PHYSICS OPPORTUNITIES IN ULTRAPERIPHERAL HEAVY ION COLLISIONS AT LHC

G. Baur
Institut für Kernphysik
Forschungszentrum Juelich, Germany

Due to coherence, there are strong electromagnetic fields of short duration in very peripheral heavy ion collisions. They give rise to photon-photon and photon-nucleus collisions with high flux up to an invariant mass region hitherto unexplored experimentally. Photon-photon and photon-hadron physics at various invariant mass scales are discussed. Due to the very strong electromagnetic fields there are interesting many-photon exchange processes like double giant dipole resonance excitation in nuclei, multiple $e^+e^-$ pair production and vector meson pair production. Maximum equivalent photon energies in the lab-system (collider frame) are typically of the order of 3 GeV for RHIC and 100 GeV for LHC. Vector meson production (coherent as well as incoherent) and photon-gluon fusion leading to heavy quark jets are processes of great physics interest. The high photon-photon luminosities in very peripheral collisions at the LHC will allow to study interesting physics channels in the invariant mass region up to about 100 GeV. It is hoped that this will bridge a gap to the physics at the future photon colliders. In pp collisions this maximum energy is even higher, and their is also the experimental possibility to tag on these photons.

1 Introduction

In ultraperipheral (UPC) heavy ion collisions nuclei interact with each other through their electromagnetic fields. In these collisions with impact parameter $b$ larger than the sum of the nuclear radii a new range of physical parameters enters. Electromagnetic fields are very strong and of short duration. The interaction can be very well described by the equivalent photon method. Fluxes are very high and extend up to energies hitherto unexplored experimentally. A review article for Physics Reports on coherent $\gamma\gamma$ and $\gamma A$ interactions in relativistic ion colliders has just been completed.\\[3pt]

It is the aim of this talk to discuss the physics of UPC. Emphasis is put on the LHC and RHIC energy regions. Detectors at RHIC as well as at LHC are built with the aim to study central heavy ion or pp collisions. The question of how to detect such UPC events at the colliders is not dealt with here. An important question is the triggering on UPC events. The STAR group at RHIC led by Spencer Klein has shown how to trigger on these events and how to study them experimentally. I refer to the discussion in these proceedings.

Since the electromagnetic fields are very strong, many photons can be exchanged in these collisions. In section 2 processes where more than one photon is emitted from a nucleus are discussed. There are a few important and interesting processes of this type. Generally, the one photon exchange mechanism is sufficient for inelastic processes.

A very useful view on the electromagnetic processes is the parton picture with the photons as the partons. In this picture the scattering is described as an incoherent superposition of the
scattering of the various constituents. For example, nuclei consist of nucleons which in turn consist of quarks and gluons, photons consist of lepton pairs, electrons consist of photons, etc.. Relativistic nuclei have photons as an important constituent. This is due to the coherent action of all the charges in the nucleus: for these conditions the wavelength of the photon is larger than the size of the nucleus, therefore it does not resolve the individual nucleons but sees the coherent action of all of them.

The coherence condition limits the virtuality $Q^2 = -q^2$ of the photon to very low values

$$Q^2 < 1/R^2,$$

where the radius of a nucleus is approximately $R = 1.2 \text{ fm } A^{1/3}$ with $A$ the nucleon number. This is due to the rapid decrease of the nuclear electromagnetic form factor for high $Q^2$ values. For most purposes these photons can therefore be considered as real (“quasireal”), see Fig.1. From the kinematics of the process one has a photon four-momentum of $q_\mu = (\omega, q_\perp, q_3 = \omega/v)$, where $\omega$ and $q_\perp$ are energy and transverse momentum of the quasireal photon in a given frame, where the projectile moves with velocity $v$. This leads to an invariant four-momentum transfer of

$$Q^2 = \frac{\omega^2}{v^2\gamma^2} + q_\perp^2,$$

where the Lorentz factor is $\gamma = E/m = 1/\sqrt{1-v^2}$. The condition Eq. (1) limits the maximum energy of the quasireal photon to

$$\omega < \omega_{\text{max}} \approx \frac{\gamma}{R},$$

and the perpendicular component of its momentum to

$$q_\perp < \frac{1}{R}.$$  \hfill (4)

At LHC energies ($\gamma = 3000$) this means a maximum photon energy of about 100 GeV in the laboratory system, at RHIC ($\gamma = 100$) this number is about 3 GeV. In section 3 γ–A interactions are discussed. γγ processes are a (small) subset of such processes. They are very important in general and they allow to study very interesting physics in a clean way. This is discussed in section 4. Conclusions and an outlook are given in section 5.

2 Strong Field Effects, Exchange of Many Photons

The Sommerfeld parameter

$$\eta = \frac{Z_1Z_2e^2}{\hbar v} \sim Z_1Z_2\alpha \sim Z_1Z_2/137$$

(5)
characterizes the strength of the electromagnetic interaction between the ions with charges $Z_1$ and $Z_2$ respectively, see Fig. 2a. This parameter $\eta$ can be $\gg 1$, e.g. for Pb-Pb collisions we have $\eta = 49$.

According to classical arguments given by N.Bohr elastic scattering can be considered as classical for $\eta \gg 1$. For relativistic heavy ions the classical trajectory is almost a straight line with an impact parameter $b$. The momentum transfer $\Delta p$ is essentially perpendicular to the beam direction and is given by

$$\Delta p = \frac{2Z_1 Z_2 e^2}{b \nu} = \frac{2\eta}{b} \hbar \tag{6}$$

This momentum transfer is built up from the exchange of many photons, see Fig. 2b. Due to the large value of $\eta$ the integral over the impact parameter $b$ in the Glauber amplitude can be evaluated using the stationary phase (or saddle point) approximation. This phase is given by

$$\phi = -qb + 2\eta \ln(kb) \tag{7}$$

where $k$ is the wave number of the projectile nucleus. The condition $\phi'(b) = 0$ leads to $b = \frac{2\eta}{q}$, i.e. $\Delta p = \hbar q$. Thus the momentum transfer $q$ (or scattering angle $\theta = \frac{q}{k}$) is related to the classical impact parameter. This is in contrast to e.g. p-p scattering where $\eta = 1/137 \ll 1$ and the Born approximation (one photon exchange) is sufficient. For the heavy ions the strong interactions for collisions with $b < R_{\text{min}}$, where $R_{\text{min}}$ is the sum of the nuclear radii, lead to complete absorption (black disk approximation). This disregards the diffuseness of the nucleus, but it is quite a good approximation for many purposes. In the case of strong Coulomb coupling ($\eta \gg 1$) the elastic scattering cross section is given by a Fresnel diffraction pattern (rather than a Fraunhofer one for $\eta < 1$). This is explained in Ref. 7, see also Sect 5.3.5 of Ref. 8.

The electric charge of the relativistic ion gives rise to an electromagnetic potential, the Lienard-Wiechert potential $A_{\mu}(\vec{r}, t)$. This potential interacts with a target current $j_{\mu}$. This target current describes e.g. nuclear states, vector mesons or $e^+e^-$ pairs in the field of a nucleus. This defines a time dependent interaction $V(t)$ as (see e.g. 9)

$$V(t) = \int d^3 r A_{\mu}(\vec{r}, t) j_{\mu}(\vec{r}) \tag{8}$$

The dependence of $V(t)$ on the impact parameter is not shown explicitly. Coupled equations for the excitation amplitudes $a_n(t)$ for certain states $n$ can be set up. The solution of these equations is greatly facilitated if the sudden approximation can be applied, see e.g. Ref. 10. This is the case if the collision time is much smaller than the nuclear excitation time. This condition is fulfilled in many interesting cases and we assume now that the sudden approximation can be used. This "frozen nucleus"-approximation is also used in Glauber theory. The relation between
the semiclassical approach and the (quantal) Glauber (or eikonal) approximation is explained in Ref.\textsuperscript{10}. This is done for the non-relativistic as well as the relativistic case. The excitation amplitude is given by

$$a_n(t \to \infty) = < n | \exp(iR) | 0 >$$

where \( R = - \int_{-\infty}^{+\infty} V(t) dt \) (we put \( \hbar = 1 \)). The operator \( R \) is a direct sum of operators in the space of nuclear states, the space of the nucleus-vector meson system, the nucleus-\( e^+e^- \) system, etc.. We can expand the exponential in eq. 9. Terms linear in \( R \) give e.g. the excitation of nuclear states, like the collective giant dipole resonance (GDR), vector meson production or \( e^+e^- \) pair production. Terms quadratic in \( R \) give e.g. contributions to double phonon GDR excitation, double vector meson production, two \( e^+e^- \) pair production. It also describes e.g. vector meson production and GDR excitation in a single collision. A contribution to the second order amplitude \( a^{(2)} \) is e.g.

$$a^{(2)} = - < GDR | R | 0 > < \rho^0 | R | 0 >$$

where \( | 0 > \) denotes the ground state of the nucleus. The factor \( 1/2! \) in the expansion of \( \exp(iR) \), see eq. 9, is compensated by the two possibilities in the time ordering of the GDR excitation and the vector meson production respectively, see Fig. 3.

For three independent processes, say GDR-excitation, vector meson- and \( e^+e^- \) pair production, there are 6 different time orderings, which compensate the \( \frac{1}{3!} \) factor in the expansion of eq. 9 and so on. In this formalism it is clearly seen that these processes are independent and the elementary amplitudes factorize, as one would have intuitively expected. This property is used e.g. in the experimental analysis of vector meson production with simultaneous GDR excitation. The neutrons from the GDR decay serve as a trigger on UPC.\textsuperscript{2,3}. The ion motion is not disturbed by the excitation process. The reason is that the kinetic energy of the ion is much larger than the excitation energy.

2.1 Exchange of Many Photons in Multi-Phonon Giant Resonance Excitation

An especially simple and important case is the excitation of a harmonic oscillator. In terms of the corresponding creation and destruction operators \( a^\dagger \) and \( a \) the Hamiltonian of the system is given by

$$H = \hbar \omega (a^\dagger a + \frac{1}{2})$$

where \( \omega \) denotes the energy of the oscillator. We have the boson commutation rule \([a, a^\dagger] = 1\). Only one mode is shown explicitly, in general one has to sum (integrate) over all the possible modes. The excitation operator is assumed to be linear in the destruction and creation operators

$$R = -(ua + u^*a^\dagger)$$
where \( u \) is a c-number which characterizes the excitation process (the matrix element of \( R \) between the ground state and the one-phonon-state). This leads to the excitation of a so-called coherent state, see [11]. For the excitation of multiphonon states this is explicitly shown in [12].

One has

\[
a_n = \langle n | e^{-i(u^*a + ua)} | 0 \rangle = \left( -iu^* \right)^n \sqrt{(n!)} e^{-\frac{1}{2} uu^*} \tag{13}
\]

where the operator identity \( e^{A+B} = e^A e^B e^{-\frac{1}{2}[A,B]} \) was used, which is valid for two operators \( A(= -iu^*a) \) and \( B(= -iua) \) for which the commutator is a c-number.

Electromagnetic excitation of nuclear states, especially the collective giant multipole resonances was discussed at this workshop by Carlos Bertulani [13]. The possibility to excite multiphonon GDR states is discussed in [14], where also its main properties like decay widths are discussed. The parameter which describes the probability \( \Phi \) of GDR excitation is

\[
\Phi = \frac{2\alpha^2 Z_1^2 Z_2^2}{A_2^2 m_N \omega b^2} \tag{14}
\]

where \( m_N \) denotes the nucleon mass, the neutron-proton-, and mass-number of the excited nucleus are given by \( N_2, Z_2, \) and \( A_2 \) respectively. The excitation probability is inversely proportional to the energy \( \omega(\sim 80\text{MeV}A^{-1/3}) \) of the GDR state. Thus soft modes are more easily excited, as one may have expected. In this (rather accurate) estimate, it was assumed that the classical dipole sum rule (Thomas-Reiche Kuhn sum rule) is exhausted to 100 percent. For the excitation of an \( N \)-phonon state, a Poisson distribution is obtained. For the heavy systems \( \Phi \) is of the order of \( \frac{1}{2} \) for close collisions \( (b \sim R_1 + R_2) \).

Quite similarly, double \( \rho^0 \) production was studied in Ref. [16]. In addition to the label \( m \) for the magnetic substates of the GDR, one has a continuous label (the momenta) in the case of vector meson production. The probability to produce a vector meson in a close collision is of the order of one to three percent for the heavy systems.

### 2.2 Production of Multiple Electron-Positron Pairs

In Ref. [17] it was shown that multiple \( e^+e^- \)-pairs can be produced in relativistic heavy ion collisions. In this work the sudden (or Glauber) approximation and a quasiboson approximation for \( e^+e^- \) pairs was assumed. This will be well fulfilled in practice. Using a QED calculation (including Coulomb corrections in the Bethe-Maximon approach) for one pair production as an input, a Poisson distribution is obtained for multiple pair production. This is quite natural, since this problem is now reduced to the excitation of a harmonic oscillator (the modes are labelled by the spins and momenta of the \( e^+e^- \) pairs), see above.

The characteristic dimensionless parameter for this problem is \( \Xi = \frac{(Z_1 Z_2 \omega^2)^2}{(mb)^2} \) where \( m \) is the electron mass and \( b > 1/m \). For impact parameters \( b \sim 1/m \) and heavy systems like Pb-Pb or Au-Au the parameter \( \Xi \) is of the order of unity. In a series of papers by K.Hencken et al. (see [18]) the impact parameter dependence of \( e^+e^- \) pair production was studied numerically in lowest order QED. Only recently an approximate analytical formula for the total pair production probability in lowest order \( P^{(1)} \) was found. In an impact parameter range of \( 1/m < b < \gamma/m \) it is given by

\[
P^{(1)} = \frac{28}{9\pi^2} \Xi (2\ln \gamma^2 - 3\ln(mb)) \ln(mb) \tag{15}
\]

The \( N \) pair-production probability decreases strongly with increasing impact parameter \( b \) (approximately like \( \sim b^{-2N} \)). Therefore the probabilities \( P^{(1)}(b) \) should be known accurately for an impact parameter range of \( 0 < b < \text{several } 1/m \).

Muon pair production is also of interest. In close collisions, the pair production probability is of the order of 1, as can be seen from eq. 15. For a more exact evaluation, form factor effects
would have to be taken into account. Due to the much smaller Compton wave length of the muon, total cross sections are smaller than about a factor of $(m_e/m_\mu)^2 \sim 40000$.

3 \( \gamma A \) interactions

It seems appropriate at this point to recall various interesting results which have been obtained in the past decade in UPC experiments at lower energies. References to these experiments can be found e.g. in (1). At beam energies in the GeV region, the equivalent photon spectrum extends up to \( \omega_{\text{max}} = \frac{197 \text{ MeV/fm}}{R_{\text{min}}} \gamma \sim 10 - 20 \text{MeV} \). With such a soft spectrum of photons up to the GDR region, many interesting topics in nuclear structure physics and astrophysics could be investigated. The excitation of the DGDR was already briefly discussed above in subsection 2.1. Strong (quasireal) photon sources are essential for such investigations. Another application is the study of radiative capture processes: they are related to photodissociation via time reversal (20,21). E.g. the astrophysical S-factor for the \( ^7 \text{Be}(p, \gamma)^8 \text{B} \) reaction could be studied with the electromagnetic dissociation of \(^8 \text{B} \) rare isotope beams at RIKEN (Japan), GSI (Darmstadt) and Michigan State University. This is of great interest for the solar neutrino problem: most of the neutrinos detected in the Kamiokande or SNO detectors originate from the weak decay of \(^8 \text{B} \). This nucleus is solely produced in the \( ^7 \text{Be}(p, \gamma) \) capture reaction, thus this astrophysical S-factor directly determines the (high energy) neutrino flux from the sun.

While GDR excitation and subsequent particle (mainly neutron) decay is a source of beam loss, a means to trigger on UPC as well as a tool for a luminosity monitor ("yesterday’s sensation is today’s calibration"), the physics interest concentrates on the higher equivalent photon energies available at RHIC (up to about 600 GeV) and LHC (up to about 600 TeV), as viewed from the nucleus rest frame. The physics is quite similar to what is done at HERA, with essentially two differences: now the photons are only quasireal \((Q^2 \sim 0)\) and the hadron is now a nucleus instead of a proton. There is (diffractive) coherent and incoherent vector meson production with many interesting applications. Indeed, relativistic heavy ion colliders are vector meson factories (22,23). This opens the way for interesting experimental studies, like the interference effect in exclusive vector meson production (25). As explained in this reference, this provides also an example of the Einstein-Podolsky-Rosen paradoxon. Double \( \rho^0 \) production was already mentioned above and the prospects for vector meson spectroscopy were discussed in (23). Certainly, the forthcoming experimental results will spur further theoretical developments.

Another interesting topic is photon-gluon fusion into \( q\bar{q} \). The two jets can be identified and the kinematics reconstructed. These processes were first studied in Ref. (24) and Ref. (22). Quite recently, it was suggested to investigate the colour glass condensate with this method (28,29). In this way, the low-x gluon distribution can be directly studied experimentally. Top quark production will also be possible (30).

The points above are most important also for the future experiments at RHIC and LHC. I only refer here to (23) and (31). Further discussions and calculations are also reported at this workshop in (31).

4 \( \gamma \gamma \) physics

At LHC ultraperipheral collisions provide equivalent photons with energies up to 100 GeV in the c.m. system. \( \gamma \gamma \)-collisions have been investigated at LEP in the invariant mass region up to 185 GeV. The effective \( \gamma \gamma \) luminosity for medium mass heavy ions exceeds the one achieved at LEP, see e.g. Fig.6 of the recent review (1). A review of \( \gamma \gamma \) physics is also given there, so I will only mention a few considerations here, see also the talk of Kai Hencken (31). These very high effective \( \gamma \gamma \) luminosities will allow QCD studies like the study of \( \gamma \gamma \) widths of \( C = +1 \) (heavy)
Figure 4: Cross section per GeV for fermion pair production at the LHC for Ca-Ca collisions. A luminosity of \(L_{\text{CaCa}} = 4 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}\) was assumed. The process \(\gamma\gamma \rightarrow \text{hadrons}\) is also shown. A "(heavy ion) year" corresponds to \(10^6\) s. For further details see [1].

mesons and the total cross section for \(\gamma\gamma \rightarrow \text{hadrons}\), see Fig. 4. Also the study of new physics will be possible.

One can speculate about new particles with strong coupling to the \(\gamma\gamma\)-channel. Large \(\Gamma_{\gamma\gamma}\) widths will directly lead to large \(\gamma\gamma\) production cross-sections. The two-photon width of quarkonia is proportional to the wave function squared in the center of the system. Thus we can expect, that if a system is very tightly bound it should have a large two-photon width due to the factor \(|\Psi(0)|^2\) which is large in these cases. Examples for such tightly bound systems were discussed in the eighties e.g. in Refs. [32, 33]. Composite scalar bosons at \(W_{\gamma\gamma} \approx 50\text{ GeV}\) are expected to have \(\gamma\gamma\)-widths of several MeV [32, 33]. The search for such kind of resonances in the \(\gamma\gamma\)-production channel will be possible at LHC. In the TESLA Report part3 p.110 (Ref. [34]) the reader can find some remarks about the "agnostic" approach to compositeness. From eq. 68 and figure 14 of Ref. [1] one can directly obtain a value for the production cross-sections of such states and the corresponding rates in the various collider modes. Due to the high flux of equivalent photons such searches seem worth-while, and a possible discovery would be quite interesting.

Certainly one will have to wait for the future \(\gamma\gamma\) colliders in order to study \(\gamma\gamma\)-physics in the region of several 100 GeV. However, it may be possible to have a glimpse into this region with the (ultra)peripheral collisions at LHC which will be working (taking data) in a few years from now.

With their high luminosities pp collisions are also a very interesting source of equivalent photons. Their energy spectrum extends up to very high photon energies beyond 200 GeV. In Refs. [35, 36] \(\gamma\gamma\)-processes at pp colliders are studied. It is observed there that non-strongly interacting supersymmetric particles (sleptons, charginos, neutralinos and charged Higgs bosons) are difficult to detect in hadronic collisions at LHC. The possibility of producing such particles in \(\gamma\gamma\) interactions is examined. Clean events can be generated which should compensate for the small production number. This is even more important since there is a new experimental approach to tagging in pp collisions by measuring very forward proton scattering [37, 38]. Particularly exciting is the possibility to detect Higgs boson production via the \(\gamma\gamma\) fusion [39].

In [38] it was proposed to search for heavy magnetic monopoles in \(\gamma\gamma\) collisions at hadron colliders like the Tevatron and LHC. The idea is that photon-photon scattering below the monopole
production threshold is enhanced due to the strong coupling of magnetic monopoles to photons. The magnetic coupling strength $g$ is given by $g = \frac{2n\pi}{e}$ where $n = \pm 1, \pm 2, \ldots$. Since $\frac{e^2}{4\pi} = 1/137$ the magnetic coupling strength is indeed quite large. In this reference differential cross sections for $\gamma\gamma$ scattering via the monopole loop are calculated for energies below the monopole production threshold. The result depends strongly on the assumed value of the spin of the monopole. With this elementary cross section as an input, the cross section for the process $pp \rightarrow \gamma\gamma X$ is calculated. Elastic (i.e. $X = pp$) and inelastic contributions are taken into account. The signature of such a process is the production of two photons where the transverse momentum of the pair is much smaller than the transverse momentum of the individual photons. At the Tevatron such a search was performed. They looked at a pair of photons with high transverse energies. No excess of events above background was found. Thus a lower limit on the mass of the magnetic monopole could be given. A mass of 610, 870, or 1580 $GeV/c^2$ was obtained, for the assumed values of a monopole spin of 0, 1/2, or 1 respectively. For further discussions see also. Such kind of searches could also be performed at the heavy ion colliders: the flux is enhanced by a factor of $Z^4$, on the other hand, the maximum equivalent photon energy is lower. Some exploratory theoretical calculations would be useful.

5 Conclusions. Outlook

Ultraperipheral heavy ion collisions provide a strong source of equivalent photons up to very high energies. This offers the unique possibility to study photon-hadron(nucleus) and photon-photon processes in hitherto inaccessible regions. Some of these comparatively silent (as compared to the violent central collisions) events are very interesting. With the forthcoming experimental results from RHIC the field of ultraperipheral collisions is rapidly expanding. These results will also be helpful for the planning of UPC experiments at LHC. This kind of physics is of great interest and potential.

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