

EXCESS PHOTON NOISE AND SPECTRAL LINE SHAPE
OF LASER BEAM

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Photons having spin one unit obey Bose-Einstein statistics. In a light beam they do not move independently but tend to group together. Because of this "bunching" effect the fluctuation in the radiation power will be larger than the value predicted by applying classical Poisson statistics to the photon flow.

There are two equivalent ways of describing these excess fluctuations. Either, one treats the photons as bosons, or one treats them as independent particles following Poisson statistics and in addition takes into account the intensity fluctuations associated with the wave character of electromagnetic radiation¹). The latter fluctuations may be understood by considering the radiation as composed of waves with different frequencies interfering with each other. Because of this "beating" the resulting wave amplitude is not constant but fluctuates irregularly. Since the photo-electric emission, i. e., the number of electrons emitted per sec is proportional to the radiation intensity, i. e., the square of the wave amplitude, this amplitude fluctuation causes an excess noise (over and above the shot noise) in the photo-current of the detector ref. 2-5). This "wave-interaction noise" is precisely what is predicted by applying B. E. -statistics in the corpuscular description of the radiation. The excess noise, however, becomes important only if the number of photons per unit Bose cell is at least of order unity and if the photo-electric quantum yield is not too low. At optical frequencies the former condition can hardly be met with conventional light sources as it would imply radiation temperatures of the order 20.000°K or higher.

When we are dealing with a distant light source of very small angular diameter the wave-front is virtually plane and spatial correlation of this excess noise effect is to be expected. This has actually been shown by measuring the cross correlation of the fluctuations in the photo currents of two photocells viewing the same star²).

When we have a monochromatic light source radiating within a frequency interval of total width B , the upper limit of the beat frequencies of the interfering wave components will be B . As a conse-

quence the excess noise in the photo current of the photocell will be confined to a frequency band $O - B$. Therefore, a frequency analysis of the excess noise in the photo current (or the determination of the auto-correlation function) reveals the width and even the shape of the optical spectral line. A theoretical treatment has been given by one of us in the case of a symmetrical line shape⁶). Calculations have been carried out both for a photo-emissive cell and a photoconductive cell (cf. also 7-9, 18)).

The optical maser is an excellent source of monochromatic, high-intensity radiation for testing the theory of the excess noise effect^{10, 8, 11}). Moreover, electronic noise analysis, which is easily performed down to the audio-frequency range, seems to be an attractive method for determining the width and shape of the extremely narrow optical maser line(s).

In the experiment to be described here, the noise power spectrum of a photo sensitive p-n junction cell illuminated by a continuous optical gas-maser beam was determined.

The maser used was developed by Van Bueren et al. at Philips Research Labs. at Eindhoven and has been described earlier in this journal¹²). It is a compact, continuous He-Ne maser fed by a d. c. discharge, emitting maser line(s) at 1.153μ . The area of the circular window is about 7 mm^2 . No monochromator or lens system was used. Only a polariser was inserted in the maser beam. The contribution of the visible light output of the gas-discharge was completely negligible. A small circular diaphragm (diameter 1.5 mm) was placed at the centre of the output window.

A Ge p-n junction cell (Siemens type TP 50) with reverse bias (cell voltage = 30 V, load resistance = $75 \text{ k}\Omega$) was placed at the axis of the maser beam at a distance of about 20 cm. The output current of the cell was measured by a dc microammeter. The dark-current of the (uncooled) cell was about $1 \mu\text{A}$. For a similar diode a photo-electric quantum yield of 64% was found in the near infrared region up to 1.5μ ¹³). The effective photo-sensitive area of the cell is 0.5 mm^2 .

The noise output of the cell was amplified by a

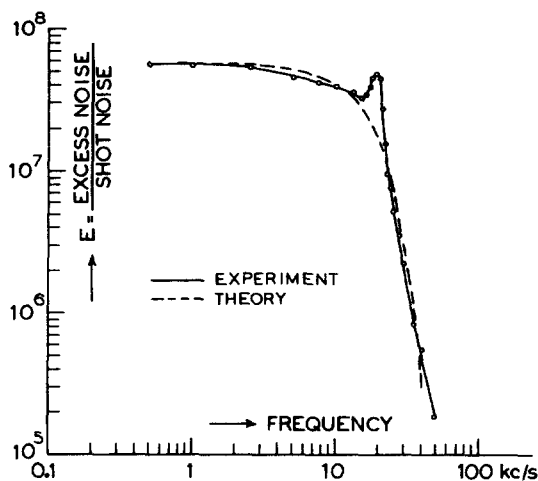


Fig. 1. Relative excess noise E in photo-current plotted as a function of frequency. Circles represent experimental results. Dotted curve is predicted by theory when adapted to fit the experimental curve for vanishing f .

conventional ac amplifier. It was analysed as a function of frequency by means of an electronic synchronous noise analyser with a constant bandwidth of 100 and 500 c/s, resp. and with a continuously controllable tuning frequency ¹⁴). The apparatus was calibrated by a standard noise source (diode tube showing full shot noise ¹⁵). The photo-current of the junction diode showed full shot noise when illuminated by a conventional light-source. Dark-current noise and amplifier noise were completely negligible when compared to the maser-induced noise. During measurements the stability of the maser operation was checked by reading the diode current and by viewing the far-field pattern of the maser-beam with the aid of an infra-red converter. Moreover, the output of the ac amplifier was displayed on an oscilloscope screen and measured with a broad-band ac voltmeter.

In fig. 1. we have plotted the relative excess noise power E which was measured as a function of frequency when the polariser was turned into a position giving maximum photocurrent ($= 2.85 \mu\text{A}$). E is defined as the ratio of excess noise power to full shot noise power which would occur if the photo-electrons were emitted independently ¹⁵). An inaccuracy of about 10% may be expected in the measured E -values. Under the conditions of the experiment the light-source is not resolved by the detector, i. e., the solid angle under which the detector receives the laser radiation is markedly smaller than λ_0^2/A where λ_0 is the central wave length of the radiation and A is the detector area. Under this condition and under the assumption that only one mode of the laser oscillation contributes to the photo-current, formulae (10) in ref. 6) apply.

These formulae predict the power spectrum of the photocurrent noise for the case where the (symmetrical) optical line has a Doppler-, a Lorentz-, or a rectangular intensity distribution, respectively.

Neglecting the peak at 19 kc/s in fig. 1 the (smoothed) experimental curve seems to fit best the case of a Doppler line shape. In this case the theory gives the following expression for E

$$E(f) = (\bar{i}/2eB\sqrt{\pi}) \exp[-f^2/4B^2]$$

where \bar{i} is the mean photo-current, $-e$ is the electron charge, f is the frequency of noise measurement, and B is the frequency bandwidth of the optical line, \bar{i} being known from measurement, this formula contains *only one* parameter, B , which is to be determined. When one adapts B in such way that the limiting value of E for vanishing f agrees with experiment, then the above formula predicts the decay of E with increasing frequency. The dotted line in fig. 1 shows the theoretical function $E(f)$ when $B (= 9.0 \text{ kc/s})$ is chosen such that theoretical and experimental curves coincide for vanishing f . The agreement found in the whole frequency range under investigation is satisfactory. Of course it should be noted that the optical line may differ from a pure Doppler intensity profile.

When working with other directions of polarisation or without polariser, we found similar curves for E with substantially the same frequency width but with plateau values which are lower by at most a factor 3. A lowering of plateau value (at the same frequency width) is to be expected when one assumes that more than one (independent) oscillation mode contributes to the photo-current ⁶). It is essential to note that we have never found curves with *higher* plateau values (at the same frequency width).

The additional peak at 19 kc/s in fig. 1 seems to be correlated to plasma instabilities (e.g., striations) in the dc gas discharge (cf. also ref ¹²). With decreasing discharge current the peak frequency decreased while the height of the peak increased. An oscillation of the same frequency was also found when observing the gas-discharge from a transverse direction. It is conceivable that plasma instabilities are responsible also for the rather large optical bandwidth found (cf. also refs. ¹⁶⁻¹⁷). This might explain why the theory of the excess photon noise, based on the assumption of a Gaussian random light source, appears to be applicable to the fluctuations of a laser beam (cf. also ref. ⁹).

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NUCLEAR MAGNETIC PROPERTIES OF ADSORBED He^3 *

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We have measured the temperature dependence of the nuclear magnetisation M of a monolayer of He^3 adsorbed on zeolite, by the technique of nuclear resonance at liquid helium temperatures. We found M not to follow the Curie law, but to exhibit the behaviour shown in fig. 1, which closely reminds one of the curve of spontaneous magnetisation of ferromagnetics below the Curie temperature.

The relative values of M have been measured by the continuous wave method, namely looking at the absorption signal area far from saturation ref. 1, 2). As is well known, for low values of the rf field H_1 this area is proportional to MH_1 , and therefore the initial slope of the area versus H_1 curve yields the static magnetisation M . Care was taken in all these measurements that this linear relationship was fulfilled, and in this way we excluded any temperature dependent effect of the relaxation times. Incidentally, the absorption line width increased about twice in the adsorbed He^3 lowering the temperature from 50° to 1°K.

Our electronics works at 12 Mc/s, and has been described elsewhere 3). The absorption signals are observed in an oscilloscope and now are also recorded as a dc signal after a convenient rectifier, finally giving a number proportional to the area. The magnetic field was modulated at 50 c/s, the passage through resonance being not a true low-pass, but it was verified that the rate of passage was affecting only the saturation region and not the linear initial region.

When applied to pure He^3 above 1°K, the above

technique yields an initial slope which is inversely proportional to the absolute temperature, according to the Curie law $\chi = C/T$, where χ is the nuclear magnetic susceptibility, T the absolute temperature and C a constant. In this particular experiment, to reduce the relaxation time of the pure He^3 , the pyrex cell filled with some potassium chromium sulfate deposited on a strip of scotch tape.

The results of the adsorbed He^3 were quite different. In these experiments a nearly spherical pyrex cell of 1 cm diameter was filled with about 1 g of type 13 X synthetic zeolite **. The cell was placed in a liquid helium dewar and the He^3 gas was allowed to be adsorbed in a controlled amount. The zeolite was baked under vacuum at 350°C before the experiment and the He^3 gas was purified in a trap at liquid helium temperatures. During every run the He^3 pressure was constant in the temperature range so far investigated, and was monitored by a gauge to be sure that no desorption was taking place. The amount of He^3 never exceeded 120 cm³ STP, therefore the average surface coverage is about 0.10 cm³/m² and is much less than the quantity needed to form the first monolayer 4).

Several experiments have been carried out, and they all agreed showing a temperature independent magnetisation towards the lowest temperatures. The results of two runs are shown in fig. 1, these runs were made during different days with the

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** Manufactured by Linde Company.