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Dirac and Photon Interference

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Students' difficulties in applying a statement of Dirac to two-laser interference should have been brought up in connection with many of the traditional beam-splitting experiments, which also involve more than one source. The temptation to add intensities rather than wavefunctions is a throw-back to the classical concept of distinguishable particles, and the intuitive feeling that one can divide radiating matter into distinct sources, each emitting distinct photons.

Recent experiments[1,2] have shown that overlapping beams from separate lasers can produce observable interference effects. Not a few students (and graduates) have expressed difficulty in reconciling this phenomenon with a famous comment by Dirac[3] on the Young double-slit experiment: "...each photon interferes only with itself. Interference between different photons never occurs."

This statement of Dirac is simply the orthodox quantum-mechanical explanation of an interference phenomenon of the Young double-slit type. That is, if two slits are illuminated by a single photon beam, the interference pattern which appears on a distant screen is not to be thought of as an interaction at the screen between two photons, each of which passed through different slits of the pair. Rather, each photon has a probability of arriving at a given spot on the screen and this probability is calculated as the absolute square of the sum of the probability amplitudes over all possible paths from the source to the point of observation. This interpretation predicts the build-up of an interference pattern even if only one photon is let through the apparatus at a time. It is in this sense that Dirac speaks of a single photon interfering with itself and not with other photons.

The students' difficulties with the two-laser experiment seem to stem from the assumption that since the two photon beams originate in two different lasers, the effect must therefore be viewed as being interference between different photons. It should be pointed out that, if this two-laser experiment is to be interpreted as producing interference between different photons, then so also must many other interference experiments, such as the Lloyd mirror, even though macroscopically they seem to be experiments of the "pure Young" type in which two alternative paths are offered to each photon so that it can "interfere with itself" in the Dirac sense.

In the Lloyd-mirror experiment, part of the photon beam is reflected from a mirror so that it overlaps the direct beam on a screen, where an interference pattern results. Does this mirror simply offer an alternative path from source to screen and thus allow each photon to interfere with itself? Macroscopically, it would seem so. However, any present microscopic theory of reflection does not view the mechanism of reflection simply as a change of direction of a photon, which then preserves its identity after the reflection process. Rather, it would seem that the molecules of the reflecting surface absorb the incident photon and emit another photon. There is no reason to suppose that the photon preserves its identity upon reflection; every known mechanism of reflection argues to the contrary. Even in the Compton effect, where one usually speaks of the incident photon as being scattered rather than absorbed, it is difficult to preserve any concept of identity between the incident and scattered photons. In all scattering processes it is usually much more useful—and always admissible—to consider the over-all effect as the result of a two-step process: the annihilation of the incident particle and the creation of the scattered particle.

Upon microscopic analysis, then, the Lloyd

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[1] G. Magyar and L. Mandel, Nature **198**, 255 (1963).

[2] R. L. Pfleeger and L. Mandel, Phys. Rev. **159**, 1084 (1967).

[3] P. A. M. Dirac, *Quantum Mechanics* (Oxford University Press, London, 1958), 4th ed., Chap. I, p. 9.

mirror is a second source of photons just as is the second laser in the two-laser experiment. The Lloyd-mirror experiment, along with similar beam-splitting interference experiments, is already an interference phenomenon resulting from the overlapping of beams from separate photon sources. Using part of the main beam to illuminate the mirror can be thought of merely as a method of synchronizing the two photon sources.

The students' present difficulty with Dirac's statement should, then, have been long ago discussed in connection with the traditional beam-splitting experiments, where one should have faced this same question: Does it follow that interference between the overlapping beams of different photon sources means interference between different photons? Beams and sources are macroscopic objects; photons are elementary particles and are essentially indistinguishable. Indeed, in the two laser experiment does a given photon have any labeling which specifies its source, so that one can, in the interference pattern, meaningfully speak of two different kinds of photons? Is there any operationally valid distinction between the photons coming from each of the two sources? Certainly not. By the same arguments that apply to the "pure Young" experiment, it is impossible to determine the particular source of each photon without destroying the interference pattern as a necessary part of that determination.

One should not, then, calculate the probability of a photon arriving at a given observation point by adding the probabilities of a photon coming from each source, as if each source produced its own identifiable photons. This would be going back to the gross corpuscular-light theories of the past, as if light were composed of classical particles. It would pretend to be able to measure what is in principle not measureable—the particular path and source of any given photon.

One should, rather, calculate the probability amplitude for a photon arrival as the sum of the amplitudes for arrival from each source. One superimposes amplitudes (wavefunctions) and not probabilities (intensities) in the two-laser experiment for the same physical reason that one does so in the "pure Young" type experiment: because one cannot in principle trace the path and determine the point of origin of any given photon in the interference pattern.

The basic difficulty seems to stem from an intuitive temptation to view spatially separated sources as necessarily producing physically different photons, so that one adds intensities and not amplitudes. One should, however, take an over-all "world view," which sees all photon sources in the universe merely as one source with a certain spatial distribution, and calculate its photon wavefunction, rather than calculating individual wavefunctions and intensities for individual parts of the "world source," and then adding intensities. Indeed, this division of the world source into independent parts is in general quite arbitrary and might just as logically be extended to atomic dimensions within a single laser. Such a view would obviate any possibility of coherence among the radiations of the atoms composing the laser, since each atom could then be considered as a separate source of its own photons and we would add intensities, not amplitudes.

This world source view of the photon wavefunction and its sources—quite like the classical view of fields and their sources—recognizes that in the general situation an observed photon carries with it no label identifying its previous path or the location of its source. It is only under special experimental situations that one can associate a definite source location with an observed photon, i.e., when the probability amplitude for paths from all other source locations to the observation point is negligibly small. This, of course, is the reason for shielding and for performing optical experiments in a darkened room.

The world source produces a "world photon wavefunction." The division of this photon wavefunction into separate pieces, each of which represents a different kind of photon, is in the general case quite arbitrary and often meaningless. Photon-detection systems do not in general measure separate intensities, but only the intensity which results from the absolute square of the net wavefunction.

Energy-sensitive detecting systems can be used to Fourier analyze the net photon wavefunction into its various frequency (i.e., energy) components. In such experiments we can, if we choose, meaningfully speak of different kinds of photons, since energy discrimination provides an operational basis for the distinction. This parallels the theoretical process of second quantization which usually begins by treating the Fourier components of the wavefunction, and then defines a number operator for each Fourier component.

To speak of different kinds of photons all of the same energy, however, one must have some other operational basis for the distinction. In the interference pattern of the two-laser experiment one would like to distinguish between two kinds of photons, each kind having originated in a different laser. A measurement of momentum might provide the basis for such a distinction, but one finds, exactly as in the pure Young experiment, that the uncertainty principle forbids such a distinction without destruction of the interference pattern. One cannot operationally speak of two kinds of photons in the interference pattern. Rather, each detected photon might be thought of as the result of the cooperative production of the entire source—which here happens to be two separated lasers.

This is not different, in principle, from the standard interpretation of a single-slit diffraction pattern, where one cannot determine which part of the slit was the origin of a given detected photon. It makes no operational sense to say that each photon did originate at a definite location in the slit if it is in principle impossible to determine that location. Rather, the entire slit—as one source—cooperatively generates each photon. Blocking off the middle of the slit so as to produce two slits, or even replacing the two slits with two different lasers, cannot introduce any new principle for calculating the resultant wavefunction in terms of its total source. It does not introduce a new basis for distinguishing different kinds of photons in the interference pattern in terms of their point of origin in the total source.

In short, the interpretation of a photon wavefunction as representing one or many kinds of photons has meaning only when there is an operational basis for the distinction. The world source produces a "world wavefunction." Whether this wavefunction represents one or many kinds of photons is entirely dependent upon one's definition of "kinds of photons." Such a definition must be operational and consistent with the uncertainty principle in order to have physical meaning, i.e., a detection system which makes this distinction must be physically possible.

These notions are basic to the quantum-mechanical concepts of wavefunctions and particles and go to the heart of the profound differences between these concepts and the classical concept of a particle. Even the very basic intuitive distinction between "one" and "many" is a classical concept with classically operational bases, such as complete spatial separation of groups of observables. Such bases for this distinction are not always possible in quantum mechanics.

The students' "hangup" with some such classical concept will be the weakest link which limits the validity of his conceptual model of quantum mechanics. Lectures and texts in introductory quantum mechanics must address themselves more to the student's torturous problem of forming conceptual models and realizing their limitations, rather than merely giving him recipes for calculating numbers which correspond to meter readings. A student is a classical object and thinks in terms of classical concepts. If he does not clearly recognize the limitations of his conceptual models, he may fall into serious error in applying his calculational recipes to unfamiliar experimental situations. The two-laser experiment is a spectacular case in point. That our lectures and texts have been satisfied in presenting oversimplified models of quantum mechanics, without exposing their limitations, is embarrassingly apparent in the mental gymnastics which so many students (and graduates) are now undergoing in trying to resolve an apparent contradiction between the two-laser experiment and Dirac's statement, in spite of the fact that both Dirac's statement and two-source interference have long been well "known" and "taught."