Two Slit Interference of Bremsstrahlung Photons from Heavy-ion Reactions

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Two-slit interference of bremsstrahlung photons from heavy-ion reactions

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Abstract

The detailed structure of the hard-photon source created in intermediate-energy heavy-ion reactions is deduced from the analysis of intensity interference measurements. In analogy with the pattern observed in two-slit experiments at visible wavelengths and the correlation function measured for binary stars in astronomy, we find that the data favour the scenario where two nuclear fragments radiate simultaneously during the recompression of the system.

The technique of intensity interferometry has been extensively applied [1–3] to boson pairs produced in heavy-ion reactions over a wide range of bombarding energies with the aim of studying the properties of their source. Only recently this technique has been successfully applied to photons by the TAPS Collaboration [4,5]. In heavy-ion reactions at bombarding energies of several tens of MeV/N, photons above 25 MeV energy (above the giant dipole resonance) originate mainly from individual proton-neutron (pn) bremsstrahlung [6,7]. A detailed experimental study [5,8] has revealed the complex space-time nature of the photon source distribution. In light of dynamical phase-space calculations [7], the experimental data were interpreted by the existence of two distinct photon emissions reflecting the density oscillations that the dinuclear system undergoes during the first stage of the reaction. These two sources are of particular interest for the determination of nuclear matter properties since both are in a well-defined excited state. The first one consists of compressed nuclear matter, which emits bremsstrahlung (direct) photons in first-chance pn collisions; the second one of thermalising nuclear matter, which emits bremsstrahlung (thermal) photons in secondary pn collisions [8].

The quantitative analysis of Ref. [5] lead to the size and relative intensity of both sources. However, since the data were analysed with the analytical correlation function projected onto Q [4], the space and time separation between the two sources could not be resolved. We found that the values of the separation parameter were closer to an estimate of the spatial separation than to the temporal one. To gain a closer insight in the space-time distribution of these sources, we have reconsidered the analysis of the interference pattern generated by two independent bremsstrahlung

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[4] The Lorentz-invariant relative momentum $\sqrt{\mathbf{q}^2 - q_0^2}$.

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photons measured [4,5] for the systems Kr+Ni at 60 MeV/N and Ta+Au at 40 MeV/N. Because of the analogy with experiments belonging to other fields of physics, we shall briefly discuss the two-slit experiment in optics and the measurement of the size of stars in astronomy. Applying similar concepts to the heavy-ion reaction problem, we find that the existing data are best described if the second source consists of a binary system created during the expansion phase following the initial compression of the system.

Amplitude (or first-order) interferometry was established in the early XIX century by Thomas Young to interpret the fringes in the light pattern generated on a screen by two slits illuminated by a single light source. In astronomy, the Michelson interferometer exploits this effect to measure the angle subtended by stars [9]. Each emitting point of the star plays the role of the light source and the two aerials of the interferometer act like the two slits. Averaging over the spatial distribution $\rho(\mathrm{r})$ of the star leads to a first-order correlation function depending on its Fourier transform $\varrho(\mathrm{k}\alpha\mathrm{L})$ [9], where k is the energy, α the angle subtended by the star and L the distance between the aerials. Because of the relatively short distances L technically achievable, the angular resolution of this technique was limited.

In the 50s Hanbury-Brown and Twiss developed intensity (or second-order) interferometry, an alternative technique to measure the angular size of stars [10]. Since intensity interference appears for incoherent sources, each emitting point of the star plays the role of a slit and thus the interference pattern results from a many-slit effect. The second-order correlation function, constructed from the electronic coincidence between the two detectors of the interferometer, provides again the mapping of the spatial distribution of the star through its Fourier transform [11]:

$$C_{12}(\mathrm{L}) = 1 + |\varrho(\mathrm{k}\alpha\mathrm{L})|^2 . \tag{1}$$

The main advantage of this technique is the possibility to extend the distance L between the detectors, which consequently increases the resolving power of the measurement. However, with the application of the technique to astronomy the notion of discrete slits is lost and replaced by a single spatial distribution $\rho(\mathrm{r})$. Hanbury-Brown revived the two-slit aspect of the problem [11] when analysing multiple stars. Con-

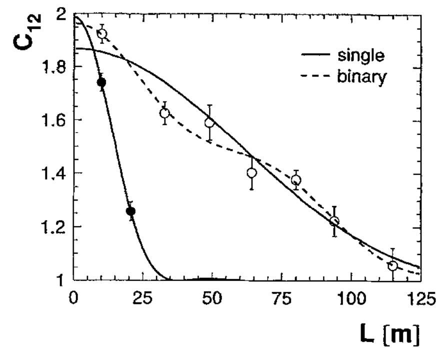

Fig. 1. Correlation function measured for two stars, α-Lyrae (solid circles) and β-Crucis (open circles), adapted from Ref. [11], Fig. 10.2. For the lines see the text.

sidering the simplest case of a binary star, the correlation function of Eq. (1) becomes [11]:

$$C_{12}(\mathrm{L}) = 1 + I_1^2|\varrho_1(x_1)|^2 + I_2^2|\varrho_2(x_2)|^2 + 2I_1I_2|\varrho_1(x_1)||\varrho_2(x_2)|\cos(\Delta x) , \tag{2}$$

with $x_i = \mathrm{k}\alpha_i\mathrm{L}$ and $\Delta x = \mathrm{k}\Delta\alpha\mathrm{L}$, where the indexes 1 and 2 refer to the two components of the star, I_i is the relative intensity of each component, and $\Delta\alpha$ is the angular separation they subtend. In fact Eq. (2) represents the folding of Eq. (1) with a two-slit pattern, since a binary star can be viewed as two slits each presenting a spatial distribution $\rho(\mathrm{r})$. For illustration we have fitted Eqs. (1) and (2) to the experimental correlation functions obtained for two stars (Fig. 1) considering uniform disc distributions and the central value of the wavelength pass-band reported in Ref. [11]. The fit of Eq. (1) revealed that β-Crucis had a faint companion [11]; the use of Eq. (2) shows how intensity interferometry can be sensitive to several details of the binary system.

The bremsstrahlung-photon source observed in heavy-ion reactions has some similarity with the distribution of binary stars. It is granular and consists of two components [5,8], but the dynamics of the collision adds the time dimension to the formalism [1-3]. Noting the relative intensities of both sources by I_d (for direct photons) and $I_\mathrm{t} = 1 - I_\mathrm{d}$ (for thermal photons), the correlation function reads:

$$C_{12}(q) = 1 + I_\mathrm{d}^2|\varrho_\mathrm{d}(q)|^2 + I_\mathrm{t}^2|\varrho_\mathrm{t}(q)|^2 + 2I_\mathrm{d}I_\mathrm{t}|\varrho_\mathrm{d}(q)||\varrho_\mathrm{t}(q)|\cos(q\Delta r) , \tag{3}$$

with $q = k_1 - k_2 = (q_0, \mathbf{q})$ the relative four-momentum between photons. It is similar to Eq. (2), except for Δr which represents the space-time separation between both sources. However, this picture is not exactly equivalent to the binary star picture, since the two sources, occurring at different instants of the reaction, do not coexist [5,8].

The photon source distribution generated by Boltzmann-Ühling-Uhlenbeck (BUU) calculations has been recently used [12,13] to construct the two-photon correlation function assuming that both photons in the pair are emitted independently. The analysis of Ref. [12] was limited to the case of isotropic photon emission in the calculation of the correlation function, and biased by the use of a simplified experimental filter; the results of Ref. [13] show that these calculations are consistent with the picture established in Refs. [5,8]. Nevertheless, the modulation observed for the system Ta+Au at 40 MeV/N (Fig. 4), which leads to an absence of correlation at low Q, did not appear in any of the calculations. Therefore, despite the limited statistical significance of this measurement, some doubt was put forward [12,13] on the ability of the BUU model to precisely describe the evolution of the system beyond the initial compression.

In order to find a phenomenon responsible for a loss of correlation at low Q, and clarify the values of the space-time separation between sources obtained in Ref. [5], we have reconsidered the slit aspect of the experiment. Indeed the modulation in the correlation function of a binary star (Fig. 1), equivalent to the fringes in a two-slit experiment, results from the simultaneousness of both sources, which is apparently not the case in the heavy-ion reaction. However, at least for the Ta+Au reaction the dinuclear system has most likely dissociated into two (oscillating) nuclear fragments during the expansion phase following the initial compression of the system. This hypothesis is supported by measurements [14,15] showing that the reaction mechanism for collisions between such heavy nuclei at the given bombarding energy is mainly binary. Therefore the second source would consist of two fragments emitting photons *simultaneously*, which could thus generate a slit-like modulation.

We have performed Monte Carlo simulations of the source distribution and calculated the corresponding correlation functions. This method provides a test of the sensitivity of photon interferometry to the structure of the system beyond the initial compression. Fig. 2 displays the different scenarios considered. The overlap of the two colliding nuclei leads to the direct photon emission, and the oscillation of the system at an instant Δt later (β_{AA} represents the nucleus-nucleus center-of-mass velocity) generates thermal photons, either from the compound system, either from a binary system:

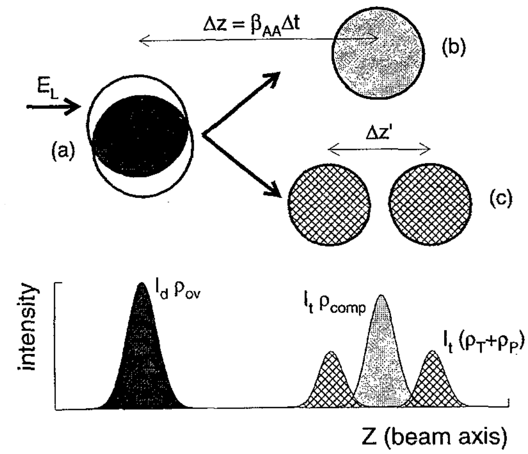

Fig. 2. Schematic view of the photon source distribution used for the Monte Carlo calculations of Eq. (7). It consists of the direct photon emission from the overlap zone of the colliding nuclei (a) followed by a thermal photon emission, at an instant Δt later, originated in the oscillation of either the compound system (b) either the binary system (c).

$$\rho(r) = I_\mathrm{d}\ \rho_\mathrm{ov} + I_\mathrm{t} \begin{cases} \rho_\mathrm{comp} \\ \rho_\mathrm{T} + \rho_\mathrm{P} \end{cases} . \tag{4}$$

The ρ_i distributions are Gaussian functions of the form $\exp(-r^2/2R^2 - t^2/2\tau^2)$. Since all the distributions in Eq. (4) have similar sizes ([16], Fig. 20) we assume a single space extent R, and set the duration to $\tau = 2R$ but, due to photon kinematics, the results are not very sensitive to this parameter [16]. For the compound nucleus scenario the correlation function of Eq. (3) becomes:

$$C_{12}(q) = 1 + |\varrho(q)|^2 \{I_\mathrm{d}^2 + I_\mathrm{t}^2 + 2I_\mathrm{d}I_\mathrm{t}\cos(q_0\Delta t - q_z\Delta z)\}, \tag{5}$$

while for the case of a binary-thermal source one must fold to the "thermal part" of the previous expression the two-slit pattern resulting from the interference be-

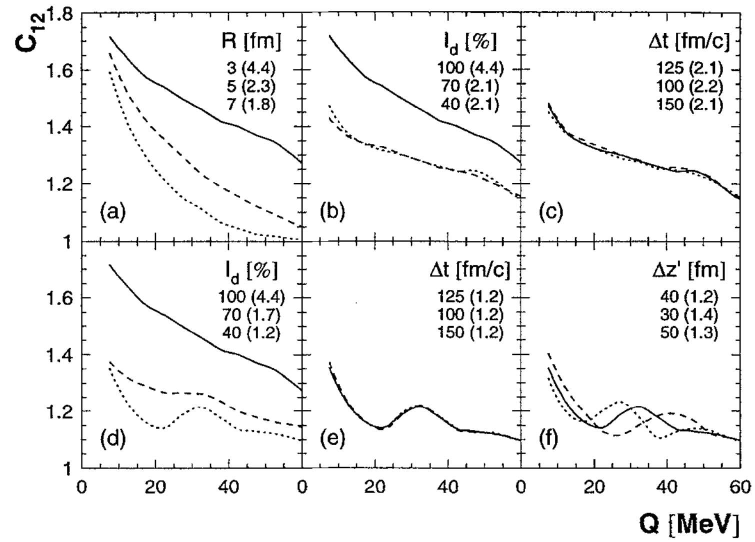

Fig. 3. Influence of the different parameters of the photon source on the correlation function, calculated for the system Ta+Au at 40 MeV/N. The three values of each parameter correspond to the solid, dashed and dotted lines, respectively (in parenthesis the χ^2 of the calculation and the data of Fig. 4b).

tween photons emitted simultaneously by the two fragments (Fig. 2):

$$C_{12}(q) \equiv \Big\{\text{Eq. (5)}\Big\}_{\mathrm{d}} + \Big\{\text{Eq. (5)}\Big\}_{\mathrm{t}} \otimes \Big\{1 + |\varrho(q)|^2\{1+\cos(q_z\Delta z')\}\Big\}. \tag{6}$$

To avoid the analytical derivation of this correlation function, we have chosen the mathematical solution of generating the photon source distribution and performing the Fourier transform event-by-event. The photon energy follows a two-component exponential distribution with inverse slope parameters $E_0^{\mathrm{d}} = E_{\mathrm{beam}}/3$ and $E_0^{\mathrm{t}} = E_{\mathrm{beam}}/6$, which take into account the different energy available in the system at each photon emission [8]. We then consider at two space-time coordinates $r_{1,2}$ a plane wave with four-momentum $k_{1,2}$ and calculate the two-photon probability as:

$$\begin{aligned} P_{12} &= P_{1\otimes 2}\ \left|A\, e^{i(k_1r_1+k_2r_2)} + B\ e^{i(k_1r_2+k_2r_1)}\right|^2 \\ &= P_{1\otimes 2}\left(1 + 2AB\cos\{q(r_1-r_2)\}\right), \end{aligned} \tag{7}$$

where A and B take into account the eventually different probabilities of the direct and cross terms:

$$A = \sqrt{P_{1\otimes 2}/(P_{1\otimes 2}+P_{2\otimes 1})}\,,$$

$$B = \sqrt{P_{2\otimes 1}/(P_{1\otimes 2}+P_{2\otimes 1})}\,,$$

$$P_{1\otimes 2} = P_1(\mathrm{k}_1)\ P_2(\mathrm{k}_2)\,,$$

$$P_{2\otimes 1} = P_2(\mathrm{k}_1)\ P_1(\mathrm{k}_2)\,,$$

$$P_i(\mathrm{k}) = (I_{\mathrm{d,t}}/E_0^{\mathrm{d,t}})\exp\{-(\mathrm{k}-\mathrm{k}_{\mathrm{min}})/E_0^{\mathrm{d,t}}\}\,. \tag{8}$$

The interference term in Eq. (7) was weighted by 0.75 in order to take into account the anisotropic component observed in the angular distribution of bremsstrahlung photons [13]. We finally apply the exact experimental filter [17] to the projection onto Q of the resulting distributions P_{12} and $P_{1\otimes 2}$ of Eq. (7), and calculate the correlation function as $C_{12} = P_{12}/P_{1\otimes 2}$.

In Fig. 3 we study the influence of the different parameters of the source distribution of Eq. (4) on the correlation function. We will discuss the results for the system Ta+Au at 40 MeV/N:

(i) Direct scenario (a). The only parameter entering the correlation function is the size of the overlap zone between the colliding nuclei ($R \approx 3$ fm for this system [18]). To obtain a satisfactory description of the data this size must be increased, leading to a narrower correlation. However, the sizes required are larger ($R_{\mathrm{rms}} = \sqrt{3}R$) than the whole system itself [4].

(ii) Compound-thermal scenario (b,c). The additional factor between brackets in Eq. (5) leads, for the expected source size, to a decrease of the correlation function (b). Nevertheless, this decrease is limited at $I_d = 0.5$ as Eq. (5) is symmetric around this value. In addition, the fact that $\beta_{AA} = 0.14$ ($\Delta t = \Delta z/\beta_{AA}$) makes the argument of the cosine being dominated by q_0, which contrary to q_z is not correlated with Q ([16], Fig. 9). Therefore the cosine term averages to zero and the correlation uniformly decreases by as much $I_d^2 + I_t^2 = 0.5$. This effect is not affected by variations in the frequency of the oscillation (c), since the space and time separation are still linked by β_{AA}.

(iii) Binary-thermal scenario (d–f). Eq. (6) is no longer symmetric with respect to I_d, and the simultaneousness of the thermal emission from the two fragments results in a cosine term independent of q_0. Therefore the two-slit-like pattern generated by the two fragments leads to a reduction *plus* a modulation of the final correlation function (d). The frequency of the oscillation does not affect either the results (e), and the shape of the modulation is mainly determined by the distance between the two fragments.

The results of these calculations confirm the sensitivity of two-photon interferometry to the different reaction mechanisms through both the magnitude and the shape of the correlation function. We find that the binary channel represents the only plausible mechanism which could generate a significant loss of correlation at low Q.

In Fig. 4 we compare the calculations corresponding to the three different scenarios to the data of both systems. The parameters used are: $R = 2$ and 3 fm, $I_d = 60$ and 40 %, $\Delta t = 100$ and 125 fm/c, and $\Delta z' = 20$ and 40 fm for the systems Kr+Ni and Ta+Au, respectively. The comparison of the direct scenario with the other two confirms the need of a second photon source to describe the experimental data [5,8,13]. A second emission from a compound nucleus leads to results similar to the ones obtained with BUU [13]; the correlation decreases uniformly, by about a factor 0.5, but no selective loss of correlation is predicted at low Q. This effect is only observed by considering a fragmented second source, where the two-slit pattern issued from the thermal emission of the binary system modulates the correlation function. In this case we find a better agreement with the data for both systems.

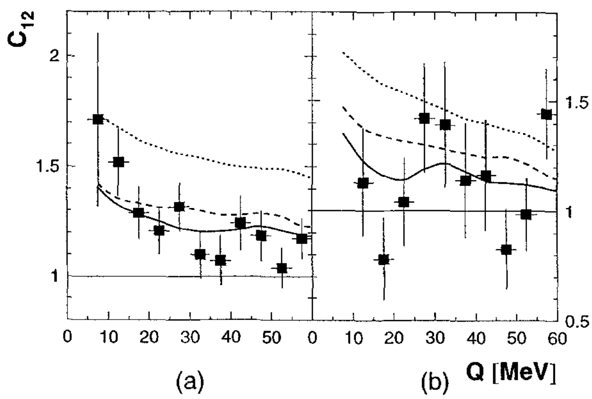

Fig. 4. Results of the calculations described in the text for the systems Kr+Ni at 60 MeV/N (a) and Ta+Au at 40 MeV/N (b) for the direct (dotted), compound-thermal (dashed) and binary-thermal (solid line) scenarios.

In conclusion, the correlation functions measured for bremsstrahlung photons emitted in heavy-ion reactions can be interpreted by the existence of two distinct photon emissions reflecting the density oscillations that the system of colliding heavy ions undergoes during the first stage of the reaction. Monte Carlo simulations of the photon source demonstrate the ability of intensity interference measurements to disentangle between different reaction mechanisms. Specially appealing is the prediction of a modulation in the correlation function due to the folding of the direct emission from the overlap zone and the two-slit pattern generated by the thermal emission from two nuclear fragments, in analogy with the pattern generated by two-slits in optics and binary stars in astronomy. Although statistically limited, such modulation is observed in the experimental correlation function of the heavy system. These results confirm the strong interest in developing this technique as a probe of the reaction dynamics.

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