Hard Photon Intensity Interferometry in Heavy Ion Reactions

M. Marqués,* R.W. Ostendorf,† P. Lautridou,‡ F. Lefèvre,§ T. Matulewicz,‖ W. Mittig, P. Roussel-Chomaz, and Y. Schutz
Grand Accélérateur National d'Ions Lourds, BP 5027, 14021 Caen, France

J. Québert
Centre d'Etudes Nucléaires de Bordeaux-Gradignan, 33175 Gradignan, France

J. Díaz, A. Marín, and G. Martínez
Istituto de Física Corpuscular (CSIC - Universidad de Valencia) and Departamento de Física Atómica, Molecular y Nuclear, 46100 Burjassot, Spain

R. Holzmann, S. Hlávač,¶ A. Schubert, R.S. Simon, and V. Wagner**
Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany

H. Löhner, J.H.G. van Pol, R.H. Siemssen, and H.W. Wilschut
Kernfysisch Versneller Instituut, 747 AA Groningen, The Netherlands

M. Franke
II. Physikalisches Institut Universität Giessen, D-35392 Giessen, Germany

Z. Sujkowski
Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland
(Received 16 November 1994)

Intensity correlations between hard photons produced in heavy ion collisions have been measured for $E_\gamma \geq 25$ MeV in the reaction ^{86}Kr + $^{\mathrm{nat}}$Ni at 60A MeV bombarding energy. The observed correlation pattern is interpreted in terms of intensity interference. A correlation length of $C_\sigma = 16 \pm 4$ MeV is found and the deduced photon source extent is discussed.

PACS numbers: 25.70.Pq

Since the discovery [1] of quantum statistical interference between identical particles emitted from a chaotic source, the two-particle correlation technique has been used extensively in subatomic physics to extract its space-time dimensions [2,3]. The interference arises from the inability to distinguish between identical particles and the symmetrization (for bosons) or antisymmetrization (for fermions) of the two-particle wave function. An often cited and comparable method was introduced by R. Hanbury-Brown and R.Q. Twiss in radio astronomy for photons where intensity interference patterns were observed at optical and longer wavelengths [4]. However, no attempts have been made as yet to test the presence of this effect between photons at γ-ray wavelengths. Such photons are an ideal probe to exploit quantum statistical interference effects in nuclear physics, because they are only weakly absorbed in nuclear matter and do not experience strong final-state interactions, in contrast to light charged particles and pions.

Photons produced in heavy ion collisions at several tens of A MeV in the region above the giant dipole resonance ($E_\gamma \geq 25$ MeV) mainly represent the incoherent superposition of bremsstrahlung emitted from individual proton-neutron collisions [5,6]. Dynamical phase space calculations [5] indicate that, due to Pauli blocking, only the first-chance collisions effectively produce these hard photons. Therefore the average time scale of the production of hard photons should be of the order of the duration of a single nucleon-nucleon collision, while the source size should be restricted to the overlap zone of the two interacting nuclei at the early stage of the collision. This is in sharp contrast to the emission of light charged particles that has been shown to be more sensitive to the freeze-out time [7,8]. In this Letter for the first time results are presented from a measurement of hard photon intensity correlations at intermediate energies. We find that the observed pattern can be interpreted in terms of intensity interference.

The major experimental difficulties are the low production cross section (a few μb) of two coincident hard photons and the high $\pi^0 \rightarrow 2\gamma$ background, requiring an efficient setup, high angular and energy resolutions, and an effective background suppression (hadrons, e^+e^- conversion pairs, and cosmic rays). The reaction was ^{86}Kr on $^{\mathrm{nat}}$Ni at 60A MeV. The ^{86}Kr beam was delivered by the GANIL accelerators at an average intensity of 10 electrical nA. The nickel target was 11.89 mg/cm^2 thick and rotated by 10° from the direction vertical to the beam axis. The total accumulated beam was 8.1×10^{14} particles.

0031-9007/94/73(1)/34(4)$06.00

Hard photons were detected by the 320 hexagonal BaF_2 scintillation detectors of TAPS [9] with a length $L = 250$ mm and an inner diameter $\phi = 59$ mm, each one equipped with a charged particle plastic detector in front acting as a veto. To optimize the shower collection we selected a geometry in which the detectors were assembled in 5 square blocks of 64 detectors each, positioned around the target at an average distance of 60 cm. The solid angle covered was $\Omega \approx 0.17 \times 4\pi$ sr, spanning a nearly continuous angular range of θ between 35° and 165°. In addition to TAPS, the KVI hodoscope [10] for light charged particles consisting of 60 phoswich modules was placed in the reaction chamber, covering angles between 3.7° and 24.5°. For the present experiment the information from the hodoscope was used as a reaction trigger when at least 3 phoswich modules fired. In the data analysis the charged particles detected in TAPS, mainly protons and electrons (positive and negative), were rejected by using the information from the plastic detector as a veto signal, with a measured efficiency of 80% for protons and 70% for electrons. In addition, photons and light particles were identified by using their difference in the pulse shapes generated in the BaF_2 detectors and their different flight times. The time of flight resolution for photons was 600 ps FWHM, dominated by the beam pulse resolution which on average was 550 ps. The residual contamination due to improperly identified hadrons was negligible. Before and after the experiment the BaF_2 detectors were calibrated using γ-ray sources with energies up to 4.4 MeV. A high energy calibration point at 38.5 MeV was taken from cosmic-ray muons whose deposited energy was calculated with a GEANT Monte Carlo simulation [11]. The reliability of such a calibration method has been checked in measurements using tagged photons [12]. The cosmic-ray events were recorded during the experiment (including beam-off periods) and served as a gain monitor. The time of flight and energy of all detector modules with an energy of at least 1.5 MeV were recorded for events in which one or more detectors surpassed a 20 MeV energy threshold. The energy and emission angle of the photons were obtained by reconstructing the electromagnetic shower [13]. For 70 MeV photons, the final energy resolution $\Delta E/E$ was 5% and the angular resolution $\Delta\theta$ was 1°.

In order to be compared to previous data [6], the hard photon ($E_\gamma \geq 25$ MeV) spectrum was fitted with the commonly used parametrization assuming an exponential energy spectrum and an isotropic + dipolar angular distribution in the center of mass system of a moving source. The analysis of the angular distribution leads to a photon source velocity $\beta = 0.18 \pm 0.01$ and a dipolar term $\alpha = 0.18 \pm 0.04$. In this system the measured slope parameter is $E_0 = 21.5 \pm 0.3$ MeV, after correction for the energy response of the TAPS detectors. Taking into account the center of mass velocities of the nucleon-nucleon and nucleus-nucleus systems ($\beta_{NN} = 0.177$ and $\beta_{AA} = 0.214$) our data support the picture of hard photons being mainly produced by individual p-n bremsstrahlung. The hard photon production cross section is $\sigma_\gamma = 3.81 \pm 0.13$ mb. It can be parametrized as $\sigma_\gamma = \sigma_R \langle N_{pn} \rangle P_\gamma$, where σ_R is the geometrical reaction cross section [14], $\langle N_{pn} \rangle$ is the average number of p-n collisions, and P_γ is the hard photon production probability per p-n collision. With the value of $\langle N_{pn} \rangle = 7.0$, calculated from a geometrical model [15], this leads to $P_\gamma = (1.25 \pm 0.04) \times 10^{-4}$, which compares well with the previously established systematics of Ref. [5].

Experimentally the correlation function $C_{12}(p_1, p_2)$ is constructed as the ratio of the two-photon coincidence yield $Y_2(p_1, p_2)$ over an uncorrelated background generated by folding the single photon yields $Y_1(p_1)$ and $Y_1(p_2)$:

$$C_{12}(p_1, p_2) = \frac{Y_2(p_1, p_2)}{Y_1(p_1) \otimes Y_1(p_2)}, \quad (1)$$

where the p_i are the four-momenta of the hard photons and C_{12} has to be normalized to 1 in the region where the quantum statistical effects vanish. To extract two-photon events it is necessary to reject—on an event by event basis—cosmic-ray muons which can fire several detectors giving rise to false $\gamma\gamma$ events and consequently distorting the two-photon correlation signal. Cosmic-ray induced events recorded in random coincidence with the beam were eliminated in the analysis by requiring the hodoscope in the reaction trigger and by analyzing the shape of the shower [16]. Furthermore, to eliminate leftover e^+e^- conversion pairs (the probability of identifying these events as two hard photons was 9%) and noncontinuous showers, a minimum distance of at least 3 detectors ($\Delta\theta \approx 18°$) between the two coincident showers was requested [13]. The $\pi^0 \rightarrow 2\gamma$ contribution at low invariant mass was restricted by requiring that at least 20% of the shower energy was deposited in the fiducial volume of a TAPS block, improving the invariant mass resolution of the π^0 peak (10% FWHM). In this way 20 649 events were left and identified as two-hard-photon events. We estimate that the contributions from leftover cosmic events (4 events over the whole spectrum) and from conversion pairs (6 events for invariant masses between 20 and 80 MeV) are negligible.

The numerator and the denominator of Eq. (1) are displayed in Fig. 1 as a function of the invariant relative four-momentum $Q_{\text{inv}} = \sqrt{-(p_1 - p_2)^2}$, equivalent to the invariant mass for photons. The use of this variable instead of the more appropiate relative three-momentum $q = |\mathbf{p}_1 - \mathbf{p}_2|$ is justified because the energy distribution of hard photons, the acceptance of our setup, and the cut in the opening angle made us select photon pairs with $\mathbf{q}$ mostly transverse to the total momentum. This leads to $Q_{\text{inv}} \approx q$. At $Q_{\text{inv}} = 135$ MeV the spectrum of

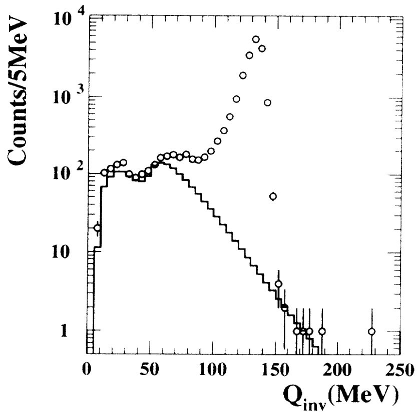

FIG. 1. Invariant relative momentum distribution for the photon pairs $Y_2(p_1, p_2)$ (data points) and for the normalized (see text) combinatorial background $Y_1(p_1) \otimes Y_1(p_2)$ (histogram) for $E_\gamma \geq 25$ MeV in the reaction ^{86}Kr on $^{\rm nat}$Ni at $60A$ MeV.

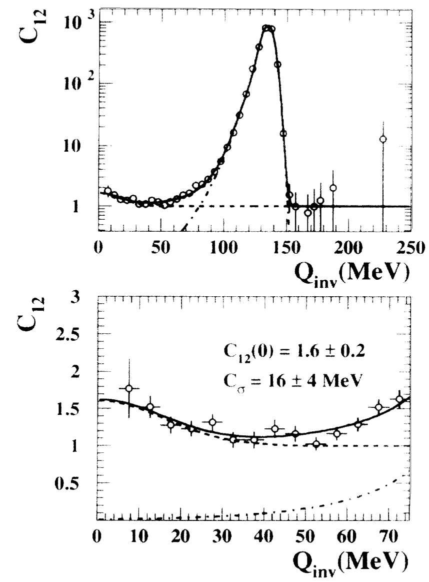

FIG. 2. Correlation function measured in the reaction ^{86}Kr on $^{\rm nat}$Ni at $60A$ MeV for photons with $E_\gamma \geq 25$ MeV. The solid line represents the fit by Eq. (3), decomposed in the contributions from the Bose-Einstein correlation (dashed line) and from the neutral pions (dot-dashed line).

the coincidence photons Y_2 exhibits a peak due to photons stemming from π^0 decay. The uncorrelated yield $Y_1 \otimes Y_1$ shown in Fig. 1 is normalized to the coincidence yield Y_2 via the fitting procedure described later. From the two spectra, we obtain the production cross sections for $\pi^0 \sigma_{\pi^0} = 29.0 \pm 1.1$ μb and for two hard photons $\sigma_{\gamma\gamma} = 7.2 \pm 0.5$ μb. Following the same parametrization used for σ_γ, we deduce for two bremsstrahlung photons $\sigma_{\gamma\gamma} = \sigma_R \langle N_{pn}(N_{pn} - 1)\rangle P_\gamma^2$, which leads to $\sigma_{\gamma\gamma} = 6.9 \pm 0.5$ μb, in agreement with the experimental value.

The correlation function obtained from the ratio of the two spectra in Fig. 1 is shown in Fig. 2. The variable $Q_{\rm inv}$ allows for a good parametrization of the component originating from $\pi^0 \rightarrow 2\gamma$ with the help of a GEANT Monte Carlo simulation (dot-dashed line), indicating that the contribution from neutral pions to the correlation spectrum at low $Q_{\rm inv}$ is negligible. Therefore below 60 MeV the spectrum contains mainly bremsstrahlung photons and the rise towards low $Q_{\rm inv}$ in the interval from 40 MeV down to 5 MeV is attributed to the expected interference effect between photons.

Theoretically, the interference between identical particles emitted from N points in the source has been described in the pioneering work by Gyulassy *et al.* [17]. Within the same formalism, Neuhauser has derived the correlation function for the $\gamma\gamma$ intensity interference [18]:

$$C_{12}(p_1, p_2) = 1 + \tfrac{1}{4}\left(1 + \cos^2\theta_{12}\right)[|\rho(p_1 + p_2)|^2 + |\rho(p_1 - p_2)|^2], \quad (2)$$

where $\rho(p)$ is the Fourier transform of the normalized space-time source density $\rho(x)$. The factor $1 + \cos^2\theta_{12}$, where θ_{12} is the angle between the two photons, reflects the fact that orthogonally polarized photons are nonidentical bosons and therefore do not interfere. For nearly parallel photons ($\cos^2\theta_{12} \approx 1$) and for $E_\gamma \geq 25$ MeV $[|\rho(p_1 + p_2)|^2 \rightarrow 0]$, the intercept of the correlation function is $C_{12}(p, p) = 1.5$ (as for $N = 2$ in Ref. [17]). Within this representation, the width C_σ of the correlation function is a direct measurement of the space-time extent of the source. Experimentally the average measured photon energy equals 40 MeV, and the acceptance of our setup allows us to measure pairs of bremsstrahlung photons with $Q_{\rm inv}$ between 10 MeV and 100 MeV (Fig. 1). Therefore invariant radii between $\hbar c/100 = 2$ fm and $\hbar c/10 = 20$ fm can be measured.

A more detailed model [19] including the production mechanism of bremsstrahlung photons via individual p-n collisions shows that the correlation function depends also on the dynamics of the p-n scattering in matter. This dependence is dominated by the relation between the average of the transverse and longitudinal proton momentum transfer distributions in the p-n bremsstrahlung process. For higher transverse momentum transfers we find Eq. (2), therefore leaving us with an intercept of 1.5, while in the other limit, for higher longitudinal momentum transfers, we find a maximum intercept of 2.0 (as for large N in Ref. [17]).

The experimental correlation spectrum was fitted by a distribution of the form

$$f(Q_{\rm inv}) = K_0 + K_1 g_{\gamma\gamma}(Q_{\rm inv}) + K_2 g_{\pi^0}^A(Q_{\rm inv} - m_{\pi^0}),$$

where K_0 is the coefficient used to normalize the correlation function to 1 for noninterfering photons. This coefficient is thus deduced from a fit to the whole invariant mass spectrum and not only to the region above the π^0 mass free of correlated photons. In this way the errors on the fitting parameters contain the uncertainties in the normalization. The uncorrelated yield $Y_1 \otimes Y_1$ shown in Fig. 1 was normalized to the coincidence yield Y_2 via K_0. The function $g_{\gamma\gamma}$ is a Gaussian describing the interference effect at low $Q_{\rm inv}$, as deduced when a Gaussian density distribution for the source is assumed. The additional effect in the correlation spectrum due to the $\pi^0 \to 2\gamma$ background is described as an asymmetric Gaussian function $g^A_{\pi^0}$, with parameters adjusted to the corresponding simulated distribution. After the fit the correlation function can be written as follows:

$$C_{12}(Q_{\rm inv}) = 1 + \lambda_{\rm inv} \exp\left(-\frac{Q^2_{\rm inv}}{2C^2_\sigma}\right) + \alpha g^A_{\pi^0}(Q_{\rm inv} - m_{\pi^0}), \quad (3)$$

where the parameter $\lambda_{\rm inv}$ (K_1/K_0) includes possible additional effects that reduce the interference, like partial coherence of the source and chance coincidences. The result of the fit to the whole spectrum is shown in Fig. 2 as the solid line. The first two terms of Eq. (3) (the Bose-Einstein correlation) are shown as the dashed line and the third one (the neutral pions contribution) as the dot-dashed line. The intercept is found to be $C_{12}(0) = 1.6 \pm 0.2$, consistent with the values predicted in Refs. [18,19]. The width of the correlation function (correlation length) is found to be $C_\sigma = 16 \pm 4$ MeV. Defining the invariant radius of the source as $R_{\rm inv} \equiv \hbar c/C_\sigma$, we find $R_{\rm inv} = 12 \pm 3$ fm.

A geometrical [15] estimate of the average number of participant nucleons producing two hard photons gives $\langle N_{\rm part}\rangle_{\gamma\gamma} = 76.6$, which leads to an average impact parameter of $\langle b\rangle = 3.1$ fm and a Gaussian radius [20] of the two nuclei overlap zone of $R_{\rm ov} = \sqrt{2/5}(1.2\langle N_{\rm part}\rangle^{1/3}_{\gamma\gamma}) = 3.2$ fm. This value is smaller than $R_{\rm inv}$, although it should be noted that $R_{\rm inv}$ includes both the space and time dimensions. Assuming that the two contributions add quadratically, the lifetime of a source with a spatial extent equal to the one of the overlap zone would be $\tau = (1/c)\sqrt{R^2_{\rm inv} - R^2_{\rm ov}} = 3.8 \times 10^{-23}$ s. However, because of photon kinematics the relative three-momentum governing the space contribution is always larger than the relative energy governing the time contribution, and thus the unfolding of $R_{\rm inv}$ becomes more complex.

In summary, we have applied the technique of intensity correlation to reveal for the first time the Hanbury-Brown–Twiss effect between independent hard photons. This effect has been interpreted within the frame of the interferometry model of Neuhauser [18] and Razumov and Weiner [19], and the invariant radius of the photon source has been estimated and found to be larger than the participant zone. This result calls for new experiments with different system sizes to study this intriguing phenomenon.

We wish to thank our colleagues at the Oak Ridge National Laboratory, J.R. Beene, P. Mueller, and R. Varner, for their help in setting up the experiment, and V. Metag for many interesting suggestions and remarks on the manuscript. We thank the members of the technical staff of the Grand Accélérateur National d'Ions Lourds (GANIL) for their help and delivery of the high quality beam required for our measurements, and finally the Bordeaux target laboratory for producing the Ni targets. This work was in part supported by the CICYT Research Project PB90-091 (Spain), IN2P3 (France), FOM (The Netherlands), and BMFT (Germany). The experiment was performed at the GANIL facility, Caen, France.

* Present address: IFIC, 46100 Burjassot, Spain.
† Present address: University of Utrecht, The Netherlands.
‡ Present address: LPN, F-44072, Nantes, France.
§ Present address: GSI, D-64220, Darmstadt, Germany.
‖ Permanent address: Warsaw University, PL-00-681, Warszawa, Poland.
¶ Permanent address: Slovak Academy of Sciences, Bratislava, Slovakia.
** Permanent address: Czech Academy of Sciences, Řež u Prahy, Czech Republic.

[1] G. Goldhaber *et al.*, Phys. Rev. **120**, 300 (1960).
[2] B. Lörstad, Int. J. Mod. Phys. A **4**, 2861 (1989).
[3] D. Boal *et al.*, Rev. Mod. Phys. **62**, 553 (1990).
[4] R. Hanbury-Brown, *The Intensity Interferometer* (Taylor & Francis Ltd., London, 1974).
[5] W. Cassing *et al.*, Phys. Rep. **188**, 363 (1990).
[6] H. Nifenecker and J.A. Pinston, Prog. Part. Phys. **23**, 271 (1989).
[7] D. Fox *et al.*, Phys. Rev. C **38**, 146 (1988).
[8] J. Québert *et al.*, in *Proceedings of the Symposium on Nuclear Dynamics and Nuclear Disassembly, Dallas*, edited by J.B. Natowitz (World Scientific, Singapore, 1989), p. 337.
[9] R. Novotny, IEEE Trans. Nucl. Sci. **38**, 379 (1991).
[10] H.K.W. Leegte *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **313**, 26 (1992).
[11] R. Brun *et al.*, CERN Report No. DD/EE/84-1, 1986 (unpublished).
[12] T. Matulewicz *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **289**, 194 (1990).
[13] M. Marqués *et al.*, Nouvelles GANIL **45**, 45 (1993).
[14] R. Bertholet *et al.*, Nucl. Phys. **A474**, 541 (1987).
[15] H. Nifenecker and J.P. Bondorf, Nucl. Phys. **A442**, 478 (1985).
[16] T. Matulewicz *et al.*, Nouvelles GANIL **45**, 33 (1993).
[17] M. Gyulassy *et al.*, Phys. Rev. C **20**, 2267 (1979).
[18] D. Neuhauser, Phys. Lett. B **182**, 289 (1986).
[19] L.V. Razumov and R.M. Weiner, in Proceedings of the II TAPS Workshop, Guardamar, Spain, 1993, edited by J. Díaz and Y. Schutz (World Scientific, Singapore, to be published).
[20] W.A. Zajc *et al.*, Phys. Rev. C **29**, 2173 (1984).