Philons from spectators

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Abstract. For Pb-Pb collisions at the LHC, the spectators, those parts of the Pb nuclei that are not involved in nucleon-nucleon collisions, continue on in the original beam direction, but they are not inert objects. If they are not too large a fraction of the original nucleus they are completely disintegrated into neutrons and protons. The spectators are subject to huge electric fields, fields causing accelerations so large that the quarks in the nucleons will radiate almost all of the energy they acquire from the field. Because of the extreme Lorentz transform most of the photons can be found in the 10 cm between the ingoing and outgoing beam pipes 140 m from the collision point. Spectator radiation may be the source of cosmic-ray photons seen in emulsion stacks at 100,000 ft.

1. Introduction

In a reaction between two highly relativistic heavy ions the overlap region where nucleon-nucleon collisions occur becomes quark-gluon plasma. Those parts of the original ions that are outside of the overlap region are known as spectators, figure 1. There have been extensive studies of many aspects of the quark-gluon plasma, but the physics of the spectators has been mostly ignored. The spectators are pieces of nuclear matter subject to extreme and unusual conditions. The spectators from LHC Pb-Pb collisions are subject to huge electromagnetic fields, which cause the spectators to emit EM radiation. Because of the large velocity of the spectators most of the radiation is confined to small angles, $\theta < 1.0$ mrad. When the spectators are small, less than half of the original nucleus, they are completely disintegrated into protons and neutrons. The disintegration process almost certainly produces photons. When the overlap region is small, and the spectators large, some of the spectator matter is in the form of a small nucleus, which is usually in an excited state that emits photons. The photons may be of moderate energy, in the MeV range, but the Lorentz transformation boosts them into to the GeV range.

Figure 1. b is the distance between the centers of the two heavy ions as they collide. $b = 0$ is a central collision. b is often called “impact parameter.”

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Little is known about these photons, but there are many interesting possibilities, some of which are discussed below.

2. Photons in the CMS ZDC
The part of the CMS [1] experiment at the LHC [2] that could observe the spectator photons is the Zero Degree Calorimeter, ZDC [3]. The ZDC is about 9 cm wide and is located between the incoming and outgoing beam pipes at 140 m from the center of CMS (the closest point for which the two beams are in separate pipes). There are two ZDCs, one on each side of CMS.

The Lorentz transformation for a photon at 90° in the spectator frame is easily understood. The transverse momentum is not affected by the transformation. The photon can be regarded as a particle of a given energy; this energy (momentum) is multiplied by the relativistic γ. The transverse momentum is unchanged, and the longitudinal momentum ends up being the transverse momentum multiplied by γ. So the tangent of the angle is 1/γ. With an isotropic distribution for photons in the spectator frame, half of the photons are within the angle 1/γ.

For the 2010 and 2011 Pb-Pb runs the Pb beams were at 1.375 TeV/nucleon with γ = 1463. Half of the photons are in a cone with a diameter of 19 cm at the ZDC. After the forthcoming 2-times energy upgrade the cone will have a diameter of only 9.6 cm so that almost half of the photons will hit the ZDC, which is a square with sides of almost 9 cm. The ZDC also detects the spectator neutrons; the protons and light nuclei are swept away by magnets along the 140 m path.

![Figure 2. The parts of the ZDC.](image)

Figure 2 is a schematic of the ZDC. The EM, electromagnetic, part is 19 X0 thick and is divided horizontally into five sections. It is followed by four thicker sections of 1.4 nuclear interaction lengths each that together stop most of the neutrons. The absorbing material is W metal. Hadrons start their showers in the EM part 50% of the time. There is a prediction by the ALICE group that to the 1 sigma level the neutrons should be in a spot only 6 mm across at 116 m (7 mm at 140 m) [4]. If this were correct the neutrons would be in one or two of the central sections and the photons would be in all of the sections. With this assumption, the data show that the proton/neutron ratio increases as the reactions become more central. It appears that ALICE assumed that the transverse momentum is entirely due to a traditional Fermi momentum distribution in the Pb nucleus. More recent calculations by ALICE [5] show a broadening of the neutron distributions resulting from the transverse beam divergence and the beam diameter at the interaction point along with a directed flow of the spectator neutrons [6].

Another broadening effect results from short-range correlations [7]. The strong short range repulsion and intermediate range attraction between nearby nucleons provides a deep potential well such that the relative motion of the nucleon pair has a momentum substantially larger than the Fermi momentum characteristic of the nucleus. If during the collision one of the pair is swept away into the participant region, the one remaining in the spectator is left with the large momentum. It can escape into the direction of the open hemisphere, figure 3, with considerable energy or go into the spectator and raise its temperature. This process should lead to an asymmetric distribution of neutrons at the
ZDC. A measurement of this distribution could provide a measure of the reaction plane and also the direction of the impact parameter vector.

Figure 3. Asymmetric distribution of spectator nucleons

The fraction of the neutrons that are part of a broken pair becomes larger as the spectator becomes smaller with decreasing impact parameter. At this time it is not clear whether the change in the five point EM distributions is caused by a change in the photon/neutron ratio or simply an increase in the transverse energy of the neutrons as the spectators become smaller.

Another possible contribution to the flattening of the five point EM distributions as reactions become more central is the production of $\Lambda^0$ baryons along the boundary between the spectator and the quark-gluon plasma. The signal from a $\Lambda^0$ going into the ZDC is the same as for a neutron, but if it decays in flight to $n + \pi^0$ some of the photons from the $\pi^0$ decay will be seen in the EM section. For the 2011 runs 70% of the $\Lambda^0$ decay along the 140 m path. The decay into $p + \pi^-$ will be seen by the ZDC if it occurs in the last half of the 140 m, which is free of magnets.

Detailed studies of the photon and neutron distributions would require improvements to the EM section. Presently it consists of 2 mm thick W-metal plates interleaved with ribbons of quartz fibers that are divided horizontally into five groups. Čerenkov light from each of the five fiber bundles is viewed with a photomultiplier tube. For an improved version the fiber ribbons could be replaced with pixilated silicon detectors. For better measurements of the neutron distributions the last layer would be preceded by a 1 cm thick W-metal plate to block the remnant of the photon showers and to increase the detected fraction of the neutrons to 55%. The improved EM section would be used only with heavy ions, for which the luminosity is orders of magnitude smaller than for protons. Even with heavy ions, radiation damage must be considered. It may be necessary to use the more radiation resistant diamond detectors. This is a small detector with transverse dimensions of only 9 cm by 15 cm. The electronics would be similar to that in the CMS silicon tracker.

3. Cosmic Ray Data

Unexplained jets of pure photons have been observed with balloon flights using nuclear emulsion stacks at 100,000 ft [8]. There were a dozen or so GeV photons in a small region less than 50 µm across. No charged particles of any kind were found to accompany the incident photons. Many single photons were observed, as might be expected from spectators derived from heavy ions, such as iron, striking nitrogen and oxygen at 140,000 ft. Most of the photons from such spectators would be well separated from the nucleon component. The photons could easily reach the detectors; there is only 12 g/cm$^2$ of air above 100,000 ft, and $X_0 = 36.5$ g/ cm$^2$ for air.

It is worth considering the possibility that a highly directed beam of photons might sometimes be emitted from a spectator. Assuming a $\gamma = 10,000$, the Lorentz contraction makes 40,000 ft of travel only 4 ft. A photon beam that expands to 50 µm in one or two meters seems within the realm of possibility.

At the LHC with $\gamma = 2925$ the 140 m to the detector is Lorentz contracted to only 4.8 cm with a corresponding reduction in the spreading of the photon beam by one or two orders of magnitude. The
only way to differentiate between a dozen photons at essentially the same point and one photon of a higher energy is by the depth penetration of the shower.

4. Extreme Electric Fields
The magnitudes of the various features for Pb-Pb at the full LHC design energy of 5.5 TeV/nucleon-pair are spectacular. The spectators are subjected to a brief but huge electric field directed radially outward from the beam axis. The electric field at a distance of 10 fm from the center of a Pb nucleus at rest is $1.18 \times 10^{21}$ V/m. The value of the relativistic gamma of one Pb seen by the other is $1.71 \times 10^7$. Multiplying these gives $E = 2 \times 10^{28}$ V/m. This should be compared with $E_{\text{crit}} = 1.6 \times 10^{18}$ V/m, which will produce electron-positron pairs out of the vacuum by the Schwinger mechanism [9]. $E_{\text{crit}}$ is also the field that will cause an electron to accelerate at a rate such that the reaction to the radiated power given by the Larmor formula is a major contributor to the motion of the electron. There are currently several projects that are trying to reach $E_{\text{crit}}$ with high powered lasers. With electric fields that are millions of times larger the effect of the field on u and d quarks would be to produce radiation but virtually no change in the kinetic energy of the quarks.

The time that the force is applied must be divided by gamma so that the total momentum transferred, $F \times t$, is independent of gamma. If there were no radiation an electron would acquire about 28 MeV. From another point of view, the uncertainty principle sets an upper limit of 28 MeV on the transverse momentum of a photon emitted by a moving Pb ion, see p. 4 of [10].

5. Superradiance and Solitons
The hyper critical acceleration issue raises fascinating questions and possibilities. What actually happens when a force attempts to accelerate a charged particle by much more than the critical value? With the LHC the electric field seen by the spectator is $2 \times 10^{28}$ V/m, but for only $3 \times 10^{-30}$ seconds. By the uncertainty principle the energy available during the interaction could be over 200 TeV. The initial radiation is most likely not a photon but a particle-antiparticle pair. High energy photons interact with matter by producing pairs. Compton scattering is only effective for photon energies round $m_e c^2$. It would be the annihilation of the pairs that produces the EM radiation. The final electromagnetic energy radiated per quark, in the spectator system, is sufficiently low that the wave length of the radiation is larger than the spectator dimensions. This suggests the possibility of superradiance effects. A superradiant medium can be considered as a mirrorless laser pumped in a percussional way at time $t = 0$. In the current literature the medium has the energy stored as excited states of atoms. In our case the energy would be in particle-antiparticle pairs, electrons excited out of the Fermi sea. A d quark would have less energy associated with it than a u quark because of its smaller charge and larger mass. Perhaps most of the EM energy would be emitted as two highly directed bunches.

A wave form that propagates without changing shape is called a soliton. They were first observed in water canals in which the normal effects of dispersion are canceled by nonlinearities. Such one dimensional solitons have proved useful with light signals travelling in specially tailored fibers.

A light beam in free space will normally expand because of diffraction, however a light beam with amplitude cross section given by a $J_0$ Bessel function is diffraction free [11]. Such beams are sometimes called 2-D solitons.

There have been many unsuccessful attempts to explain elementary particles as 3-D solitons, where the shape of the wave packet remains constant along all three axes. There does exist at least one 3-D electromagnetic soliton [12]. It requires a radial energy distribution of the form of a $J_0$ Bessel function and a time distribution of an Airy function, figure 4. Experiments [12] have shown that a reasonable approximation to such a shape degrades only slowly as it propagates. The balloon data require only that the transverse dimension expand slowly; the temporal features of a 3-D soliton are not needed.
6. Conclusions
There have been no definitive measurements of photons from spectators from highly relativistic heavy ion collisions, although such photons may have been seen in cosmic rays. At LHC Pb-Pb collisions energies of 5.5 TeV/nucleon-pair the Lorentz transformation puts all photons from the forward hemisphere of the spectator into a cone that is only 9.5 cm across at 140 m from the interaction point. Better theoretical predictions are needed along with improved detectors for measuring the distributions of photons and neutrons. Designing such detectors will be challenging but not expensive, because the area to be covered is only 135 cm$^2$.

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