HOW TO TEST THE EXISTENCE OF THE EARLY PARTON CASCADE USING PHOTON HBT CORRELATIONS?  

DANIEL FERENC

University of Regensburg,
Physics Dep.,
93040-Regensburg,
Germany

Div. PPE,
CERN,
1211-Geneva,
Switzerland

E-mail: Daniel.Ferenc@CERN.ch

We report on a possible application of the HBT phenomenon in testing the existence of two hypothetical phenomena. First, it is argued that the existence of a rapidly developing parton cascade in the earliest stages of a high energy nuclear collision process can be tested by studying two-photon HBT correlations over a wide longitudinal momentum scale – corresponding to the early photon emission time from the hypothetical parton system. This method provides the selectivity for the early emitted photons, since the photons emitted at later times correlate over progressively narrower momentum scales. Second, in a similar way we argue that the existence of a hypothetic dark matter candidate, the Weakly Interacting Massive Particle (WIMP), may be tested by studying HBT correlations of cosmic gamma rays at a relatively long detection time scale – corresponding to the very narrow spectral line of the photons emerging from WIMP annihilations. Background photons leave no signature since they do not correlate.

1 Introduction

The discovery of the photon intensity interference phenomenon by Hanbury Brown and Twiss (HBT) has initiated, in a rather dramatic way, a new field of physics – the field of quantum optics. The phenomenon has ever since been also utilized in different fields of science as a unique tool capable of revealing important properties of various physical systems. While in astronomy the "HBT tool" has been originally used to study angular sizes of stellar objects, in high energy physics it has provided information on the space-time evolution of expanding hadronic systems created in particle collisions.

a To the memory of Klaus Geiger
b Presented at the 2nd Catania Relativistic Ion Studies, CRIS'98, Catania, Sicily, Italy, June 8-12, 1998. To appear in the Proceedings, World Scientific.
In this paper we report on another possible application of the HBT phenomenon, namely in testing the existence of certain hypothetical phenomena. Two applications are proposed. First, the study of the existence of a rapidly developing parton cascade in the earliest stages of a nuclear collision process at very high collision energies (at RHIC and LHC). According to parton cascade models, a rapid partial parton thermalisation establishes already within a fraction of one fm/c time. Very strong photon radiation – a flash – should be among the most prominent consequences and signatures of the phenomenon. In practice, the problem is that the photons are radiated also during all the subsequent evolution stages of the system, most of them from the decays of neutral pions and other hadrons, and in principle there is no way to distinguish between the interesting early photons and all other photons, as long as single–photon momentum spectra are studied. In that case, the most one can do is to estimate the time-integrated yield of all the direct photons, by subtracting the estimated yield of photons emerging from hadron decays from the total measured contribution.

However, it is possible to distinguish the early photon component from the rest by exploring the emission time information which is imprinted into the HBT correlation pattern. The early emitted photons are HBT correlated over a very wide longitudinal momentum scale – thanks to their very early emission time. The HBT effect appears, roughly speaking, when the product of these two quantities becomes as small as $\bar{\hbar}$, or in other words when the photons are found to occupy the same phase space cell in the phase space (in fact in all three directions simultaneously). For example, photons radiated at a time of 0.5 fm/c after collision will correlate over longitudinal momentum difference of about 0.4 GeV/c. All the other photons that emerge later are correlated at progressively narrower longitudinal momentum scales, which provides a possibility to distinguish the contribution of the early photons, and to verify the existence of the hypothetical rapidly developing parton cascade.

Another example, discussed here only briefly and qualitatively, is the search for the Weakly Interacting Massive Particle (WIMP, possibly the lightest SUSY particle) as a dark matter candidate. Abundant annihilation of WIMPs into pairs of photons may be expected in the vicinity of very massive cosmic objects that would assure high annihilation rates due to high dark matter densities. Again, the annihilation photons will be detected together with photons originating from all the other sources, and the phenomenon will be hard to detect, unless a very strong annihilation peak existed above the background (at an energy equal to the WIMP’s mass, presently expected at around 100 GeV – in the so far unexplored energy region). The HBT correlation tool can in principle again provide selectivity, because photons emerging
from the annihilations could have a very narrow frequency spectrum around
the WIMP mass, the spectral width being determined by Doppler smearing
due to WIMPs’ motion, which is probably very slow. Due to the narrow fre-
quency spectrum, photons from WIMP annihilations will be HBT correlated
over a very long time, while the background photons will not be HBT corre-
lated at all. A possible way to search for the annihilation process is therefore by
searching for the HBT temporal photon correlations over a relatively long time
scale. This time scale depends on the actual WIMP’s kinetic energies. In case
that the effective temperature of WIMPs would be as high as the microwave
background temperature (∼ 3 K), the spectral width would be ∼ 10^{-4} eV,
and the HBT coherence time would be ∼ 10^{-11} seconds. One of the lessons we
have learned from the original table-top photon HBT experiment is that the
actual time-resolution of the apparatus may be by several orders of magnitude
larger than the coherence time. Taking care of the other coordinates in phase
space, one also has to make sure that the spread in transverse momentum of
the detected photons be sufficiently small (small angular acceptance) to fit a
single phase space cell.

The paper is structured as follows: the HBT measurement tool is discussed
in Sect.2., momentum variables are defined in Sect.3, photon detection tech-
niques are discussed in Sect.4, and the results of our simple considerations are
presented and discussed in Sect.5.

2 The HBT Measurement Tool

Statistical fluctuations of a chaotic system consisting of noninteracting iden-
tical bosons in the six–dimensional phase space are not Poissonian, like for
macroscopic particles, but of a Bose–Einstein type. When a phase–space vol-
ume smaller than a single phase–space cell is considered, boson multiplicities
fluctuate according to the so called geometric count probability function

\[ P(n) = \frac{< n >^n}{(< n > + 1)^{n+1}} \]  

(1)

where \(< n >\) is the average count number. This function is very wide – a small
number of counts is most probable, but there is also a rather high probability
to count a large number of bosons. The count probability distribution for a
large phase–space volume which contains many phase–space cells, approaches
the Poissonian law, but never reaches the Poissonian limit – fluctuations within
single phase space cells always remain geometric and only get diluted in bulk
as the number of independent cells increases.
The general idea of all HBT measurements is to scan the statistical behavior of identical bosons as a function of the size of the considered phase–space volume. Typically one or more dimensions of the phase–space volume are unknown, while the others are accessible to the measurement; in particle and nuclear physics the volume in the configuration space is unknown (i.e. the physical size of the system at the freezeout), while the momentum space for pions is accessible in the measurement. The goal of a correlation measurement is to find the scale in the accessible coordinate of the phase–space for which the fluctuation pattern turns from the Poissonian to the geometric law – this indicates that the overall observed phase–space volume (including the unobservable dimensions) corresponds to a single phase–space cell. Knowing the volume of a single phase–space cell, \((\Delta p_x \Delta x \sim \hbar, \Delta p_y \Delta y \sim \hbar, \Delta p_z \Delta z \sim \hbar)\), it is straightforward to deduce the scale of the system along the unaccessible coordinates.

In contrast to the particle and nuclear physics, in the famous Hanbury–Brown Twiss stellar interferometry\(^1\) the volume in the configuration space is well known and in fact defined by the detector acceptance, while the transverse momentum spread of light coming from a star is the unknown required quantity; this momentum spread \(\Delta p_T\) is related to the opening angle of the star \(\theta\) as viewed from the Earth \(\Delta p_T \simeq p\theta\), which enables one to estimate the so called angular size of a star (not to be confused with the real size!). In the particle and nuclear physics the phase–space cell is placed at the particle source, while in the stellar interferometry it is placed between the photon detectors on the Earth.

The following methodological problem is how to check the fluctuation pattern in real experiments. There are basically two different methods. First, one can perform a direct study of the count probability statistics as a function of the observational phase–space volume; a still better way is to study moments, e.g. factorial moments. Another method is to study the two–particle correlation functions. Essentially, this means to study a distribution of distances between particles in the accessible part of the phase–space (in particle physics in the momentum–space and in astronomy in configuration space) and to compare this distribution to (or in fact divide by) a somehow synthesized distribution corresponding (locally) to a Poissonian statistics. At a certain small scale a correlation peak emerges, indicating where the actual statistics deviates from the Poissonian, and thus indicating the scale corresponding to the single phase–space cell. As long as two–particle correlations are studied, the correlation technique is very suitable, but when higher–order correlations are to be studied, a serious conceptual problem arises with the definition of the fundamental quantity – the distance between several particles – and it is
more natural to study count probability moments.

For expanding particle sources, a correlation arises between momenta and emission coordinates of particles. Due to the Doppler shift, particles emitted from distant parts of the source cannot occupy the same phase-space cell \((\Delta x \Delta p_x >> h)\) and they are not mutually correlated. Only particles emitted from a smaller relative distance \(\Delta x\), and consequently with a smaller \(\Delta p_x\), demonstrate correlation. This in turn enables us to exploit the Doppler effect in order to study the way how the system expands.

### 3 Momentum Variables and the Correlation Function

The two single–particle momentum vectors \(\mathbf{p}_1\) and \(\mathbf{p}_2\) may be decomposed into the average \(\mathbf{k} = 0.5 (\mathbf{p}_1 + \mathbf{p}_2)\) and the relative \(\mathbf{Q} = (\mathbf{p}_1 - \mathbf{p}_2)\) momentum vectors of the pair, each carrying three degrees of freedom. The relative momentum vector may be decomposed into transverse sideward \(Q_S\), transverse outward \(Q_O\), and longitudinal \(Q_L\) components; the longitudinal component is parallel to the collision axis, while the transverse sideward and outward components are perpendicular and parallel to the average transverse momentum vector \(\mathbf{k}_T\), respectively:

\[
\begin{align*}
Q_L &= (p_{L1} - p_{L2}) \\
\mathbf{k}_T &= \frac{p_{T1} + p_{T2}}{2} \\
Q_T &= (p_{T1} - p_{T2}) \\
Q_S &= \frac{|\mathbf{Q}_T \times \mathbf{k}_T|}{|\mathbf{k}_T|} \\
Q_O &= \frac{\mathbf{Q}_T \cdot \mathbf{k}_T}{|\mathbf{k}_T|}
\end{align*}
\]

The correlation function used in the simulations presented in this paper is a function of the three relative momentum components and was assumed to be a Gaussian in all three dimensions:

\[
C(Q_S, Q_O, Q_L) = 1 + \lambda e^{(-Q_S^2 R_S^2)} e^{(-Q_O^2 R_O^2)} e^{(-Q_L^2 R_L^2)},
\]

where \(\lambda\) is the correlation intensity (0.5 for photons), and \(R_S\), \(R_O\) and \(R_L\) are the parameters which characterize the photon source, or the effective interferometric source sizes.
4 Photon Detection Techniques

The first problem to be discussed is whether and how the high energy photons may be detected in a realistic experiment. In our discussion we shall consider the ALICE experiment at LHC/CERN.

The experimental parameters of the highest relevance for the proposed correlation study are the acceptance of the photon detector, and the photon detection probability.

![Transverse momentum spectra $dn/dp_T$ for the “early photon component” (dotted line), “late photon component” (dashed line) and the sum of the two (full line).](image)

Figure 1: Transverse momentum spectra $dn/dp_T$ for the “early photon component” (dotted line), “late photon component” (dashed line) and the sum of the two (full line).

The acceptance is of twofold importance: first, the statistics increases with the acceptance, and second–more important–acceptance determines the maximal range of relative momenta of particle pairs in correlation analysis. If the acceptance were too narrow, a measured correlation function would not reach its “plateau” (the flat region outside the correlation peak), and the correlation measurement would not be possible. This is of particular importance in the proposed photon correlation measurement, because we are interested in the correlation intensity at a very large longitudinal relative momentum, up to around 2 GeV. For photons of 1 GeV momentum the acceptance in the polar angle should then be around ±45 degrees. The dedicated photon detector in ALICE, the Photon Spectrometer (PHOS) (a matrix consisting of lead-tungstenite crystals) is too short since it covers less than a half of the
Figure 2: Distribution of photon pairs as a function of $Q_s$. Pairs of early photons (dotted line) constitute a very small fraction of the total photon contribution (full line); late photons (dashed line). No $p_T$ cuts are applied.

Figure 3: Distribution of photon pairs as a function of $Q_s$, with a transverse momentum cut $p_T > 1$ GeV. Pairs of early photons (dotted line), late photons (dashed line) and total (full line).
needed acceptance, but fortunately, one can apply another photon measurement technique, namely the photon conversion technique, which has been used in modern satellite borne cosmic gamma ray experiments. In ALICE, photons will convert into electron–positron pairs in the material of the inner tracker system, inner field cage of the Time Projection Chamber (TPC), and in the gas inside the TPC. The created electrons and positrons may be tracked through the TPC, and the information on the original converted photon will be obtained from the electron-positron pair reconstruction. The TPC acceptance for electron-positron pairs is sufficiently wide, and a good resolving power for the two tracks of a conversion pair is confirmed in the simulation.

The integral amount of material contributing to photon conversion will lead to about 5-10% conversion efficiency, and we shall assume 5% overall detection probability.

5 Results

It remains to be seen under which conditions the HBT correlations of the early direct photons will be observable, specifically in the ALICE experiment at LHC. The main problem is the presence of photons emitted later than the early photons, from all other photon sources, particularly from the decays of neutral pions. The HBT correlation at a large relative momentum – the signature of the presence of the early direct photon component – will therefore be strongly suppressed.

For simplicity, in the simulations presented we assume only two photon components: the “early photons”, emerging at time 0.3 fm/c, from the rapidly developing parton cascade at 750 MeV effective temperature, and the “late photons”, comprising the later direct photons and the photons emerging from the decays of neutral pions (in this simplified approach the late direct photons are not separately simulated, but are effectively assigned as a part of the pion-decay component). We assume further that the fraction of the early direct photons is 5% of the total photon yield.

Assuming a total number of 5000 neutral pions per Pb+Pb central collision in the acceptance of two rapidity units, one arrives at 10,000 photons from pion decays, and 500 early photons per event. Assuming further a detection probability of 5%, one would detect 500 late photons and 25 early photons per event.

Fig. 1 shows the transverse momentum spectrum of the early direct photons, the late photons, and their sum. The high-temperature early component is strongly suppressed at low transverse momenta, below 1 GeV. Fig. 2 shows the distribution of photon pairs as a function of the invariant momentum dif-
Figure 4: Two-photon correlation function as a function of $Q_L$, with transverse momentum cut $p_T > 2$ GeV. Full line: $R_L = 0.3$ fm, $R_s = 3$ fm and $R_o = 3$ fm; the correlation enhancement is due to the presence of the early photon component. Dashed line: the early photon component is shifted to later times by setting $R_L = 6$ fm; no correlation enhancement is seen. The $\pi^0$ decay peak is also visible. The presented error bars are rescaled and correspond to the statistics expected in the experiment, and not to the actual low statistics used in the simulation.

The expression $Q_L^2 = -(p_1^\mu - p_2^\mu)(p_1^\nu - p_2^\nu)$, where $p_1$ and $p_2$ are the four-momenta of the two photons. The contributions shown in Fig. 2 are by early and late photon pairs, while the presented total contribution contains also the mixed early-late photon pairs. The interesting early direct photon component is negligibly small compared to the rest, and in this situation there is no chance to observe the early photons' correlations. The natural way to proceed is therefore to “enhance” the early direct component by applying a high transverse momentum cut, as suggested by Fig. 1. Fig. 3 shows that already a cut at 1 GeV indeed leads to a significant improvement. In the example presented below we applied a yet “stronger” cut, at 2 GeV.

Two-photon HBT correlations have been simulated with the longitudinal effective length of 0.3 fm, which corresponds to the early appearance of the hypothetical high effective temperature parton gas. The transverse r.m.s. effective radius was set to 3 fm, which corresponds to the r.m.s. transverse size of the colliding Pb nuclei.

Gaussian shape has been assumed for the correlation function in all three dimensions, with an intercept of 1.5 (taking into account that photons are bosons of spin 1). In the results presented we have used an ideal uncorrelated background.

Fig. 4 shows the 3-dimensional correlation function projected onto the $Q_L$.
axis, with a cut $Q_S < 0.1$GeV and $Q_O < 0.1$GeV (to reduce ”dilution” of the correlation effect). A transverse momentum cut at 2 GeV has been applied. Only 300,000 events have been generated for this analysis, but the error bars presented in Fig. 3 are rescaled to correspond approximately to the expected full statistics of $10^7$ events! The expected wide HBT correlation in $Q_L$ due to early photons is indeed seen. In this measurement scheme the correlation intensity at large $Q_L$ is the measure of the yield of the early photon component. The correlation at large $Q_L$ is missing when the early emission time is replaced by a late one (6 fm/c) in the simulation, as shown in Fig. 3, dashed line.

Summary

A method is proposed to test the existence of rapidly developing parton cascades in ultrarelativistic nuclear collisions at RHIC and LHC. An early onset of parton cascades in the collision process should be reflected in abundant emission of photons which are mutually HBT correlated over a wide longitudinal momentum scale. This method provides the necessary selectivity for the early emitted photons, since the late photons correlate only over narrower longitudinal momentum scales. Based on a rather simple approach, our study indicates that such a measurement could be feasible in the ALICE experiment at LHC. The next step is to replace our simplistic assumptions by input from different detailed models.

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