Interferometry of direct photons in $^{208}$Pb+$^{208}$Pb collisions at 158 AGeV

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Abstract. We present final results from the WA98 experiment which provide first measurements of Bose-Einstein correlations of direct photons in ultrarelativistic heavy ion collisions. Invariant interferometric radii were extracted in the range $100 < K_T < 300$ MeV/c and compared to interferometric radii of charged pions. The yield of direct photons for $100 < p_T < 300$ MeV/c was extracted from the correlation strength parameter and compared to the yield of direct photons measured in WA98 at higher $p_T$ with the statistical subtraction method, and to predictions of a fireball model.

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Hanbury Brown-Twiss (HBT) interferometry provides a powerful tool to explore the space-time dimensions of the emitting source created in elementary particle or heavy ion collisions. Historically, such measurements have concentrated on pion pair correlations, but have also been applied to kaons, protons, and even heavy fragments [1]. Hadron correlations reflect the space-time extent of the emitting source at the time of freeze-out. Photon interferometry has several important differences with respect to hadron interferometry. First, photons having extremely large mean free path length provide the possibility to measure directly the size of the innermost hottest zone of the collision [2]. Second, photons emitted at different stages of the collision dominate different regions of transverse momentum, so, extracting correlation parameters in different regions of average transverse momentum of the photon pair, one can measure the space-time dimensions of different stages of the collision. Here we present first measurements of photon HBT correlations in ultrarelativistic heavy ion collisions.

A detailed description of the layout of the CERN experiment WA98 can be found in [3]. Here we briefly discuss those subsystems used in the present analysis. The WA98 photon spectrometer, comprising the LEad-glass photon Detector Array (LEDA), was located at a distance of 21.5 m downstream from the $^{208}$Pb target and provided partial azimuthal coverage over the rapidity interval $2.35 < y < 2.95$. Further downstream, the total transverse energy was measured in the MIRAC calorimeter. The total transverse energy measured in MIRAC was used for offline centrality selection. The analysis presented here was performed on the 10% most central $^{208}$Pb+$^{208}$Pb collisions at 158 AGeV with a total sample of $5.8 \times 10^6$ events collected during runs in 1995 and 1996. Similar analysis was performed on the 20% most peripheral collision data sample of $3.9 \times 10^6$ events but the statistical errors were at least an order of magnitude larger than the expected signal.

† See [3] for the appropriate WA98 collaboration author list.
Examples of the two-photon correlation functions, extracted for the 10 % most central events are presented in figure 1. The small yield of direct photons and enormous background from decays of final hadrons, mainly $\pi^0$, result in strength for the two-photon correlations on the level of a tenth of a percent. Measurement of such correlations requires a good understanding of the detector response and of possible backgrounds. Possible sources of distortion of two-photon correlation function are: 1) Interference of nearby clusters in LEDA, erroneous splitting or merging of some clusters by the reconstruction program; 2) Hadron misidentification; 3) Photon conversion in front of LEDA; 4) Photon background correlations, i.e. remnants of correlations of parent hadrons: HBT correlations of parent $\pi^0$, elliptic flow, decays of resonances.

To estimate the contribution of apparatus effects we constructed a set of two-photon correlation functions, calculated with different cuts on the minimal distance between clusters in LEDA. Then, we fitted each varying the lower boundary of the fitting range and compare the extracted correlation parameters. We find that for distances between clusters larger than some minimal distance $L_{12}^{\text{min}} \approx 20$ cm, depending on purity of the photon spectrum, and/or for relative momenta larger than some minimal relative momentum, also depending on the purity of the photon spectrum, there is no dependence of the fit result on the minimal distance cut or on the minimal relative momentum. That is, correlations in this region are free from apparatus effects.

Contamination of the photon spectrum by charged particles and neutral hadrons also can distort the photon correlation function. Although hadrons deposit only a fraction of their energy, one might still observe remnants of, e.g. their Bose-Einstein correlations. Similarly, electron-positron pairs, from conversion of photons between target and LEDA could also produce enhancement at small relative momenta. To estimate contribution of these effects we compared correlation parameters, evaluated from correlation functions obtained with different identification criteria and corrected for contamination of photon spectrum. The contamination of charged particles varied with identification criteria from 1 % in "neutral" and "narrow neutral" to 16 % in
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Figure 2. Left plot: Comparison of the fit parameters, corrected for efficiency and contamination, obtained for different identification criteria: △ - "all", ▼ - "narrow", □ - "neutral", ◦ - "narrow neutral" (no significant result for high $K_T$).
Right plot: Simulated background photon correlations: ⋄ - $\pi^0$ HBT correlations, △ elliptic flow, ● - kinematic correlations (c.f. shifted vertically for clarity).

"narrow" and 37% in "all" conditions. Similarly, the contamination of neutral hadrons into the photon spectrum decreases from 5% ("all", "neutral") to 1% ("narrow", "neutral narrow") when a cut is imposed on the width of the shower. Despite the strong variation of the contamination, the corrected correlation strengths, calculated for different identification criteria coincide, see figure 2.

Background correlations, i.e. correlations between products of decays of correlated hadrons, could result in enhancement at small relative momenta. The dominant part of decay photons comes from $\pi^0$ decays. We considered the following correlations: Bose-Einstein $\pi^0$ correlations, elliptic flow, and correlations due to decays of heavier resonances. To estimate value of all these correlations, we performed Monte-Carlo simulations. In all cases we used realistic rapidity and $p_t$ distributions, we take into account acceptance and energy and position resolutions of the LEDA. We used Bose-Einstein correlation parameters of $\pi^\pm$ as well as flow parameters of charged pions. In the case of Bose-Einstein correlations we obtain step-like correlations with small slope at small relative momenta, in accordance with analytical calculations. Similarly, elliptic flow results in the appearance of the even smaller slope at small relative momenta. As for kinematic correlations, they are completely negligible in this analysis. We find that all observed correlations result in appearance of small slope at small relative momenta. Calculating final values of parameters of two-photon correlations we account for this slope.

As far as photons are massless particles, their invariant correlation parameters have considerably different meaning than those of hadron ones. One can express the correlation function on invariant relative momentum as an integral over directions of relative momenta in the center-of-mass frame of the pair:

$$
C_2(Q_{inv}) = 1 + \frac{4}{4\pi} \int \! d\Omega \exp \left\{ - (Q_{inv}^2 + 4K_T^2)R_s \cos^2 \theta \right\}
$$

$$
- Q_{inv}^2 (R_s^2 \sin^2 \theta \sin^2 \phi + R_l^2 \sin^2 \theta \cos^2 \phi) ,
$$

(1)
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![Figure 3](image.png)

Figure 3. Left plot: Comparison of photon invariant correlation radius ($\bullet$) with charged pion correlation radii $R_{long}$ (▲) and $R_{side}$ (■) [4]. Right plot: Direct photon yield, obtained with two methods and theoretical predictions [5].

Note that in this formula both correlation radii and projections of relative momenta are taken in the local co-mover system. We find that for massless particles the invariant correlation radius is an average over long and side correlation radii and that the invariant correlation strength decreases with respect to the true correlation strength with increasing average transverse momentum. Therefore, we should compare the photon invariant radius to hadron long and side correlation radii, see figure 3. We find that the direct photon correlation radius is consistent with pion correlation radius.

Having the invariant correlation strength parameter, we extract the direct photon yield. As we have seen in [1], the invariant correlation strength decreases with respect to the true correlation strength with increase of $R_{out} \cdot K_T$. We have not extracted the $R_{out}$ correlation radius, so we can only find a lower limit on the direct photon yield, by assuming $R_{out} = 0$ and in addition - a probable direct photon yield, corresponding to $R_{out} = 6$ fm. We compare our result with the result obtained earlier with the subtraction method and with theoretical predictions, see figure 3. We find that results obtained with the correlation method are considerably above theoretical predictions.

To conclude, the two-photon correlation function was measured for the first time in ultrarelativistic heavy ion collisions. The invariant correlation radius was measured at $100 < K_T < 300$ MeV/c. The photon correlation radius is very similar to those of charged pions. From the correlation strength parameter the lower limit on the direct photon yield was extracted. Even lower limit appears to be considerably larger than theoretical predictions.

[1] See e.g. these proceedings.
[2] D.K. Srivastava and J.I. Kapusta, Phys. Lett. B 307 (1993) 1; Phys. Rev. C 48 (1993) 1335; Phys. Rev. C 50 (1994) 505. A. Timmermann, M. Plumer, L. Razumov and R.M. Weiner, Phys.Rev. C 50 (1994) 3060. D. Peressounko, Phys. Rev. C 67 (2003) 014905.
[3] M.M. Aggarwal et al., Phys. Rev. Lett. 85 (2000) 3595; M.M. Aggarwal et al., nucl-ex/0006007.
[4] M.M. Aggarwal et al., Phys. Rev. C 67 (2003) 014906.
[5] S. Turbide, R. Rapp, and C. Gale, hep-ph/0308085.