Arguments Concerning Photon Concepts

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Many contemporary textbooks innocently speak of light in terms of waves, particles, or both.[1] Because many specialists in quantum optics believe that such vague and contradictory conceptions are incorrect, published articles protesting these photon concepts are now prevalent.[2] But are these recent arguments well formulated? I will first briefly outline how arguments concerning unobservables such as light quanta should be constructed. Next, I will examine two recent papers by W. E. Lamb and Geoff Jones that argue against traditional photon concepts and indicate why these attempts are inadequate. Finally, I will argue, like Lamb and Jones, against these photon conceptions but do so by utilizing only admissible methods for arguing unobservables.

I. Models

Over the course of this paper, in order to better distinguish various photon concepts, it will prove beneficial to quickly review and term basic models. Note that photons I-III will be collectively referred to as traditional photon conceptions.

Early Photons. Hertz's discovery of the photoelectric effect in 1887 and Rayleigh's treatment of blackbody radiation in 1900 could not be explained with a classical (Maxwellian) wave interpretation.[3] Plank's derivation of the Rayleigh law introduced an underdeveloped discrete concept of radiation.[4] Einstein suggested the concept of light quanta (Lichtquanten) to explain, among other observations, the photoelectric effect.[5] Many competing theories have accounted for the empirical evidence,[6] however, and it has been argued that Einstein's conclusions were not fully justified.[7] In 1926, G. N. Lewis invented the term "photon" in intentional imitation of the "proton" or "electron".[8] The Lewis photon was a particle that transmitted radiation from one atom to another and was *not* the light quantum of Einstein. According to one physicist, "the word 'photon' caught on, but not Lewis' meaning."[9] Since the term's conception, the interpretation of the 'photon' has changed considerably. Kidd, Ardini, and Anton have outlined four major versions of this entity.[10]

Photon I. This conception is often referred to as the "particle model."[11] As this term suggests, photon I is described as a localized "globule"[12] or "particle of light".[13] The rest mass of photon I is usually considered to be zero but must be less than 8×10^{-46} kg[14] if any mass is possessed at all. The volume of such a particle is required to be between zero and $[c/f_0]^3$ where f_0 is the frequency of the particle's motion and c is the speed of light.[15] This "billiard ball" conception is frequently used in elementary textbooks to describe momentum transfers and the Compton effect.[16]

Photon II. This photon conception has been called the composite model[17] and describes both wave-like and particle-like phenomena. Given the difficulties of Photon I, Einstein attempted to reformulate his light quanta. He proposed a conception that could be interpreted as "a kind of fusion of the wave and emission theory."[18] Although Einstein never produced a significant dual theory, Bohr's famed complementarity principle vaguely accounted for both wave and particle behavior of light. The orthodox complementarity principle[19] implies that a photon can exhibit either particle-like properties or wave-like properties but never both at the same time.[20] According to Kidd, Bohr's conception of the photon (hereafter photon II) could be considered as the "alternate use of Photon I and the classical wave model…"[21]

Photon III. This photon concept is referred to as the "wave packet model."[22] The superposition of classical waves at varying frequencies can produce a continuous wave with a localized high amplitude region. This "packet" within the wave can only be localized within a small region *dx* at the cost of increasing the number of wave frequencies and the uncertainty of the associated momenta or *dp*.[23] Thus, like an electron, Photon III would obey Werner Heisenberg's familiar uncertainty relation. Many of today's undergraduate quantum mechanics textbooks utilize the Photon III model to explain both the uncertainty principle and the dual nature of light.[24] It is important to note that wave packets created by superimposing classical (i.e. Maxwellian) waves are themselves classical.[25]

QTR Model (Photon IV).[26] This conception was developed between 1927-1932 by (among others) Dirac[27] and Fermi[28] and is often called the QED (Quantum Electrodynamics) or QTR (Quantum Theory of Radiation) model.[29] To conceptualize this model, visualize an electromagnetic field that is confined to a perfectly reflecting cavity. The standing waves (modes) produced by the boundary conditions are quantized in such a way that the excitation of the modes are only permitted in integer multiples of hω. According to Louden,[30] a single mode "in its *n*th excited state unambiguously contains *n* photons." Thus, photons in this model have "a more-or-less uniform spatial distribution…" and "…are thus delocalized."[31] It is important to note that the QTR model is fundamentally different from photons I-III because it is modeled after neither classical wave nor particle.

II. Arguments Concerning Unobservables

Neither waves nor particles of light can be observed directly. Accordingly, theories about the unobservable nature of light must infer their conclusions from statements regarding observable phenomena. In what ways, then, should scientists construct theories concerning unobservables? Among others, two "leading scientific methods" supply the answer: inductivism and the hypothetico-deductive or H-D method.[32] Historically, these two methods have often been utilized to construct arguments concerning the unobservable nature of light.[33]

The main idea of the H-D method is summarized by Peter Achinstein: “the fact that hypothesis *h* if true would correctly explain observed phenomena [*O*] constitutes at least some reason to think that *h* is true.”[34] William Whewell added two more steps to the traditional version of the H-D method. His “consilience of inductions” also requires the hypothesis to deduce phenomena “which have not yet been observed”[35] as well as show that such predictions are verified by actual observations $O_1,\ldots,O_n$.

One obvious problem with this method, however, is the possibility of more than one incompatible hypothesis, say $h_1,\ldots,h_n$, that could equally well explain the observed phenomena.[36] Thus, except for extremely limited cases, arguments modeled after the H-D method are generally considered unable to conclude that the truth of some hypothesis *h* is “highly probable.”[37] These problems can be overcome, however, with a stronger version of Whewell’s method. If all possible theories except one are somehow systematically disproven, the remaining theory can be considered highly probable.[38]

Seeing the difficulties with the H-D method, John Stuart Mill proposed his own method for arguments concerning unobservables. He ironically termed his inductive model the “deductive method” and outlined three steps:[39] First, an inductive inference is made about the (unobservable) cause of an effect by surveying similar effects with observable causes. Second, logically deduced consequences are made from the assumed cause. Third, these consequences “must be found, on careful comparison, to accord with the results of direct observation wherever it can be had.”[40]

The following argument, proposed by Achinstein, is modeled after Mill’s method.[41] This argument is characteristic of what an early 19th century wave theorist would be in a position to offer based on the available observational data of the period.[42]

First, assume that light travels in straight lines with uniform speed. Next, suppose that whenever something travels in a straight line with uniform speed, it is caused by either wave phenomenon or particulate (corpsular) phenomenon. Thus, light is either a wave or a particle phenomenon. Let T_1 be the hypothesis that light consists of particles, T_2 that light consists of waves. Given certain observed facts *O*, including ones pertaining to the motion of light and *b* accepted background information, the probability is high (close to one) that either T_1 or T_2 are true.[43] In Achinstein’s notation we have our first premise:

(1) $p(T_1 \text{ or } T_2/O\&b) \approx 1$

Next, given certain aspects of *O* (such as the observations of diffraction and polarization), it is supposed that the probability of the particle theory is close to zero.[44]
We now have

(2) $p(T_1/O\&b) \approx 0$

From (1) and (2) we can deduce that the probability of T_2, given O and b, is close to one or

(3) $p(T_2/O\&b) \approx 1$

Additional effects are then deduced directly (mathematically) from T_2 that explain actual observations $O_1,\ldots,O_n$ (reflection, refraction, etc.) other than O and b. It follows then[45] that

(4) $p(T_2/O_1,\ldots,O_n\&O\&b) \approx 1$

The conclusion of the wave theorist's argument, based on Mill's method, states that "the wave theory is highly probable given a range of observed phenomena".[46]

The methods of Mill and Whewell as outlined above provide scientists with two ways to vindicate (or probabilistically show the truthfulness of) a particular theory. Such methods do not require the subject to be directly detectable and therefore are "frequently employed by scientists postulating unobservables."[47]

III. Recent Arguments Concerning Unobservables (Photons)

W. E. Lamb and Geoff Jones have written two of the most recent and outspoken papers denouncing traditional photon concepts as well as supporting the QTR model.[48] Yet, I believe these physicists have unnecessarily compromised a potentially strong argument by not utilizing variations of either the H-D method or inductivism as outlined by Whewell and Mill. After brief summaries of the Lamb and Jones papers, emphasizing the scarcity of clear logical structure, I will outline the only explicitly constructed argument contained therein. Finally, I will object to this argument by disputing one premise that appeals to the principle of parsimony.

Lamb in Anti-photon:[49] After a short history of "pre-photonic radiation"[50] and the "photon of G. N. Lewis,"[51] Lamb discusses the development and structure of the quantum theory of radiation (photon IV).[52] This section includes applications of QTR to several well-known phenomena such as reflection and refraction.[53] No explanations from competing photon models are mentioned except to say that in describing such phenomena, "it is terribly difficult to talk meaningfully about 'photons' [models I-III] at all."[54] The paper concludes with the suggestion that the QTR be utilized and other photon models abandoned because "such concepts [particularly complementarity principles consistent with photon II] are really not useful or appropriate."[55]

Void of any clear line of reasoning, the only hint of an argument comes in his reference to the “difficult” nature of discussing (and presumably conceptualizing) other photon models. It seems that, here, Lamb is appealing to Ockham’s razor or the principle of parsimony to support his conclusions. This principle implies that between theories that equally well describe experimental data, the simplest theory is to be preferred.[56] Because he explicitly made no mention of any inconsistencies between competing photon models and any empirical data, and because he emphasized the difficulties in conceptualizing these other models, it can only be assumed that Lamb’s argument is founded in parsimony.

Jones in Two Slit Interference-Classical and Quantum Pictures:[57] Jones begins by citing numerous undergraduate textbook explanations of light.[58] Directly from these explanations, he develops a conceptual picture that includes the following “incorrect”[59] ideas:

1. Light consists of a stream of photons which are localized particles. They can be thought of in the same way as electrons, with a well-defined position and size (presumably small compared with an atom).

2. However, interference experiments show that some form of wave motion must be associated with light. This can be seen in terms of a classical electro-magnetic wave, with the consequences that, depending on which experiment you do or, given a particular experimental set-up, which part of the experiment you observe, you have to use one or other mutually contradictory model.[60]

It is clear that this conceptual picture as outlined by Jones is consistent with the mutually exclusive classical wave/particle model of photon II. Next, Jones considers the classical (Maxwellian) interpretation of the interference of light in order that he may compare this interpretation with that of another (QTR) model. Jones then outlines basic features of the quantum theory of radiation[61] including light detection and the interaction of two modes (light quanta interference) as they relate to a double slit experiment.[62] He notes that QTR is consistent with the Maxwellian interpretation of interference (wave phenomenon) and also accounts for the detection process (particle phenomenon).[63] After a brief section[64] discussing various light sources that could be used in two slit experiments, Jones concludes with the following:

> The idea of a single ‘photon’ [photon II] propagating through space is meaningless…If the idea of a ‘photon’ is introduced in terms of the decrease in field energy resulting from the detection process [QTR interpretation], many ambiguities and varieties of ‘double-think’ disappear.[65]

Here, Jones' conclusions are very similar to Lamb's. Both arguments are unclear on exactly how the concluding claims are justified. Each Physicist dismisses Photon II on the grounds of conceptual difficulties and prefers QTR because of conceptual simplicity. Although Jones, in his abstract, characterizes the photon II concept as "wrong,"[66] he, like Lamb, never justifies this by providing an example where photon II fails to explain any empirical evidence. In addition, the way Jones argues for QTR as the simpler, and therefore the favored model is similar to Lamb's use of parsimony. The arguments of the two physicists are so much alike that they can be generalized into the following form (hereafter the LJ argument):

a. QTR and photon II describe all empirical data equally well.
b. QTR is conceptually simpler theory than photon II.
c. Between theories that describe all empirical data equally well, the conceptually simpler theory should be favored.
d. Thus, QTR should be favored.

It must be noted that this is *neither* Lamb's *nor* Jones' actual argument; it is only my piecemeal interpretation of these two papers. In fact, I believe that both Lamb and Jones would quickly reject such an argument as his own. But this is precisely my point. Their (intended) arguments were carelessly construed and the conclusions (to prefer QTR and abandon other models) are weakly justified. Because stronger arguments in these papers do not exist, only the present argument (LJ) can be considered. Although this argument is a valid one, the veracity of all three of the premises can be seriously doubted. Only 'c' will be considered, however, because a refutation of line 'a' could actually be used to build a stronger argument with similar conclusions as LJ while line 'b' is highly debatable.

Although 'c' may be methodologically or epistemologically justified, the truthfulness of such an axiom has no ontological foundation.[67] William of Ockham's objection to Grosseteste's ontological axiom of parsimony is well reviewed by Losee. In short: "to insist that nature always follows the simplest path is to limit God's power. God may very well choose to achieve effects in the most complicated of ways."[68] Of course, one may object to the claim that Lamb and Jones were arguing about the ontological nature of light. Couldn't it simply be that these scientist/teachers prefer QTR to photon II for pedagogical reasons? Despite a clear interest in pedagogy, I believe that both Lamb and Jones argue for the photon IV model also for ontological reasons. While simultaneously discussing methodological advantages to QTR, Lamb is certainly arguing about light's ontological structure. He states that "there is no such thing as a photon"[69] while elsewhere admonishing the reader to become informed about the situation or "forever go on thinking that photons exist."[70] Statements from Jones on the ultimate nature of light are subtler but he, too, seems to be conducting an ontological dialogue. Despite a strong pedagogical slant presented in his paper, the references by Jones to the photon II model as both "wrong"[71] and "incorrect"[72] must be considered ontological. This is because a theory could only be pragmatically described with the words 'wrong' or 'incorrect' if the theory simply fails to describe the phenomena. But Jones never discusses such flaws in the photon II model. If photon II is empirically consistent with the data, how could it be methodologically "wrong" or "incorrect"? Had Jones instead used the words "confusing" or "complicated", I would admit the possibility of his pedagogical intent. As it is, however, it can only be assumed that he is speaking ontologically.

In sum, the conclusions of Jones and Lamb are unconvincing. Whether or not they intended to utilize an argument like LJ is irrelevant. Forthright denunciations of other photon models made by these scientists must be validated in any case. The assertive claims supporting the QTR model made by Lamb and Jones must be logically substantiated whether or not the LJ argument was intended. No such corroboration is present in either instance. If Jones and Lamb intended the LJ argument, the ontological assumption of parsimony proves unpersuasive. If the LJ argument was not intended, no other explicit line of reasoning (and therefore corroboration) can be identified.

IV. Proposed Arguments Concerning Photons

Photons are unobservable entities. As such, arguments concerning photons should be variations of either Mill's "deductive method" or Whewell's method of the "consilience of inductions". The contemporary arguments of Lamb and Jones, as shown in the preceding paragraphs, have not utilized these models. Is it possible to argue the conclusions of these scientists by using the methods of Mill or Whewell? The answer, it seems, is different for each of the methods. I will first show that because light behaves differently than any known observable cause, Mill's deductive method proves unpromising in vindicating a particular photon concept. Naïve development of Mill's approach, however, will be useful in contesting photon models I-III. Next I will show that, in light of well-established results in experimental physics, a strong version of Whewell's method of the consilience of inductions can be used to argue for the QTR model.

The first step in Mill's method is to make an inductive inference about the unobservable cause of an effect. For light, we naïvely proceed with the assumption that light propagates in straight lines with uniform speed and that whenever something travels in a straight line with uniform speed, it is caused by either a (classical[73]) wave phenomenon or particle phenomenon. We also introduce a time dependence[74] to the theories. Light, therefore, is either a classical wave or a particle at any time *t*. Similar to our previous outline of Mill's method, we let $T_1(t)$ be the hypothesis that light consists of particles at time *t*, $T_2(t)$ that light consists of classical waves at time *t*. Given certain observed facts *O*, including ones pertaining to the motion of light and *b* accepted background information, the probability (we innocently assume) is high that either $T_1(t)$ or $T_2(t)$ are true. We have:

$$(5)\ p(T_1(t) \text{ or } T_2(t)/O\&b) \approx 1$$

Note that because photon II must be either a classical wave or a particle at any given time *t* (5) states that the probability is high that the photon II theory at time t is true given *O* and *b*. Also note that at time *t*, $T_1(t)$ represents the photon I theory while $T_2(t)$ represents photon III theory.[75] Consistent with Mill's method, each alterative will be examined. As we proceed, if it is shown that, contrary to inductive experience, Mill's first assumption, (5) is not probable (roughly equal to zero instead of one), then photon models I-III will also be improbable.[76] To disprove such an assumption, an experiment must simultaneously show a low probability of both the classical wave and particle natures of light. Such an experiment has recently been executed.[77]

An Experiment to Throw More Light on Light:[78] The following set-up can be understood as two experiments that are performed at once. The first demonstrates a low probability of the photon I theory or $T_1(t)$ at time *t*: all light passed through a 45° prism is internally reflected, while a second 45° prism placed in contact with the first one (hypotenuse to hypotenuse) allows all the light to pass straight through. It is a property of light,[79] however, that if a small enough separation between the prisms is maintained, some of the light will be transmitted (tunnel[80]) across the gap. Because classical particles cannot tunnel, any detection of transmission falsifies $T_1(t)$ or the photon I theory at time *t*, (when confronted by the separation). The second experiment shows the low probability of the classical wave theory (photon III). If the space between the prisms is roughly one-tenth the wavelength of the light, "about half the beam will be internally reflected while the other half will tunnel across the gap."[81] Sensors are placed where these two beams of light emerge from the prism. These sensors record the precise time the light quanta are detected (both the reflected and transmitted). If light is a classical wave, when confronted by the gap, the wave would split into equal segments of lower intensity and the detectors would click at exactly the same time (correlation).[82] Any unsynchronized clicking of the detectors (anti-correlation), then, invalidates the photon III theory or $T_2(t)$ at time *t*, when confronted by the gap. When this experiment was preformed in 1992 by Mizobuchi and Ohtake (hereafter the MO experiment), they observed both tunneling as well as anti-correlation effects at the same time *t*.

Returning to our undertaking of Mill's method, from certain aspects of *O* at time *t* (such as the non-particle "tunneling" behavior of the MO experiment), it is supposed[83] that the probability of the particle (Photon I) theory being true is close to zero.[84] We now have:

$$(6)\ p(T_1(t)/O\&b) \approx 0$$

Alternatively, given other aspects of *O* at the same time *t* (such as the non-classical wave like behavior resulting in anti-coincidences in the MO experiment), it is supposed that the probability of the classical wave (Photon III) theory being true at time *t* is close to zero. We have:

(7) $p(T_2(t)/O\&b) \approx 0$

From (6) and (7) we can deduce that at time *t* the probability of $T_2(t)$ or $T_1(t)$ (collectively Photon II) being true given *O* and *b*, is close to zero or

(8) $p(T_1(t) \text{ or } T_2(t)/O\&b) \approx 0$

Thus photon theories I-III are disproved by (6), (8), and (7) respectively. At this point, however, we run into problems using Mill's deductive method. Because (8) contradicts the original assumption (5), and (8) was deduced purely from (6) and (7), then either (5), (6), or (7) must be incorrect. (6) and (7) were deductively derived by the falsification of theories. (i.e. if a theory is true, it predicts certain effects, those effects are not observed, the theory is false.) Line (5), on the other hand, was inductively formulated. (i.e. cause y or z create effect x, light creates effect x, therefore light is y or z). Because, generally speaking, deductive arguments are considered stronger than those of induction,[85] we will assume that (5) is not likely (roughly zero) when compared with (8).

In theory, the rejection of (5) is not a problem for Mill's model; (5) could be reformulated by more careful induction to allow for a third possibility. In a reformulation of this type, it will be assumed that (a) light travels in straight lines with a finite speed and (b) whenever something travels in a straight line with uniform speed, it is caused by (and observed directly as) a wave phenomenon or particle phenomenon or a third theory phenomenon. Such a reformulation will result in the following assumption where $T_3(t)$ is the third theory at time *t*:

(5*) $p(T_1(t) \text{ or } T_2(t) \text{ or } T_3(t) /O\&b) \approx 1$

In practice, however, (5*) is difficult to formulate. What directly observable cause, other than waves and particles can produce uniform motion? No such cause has been recognized.[86] QTR cannot be such a cause because it is not directly observable. Here, without a known alternative theory, Mill's method breaks down and one can proceed no further. No photon concept can be upheld using this argument model. Photons I-III can be successfully invalidated, but Mill's first step, causal induction, does not allow for a quantum theory of radiation.[87]

Unlike Mill's model, Whewell's method of the consilience of inductions allows for theories that are not analogous to well-established principles. According to Whewell, "scientific discovery must ever depend upon some happy thought…some fortunate cast of intellect, rising above all rules."[88] Photon IV, clearly founded on the "happy thoughts" of Dirac and Fermi is thus permissible in the consilience of inductions. In arguing theories like QTR, however, Whewell's method is generally not sufficient to show a high probability for such theories.[89] Because of the possibility of competing theories being equally good predictors of phenomena, a stronger version of Whewell's model must be formulated to eliminate these competitors. I propose the following version:[90] suppose a partition of hypotheses on *b* is made such that $h_1,\ldots,h_m$ are mutually exclusive and exhaustive on *b*, with the probability of disjunction on *b* being one:

$$(9)\ p(h_1 \text{ or } h_{2\ldots} \text{ or } h_m / O_1,\ldots,O_n\&b) = 1$$

If it can be shown that each hypothesis is not probable excepting one (say h_1) as the number of predicted observations performed increases, then Whewell's method can establish a high probability (close to one) for h_1. This eliminative variation can be expressed in the following provable theorem:

(10) Let $\{h_{1,\ldots,}h_m\}$ be a set of mutually exclusive hypotheses that are exhaustive on *b* (such that $\sum_{i=1}^{m} p\ (h_i/O_1,\ldots,O_n\&b) = 1$). If $\sum_{i=2}^{m} p\ (h_i/O_1,\ldots,O_n\&b) \approx 0$ then $p(h_1/O_1,\ldots,O_n\&b) \approx 1$

I believe that this variation of Whewell's method, in conjunction with well-established empirical evidence, can be used to argue for the quantum theory of radiation. The first step in such a proof will be to designate a set of mutually exclusive hypotheses that are exhaustive on *b*. One of these hypotheses must be the QTR theory. We naturally define QTR as a composite of a wave hypothesis and a quantum hypothesis.[91] Next, consider that every hypothesis on *b* must be either a wave or a non-wave hypothesis. Similarly, each wave or non-wave hypothesis on b must be either a quantum or a non-quantum (either allows for the discreet nature of light or not) hypothesis. An exhaustive set of hypotheses on *b* can now be created. Every feasible hypothesis about light must be one of the following four possibilities: quantum wave (h_1), non-quantum wave (h_2), quantum non-wave (h_3), and non-quantum non-wave (h_4). We have:

$$(11)\ p(h_1 \text{ or } h_2 \text{ or } h_3 \text{ or } h_4 / O_1,\ldots,O_n\&b) = 1$$

The next step will be to show that h_2, h_3, and h_4 are improbable hypotheses for light as more and more results of the predicted observations are accumulated.

Evidence against h_3, *and* h_4*:* Two well-established phenomena of light show a low probability of a non-wave theory: interference and tunneling. Only waves produce interference patterns. For this reason, these patterns have, since Young's double slit experiment in 1801, long been considered evidence for wave theories.[92] During the past two centuries, even extreme variations of Young's experiment have consistently produced the predicted interference patterns opposing any non-wave theory.[93] Like interference patterns, tunneling is a phenomenon unique to waves. Bose first showed that microwaves (non-visible light) could tunnel through a gap in a prism.[94] Many variations of the Bose experiment[95] have been performed and in each case the predicted tunneling is observed. These observations yield much evidence against non-wave theories and thus provide "no problem proving the wave nature of light."[96] It is important to note that the results of the MO experiment, as well as all other observations falsifying a classical wave interpretation as discussed before, *cannot* be considered as evidence against wave theories in general. Classical waves are merely a subset of waves. The fact that light is not an element of the set of classical waves does not preclude it from being an element of a larger (and more general) set of waves.[97] Because h_3 and h_4 are types of non-wave theories, we have:

(12) $p(h_3/O_1,\ldots,O_n\&b) \approx 0$.

(13) $p(h_4/O_1,\ldots,O_n\&b) \approx 0$.

Evidence against h_2*:* Having eliminated the possibility of non-wave theories, we now turn our attention to whether light is a quantum or non-quantum wave. Unique to quantum wave theories is the phenomenon of anti-correlation or "photon" anti-bunching.[98] As previously discussed in regards to the MO experiment, anti-correlation occurs when two detectors that are illuminated with the same source fail to detect the light simultaneously.[99] Despite early observations of correlation by Hanbury-Brown and Twiss in 1956,[100] anti-correlation is now a well-established phenomenon. Predicted observations of anti-correlation have been documented in a wide variety of situations by (among others) Clauser,[101] Grangier, Roger, and Aspect,[102] as well as Kimble, Dagenais, and Mandel.[103] These observations falsify non-quantum theories and therefore provide much "evidence for the quantum nature of light."[104] We now have:

(14) $p(h_2/O_1,\ldots,O_n\&b) \approx 0$

From the theorem (10), the vindicated assumptions (11)-(14), and the definition of QTR as h_1, we conclude that the probability of QTR being true is high given the results of the predicted observations and background information:

(15) $p(QTR/O_1,\ldots,O_n\&b) \approx 1$

Thus, this version of Whewell's method of consilience can be used to argue for the QTR or photon IV model.

V. Conclusion

The conclusions of Jones and Lamb, namely, (a) that photon models I-III are "incorrect" conceptualizations and (b) that the QTR is the "only proper description" of light, have now been probabilistically corroborated. These conclusions were originally not justified in the papers of Lamb and Jones. Bereft of any clear logical structure, their only feasible argument, LJ, proves unconvincing because of an ontological assumption of the principle of parsimony. When arguing about unobservables, well-formulated versions of hypothetico-deduction and inductivism can, and should, be employed. Specifically, variations of the methods of Mill and Whewell were systematically applied to reach Jones' and Lamb's initial conclusions.

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[1] For a list, see D. G. C. Jones, "Two Slit Interference—Classical and Quantum Pictures," *European Journal of Physics* 15 (1994): 170-178. 170-171.

[2] See W. E. Lamb, "Anti-Photon," *Applied Physics B* 60 (1995): 77-84; W. E. Lamb and M. O. Scully, "The Photoelectric Effect Without Photons," in *Polarisation Matiere et Rayonnement*, ed. A. Kastler (Paris : Presses Universitaires de France, 1969) 363-369; M. O. Scully and M. Sargent, "The Concept of the Photon," *Physics Today* 25 (1972): 39-47; and Jones, "Two Slit Interference."

[3] P. L. Knight and L. Allen, *Concepts of Quantum Optics* (New York: Pergamon Press, 1983), 2.

[4] Lamb, "Anti-photon," 78.

[5] Albert Einstein, "Concerning an Heuristic Point of View Toward the Emission and Transformation of Light," reprinted in *American Journal of Physic*s 33 (1965): 367-374.

[6] For a list, see R. Kidd, J. Ardini, and A. Anton, "Evolution of the Modern Photon," *American Journal of Physics* 57 (1989): 27-35. 30.

[7] G. Greenstein and A. Zajonc, *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics* (Sudbury, MA: Jones and Bartlett, 1997) 23. For a differing view see Jon Dorling, "Einstein's Introduction of Photons: Argument by Analogy or Deduction from the Phenomena?" *British Journal of Philosophy of Science* 22 (1971): 1-8.

[8] G. N. Lewis, "The Conservation of Photons," *Nature* 118 (1926): 874-875. 874.

[9] Lamb, "Anti-Photon," 79.

[10] Kidd et. al, "Evolution," 30-33. The names of the different models are taken directly from this paper (i.e. photon I, photon II, etc.)

[11] Ibid. 30.

[12] Rodney Loudon, *The Quantum Theory of Light* (Oxford: Oxford University Press, 2000) 1.

[13] John Gribbin, *Q is for Quantum: An Encyclopedia of Particle Physics* (New York: Free Press, 1998) 282.

[14] L. Davis, A. Goldhaber, and M. Nieto, "Limit on the Photon Mass Deduced from Pioneer-10 observations of Jupiter's Magnetic Field," *Physical Review Letters* 35 (1975): 1402-1405. 1402.

[15] D. Shanks, "Monochromatic Approximation of Blackbody Radiation," *American Journal of Physics* 24 (1956): 244-246. 244.

[16] R. Serway and R. Beichner, *Physics* (Orlando, FL: Saunders College Publishing, 2000) 1301.

[17] Kidd et al., "Evolution," 32.

[18] Abraham Pais, *Subtle is the Lord: The Science and the Life of Albert Einstein* (Oxford: Oxford University Press, 1982) 420.

[19] Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge: Cambridge University Press, 1961) 10.

[20] A recent suggestion by Englert (1996) in which a photon can simultaneously exhibit wave and particle behavior in accordance with an uncertainty-type relation will not be considered here. B. G. Englert, "Fringe Visibility and Which-Way

Information: An Inequality," *Physical Review Letters* 77 (1996): 2154-2157.

[21] Kidd et al., "Evolution," 32.

[22] Ibid.

[23] Gribbin, *Quantum*, 428-429.

[24] Kidd et al., "Evolution," 32; P. Tipler and R. Llewellyn*, Modern Physics* (New York: W.H. Freeman and Company, 1999 210.

[25] Quantum wave packets can be created but these are members of the photon IV group. See Loudon, *Quantum Theory o Light*, 2.

[26] Depending on how 'photon' is defined, QTR may or may not be considered as a 'photon' concept. Here, as with mos physicists, I will term the fundamental entities of light described by the QTR model as 'photons'.

[27] P. Dirac, "The Quantum Theory of the Emission and Absorption of Radiation," *Proceedings of the Royal Society o London* A 114 (1927): 243-265. 243.

[28] E. Fermi, "Quantum Theory of Radiation," *Reviews of Modern Physics* 4 (1932): 87-132. 87.

[29] Kidd et al., "Evolution," 32.

[30] Loudon, *Quantum Theory of Light*, 1.

[31] Ibid. 1.

[32] Peter Achinstein, "Observation and Theory," in *A Companion to the Philosophy of Science*, ed. W. H. Newton-Smith (Malden, MA: Blackwell Publishers, 2000) 325-334. 325. The author is aware of alternative methods but will not consider them here. For further reading on scientific research methodology see Imre Lakatos, "Falsification and the Methodology of Scientific Research Programs," in *Criticism and the Growth of Knowledge,* ed. I. Lakatos and A. Musgrave (Cambridge: Cambridge University Press, 1971) 91-195.

[33] See Achinstein's historical account in *Particles and Waves: Historical Essays in the Philosophy of Science* (Oxford Oxford University Press, 1991).

[34] Ibid. 72.

[35] William Whewell, *The Philosophy of Inductive Sciences, Vol. 2* (New York: Johnson Reprint, 1967) 62-65.

[36] Hugh Gauch, *Scientific Method in Practice* (Cambridge and New York: Cambridge University Press, 2003) 82-84; W. H. Newton-Smith, "Underdetermination of Theory by Data," in *A Companion to the Philosophy of Science*, ed. W. H. Newton-Smith (Malden, MA: Blackwell Publishers, 2000). 532-536. 532.

[37] Achinstein, "Observation," 327.

[38] See Achinstein, *Particles*, 133.

[39] John Stuart Mill, *A System of Logic* (London: Longmans, 1959) 303.

[40] Mill, *Logic*, 303.

[41] Mill himself was not inclined to use the proposed probabilistic methods. See Geoffrey Scarre, "Induction and the Scientifi Method," in *The Cambridge Companion to Mill*, ed. J. Skorupski (Cambridge and New York: Cambridge University Press 1998) 112-138. 137.

[42] Achinstein, *Particles*, 74.

[43] Achinstein, *Particles*, 81.

[44] Achinstein, "Observation," 328

[45] The general theorem is that for any r such that 0 < r < 1, p(T/O1,…,On&O&b) > r if: (i) p(T/O&b) > r and (ii) O1,…O are explainable via derivation from T (plus b). See Achinstein, *Particles*, 82.

[46] Achinstein, *Particles*, 82.

[47] Achinstein, "Observation," 328. See also p. 326 of the same work.

[48] Lamb, "Anti-Photon," 77-84 and Jones, "Two Slit Interference," 170-178.

[49] See also Lamb and Scully, "The Photoelectric Effect," 363-369.

[50] Lamb, "Anti-Photon," 77.
[51] Ibid. 79.
[52] Ibid. 81.
[53] Ibid. 81-82.
[54] Ibid. 83.
[55] Ibid. 84.
[56] Gauch, *Scientific Method*, 269.
[57] See also John Gribbin, “Do Photons Really Exist?” *New Scientist* 143 (1994): 16-17.
[58] Jones, "Two Slit Interference," 170-171.
[59] Ibid. 171.
[60] Ibid.
[61] Ibid. 172-174.

[62] Thomas Young originally preformed the two-slit experiment. For a thorough examination of the history and set-up of the experiment see Alan A. Grometstein, *The Roots of Things: Topics in Quantum Mechanics* (New York:Plenum Publishers, 1999. 65. See also Thomas Young, “The Bakerian Lecture: Experiments and Calculations Relative to Physical Optics” in *Philosophical Transactions of the Royal Society of London* 94 (1804):1-16.

[63] Jones, "Two Slit Interference," 174.
[64] Ibid. 175-177.
[65] Ibid. 177.
[66] Ibid. 170.

[67] Philotheus Boehner, *Ockham: Philosophical Writings* (New York: Nelson, 1957) xxi. Also see Elliott Sober, “Simplicity,” in *A Companion to the Philosophy of Science*, ed. W. H. Newton-Smith (Malden, MA: Blackwell Publishers, 2000) 532-536. 433.

[68] J. A. Losee, *A Historical Introduction to the Philosophy of Science* (Oxford: Oxford University Press, 1993) 38-39.
[69] Lamb, "Anti-Photon," 77.
[70] Ibid. 81.
[71] Jones, "Two Slit Interference," 170.
[72] Ibid. 171.
[73] Here, the distinction between classical and other (quantum) waves becomes useful.
[74] This is in order to refute Bohr’s mutually exclusive wave/particle photon II.
[75] As discussed before, because a superposition of classical waves is itself a classical wave, strictly speaking, photon III must be considered a classical wave.

[76] This is because the probability of the disjunction of two theories is equal to the sum of the probabilities of the theories considered separately. If the probability of the photon I theory is close to zero and the probability of the photon III theory is close to zero then the probability of the photon II theory (the disjunction of photons I and III), will be close to zero as well.

[77] Y. Mizobuchi and Y. Ohtake, “An ‘Experiment to Throw More Light on Light,’” *Physics Letters A* 168 (1992): 1-5.

[78] The original theoretical conception of such an experiment was termed "An experiment to throw more light on light" by Partha Ghose, Dipankar Home, and G. S. Agarwal. See P. Ghose, D. Home, and G. S. Agarwal, “An Experiment to Throw More Light on Light,” *Physics Letters A* 153 (1991): 403-406.

[79] This was established by J. C. Bose in 1897. See J. C. Bose, “On the Influence of the Thickness of Air Space on the Total Reflection of Electric Radiation,” *Proceedings of the Royal Society of London* 62 (1897): 300-310.

[80] Tunneling is the phenomenon that allows waves to pass through barriers. In this case, the probability of the light passing through the separated prisms is inversely proportional to the distance of the gap. See Tipler and Llewellyn, *Modern Physics*, 268-276.

[81] Mizobuchi and Ohtake, "An 'Experiment,'" 1.

[82] Arthur Zanjonc, *Catching the Light: The Entwined History of Light and Mind* (Oxford: Oxford University Press, 1993) 294-296.

[83] This does not take into account any auxiliary hypothesis *h*, proposed by Photon I theorists, that explains a particle's tunneling behavior. If such a hypothesis can be assumed unlikely, Bayesian probabilities can show that the theory that is supported by *h* is also improbable. See Achinstein, *Particles*, 85-90.

[84] Achinstein, "Observation," 328.

[85] Karl Popper, *The Logic of Scientific Discovery* (New York: Routledge, 2002) 3-7.

[86] Of course, other causes and/or theories have been proposed. However, these are not directly observable as Mill's method requires.

[87] Scarre, "Induction," 136.

[88] Robert Butts, *William Whewell's Theory of Scientific Method* (Pittsburgh: University of Pittsburgh Press, 1968) 117.

[89] Achinstein, *Particles*, 117.

[90] This version of Whewell's method is based on ideas proposed by Achinstein. See his *Particles*, 136-137.

[91] QTR is created by a "quantum" theory being applied to the classical Maxwellian (wave) theory of light. See Louden, *Quantum Theory of Light*, 1-2 and Scully, *Quantum*, 26.

[92] Grometstein, *Roots*, 76-77.

[93] See G. I. Taylor, "Interference Fringes with Feeble Light," *Proceedings of the Cambridge Philosophical Societ*y 15 (1909): 114-115; and G. Magyer and L. Mandel, "Interference Fringes Produced by Superposition of Two Independent Maser Light Beams," *Nature* 198 (1967): 255-256.

[94] Bose, "Influence of the Thickness of Air Space," 300-310.

[95] See P. Balcou and L. Dutriaux, "Dual Optical Tunneling Times in Frustrated Total Internal Reflection," *Physical Review Letters* 78 (1997): 851-854 and L. I. Deych, D. Livdan, and A. A. Lisyansky, "Resonant Tunneling of Electromagnetic Waves through Polariton Gaps," *Physical Review E* 57 (1998): 7254-7258.

[96] D. Home and J. Gribbin, "What is Light?" *New Scientist* 132 (1991) 30-33. 31.

[97] If my wife asks me whether I ate any potato chips yesterday, I can truthfully answer no even if I munched on chips (corn chips) all afternoon.

[98] D. F. Walls, "Evidence for the Quantum Nature of Light," *Nature* 280 (1979): 451-454. 451. See also Roy J. Glauber, "The Quantum Theory of Optical Coherence," *Physical Review* 130 (1963): 2529-2539.

[99] Greenstein and Zajonc, *The Quantum Challenge*, 26.

[100] R. Hanbury-Brown and R. Q. Twiss, "Correlation between Photons in Two Coherent Beams of Light," *Nature* 177 (1956): 27-29. 192. This was due to the fact that Hanbury-Brown and Twiss did not use single photon states for their set-up. Statistically, the light arrived at the detectors at the same time. See Greenstein and Zajonc, *The Quantum Challenge*, 32-33.

[101] John Clauser, "Experimental Distinction Between the Quantum and Classical Field Theoretical Predictions for the Photoelectric Effect," *Physical Review D* 9 (1974): 853-860.

[102] P. Grangier, G. Roger, and A. Aspect, "Experimental Evidence for a Photon Anticorrelation Effect on a Beamsplitter: A New Light on Single Photon Interferences," *Europhysics Letters* 1 (1986): 173-179.

[103] H. J. Kimble, M. Dagenais, and L. Mandel, "Photon Anti-bunching in Resonance Fluorescence," *Physical Review Letters* 39 (1977): 691-695.

[104] Walls, "Evidence," 451-454.