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Time correlations in stimulated emission*

D. B. Scarl
Department of Physics, Polytechnic Institute of New York, Brooklyn, New York 11201

Stephen R. Smith
Department of Physics, Princeton University, Princeton, New Jersey 08540
and Department of Physics, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010†

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Measurements of two-photon coincidences in single-mode light from a He-Ne 633 nm gain tube in which each spontaneously emitted photon has an average probability of 12% of inducing a second photon, show no time correlation between inducing and induced photons in the range from zero to 3.4 nsec.

A continuous beam of electromagnetic radiation contains information about the times at which individual photons were emitted from the atoms, molecules, or nuclei that were the source of the radiation. Measurements of coincidences between pairs of γ rays from nuclear cascades, or from positron-electron annihilation, exploit this information, as do time difference measurements of the pair of optical photons from a three-level atomic cascade,[1] or from parametric fluorescence in an optical crystal.[2] In each case, after detecting one photon of the pair, the time of detection of the other photon can be predicted. This time correlation between pairs of photons is essential in experiments that measure intermediate-state lifetimes and spin (polarization) and propagation vector correlations between pairs of photons emitted from a single atom or nucleus. (Measurement of a nuclear or atomic recoil could also allow prediction of the time of photon emission and subsequent detection.) These predictions of the time of detection of single photons can, of course, only be made within the limits set by the uncertainty principle and the spectral bandwidth of the radiation. The predictions are in the form of quantum statistical probability distributions for the photon detection times.

Since time correlations between pairs of photons are observable, the electron emitted from an atom of a photocathode or a scintillation crystal must also be correlated in time with the arrival of a photon. This generally accepted idea is the basis for single-photon timing. Two-photon correlation experiments require that emission time information be carried by a continuous beam and that this information be translated into time-related events by the detection process.

In contrast to spontaneous emission and absorption, no evidence exists for time correlations between the incident and emitted radiation in the process of stimulated emission. Although the phase of the emitted radiation is determined by the incident radiation in stimulated emission, but not in atomic cascades, recoil, or absorption, time correlation in stimulated emission within the uncertainty principle limits would not be excluded. If time correlation exists between inducing and induced photons in stimulated emission, it should be detectable in a beam of light that contains an appreciable amount of stimulated emission. We have found no time correlation in the range of 0–3.4 nsec that could be attributed to stimulated emission in light from gas discharge in which each photon had an average probability of 12% of stimulating a second photon.

FULL AND REDUCED DENSITY MATRICES

Fields A and B that are generated by a single physical process, such as an atomic cascade or positron annihilation, and that are correlated in space, time, or spin, are described by a single density matrix ρ_{AB}. Because of the correlation, the density matrix does not reduce to the product of ρ_A and ρ_B, the density matrices for the individual fields.[3] For measurements on the A field alone, after taking the trace over the B variables, ρ_{AB} reduces to ρ_A, the conventional density matrix for the A field, retaining no evidence of AB correlations. Since most of the "photon-like" properties of the field are due to space, time, and spin correlations, these properties will not survive in the single-field density matrix.

In the case of stimulated emission, the A (stimulating) and B (stimulated) fields have the same wave vector, polarization, and phase, and are indistinguishable. Since it is not possible to make a measurement on either the A or the B fields alone, the complete matrix ρ_{AB} must be used to describe the field and to predict the results of measurements in a beam containing significant amounts of stimulated emission. The lack of time correlation found in the present experiment seems to indicate that the density matrix ρ_{AB} is similar in structure to the density matrix for a field without stimulated emission.[4]

EXPERIMENTAL APPARATUS

A 74-cm-long He-Ne discharge tube of 2×25-mm cross section acted as light source and gain tube. The tube was filled with 1.6 Torr of He^3 and 0.2 Torr of Ne^{20} and was run at a current of 35 mA. The discharge occupied a volume 68 cm $\times 2$ mm $\times 10$ mm. A set of three 1-m focal length mirrors[5] with reflectivities of 99% for 633-nm light sent light from one end of the tube on a zigzag path that passed through the tube 12 times, giving an effective discharge length of 816 cm. (Fig. 1).

The system was aligned and the gain was measured with a 2-mW polarized He-Ne laser, whose beam made 12 passes through the gain tube. The gain at 633 nm, defined as the ratio of the intensity of the alignment laser after 12 passes through the excited tube to the intensity after 12 passes through the unexcited tube, was 1.25 ± 0.02. A photon spontaneously emitted from an atom at the end of the gain tube farthest from the detectors has a probability of 25% of inducing an atom along its path to emit a second photon into the same transverse mode. The average probability for induced emission for a spontaneously emitted photon anywhere along the gain tube is 12.5%. The gain was unchanged when the incident laser intensity was attenuated by a factor of 100, indicating that the gain tube was operating well below saturation.

A 1.2-cm-thick plate of BK-7 glass suppressed amplified spontaneous emission of the high-gain Ne transition at 3.39 μ. Both the glass plate and the Suprasil gain tube windows were at Brewster's angle. Attenuation of the incident laser beam due to mirror and diffraction losses was 59% for 12 passes. The spectral width of the Ne 632.8-nm line radiated by the gain tube along the 12-pass path was measured with a scanning Fabry-Perot interferometer to be 1.72 ± 0.08 GHz [full width at half maximum (FWHM)], about 8% narrower than the light from a short end-on discharge tube with negligible gain.

A 1.0-mm-diam circular aperture 90 cm downstream from the end of the gain tube, and a 0.41-mm aperture 1.50 m farther downstream, selected a single transverse mode of the light traveling down the tube. A 51-cm focal length lens imaged the middle of the gain tube at a point midway between the two apertures. An interference filter with a bandpass of 0.3 nm (held at a temperature of 45 °C) selected only the 632.8-nm Ne line from the discharge tube. A Polaroid HN22 linear polarizer selected the vertical polarization component of the field. The photomultiplier detectors and electronics were identical to those previously described,[6] and had a time resolution for simultaneous incident photons, measured with a Čerenkov source, of 1.2 nsec (FWHM).

The detection efficiency for a single photon produced halfway along the gain tube in a single mode was 3.2×10^{-4} for each detector. This efficiency is the product of the 70% average transmission of the gain tube and folding mirrors, the 11% of single-mode light passed by the second aperture, the 55% transmission of the 633-nm interference filter, the 46% transmission of vertically polarized light by the HN22 polarizer, the 50% transmission of the beam splitter, and the 3.3% single-photon counting efficiency of each photomultiplier. Since the counting rate in each detector was 1.8×10^5 counts/sec, and the average gain was 1.12, H (the spontaneous emission beam intensity into a single vertically polarized mode at the output of the gain tube) was calculated to be 5.0×10^8 photons/sec.

MEASURED COUNTING RATE

The time distribution between pairs of detected photons from a beam of amplified spontaneous emission is shown in Fig. 2. The peak near zero time difference is due solely to the Hanbury Brown–Twiss effect in a beam with a purely Gaussian amplitude distribution. The peak is 1.2

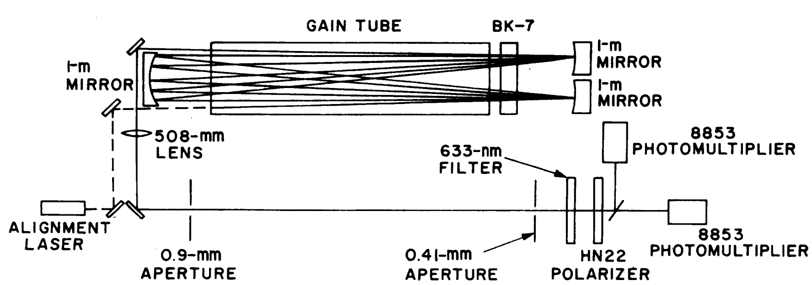

FIG. 1. Experimental arrangement. The amplified spontaneous emission mode selected by the two apertures has made 12 one-way passes through the gain tube. The He-Ne laser is used only for alignment and gain measurement.

nsec wide and has a height of 26% of the background.[7] No evidence for time correlation between inducing and induced photons is seen. The sensitivity of the experiment is such that deviations from the normal Hanbury Brown–Twiss effect of 3% of the background counting rate could have been detected. The shape of the peak and its height relative to the background counting rate were unchanged as the sizes and separation of the apertures that defined the spatial coherence of the beam were changed, keeping the product of the aperture diameters divided by their separation, and hence the spatial coherence factor, constant.

The correlation measurement in Fig. 2 has a time scale of 50 psec per channel and a total time range of ± 2.2 nsec. When the measurement was repeated with a scale of 500 psec/channel and a total time range of ± 45 nsec, no long-range correlations were found, although correlations that exceeded 3% of the background counting rate could have been detected.

EXPECTED COUNTING RATE

The counting rate for the detection of inducing-induced photon pairs as a function of the time Δt between the detection of the two members of a pair can be written

$$W(\Delta t)\delta t = W_S f(\Delta t) * p(\Delta t)\delta t. \quad (1)$$

W_S is the total number of pairs detected, $f(\Delta t)*p(\Delta t)$ is the convolution (normalized to unit area) of the expected detected pair time spread function and the time response function of the photomultipliers, and δt is the counting channel or coincidence width. The total number of detected pairs is

$$W_S = H\epsilon^2(g-1), \quad (2)$$

where H is the rate of spontaneous photons emitted into the mode which the detectors are sampling, ϵ is the detection efficiency for each photon, and g is the average gain of the gain tube.

If the time spread function for inducing-induced photon pairs is the Fourier transform of the Doppler-broadened spectral density of the amplified spontaneous emission light leaving the end of the gain tube, $f(\Delta t)$ is a Gaussian function with a standard deviation T_d of 0.22 nsec. The photomultiplier response function $p(\Delta t)$ is a Gaussian with a standard deviation T_p of 0.51 nsec. Convolution of the two-photon time spread function and the photomultiplier response function results in a Gaussian function with standard deviation

$$T_1 = (T_d^2 + T_p^2)^{1/2}. \quad (3)$$

The detected counting rate as a function of time between photons would be

$$W(\Delta t) = \frac{H\epsilon^2(g-1)}{(2\pi)^{1/2}T_1} e^{-\Delta t^2/2T_1^2}. \quad (4)$$

ACCIDENTAL COINCIDENCE BACKGROUND

The accidental coincidence counting rate for two detectors, each counting at the rate $H\epsilon g$ and sensitive to pairs that arrive within a time interval δt, is

$$W_b = (H\epsilon g)^2 \delta t. \quad (5)$$

The accidental background is independent of Δt, the time between photons.

SIGNAL TO BACKGROUND AT $\Delta t = 0$

The predicted counting rate is most easily compared with the measured counting rate by considering the ratio of true pairs to accidental pairs at zero time difference. The predicted ratio is

$$W(0)/W_b = (g-1)/g^2(2\pi)^{1/2}HT_1. \quad (6)$$

Using the experimental values $g = 1.12$, $H = 5.0 \times 10^8$, and $T_1 = 0.56$ nsec, the coincidence-to-back-

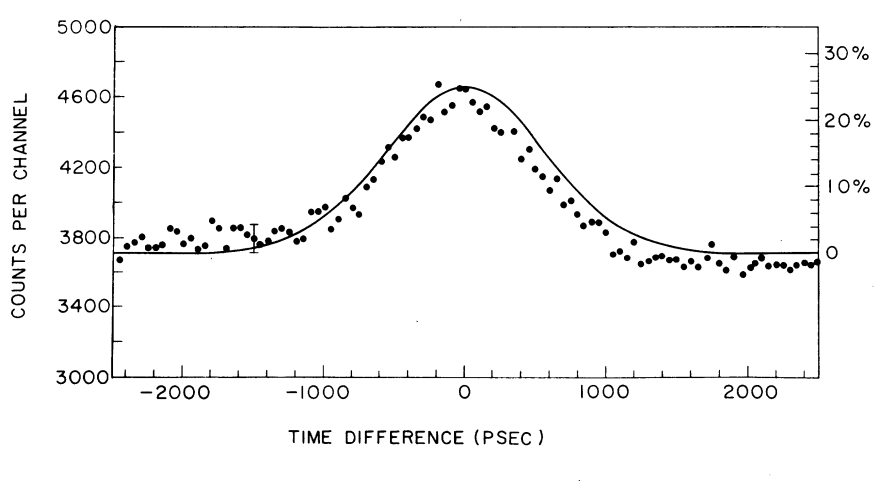

FIG. 2. Counting rate versus time between consecutive detected photons. The error bar shown applies to all experimental points. The solid line is the calculated background plus the Hanbury Brown–Twiss effect.

ground ratio at zero time difference would be

$$W(0)/W_b = 0.14\,. \tag{7}$$

The observed number of coincidences above the expected Hanbury Brown–Twiss peak is less than one-quarter of this number.

LONG-TIME CORRELATIONS

If the characteristic correlation time between inducing and induced photons is longer than the inverse of the Doppler-broadened spectral line width, the expected signal-to-background ratio at $\Delta t = 0$ would be reduced from that of Eq. (7). An exponential correlation function

$$f(\Delta t) = (1/2T_n)e^{-|\Delta t|/T_n} \tag{8}$$

leads to an expected signal-to-background ratio at $\Delta t = 0$ of

$$W_n(0)/W_b = (g-1)/2g^2 H T_n\,. \tag{9}$$

With $g = 1.12$ and $H = 5.0\times 10^8\ \text{sec}^{-1}$, the largest T_n that would give a detectable signal ($W_n(0)/W_b > 0.03$) is 3.4 nsec. In the present experiment, correlation times longer than this could not be observed. In particular, if the correlation time corresponds to the natural lifetime of the $3s_2$ level in neon[8](62 nsec at a neon partial pressure of 0.2 Torr, with the resonance radiation completely trapped), the correlation between inducing and induced photons would be undetectable.

SUMMARY

No time correlation was found between inducing and induced photons in a beam of 633-nm light from a long discharge tube with an average gain of12%. Two-photon correlations in the time range from 0 to 3.4 nsec could have been detected above the background counting rate. The lack of observed correlations may indicate that the temporal properties of the pair of indistinguishable photons involved in stimulated emission differ from those of the photons from an atomic cascade or from positron annihilation. Since stimulated emission does not destroy the incident photon field and does not randomly change its phase, the process of stimulated emission may not constitute a measurement in the sense of quantum measurement theory.

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APPENDIX: HANBURY BROWN-TWISS COUNTING RATE

The expected Hanbury Brown–Twiss counting rate can be calculated from the density matrix of the detected field. For amplified spontaneous emission considered as a stationary stochastic process, the field density matrix will be diagonal in a coherent-state basis, and will have a Gaussian distribution of amplitudes.[9] The weight function for each mode is[10]

$$P(\alpha) = (1/\pi\langle n\rangle)e^{-|\alpha|^2/\langle n\rangle}\,. \tag{10}$$

For two detectors of efficiency ϵ sampling the fields A_1 and A_2, the two-photon counting rate can be calculated from[10]

$$W = \mathrm{Tr} A_1^\dagger A_2^\dagger A_1 A_2 \epsilon^2\,. \tag{11}$$

After convolution with the detector time resolution response function and integration over the spatial coherence area, the counting rate for events separated in time by Δt is

$$W_h(\Delta t)\delta t = (Hg\epsilon)^2(1 + Ce^{-\Delta t^2/2T_2^2})\delta t\,, \tag{12}$$

where

$$T_2 = (T_h^2 + T_p^2)^{1/2} = (0.16^2 + 0.51^2)^{1/2} = 0.53\ \text{nsec}\,. \tag{13}$$

and

$$\begin{aligned} C &= SNT_p/T_2 \\ &= (0.895)(0.97)(0.16\times 10^{-9})/0.53\times 10^{-9} = 0.25\,. \end{aligned} \tag{14}$$

T_h is the standard deviation of the Gaussian-shaped Hanbury Brown–Twiss peak centered at zero time difference. This peak is the square of the Fourier transform of the spectral density of the light from the gain tube. S is the spatial coherence factor obtained by integrating the spatial part of the first-order coherence function over the second aperture.[11] N is the ratio of the number of counts due to photons to the sum of the photon counts and the photomultiplier noise counts.

The curve of $W_h(\Delta t)$, derived from a diagonal density matrix with Gaussian weight functions, is plotted as a solid line in Fig. 2.

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†Present address.

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