TWO-PHOTON INTERFEROMETRY IN Ta+Au COLLISIONS AT $40A$ MeV*

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(Received November 14, 2005)

The space-time dimensions of the Ta+Au collision zone at $40A$ MeV energy are investigated using the HBT interferometry technique of $\gamma\gamma$ pairs. The bremsstrahlung photon energy spectrum exhibits 2 exponential contributions, described by the inverse slopes 13.0 ± 0.2 MeV and 5.1 ± 0.3 MeV, and the ratio of integrated intensities 2.2 ± 0.3. The correlation function, investigated inclusively and for peripheral reactions, reveals no HBT signal. For central collisions there is a strong indication for such signal, best described by the invariant radius 10.3 ± 2.7 fm within the model of the Gaussian space-time distribution of the photon emission source. The appearance of the HBT signal for central collisions only can be explained within simple models of photon emission in two stages of reaction.

PACS numbers: 25.70.–z

1. Motivation

During the first stage of a nucleus–nucleus (AA) collision, in the overlap zone the nuclear matter is compressed and acquires energy transferred from the relative AA motion. Part of the energy can be used for the production of new particles: photons and mesons. The AA collision in the intermediate beam energy region cannot be properly described either by the mean field approaches, or by participant–spectator models. Although rough estimates about the spatial extent and duration of first stages of the nuclear collision can be made (few fm and 10^{-22} s), the HBT intensity interferometry remains up-to-now the only method of experimental determination of these dimensions. In this work the mentioned approach for $\gamma\gamma$ correlations is employed for collisions of $40A$ MeV beam energy Ta projectile on Au target.

* Presented at the XXIX Mazurian Lakes Conference on Physics August 30–September 6, 2005, Piaski, Poland.

2. Basic of HBT interferometry

For the brief introduction to the HBT interferometry technique [1], let us consider 2 indistinguishable particles emitted from a quantum source (*i.e.* such that the distance between the emission points Δx is smaller then $\hbar/\Delta p$, where Δp is the difference between the momenta of particles [2]). If they are registered by 2 detectors, a given trajectory cannot be assigned to a given particle. Thus the 2-particle wave function of bosons (fermions) has to be (anti)symmetrized, which results in preferring more similar (different) momenta by boson (fermion) pairs. As a result, their momenta are correlated. The degree of correlation can be measured by the correlation function:

$$C(k_1, k_2) = \frac{P(k_1, k_2)}{P(k_1)P(k_2)}\,, \tag{1}$$

where $k_{1,2}$ are four-momenta of particles, $P(k_1, k_2)$ is the probability of detection of particles in coincidence, and $P(k_{1,2})$ are corresponding probabilities for each particle separately. For uncorrelated particles, the correlation function should be equal to 1.

The correlation function keeps the information about the space-time distribution of the source of particles [3]. For bosons,

$$C(\Delta k) \approx 1 + \lambda \cdot |\hat{\rho}(\Delta k)|^2\,, \tag{2}$$

where $\hat{\rho}(\Delta k)$ is the Fourier Transform of the source distribution $\rho(x)$, and $\Delta k = k_1 - k_2$. The parameter $\lambda \in [0, 1]$ has to be introduced to account for possible suppression of the correlation signal due to coherence between emitted particles, their emission dynamics and spins (see [4] for general considerations and [5, 6] for photon pairs).

The limited statistics of the experimental data forces to use a simplified parametrization of the source: the 3-dimensional Gaussian function with equal radii R describing the spatial dimensions and the Gaussian evolution in time (described by the dispersion τ). Assuming the shape above, fitting the Eq. (2) to the experimentally measured correlation function allows in principle to extract values of R and τ. However, final state interactions of emitted hadrons can smear out the original correlation signal [4]. This problem is not present for photon pairs. Among all the γ radiation produced in the AA collision, bremsstrahlung photons are emitted only during its first phases, thus the interferometry analysis of $\gamma\gamma$ pairs should shed light on the size and duration of the hot collision zone.

High energy photon pairs can be also produced from $\pi^0 \to \gamma\gamma$ decay (BR=98.9%). However, for the correlation function investigated as a function of the invariant mass M_{INV}, these events are concentrated around M_{π^0}, leaving the rest of M_{INV} region free from this background. The correlation function is then defined as the ratio of the experimentally measured $M_{\rm INV}$ distribution over $M_{\rm INV}$ spectrum that would be measured if HBT correlations were switched off. The latter distribution, inaccessible in nature, can be obtained employing the event mixing technique (constructing pairs from photons in different events). In this way the $M_{\rm INV}$ spectrum is constructed of physical photons, but not correlated in pairs. Projecting the correlation function to $M_{\rm INV}$ reduces the number of free parameters to 1. For the source described in space and time by the 4D Gaussian distribution, the $C(M_{\rm INV})$ is shown to have also the nearly Gaussian shape [3], and its dispersion, named the invariant radius ($R_{\rm INV}$), has the meaning of the combined space-time extent of the source.

3. Experiment

During the experiment carried out in GANIL (Caen) ^{181}Ta+^{197}Au reactions at 39.5A MeV beam energy were studied. The apparatus consisted of TAPS spectrometer [7], arranged in 6 rectangular blocks of 64 hexagonal modules, and the KVI Forward Wall (FW) [8, 9] composed of 92 phoswich ΔE–E detectors. TAPS blocks were positioned in a horizontal plane, symmetrically with respect to the beam axis, covering $\sim 20\%$ of the full solid angle. Each TAPS module is composed of 25 cm long BaF_2 scintillator and equipped with the thin Charged Particle Veto (CPV) plastic scintillator at its front. Photon pairs were detected by TAPS, while FW was measuring the multiplicity of light charged fragments ($Z \lesssim 9$) produced during the AA collision. The probability of registering a pair of photons from different reactions is estimated to be 1.5%.

The scintillation light from a BaF_2 crystal has 2 components of relative intensity depending on the type of incident particle. This feature, together with the time-of-flight and the information about particle's charge from CPV, allows for a nearly unambiguous identification of photons. The energetic photon hitting TAPS produces the electromagnetic shower, which can spread out into adjacent modules, creating a cluster. The off-line procedures perform the cluster recognition. Mixed clusters (*i.e.* ones having some fraction of non-photonic type) are also accepted, but the reconstruction of γ in such case is based only on the photonic part of a cluster [10]. Cosmic particles that are misidentified as photons are filtered out on an event-by-event base, using algorithms analyzing cluster's topology (see [10–12] for details), which leaves this contamination at the level of 0.7% of the $\gamma\gamma$ sample.

4. Analysis and discussion

The photon energy spectrum in the nucleus–nucleus (NN) frame, E_γ^{NN}, clearly exhibits two exponential contributions, which points to the existence of two sources of photon production, a direct and a thermal one [13].

Fitting the sum of two exponential functions allows for the extraction of the inverse slope coefficients of these contributions, $E^0_{\rm d} = 13.0\pm\ 0.2\,{\rm MeV}$ and $E^0_{\rm t} = 5.1\pm 0.3\,{\rm MeV}$, respectively, and their integrated intensity ratio $I_{\rm d}/I_{\rm t} = 2.2\pm 0.3$. The existence of two stages of photon emission is supported by the results of the simulations within BUU [13] and QMD [14] models.

The invariant mass plot of coincident $\gamma\gamma$ pairs (Fig. 1) shows a clear separation between bremsstrahlung photon pairs and neutral pions. The $M_{\rm INV}$ spectrum of uncorrelated photon pairs was constructed using the event mixing technique (see dashed line on a plot). Both above spectra are divided in order to obtain the experimental correlation function, shown on Fig. 2. The large signal for $M_{\rm INV} > 100\,{\rm MeV}$ originates from neutral pions. At this stage the correlation function is not normalized, due to different integrals of its components. The normalization is done in each considered scenario separately by introducing the multiplicative coefficient to the correlation function.

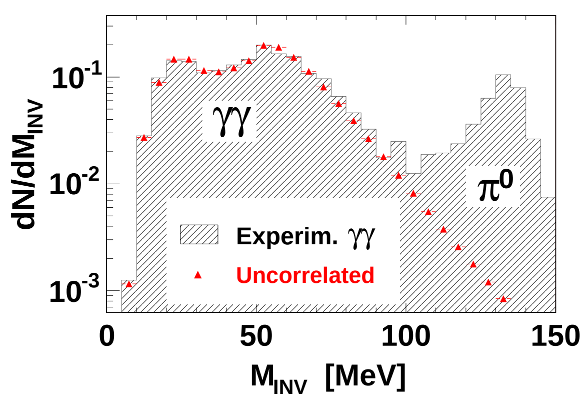

Fig. 1. Invariant mass spectrum of experimental (dashed histogram) and uncorrelated (triangles) $\gamma\gamma$ pairs.

As illustrated in the inset of the Fig. 2, for $M_{\rm INV} < 80\,{\rm MeV}$ the correlation appears to be flat. Hence, the first considered scenario is the lack of the HBT signal, thus the model function $C(M_{\rm INV}) = N\times 1$ (where N is the normalization coefficient) was fitted, yielding $\chi^2/\nu = 1.0$. No strict conclusions are drawn here, since all collision centrality classes contribute to the analyzed function. In the inset, $C(M_{\rm INV})$ obtained in [15] for the same system, is also plotted, for which, however, fluctuations are much larger due to 8× smaller statistics compared to the data analyzed in this work. The hypothesis of the oscillatory profile of $C(M_{\rm INV})$ [3], inspired by these data, does not find confirmation in the function obtained at present.

The model of the 4D Gaussian source was applied to verify, which values of $R_{\rm INV}$ and λ parameters can be rejected by the obtained $C(M_{\rm INV})$.

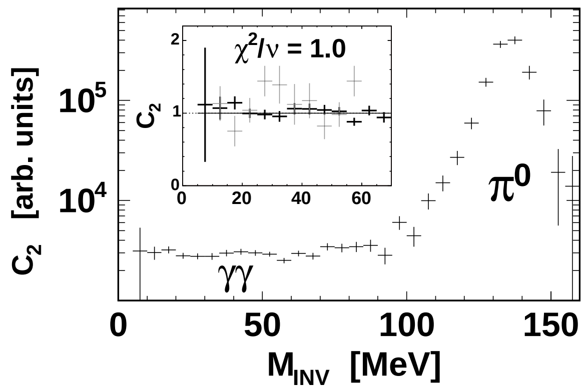

Fig. 2. Inclusive, not normalized correlation function (main window). In the inset, $C(M_{\rm INV}) = 1$ was fitted. The experimental $C(M_{\rm INV})$ obtained in [15] are shown in light grey.

The results are shown in Fig. 3. Assuming the incoherent bremsstrahlung radiation, the λ parameter should stay within [0.5, 1], value depending on the angular distribution characteristics of emitted photons [5, 6]. Within these bounds, regions symbolized on the figure by A and B cannot be rejected by the present data. The existence of the region B corresponds to wide profiles of model $C(M_{\rm INV})$ distributions for low $R_{\rm INV}$, for which the normalization coefficient cannot be properly obtained.

The commonly accepted effect of the anti-correlation between the impact parameter and the mean multiplicity of charged particles emitted during the reaction and detected by FW, allows for studying the $C(M_{\rm INV})$ for different collision centrality classes. No HBT signal was found for peripheral collisions. For the class of central collisions (multiplicity in FW, MUL>7) the

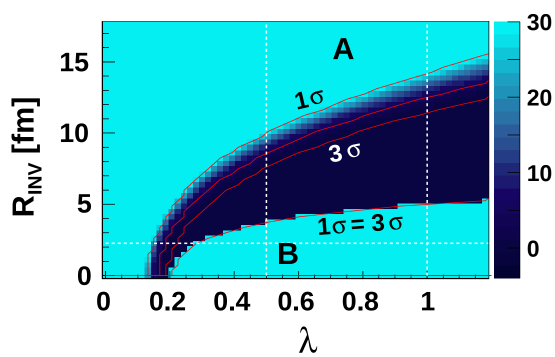

Fig. 3. Probability of agreement between experimental and model (4D Gaussian source) correlation function for different values of $R_{\rm INV}$ and λ.

$C(M_{\rm INV})$ profile probably exhibits the excess for $M_{\rm INV} < 25$ MeV (see Fig. 4), however, the limited statistics available for this class does not allow to confirm its appearance basing on the 3σ criterion. Fitting the model correlation function of the Gaussian source yields $M_{\rm INV} = 10.3 \pm 2.7$ fm (see Table I). For MUL $\in [7,9]$, the resultant value of χ^2/ν indicates that the considered model describes the obtained $C(M_{\rm INV})$ much better than the scenario of lack of the HBT signal.

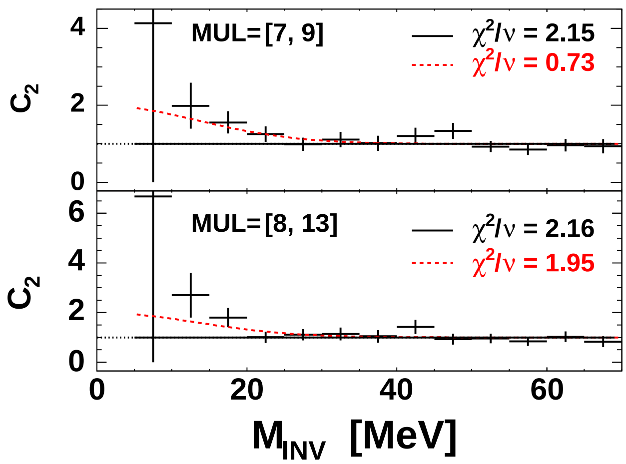

Fig. 4. Correlation function for the central collision class. Model functions for no HBT signal (solid) and Gaussian one (dashed) hypotheses are fitted.

TABLE I

Values of χ^2/ν for two hypotheses of $C(M_{\rm INV})$ profile. For HBT signal hypothesis, $R_{\rm INV}$ values are extracted from fitting Eq. (2).

	$C(M_{\rm INV}) = 1$	Gaussian source	
MUL	χ^2/ν	$R_{\rm INV}$ $[fm]$	χ^2/ν
[7,9]	2.2	10.3±2.3	0.7
[8,13]	2.2	10.3±3.0	2.0

Strong indications for the hypothesis of 2 stages of photon emission, supported by the existence of two components of the energy distribution, suggest that the model of the space-time distribution of the photon source should be more complex. For the nearly symmetric Ta+Au system, two simplest models can be considered [16]: *(i)* two Gaussian sources of identical size and duration, separated in time, and *(ii)* the primordial source followed, after time ΔT, by two identical sources, separated in space by ΔR, and identified as projectile-like and target-like fragments. The statistics accumulated in this experiment is insufficient to make quantitative statements on the size of the collision zone, basing on these models. However, lack of the HBT signal for peripheral collisions and its appearance for central ones can be explained on their grounds. The analysis is in progress.

The experiment was carried out at GANIL, Caen by the TAPS Collaboration (L. Aphecetche, H. Delagrange, J. Díaz, D.G. d'Enterria, F. Fernández, H. Löhner, A. Kugler, G. Martínez, T. Matulewicz, R.W. Ostendorf, Y. Schutz, R. Turrisi, V. Wagner H.W. Wilschut). This research is supported in part by the Polish State Committee for Scientific Research (KBN) under grant 2P03B 102 25.

REFERENCES

[1] R. Hanbury-Brown, R.Q. Twiss, *Philos. Mag.* **45**, 663 (1954).
[2] G. Cocconi, *Phys. Lett.* **B49**, 459 (1974).
[3] F.M. Marqués *et al., Phys. Rep.* **284**, 91 (1997).
[4] M. Gyulassy, S. Kaufmann, L.W. Wilson, *Phys. Rev.* **C20**, 2267 (1979).
[5] D. Neuhauser, *Phys. Lett.* **B182**, 289 (1986).
[6] L.V. Razumov, R.M. Weiner, *Phys. Lett.* **B319**, 431 (1993).
[7] H. Ströher, *Nucl. Phys. News* **6**, 7 (1996).
[8] H. Leegte *et al., Nucl. Instrum. Methods* **A313**, 26 (1992).
[9] M. Hoefman *et al.*, KVI Annual Report 1994, p. 53.
[10] K. Piasecki, Ph. D. Thesis, Warsaw University 2005, (unpublished).
[11] F.M. Marqués *et al., Nucl. Instrum. Methods* **A365**, 392 (1995).
[12] G. Martínez *et al., Nucl. Instrum. Methods* **A391**, 435 (1997).
[13] G. Martínez *et al., Phys. Lett.* **B349**, 23 (1995).
[14] R.W. Ostendorf *et al.*, proposal to this experiment.
[15] F.M. Marqués *et al., Phys. Lett.* **B349**, 30 (1995).
[16] F.M. Marqués *et al., Phys. Lett.* **B394**, 37 (1997).