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TWO-PHOTON INTERFERENCE IN MICRO- AND MACRO-SYSTEMS*

F.M. Marqués

Laboratoire de Physique Corpusculaire
ISMRA — 14050 Caen cedex, France
e-mail: marques@caelav.in2p3.fr

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Two-photon correlations are discussed within the formalism of Hanbury–Brown and Twiss interferometry and Bose–Einstein correlations. The technique is presented as a universal tool to study the properties of any boson source — light sources such as stars, or photon and meson sources in the early phase of heavy-ion collisions. The method is illustrated using experimental data on photon-pair production in nuclear reactions, available only in the intermediate (several tens of MeV/N) energy domain. The observed interference signal is interpreted in terms of source size and reaction dynamics.

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1. Introduction

A major part of the heavy-ion research programme in modern nuclear physics is devoted to the determination of the equation of state [1] describing the macroscopic features of nuclear matter. Colliding heavy-ions provide the only means known so far to form hot and dense nuclear matter allowing to explore its properties and phase transitions in the laboratory. A major experimental difficulty in heavy-ion collision studies arises from the fact that the phase diagram of nuclear matter can only be explored dynamically. Therefore, information on properties of nuclear matter extracted from any probe will be modified by their production and propagation dynamics.

However, energetic photons are produced during a brief instant when compared to the reaction time and, due to the absence of final-state interactions, provide an undistorted snapshot of the stage of the collision when the

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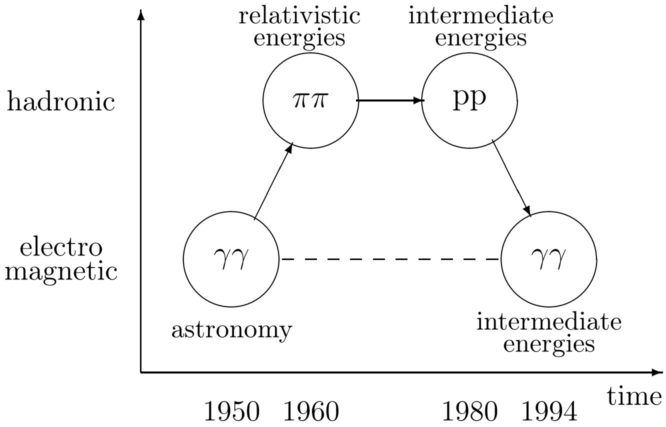

Fig. 1. Schematic view of correlations studied with hadronic or electromagnetic probes in astronomy and nuclear physics (at intermediate and relativistic energies).

highest densities and temperatures are reached. The space-time structure of this stage when photons are produced can be directly determined applying the well-known two-particle interferometry technique [2].

2. Photons from stars

Studies of two-particle correlations originated in the early 50s, when the astronomers Hanbury-Brown and Twiss proposed a new technique [3], intensity interferometry (also known as HBT), to measure the angular size of stars. The previous stellar interferometers, of Michelson type (Fig. 2(a)), were based in the principle of amplitude interferometry, first evidenced in the Young two-slit experiment.

The HBT interferometer is sketched in Fig. 2(b). The correlation function is defined as:

$$C_2(L) \;=\; \frac{I_{AB}}{I_A I_B} \;=\; 1 + |\varrho(k\alpha L)|^2\,, \tag{1}$$

where the interference term represents the Fourier transform of the spatial distribution $\rho(r)$ of the star. Therefore, for a given photon energy k, the measurement of the correlation for several values of the baseline L provided the size α of the star, independently of the phase fluctuations induced by turbulences in the atmosphere or the cables connecting the detectors to the correlator [3].

With the application of the technique to astronomy, the notion of discrete slits used in optics was lost and replaced by a single spatial distribution.

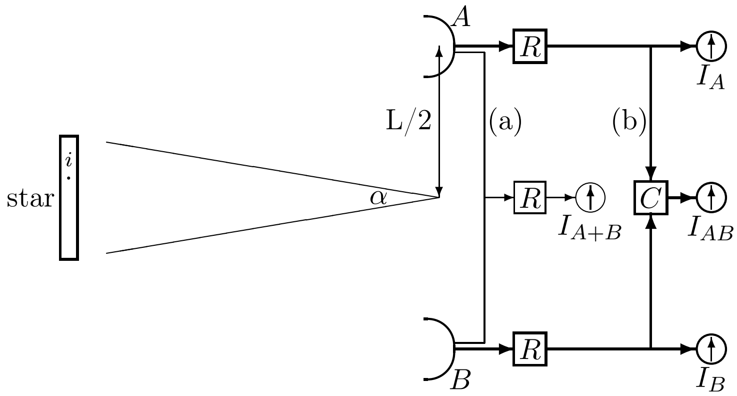

Fig. 2. Schematic view of the measurement of the angular size α of a star with: a Michelson type interferometer (thin lines, a); and an intensity interferometer (thick lines, b). They basically differ by how the signals from the two aerials are handled [4].

However, Hanbury-Brown revived the two-slit aspect of the problem when analysing multiple stars. Considering the simplest case of a binary star, the correlation pattern of each single component is modulated by a cosine, which represents the Fourier transform of two slits [4]. Indeed these objects can be seen as a two-slit experiment in optics (with a size scale extended about 10 orders of magnitude!) where each of the slits is "replaced" by a star.

3. Photons from heavy-ion collisions

In analogy with astronomy, where the small angular size of celestial objects is measured, calorimeters used as intensity interferometers can measure subatomic objects[1] in nuclear reactions of the type:

$$A_1 + A_2 \;\rightarrow\; \{\text{intermediate state}\} \;\rightarrow\; \gamma\gamma + \cdots\,, \tag{2}$$

where the two photons are emitted from an intermediate state which we identify with the source. In this case, the correlation function is defined as the ratio of coincidence and single probabilities:

$$C_2(q) \;=\; \frac{P(k_1,k_2)}{P(k_1)P(k_2)} \;=\; 1 + |\varrho(q)|^2 \tag{3}$$

[1] The angular size of a nucleus "viewed" from a calorimeter is even smaller (about six orders of magnitude) than the one of studied stars viewed from Earth.

which is similar to Eq. (1), but now the Fourier transform corresponds to the collision zone and depends on the four-product of the relative momentum between photons and the space-time extent of the source. For a Gaussian or a uniform source, the interference term presents a Gaussian-like shape [4].

Although Eq. (3) can be applied to any boson pair [2], for hadronic bosons the HBT effect in the correlation function is distorted (or even masked) by final-state interactions and/or the presence of resonances. However, at energies above 100 MeV/N the two-photon spectrum is dominated by the decay of the neutral pion, and below this energy the production cross-section is extremely low ($\sigma_{\gamma\gamma} \sim \mu$b). This explains why only recently the HBT effect between photons was measured in nuclear physics [5], with the advent of the TAPS spectrometer [6]. At intermediate energies (several tens of MeV/N), energetic photons originate from the incoherent superposition of the bremsstrahlung produced mainly in first-chance individual proton-neutron collisions. Since their source can be identified with the participant zone at an early stage of the heavy-ion collision, the HBT technique will access the properties of hot and dense nuclear matter in a well defined phase [4].

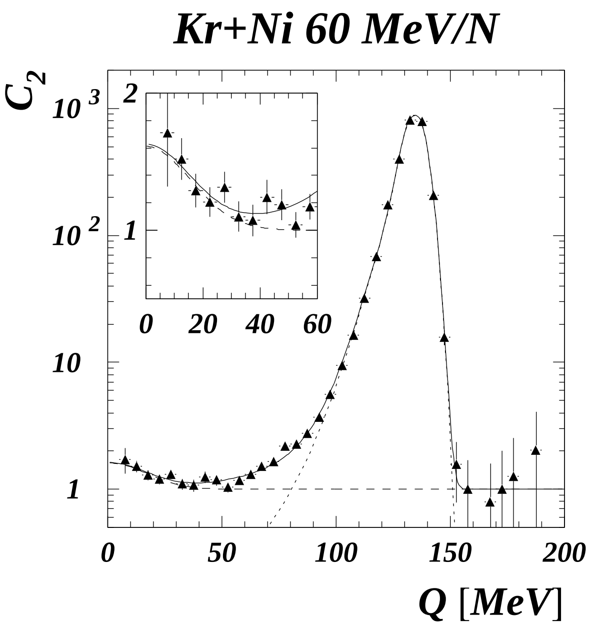

Fig. 3. Experimental two-photon correlation function [5]. The solid line represents the fit to Eq. (4), decomposed in the first two terms (dashed line) and the third term (dotted line) describing the π^0 contribution.

Two series of experiments were undertaken with the photon spectrometer TAPS at the GANIL facility in Caen (France). The second round provided an improved set of data allowing to observe for the first time the HBT effect between nuclear photons [5]. Experimentally, we chose to project [4] the correlation function onto the Lorentz-invariant relative four-momentum $Q = \sqrt{\mathbf{q}^2 - q_0^2}$, which for photons corresponds to the invariant mass. The experimental correlation function of the system ^{86}Kr+$^{\rm nat}$Ni at 60 MeV/N (Fig. 3) presents two structures deviating from 1: the asymmetric peak between 70 and 150 MeV, which is entirely due to the π^0 contribution; and the rise from 40 MeV towards zero Q, which corresponds to the interference effect between bremsstrahlung photons [5].

The spectrum was fitted to:

$$C_2(Q) \ = \ 1 + \lambda \exp(-Q^2 R_Q^2) + f_{\pi^0}(Q - m_{\pi^0}) \tag{4}$$

with the normalization procedure described in Ref. [4]. The radius R_Q is at first order a measure of the spatial extent R of the source [4]. However, despite the observation of the interference signal, the source size extracted from Eq. (4) was $R = 8.6 \pm 2.2$ fm, larger than the whole di-nuclear system. In a second experiment with a heavier system, ^{181}Ta+^{197}Au at 40 MeV/N (right panel in Fig. 4), no significant rise towards low Q values was observed.

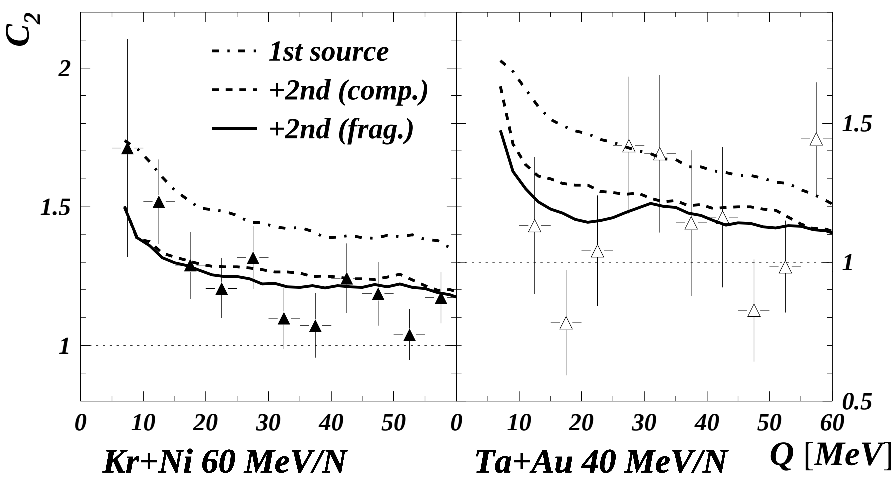

Fig. 4. Results of Monte-Carlo calculations for the two-photon correlation function [4].

4. Beyond a source size

Studying in detail predictions of dynamical phase-space calculations on bremsstrahlung-photon dynamics [7], one finds that their source is more complex than the usually adopted picture. At intermediate bombarding energies, heavy-ion collisions may lead to a density oscillation around the saturation density of the di-nuclear system. In such a scenario, bremsstrahlung photons originate from two sources distinct in space and time. In the initial stage, *direct* bremsstrahlung-photons originate from a dense source during the first compression phase and constitute the dominant contribution. In a later stage, *thermal* bremsstrahlung-photons are emitted from a thermalised source during the following compression phases.

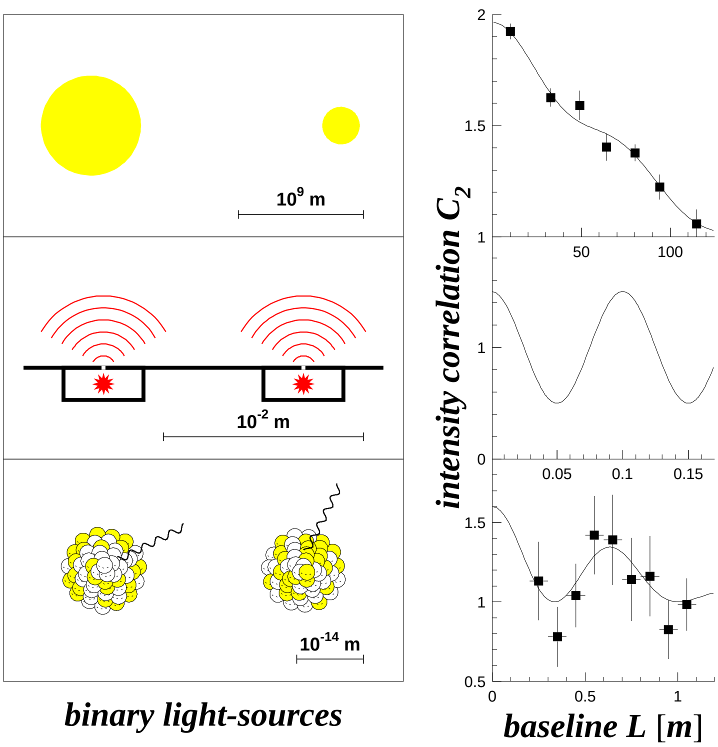

Fig. 5. Schematic representation of the observation of binary light-sources with intensity interferometers in astronomy, optics and nuclear physics, respectively.

As it was the case for binary stars, the existence of a composite source modulates the Gaussian-like correlation function of each single source by a cosine [8], explaining the loss of correlation measured and leading to source sizes in good agreement with the reaction zone. This interpretation confirms the existence of the HBT correlation between independent nuclear photons and probes the density oscillation of the di-nuclear system at intermediate bombarding energies.

We further analysed the sensitivity of the correlation function to the reaction mechanism with the help of Monte-Carlo simulations [9]. We found that, because of photon kinematics, only a simultaneous emission from two nuclear fragments can be responsible of the modulation observed for the heavier system. If the recompression of the system takes place when it has already fragmented, the two-slit pattern issued from the thermal emission of the binary system modulates the correlation function and provides the best description of the experimental data for both reactions. Curiously, the modulation generated by the simultaneous emission from two nuclear fragments reminds of the interference pattern resulting from a two-slit experiment or the observation of binary stars (Fig. 5).

5. Summary and future

Two-photon correlation measurements are by now a well established technique since over 40 years. Its formalism was grounded by two astronomers in search of a novel instrument able to improve the resolution of stellar objects with respect to the Michelson interferometer. Similar considerations led in the 60s to intensity interference between bosons in nuclear physics as a measure of the space-time extent of the nuclear reaction zone. However, the information on the nuclear source conveyed by the HBT technique was distorted by final-state interactions of the hadronic bosons with themselves and with the surrounding medium.

Only in the 90s intensity interference could be extended to nuclear photons, with the advent of the photon spectrometer TAPS. These results have unambiguously demonstrated the existence of the interference between bremsstrahlung photons. Moreover, the interpretation of the source parameters extracted revealed a source distribution more complex than the expected overlap zone between the colliding nuclei. It was found that photons are emitted as brief light flashes, and that the correlation function is sensitive not only to the source size but also to the rection mechanism.

At intermediate energies, improved sets of data will be soon provided by new experiments. At ultrarelativistic energies progress is underway and the two-photon correlation technique will be used to reveal the phase transition towards the quark-gluon plasma.

A major part of the experimental work used to illustrate this technique is the result of a common effort of the TAPS collaboration (GANIL-GSI-KVI-Gießen-IFIC).

REFERENCES

[1] H. Stöcker, W. Greiner, *Phys. Rep.* **137**, 277 (1986); G.F. Bertsch, S. Das Gupta, *Phys. Rep.* **160**, 189 (1988).

[2] B. Lörstad, *Int. J. Mod. Phys.* **A4**, 2861 (1989); D.H. Boal, C.K. Gelbke, B.K. Jennings, *Rev. Mod. Phys.* **62**, 553 (1990).

[3] R. Hanbury-Brown, R.Q. Twiss, *Philos. Mag.* **45**, 663 (1954); R. Hanbury-Brown, *The intensity Interferometer*, Taylor & Francis Ltd, London 1974.

[4] F.M. Marqués, G. Martínez, T. Matulewicz, R.W. Ostendorf, Y. Schutz, *Phys. Rep.* **284**, 91 (1997).

[5] F.M. Marqués *et al.*, *Phys. Rev. Lett.* **73**, 34 (1994).

[6] R. Novotny, *IEEE Trans. Nucl. Sci.* **38**, 379 (1991).

[7] G. Martínez *et al.*, *Phys. Lett.* **B349**, 23 (1995).

[8] F.M. Marqués *et al.*, *Phys. Lett.* **B349**, 30 (1995).

[9] F.M. Marqués *et al.*, *Phys. Rev.* **C54**, 2783 (1996); F.M. Marqués *et al.*, *Phys. Lett.* **B394**, 37 (1997).