Quantum complementarity, erasers and photons

A. F. Kracklauer

Bauhaus Universität, Weimar, Germany

Optical experiments designed to explore quantum complementarity are reanalyzed. It is argued that, for each, a classical explanation is not only possible, but more coherent and less contrived. The final conclusion is that these experiments actually constitute support for criticism of the photon paradigm of electric charged particle interaction. They offer little or nothing to say about quantum complementarity once the photon concept is not imposed by mandate.

I. BACKGROUND

Complementarity has become a catch-all concept to cover the weirdness of Quantum Mechanics (QM). Mostly, this is because its originator, BOHR, actually proposed this notion in order to capture exactly these weird features and legitimize them. It is arguably the case, however, that having been unable to remove what were at first recognized as antinomies, they were just redubbed as deep, albeit preternatural, holistic insights into atomic scale ontology. Following the popularization of the term in Physics, BOHR extended the concept to arenas outside the customary boundaries of science even, until it became for him a universal precept, the foundation of a total Weltanschaung. History seems to show that he was only marginally successful at promulgating philosophy. None of his students, nor readers of his papers, agree completely on just whatever it was he tried to convey under the term “complementarity,” even when restricted to within Physics. [1]

Nevertheless, through the decades, authors of textbooks and other secondary literature have focused the notion of complementarity on the issue of particle-wave identity. Out of this literature over time a consensus has crystallized: complementarity refers to that feature of quantum theory to the effect that ensembles of all entities, depending on the scale of the interaction or measurement scheme, exhibit alternately either the properties of waves or particles.

This has led some to suggest that there exists a single, fundamental category, instead of particles and waves, namely “wavicles.” Such abstract unification, however, does not overcome the reality of the matter, namely that this category has two obvious components: those entities which classically are particles and those that are waves. This division is obvious in terms of the characteristic of mass; classical waves can be ascribed only a mass equivalent of energy.

Through the years, various proposals have been made to render this “schizoid” phenomena less mysterious. For each of the two subcategories different conceptions have been proposed: the wave-like behavior of particle beams, for example, has been attributed to various forms of ’pilot waves.’ As is well known, DE BROGLIE, who first suggested that particles should exhibit wave phenomena, more or less explicitly envisioned that particles were a sort of material kernel embedded in such a pilot wave.[2] The wave portion was credited with navigating for the kernel without itself alone interacting with measuring devices, a behavior that eventually led to coining the term “empty wave.”[1]

Proponents of this notion seem to have abandoned it, perhaps because of the internally contradictory conception that a pilot wave can react to all material boundaries except those used in connection with measurements. How can any wave know the difference in purpose of any particular material object it encounters? When is it supposed to communicate with objects so that it can navigate, and when is it to ignore them as the intervention of an experimenter?

This writer has proposed an extention of the pilot wave idea to the effect that such pilot waves are classical electromagnetic background waves attached to particles by virtue of their motion through the random electromagnetic background radiation that is hypothesized as the basis of a theory known as ‘Stochastic Electrodynamics’ (SED), a theory which seeks to rationalize quantum phenomena. [3] Whether this effort is successful, the reader is invited to pursue independently; it is not the central theme of this paper, which concerns the other subcategory, the particle-like behavior of electromagnetic waves.

Particle-like behavior of waves is nowadays credited mostly to EINSTEIN in connection with the Photoelectric Effect. Actually, however, EINSTEIN proposed only that energy transfer occurs in ‘packets,’ it was later that the idea, that the incoming radiation itself is somehow subdivided, captured the common imagination. Still, even today, the conception is vague. Sometimes considered a ‘mode’ of the vacuum, and thereby present throughout the universe on the one hand, elsewhere such packets are envisioned as “needle radiation” with small lateral cross-section, because absorption seems to be point-like. On other occasions they are thought to be shockwave-like, because absorption can be rapid, seemingly instantaneous. In combination, such solutions are difficult to associate with the inhomogeneous wave equation (with sources), as derived from MAXWELL’s equations.

Additional support for packaged radiation was found in the scattering of electromagnetic radiation from electrons, i.e., the COMPTON Effect. This effect is, in a certain elementary manner, just a particular application of the photoelectric effect. In any case, the notion of packages, as a model for waves, particularly electromagnetic waves, has become virtually universal nowadays as the ‘photon’ paradigm. No modern commentator fails to note that, fundamentally, light is a stream of photons without branding himself an ignoramus. This, in spite of the spectacular applicability of non quantum MAXWELL theory. It is interesting to speculate on just why this is so; this writer likes to suggest that the cause is that electromagnetic waves, as such, are never detected. In fact the mechanism of the interaction of charged particles is completely beyond the reach of experimental science, which is restricted to ‘photocurrents,’ for which there are two variants: those acting as sources in antennas, and those driven by the consequences of the former on the other
end in detectors.² In spite of the vividness of the images from paradigms of what transpires in between, either as electromagnetic waves or photon streams, all effective experience for mortals is actually limited to these currents, information on which is then used mentally to infer just how these two currents have interacted in detail across space and through time. This understanding makes photo detection the crux of the matter, and arguably, the essential reason for the utility of the “photon” concept.

Here we come to the point of this paper. The digitization, or ‘quantization’ if one prefers, of charges, is not a result of quantum theory, but an independent empirical fact that serves as an hypothetical input into both classical and quantum theories of physical phenomena; thus, the “quantum” behavior of electromagnetic waves as ensembles of particles, may not be at all “quantum,” but simply a consequence of the discreteness of the charges making up the material of detectors. If we take this observation as a scientific proposition to be tested for internal (theoretical) consistency and external (empirical) verification, then it cannot be regarded as anything other than just another task for work-a-day science. In this spirit, it shall be addressed herein.

II. PROTOTYPICAL WAVE DETECTORS

Electromagnetic wave detectors come in a variety of constructions, each intended for a particular frequency range. In those lower portions of the electromagnetic spectrum where current technology enables following time development of electromagnetic fields, there is little of special interest for fundamental quantum physics analysis. It is only in that range in which this is no longer possible that quantum phenomena seem to arise. Detectors in this range do not follow the undulatory time development of incoming radiation. Instead, they absorb an undetermined number of cycles, and respond then with some bulk transition.

Photographic plates are a good example. Incoming radiation at some point triggers a chemical reaction in molecules embedded in an emulsion that, as differentiated compounds, then serve during development as seeds for some macroscopically visible effect. Likewise, for the photoelectric effect. Incoming radiation eventually results in the transition of a valence electron to the conduction band where it is then drawn off into circuitry to be amplified and registered as the ‘detection event.’ The historical photoelectric effect considered by Einstein has an additional feature that is widely taken as symptomatic of an essential quantum character. It is that the stimulated photocurrent appears virtually instantaneously after the start of illumination. The argument that this is to be explained only by assuming that the incoming energy is bundled in compact packages, nowadays called ‘photons,’ assumes that the electrons, before illumination, were all resting at an energy so low that it would require a measurable duration of exposure to the incoming radiation before they could be energized sufficiently to enable them to overcome binding forces. Such an assumption is not, however, beyond reproach. It could just as well be assumed that the electrons in the detector mass had a distribution of energies attributable to prevalent or incoming noise so that of the whole population, a certain portion at any given instant has noise energy bringing them up to nearly the escape level. Then when a coherent stimulation signal arrives, those electrons at this otherwise temporary ‘almost’ escaped energy level are boosted over the threshold very quickly, virtually instantly. In fact, Lamb and Scully long ago have shown with such ideas that photoelectric phenomena do not entail quantum theory; semiclassical ideas suffice.

The vital point made here is: the digitization of the detector reaction to incoming radiation need not necessarily be attributed to particle-like packaging of the incoming stimulus, i.e., photons. All the behavior involved can be explained fully also in terms of continuous, wave-like radiation of the classical sort known to radio, radar and communication engineers, where the discrete aspects of low intensity measurements are due to discreteness of detector charges. In other words, because charges are the ineluctable intermediaries between mortals and electromagnetic waves, their contribution to the nature of an observation cannot be evaded.

III. COMPLEMENTARITY IN OPTICAL EXPERIMENTS

It is the purpose here to parse the logic of some modern optics experiments plumbing the mysteries of complementarity of electromagnetic interaction. These are, first, two ‘quantum eraser experiments, and then ‘Afshar’s’ experiment; all three are intended to focus specifically on the issue of delimiting complementarity in light.

A. Quantum Eraser

There are several versions of experiments demonstrating this conception proposed first by Scully and Pühl in 1982. The basic idea is to elaborate on a standard two-slit experiment so as to be able to mark the signal passing through at least one of the slits, thereby permitting the determination of which slit the purported ‘photon’ passes through. An extra feature in this proposal was the notion that, with clever design, it could be possible to “erase information” so as to flip the case between wave and particle, most spectacularly after-the-fact even. As is well known, textbook orthodoxy nowadays would have it that if the slit of passage can be determined (a particle-like property), then no interference pattern (a wave-like property) will result.

The difficult trick in conceiving of and performing such an experiment is to find a method to mark a signal on passage through a slit. The original proposal was to employ multilevel atoms in place of slits. The atoms were chosen to have, at least in principle, the same emitted decay radiation but different final states readable by some other measurement. This scheme should allow the experimenter to do, even well after-the-fact, or not do the second measurement; as a consequence, the interference pattern should appear or not appear. (The sense in which the pattern appears or not results from the alternate data reduction calculations feasible with the existence of different elements in the data sets, after-the-fact. It should not be understood that some visual image of an object is made to come and go.) We gather that exactly this setup was never realized, however.

² Actually, every charge vis-à-vis all others, plays both roles; but, to date there is no widely accepted closed form of electromechanics taking this into account.
FIG. 1 A setup for optically testing the ‘quantum eraser’ effect. The basic trick is to try to use the idler emission to mark the portion of the signal passing through each of the slits in a double-slit diffraction experiment.

1. Eraser and double-slit diffraction

A particularly clean and purely optical ‘quantum eraser’ experiment involving two slits, inspired by a conceptually similar proposal of SCULLY et al. [10], was carried out by WAL-BORN et al. and reported in 2002. [11] The essential feature of this setup is that the beam sent towards the slits is the signal output of a parametric down conversion crystal (PDC); the idler is directed separately through another polarizer and then to a detector. See Fig. 1. Here the marking in the slits is considered achieved by placing polarizers before each slit. If the two polarizers before the slits are set to orthogonal positions, then the signals impinging on the registration screen are independent and do not form an interference pattern. This feature is thought to conform with the complementarity principle, i.e., that which-way information provided by a polarization tag put on the signals as they pass through the slits, is said to destroy the wave-information revealed by the interference pattern.

Now, however, if coincident counts between data points taken behind the slits with points seen from the idler beam are analyzed, then the interference effect can be made to reappear—in the coincidence counts. That is, if the polarizer in the idler beam (let us assume from a Type-I PDC) is set to horizontal, then the signal in the vertical channel behind the slits will yield correlated “hits,” (Fig. 2) by effectively filtering out those hits in the horizontal channel for lack of a mate in the idler channel. If the idler polarizer is changed to vertical, then the correlated hits are in the horizontal channel behind the slits, as now the vertical component is filtered out (Fig. 3). If the polarizer is removed from the idler beam, then no correlations with the slits can be made; the only hit pattern available shows no interference, and it is said that “which-way information has been erased” (Fig. 4).

This behavior is said to illustrate quantum complementary. But does it? First note that the various signals used are just different states of polarization. This is very significant because polarization is a phenomenon fully explained by STOKES circa 50 years before the need for quantum theory was known. [12] It is a fully classical phenomenon. How then, can this phenomenon be used to plumb a principle of quantum mechanics? The only even remotely quantum aspect to this story is the implicit assumption that the signals are made up of ‘quantum’ objects, i.e., photons, so that it is presumed their behavior must be regulated by quantum mechanics. But, as was argued above, the possibility of fully non quantum character has not been rigorously excluded.

Moreover, since there are two slits and two different interference patterns, with arguments that are brief and loose (i.e., “it is clear that . . .”) in the customary interpretation, an association is made to ‘which-way’ information. This is done in spite of the fact that each interference pattern is indisputably a two slit pattern. Thereafter, even while observing that the sum of these two patterns is what is observed when the idler polarizer is removed, is is said that this results from erasing some information. One ought be excused for finding this apologia at least lexicographically pathological.

Thus, those who find such imagery based on quantum mechanics at all obscure and contrived may be well disposed to consider the following classical rendition. Let us take it that the signal directed towards the slits is a vertically polarized classical electromagnetic beam. If there are no polarizer filters in front of the slits, after passing through both slits the signal shows inter-
ference on the registration screen. Next let us place polarizers with axes set at $-\pi/4$ to the vertical before one slit, and at $+\pi/4$ before the other slit. Now, each polarizer will split the incoming vertically polarized electric field into two components one vertical and one horizontal, each with amplitude $1/\sqrt{2} \times 1/\sqrt{2}$ times the ‘mother’ signal as determined by Malus’s Law, once as a projection onto the polarizer axis and then again to find the component in either the vertical or horizontal direction. In turn, each orthogonal component or ‘daughter’ signal will result in an interference pattern on the registration screen. But, one pattern will be fringes (Fig. 2), while the other is antifringes (Fig. 3). Because the horizontal diffraction pattern is the sum of opposing components, a phase term of $\pi$ is inserted and the pattern comprises antifringes; in contrast the vertical components are codirectional and in phase. These two patterns together add up to a total pattern without interference (Fig 4). That is, if the daughter horizontal interference pattern can be written

$$I_h(x) = ke^{-ax^2} \cos^2 bx$$

and the daughter vertical pattern

$$I_v(x) = ke^{-ax^2} \sin^2 bx,$$

then the sum

$$I_h(x) + I_v(x) = ke^{-ax^2} (\cos^2 bx + \sin^2 bx) = ke^{-ax^2},$$

shows no interference.

In the terminology of this explanation, it can not be said that information has been erased, although it has been concealed, using, as it were, a kind of secret writing. It can be refound (rendered legible) as follows. As the signal was one output from a parametric down conversion crystal (PDC), the conjugate idler then, depending on whether the crystal was of type I or II, will be horizontal or vertical polarization respectively. If type I, then the vertical contribution to the total pattern behind the slits will have nearly perfect correlated partner pulses in the horizontal mode in the idler branch. By counting only those hits in the signal pattern behind the slits for which there is a companion hit in the horizontal idler mode, effectively the horizontal contribution to the signal pattern is filtered out, revealing the vertical interference pattern. This procedure can be called ‘coincidence filtering.’ When such coincidences are the result of polarization, such filtering is a purely non quantum procedure.

On the basis of this analysis it can be said that such a “quantum eraser” is neither quantum nor an eraser; as such, it has little to contribute to a debate regarding the significance of quantum complementarity. Furthermore, the only feature resembling quantum theory is the fact that the intensity of the signals used is so low that detailed structure, i.e., its composition as a stream of point charges, that is electrons, is visible as individual “hits.”

2. Delayed choice eraser

Another particularly interesting ‘quantum eraser’ experiment put the decision to measure wave- or particle-like characteristics to the internals of the setup, thereby taking it away from the experimenter. The experimental setup is depicted in Fig 5.

The salient feature in this experiment, and distinguishing it from the one just considered, is the use of beam splitters. At the so-called single photon level they are known to be virtually absolutist in splitting a beam by whole photons; either a whole photon goes through, or a whole photon is reflected, not both by dividing incoming energy. In this experiment their role is to take the decision regarding which correlation shall be registered out of the hands of a mortal, i.e., the experimenter, and put it in the hands of Zeus. Then, after-the-fact, each subensemble marked by which detector combination fired, is separately analyzed for intensity as a function of lateral detector displacement in the idler branch. Ensembles that correspond, again, to those made by coincidences triggered by just one of the components in one or the other dimension, corresponding to Eqs. 1 or 2, show interference.

Beam splitters operating on a beam of the intensity yielding single hits in the detectors, show strict anticorrelated hits, which is interpreted nowadays as reflecting the essential, ineluctable, distinct identity of photons. According to current understanding, the random choice of transmission or reflection is a reflection of the fundamental uncertain, statistical, i.e., “quantum”
character of the universe at an atomic scale. This feature might seem, therefore, to vest this experiment with an essential quantum element. For this experiment, however, it is immaterial how the choice is made; the phenomena under study does not depend on the mechanism (or lack thereof) of choice. The only relevant feature is that the separate subensembles be compiled; because only within each does the phenomenon of interest takes place.

The quantum character of beam splitters, although logical on its surface, is actually not inevitable. For it to be necessary, would require that alternative theories are logically and rigorously excluded. Insofar as non quantum alternatives exist, e.g.:[14], the viability of the photon paradigm is just provision.

B. Afshar’s experiment

This experiment also aims to study complementarity [15]. The basic idea is to set up a double-slit diffraction pattern at a middle stage of an optics train which is continued through a lens to end in a sharp image of the slits; see: Fig. 6. Then, its conceptual novelty consists in showing that thin opaque obstacles placed in the beam exactly at the locations of destructive interference in the fringe pattern midway through the train have no effect on the intensity of the slit’s image at the end of the train. The image of the slits can be sharp only if those photons, which it would seem have to have been intercepted by the obstacles, are in fact not removed from the beam. Indeed, if one slit is blocked, the obstacles do substantially degrade the image of the open slit. Thus, one is led to question how to reconcile these contradictory facts.

The very precise final image of the slits gives very precise which-way, i.e., particle-type information (in the sense of geometrical optics) on which slit the light for each slit image has passed through. At the same time, knowing just exactly where the light passes through the ‘prober’ slit only within each does the phenomenon of interest takes place.

Finally the image of the slits is observed on the image screen. The very precise final image of the slits gives very precise location for opaque objects (wire grid, seen here on end). Then this screen is removed while leaving the grid in place. Finally the image of the slits is observed on the image screen. The presence of the grid does not affect the quality of the slit image.

FIG. 6 The basic setup of Afshar’s experiment. First the location of the nodes of the diffraction pattern on the interference screen are determined as the location for opaque objects (wire grid, seen here on end). Then this screen is removed while leaving the grid in place. Finally the image of the slits is observed on the image screen. The presence of the grid does not affect the quality of the slit image.

Conclusions

When is a phenomenon a quantum phenomenon? This question can be deeper than it appears at first sight. A complication arises in that some non quantum structure from classical physics fits perfectly well within the vocabulary, notation, algorithms and interpretation of quantum theory without, however, actually depending on any hypothesis unique to quantum mechanics. Vectors of absolutely any sort, for example, can be symbolized by ‘bras’ and ‘kets.’ Insofar as the bra-ket notation encompasses abstract vector space structure, it can be self-consistently used whenever this structure obtains. To this writer’s mind, this leaves only one option open for defining the category of quantum phenomena, namely: a quantum phenomenon is one that absolutely cannot have its patterns encoded mathematically without calling on a unique fundamental hypothetical input of Quantum Mechanics. In the final analysis, this means that the noncommutivity of phase (or quadrature) space must be essential. Therefore, any phenomenon that can be explained without reference to this noncommutivity, no matter how unappealing the non quantum argument, is not a genuine “quantum phenomenon,” even when it can also be explained with quantum mechanics.

Just here there arises a premier example of non quantum structure embedded in the quantum formalism. The noncommutivity found in ‘qubit’ space of polarization space or of spin space is widely thought to be of a quantum nature. However, the group in play here is SU(2) which is homeomorphic to O(3). The latter encodes the structure of rotations on a sphere which is a totally geometric structure having nothing to do with quantum mechanics. By cause of homomorphism, if O(3) is geometric, then SU(2) must be also. The noncommutivity uniquely evident in quantum mechanics is in phase space and is a dynamical feature, not just geometry.

In the experiments considered above, noncommutivity on phase space plays no role in describing the observed phenomenon. Thus, it is concluded that ‘quantum’ is not an appropriate adjective. The term ‘eraser’ is also inappropriate. To erase, etymologically, is derived from Latin words meaning ‘to scrape out.’ Clearly this meaning is derived from times when writing was often carved in stone. Carving out words is essentially different than filling in the letters rendering them illegible (with due attention to color and texture). Competent restoration
can recover a concealed message; destroyed informations is lost forevermore. None of this has anything to do with the depths of a complementarity principle for electromagnetic radiation.

The key or essential feature of what heretofore goes under the rubric of (optical) “quantum eraser” is the phase shift between the vertical and horizontal components. This shift allows the two components to fully compliment each other as seen in Eq. (3). Because this is a simple geometric effect, it must arise in a great variety of situations. The euphoric bedazzlement at its implications for the nature of ‘time’ in Quantum Mechanics as reported for some observers in [17], from this point of view, is a reaction to the logical jujitsu entailed in trying to understand nature on the basis of inappropriate assumptions, in this case, the photon paradigm.

This is not to claim that a complementarity principle has nothing to do with quantum mechanics. Although any such principle seems to be an expression of bandwidth considerations from classical wave theory, in fact the quantum one is intimately connected to the Heisenberg uncertainty relation, which, unlike electromagnetic bandwidth, is scaled by Planck’s constant, and must, therefore, refer essentially to a quantum phenomenon. The pertinent question then may be: how and why for De Broglie waves (sometimes called ‘matter waves’) is bandwidth regulated in a fundamentally distinct manner from that for electromagnetic waves? But, this issue pertains to entities that are indisputably particulate in a classical limit, and not to continuous, undulatory radiation.

References

[1] Beller, M., ‘Quantum Dialogue,’ (U. Chicago Press, Chicago, 1999).

[2] De Broglie, L., ‘Recherches sur la Théorie des Quanta,’ Ann. de Phys., 10e série, III (1925).

[3] Selleri, F., ‘Quantum Paradoxes and Physical Reality,’ (Kluwer, Dordrecht, 1990), Chapter IV.

[4] Kracklauer, A. F., Found. Phys. Lett. 12 (5), 441 (1999).

[5] Kracklauer, A. F. and Kracklauer, P. T. ‘Electrodynamics: action-at-no-distance,’ in Has the Last Word Been Said on Classical Electrodynamics?, Chubykalo, A.; Espinoza, A.; Onoochin., V and Smirnov-Rueda, R. (eds.) (Rinton Press, Princeton, 2004) pp. 118-132.

[6] Pearsall, T. P., ‘Photonics Essentials,’ (Mc-Graw-Hill, New York, 2003).

[7] Greenstein, G. and Zajonc, A. G., ‘The Quantum Challenge,’ (Jones and Bartlett, Sudbury, 1997).

[8] Lamb, W. and Scully, M. O., ‘The photoelectric effect without photons,’ in Polarization: Matiere et Rayonnement, (Presses Univ. Fr., Paris, 1969) 363-369.

[9] Scully, M. O. and Drühl, K., Phys. Rev. A, 25 (4), 2208 (1982).

[10] Scully, M. O., Englert, B. G. and Walter, H., Nature (London), 351, 111 (1991).

[11] Walborn, S. P., Terra Cunha, M. O. Padua, S. and Monken, C. H., Phys. Rev. A, 65, 033818.

[12] Stokes, G. G., Trans. Camb. Phil. Soc. 9, 339 (1852).

[13] Kim, Yoon-Ho; Rong, Yu.; Kulik, S. P.; Shih, Yanhua and Scully, M. O., Phys. Rev. Lett. 84 (1) 1 (2000).

[14] Santos, E., Proc. SPIE, 5866, 36 (2005).

[15] Afshar, S., Proc. SPIE, 5866, 229 (2005).

[16] Roychoudhuri, C., Proc. SPIE, 5866, 26 (2005).

[17] Aharonov, Y. and Zubairy, M. S. Science 307, 875 (2005).

5 The writer’s English translation of this ref., and preprints of refs. [3] and [5], can be downloaded from his webpage.