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$\gamma-\gamma$ Physics with Peripheral Relativistic Heavy Ion Collisions

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The high flux of equivalent photons present in relativistic heavy ion collisions of two charges Z_1 and Z_2 gives rise to the collision of two equivalent photons. The cross-sections for various processes are directly related to the corresponding $\gamma-\gamma$ cross-sections. As compared to $\gamma-\gamma$ physics being studied at e^+e^- colliders, we find that high energy states will not be so easily accessible at the existing facilities, however, the enhancement factor $(Z_1 Z_2)^2$ in the expression for the cross section will provide very large photon fluxes for lower energies.

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An extensive programme of $\gamma-\gamma$ physics is going on at high energy e^+e^- colliders. The dominant graph is shown in Fig. 1. The charged particles e^+ and e^- emit "virtual" (sometimes also called "equivalent") photons which collide to form a neutral system X with charge parity $C=+1$. There exists a vast literature on this subject, the properties of the virtual γ's are calculated in great detail and the cross sections in e^+e^- collisions are directly related to the corresponding $\gamma-\gamma$ cross sections. (See [1, 2, 3] where many further references are contained). An early result is due to F.E. Low [4] where the measurement of the π^0 lifetime by π^0 production in e^-e^- or e^-e^+ collisions is proposed. Using a variant of the Weizsäcker-Williams method, the cross section for the process $e^-e^+\to e^-e^+X$ is found to be related to the cross section for $\gamma+\gamma\to X$ by (we use the notation of [5])

$$d\sigma_{e^-e^+\to e^-e^+X}(s)=\eta^2\int d\omega f(\omega)\, d\sigma_{\gamma\gamma\to X}(\omega s) \tag{1}$$

with

$$s=(p_1+p_2)^2 \tag{2a}$$

$$\eta=\frac{\alpha}{2\pi}\ln\left(\frac{s}{4m^2}\right)=\frac{\alpha}{\pi}\ln\gamma \tag{2b}$$

and

$$f(\omega)=\frac{1}{\omega}\left[(2+\omega)^2\ln\frac{1}{\omega}-2(1-\omega)(3+\omega)\right]. \tag{2c}$$

For a collider s is given by $s=4E^2$ where E is the $e^+(e^-)$ energy in the labsystem, m is the electron mass and $\gamma=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}=\frac{E}{m}$. In addition to the situation pertaining to (1), where the final momenta of e^+ and e^- are not measured ("untagged luminosities") one can study cases where these momenta are measured ("tagged" and "double tagged" luminosities, see e.g. [2]).

It is the purpose of the present paper to discuss the $\gamma-\gamma$ processes which occur in relativistic heavy ion (RHI) collisions. It is the additional factor $(Z_1 Z_2)^2$, where Z_1 and Z_2 are the charge of the colliding heavy ions, which increases strongly the RHI cross section as compared to the e^+e^- case. We study the collisions of two "equivalent" photons in the system, where the two heavy ions move with opposite velocities v and $-v$ towards each other (see Fig. 2).

This is equivalent to the collision of two photons with frequency distributions $n_1(\omega_2)$ and $n_2(\omega_2)$ moving in opposite directions. The expressions for the frequency distributions, integrated over the impact

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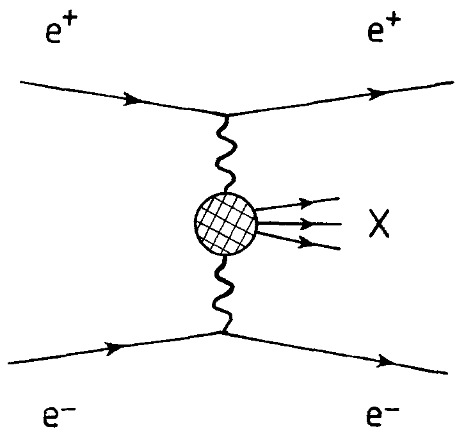

Fig. 1. Production of neutral $C=+1$ states X in the collision of two charged particles (e.g. e^+e^-) via the two photon mechanism

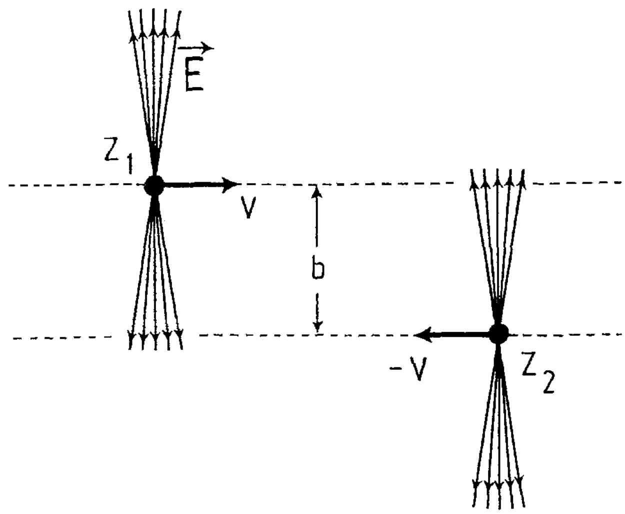

Fig. 2. Two relativistic heavy ions collide in a system where they move with opposite velocities v and $-v$ towards each other. This corresponds to a collision of two photons with opposite momenta with photon energy distributions given by $n_1(\omega_1)$ and $n_2(\omega_2)$, according to the Weizsäcker-Williams method

parameter, are derived e.g. in [6] they are given by the Weizsäcker-Williams method. This is further discussed also in [7, 8]. For $\gamma \gg 1$ we can use the expression

$$n_i(\omega_i)=\frac{2Z_i^2\alpha}{\pi}\ln\frac{\gamma c}{\omega_i R_i} \tag{3}$$

where the radius R_i of the ion i determines the minimum impact parameter. The adiabatic cut-off sets in at

$$\omega_i^{\max}=\frac{\gamma c}{R_i} \tag{4a}$$

and we put, for simplicity,

$$n_i(\omega_i)=0 \quad \text{for } \omega_i>\omega_i^{\max} \tag{4b}$$

The Lorentz-factor γ is related to the corresponding Lorentz-factor γ_p of the projectile (for a fixed target machine) by

$$\gamma_p=2\gamma^2-1 \tag{5}$$

The total cross section σ_c for the two-photon process $Z_1+Z_2\to Z_1+Z_2+X$ is given by

$$\sigma_c=\int\frac{d\omega_1}{\omega_1}\int\frac{d\omega_2}{\omega_2}n_1(\omega_1)n_2(\omega_2)\sigma_{\gamma\gamma\to X}(\omega_1\,\omega_2). \tag{6}$$

Introducing the variable $x=\omega_1\,\omega_2$ ($4x$ corresponds to the square of the invariant mass of the 2γ-system) one obtains

$$\sigma_c=\left(\frac{Z_1 Z_2\alpha}{\pi}\right)^2\int dx\,\sigma_{\gamma\gamma\to X}(x)\,I(x), \tag{7a}$$

where

$$I(x)=\frac{16}{3x}\left[\ln\frac{\gamma c}{\sqrt{xR_1R_2}}\right]^3. \tag{7b}$$

This new and rather simple formula is very powerful, It allows the calculation of $\gamma-\gamma$ processes in RHI collisions in terms of the corresponding $\gamma-\gamma$ cross section. For $x>\frac{(\gamma c)^2}{R_1 R_2}$ one can no longer use (7b) and one has to treat the exponentially decreasing part of the equivalent photon spectrum (see (4b)) in a better way. Unfortunately, we have found no simple way to deal with this case in an analytic form. This case could be relevant for the production of heavy particles, and a numerical treatment seems appropriate. There are important differences of this equation as compared to the one used for the e^+e^- collisions [4, 5]. In the derivation of (1) and (2), it was assumed that $\gamma \gg 1$ (as is appropriate for the e^+e^- colliders). This means that the adiabatic cut-off, (4), which is relevant for the RHI collisions, is not important for the e^+e^- case. The maximum energies of the equivalent photons are determined there by the kinematics of the process (total energy loss for e^+ or e^-, see e.g. (15) of [4]. This means that the higher energies will not be easily obtained in RHI collisions.

An important process in $\gamma-\gamma$ collisions is the e^+e^- pair production

$$\gamma+\gamma\to e^+ + e^-. \tag{8}$$

The corresponding e^+e^- pair production in charged particle reactions has been studied before (see e.g. [9, 10]) where different methods have been used. In [10], for example, the equivalent photon spectrum of one of the heavy ions is folded with the Bethe-Heitler cross section for the $\gamma+Z\to e^+e^-Z$ process. Since the Bethe-Heitler cross section can also be derived with the equivalent photon method (see e.g. [11]) it is evident that one can obtain the cross section for $Z_1+Z_2\to Z_1+Z_2+e^++e^-$ with the help of (7) and the well-known expression (see e.g. [11]) for the cross section for pair production with two γ's. As it is discussed for example in [10], the minimum impact parameter, where the equivalent photon method works is given by the Compton-wavelength $\lambda=\frac{1}{m_e}$ of the electron. In this case, the expression $\sqrt{R_1 R_2}$ in (7b) has to be replaced by $\frac{1}{m_e}$.

Another purely quantum electrodynamical process is $\gamma+\gamma\to\gamma+\gamma$, the elastic scattering of light on light (see e.g. [11]). Its cross section involves an additional factor of α^2 as compared to the pair production, it is, therefore, rather small and it has never been possible to study it directly. On the other hand, the elastic scattering of γ's in the Coulomb field of nuclei has been experimentally investigated (Delbrück scattering). It is also possible to study the elastic scattering of two photons with RHI collisions by means of the process $Z_1+Z_2\to Z_1+Z_2+\gamma+\gamma$. In order to calculate the total cross section $\sigma_{Z_1Z_2\to Z_1Z_2\gamma\gamma}$ for this process we use the simple expressions (see e.g. [11]) for the low and high energy limits. One has

$$\sigma_{\gamma\gamma\to\gamma\gamma}=\frac{973}{10125}\pi\alpha^2 r_e^2\left(\frac{\omega}{mc^2}\right)^6 \tag{9a}$$

for

$$\omega\ll m \tag{9b}$$

where $r_e=\frac{e^2}{mc^2}$ is the classical electron radius and ω is the energy of each photon in the c.m. system. In the high energy limit one has

$$\sigma_{\gamma\gamma\to\gamma\gamma}=4.7\alpha^4\left(\frac{c}{\omega}\right)^2 \tag{10a}$$

for

$$\omega\gg m. \tag{10b}$$

Inserting (9) and (10) into (7) one obtains the cross section for purely electrodynamical production of 2γ's in a RHI collision. We divide the cross section into two parts, according to the conditions (9b) and (10b).

$$\sigma_{Z_1Z_2\to Z_1Z_2\gamma\gamma}=\sigma^{(1)}+\sigma^{(2)} \tag{11}$$

where the cross section $\sigma^{(1)}$ for the low energy photons is found to be

$$\sigma^{(1)}=5.51\cdot 10^{-3}(Z_1 Z_2\alpha^2)^2 r_e^2 \cdot(\ln^3\xi+\tfrac{1}{2}\ln^2\xi+\tfrac{1}{6}\ln\xi+\tfrac{1}{36}) \tag{12a}$$

where $\xi=\frac{\gamma c}{m\sqrt{R_1 R_2}}$. For the high energy photons one finds

$$\sigma^{(2)}=2.54(Z_1 Z_2\alpha^2)^2 r_e^2(\ln^3\xi-\tfrac{3}{2}\ln^2\xi+\tfrac{3}{2}\xi-\tfrac{3}{4}). \tag{12b}$$

We see that $\sigma^{(1)}\ll\sigma^{(2)}$, so the total cross section, (11), is entirely dominated by the high energy photons, given by (12b).

For the present kind of RHI experiments at CERN (200 GeV/A ^{32}S beams on a U target) one obtains a value of $\sigma_{SU\to SU\gamma\gamma}\simeq 300$ mb. This is not a very small effect, it may be viewed either as an (unwanted) "background", or it might be used as an alternative to the experimental study of $\gamma-\gamma$ elastic scattering with Delbrück scattering.

It is also possible to form strongly interacting neutral, $C=+1$, particles in 2γ-collisions, like $\pi^0, \eta, \eta_c, \ldots$. The π^0 production was originally suggested by Low [4], the η_c-particle was recently produced at PETRA [12]. The resonances are usually sufficiently narrow, so that their Breit-Wigner form can well be approximated by a δ-function in the integral, (7a, b). For example, the π^0 production cross section is given by [4]

$$\sigma_{\gamma\gamma}=\frac{8\pi^2}{\mu\tau}\delta(\mu^2-4x) \tag{13}$$

where $\tau=0.83\cdot 10^{-16}$ s and $\mu=134.9$ MeV are the lifetime and mass of the π^0; respectively [5]. A similar formula can also be used for the production of other $C=+1$ particles of mass m_R, spin J_R and $\gamma-\gamma$ width $\Gamma(R\to\gamma\gamma)$. One obtains for its $\gamma-\gamma$ production cross section in a RHI collision:

$$\sigma_c=\frac{128}{3}(Z_1 Z_2\alpha)^2\cdot\frac{\Gamma(R\to\gamma\gamma)}{m_R^3} \cdot\left(\ln\frac{2\gamma}{m_R\sqrt{R_1 R_2}}\right)^3(2J_R+1). \tag{14}$$

This new formula reduces the problem of calculating the production cross section by the $\gamma-\gamma$ mechanism to the knowledge of its basic properties, spin mass and $\gamma-\gamma$ width. It can be easily applied to a variety of different cases.

It might be argued that the strong Coulomb field present in the RHI collision could lead to final state interaction effects with the charged particles produced in the subsequent decay. This might lead to a complication which might not be of importance in the case of $\gamma-\gamma$ physics at e^+e^- colliders. However, very simple estimates of the collision time and the decay time of any reasonably well defined resonance show immediately that such final state effects are clearly negligible in the RHI case also.

One obtains a value of 30 μb for the π^0 production by the two-photon mechanism for the conditions of the present RHI experiments at CERN (200 GeV/A ^{32}S beams on a U target). A list of known neutral $C=+1$ particles, their total widths and their $\gamma-\gamma$ branching can be found in [5]. Apart from the π^0, the η and η' mesons are the most likely candidates for production in $\gamma-\gamma$ collisions (we have $m_\eta=549$ MeV, $\Gamma(\eta\to\gamma\gamma)\simeq 0.324$ keV, and $m_{\eta'}=958$ MeV, $\Gamma(\eta'\to\gamma\gamma)\simeq 4.5$ keV). For present day accelerators, like at CERN, the γ-values (see (5)) are hardly large enough to lead to a substantial production rate, this is directly due to the adiabaticity condition, given by (4). As a side remark we mention that the 2γ-decays of K_S^0 and K_L^0 were recently found experimentally [13]. Of course, the $\gamma-\gamma$ production cross sections of K_S^0 and K_L^0 will be extremely small, since the width $\Gamma(K_S^0\to\gamma\gamma)\simeq 1.7\cdot 10^{-11}$ eV involves the weak coupling constant.

Certainly, with future high energy (heavy ion) accelerators, especially with colliders like RHIC, or even SSC and LHC, higher equivalent photon energies will become available (see (4)) and one can study $\gamma-\gamma$ collisions at the ~ 100 GeV energy scale (see the recent preprint, [14]).

Let us compare the characteristics of the RHI collisions with the e^+e^- collisions. Even in the highest energy RHI experiments, the γ-values achieved are rather low: for $\gamma_p=60$ or 200, appropriate for the CERN experiments, the corresponding γ- values (see (5)) are rather modest. For a 1 GeV electron, e.g., one has already $\gamma\simeq 2000$. The γ-factor enters, however, only logarithmically in the cross section, whereas the $(Z_1Z_2)^2$ factor enters directly in the cross section formula, giving a distinct advantage for the RHI collisions. The comparatively low value of γ for RHI collisions leads to a limitation of the invariant mass of the 2γ-system. This was already noted before in the study of heavy lepton ($\mu^+\mu^-$ and $\tau^+\tau^-$) pair production [15].

We cannot say too much about the actual experimental problems which one will have to face in such studies. Certainly, the strong interaction background will be serious, as compared to the leptonic e^+e^- collision system. Clearly one must find suitable ways to veto the violent nuclear collisions. In the context of electromagnetic excitation of nuclear states, there exist proposals for veto-detectors of these central collisions (see [16]). This method opens a way to study such processes for their own sake. On the other hand, it is important to have the purely electromagnetic processes under control as a possible source of background in the search for new states of nuclear matter (like the quark-gluon-plasma).

Finally, let us mention some speculations. Due to the large flux of equivalent photons in the MeV range, RHI collisions would be of interest to look for resonances in the $\gamma-\gamma$ system. This could be of special interest at present in the search for an unknown particle which decays into e^+ and e^- (for a recent review on the GSI experiments on positron emission in (low energy) heavy ion collisions see [17]). Various proposals using $\gamma-\gamma$ collisions [18] or the Primakoff effect (as mentioned in [19]) exist in order to look for such an unknown particle. If it is heavier than $2m_ec^2$ then it could decay into e^+e^- pairs and one can look for peaks in the invariant e^+e^- mass spectrum as produced in RHI collisions. This would also complement the search for resonances in e^+e^- collisions in the MeV region (see e.g. [20]).

All these proposals are, of course, quite speculative and involve some kind of non-standard physics. Assuming a "standard axion" (which is ruled out now) with a decay width given by $\Gamma_{a\to\gamma\gamma}=1.4\left(\frac{m_a}{100\,\text{keV}}\right)^5$ sec^{-1} (see e.g. [21]) one would obtain rather small values for the axion production cross section. E.g. for a 200 GeV/A ^{32}S on U collision one would have a cross section of 0.17 nb for the axion production via the 2γ-mechanism, with an assumed axion mass of $m_a=100$ keV. Thus the investigation of new physics with $\gamma-\gamma$ collisions in RHI collisions is rather speculative. The observation of the elastic $\gamma-\gamma$ scattering or e^+e^- production would be a further (probably low precision) test of QED. On the other hand, it seems also important to keep control about "standard" $\gamma-\gamma$ processes which will show up in RHI collisions. The present paper has provided a simple basis for a discussion of "standard" as well as "exotic" $\gamma-\gamma$ physics in RHI collisions.

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