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LIGHT QUANTA AND INTERFERENCE

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Abstract

Interference experiments were carried out in which the source was so faint that effects could be attributed to separate quanta of radiation. The energy radiated in the helium line 4471A from a glow discharge was measured by comparison with a black body, and from the known decay constant of the atomic radiation process, the separation of atomic radiations in time was deduced. With an echelon diffraction grating the characteristic double order pattern was photographed when each quantum of light passed separately through the instrument. Under these conditions it gave rise to a pattern due to simultaneous passage through several steps. With an air film between two parallel plates, interference fringes were photographed in 4471, when the quanta emitted from the volume of the source used were completely separated in time, showing that a single quantum obeys the classical laws of partial transmission and reflection at a half silvered mirror and of subsequent combination with the phase difference required by the wave theory of light.

Several recent experiments with x-rays have suggested that the process of radiation from a single atom may be quite different from that considered in the classical theory. Experiments by Compton and Simon,[1] Bennett,[2] and Bothe and Geiger,[3] have suggested that the radiation scattered by an electron is sent out in a definite direction with respect to the recoil electron, and experiments by Bothe[4] show that the resonance radiation excited by x-rays is emitted in one direction, and not spread over a spherical wave-front.

Experiments with visible radiation have failed to show any such peculiarities, although Joos[5] suspected differences in the scintillations observed with narrow bundles in different directions. Schroedinger[6] and Gerlach and Lande[7] found no lack of ability to interfere in bundles of light with different directions. Many experiments have been carried out with faint sources by G. I. Taylor;[8] R. Gans and P. Miguez[9] and by P. Zeeman;[10] but no anomalous effects were detected. In these experiments, however, it was always possible that the effects obtained were due to the action of many light quanta, so that the peculiarities observed with x-rays may still be associated with the radiation emitted from a single atom. By means of the Wilson cloud expan-

[1] A. H. Compton and Alfred Simon, Phys. Rev. **26,** 289 (1925).
[2] R. D. Bennett, Proc. Nat. Acad. Sci. **11,** 601 (1925).
[3] Bothe and Geiger, Zeits. f. Physik **32,** 639 (1925).
[4] Bothe, Zeits. f. Physik **37,** 547 (1926).
[5] Joos, Phys. Zeits. **24,** 472 (1923).
[6] E. Schroedinger, Ann. d. Physik **61,** 69 (1920).
[7] Gerlach and Lande, Zeits. f. Physik **36,** 169 (1920).
[8] G. I. Taylor, Proc. Camb. Phil. Soc. **15,** 114 (1909).
[9] R. Gans and P. Miguez, Ann. d. Physik **52,** 291 (1917).
[10] P. Zeeman, Physica, November 1925, p. 329.

sion chamber and the Geiger counter, effects due to elementary emission processes may be observed with x-rays. These direct observations cannot be carried out with visible radiations; but experiments in which we may be sure we are dealing with the radiation from a single atom are made possible by the observation with canal rays of the upper time limit for the elementary radiation process from the atomic source used.[11] In these observations rapidly moving radiating atoms passed into a highly evacuated chamber, and it was found that the radiation decreased to a small value in three to four centimeters. Professor Wien[12] found that the radiation emitted by helium atoms of wave-length 4471A decays according to the factor $e^{-2\alpha t}$ where $2\alpha = 5.42 \times 10^7$ sec^{-1}, so that after 5×10^{-8} seconds the intensity is reduced to 1/15th. On one point of view we may regard the actual atomic emission process as very brief, so that the experimental factor gives the rate of decay of the excited states. We may, on the other hand, regard each source as radiating continuously and gradually dying out according to the exponential law.[13] In either case the observations set an upper limit to the time required for an atom to send out the energy involved in an elementary radiation process.

In the present experiments the energy radiated from a certain volume of the tube in one spectrum line was measured, and the number of elementary emission processes per second was obtained by dividing the energy per second by the value of $h\nu$ for the frequency selected. If the time for each emission process multiplied by their number is much less than one second, the individual quantum of radiation from any atom must be separated in time from the radiation emitted by other atoms.

I. The Wave Front Covered by a Single Light Quantum

The first experiment was designed to see if the energy of wave-length 4471A radiated from a single helium atom was spread over a wave front greater than that subtended by 32 sq. mm at a distance of 34 cm. The experimental arrangement is shown in Fig. 1. A high potential battery supplied a continuous current of about 10^{-5} amperes to the discharge tube which contained helium at low pressure. The current was controlled by a kenotron and the energy emitted per second in any line was obtained by comparison with the black body *F*. The light from the tube passed through an echelon grating and prism as indicated. The echelon was tipped slightly so that the different parts of each spectrum line gave interference patterns that alternated between the single order setting shown at *A*, and the double order setting *B*. A glass plate with horizontal opaque lines was placed in front of the slit to limit the areas from which interference patterns were obtained. Behind the helium tube was placed the electric furnace *F* for measuring the energy radiated from the tube.

Many photographs were taken of the helium lines with different currents through the tube, and showed the usual interference patterns, in one case

[11] W. Wien, Ann. d. Physik **60**, 597 (1919); A. J. Dempster, Phys. Rev. **15**, 138 (1920).

[12] W. Wien, Ann. d. Physik **73**, 487 (1924).

[13] Recent experiments by McPetrie, Phil. Mag. **1**, 1082 (1926), tend to show that the "time of excitation" and "time of radiation" are of the same order of magnitude.

an exposure of 24 hours with a current of 1.2×10^{-5} amperes was required. The energy in this case was found by widening the slit from 0.01 to 0.8 mm, removing the echelon grating from the arrangement in Fig. 1, and observing that the furnace at 1125° absolute gave the same intensity at 4471A as the helium tube with the current used. This was done by comparing each in turn with a lamp L. The energy radiated from an area S of a black body to an area A at a distance r is given by the formula $2E_\lambda\Delta\lambda\ SA/r^2$[14]. Here $E_\lambda = hc^2\lambda^{-5}\ (e^{-hc/k\lambda T}-1)^{-1}$ and $\Delta\lambda$ is the change in wave-length corresponding to the width of the image at the wave-length used. Substituting for S the slit area, for A the area of the end of the echelon 4.82 cm² and for r the focal-length of the collimator objective it was found that 4.2×10^{-10} ergs per second reached the end of the echelon from an opening of the narrow slit that gave a normal interference pattern. Since $h\nu$ for $\lambda = 4471$A is 4.41×10^{-12} ergs the energy photographed was only 95 quanta per second.

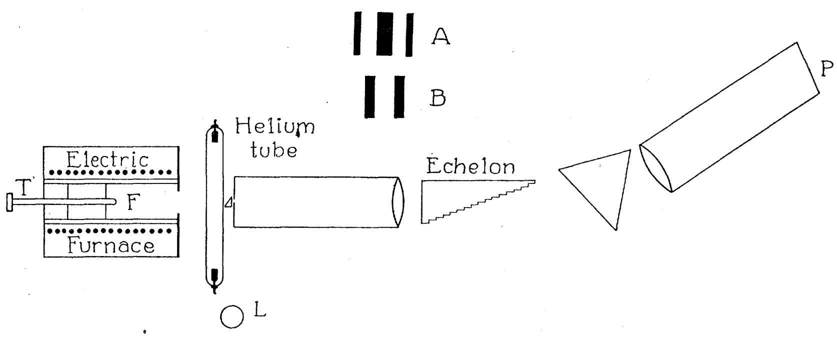

Fig. 1. Experimental arrangement for Part I.

As discussed above these quanta must have passed through the echelon separately, since 95 times 5×10^{-8} seconds is much less than unity.

We conclude then, that a single light quantum can produce effects that are due to its passing through several steps of the echelon simultaneously, that is, it must cover a wave-front larger than that subtended by the end of each plate, or 32 sq. mm at a distance of 34 cm.

On the wave theory the diffraction pattern of a single atomic source produced by a slit 0.01 mm wide on the end of the echelon is of appreciable intensity over several steps, so that there is no difficulty in explaining the interference pattern on this theory.

II. Coherence of Reflected and Transmitted Parts of a Light Quantum

In interference patterns produced by an air film between two parallel plates, we have interference of the part of the radiation reflected at the first surface with the part transmitted at the first surface and reflected from the second. On the quantum theory we might expect an individual

[14] W. Wien, Ann. d. Physik **23,** 415 (1907); M. Planck, Wärmestrahlung, p. 17–19 and p. 182.

light quantum to follow either one path or the other according to the laws of probability.[15] Interference photographs were made with the arrangement shown in Fig. 2.

The source H shown in detail in the lower part of the figure was a tube with helium at low pressure, in which light was excited by electrons from the hot cathode C. The anode to which several hundred volts were applied was at the end of a small side tube 1.25 mm in diameter. This small tube was placed vertically in front of the plane parallel plates P which were inclined slightly so as to form horizontal interference fringes at the reflecting surface. The spectrograph gave an image of these fringes crossing each line of the spectrum. The volume V of the source that contributed radiation to form a light or dark point in the image could be calculated from the geometry of the arrangement. By placing the tube between a black body radiator and the spectroscope as explained above, the total energy of wave length

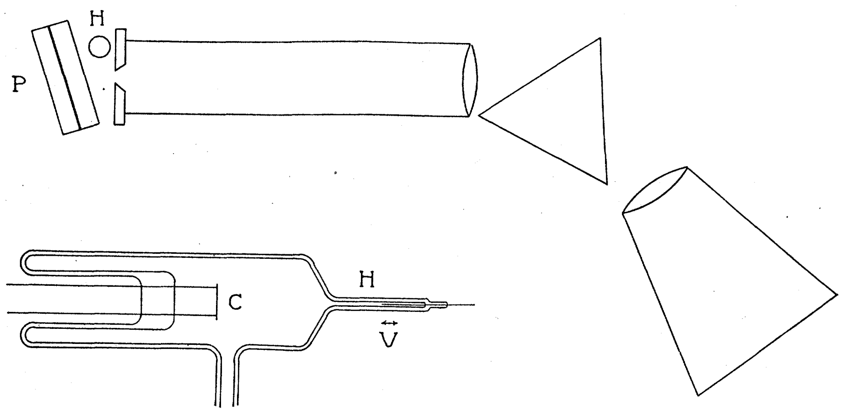

Fig. 2. Experimental arrangement for Part II.

4471A, radiated by volume V was measured for different current strengths. With the smallest currents ($<2.1\times10^{-6}$ amperes) the direct comparison was made with the brighter line at 5016A, and the energy at 4471A was deduced from the ratio of the energies as found with the larger currents. The assumption of constant energy ratio in the two lines is justified since the changes in intensity were made by varying the electron emission while keeping the velocities of the electrons the same.

It was found possible to make photographs when the source was so faint that only one atom in the volume V was emitting radiation at one time. This is a more stringent limitation on the source than that obtained in the first part of this paper. There, it was shown that the light quanta, if limited to a solid angle less than that subtended by the end of the echelon at the slit, must have passed the echelon separately. This was sufficient, since the point in question was the solid angle covered by the radiation from a single atom. Here the energy of wave length 4471 radiated in all directions from volume

[15] Einstein, Phys. Zeits. **24**, 472 (1923).

V was made up of elementary radiation quanta which were completely radiated before the next began.

The results of a series of photographs under these conditions is given in Table I.

TABLE I

Current through tube (micro amp.)	Exposure (hours)	Volume of source (mm³)	Energy radiated per sec (ergs)	No. of quanta per sec.	Probability of overlapping	Fringes
1.17	12	1.54	4.53×10^{-5}	1.03×10^{7}	0.355	Plain
.22	9	1.54	8.67×10^{-6}	1.97×10^{6}	.080	Doubtful
.40	6	1.54	1.54×10^{-5}	3.50×10^{6}	.138	Plain
.10	17	1.54	3.17×10^{-6}	7.21×10^{5}	.030	Plain
.05	26	.75	8.36×10^{-7}	1.90×10^{5}	.008	Fair; under exposed.

The probability of overlapping is the probability that the radiation of a second atom should begin less than 4.25×10^{-8} seconds after the first. Within this time according to Wien's observations, the atom would have radiated 90 percent of its energy on the idea of a continuous emission from the atom. The interference pattern observed must be produced by the radiation emitted in a single elementary emission process, and we must conclude that this bundle of energy obeys the classical laws of separation at a half silvered mirror and of subsequent combination with the phase difference required by the wave theory of light.

If we assume that the interference pattern is determined by a virtual radiation field before the emission of energy (thought of as sudden) takes place, it is necessary to suppose the pattern to be formed anew by each individual atom before it radiated. For, if the number of excited atoms present at any instant disappears according to the law $e^{-2\alpha t}$ as found by Wien, the probability of the emission of a quantum in Δt for each atom is $2\alpha\cdot\Delta t$. If in the equilibrium state of a radiating gas under constant excitation, there are N excited atoms present at any time, then $2\alpha N$ is the number of emissions and excitations per sec. Our experimental conditions were chosen so that this number divided by 2α was small compared with unity. That is $N\ll1$. Thus the greater part of the time no excited atom at all was present in the gas. When one is formed it must, on this point of view, form the interference pattern, and emit the quantum of energy before a second is excited.

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