ON THE NATURE OF QUANTUM DYNAMICAL VARIABLES

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ABSTRACT: An elementary review of the origin of quantum theory, with focus on the nature of the quantum dynamic variables, reveals the essential wave-likeness of quantum dynamics. The introduction of the concept of point-particle entities resulted from influence of classical perspectives, and an issue of language: conflation of the concepts of point-particle localization, and discreteness of quantum detections. Keeping in mind a sharp distinction between point-localization and discreteness of quantum exchange, it is clear that there is no experimental evidence for point-localization. A simple review of the origin of quantum theory, and review of several experiments designed to explore "wave-particle duality" and "complementarity" support this perspective.

I. INTRODUCTION

This "review" is rooted in the origins of quantum theory, the source of current beliefs that are challenged herein. It is a simple, elementary investigation of the wavelike mathematical nature of the fundamental canonically conjugate dynamic variables, described in N. Bohr's "Quantum Postulate",[1] based on the discoveries of M. Planck,[2] A. Einstein,[3] L. de Broglie,[4] W. Heisenberg,[5] and others. (There are no assumptions regarding the ontological and/or epistemological nature of these variables.) Along with these discoveries, particle tracks (first discovered in C. Wilson's cloud chamber)[6] lead to the concept of wave vs. particle ("corpuscle") duality.

It is argued here that the dynamics of both the electromagnetic (EM) field and elementary particles are wave-like. There are no point-localized quantum dynamic entities; assumption of their existence is based primarily on erroneous conflation of concepts of

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[1] N. Bohr, Supplement to "Nature" **121**, 580-590 (1928).

[2] M. Planck, Verhandlungen der Deutschen Physikalischen Gesellschaft 2, 237-245 (1900); Annelen der Physik 4, 553-563 (1901).

[3] A. Einstein (1905), in A. B. Arons and M. P. Peppard, Am. J. Phys. **33**, 5, pp. 367-374.

[4] L. de Broglie, Nature **112**, 540 (1923); Ann. Phys. (Paris) (10) **3**, 22 (1925).

[5] W. Heisenberg, Zeit. Fur Phys.vol. 43, pp.172-198 (1927).

[6] C. Wilson, Proceedings of the Royal Society, A, 85, 285, 1911.

particle-likeness and discrete quantum exchange. (Language issues are addressed in section IV.)

Bohr's modelling of the hydrogen atom's spectra[7] led to successful quantization of classical physics (via the "adiabatic" and "correspondence" principles) to develop the "older quantum theory".[8] Classical physics played a fundamental role the development of quantum theory . In Bohr's "Quantum Postulate" lecture,[9] and after, erroneous mixing of quantum and classical perspectives has lead to faulty concepts: "wave-particle duality" and "complementarity", involving conflation of concepts of discrete quantum exchange and evolution of point-localized entities, and also to the mistaken view that Heisenberg indeterminacy (HI) is a consequence solely of "disturbance due to measurement" at detections.

(HI is based on a property of all waves represented by Fourier transforms, thus to any change in a quantum state. It is an immediate consequence of the wave-like nature of the quantum canonical variables, relevant to any kind of change, evolution or quantum exchange in measurement events. It is a weak statement, involving only standard deviations, weaker yet if the original indeterminacy product is not the minimum.)

The Fourier transform relationships of the space-time canonical variables are at the foundation of quantum dynamics. Point-localization is not required in quantum exchange of energy, momenta, etc., at detections. Language issues regarding such are addressed in section IV.

(Deeper consideration of the process of detection, "observation", involves the role of observers, requiring consideration of consciousness-awareness – beyond scope here.) Several experiments are cited (in section VII) to provide support for the perspectives presented here.

The next five sections address: (II) Fourier transforms generally, (III) the quantum postulate, (IV) language issues regarding "particles", etc., and criticism of : (V) wave-particle duality, and (VI) complementarity.

II. THE FOURIER TRANSFORM

This purpose of this section is to show, to a general audience, the nature of the Fourier relationship between location and frequency variables. This is intended as a fairly "quick read": only a rough sense is sufficient. (Sinusoidal [sine and cosine] waves were discovered by ancient Greeks' geometric exploration of circles, and the vertical and horizontal location, of a point on the circumference, seen from the side, of a point on the circumference of a circle as it rotates. This led to trigonometry, involving sinusoidal functions. Sines and cosines

[7] M. Jammer, The Conceptual Development of Quantum Theory (McGraw-Hill Book Co., New York, 1966) pp. 69-118.

[8] Ibid., pp 89-118.

[9] Bohr (1928), Loc. Cit. (The dynamic equations were <u>inappropriately</u> called "equations of wave-particle duality".)

are the smoothest oscillating waves. The rates of change [derivatives] of sinusoidal waves (e.g., velocity, acceleration, etc.) are all themselves sinusoidal waves. The Fourier transformation is based on these sinusoidal waves.
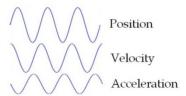

Figure 2.1 Sine wave and its derivatives.

The Fourier transformation of a set of points, representing a waveform, produces a set of frequencies (amplitudes and phases) that also represent the waveform. Each of these two "Fourier distributions" (each being a Fourier transform, direct or inverse, of the other), represent the same wave. (In Section III, these two distributions will be used to describe quantum dynamic variables.). Some mathematical properties of the Fourier transform are described here, so that their equivalent in quantum dynamics will be clearly seen in the definition of quantum canonical variables.)

Figure 2.2 (below) is a simple example of the Fourier transform: a "square wave" having value 1.0 from x=0 to x=0.5, and value of -1.0 from x=0.5 to 1.0, repeating before and after.

In the left panel, sine waves of frequency 1, 3, 5, 7, 9 cycles per second (Hz) are shown (on a background of the 1 Hz wave). The right panel shows partial weighted summations of these Fourier frequency components, and how these partial sums approach a square wave. (If these components represented the sound of a plucked string on a harp, say, the single [fundamental] frequency would sound like the tone of a signal generator. As the harmonics are added the rich sound of the harp emerges.)
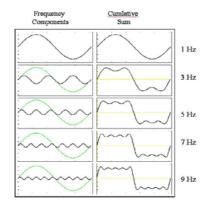

Figure 2.2

Frequencies of a square wave

There are three mathematical descriptors: the (abstract) phenomena itself, its spatial distribution, and its frequency distribution.[10] E.g., for a plucked harp string, there is the sound you hear, the visible vibration of the string, and the harmonic modes that make up the sound. The first is abstract (in your mind). The last two are equivalent "complementary" Fourier distributions (relating to space or frequency) – two different mathematical views of the same phenomena.

There are two fundamental relationships that are easily derived for the pairs of Fourier distributions: 1) (very easy) a commutation relation between the location and frequency variables, and 2) an indeterminacy relation that puts a lower limit on the product of the standard deviations of the two Fourier distributions. These are valid for all Fourier distributions regardless of what they represent; and are of central importance in quantum physics.

[For those not familiar with the math, these equations may be treated as "icons". Hopefully, the words will give some indication of the simple meaningful relationships involved.] The first of these is easily derived, using very simple math (the main element involving four simple steps) to show that, within a Fourier integral (and a corresponding mathematical Hilbert space), the spatial frequency operator $\mathbf{\omega_x}$ is equivalent to a derivative with respect to the position operator $\mathbf{x}$, times i (square root of -1), leading to the commutation relation:

$$\left[\mathbf{x},\mathbf{\omega_x}\right] \equiv \left(\mathbf{x}\mathbf{\omega_x} - \mathbf{\omega_x}\mathbf{x}\right) = -i \,.$$

This commutation relationship leads mathematically to an indeterminacy relation specifying the minimum product of standard deviations of the two "complementary" Fourier distributions:

$$\Delta\mathbf{x} \cdot \Delta\mathbf{\omega_x} >= \tfrac{1}{2},$$

(where Δ represents standard deviation of the distributions of $\mathbf{x}$ or $\mathbf{\omega_x}$). These are fundamental properties of the Fourier transform. Multiplying these mathematical equations by Planck's constant yields the fundamental equations of quantum dynamic variables, as shown next.

III. THE QUANTUM POSTULATE

After Max Planck's discovery of the quantum of energy in thermodynamic description of blackbody radiation,[11] Albert Einstein used Planck's concept of the quantum, as direct physical law, in describing photodetection. And, he added a thermodynamic approximation to support an *ad hoc* concept of travelling point-particles of light[12] (rejected herein). Then,

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[10] In physics notation, three distinct symbols: $\left|g\right\rangle, \left\langle x\middle|g\right\rangle, \left\langle k_x\middle|g\right\rangle$

[11] M. Planck, Loc. Cit..

[12] A. Einstein, Loc. Cit.

Luis de Broglie introduced the quantum of energy and momentum for particles with mass,[13] verified by Compton.[14] Niels Bohr discovered a quantum model for hydrogen spectra (leading to the adiabatic and correspondence principles,[15,16] that used classical physics to generate quantum models), and Werner Heisenberg introduced the indeterminacy principle.[17] All this was encapsulated in Bohr's formulation of "The Quantum Postulate", described in his 1927 Como lecture:[18] 1) discrete quantum exchange in detections, and 2) smooth evolution: in accord with the nature of the fundamental dynamic variables introduced by Planck, Einstein, and de Broglie, described below. Bohr also introduced concepts of "wave-particle-duality" and "complementarity" (challenged here because of his mixing of classical and quantum concepts).

Bohr's quantum postulate[19] encapsulated the discoveries of Planck,[20] Einstein[21] and de Broglie,[22] in two distinct kinds of change: 1) detections ("measurement events", "probings", or "samplings"), involving discrete exchanges of quanta of energy-momentum, interrupting: 2) smooth evolution of canonical variables (energy, and position & momentum, etc.), as defined by the Planck-Einstein-de Broglie ("PEdB"), equations:[23]

$$E = \hbar\omega_t, \qquad p_x = \hbar\omega_x ,$$

where ω_t and ω_x are angular frequencies with respect to time t and position x, and $\hbar$ is the appropriate Planck's constant. Thus, the pair of canonically conjugate variables, e.g., for momentum, ($x, \quad p_x = \hbar\omega_x$) are Fourier transform pairs (with the frequency distribution multiplied by Planck's constant).[24,25] (Thus, the quantum superposition principle is a quantum version of the wavelike mathematics of geometric optics.)

Without further assumptions, multiplying the two equations in the previous section by Planck's constant, and substituting from the PEdB equations,

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[13] L. de Broglie,Loc. Cit.

[14] A. H. Compton, Phys. Rev., 21, 715 (1923).

[15] Bohr, N. (1920), , Zeitschrift für Physik 2 (5): 423–478.

[16] (The long-term use of the Correspondence.Principle may have contributed to "attachments" to intrusion of classical perspectives criticized herein.)

[17] W.Heisenberg, Loc. Cit.

[18] N. Bohr (1928), Loc. Cit. (These equations were inappropriately called "equations of wave-particle duality".)

[19] *Ibid.*.

[20] Planck, Loc. Cit.

[21] Einstein, Loc. Cit.

[22] de Broglie, Loc. Cit.

[23] (These one-dimensional equations, are easily generalized to higher dimensionality. This presentation uses a notation that highlights the location and frequency-with-respect-to-location nature of the canonical variables.)

[24] (Time and energy require special treatment, because time is both a canonical variable and an axiomatic referent for change.)

[25] (These equations apply to the EM field and particles, respectively. The momentum of a quantum of light is E/c, where c is the speed of light, and the energy of a particle, or object, is determined by the nature of the forces acting upon it.)

$$\left[x, \hbar\omega_x\right] \quad = \quad \left[x, p_x\right] = i\hbar,$$

$$\Delta x \cdot \Delta \hbar\omega_x = \quad \Delta x \cdot \Delta p_x >= \tfrac{1}{2}\,\hbar\,.$$

These two relationships are *top*): the "basic commutation relation", the "exact quantum condition", having "axiomatic status …", the "fundamental quantum-mechanical relation", etc,[26] and *bottom*): the Heisenberg indeterminacy (HI) relation.[27] These are a simple direct consequence of the wave-likeness of the two Fourier distributions that represent the canonical variables. The classically independent single values for each of the canonical variables are, in quantum dynamics, replaced by interdependent Fourier distributions in location and frequency.[28] Any change in one of the distributions representing state is accompanied by a change in the complementary distribution, since one is always a Fourier transform of the other. (Classical experience may involve highly peaked Fourier distributions with very small standard deviations, such that the means of the canonical variables seem to be independent and sharp.)

The first part of Bohr's quantum postulate describes instantaneous discrete exchange of quanta in "measurement events" ("detections", "probings" or "<u>samplings</u>"). Classical experience of quantum reality might involve averages of nearly-continuous "samplings" of a common source, in which both canonical Fourier distributions are highly peaked (or by other mechanisms). <u>Only discreteness, not point-localization, is essential to exchange of quanta.</u>

Heisenberg wanted a more direct empirical basis for the concepts involved in this new science, especially the inability to determine simultaneously the classically independent properties of position and momentum.[29] (Regarding this, Einstein said "It is the theory which decides what one can observe.")[30] Heisenberg looked at measurement of the position of an electron, using a high frequency (high resolution) gamma-ray microscope. Viewing the electron as a classical object, the disturbance in its momentum, due to the momentum exchange in reflecting the photon, led to the momentum indeterminacy predicted by HI. Here, HI is related to the quantum wavelike nature of the measuring instrument's photons, not the electron. The Fourier transform relationship between canonical variables guarantees that any change in one causes change in the other. This is stronger than HI.

Quantum dynamics involves smooth evolution in accord with the PEdB equations (and equations of motion), interrupted by exchange of quanta in measurement events. – all in

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[26] M. Jammer (1966), Loc, Cit., pp.210-212.

[27] (See, Ibid., pp. 345-361.)

[28] (Note, eigenstates of position or momentum are excluded; they are physically unrealizable delta functions.)

[29] "The Uncertainty Principle", http://plato.stanford.edu/entries/qt-uncertainty/ [Stanford encyclopedia of Philosophy"; Sect. 2.2.

[30] Ibid.; Sect 2.3-2.4.

accord with conservation laws. Preparing for discussion of "wave-particle duality", language issues regarding the word "particle" need to be addressed.

IV. LANGUAGE

The primary connotation of the word "particle" is that which is studied in particle physics: a local entity possessing enduring attributes, capable of energy exchanges.[31] Conflation of multiple connotations of the word "particle" is a serious language issue that has contributed strongly to the perspectives challenged here. Common connotations of the word "particle" include:

1) point-like localization ("point-particles"),
2) possessor of single-valued dynamical physical attributes,
3) possessor of enduring attributes such, as mass and charge (perhaps a quality of permanence), capable of energy exchanges, and
4) discrete exchange of energy-momentum, in normal modes of vibration or in the electromagnetic (EM) field, ["quasi-particles" or "photons"].

The first three of these, together, are the foundation of classical physics; the first two, violating physically relevant PEdB equations, are excluded from quantum dynamics. The third pertains to a specific quantum physics discipline: "particle physics". The fourth, relevant to quantum dynamics only, relates to excitation level and quantum exchanges in normal modes of vibration and in the EM field. The discreteness of quantum exchanges, or energy levels, does not, by itself, imply point-particle-likeness or object-likeness, in either quantum exchange or the process of evolution.

(For systems having energy that is linear in quantum number [e.g., the EM field, and collective modes of vibration], the size of discrete quantum exchanges are constant; and energy changes may be viewed as changes in quasi-particle number – often, erroneously, called "particle number").[32]

Quantum exchange is somewhat like a "resonant" interaction.[33] Yet, most physicists, including Albert Einstein[34] and Richard Feynman[35] have advocated the concept of point-particle photons in dynamic evolution, due to the discreteness of detections. (Feynman

[31] Geoffrey Chew (informal conversation, 2008, for which the author is grateful).

[32] E.g., E. M. Henley and W. Thirring , Elementary Quantum Field Theory (McGraw-Hill Book Company, Inc., San Francisco, 1962), p.20. Regarding coupled oscillators: "The fact that the eigenvalues of the energy are integer multiples of basic frequencies lends itself to a particle interpretation. . . . It appears that particles are more like vibrations than like classical bodies, . . ." [In this, the word "particle" should have been "quasi-particle".]

[33] E.g., W.E. Lamb, Jr. and M.O. Scully, "The photoelectric effect without photons" in Polarisation, Matiere et Rayonement (Presses University de France 1969); cited in G. Greenstein & A. G. Zajonc, The Quantum Challenge. (Sudbury, MA: Jones and Bartlett Pub., 1997), pp. 23-25.

[34] A. Einstein Loc . Cit., pp. 370-371.

[35] R. P. Feynman, "The Concept of Probability in Quantum Mechanics", Proc. II Berkeley Symp. Math. Stat. and Prob., 1951, p. 534.

wrote: "The temporally and spatially discrete nature of detections is the reason we say electrons are particles".) The words "quantum", "quasi-particle" or "photon" are appropriate for quantum exchange (or excitation level), and "quasi-particle" is appropriate for normal modes in collective phenomena. Erroneous conflation of connotations of point-particle localization and quantum exchanges is ubiquitous in descriptions of quantum dynamics; it is a major source of the criticisms herein.

Also, there is an interesting conflation of the meanings of "objective" and "objectivity", defined in most dictionaries as (roughly): 1) having "truth value", separate from personal biases, etc., and 2) being object-like and being separate from self. [Herein, the words "objective" and "objectivity" will indicate "free of subjective bias", or similar.] Object-likeness and "objectivity" are very different concepts. "Objectivity" ("truth-value") does not require object-likeness. (The possession of enduring attributes may indicate a quality of object-likeness, not the concept of point-localization.)

V. WAVE-PARTICLE DUALITY

While there is abundant verification of the discreteness of photon exchange in detections, there is no experimental verification of point-particle localization of photons. As indicated in the previous section, Richard Feynman's declaration of particle-likeness for electrons and photons is an example of projecting the nature of quantum (quasi-particle / photon) exchange onto the process of evolution. (His particle-like photons have an internal "phase-meter" [based on optical path length]; and each photon is "paranormal": it "smells the neighboring paths around it, and uses a small core of nearby space.")[36] Also, he associated quantum electrodynamics, QED, with his assumption of particle-likeness in evolution,[37] giving the false impression to some that the beautifully constructed QED, and the impressive accuracy of predictions, depended on his assumption of particle-likeness. The phase computations could be done, more directly, by using geometric optics (the superposition principle). The numerical results are the same either way.

Regarding the wave-particle duality that Feynman was trying to escape, the concept that "sometimes a quantum system behaves like a particle, and sometimes like a wave, depending on the situation", has no validity. The quantum canonical variables are, without exception, fundamentally wave-like, with discrete discontinuities due to quantum exchanges at detections.

VI. COMPLEMENTARITY

Bohr's first introduction of the concept of "complementarity"[38] involved quantum definition of dynamic variables, the wavelike PEdB equations, followed immediately by a

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[36] Ibid., p. 54. (While rejecting paranormal phenomena in humans, he attributed it to particles.)

[37] Ibid., p.37.

[38] Bohr (1928), Loc. Cit., p. 582, following equation (1).

contradictory classical association of energy and momentum with particles. This created a "wave-particle duality" between conflicting quantum and classical perspectives of the quantum dynamic variables. He then cited the quantum superposition principle (geometric optics for quantum variables), to reinstate the wave-likeness of the quantum canonical variables. At the end of the first paragraph of that page: "The two views of the nature of light are rather to be considered as different attempts at an interpretation of experimental evidence in which the limitation of the classical concepts is expressed in complementary ways." Without the erroneous *ad. hoc.* classical association of point-particle-likeness with the quantum canonical variables there is no story, no issue. The main point here is that it is not possible to discuss this issue without disambiguating the various connotations of the word "particle".

Language is critical here.

Citing Heisenberg indeterminacy, Bohr said: "This indeterminacy exhibits, indeed, a peculiar complementary character which prevents the simultaneous use of space-time concepts and the laws of conservation of energy and momentum, which is characteristic of the mechanical mode of description."[39] But, quantum change involves a piece-wise continuous process involving evolution of state, interrupted by discrete quantum exchanges; <u>all of which is subject to conservation laws</u>. There is no inherent issue here, within the quantum domain.

While human experience requires some degree of classical description, quantum law is not bound by such. The language used for description of quantum process needs to be "faithful" to that process, to the extent possible – not bound by classical concepts. These major examples involve clashes generated by inappropriate association of classical concepts with quantum situations. Unfortunately, these perspectives have inundated the common lore. (See experiment E4, below.)

The two basic quantum processes: (1) smooth wave-like evolution, (2) interrupted by discrete exchange of quanta in detections, fit the concept of "complementary" (each in their own separate domain of change) – but not "complementarity" of different experimental situations.

VII. EXPERIMENTS

E1. Double-Slit Interference, Etc.

The double-slit interferometer has been considered by many to be the "iconic" experiment of quantum theory.[40] In the past, double and single slit interferometers were considered to

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[39] N. Bohr, The Philosophical Writings of Niels Bohr, Vol. 1, Atomic Theory and the Description of Nature (1934, reprinted by Ox Bow Press, Woodbridge, Conn. 1987); p.11.

[40] Feynman quote: the double-slit experiment ". . . has in it the heart of quantum mechanics. In reality, it contains the only mystery." [R. P. Feynman, R. B. Leighton, and M. Sands, Quantum Mechanics, The Feynman Lectures on Physics. Vol. 3 (Addison-Wesley, Reading Mass.).

provide examples of wave-likeness and particle-likeness, respectively. (Interference is easily discernable with the double-slit, but diffraction with the single-slit may be not visible). Actually, particle-likeness and wave-likeness are associated with the individual discrete detections, and the diffraction/interference patterns in the accumulation of such – the wavelike interference pattern and discrete detections exist in the same experiment.
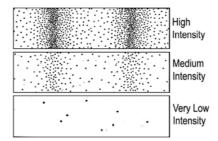

Figure 7-E1.[41] Interference seen in accumulations of individual detections (only two of many fringes are shown).

   This "iconic" experiment violates concepts of wave-particle duality and complementarity. Double and single slits, and a "half-slit" (a knife edge), all produce diffraction patterns.[42] In all of these, discrete exchange of a quantum is involved in each detection, and a wave-like pattern (including a smooth half-lobe for a "half-slit") is generated in the collection of detections – all within the same experiment. Each detection seems random.

   Discrete quantum exchange and wave-likeness are evident in the same experiment. There is no (one-or-the-other) "wave-particle duality". This is an "iconic" demonstration of the wave-like nature of evolution, and the discrete nature of detections.

E2. Hanbury Brown and Twiss: Fluctuations in a partially coherent beam. (1954-58)[43]

This experiment was part of an ongoing (successful) fundamental exploration of the use of intensity interferometry to create a new class of low-noise wide-baseline telescopes. In the late 1960s, when the need to quantize the EM field was being challenged, there was interest in looking at normalized photon coincidence counting rates in very weak fields: lower coincidence rates in weak fields could be an indication of point-particle photons. Hanbury

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[41] Illustration from: P. M. Morse and H. Feshbach, Methods of Mathematical Physics Vol. 1 (McGraw Hill Book Company, New York, 1953) p. 225.

[42] In the 1960s, roughly, a slow neutron beam was passed over a knife edge – a "half-slit", and roughly 100+ data points were tightly packed on the theoretical single-lobe diffraction pattern. (Seen in a journal in the physics library at Dalhousie University in Halifax, Nova Scotia, 1968-1970.)

[43] R. Hanbury Brown and R. Q. Twiss, "Correlation between photons in two coherent beams of light", Nature **177**, 27-29 (1956); see also, "Interferometry of the intensity fluctuations in light", Proc. Royal Soc. London A, **242**, pp. 300-324 (1957); **243**, pp.291-319 (195[43] N. Bohr, Supplement to "Nature" **121**, 580-590 (1928).

Brown and Twiss had earlier found, not less, but twice the classically expected coincidence counting rates in very weak partially coherent fields (due to the bosonic nature of the field, and lack of coherence). The experimental search for weaker normalized coincidence counts with weaker fields had already been done, there was no such evidence. (These authors indicated, often, that the concept of point-particle photons was not useful.)

E3. Pfleegar and Mandel "Two-Laser" Experiment. (1967, 1968)[44]

(In their second paper, there was a caveat: "insofar as particle concepts are applicable to photons". This experiment indicates they are not.)

First, this experiment is easily explained as superposition of two quantum EM fields at times when there is significant coherence between the two lasers, and thus coherence in the combined fields. This was part of an ongoing fundamental exploration of "the appropriate description the state of a laser field, and on the question whether the experiment disproved a famous statement of Dirac",[45] that photons can interfere only with themselves, not with others. The slightly angled superposed outputs of two lasers were incident on a clever interference detector. Data were recorded only when the beat frequency between the two lasers was <= 50 KHz (6000m coherence length: very long coherence lengths for individual photon wave-packets). The two laser beams were attenuated such that the time between photon detections was roughly 50 times the transit time through the 0.9m apparatus. (Given the 6000m coherence length, over 130 overlapping wave-packets would have to be present in the apparatus, suggesting the usefulness of the concept of a field.) Interference was demonstrated.

The authors, analyzing particle paths and applying the indeterminacy relation (a property of waves), stated:

> It seems better to associate the interference with the detection process itself, in the sense that the localization of a photon at the detector makes it intrinsically uncertain from which of the two sources it came. … The interference effect can therefore be thought of as being associated with the detection of each photon.

This is a very awkward way of viewing geometric optics (the superposition principle). The field at a detector is the sum of all field contributions, along optical paths, from the two lasers to the detector. There is simple clarity here; there is no need for an *ad. hoc.* assumption of evolving point-particle photons.

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[44] R.L. Pfleegor and L. Mandel, "Interference of Independent Photon Beams." Phys. Rev. **159**, 1084 (1967); "Further experiments on Interference of Independent Photon beams at Low Light Levels", J. Opt. Soc. Am. **58**, 946 (1968).

[45] P.A.M. Dirac, Quantum Mechanics, 4th ed. (Oxford Univ. Press, London, 1958), p. 9.

The concept of point-particles, and the view that "Heisenberg's uncertainty principle limits our knowledge of the world"[46], are grounded in irrelevant perspectives that assume a classical world.

E4. Grangier, Roger and Aspect "Complementarity". (1986)[47]

This was a two part experiment designed to demonstrate "complementarity": particle vs. wave behavior in different experimental configurations. In both of their experimental configurations, a source of entangled photon pairs was used, so that detection of one member of the entangled pair would enable the experiment to be done on the other member – thus providing a sharp single-photon state for the experiment.
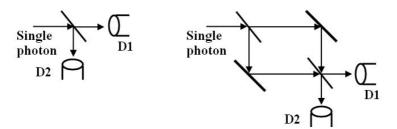

Figure 7-E4. Anticoincidence and Interference

In the first experiment (left), the sharp 1-photon beam was directed into a beam splitter, with the split beams directed to detectors D1 and D2. Each were attached to individual and coincidence counters. Only insignificant ("noise") coincidence counts were detected. This was supposed to indicate the "particle" nature of the input. But, it demonstrated only that the 1-photon field did <u>not</u> do a never before experienced spontaneous, free-space, down-conversion into two half-frequency photons! (This is no more than a local detection from a spatially distributed field.)

In the second experiment, the two split beams of the first experiment were directed into a Mach Zhender interferometer, with a controllable distance between the two detectors, D1 and D2, therein. They found interference – and claimed to have demonstrated Bohr's "complementarity": particle-likeness in the first experiment, and wave-likeness in the second:

> They illustrate the wave-particle duality of light. Indeed, <u>if we want to use classical concepts, or pictures</u>, to interpret these experiments, we must use a particle picture for the first one (<<the photons are not split on a beam splitter>>), since we violate an inequality holding for any classical wave model.

[46] E.g., G. Greenstein & A. G. Zajonc, The Quantum Challenge. (Sudbury, MA: Jones and Bartlett Pub., 1997), pp. 51-52.
[47] P. Grangier, G. Roger & A. Aspect, Europhysics Lett. **1** (4) 173-179 (1986).

On the contrary, we are compelled to use a wave picture (<<the electromagnetic field is coherently split on a beam splitter>>) to interpret the second (interference) experiment. Of course, the two complementary descriptions correspond to mutually exclusive experimental set-ups.[48] [underlines added]

But, in this second experiment, the authors ignored recorded coincidence data that was identical to data found in the first experiment.[49] There was evidence against photon splitting at a beam-splitter in both experiments. These data were ignored in the discussion of complementarity.

(A truly quantum picture would involve simple wave-like evolution of a field in both situations, and discrete detections from the field(s) thus produced – simple and in accord with the quantum mathematical description.)

Regarding the first experiment, coincidence counts would require spontaneous half-frequency down-conversion in free space at a beam-splitter (never seen, nor expected). It is highly unlikely, regardless of particle-likeness or not. Photon particle-likeness is problematical, while a purely wave-like perspective is easy to comprehend, and is trouble-free.

E5. Hellmuth, Walther, Zajonc, and Schleich (1987)[50]

In 1978, John Archibald Wheeler proposed several "delayed choice" ("particle or wave") experiments to probe our lack of understanding of quantum theory.[51] In his beautifully stated platform for questioning:

> We search here, not for new experiments or new predictions, but for new insight.
> Experiments dramatize and predictions spell out the quantum's consequences; but what
> is its central idea?

(As an example, the work of Copernicus would have had little import without the central idea that the 'Earth goes around the Sun'.)

> In contrast, if the essential point could be grasped in a single phrase, we can well
> believe that the quantum would seem so natural that we would recognize at once that
> the universe could not even have come into being without it.

Wheeler's suggestion of "delayed choice" (particle or wave) experiments involved his search for a "central idea" regarding quantum theory. Wheeler started with a word that Bohr used in discussions with Einstein: "phenomenon".[52] He stated,

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[48] Ibid., pp. 178-179.

[49] Page 178.

[50] T. Hellmuth, H. Walther, A. Zajonc, and W. Schleich, "Delayed-choice experiments in quantum interference", Phys. Rev. A, **35**, 2532-2541.

[51] J. A. Wheeler, In Mathematical Foundations of Quantum Mechanics, edited by A.R. Marlow (Academic Press, NY, 1978). pp. 9-48.

> No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon. It is wrong to speak of the "route" of the photon in the experiment of the beam splitter. It is wrong to attribute a tangibility to the photon in all its travel from the point of entry to its last instant of flight. A phenomenon is not yet a phenomenon until it has been brought to a close …[53]

Wheeler's introduction of delayed-choice experiments was his attempt to find "the central idea", "the essential point" of quantum theory.

In one of the responses to Wheeler's questioning, Hellmuth, Walther, Zajonc, and Schleich,[54,55] devised an experiment that combined both of the experimental arrangements formerly used separately by Grangier, Roger and Aspect (above), and a means to select one or the other, after a single-photon laser pulse had passed through the first beam-splitter in the experimental apparatus: a "delayed choice". (The photon supposedly made the choice to split, or not split, at the first beam-splitter, long after it had passed through it. This, along with application of conservation of energy for split-photons is in the domain of incredulity.)
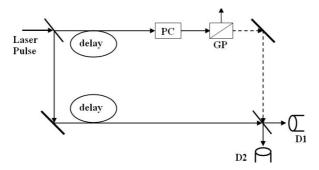

**Figure 7-E5. Delayed Choice. Solid lines only: simple beam-splitter
at bottom right; all paths: interferometer + beam-splitter.**

When the "GP" diverts the upper split-beam upward (dashes represents no split beam), the lower path involves only coincidence counts following the lower-right beam-splitter (and recombiner). Otherwise upper and lower split beams are spit and recombined, in the Mach-Zhender interferometer. Delays were placed in the originally split beams, so that the choice to divert the upper split-beam, or not, takes place well after the laser pulse has passed through the first beam-splitter. Thus, the choice to have either a beam-splitter, or an interferometer, was made after the photon had already passed through the original beam splitter: a delayed choice.

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[53] Ibid., p. 184.

[54] Hellmuth, …,(1987). Loc. Cit.

[55] Following, C. O. Alley, O. Jakubowicz, C. A. Steggerda and W. C. Wickes, *Proceedings of the International Symposium on the Foundations of Quantum Mechanics – Tokyo*, edited by S. Kamefuchi (Physics Society of Japan), pp. 158-164 (1983).

The author's phrase: "*if we want to use classical concepts, or pictures, to interpret these experiments …*" is an example of the ubiquitous miss-use of classical concepts of particles advocated by Bohr,[56] Heisenberg,[57] and others, in support of an erroneous view of "wave-particle-duality" – an often internally inconsistent view in this context, not supported in this or other experiments.

The authors conclude with references to statements by Wheeler that support the perspective described herein. They wrote:

> Another possibility has been pointed out by Wheeler[58] who noted that it was just "<u>bad use of language</u>" which got us in the dilemma of deciding whether the photon "shall have come by one route, or by both routes" after it has "already done its travel." Reminding us of N. Bohr who introduced the word "phenomenon" into his dialog with Einstein, Wheeler emphasizes that "No elementary phenomenon is a phenomenon until it is a recorded phenomenon, … until it has been brought to a close by an irreversible act of amplification such as the blackening of a grain of silver bromide emulsion or the triggering of a photodetector." <u>We therefore have no right to say what "the photon is doing" during its journey in the interferometer.</u> … As Wheeler has frequently pointed out, the strangeness of the delayed-choice experiment reminds us more explicitly than ever that "<u>the past has no existence except as it is recorded in the present</u>." [underlines added]

In accord with Wheeler's statements, the concept of split photon paths prior to detection is invalid. Simply, the electromagnetic field is split into two segments (fields, wavefunctions) in the apparatus; they may recombine, or not, depending on the setting of the "GP" switch, i.e., according to choice of experimental configuration – after the field had already entered the interferometer.

Loss of familiar concepts of evolving photons prior to detection, and of associated conundrums, need not seem strange. In all cases, simple concepts of an evolving field or wavefunction is all that is required.

(It should be kept in mind that the concept of the photon usually involves conflation of point-particle-likeness [here involving transit through the interferometer], and the discreteness of quantum exchange that does not represent travel in space-time. Wheeler is dismissing the former, not the latter.)

[56] Bohr (1928,1934), Loc. Cit. – concepts & pictures
[57] W. Heisenberg, The Physical Principles of the Quantum Theory, (Dover Publications, Inc., 1949). (Original: 1930).
[58] J. A. Wheeler, in Mathematical Foundations of Quantum Theory, edited by A. R. Marlow (Academic Press, New York, 1978), p. 9; in Some Strangeness in the Proportion, edited by H. Woolf (Addison-Wesley, Reading, Mass., 1980)

VIII. CONCLUSIONS

This narrow focus, solely on the nature of the canonically conjugate variables, is intended to demonstrate 1) the deeply fundamental role of these definitions, leading to 2) the wave nature at the foundation of quantum dynamics, and 3), to disavow the concept of point-particle photons, in accord with Wheeler:

> It is wrong to speak of the "route" of the photon in the experiment of the beam splitter.
> It is wrong to attribute a tangibility to the photon in all its travel from the point of entry
> to its last instant of flight.[59]

The presence of frequencies in the definitions of canonical variables implies wave-likeness. The concept of a point-particle photon in "flight" is inappropriate. The photon is relevant only as a quantum of exchange at the moment of detection (or the excitation level of an evolving, or trapped, photon field). With this understanding, all the imagined paradoxes addressed herein vanish. This wave-likeness implies geometric optics (i.e., the superposition principle).

(Also, the behaviour of entangled states may be formulated in terms of, e.g., two-body wave-like states, not concepts of "Alice's photon" and/or "Bob's photon", etc. [Only their photodetections are relevant.])

There are issues, such as the passage of enduring attributes through a double-slit, that cannot be addressed independent of assumptions regarding epistemological vs. ontological perspectives. Also, the inescapable informational nature of the canonical variables (recognized early in quantum theory) was intentionally not addressed above. Thus, the conclusions reached here are independent of assumptions regarding epistemology vs. ontology. Many physicists, along with others, have been pursuing perspectives with respect to human knowledge and participation, i.e., along with individual and/or collective consciousness. It will be interesting to see how the fundamental wave-like nature of quantum reality is related to such.

(Older references were used here, because this paper is aimed at old perspectives, that have persisted [primarily concepts of: photon paths, wave-particle-duality and complementarity], inhabiting today's common lore.)

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[59] J. Wheeler, "Law Without Law", in J. A. Wheeler and W. H. Zurek, *Quantum Theory and Measurement* (Princeton University Press, Princeton 1983), p. 184.