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TWO BEAM INTERFERENCE EXPERIMENTS AND SOME QUANTUM CONCEPTS

Chandrasekhar Roychoudhuri

SUMARIO

Algunos experimentos de interferencia de dos haces como una doble-rendija simple, una doble-rendija holográfica y un interferómetro de Michelson han sido descritos y analizados con el propósito de demostrar que hay conflictos de concepto en las suposiciones de los libros de texto para explicar la "dualidad partícula-onda".

ABSTRACT

Some two-beam interference experiments like the simple double-slit, the holographic double-slit and the Michelson interferometer are described and analysed with a view to demonstrate that there exist conceptual conflicts behind the usual text book assumptions to explain the so-called "wave-particle duality."

I. *Introduction*

Since Young's demonstration of interference phenomena of light and Maxwell's mathematical formulation of the existence of electromagnetic waves, we have grown accustomed to think of light as some kind of wave phenomenon. Such concepts of scientists were further strengthened by the fact that most of the effects of light from ordinary interference and diffraction effects to photoelectric emission can be explained rigorously treating light as a wave phenomenon (even though the particle concept of light (photon) was first firmly established to explain the photoelectric effect by Einstein). At the same time, one finds that during the last few decades, various phenomena like the Lamb-shift, the anomalous magnetic moment of the electron, spontaneous emission, etc., that cannot be rigorously explained without the "particle concept" in the sense that the electromagnetic field needs to be quantized (Scully and Sargent 1972). Thus, the electromagnetic radiation appears to show a duality in its character. This same kind of duality is also ascribed to the elementary particles and atoms since they leave particle-like trajectories, well defined by our mechanics, in cloud or bubble chambers, while in other experiments, they can also produce interference patterns like electromagnetic waves. Landé (1975) has attempted to do away with this duality, at least for particles, by using Duane's (1923) momentum quantization rule of scattering of an x-ray photon by periodic potentials like crystals and gratings. In his description the incident single particle does not have to know the spatially extent periodic "scatterer"; the "scatterer" knows its periodicity and exchanges quantized momenta with the "particle" following the relation (Landé 1975),

$$\Delta p = nh/L \qquad (1)$$

where Δp is the momentum exchanged, n is an integer, h is Planck's constant and L is the separation of lattice planes in a crystal or separation between the slits in a grating. Although the spirit of Landé's approach is very commendable, he has not given a completely satisfactory answer as to how one part of a very large crystal, or worse, the edge of one "slit" of a large grating made of many rods each one hung from a different mount, can have knowledge about the existence of a periodic structure in space lying by its side. [In the Mössbauer (1964) effect one does make gamma quanta exchange momenta with the whole crystal instead of the single nucleus which is emitting or absorbing it, but only in a crystal at low temperature and when the energy of the Einstein oscillators in the crystal is much larger than the recoil energy of the gamma quanta.]

One notable outcome of Landé's particle scattering concept is to further support a prevalent opinion that even if a single particle (or photon) is incident on the system, the appropriate diffraction or interference pattern will be generated when the total number of particles passed through the system is very large. The oft cited system is that of a double slit diffraction pattern. It is almost universally accepted that even though the single incident particle passes through one slit, the associated wave packet knows (Copenhagen School, Stapp 1972) or the slit system knows (Landé 1975) the existence of the two slits and the particles appear on the screen with a density distribution resulting from the square of the modulus of the simple classical superposition of wave amplitudes. Almost all the authors of the text books on Quantum Mechanics (QM) state that "accepting" this addition of probability amplitudes (in contrast to classical probability density) to arrive at the final density distribution is at the heart of "understanding" QM. Such a trend of thinking has been epitomised by the strongly supported (Mandel 1964) famous statement by Dirac (1967), "each photon then interferes with itself. Interference between different photons never occurs". As before, we shall raise a few philosophical questions as to the validity of such statements and then we shall proceed to describe a few thought experiments to test such statements.

We are all very familiar with the beat phenomenon. When two electromagnetic waves of two frequencies (ν_1 and ν_2) overlap, they produce a resultant oscillation at the difference frequency, $\nu_2 - \nu_1$. By the photon concept, certainly $h\nu_1$ and $h\nu_2$ are distinguishable particles and they must be accepted as "different photons" (Schiamanda 1972). Further, philosophically it is very hard to accept that an elementary particle or some other object can make itself appear or disappear to produce the desired interference pattern by itself. Then, we can also raise the following question. The statistical interpretation of QM is the only accepted one at present, in spite of the variations in the detailed outlook (Ballentine 1970). Then, does this statistical QM have any mathematical authority to describe the physics of any process that strictly involves a single particle? The question of ensemble comes in here. Usually we accept even if we had one particle at a time, a large number of similarly prepared particles form a quantum mechanical ensemble and one can apply the probabilistic laws of QM to this ensemble. Whereas in almost all the experiments, one has an ensemble which consists of a large number of identically prepared particles, but all of them present at a time. Then, we should be able decisively to answer the identity of the two ensembles, both of which consist of similarly prepared particles, but one has only one particle at a time and the other has the entire set of particles present at a time.

We shall next describe a few experiments which are related to the interpretation of single particle interference.

II. *The Double Slit Pattern*

The experimental set up is shown in Figure 1. S is the screen which detects the double slit pattern. DE is a conventional double slit but could be made of three separate pieces mounted separately. The illumination of the system is slightly unconventional. We are using a plane parallel Fabry-Perot interferometer suitably tilted to an incident laser beam so that two consecutive transmitted beams pass through the centers of the slits D and E respectively; the higher order transmitted beams are blocked off by an appropriate screen. At the focal plane of the lens L, one can record conventional double slit cosine fringes (Roychoudhuri 1975).

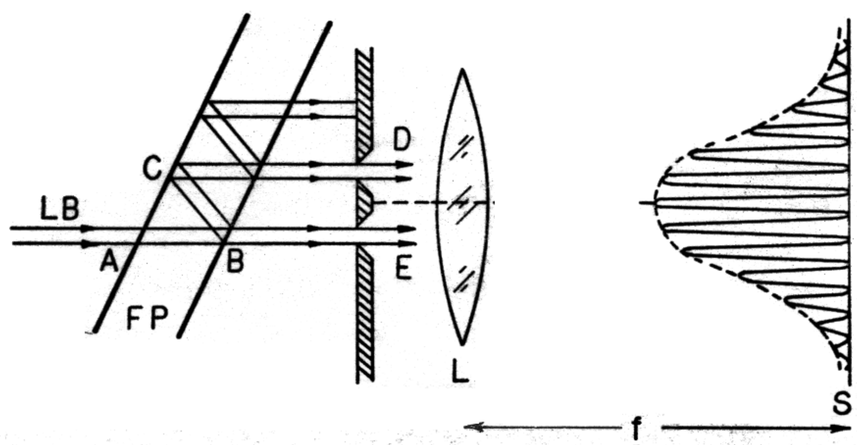

Fig. 1. *Simulation of a double-slit experiment using a tilted Fabry-Perot interferometer and a laser beam. LB—laser beam; FP—Fabry-Perot; L—focussing lens; f—focal length of L; S—observation screen.*

Now, from a knowledge of the waist size of the laser beam, one can make the width of the slits D and E large enough so the two beams can pass through the appropriate slit almost unobstructed. Then, actually one can remove the slits and still record the double slit pattern, of course, the higher order transmitted beams should remain obstructed. Under these circumstances, because of the limited waist size of the laser beam, the probability that a photon belonging to the beam D will pass through E is negligibly small. Thus the statement that the particle passing through D is affected by the existence of the slit E appears to be baseless. As a matter of fact, this experiment can be extended to simulate a grating pattern without using a grating at all (Roychoudhuri 1975).

One might argue that the trick lies in using two beam splitters of the Fabry-Perot interferometer. As a matter of fact Dirac (1967) does say, "the new theory (QM) which connects the wave function with probabilities for one photon, gets over the difficulty by making each photon go partly into each of the two components." It is hard to justify such a statement because the "two components" of the same photon from B would arrive at different times at D and E. The time and position coordinates being valid quantum mechanical observables, the "two components" of the same photon or two "complete" photons must be distinguishable, even if they have the same frequency, by virtue of their different time and position coordinates. After all, a photon is emitted over a finite period of time from an atom of finite spatial size, so the photon must also have a finite space-time extension. One would find it difficult to support Dirac's statements by saying that photons are indistinguishable particles and there exists only a "world photon function" (Schiamanda 1972). [A brief digression. If a photon has a finite space-time extension, how can it be represented by $h\nu$, ν being a single (monochromatic) frequency? Then, it cannot carry the information of the atomic line width. Nor does the concept of Fourier expansion allow it. The question may be more fundamental. What does an atom emit, an indivisible photon or a spreading packet of electromagnetic radiation? Again we have the philosophical problems whether statistical QM has the authority to or can answer such single-particle phenomena or shall one cease to ask such questions since the Copenhagen School claims QM to be complete and we cannot get any more information regarding a single event than QM delivers. Or should one try to develop Micromechanics for single events? Further, if a photon is a space-time limited packet of radiation, why should it be able to produce a steady state interference pattern while a classical short pulse of light produces a time-varying pattern? (Roychoudhuri 1975).]

Let us come back to the double slit pattern. Performing an experiment as described in Figure 1, one can clearly see that only in the focal region, where the two beams are superposed by the lens, can one record the two beam pattern. Thus, it is the real physical superposition of different wavefronts carrying different phase and amplitude information that produces the interference fringes.

The response of the detecting materials being proportional to the square of the modulus of the resultant amplitude, the detector cannot detect any presence of electromagnetic energy in the regions corresponding to the dark fringes; this is not, as Landé's concept would have it, because no photons arrive at the dark regions. This difficulty can be further appreciated by following the two beams beyond the focal plane as they diverge as two independent beams without bearing any effect of having interfered in the focal zone. Then, is it possible that even a single photon in the system can give the information of two-beam energy distribution in the focal region of the lens while, immediately after this region, it gives the information regarding the energy distribution of any one of the two but separate and independent beams? Or in other words, if one follows one of the beams, one finds that it has a given uniform distribution of electromagnetic energy (photons) from the Fabry-Perot (Figure 1) to the beginning of the focal region; then suddenly in the focal region (only when the other beam is present) the distribution of the photon density follows a cosinusoidal variation; but the distribution again becomes uniform immediately beyond the focal region. Can one reconcile such an observation with the statement that no photon arrives the dark regions, especially, if one assumes that a "particle" should travel in straight lines in a field-free region? [Such a question has been raised before (Roychoudhuri and Cornejo 1975).] The conceptual difficulty in accepting that no photon arrives at the dark regions becomes more acute when one considers the interference of two coaxial beams propagating in exactly opposite directions. A photographic record with high resolution plates will show parallel layers of dark planes. Then, is it possible to accept that photons did not arrive in one set of alternate planes while their presence has been detected in the other set of alternate planes? Would not they have to pass through "no photon arrival planes"?

Most of our discussion is centered around photons or electromagnetic radiation. But many basic two-beam interference and diffraction experiments have also been reported for electrons (Merli et al. 1974 and Jönsson 1974). Therefore, arguments very similar to the ones in this paper can also be constructed for the interference experiments with particles that, unlike photons, have non-zero rest-mass.

III. *Michelson (Twyman-Green) Interferometer*

Since the dominant features of a double-slit diffraction pattern can be described as two-beam interference, we also use a Michelson (Twyman-Green) interferometer to question the feasibility of interference with a single photon. At the same time, we also question the classic argument of QM that knowledge of which of the slits the photon is passing through and observation of a two-slit pattern are mutually exclusive.

The interferometer is shown in Figure 2. A is a point source, L is a collimating lens, B is a 50% beam-splitter, C and D are two 100% reflecting mirrors and O is an observer or a photodetector. If C and D are stationary, then whether an incident photon will be reflected back to the source or arrive at O depends upon whether the relative path difference, BCB − BDB, is an odd multiple of $\lambda/2$ or an integral multiple of λ, respectively. Can a single incident photon gather the

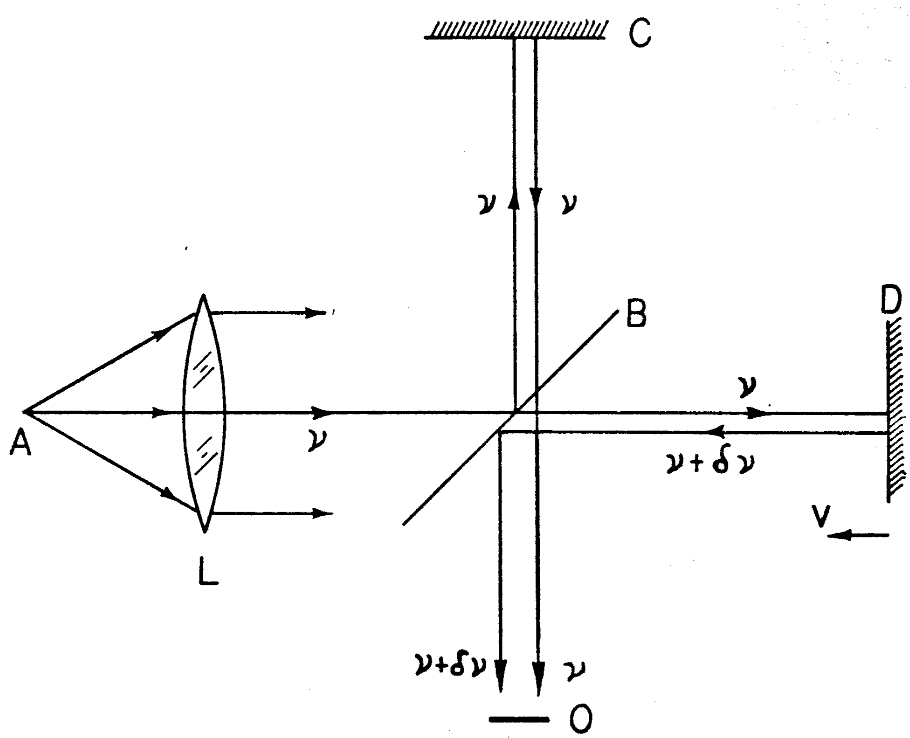

Fig. 2. *Counting fringes in a Michelson interferometer with one of the mirrors moving. A—point source; L—collimating lens; B—beam-splitter; C—stationary mirror; D—moving mirror; O—observer or detector.*

information of both the optcial paths, BCB and BDB? If the photon is indivisible, the paths are mutually exclusive. If the photon is divisible the "two components" cannot come back at the same time on B whenever the path difference, BCB − BDB, is appreciable.

Let us dramatize the situation a bit more strongly by giving a steady velocity to one of the mirrors, say, to D. If it has been displaced by a distance v per second, then the number of cosinusoidal fringes which will cross through O per second, will be given by

$$n = 2v/\lambda \tag{1}$$

But this steady velocity will introduce a frequency shift due to the Doppler-Fizeau effect to the photon that is reflected from D,

$$\delta\nu \equiv \nu - \nu' = 2v(\nu/c) = 2v/\lambda \tag{2}$$

This is precisely the frequency of the cosine beat signal produced due to interference of two radiations of frequencies ν and ν'. The identities of the frequencies in equations (1) and (2) are not at all surprising and are routinely observed in almost all the laboratories. But the interpretation of the experiment through equation (2) leads to further doubt as to the feasibility of interference with a single photon. Can a single incident photon $(h\nu)$ carry different information, $h\nu$ and $h(\nu + \delta\nu)$, and make itself appear and disappear to O at a frequency $\delta\nu = 2v/\lambda$? Further, if one imagines that the two slits of a double-slit experiment have been split apart to C and D with the help of B (Figure 2), then one can argue that it is possible to identify through which of the "slits" the photon has passed, because if it comes from C, it should have frequency ν, while if it comes from D, then it should have frequency $(\nu + \delta\nu)$. In that case, these must be distinguishable photons.

IV. *Double Slit Pattern through Holographic Interferometry*

In the first experiment of a double-slit pattern we have emphasized the importance of the real physical superposition in interferometry. We further illustrate our point with the help of holographic interferometry. The experimental arrangement is shown in Figure 3, where the pattern due to two slits can be synthesized through holography from the individual slits, A and B. Either of these slits, say B, can be closed with a screen S and the pattern due to the other can be recorded holographically in the focal plane of the lens L. Then one can reconstruct the pattern due to slit A and interfere it (in "real time") with that due to B by closing slit A. The observation will clearly show a double-slit pattern. Thus one can separate the information due to two slits (if they are sufficiently large) and yet observe the appropriate double-slit pattern. Thus, it is difficult to accept the statements that either the diffracted particle or the "diffraction grating" knows the existence of the "periodic structure".

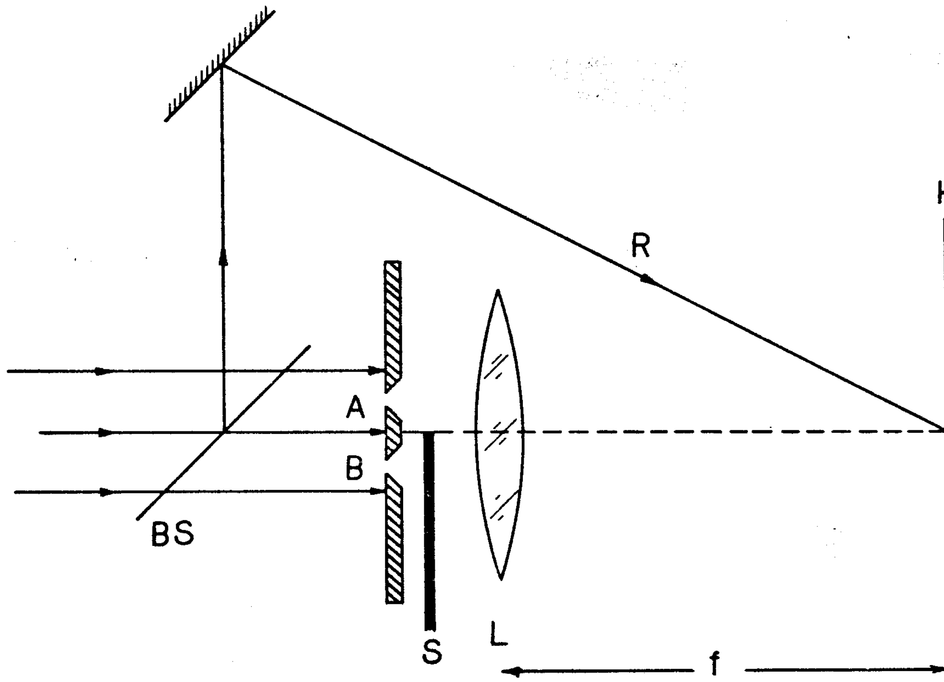

Fig. 3. Holographic recording of two individual single-slit patterns and reproduction of the double-slit pattern. BS—beam-splitter; A, B—two single slits; S—screen to cover one of the slits, A or B; L—fringe focusing lens; R—holographic reference beam; H—hologram or fringe plane.

The experiment can also be performed in a slightly different way. One can record, in two successive holographic exposures, the diffraction patterns due to the two slits separately. Then, after closing both the slits, the holographic reconstruction will show a double-slit pattern, instead of a single-slit pattern. Thus, one can produce a double-slit pattern even after recording the two one-slit patterns in succession, provided one is capable of recording (through holography) both the amplitude and the phase of each pattern.

Most of the introductory books on QM (Feynman 1966, Schiff 1968, Dicke and Wittke 1973) attempt to introduce concepts of Quantum Mechanics by stating that one can never know which slit the particle (photon or electron) is passing through in the double-slit experiment; as if it were a wave and hence the concept of wave-particle duality comes in. These authors emphasize their point by arguing that if one records the diffraction patterns due to the two slits, one slit at a time, by keeping the other one closed, the resultant pattern does not show the double-slit pattern. This is true only if one records the square modulus of the incident beam by means of ordinary photography. But, we have described how, using holography, one can record both the amplitude and the phase of two independent single-slit patterns separately, thus knowing decisively which slit the photons have passed through and still one can reproduce the resultant double-slit pattern. With steady-state beams of light, one can perform such experiments even in a modestly equipped laboratory. But, whether one can perform such experiments with single photons is yet to be determined since controversy still exists regarding the experimental verification of single photon interference (Dontsov and Baz 1967).

V. *Conclusions*

The essential aim of the paper has been to bring forth some conceptual difficulties behind the assumptions which are normally used to introduce the students to concepts of Quantum Mechanics and are also used to support and explain that even a single particle or photon can produce interference effects. The three major questions we have raised in the three experiments described are as follows. Normally, it is assumed that no photons arrive at the zero-intensity points of the interference pattern. How can this concept be reconciled with the experiment where two coherent but spatially distinct beams produce fringes in the region where they overlap while maintaining their independence beyond the region of superposition? Second, whenever the interference fringes vary with time (beat phenomenon) or the incident beam is time varying, severe conceptual difficulty arises as to the possibility of producing such interference phenomena with single photons. Third, the interference patterns can be reproduced (using holography) even after recording the interfering beams successively and independently. Then statements like "the knowledge as to which slit the photon is passing through and the recording of the double-slit pattern are mutually exclusive" appear unsupportable.

In spite of the mathematical self-consistency of QM and its towering success in explaining microscopic phenomena, many philosophical questions regarding the foundation of QM have been raised time and again. Interests along these lines have been recently revived and two major schools of thought can be identified from the papers of Stapp (1972, Copenhagen School) and Ballentine (1970, Statistical Interpretation School). Both these schools agree to the non-arrival of photons at the dark regions of an interference pattern, agree to the reality of single photon interference and to the impossibility of knowing which slit a photon passes through in a double-slit or a grating experiment. After raising arguments against these concepts, we would like to conclude that either there exist contradictory assumptions, hidden or explicit, at the foundation of QM while explaining single-particle phenomena or else the probabilistic (statistical) QM is inherently incapable of explaining the physics behind such single-particle phenomena.

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SOME INTERFERENCE EXPERIMENTS AND QUANTUM CONCEPTS II

C. Roychoudhuri, R. Machorro and M. Cervantes

SUMARIO

Continuamos con nuestro intento de demostrar las razones de nuestra inconformidad con las interpretaciones de Mecánica Cuántica sobre los fenómenos de interferencia y difracción dadas por las Escuelas de "Copenhagen" y "Statistical". En este artículo proponemos que el principio de superposición se acepte como una realidad física, no como una construcción matemática proyectada para obtener resultados y se debe escudriñar hasta el último para averiguar sus límites en el reino Cuántico.

ABSTRACT

We continue our attempt to demonstrate the reasons for our disagreement with Quantum Mechanical interpretations of basic interference and diffraction phenomena given by both Copenhagen and Statistical Interpretation Schools. And we are proposing that the principle of superposition be understood as a physical reality rather than as a mathematical construction devised to arrive at results and should be pursued to the extreme to ascertain its limits in the Quantum realm.

I. *Introduction*

In a previous article (Roychoudhuri 1975a) we discussed a few two-beam interference experiments from the view point of an experimentalist to show "that there exist conceptual conflicts behind the usual text-book assumptions to explain the so-called wave-particle duality". In this follow-up paper we present some simple classical experimental results that are routinely produced in laboratories in some form or another with explanations direct from classical wave theory. But these results, as we shall see later, can be interpreted as the demonstration of the reality of the principle of superposition (interference). To put it differently, the effect of redistribution (or redirection in the propagation) of energy due to interference arises only when at least two similar physical entities carrying different physical information (phase, amplitude, etc.) are simultaneously present. Thus, when an interferometer or a grating is irradiated (i) with a single pulse of width narrower than its characteristic path-delay, or (ii) with a series of coherent narrow pulses of separation larger than the said path-delay, one does not observe customary stationary interference patterns (Roychoudhuri 1975b, c). All these are understood from simple classical real physical superposition (or classical causality).

Let us then define our methodology of thinking for this paper. We assume that the method of accumulation of knowledge is never direct. Every piece of our information is gathered in two stages of interaction or scattering between a minimum of three physical entities; the first stage of interaction is between the entities under study and the chosen "standard" (at least partially known), and the final stage of interaction is between the observing or detecting entity and one of the entities of the initial interaction. Thus any observation whatsoever forces all the three entities involved into new states and hence a complete description of past, present and future requires a complete knowledge of all the states in every detail correlated by an objective physical theory attempting to model nature. Until we can ascertain all the details, we can repeat similarly prepared experiments and then apply that knowledge to predict the future behavior of another similarly prepared system. Further, when the entities involved in a multistage interaction during an observation have space and time extension and are compound in the sense that they can carry more than one quantity of the same physical property (like phases), then the final information must constitute a superposition of all the similar information. Here we should emphasize that such superposition is real, physical and causal, i. e., the entities carrying the different information must be present in the same local region and must be present simultaneously for physical communication of information. We note in passing that an elementary particle to be elementary should not be able to carry more than one quantity of the same physical property at the same instant.

II. *Holographic Double-slit*

One of the most discussed problems in the explanation of phenomena of interference and diffraction by Quantum concepts is the double-slit pattern. [The very acceptance of the wave-concept for light was strongly established first by Young's (1802) principle of interference demonstrated by his famous double-slit pattern. For an accurate and lucid demonstration of double-slit patterns with light see Hecht and Zajac (1974).] From published books and literature, it appears that the majority of the Quantum physicists explain the origin of the double-slit pattern in one of the following two ways. First, the constituent "particle" of the wave (electron, photon, etc.) has extension and "interacts" with the extended periodic "potential" of the double-slit in some "mysterious" way (Feynman 1966) to produce the observed pattern. This is, probably, to "explain" the still controversial claim that even a single photon can produce interference (Mandel 1968, Dontsov and Baz 1967). This group also accepts that "the condition under which the interference pattern is produced forbids a determination of the slit through which the particle passes" (Merzbacher 1970) and the adherence of this group is generally to the Copenhagen Interpretation School (Stapp 1972). The second group generally belongs to Statistical Interpretation School (Ballentine 1970). Their explanation of the double-slit or grating pattern is that the grating "knows" its periodicity and acts "as a whole" to exchange momenta with the constituent "particles" of the wave and that diffraction is a process of scattering (Landé 1975). Before criticizing these interpretations we should like to mention that there are other Quantum physicists who are trying to develop a different mechanics (de la Peña and Cetto 1975, Phipps 1975, Boyer 1975) instead of just stretching the interpretation of the existing Quantum Mechanics.

The angular distribution of energy is different in the near-field (Fresnel) and the far-field (Fraunhofer) patterns. Neither of the above schools can explain how the trajectories of particles after passing through the grating change without hypothesizing the existence of a new long-range force between the grating and "particles" (Feyerabend 1968, 1969; Roychoudhuri and Cornejo 1975). It is also an observed fact that a second screen isolated from the double-slit but placed immediately after it, just covering one of the slits, gives rise to a single-slit pattern instead of a double-slit pattern. But by either school of interpretation, one should still see a double-slit pattern, maybe with reduced irradiance, since neither the "photons" nor the double slit should have a priori knowledge of the existence of a screen beyond the double-slit.

We want to demonstrate that the double-slit pattern arises simply due to real physical superposition of two similar physical enties each passing through one of two slits. The lateral separation of the two parts corresponds to two different bits of phase information at the region of real physical superposition giving rise to a new distribution of detectable energy. Then one must be able to demonstrate that each slit allows a part of the incident wave to pass through carrying the corresponding phase information.

Here one must recognize the experimental limitation of our detection devices for very high frequency electromagnetic radiation or "particles". They are without exception square-law detectors. They detect the square of the modulus of the incident complex amplitude and thus destroy our capability of ever recording the absolute phase. But, even so, we know that the relative phase can be recorded through interferometry that constitutes superposition of more than one wave. Further, using holographic interferometry (Gabor 1948, Smith 1969), one can even reproduce the complex amplitude information of any wavefront. If the complex amplitudes from the two slits are recorded separately but holographically with the help of the same reference beam, one can reproduce the two-slit pattern even after recording one slit at a time. Thus, the reality that a physical entity is passing through each slit can be demonstrated.

The conventional double-slit experimental set up is shown in Fig. 1a; Fig. 1b is a sketch of the resultant irradiance. The complex amplitudes at the plane of observation due to slits 1 and 2 are represented by

$$\psi_1 = a\, e^{i\phi_1} \text{ and } \psi_2 = a\, e^{i\phi_2} \tag{1}$$

Then the resultant irradiance is,

$$|\psi_1 + \psi_2|^2 = 2a^2\,[1 + \cos\,(\phi_2 - \phi_1)]. \tag{2}$$

The relative phase difference, $\phi_1 - \phi_2$, is the essential characteristc of the double-slit pattern. The central region of such a pattern is shown in Fig. 2a. But, if one records the square modulus of each of ψ_1 and ψ_2 the resultant pattern will be completely devoid of the double-slit characteristics,

$$|\psi_1|^2 + |\psi_2|^2 \neq |\psi_1 + \psi_2|^2. \tag{3}$$

So, let us now introduce the holographic recording with a reference beam (Fig. 3) so that we can record and reconstruct the phase information. The steps are as follows (Smith 1969):

(a) Holographic recording.

$$|\psi_R + \psi_1|^2 = |\psi_R|^2 + |\psi_1|^2 + \psi_R^*\,\psi_1 + \psi_R\,\psi_1^* \tag{4}$$

(b) Holographic development.

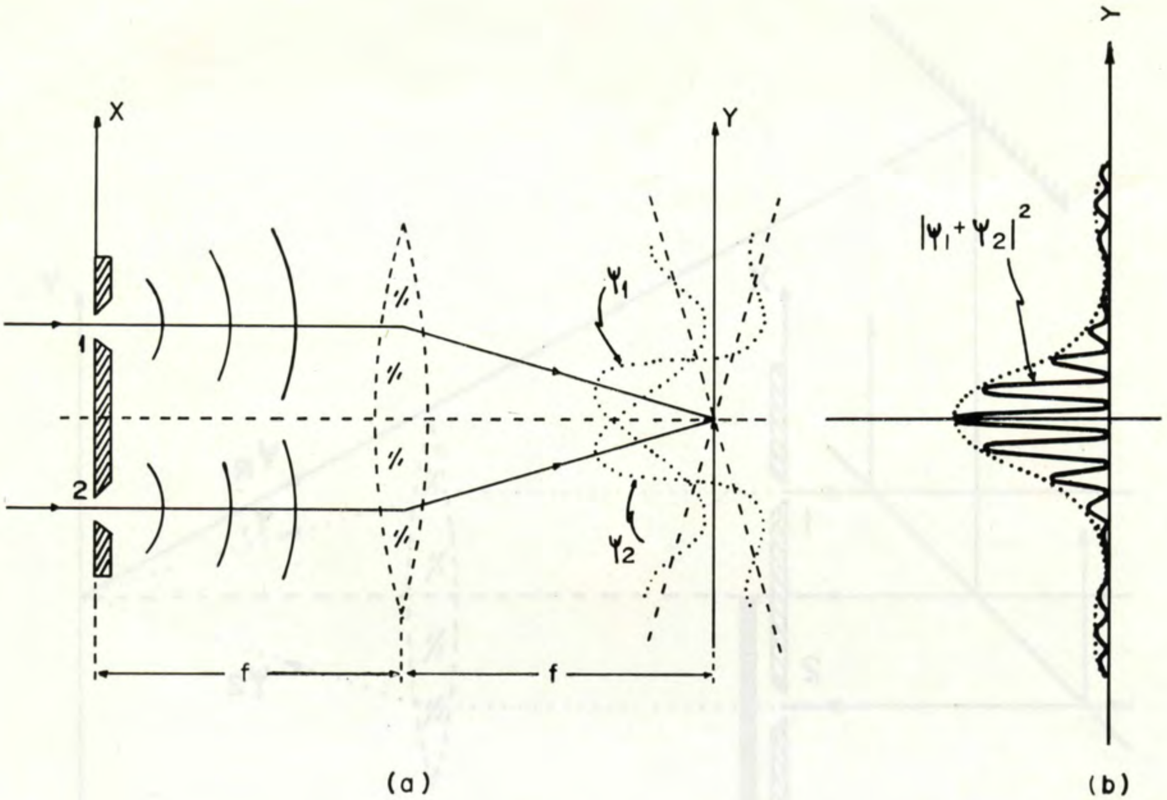


Fig. 1. *A conventional arrangement to obtain a Fraunhofer double-slit pattern.* (a) *X-double-slit plane: Y- Fraunhofer pattern plane; ψ_1 and ψ_2 are two single-slit patterns at the Y-plane due to slits 1 and 2.* (b) *The cosinusoidal double-slit patterns,* $|\psi_1 + \psi_2|^2$.

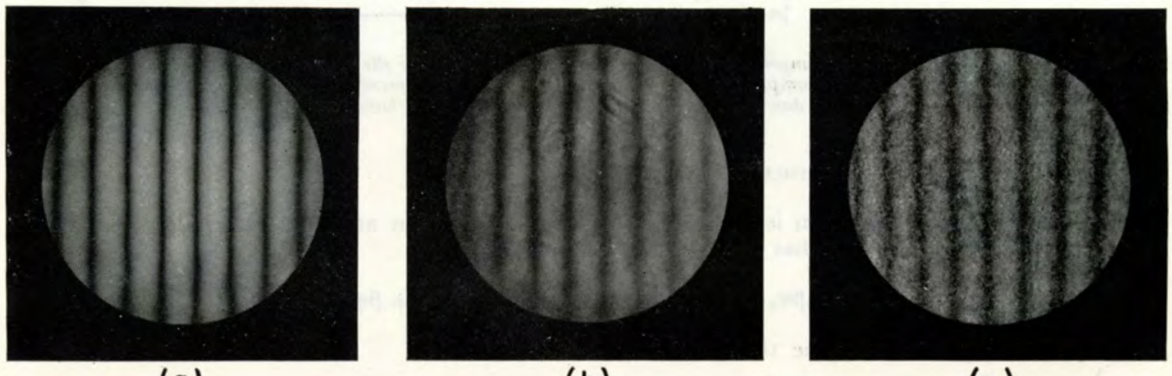


Fig. 2. *Photographs of the experimental cosinusoidal fringes of the central region of the Fraunhofer double-slit pattern.* (a) *Regular double-slit pattern recorded with the arrangement of Fig. 1.* (b) *Holographic double-slit pattern due to the same double-slit but after recording the single-slit patterns due to each slit separately.* (c) *Holographic double-slit pattern of the same double-slit where the single-slit pattern due to slit-1 was recorded and then reconstructed at the hologram plane (Y) while the other single-slit pattern due to slit-2 arrived at the Y-plane "live" from the X-plane (while slit-1 was closed). See text for details.*

This gives rise to a characteristic transmission of the hologram that is proportional to the recorded irradiance of Eq. (4),

$$t = \beta\,[|\psi_R|^2 + |\psi_1|^2 + \psi_R^*\,\psi_1 + \psi_R\,\psi_1^*], \tag{5}$$

where β is a constant.

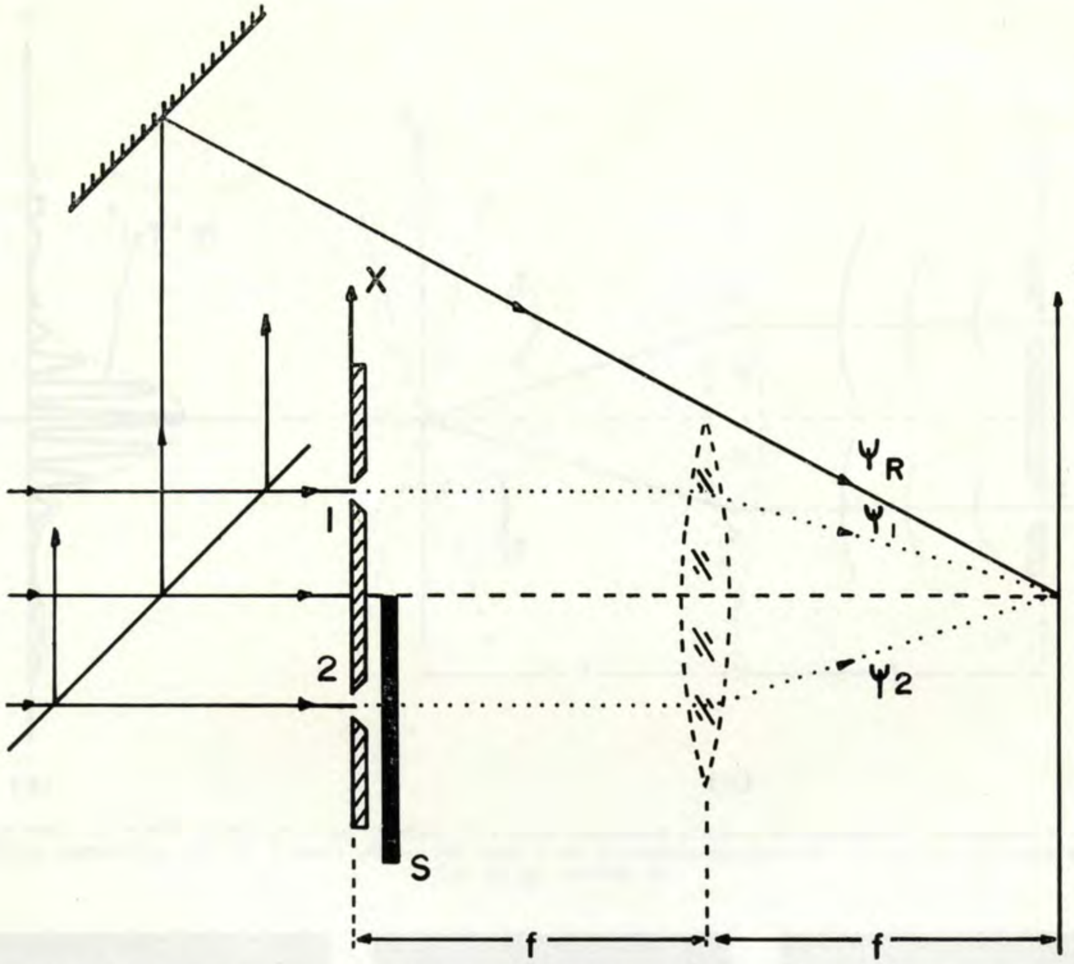


Fig. 3. *Holographic experimental arrangement to record the pattern due to one slit at a time and then to reproduce the conventional double-slit pattern in complete detail. ψ_R is the holographic reference beam and ψ_1 and ψ_2 are single-slit waves due to slits 1 and 2. Y is the plane of the hologram.*

(c) Holographic reconstruction.

The developed hologram is replaced in its original position and it is reilluminated with the same reference beam, ψ_R, that has a uniform amplitude,

$$t\psi_R = \beta\psi_R|\psi_R|^2 + \beta\psi_R|\psi_1|^2 + \beta|\psi_R|^2\,\psi_1 + \beta\psi_R{}^2\,\psi_1{}^*. \tag{6}$$

β and $|\psi_R|^2$ being constants ,the third terms,

$$\psi_1' = \beta|\psi_R|^2\,\psi_1 \equiv c\psi_1, \tag{7}$$

corresponds to the reconstruction of the original complex amplitude ψ_1. The wavefronts corresponding to other terms propagate in directions other than ψ_1 and hence can be physically separated from ψ_1.

Then a similar but separate recording of ψ_2 on the same hologram and corresponding reconstruction will produce

$$\psi_1' + \psi_2' = c\,(\psi_1 + \psi_2), \tag{8}$$

that will give us the same pattern as that of Eq. (2), but with a multiplying constant. The proper experiment can be carried out as follows. One records ψ_1 using a screen S (Fig. 3) to cover slit-2. Then, changing the position of S, ψ_2 is recorded after covering slit-1. The reconstruction of the hologram, after covering both slits, gives rise to the same two-slit pattern (Fig. 2b) that one obtains directly from the two-slit system without any holography or screening (Fig. 2a). Thus the reality of ψ_1 and ψ_2 is established.

A variation of the above experiment goes as follows. First ψ_1 is stored in the hologram as in Fig. 3. Then slit-1 is kept closed and slit-2 is opened and simultaneously the hologram is reconstructed. If the hologram characteristic and illumination are so adjusted that the complex amplitude ψ_2 after passing through the hologram changes by a constant factor c to $c\psi_2$, then one has, because of holographic reconstruction,

$$c\psi_1 + c\psi_2 = c\,(\psi_1 + \psi_2). \tag{9}$$

This is the same as Eq. (8). Once again the two-beam pattern as shown in Fig. 2c is observed, which is similar to the patterns shown in Figs. 2a and 2b. Here we see that ψ_1 can be stored in one plane and ψ_2 can still be allowed to be generated from the original slit-2, again showing the real existence of both ψ_1 and ψ_2.

This holographic technique can be extended to prove the real existence of all the wavelets from every single slit of a grating using a suitable holographic material that can reconstruct many different wavefronts.

III. *Large Grating Illuminated by a Limited Wavefront*

The model of real physical superposition implies that interference phenomena are due to local "interaction". But this is categorically denied by both the schools we have mentioned. In fact d'Espagnat (1971) explicitly says, "the local effect of these waves is certainly not a correct hypothesis". Therefore, we are reviewing an elementary classical experiment of a large but finite size grating or a crystal illuminated by a wavefront of spatial size smaller than the diffractor (Fig. 4).

Let us take an ordinary grating of N slits each of width $2a$; the separation between the consecutive slits is $2b$,

$$g_N(x) = \left[\sum_{n=0}^{N-1} \delta(x - 2nb)\right] \oplus r(x/2a), \tag{10}$$

where $r(x/2a)$ is a rectangular function of width $2a$ representing each slit of the grating and $\oplus$ denotes convolution. The grating is illuminated by a plane wave, $w(x)$, of spatial width, say,

$$d \simeq m(2b), \tag{11}$$

where

$$m < N \tag{12}$$

So only a small area of the grating is illuminated (Fig. 4a). Mathematically, the combined effect of the grating and the illuminating wavefront is

$$t(x) = w(x)g_N(x). \tag{13}$$

Then the Fraunhofer pattern at the Y-plane is

$$T(y) = W(y) \oplus G_N(y), \tag{14}$$

where,

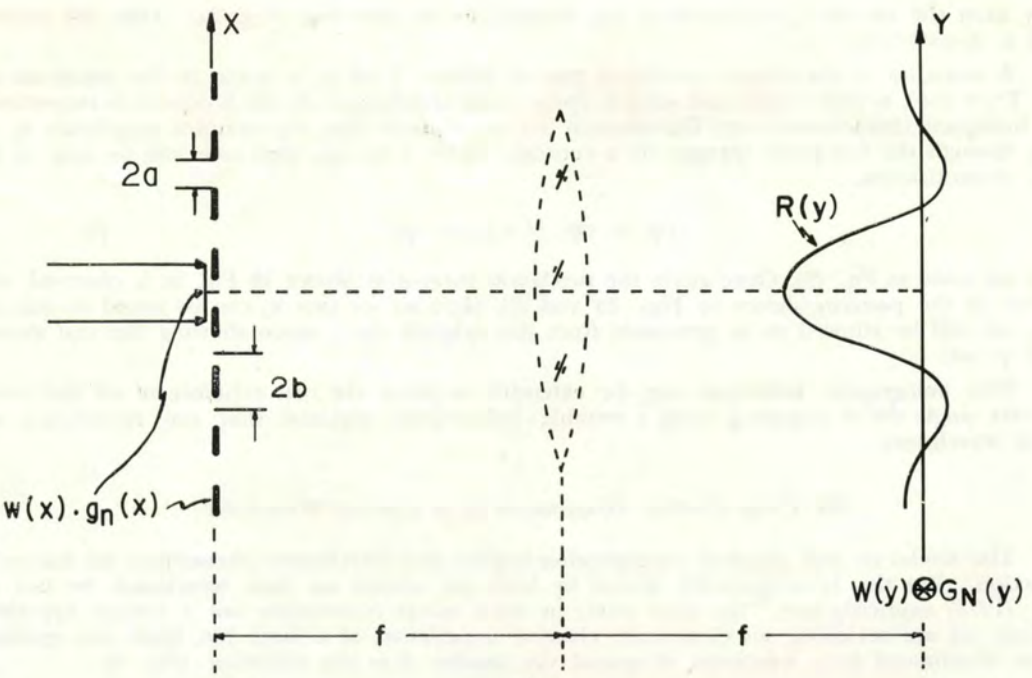
$$G_N(y) = e^{ikby\,(N-1)/f} \cdot \frac{\sin Nkby/f}{\sin kby/f} \cdot R(y) \tag{15}$$

where

$$R(y) = 2a\,\frac{\sin\,(kay/f)}{(kay/f)}\,. \tag{16}$$

If, as a particular example, we assume that $w(x)$ is a rectangular function of width $2a$ (that is, equal to the width of a single slit of the grating),

$$W(y) = 2a\,\frac{\sin\,(kay/f)}{(kay/f)} \equiv R(y), \tag{17}$$



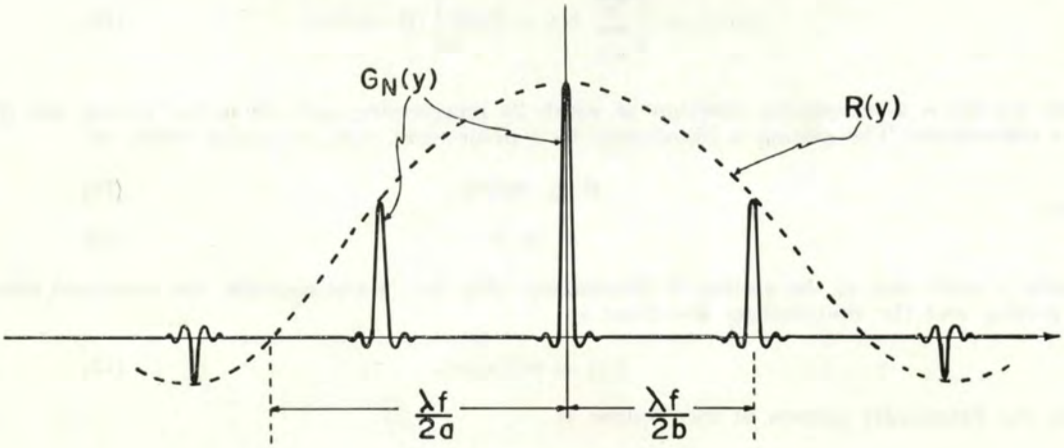


Fig. 4. *Diffraction experiment with a large grating illuminated by a space limited wave-front.* (a) *The large grating $g_N(x)$ is illuminated by a small wavefront $w(x)$ at the X-plane that encompasses only a single slit. Then the observed pattern $R(y)$ at the Y-plane is due to a single slit.* (b) *If the grating acts "as a whole", then the pattern should be a convolution of the single slit pattern $R(y)$ with the N-line grating pattern $G_N(y)$.*

where f is the focal length of the lens used to obtain the Fraunhofer pattern. Then the resultant pattern, according to Eq. (14), should be given by the convolution of the dashed curve of Fig. 4b with the grating spectra denoted by the solid curve. But we know that the result will be a simple single slit pattern because the wavefront that passed through the grating encompassed only a single slit of the grating. Even though $G_N(y)$ exists mathematically, physically it does not, in spite of the fact that the Statisitcal Interpretation School claims that the grating exchanges momenta with the "particles" "as packet associated with a particle, irrespective of

a whole". What physically exists is $R(y)$ because the wave has passed through one $r(x)$ (single slit) and has brought oniy that information to the Y-plane. To predict this observed result, the Copenhagen Interpretation School would have to introduce a new hypothesis to the effect that the size of the wave ~~Figure 5 shows a Fraunhofer pattern that~~ its other physical properties, depends upon the particular instrument that produces it.

Figure 5 shows a Fraunhofer pattern that is characteristic of an 8-line grating (there are six secondary maxima) even though the grating used has 21 lines. This was produced by using a wavefront whose spatial extension was such that it could illuminate only 8 lines of the grating. We shall cite a somewhat similar experiment with a crystalline substance. A transparent solid body of CaF_2, roughly 1 cm^3, made of randomly oriented crystallites of average size 200 micron was illuminated with a focussed laser beam of 20 micron diameter. Brillouin spectra characteristic of a pure single crystal was obtained (Brody, Roychoudhuri and Hercher 1973). If the "photons" did exchange momenta with the entire solid block of crystallites, no Brillouin lines could have been clearly visible.

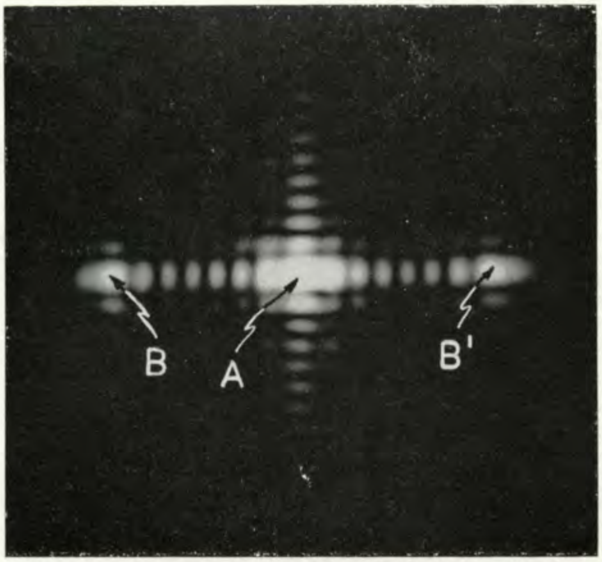


Fig. 5. *A photographic record of the central region of a 21-line grating illuminated by a space-limited wavefront that encompassed only 8 lines of the grating. The pattern shows 8-line, rather than 21-line, characteristics. There are 6 secondary maxima between two consecutive major maxima (AB or AB').*

IV. *Discussion*

We have attempted to emphasize that the "explanations" given by Quantum physicists for interference and diffraction phenomena are incomplete and also have built-in contradictions. The experiments with light we have presented are routinely carried out in laboratories in some form or another. But we are not aware whether anybody has done precisely similar experiments with particles like electrons. While we are eagerly looking forward to see experiments with electron beams in the hope that a very critical investigation might show some distinction between electromagnetic waves and particle waves in the realm of interference and diffraciton phenomena, we do believe that the essential results will be very similar to that due to electromagnetic waves. This is because in the basic single and multiple slit experiments with electron beams the electrons show very similar diffraction characteristics to those of light (Jönsson 1974, Merli et al. 1974).

The arguments we present here against the established interpretations of interference are based on elementary classical physics without any new theory. We are proposing that rejecting the classical principle of real physical superposition is premature; that a thorough investigation is necessary to ascertain if a limit exists beyond which this principle does not apply. We believe that this is directly related with the problem of reality that is extensively discussed in the literature of the philosophy of Quantum Mechanics (Bunge 1967, d'Espagnat 1971, Jammer 1974). A Quantum physical model should take into account the details of the observed classical interference effects mentioned here and in other papers (Roychoudhuri 1975a, Roychoudhuri and Cornejo 1975) and should be able to sucessfully explain them.

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