What do correlations tell us about photons?*

A. F. Kracklauer

Bauhaus Universität; Weimar, Germany

Finding a model or paradigm to capture the essence of light, is an enterprise of historic legend. The two main contenders, particle beams and waves have alternated in acceptance, with each ultimately proving unsatisfactory. Currently, the particle variant is predominant, but with strong caveats encompassed in BOHR's Principle of Complementarity. Herein a study of *correlated* pairs of photons is presented. It reveals additional challenges for the particle paradigm. Finally, it is suggested that as neither of these two paradigms is optimal, the direct-interaction paradigm as originally introduced by SCHWARZSCHILD deserves further consideration.

I. WHY WORRY?

"What is a photon?"

Part of the answer is: "photon" is the name of a paradigm for the interaction of charged massive particles.

"Paradigms," in turn, in Physics can be considered to consist of three components: sets of 1) words, 2) images and 3) algorithms.

For the "hard nosed" physicist, the algorithms with which the systematic features of the phenomena are encoded, are usually the most important as they are what is needed to predict how the phenomena behaves in new regimes. For the philosopher, words seem to be a central issue, whereas the pedagog makes good use of the images.

But these are just the usages of a paradigm once it has been developed. Paradigms also play a very important role in the development of theory in that they are essential in the 'feedback' process to refine the theory itself (in whatever form). It is this aspect that is the main concern here. The issue is: is the photon paradigm optimal; is it faithful to the phenomena it is supposed to cover in all details, or does it mislead? Does it suggest the most inclusive mathematical formulation, or does it effectively restrict imagination?

The purpose herein is to examine the internal consistency of the photon paradigm with respect to certain correlated signals to see if it logically consistent or 'hangs together.'

II. THE CHALLENGE

One of the obstacles to analyzing the 'photon' paradigm is, that the definition of a photon is especially vague or diffuse. In addition, there has been an enormous amount written about the various conceptions, and the vagueness has contributed to generation of a social imperative to the effect, that whatever any individual thinks, in fact the paradigm is to be taken as coherent and complete, regardless of one's own gaps.

Perhaps the best that can be done to specify just what is in fact meant by the term, is to return to the very early papers. This tactic has the advantage that in such papers the degree of guilelessness is maximum; initiators of concepts typically are the most forthcoming on weaknesses.

The most renowned initiators of the 'photon' conception were PLANCK, EINSTEIN and DE BROGLIE. In reading their papers, one sees quite clearly, that all three motivated their considerations with images of photons as spatially demarcated parcels of radiation. However, at the same time it is just as clear that they all actually restricted calculations to just the issue of the interaction of radiation, in whatever form, with matter—where the latter was comprised exclusively of charged particles.(1) In the end, no doubt, this is a consequence of the fact that electrodynamics is a theory of the interaction between charged particles, and no matter how that interaction occurs, in the end it is manifested only by the motion of the main actors: charged particles. This feature is further enhanced by the universal character of the minimal charge size, e; were it continuously variable, the task of sorting out just how charges interact, would be much more challenging.

Nevertheless, the 'photon' paradigm is not completely satisfying. There are a number of places where the imagery, and words, cannot be made to fit comfortably into a coherent paradigm, although the associated algorithms have been tailored to work.(2)

It is the main purpose of this note to consider just those features of the photon paradigm as applied to *correlated pairs*, in order to examine its general coherence.(3)

III. THE QUANTUM MECHANICS OF CORRELATED PAIRS

As is always the case for the interaction of charges, the structure of the interaction is made manifest only through the behavior of charged particles; i.e., correlated photons arise just there, where there are correlated charges. The first instance of quantum analysis of such pairs in the literature appears to be in HEISENBERG's paper in which he attacks the issue of the spectrum of helium.(4)

His initial efforts to solve this problem were aimed primarily at getting a useful answer for spectroscopy and secondarily at defending his matrix mechanics in the face of competition from SCHRÖDINGER's then recently proposed 'wave mechanics.'(5) As a 'test bed' for developing the appropriate formalism, HEISENBERG chose the problem of coupled harmonic oscillators. This problem is parallel to the problem of the helium atom in that each electron is mainly influenced

---

*Presented af: SPIE Session: *The Nature of Light: What Are Photons?*, San Diego, 26-27 Aug. 2007.

by the nucleus and just perturbed by the other electron, analogously to oscillators whose behavior is primarily determined by the 'spring constant(s)' but modified by relatively weak coupling between the oscillators.

HEISENBERG observed, that it is a characteristic feature of atomic systems, that the components of which they are comprised, namely electrons, are identical and subject to identical forces. Therefore, in order to invest this feature in his 'test bed', he assumed the HAMILTONian to be of the form:

$$H = \frac{1}{2m}p_1^2 + \frac{m}{2}\omega^2 q_1^2 + \frac{1}{2m}p_2^2 + \frac{m}{2}\omega^2 q_2^2 + m\kappa q_1 q_2; \qquad (1)$$

i.e., the frequencies and masses of the coupled oscillators are taken to be identical. In Eq. 1), q_1, q_2 denote the coordinates, p_1, p_2 the momenta, m and ω the mass and frequency respectively, and κ the interaction constant. With help of the well known transformations:

$$q_1' = \frac{1}{\sqrt{2}}(q_1 + q_2), \quad q_2' = \frac{1}{\sqrt{2}}(q_1 - q_2), \qquad (2)$$

Eq. 1) is transformed into the separated form:

$$H = \frac{1}{2m}p_1'^2 + \frac{m}{2}\omega_1'^2 + \frac{1}{2m}p_2'^2 + \frac{m}{2}\omega_2'^2 q_2'^2, \qquad (3)$$

where

$$\omega_1'^2 = \omega^2 + \kappa, \quad \omega_2'^2 = \omega^2 - \kappa. \qquad (4)$$

In other words, H separates into the sum of two abstract oscillators, such that each corresponds to a "normal mode", in the technique long before developed by DANIEL BERNOULLI. When only the first mode, q_1', is excited, then both masses oscillate in phase, and when only q_2' is excited, out of phase.

The energies according to QM for the combined system are then give by the equation:

$$H_{n_1',n_2'} = \frac{\omega_1' h}{2\pi}\left(n_1' + \frac{1}{2}\right) + \frac{w_2' h}{2\pi}\left(n_2' + \frac{1}{2}\right), \qquad (5)$$

where n_1' and n_2' are integers.

In his scheme, the solutions that HEISENBERG obtained are matrix elements found using his version of QM. The solutions from Eq. 5) are, as is usually the case for normal coordinates, not really physically observable, but particular solutions of the abstract combined system. The observables are the inverses of Eqs. (2). If the initial conditions are appropriate, the system executes motion described by one of the normal modes, otherwise, the solution is a secular oscillation of the total system energy between the two oscillators. (4; 6)

Observing that, at the atomic scale it is not possible to determine the exact details of light absorption and emission, HEISENBERG asserted, not altogether cogently, that he considered discontinuities more faithful to reality than SCHRÖDINGER's *continuous* waves. This argument was made in conjunction with his motivation to defend his 'matrix mechanics. ' By favoring discontinuous jumps between modes, instead of secular oscillation, he laid the groundwork for the latter philosophical position to the effect, that wave functions in fact comprise mutually exclusive options, i.e., they are their superposition. Such ontologically objectionable entities are nowadays recognized (but not fully rejected) as "irreal."(7)

It is reasonably arguable, however, in spite of his stated motivation, that he actually succumbed to sociological pressure, as portrayed by FORMAN, namely to conform to the pervasive anti-deterministic philosophical proclivities prevailing in German academia following World War I.(8) Thus, with scant underpinning, seemingly in order only to accommodate the *Zeitgeist*, he simply *chose* a paradigm involving intrinsic randomness. This, HEISENBERG realized by supposing that the solutions, in place of secular oscillation, exhibit random, spontaneous, secular-like jumping back and forth.

Instantaneous jumping by itself is not necessarily irreal; implicitly there can be a hidden variable, that perhaps an extention of QM could predict, that specifies as a function of time just which electron is excited in the series of jumps back and forth. However, admitting this possibility would undermine the sociological goal of discrediting determinism; and so, for whatever reason, this possibility was rejected out of hand.

Once discontinuous combinations of elementary components for wave functions are accepted, however, there arises a serious conflict with reality, namely, no observation reveals a state that is anything like a combination of mutually exclusive components. All such measurements result in observing one or the other option. Thus, to reconcile this fact with the theory, an additional hypothesis has been taken: the "projection hypothesis" to the effect that the process of measurement itself by some mechanism independent of quantum evolution (in other words, the Schrödinger Equation), "projects" the presumed ontologically valid quantum state onto one or the other option randomly.

For single systems this hypothesis introduces a mystical but otherwise empirically indisputable feature.(3)

However, for correlated systems, the projection hypothesis introduces a major conflict with both logic and relativity theory: nonlocality. This feature arises because measurement of either one of a correlated pair must cause the wave function for both partners to collapse so as not to violate conservation laws and symmetry principles. Moreover, in principle, this must happen instantaneously regardless of how far apart the partners are separated, and naturally, such an effect violates the fundamental principle of relative, according to which no physical effect can transpire over distance faster than the speed of light. Hence, it is said, QM harbors intrinsic nonlocality.

IV. A "TEST BED" OF STANDARD PRINCIPLES

Whether all these principle are coherent and self consistent is the central question here. On the basis of a certain suspicion that this writer has had, let us apply them to a particular application to see how they accord with laboratory observations.

The particular issue is: the 'rotational invariance of the singlet state.' According to orthodoxy, as can be verified in virtually every text book, the singlet state is said to be one for which arbitrary rotations about a certain axis can have not observable effects. In particular, when such a singlet state is constructed from photons correlated in terms of their polarization, it should be rotationally invariant about the axis of the wave vector of these photons. In other words, it should make absolutely no difference at all which direction the polarization of either photon is measured first; if it is seen to be parallel to the axis of the measurement device, then the partner photon must 'collapse' the orthogonal axis of this device.(9)

In terms of the usual quantum photon paradigm, this is to be understood more or less as follows: When the photon pair is generated at the source as a unit in the singlet state, the ontological essences of each photon is ambiguous, that is, neither has a distinct polarization state; rather, each is in a limbo state possessing both or neither polarization. Thereafter, when whichever of the pair encounters a measurement device first, it is 'projected' onto just one of the optional component states; its wave function is said to 'collapse' to that of this component state. At the very same instant, moreover, the wave function of the partner photon also collapses to the complimentary state, irrespective of how far away it is.

In this projection-collapse process it is the axis of the measurement device which is not ambiguous, but fully specified by the experimenter beforehand. Thus, the projection must be onto exactly just this axis as the photon itself at this stage is thought to have no specific axis. Then, also, the partner photon is vested with a distinct polarization state too; i.e., its wave function is collapsed to the correlated state. Because the axis of the measurement device can be selected at will by an experimenter, it should make no difference which direction he has selected, the outcome of a pair of measurements should reveal complete anticorrelation regardless of the directions chosen for the first measurement in repeats of this experiment. In other words, the singlet state input is rotationally invariant.

Now, what does the main competing paradigm, wave theory, predict for this same process? Is there an observable difference?

First, consider the source from the point of view of classical wave theory. It would be a process that randomly produces one of two states, either a vertically polarized pulse emitted to the right with a horizontally polarized pulse to the left, or the opposite combination. Each pulse in both arms is well defined with a distinct polarization, it is not a superposition of the two options; thus, measurement needs no notion of 'collapse.' If the signal to the right is vertically polarized when the polarizer filter on the right is also vertical, a 'hit,' i.e., a photoelectron, is registered in the detection circuit; otherwise no signal is registered. Likewise on the left.

The next important question is: what is the coincidence between photo-currents right and left as a function of the angles of the polarizer filters at the measurement heads right and left? This is a well studied matter, the answer is given by the second order coherence function (second order in intensities, fourth order in field strengths), i.e.

$$Cor(\theta_l, \theta_r) = \frac{< E_r * (\theta_r) E_l * (\theta_l) E_l(\theta_l) E_r(\theta_r) >}{< E *_r E_r >< E_l * E_l >}, \quad (6)$$

where $E_{l/r}(\theta_{l/r})$ is the electric field from the source after passing through the polarizer filter on the right (r) or left (l) side.(10) The denominator assures that the ratio falls between -1 and $+1$, which accords with the notion of an abstract correlation. For present purposes, the issue is: what variation does this $Cor(\theta_l, \theta_r)$ have as a function, say, of θ_l for a fixed value of θ_r. If the native state is rotationally invariant, then such curves for all values of θ_r will be identical. For the purely classical electrodynamic calculation based on Eq. 6)—which is essentially just a higher order form of Malus' Law—the result is shown in the Fig. The data would be taken by fixing the polarizer angle in one arm of the EPR-B experiment, and then measuring the intensity in the other arm at various polarizer angles between 0 and 2π, then repeatedly incrementing the polarizer angle in the first arm, and measuring the second arm again through 2π for each incremental increase.

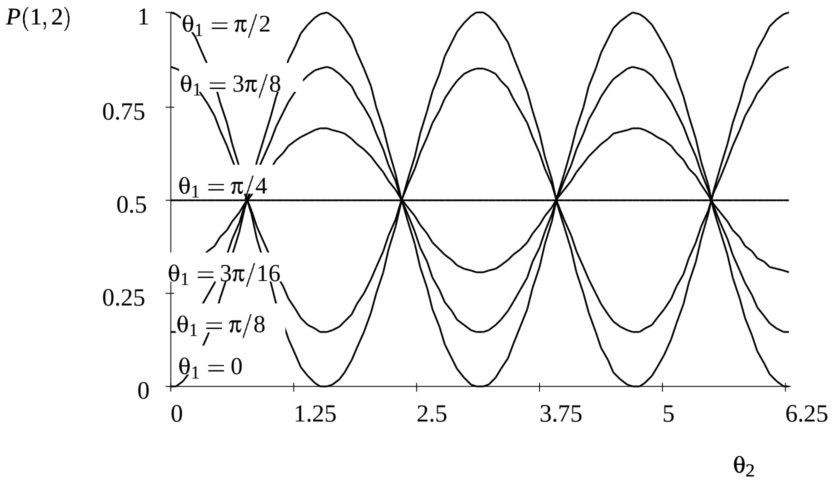
The figure clearly shows a variation in the intensity of the correlations curves as a function of the value of the angle of the polarizer in the first arm. The curves shrink about an average of $1/2$, going to zero for $\pi/4$. That is, the visibility of this curve goes to zero for this angle. Although there is no published data addressing this issue known to this writer, he has been told that indeed in EPR type experiments this visibility typically exhibits precisely this sort of variation.(11) Since the cause was not understood, and fully unexpected from quantum theory, it has been attributed to an artifact of unknown origin and its analysis differed.

V. COMMENTS

The existence of this variation of visibility is counter-evidence against the photon paradigm. The analysis employed above and based on the observation that EPR-B correlations are a consequence of Malus' Law, is not a fluke or exception. This writer has shown elsewhere that the data from all generic EPR-B and GHZ experiments can be explained only using an elaborated form of Malus' Law. At the same time, it needs to be emphasized, that properties of light *in the direction of propagation,* in contrast to the properties in the directions *orthogonal* to the direction of propagation—polarization properties—require quantum concepts. In other words, the variables of amplitude and phase are regulated by quantum structure, while the variables of polarization, e.g., vertical and horizontal polarization, *do not* require quantum principles.

The properties of 'irreality' and 'nonlocality' are all by themselves philosophically objectionable, but seem to have been so defined, that in combination they are not testable experimentally, which all by itself, according to POPPER, is an inadmissible type hypothesis for a scientific theory. That, therfore, these properties when applied to correlated pairs lead to experimental consequences, can be understood as a particularly important effect to address the issue of their viability. As such, it deserves careful numerical and experimental study and analysis; this writer looks foreword to the availability of such data.

The fact that whatever the nature of the electromagnetic interaction is, or what substance its 'carrier' (if any) has, is fundamentally of a different nature in different directions, can be



Correlations, $P(1,2)$, as functions of polarizer angles, $\theta_{1,2}$

FIG. 1 This graph shows the calculated dependence of the coincidence probabilities as functions of the measurement polarizer filters with respect to the axis of the PDC crystal axis. Observation of this variation is empirical support for the non quantum model of optical EPR-type experiments.

seen as untenable ontology. At the same time, the objections to the wave paradigm, namely that there is no evidence for the media to support the collective motion, which constitutes the very nature of a wave, is not addressed by these considerations. Thus, this argument cannot be taken as support for the wave paradigm, which leaves the issue of the “true nature” of the electromagnetic interaction an open question with respect to a choice between these two proposals.

In toto, additional reason to doubt the validity of the photon paradigm, can be seen as a contribution to the argument that the optimal model of the electrodynamic interaction is: “direct-interaction” on the light cone as suggested originally by SCHWARZSCHILD.(12) And, in any case, this is the only paradigm yielding well posed equations of motion for massive charged particles.(13)

Note: Preprints of Refs: (1; 3; 9; 13); and English translations of Refs: (4–7; 12), can be downloaded from: `www.nonloco-physics.000freehosting.com`

References

[1] A. F. Kracklauer, SPIE Proc. , Vol. **5866**, pp. 112-118 (2005); “Oh photon, photon, whither art thou gone?”.

[2] C. Roychoudhuri, SPIE Proc. , Vol. **5866**, 26-35 (2005) “If superposed light beams do not re-distribute each others energy in the absence of detectors (material dipoles), can an individual single photon interfere by/with itself?”.

[3] A. F. Kracklauer, Optics and Spectroscopy, (to appear; & quant-ph/0602080), “Are Quantum ‘Irreality’ and ‘Nonlocality’ ineluctable?”.

[4] W. Heisenberg, Z. Phys. **38**, 411-426 (1926), “The Multibody Problem and Resonance in Quantum Mechanics.”

[5] W. Heisenberg, Z. Phys. **40**, 501-506 (1927), “Wave Phenomena and Quantum Mechanics.”

[6] W. Heisenberg, Z. Phys. **40**, 551-576 (1927), “The Multibody Problem and Resonance in Quantum Mechanics II.”

[7] W. Heisenberg, Z. Phys. **43**, 172-198 (1927), “On the Imaginable Content of Quantum Theoretical Kinematics and Mechanics.”

[8] P. Forman, “Weimar Culture, Causality, and Quantum Theory, 1918-1927: Adaption by German Physicists and Mathematicians to a Hostile Intellectual Environment,” in “Historical Studies in the Physical Sciences,” R. McCormmach (ed.) (U. of Penn. Press, Philadelphia, 1971), pp 1-115.

[9] A. Kracklauer. “State visibility in q-bit space”, quant-ph/0703032.

[10] L. Mandel and E. Wolf, “Optical Coherence and Quantum Optics,” (Cambridge University Press, Cambridge, 1995), Chapter 6.

[11] T. Walther, personal communication. See: T. Walther and E. Fry, “Mercury—the Rosetta stone of physics?” J. Op. B. Quant. Semiclass. Op. **4**(4) S376-S383 (2002).

[12] K. Schwarzschild, Gött. Nachr. **128**, 126-278 (1903), “On Electrodynamics I, II & III,”.

[13] A. F. Kracklauer, J. Math. Phys. **18**(4) 838-841 (1978), “A Theory of the Electromagnetic Two-body Interaction,”.