Intensity-Correlation Linewidth Measurement*

DAVID T. PHILLIPS,† HERBERT KLEIMAN,‡ AND SUMNER P. DAVIS
Department of Physics, University of California, Berkeley, California
(Received 3 August 1966)

The optical intensity correlation technique developed by Hanbury Brown and Twiss has been used to measure the linewidth of 4358-Å light from a mercury discharge lamp which was filtered with a Fabry-Perot interferometer. A time-to-height converter was used to convert the delay spectrum of photoelectric counts to a pulse-height spectrum which was recorded by a multichannel pulse-height analyzer. Correlation times of 1.0 to 3.4 nsec were observed, corresponding to linewidths of 208 to 66 MHz.

INTRODUCTION

IN 1956, Hanbury Brown and Twiss[1] predicted and demonstrated that for light emitted by a thermally excited source there exists a measurable increase in the delayed two-photon coincidence rate $C(T)$ at zero delay ($T=0$). The experiment has been repeated in various forms.[2–5] Recently such measurements have been used to study mode coupling in GaAs injection lasers.[6] Some interest[7,8] has been expressed in using intensity correlations as a means of measuring line shapes and fundamental properties of solids.

For thermal sources, the ratio of "excess" to random coincidences may be defined thus:

$$\rho(T)=\lim_{t\to\infty}\frac{C(T)-C(t)}{C(t)}.$$

In the early experiments, $\rho(T)$ was only a few percent for radiation from water-cooled mercury isotope lamps, and the shape of the function $\rho(T)$ was determined almost solely by the response of the detectors.

In the experiments described here, $\rho(0)$ reached values of over 15%, and the shape of the function $\rho(T)$ was measured and found to vary with changes in the power spectrum of the light. This improvement is the result of the use of fast transistor electronics and higher detector quantum efficiency. The high sensitivity of the detectors allowed the use of small collimating pinholes, polarized light, and a Fabry-Perot filter to obtain very narrow band light. Multichannel recording was used to measure the whole function $\rho(T)$ in a single run. The apparatus is shown schematically in Fig. 1.

SUMMARY OF THEORY

The following relation between $\rho(T)$ and the power spectrum $W(\omega)$ was derived for light beams by Hanbury Brown and Twiss[1] on the basis of the wave theory of light. It can also be derived with quantum theory.[9]

$$\rho(T)=\left|\int_{-\infty}^{\infty}e^{i\omega T}W(\omega)d\omega\right|^2.$$

Since the phase of the transform of $W(\omega)$ is lost, only the convolution of W with itself can be obtained by Fourier inversion of $\rho(T)$, unless the line shape is known to be symmetric. Averaging the above expression over the finite response time t_c of the detector yields:

$$\rho(T,t_c)=2\int_0^{\infty}d\omega\left[\int_{-\infty}^{\infty}W(s)W(s+\omega)ds\right]\frac{\sin\omega t_c}{\omega t_c}\cos\omega T.$$

The $\sin\omega t_c/\omega t_c$ factor destroys information above its first zero. In the limit of a wideband source, $\rho(T,t_c)$ has width $2t_c$ and the shape of the function depends only on the response characteristic of the detectors. Thus the method can only be used to study lines of width less than $\Delta\nu=1/t_c$. In these experiments $t_c=1$ nsec and so the line to be studied had to be less than 1000 MHz in width. The line profile of the Hg^{198} lamp was measured with a scanning Fabry-Perot interferometer and found to be a Doppler profile with width 900 MHz. Reducing the linewidth by up to a factor of 10 with the Fabry-Perot filter made observable changes in $\rho(T,t_c)$, as shown in Fig. 2.

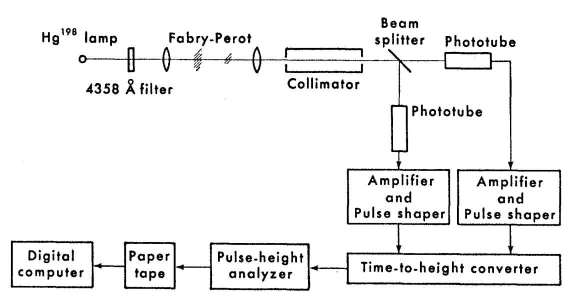

FIG. 1. Diagram of the experimental apparatus.

* Work supported in part by the National Science Foundation.
† National Science Foundation Predoctoral Fellow, now at Physics Department, University of California, Santa Barbara.
‡ Now at Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Massachusetts.
1 R. Hanbury Brown and R. Q. Twiss, Nature **177**, 27 (1956); Proc. Roy. Soc. (London) **A243**, 291 (1957).
2 R. Q. Twiss and A. G. Little, Australian J. Phys. **12**, 77 (1959).
3 G. A. Rebka and R. V. Pound, Nature **180**, 1035 (1957).
4 B. L. Morgan and L. Mandel, Phys. Rev. Letters **16**, 22 (1966); **16**, 1012 (1966).
5 D. B. Scarl, Phys. Rev. Letters **17**, 12 (1966); **17**, 663 (1966).
6 A. W. Smith and J. A. Armstrong, Phys. Rev. Letters **14**, 3 (1966); **14**, 68 (1965).
7 M. L. Goldberger, H. W. Lewis, and K. M. Watson, Phys. Rev. **142**, 25 (1966).
8 A. L. Fetter, Phys. Rev. **139**, A1616 (1965).
9 R. J. Glauber, in *Quantum Optics and Electronics*, edited by C. Dewitt (Gordon and Breach, Science Publishers, Inc., New York, 1965).

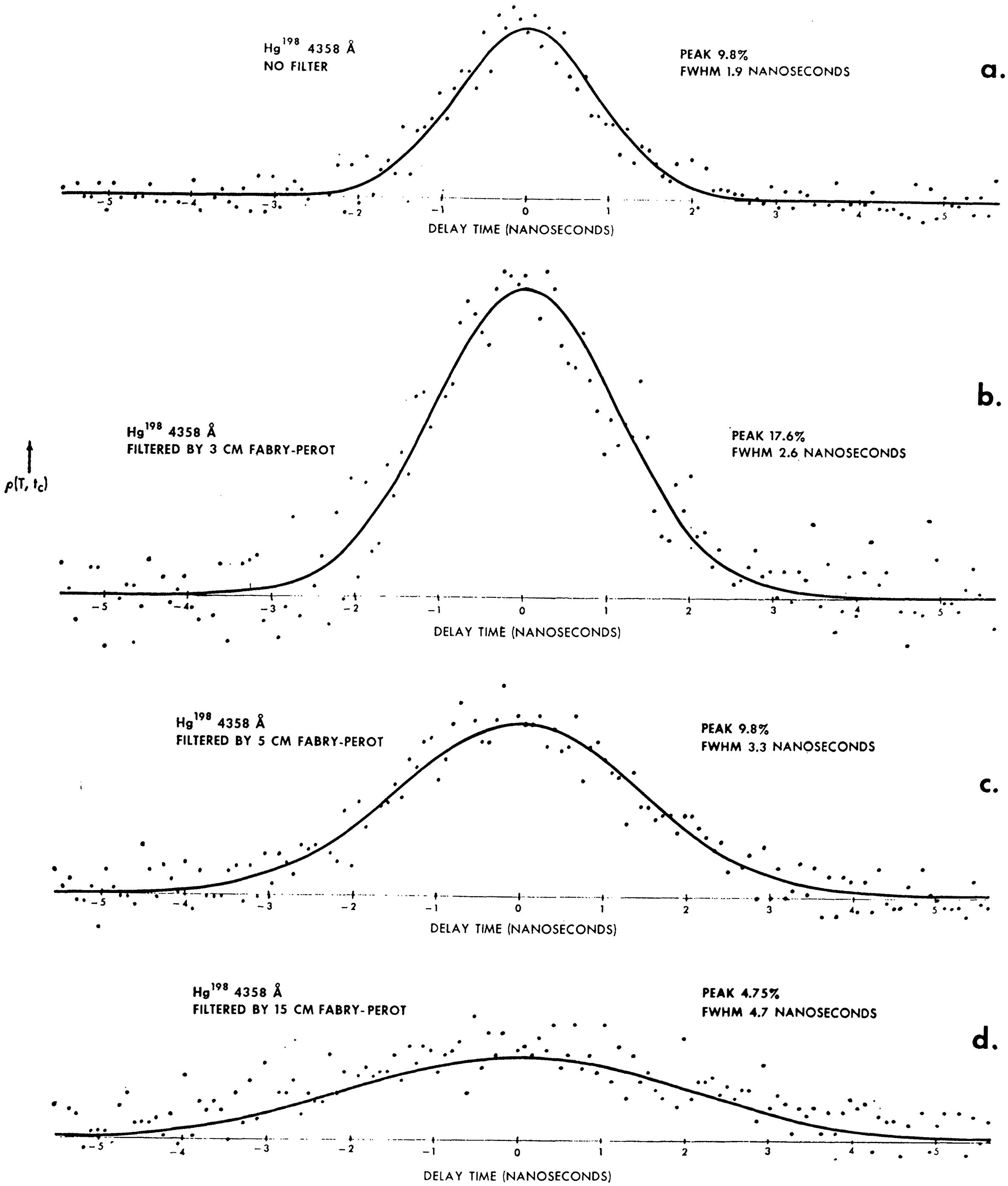

FIG. 2. Number of coincidences versus delay time for filtered Hg^{198} 4358 Å light. (a) No filter. (b) 3-cm Fabry-Perot filter. (c) 5-cm Fabry-Perot filter. (d) 15-cm Fabry-Perot filter.

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The light source was a small quartz electrodeless discharge tube containing about 0.1 mg of mercury-198 in 0.2 Torr of argon, excited by a low-power 25-GHz magnetron oscillator, and cooled with a room-temperature air blast. An interference filter was used to isolate the 4358 Å line. The light from the source was collimated by two pinholes with diameters ranging from 0.3 to 2.0 mm, separated by a distance of 1.5 m. The light emerging from the collimator was polarized by a Glan-Thompson prism and divided into two beams by a partially reflecting dielectric mirror. The two beams were detected by separate RCA C-31000 photomultipliers operated at room temperature with an over-all potential of 2600 volts. Pulses from the phototubes were amplified by limiting transistor amplifiers with gain 100 and rise time less than 2 nsec and then fed to pulse shapers and a time-to-height converter manufactured by Chronetics, Incorporated. The resulting pulse spectrum was analyzed and recorded by a RIDL 34-27 multichannel analyzer.

During the filtered runs the linewidth was narrowed by imaging the fringe pattern of a Fabry-Perot interferometer on the first pinhole of the collimator. When the beam was filtered severely it was necessary to compensate for the loss of light by increasing the size of the collimating pinholes. The loss of spatial coherence and the effect of dark current kept $\rho(0)$ from approaching 1 as the bandwidth of the light was narrowed. The single-count rate ranged from about 1×10^5 to 3×10^4 counts per second, while dark current was about 2×10^3 counts per second.

DISCUSSION OF RESULTS

The curve $\rho(T,t_c)$ obtained for polarized but otherwise unfiltered 4358 Å light is shown in Fig. 2(a). Since the line was measured to be a Gaussian of width 900 MHz, the expected $\rho(T)$ is a Gaussian of full width at half-maximum (FWHM) equal to 0.68 nsec. The measured value of 1.9 nsec implies that the jitter in the detector contributed 1.77 nsec to the observed width of $\rho(T,t_c)$. The detector jitter seems to be largely due to the photomultiplier, since independent checks of the electronics lead to jitter of less than 0.5 nsec. Also, the measured rise time of single photoelectron pulses was found to be 2 nsec which implies that random processes in the phototube can randomly shift the pulse by 1 nsec.

Figures 2(b), 2(c), 2(d) show $\rho(T,t_c)$ for 4358 Å light that has been narrowed in spectral width by a Fabry-Perot filter. The filtered line shapes were approximated by Lorentzians, and the corresponding exponential correlation function was convolved with a Gaussian photomultiplier response function to obtain the observed correlation function. The linewidths implied by the observed correlation times shown in Table 1 were calculated by using tabulated values of Gaussian integrals. The linewidths may be independently estimated from the measured parameters of the Fabry-Perot filter. These widths are also shown in Table 1 and are in reasonable agreement with the values obtained by the intensity correlation method. The agreement of the two methods would be better tested by exact numerical calculations of the line profiles and the effect of detector jitter.

TABLE I. Summary of numerical results.

Light source	Unfiltered	3-cm Fabry-Perot	5-cm Fabry-Perot	15-cm Fabry-Perot
Counts/channel	75 000	4000	14 300	20 000
Counting time (h)	13	21	31	50
Spatial coherence (path diff./λ)	0.92	1.53	2.45	2.45
$\rho(0)$ (%)	9.8	17.6	9.8	4.75
FWHM of ρ (nsec)	1.90	2.60	3.30	4.70
Corrected FWHM of ρ	0.68	1.06	1.95	3.37
Linewidth from correlation measurement (MHz)	···	208	113	66
Linewidth from Fabry-Perot (MHz)	900	160	100	75

COMMENTS

The intensity correlation method described above distinguishes between amplitude and frequency modulation of a signal, and thus may be useful in special applications where the characteristic fluctuation times of the signal are between 1 and 500 nsec. However, the loss of light due to the requirement of spatial coherence usually puts this method at a big disadvantage with respect to conventional spectrographic methods of linewidth measurement.