2),t_1,t_2)\approx 8\pi r(t_1)r(t_2), \tag{3.6}$$

which is a function of the triple-pomeron vertex $r(t)$, where t is the exchanged momentum. Using the value of $r(0)$ from Ref. [22], $\sigma_{\mathcal{PP}}^{\text{tot}}=8\pi r^2(0)\approx 140\ \mu$barn. Note that we have clear differences between the approaches described above. Equation (3.5) is a parametrization valid for a wide range of momenta, and with this one we naively apply the model of Ref. [9] to compute the total cross section for multiparticle production. On the other hand, Eq. (3.6) is obtained in another specific model and it is not expected to be valid for the same range of energies as Eq. (3.5). This difference is going to be discussed in the final section.

Streng [23] applied the model of Ref. [21] for proton-proton collisions where the initial protons are scattered almost elastically, emerging with a very large fraction of the initial energy,

$$|x_1|,|x_2|\geqslant c,\ c\geqslant 0.9.$$

The double pomeron exchange produces a particle cluster within a large rapidity gap and with a mass of the order

$$M_X^2\approx s(1-|x_1|)(1-|x_2|), \tag{3.7}$$

where s is the reaction energy squared. As the scattering is almost elastic, i.e., the emerging beam has approximately the same energy as the incident one, the following kinematical boundaries can be introduced:

$$M_0\leqslant M_X\leqslant(1-c)\sqrt{s},\qquad \frac{M_X^2}{(1-c)}\leqslant s_1\leqslant(1-c)s, \tag{3.8}$$

where $M_0=2$ GeV and $c=0.9$. These limits have been translated for the case of heavy ions by Engel *et al.* [10] and we will proceed as they did. If we consider Eq. (3.6), dress it with the pomeron distribution functions within the nuclei, and subtract the central collisions considering the absorption factor computed in the Glauber aproximation [15], we reproduce the results of Ref. [10].

IV. RESULTS AND CONCLUSIONS

Peripheral collisions at relativistic heavy ion colliders provide an arena for interesting studies of hadronic physics. Resonances coupling weakly to photons can be studied due to the large photon luminosity; the continuous production of pion pairs will be observed not only as a reaction of interest but also as a possible background for some resonance decays. A hadron cluster produced within a large rapidity gap will give information about photon-photon and double pomeron exchange. In this work we estimate the cross section for these processes. One of the main points is to verify whether the double pomeron exchange is or is not a background for the purely electromagnetic process. We discussed double pomeron exchange according to the Donnachie and Landshoff [11] model and calculated the cross sections in the impact parameter space. The condition for a realistic peripheral collision is imposed integrating the cross section with $b_{\min}>2R$ in the case of two identical ions with radius R.

We considered the production of pseudoscalar resonances in the collision of ^{238}U for energies available at RHIC ($\sqrt{s}=200$ GeV/nucleon), and collisions of ^{206}Pb at energies available in LHC ($\sqrt{s}=6{,}300$ GeV/nucleon). Our results are shown in Table I. Contrary to the result of Ref. [7], the double pomeron exchange is not important when the cut in the impact parameter is introduced. For a realistic peripheral collision in the case of resonance production, the pomeron-pomeron process is at least two orders of magnitude below the photon-photon one. Note in Table I that the rate of diffractive resonance production decreases with the increase of the meson mass. The main reason for this behavior lies in the fast decrease of the pomeron-quark coupling as shown in Eq. (3.2).

Note that the results of this table assume 100% efficiency in tagging the peripheral collision. Even if we consider a small efficiency, we recall that the cross section for light resonances implies approximately billions of events/yr which easily survive the cuts for the background separation proposed by Nystrand and Klein (see the last paper of Ref. [6]). One of the most important cuts to separate inelastic nuclear reactions, associated with grazing collisions, is the small multiplicity of the final state, and this is exactly what we may expect in the final state of the particles discussed in Table I.

The decays of π^0,η, etc. will be dominated by two- (or three-) body decays in the central region of rapidity, and

TABLE I. Cross sections for resonance production through photon-photon ($\gamma\gamma$) and double-pomeron (PP) processes. For RHIC, $\sqrt{s}=200$ GeV/nucleon, we considered ^{238}U ion and for LHC, $\sqrt{s}=6{,}300$ GeV/nucleon, the nucleus is ^{206}Pb. The cross sections are in mbarn.

Meson	M_R	$\Gamma_{(R\rightarrow\gamma\gamma)}$	RHIC$_{\gamma\gamma}$	LHC$_{\gamma\gamma}$	RHIC$_{\mathcal{PP}}$	LHC$_{\mathcal{PP}}$
π^0	135	8×10^{-3}	7.1	40	0.05	0.367
η	547	0.463	1.5	17	0.038	0.355
η'	958	4.3	1.1	22	0.04	0.405
η_c	2979	6.6	0.32×10^{-2}	0.5	0.47×10^{-4}	0.27×10^{-3}
η_c'	3605	2.7	0.36×10^{-3}	0.1	0.34×10^{-5}	0.61×10^{-4}
η_b	9366	0.4	0.13×10^{-7}	0.37×10^{-3}	0.11×10^{-10}	0.77×10^{-9}

easily separated from the larger multiplicity common to inelastic collisions. It is interesting that in the case of π^0 and η production we may focus on the 2γ decay, and even if it is possible to separate the background from inelastic nuclear reactions, we still have the background of the photon-photon scattering through the QED box diagram producing the same final state. The box diagram will be dominated by light quarks, electron, and muon, and for these we can use the asymptotic expression of $\gamma\gamma$ scattering $[\sigma(s)\sim 20/s]$. Integrating this expression in a bin of energy (proportional to the resonance partial width into two photons) centered at the mass of the resonance, we obtain a cross section smaller than the resonant one with subsequent decay into two photons. We do not consider the interference between the box and resonant diagram because on resonance the two processes are out of phase. It is important to mention that the decay products will fill the central region of rapidity, which is also one of the conditions proposed in Ref. [6] to isolate the peripheral collisions.

As discussed in Sec. II, we have two different ways to enforce a realistic peripheral heavy ion collision. One is a geometrical cut in the impact parameter space where $b_{\min}>2R$ is imposed, the other is through the introduction of the absorption factor in the Glauber approximation as given by Eq. (2.14). In Table II we compare the ratios between the total cross sections for diffractive resonance production computed with Eq. (2.14) and the one with the cut on the impact parameter [given by Eq. (3.3)] in the collision of ^{238}U for energies available at RHIC ($\sqrt{s}=200$ GeV/nucleon), and collisions of ^{206}Pb at energies available in LHC ($\sqrt{s}=6{,}300$ GeV/nucleon).

TABLE II. Ratios of cross sections for diffractive resonance production calculated with the Glauber absorption factor to the one with the geometrical cut in the collision of ^{238}U for energies available at RHIC ($\sqrt{s}=200$ GeV/nucleon), and collisions of ^{206}Pb for energies available at LHC ($\sqrt{s}=6{,}300$ GeV/nucleon).

Meson	$\sigma_{AA}^{gl}/\sigma_{AA}^{\mathcal{PP}\rightarrow R}$(LHC)	$\sigma_{AA}^{gl}/\sigma_{AA}^{\mathcal{PP}\rightarrow R}$(RHIC)
π^0	3.54×10^{-3}	1.5×10^{-2}
η	3.58×10^{-3}	1.47×10^{-2}
η'	3.46×10^{-3}	1.5×10^{-2}
η_c	3.47×10^{-3}	1.32×10^{-2}
η_c'	3.61×10^{-3}	1.5×10^{-2}
η_b	3.5×10^{-3}	1.45×10^{-2}

The values of Table II show that the geometrical cut is less restrictive than the one given by the Glauber absorption factor. However, which one is more realistic also depends on the energy and on the ion that we are considering. In Table III we present the cross section for π^0 production for different ions and at different energies. From Eq. (2.14) we notice that small variations in σ_0 (the nucleon-nucleon total cross section) are also promptly transmitted to the total cross section, and modify the ratios between the different methods to exclude inelastic collisions. Table III shows that the difference between the methods also becomes less important for light ions, but the most striking fact in this table is that for light ions double pomeron exchange starts becoming a background for photon-photon processes. According to Table III for ^{28}Si the diffractive π^0 production is a factor of 2 lower than the electromagnetic one (assuming the geometrical cut). This is not surprising because we know that for proton-proton the double pomeron exchange process should be larger than the electromagnetic one for producing a light resonance.

In Table IV we show the pion pair cross section for different ions. The values were obtained using the geometrical cut, and even if with this procedure the diffractive cross section is a little bit overestimated for heavy ions, we verify that photon-photon dominates. For light ions the diffractive process is already of the order of 10% of the electromagnetic one.

The simulations discussed in the last paper of Ref. [6] have shown that the $\gamma\gamma$ interactions produce final states with small summed transverse momentum $(|\Sigma\overline{p_T}|)$. Therefore, a cut of $|\Sigma\overline{p_T}|\leqslant 40-100$ MeV/c can reduce considerably the background of nonperipheral collisions. In Table IV we present the cross section for pion pair production through

TABLE III. Cross section for π^0 production for different ions and at different energies. The energies are in GeV/nucleon and the cross sections in mbarn. $\sigma^{PP\rightarrow R}$ is the cross section computed with the geometrical cut and σ^{gl} is the one with the absorption factor.

Nucleus	$\sqrt{s}$	$\sigma_{AA}^{\mathcal{PP}\rightarrow R}$	$\sigma_{AA}^{gl^{\mathcal{PP}}}$	$\sigma_{\gamma\gamma}$
Au ($A=197$)	100	0.044	0.55×10^{-3}	2.4
Ca ($A=40$)	3 500	0.043	0.39×10^{-3}	0.14
Si ($A=28$)	200	0.34×10^{-2}	0.15×10^{-3}	0.69×10^{-2}
Si ($A=28$)	100	0.22×10^{-2}	0.12×10^{-3}	0.39×10^{-2}

TABLE IV. Cross sections for $\pi^+\pi^-$ production. The energies are in GeV/nucleon and the cross sections in mbarn. $\sigma_{\gamma\gamma}(p_T<100\ \text{MeV})$ is the pion pair production through photon-photon interaction with the cut $p_T\leqslant 100$ MeV.

Nucleus	$\sqrt{s}$	$\sigma_{\gamma\gamma}$	$\sigma_{\gamma\gamma}(p_T\leqslant 100\ \text{MeV})$	$\sigma_{\mathcal{PP}}$
U	200	9	2.15	7.47×10^{-3}
Pb	6,300	81.96	15.98	1.34×10^{-2}
Au	100	2.3	0.523	8.11×10^{-3}
Ca	3,500	0.28	0.05	5.85×10^{-3}
Si	200	0.98×10^{-2}	0.21×10^{-2}	1.02×10^{-3}
Si	100	0.49×10^{-2}	0.12×10^{-2}	8.6×10^{-4}

double photon interaction with $|\Sigma\overline{p_T}|\leqslant 100$ MeV/c. With this cut the cross section was reduced almost by a factor of 4. The electromagnetic process with the restriction on p_T is still larger than those of double pomeron exchange without this cut, and the introduction of this cut in the diffractive process produces a similar reduction.

The results for a hadron cluster production with invariant mass M_X are depicted in Fig. 1. In the figure is shown the cross section for four different ions (Pb, Au, Ag, Ca) at energies that will be available at RHIC and LHC. The results were obtained integrating the cross sections with the condition $b_{\min}>2R$. At LHC the photon-photon process will dominate the cross sections for heavy ions, whereas for light ions and small invariant mass they become of the same order. For heavy ions the diffractive process is indeed negligible. Note that our result for photons is similar to that of Engel *et al.* [10], but the diffractive cross sections are slightly smaller than that of Ref. [10]. We credit this deviation to the differences in our approaches to calculating the subprocess cross section, mainly in the use of Eq. (3.5) with the changes prescribed by Donnachie and Landshoff [11] instead of Eq. (3.6) given by the Ter-Martirosyan [21] model. They also use a value for σ_0 that is smaller than the one we considered here, which gives a smaller cut of the central collisions. We believe that the use of Eq. (3.5) and the model of Ref. [11] is more appropriate for the full range of momenta. Actually, diffractive models are plagued by uncertainties and the measurement of the double pomeron exchange in heavy ion colliders will provide useful information to distinguish between different models.

For multiple particle production we will not have the criteria of low multiplicity to help us to select the truly peripheral collisions. In addition it is far from clear if the cut in transverse momentum will be very effective to select the $\gamma\gamma$ events. However, we can separate the peripheral events on the basis of a clustering in the central region of rapidity, although an extensive and detailed simulation of the background processes will be necessary in order to set the precise interval of rapidity needed to cut the inelastic nuclear collisions [24].

As verified by Drees, Ellis, and Zeppenfeld [3], Eq. (2.10) is a reasonable approximation for the form factor obtained from a Fermi or Woods-Saxon density distribution. However, their result shows that for heavy final states the photon-photon luminosity is slightly underestimated, and we can expect the same for the pomeron one. A simple form factor expression consistent with the Fermi distribution has been recently obtained in Ref. [25], and its use would yield a few

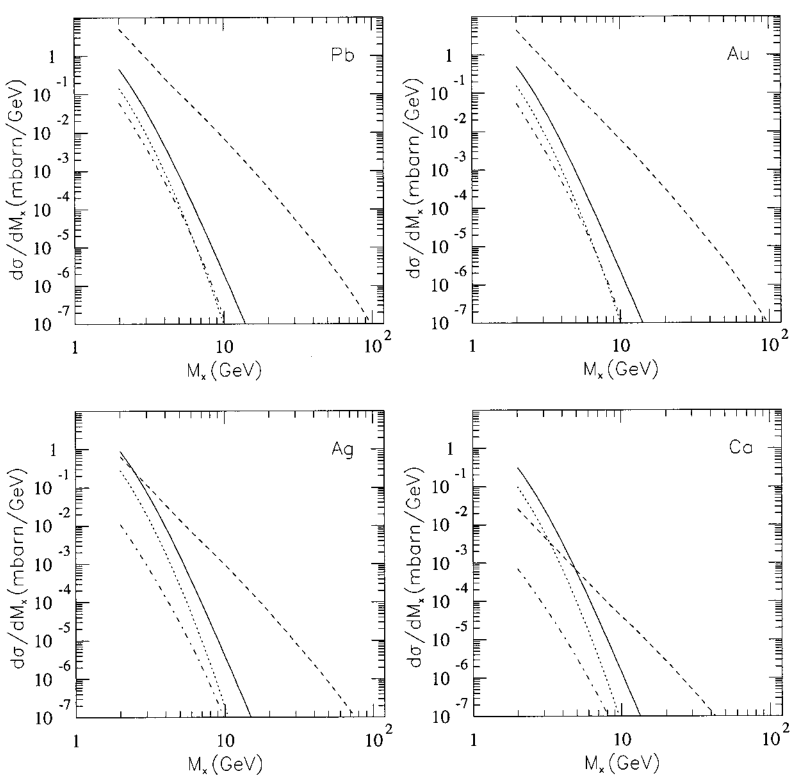

FIG. 1. Cross section for multiple particle production with invariant mass equal to M_X for different nuclei collisions. The nuclei are indicated in the upper corner of each figure. The solid line is for pomeron-pomeron interaction and the dashed line is for double photon exchange at LHC, $\sqrt{s}=6{,}300$ GeV/nucleon. In the same figures can be seen the cross section for RHIC, $\sqrt{s}=200$ GeV/nucleon. Double pomeron exchange is given by the dotted line and photon interaction by the dotted-dashed line.

percent larger cross section in the case of a very heavy hadron cluster production.

In the case of peripheral heavy ion collisions at RHIC, we surely cannot neglect the diffractive contribution. For light ions and a hadron cluster with low invariant mass it surely dominates photon-photon collisions. Notice that these results may change if we use the Glauber absorption factor to compute the cross section (depending on the energy, the ion, and invariant mass), but the actual fact is that double pomeron exchange cannot be neglected at RHIC.

In conclusion, we estimated the production of resonances, pion pairs, and a cluster of hadrons with invariant mass M_X in peripheral heavy ion collisions at energies that will be available at RHIC and LHC. The condition for a realistic peripheral collision was studied with the use of a geometrical cut, where the minimum impact parameter was forced to be larger than twice the identical nuclei radius. The introduction of an absorption factor in the Glauber approximation to eliminate central collisions was also studied. We find out that the most restrictive method to account for inelastic collisions depended on the energy, the ion, as well as on the value of σ_0 (the nucleon-nucleon total cross section). The geometrical cut is not always the most restrictive way to enforce peripheral collisions. This is a topic that should be answered by future experiments. In both cases we noticed that at energies of the LHC operating in the heavy ion mode and for very heavy ions the double pomeron exchange is not a background for the two-photon process. The situation changes considerably for light ions and mostly for the energies available at RHIC, where double pomeron exchange cannot be neglected.

ACKNOWLEDGMENTS

We thank Paulo S. R. da Silva for useful discussions, and C. A. Bertulani for a helpful remark. This research was supported in part by the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) (A.A.N.), Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP) (C.G.R. and A.A.N.), and by Programa de Apoio a Núcleos de Excelência (PRONEX).

[1] G. Baur, J. Phys. G **24**, 1657 (1998).
[2] G. Baur, K. Hencken, and D. Trautmann, hep-ph/9810418; C.A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988); G. Baur, in *Proceedings of the CBPF International Workshop on Relativistic Aspects of Nuclear Physics, Rio de Janeiro, 1989*, edited by T. Kodama *et al.* (World Scientific, Singapore, 1990), p. 127; G. Baur and C.A. Bertulani, Nucl. Phys. **A505**, 835 (1989).
[3] E. Papageorgiu, Phys. Rev. D **40**, 92 (1989); Nucl. Phys. **A498**, 593c (1989); M. Grabiak *et al.*, J. Phys. G **15**, L25 (1989); M. Drees, J. Ellis, and D. Zeppenfeld, Phys. Lett. B **223**, 454 (1989); M. Greiner, M. Vidovic, J. Rau, and G. Soff, J. Phys. G **17**, L45 (1991); B. Müller and A.J. Schramm, Phys. Rev. D **42**, 3699 (1990); J.S. Wu, C. Bottcher, M.R. Strayer, and A.K. Kerman, Ann. Phys. (N.Y.) **210**, 402 (1991).
[4] R.N. Cahn and J.D. Jackson, Phys. Rev. D **42**, 3690 (1990).
[5] J. Rau, B. Müller, W. Greiner, and G. Soff, J. Phys. G **16**, 211 (1990); L.D. Almeida, A.A. Natale, S.F. Novaes, and O.J.P. Eboli, Phys. Rev. D **44**, 118 (1991)).
[6] S. Klein and E. Scannapieco, e-print LBNL-40457, 1997, talk at Photon97 (hep-ph/9706358); e-print LBNL-40495, 1997, presented at CIPANP97 (nucl-th/9707008); J. Nystrand and S. Klein, e-print LBNL-41111, 1997, talk at Hadron97 (hep-ex/9711021).
[7] A.A. Natale, Mod. Phys. Lett. A **9**, 2075 (1994); A.A. Natale, Phys. Lett. B **362**, 177 (1995).
[8] B. Müller and A.J. Schramm, Nucl. Phys. A **523**, 677 (1991).
[9] A. Donnachie and P.V. Landshoff, Phys. Lett. B **185**, 403 (1987); **207**, 319 (1988); Nucl. Phys. B **311**, 509 (1988).
[10] R. Engel, M.A. Braun, C. Pajares and J. Ranft, Z. Phys. C **74**, 687 (1997).
[11] A. Donnachie and P.V. Landshoff, Nucl. Phys. **B244**, 322 (1984); **B267**, 690 (1985).
[12] A. Donnachie and P.V. Landshoff, Phys. Lett. B **191**, 309 (1987); Nucl. Phys. **B303**, 634 (1988).
[13] A. Schäfer, O. Natctmann, and R. Schöpf, Phys. Lett. B **249**, 331 (1990).
[14] A.J. Schramm and D.H. Reeves, Phys. Rev. D **55**, 7312 (1997).
[15] V. Franco and R.J. Glauber, Phys. Rev. **142**, 1195 (1966).
[16] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).
[17] H. Terazawa, Phys. Rev. D **51**, R954 (1995).
[18] Mark II Collaboration, J. Boyer*et al.*, Phys. Rev. Lett. **56**, 207 (1986); TPC/Two-Gamma Collaboration, H. Aihara *et al.*, *ibid.* **57**, 404 (1986); CLEO Collaboration, J. Dominick *et al.*, Phys. Rev. D **50**, 3027 (1973).
[19] S.J. Brodsky and G.P. Lepage, Phys. Rev. D **24**, 1808 (1981).
[20] L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. B **408**, 450 (1997).
[21] K.A. Ter-Martirosyan, Phys. Lett. **44B**, 179 (1973).
[22] R.L. Cool *et al.*, Phys. Rev. Lett. **47**, 701 (1981).
[23] K.H. Streng, Phys. Lett. **166B**, 443 (1986).
[24] A.B. Kaidalov and K.A. Ter-Martirosyan, Nucl. Phys. **B75**, 471 (1974).
[25] S. Klein and J. Nystrand, Phys. Rev. C **60**, 014903 (1999).