Experimental test for violation of duality on a photon beam

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Abstract

We test for evidence violating the duality invariant ratio of photon beam irradiance and wave intensity. Split beams from a 633nm HeNe laser are intersected at a diffraction grating complementary to the resultant interference pattern. An output beam from the grating, depleted in irradiance relative to wave intensity from the perspective of local realism, is transiently intersected with a beam from an independent HeNe laser and measured irradiance is amplified by ~4% in conflict with quantum mechanics.

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I.   INTRODUCTION

A basic representation of local realism presented earlier postulates that photons are comprised of separate real entities of wave structure and energy quanta [1, 2]. In this representation, the wave intensity is a relative probability density that determines the distribution of the resident energy quanta as a proportionate energy flux density consistent with Born's first principle. A wave entity is independent of its resident energy quanta, and wave entities are mutually non-interactive. These properties are essentially equivalent to those of the locally real wave structures postulated by de Broglie [3] and interpreted as propensities by Popper [4]. Interference is a consequence of the superposition of these non-interactive wave entities in a region of mutual intersection. The physical manifestation of this interference in the intersection region is the redistribution of the energy flux density proportionate to the superposition wave intensity.

Conversely, in quantum mechanics photons are treated as probabilistic entities that exhibit dualistic wave or particle properties depending upon the nature of the measurement process. The proportionality between wave intensity and energy flux density is a superfluous invariant. Moreover, a photon can interfere only with itself.

Then the class of experiments involving two intersecting independent photon beams seemingly provides a testable basis for differentiating between local realism and quantum mechanics. Many such experiments have demonstrated that interference does occur in apparent conflict with quantum mechanics [5].

However, Mandel argued that the results of these experiments do not constitute a violation of quantum mechanics since, for any photon, we do not know on which beam that photon had initially resided [6]. This lack of knowledge provides a loophole that allows any photon, with its initial beam of residence not known, to interfere with itself. Consequently, because of that loophole, this class of experiments is not generally viewed as differentially testing quantum mechanics and local realism. Mandel further contended that this conclusion was applicable to the discrete realm as well as to the continuous wave realm.

Our objective here is to close Mandel's loophole by taking this class of experiments employing intersecting independent beams an additional step. In the continuous wave realm, we prepare one of the beams in accord with the locally real representation such that the beam is in a state depleted in energy flux density (irradiance) relative to the beam's wave intensity

noting that this property of depletion is contrary to quantum mechanics [7]. A transient spatial coupling of an independent beam and that depleted beam provides for a zone of mutual interference of those beams. We still do not know for any given photon on which beam that particular photon had initially resided so we certainly continue to expect interference to occur in this zone from the perspectives of both local realism and quantum mechanics. However, for local realism the exchange of energy quanta is not completely random. A potentially measurable net redistribution of energy quanta should occur onto the depleted beam from the independent beam in an equilibration process. This net redistribution of course is not consistent with quantum mechanics since depletion itself is excluded.

II.   PRINCIPLES

In the present work, reference to "quantum mechanics" implicitly denotes the standard probabilistic interpretation of that physical representation. Conversely, "local realism" implies a physical representation devoid of the particular conflicting tenets of the probabilistic interpretation but still fundamentally consistent with the quantum mechanical formalism.

Because these two representations have distinct similarities and differences, it is essential that we precisely define several critical quantities. For some point on the cross section of a given beam the energy flux density, identified as the irradiance I, is measurable by a conventional energy sensitive detector. The associated wave intensity W, which is effectively a probability density, may be measured by assessing interference visibility with a reference beam. I and W vary proportionately across the beam's cross section consistent with Born's first principle. The "occupation value" of a beam defined as

$$\Omega = \frac{I}{W} \tag{1}$$

is then constant at all points on a beam's cross section. Integrating I over a beam cross section $\int I \, da$ gives the total beam power while the analogous integral $\int W \, da$ is recognized as the total probability. Since I and W vary proportionately, the ratio of their integrals also yields the same value of Ω. Nevertheless, it will generally be more convenient to work with the quantities I and W rather than their respective integrals. Moreover, I and W can usually be treated as representing the respective maximum values on a particular beam cross section e.g. for a Gaussian profile, the values at the geometrical center.

In the present context, the two representations fundamentally differ in the treatment of wave intensity W. For quantum mechanics W is an absolute probability density that is in a fixed proportion to I. Conversely, for local realism W is a relative probability density. The immediate consequence of this disparity is that for quantum mechanics the occupation value is inherently some constant Ω_o, rendering that quantity as superfluous, whereas for local realism a "non-ordinary" beam could, in principle, be prepared such that $\Omega \neq \Omega_o$ (although we expect that virtually all typically encountered beams will be "ordinary" with an occupation value Ω_o not in conflict with quantum mechanics). Arbitrary units can always be employed such that I and W are pure numerical values mutually scaled to equality. Consequently, for this choice of units the occupation value $\Omega_o = 1$ is universal for quantum mechanics but is applicable to local realism only for ordinary beams. Then, relative to resident energy quanta, a beam for which $\Omega < 1$ is appropriately defined as "depleted".

In the discrete realm, where at most only an individual photon is present on any macroscopic segment of beam path, an Ω for local realism may deviate from unity by means as trivial as a simple beam splitter. For the discrete realm, as well as the continuous wave realm, the incident wave intensity is always fractionally divided between the two output channels in accord with the transmission and reflection coefficients of the beam splitter, but, most noticeably for discrete events, the particular output channel assumed by the single energy quantum is random and uncontrollable, albeit, statistically predictable at the exit face of the beam splitter. Then, for a particular output channel and event, the resultant output beam is also randomly and uncontrollably transiently "depleted" or "enriched" in energy quantum relative to the wave intensity.

Quantum mechanics is not violated in this discrete phenomenon since probabilistically, on both of the output beams, we still have an expectation of an energy quantum proportionate to the fractional wave intensity.

Historically, many investigations designed to test the reality of empty (totally depleted) de Broglie waves have used related methods. However these methods can only yield the very weak wave intensities associated with discrete photon beams.

We report here the results of an experimental test of this disparity between quantum mechanics and local realism using an apparatus that should generate depleted beams in the continuous wave realm from the perspective of local realism. A transient equilibration of one of these beams with an ordinary beam is then expected to provide evidence resolving

that disparity.

As a prelude to considering the details of the apparatus, we first consider a single beam incident on two similar but critically distinctive gratings G_u and G_c (Max Levy Autograph, Inc., BA011 and ZY002, respectively). Both have the basic structure of a Ronchi ruling, an array of equal width transmissive and opaque bands, with opaque bands at 100 per inch on a glass plate. The opaque bands on G_u are thin $\sim 0.1\mu m$ depositions of black evaporated chrome whereas on G_c the opaque bands are fabricated by etching the glass support plate to a depth of $\sim 10\mu m$ and filling with black epoxy. The resultant diffractive orders of the two gratings differ measureably in relative irradiances. Most notably the irradiance ratio of the 0th order relative to the $\pm 1^{st}$ order is $1 : 0.41$ for G_u and $1 : 0.57$ for G_c. This deviation is not unexpected since the relative irradiances of diffractive orders are a very sensitive function of the periodic structures.

For an idealized Ronchi ruling, the relative irradiance of the ith order is given by $sinc^2(i\pi/2)$. The 0th to 1st order ratio, $1 : 0.405$, is very nearly equivalent to that of G_u. Accordingly, we approximate G_u as an idealized Ronchi ruling with relative wave amplitudes given by $sinc(i\pi/2)$ which is used to generate a normalized set of amplitudes $\{A_{ui}\} = 0.506$, 0.323, 0, -0.107, 0, 0.064, 0, -0.046 for the $\pm i^{th}$ order $0^{th}, \pm 1^{st}, \pm 2^{nd}$ etc. truncated at $\pm 7^{th}$ since higher orders are substantially diminished. In the scalar treatment applicable to this relatively coarse grating, the squares of these amplitudes $A_{ui}^2 = W_{ui} = I_{ui}$ where W_{ui} and I_{ui} are respectively the $\pm i^{th}$ order wave intensity and irradiance for a single beam incident on G_u. The set $\{A_{ui}\}$ is normalized here such that the sum of squares gives a 0.5 transmitted wave intensity and a 0.5 transmitted irradiance where the incident $W = I = 1$. This normalization is consistent with the 50% transmissivity of Ronchi rulings to plane radiation. Because of the equivalence of transmitted irradiance and wave intensity for a single incident beam, the theoretical occupation value computed for the total transmitted set is trivially $\Omega_{uT-th}(1) = 0.5/0.5 = 1$ where the argument specifies that one beam is incident. Equilibration further provides that the occupation value $\Omega_{ui-th}(1) = 1$ for each individual transmitted i^{th} order diffraction beam since the energy quanta at the exit face of the grating distribute onto the individual beams in proportion to their respective wave intensities. Accordingly, we suppress the subscripts T and i, and $\Omega_{u-th}(1) = 1$ is understood to apply to both the total and the individual beams of the diffraction orders.

To first order, the higher irradiance ratio for G_c relative to that of G_u is equivalent to

a relative broadening of the diffractive envelope. (This broadening could equivalently be generated by providing G_u with with plano-concave transmissive bands.) The higher orders of G_c can be approximated by numerically fitting the *sinc* argument of G_u to yield the ratio $1 : 0.57$ which results in $i\pi/2 \to 0.8i\pi/2$. The corresponding set of G_c normalized wave amplitudes is $\{A_{ci}\}$ = 0.459, 0.347, 0.107, -0.072, -0.086, 0, 0.058, 0.031 for orders $0^{th}, \pm 1^{st}, \pm 2^{nd}$ etc. again truncated at $\pm 7^{th}$. This set, like that of G_u, is also normalized such that the sum of squares gives a 0.5 transmitted wave intensity and, equivalently, a 0.5 transmitted irradiance for the chosen normalization of the incident beam. Similarly, for a single incident beam, the theoretical occupation value computed for the total transmitted set is trivially $\Omega_{c-th}(1) = 1$ and this value also applies to each individual transmitted beam. Then both $\Omega_{u-th}(1)$ and $\Omega_{c-th}(1)$ are unremarkably unit valued consistent with quantum mechanics and local realism.

With the above set of amplitudes for G_u and for G_c, we can proceed to calculations of the respective $\Omega_{u-th}(2)$ and $\Omega_{c-th}(2)$, theoretically predicted by local realism for two appropriately aligned incident beams. These calculations are intended here purely as an exercise in providing locally real predictions for the experimentally measured counterparts $\Omega_{u-exp}(2)$ and $\Omega_{c-exp}(2)$.

The two mutually coherent, mutually converging incident beams are angularly separated at some θ_i such that the resultant interference pattern has a spatial periodicity equal to that of the grating. For a relatively coarse grating, such as a Ronchi ruling with 100 opaque bands per inch, the small angle approximation and a scalar treatment of amplitudes are applicable. For the above choice of θ_i, the angular separation of the adjacent diffraction orders from either incident beam $\theta_d = \theta_i$ resulting in spatial coincidences of orders from the two incident beams.

We can treat the gratings as two-stage components, a periodic array of opaque and transmissive bands followed by some diffractive structure associated with the transmissive bands. The calculation of $\Omega_{u-th}(2)$ and $\Omega_{c-th}(2)$ requires a determination of the total transmitted irradiance and the total transmitted wave intensity for each.

The total transmitted irradiance

$$I_T(2) = 2 \frac{\int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \cos^2 x \, dx}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos^2 x \, dx}$$

$$= 1.64 \tag{2}$$

is simply the integrated peak-centered 50% of each interference pattern cycle normalized to the entire cycle ($\Delta x = \pi$). The leading factor of two is the total incident irradiance of which 82.5% is transmitted where I and W for both incident beams are normalized to unity. $I_T(2)$ is the same for both gratings since they share the same first stage array of opaque and transmissive bands.

The second stage total wave intensity for G_u is given by

$$W_{uT}(2) = \sum_{i=-n}^{n+1} (A_{ui} + A_{ui-1})^2$$

$$= 1.66 \tag{3}$$

where A_{ui} and A_{ui-1} in each term are understood to be the coincident amplitudes produced by the respective incident beams. The amplitudes for G_u were given above to $\pm 7^{th}$ order and since their magnitudes diminish substantially by that order the series is truncated by imposing $A_{ui} \equiv 0$ for $|i| > 7$ and $n = 7$.

The resultant occupation value

$$\Omega_{u-th}(2) = \frac{I_T(2)}{W_{uT}(2)}$$

$$= 0.99$$

$$\approx 1 \tag{4}$$

strongly suggests that the configuration of two beams incident on the idealized grating G_u does not generate output beams that are in conflict with quantum mechanics.

As a final exercise, we similarly calculate $\Omega_{c-th}(2)$. As before, $I_T(2) = 1.65$. The total wave intensity

$$W_{cT}(2) = \sum_{i=-n}^{n+1} (A_{ci} + A_{ci-1})^2$$

$$= 1.79 \tag{5}$$

is recognized as a summation functionally identical to Eq. (3) but using the G_c single beam amplitude set $\{A_{ci}\}$ given above with $A_{ci} \equiv 0$ for $|i| > 7$ and $n = 7$. The resultant $W_{cT}(2)$ yields an

$$\Omega_{c-th}(2) = \frac{I_T(2)}{W_{cT}(2)}$$
$$= 0.92. \tag{6}$$

The significant deviation of $\Omega_{c-th}(2)$ from unity predicts that the two beam configuration on G_c, unlike that on G_u, presents a conflict between quantum mechanics and local realism. Quantum mechanics, of course, would require that $\Omega_{c-th}(2) \equiv 1$ facilitated in the present case by a renormalization of the wave (probability) amplitudes. This renormalization necessarily must occur in G_c at the "first stage" temporally coincident with the partial collapse of amplitudes at the opaque bands since no further collapse occurs up to and at the totally transmissive "second stage". The renormalization must decrease the total transmitted probability density in order to maintain the quantum mechanically required unit value of $\Omega_{c-th}(2)$.

Quantum mechanics then, quite curiously, arbitrarily requires a probability amplitude renormalization when the grating is G_c but not when the grating is G_u. Moreover, when a strict interpretation of quantum mechanics is imposed, an even more bizarre phenomenon is evident. With the gratings treated as two-stage components, amplitude collapse and any renormalization must occur at a time $t = 0$ when the incident wave encounters the first stage. At some later time $t = \tau$, the wave encounters the second stage of either G_u or G_c. Since only the second stages of these gratings are distinguishable, the amplitude collapse and any renormalization of the wave must have anticipated at $t = 0$ which of those two gratings is in place. The implications of this anticipation go beyond even that of the non-local response of separated entangled photons or particles. However, it is not our intent here to examine the quantum mechanical consequences of the foregoing exercise in theoretical grating experiments, rather this exercise provides a motivation for constructing an apparatus with G_c and experimentally testing quantum mechanics against local realism based upon the disparate predictions of $\Omega_{c-th}(2)$.

III.   APPARATUS AND PROCEDURES

The experimental apparatus for this test is shown in Fig. 1. Aside from the lasers, all essential components and optical paths are depicted omitting only mirrors used for aligning and folding those paths. A 4mW polarized 633 nm HeNe laser generates an ordinary beam S (for which $\Omega_o = 1$) that is transmitted by a 0.7 transmissive beam splitter $BS1$ to lens $L1$ ($f = 100\ mm$) and into a diffractive beam splitter DBS (Mems Optical 1019, fused silica 16 beam splitter). An aperture $Ap1$ restricts the output of that beam splitter to two equal irradiance beams S_1 and S_2 mutually diverging at 6.5 mrad toward lens $L2$ ($f = 150\ mm$). $L2$ converges the two beams at the plane of grating G_c with a periodic structure width $b_g = 0.254\ mm$. The S_1 and S_2 individual beam self-divergences are slightly reduced relative to that of the initial S beam by the combined action of $L1$ and $L2$ serving as a beam expander. More significantly, this beam expander, straddling the diffractive beam splitter, avoids large self-divergences of S_1 and S_2 that would otherwise result if $L1$ were omitted.
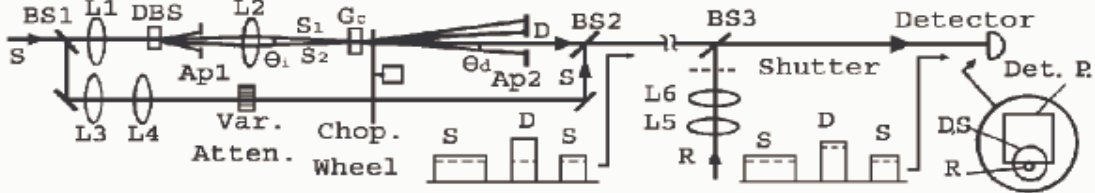

FIG. 1: Experimental setup, not to scale, showing transmitted depleted D pulse, received equilibrated D pulse, and frontal detail of beam spots incident on detector photodiode.

The S_1, S_2 beamspot at grating G_c is characterized by a linear array pattern of interference fringes with maxima separated by $b_i = \lambda/\theta_i$ in the small angle approximation. Shifting the positions of the rail-mounted diffractive beam splitter DBS and grating G_c along the optical axis permits adjustment of θ_i such that the resultant final interference pattern matches the grating's periodicity, i.e. $b_i = b_g = 0.254\,mm$, while maintaining beam spot coincidence of S_1 and S_2 at G_c. Concurrently, $\theta_i = \theta_d$ with this adjustment. A micro-translation stage is used to laterally shift G_c with respect to the interference pattern thereby centering the principal maxima over the transmissive bands of the grating and maximizing the transmitted irradiance. The output beams of G_c are intermittently blocked or transmitted by an adjacent chopper wheel.

From the perspective of quantum mechanics and local realism, we expect that the total irradiance emerging from G_c will distribute onto the output beams in proportion to the respective wave intensities given as terms in the Eq. (3) summation. For local realism, these output beam wave intensities represent real entities on the field that provide "relative" probabilities in the distribution of total transmitted irradiance onto the output beams. For clarity, only four of these beams are depicted in the figure. The two center-most beams, both with $(A_{c1} + A_{c0})^2$ wave intensities, will have the highest irradiance of the output beams. An aperture $Ap\,2$ transmits one of these two, designated as beam D, and blocks all other G_c output beams. This designation is given since local realism predicts that D is depleted. D, which is a pulsed beam as a consequence of the chopper wheel, propagates to a 0.7 transmissive beam splitter $BS\,2$.

Concurrently, when S encounters $BS\,1$, a fractional portion is reflected. That portion, still designated as S, is directed through a beam expander comprised of lenses $L\,3$ ($f = 100$ mm) and $L\,4$ ($f = 150\ mm$), into a variable attenuator (Edmund Optics G41-960 mounted on a lateral translation stage) and through the chopper wheel to produce a pulsed S beam that also propagates to $BS\,2$.

Two concentric sets of wheel apertures are configured such that D and S pulses emerge non-simultaneously. The two pulsed beams are incident at a common point on beam splitter $BS\,2$ where they are angularly combined and "transmitted" as a single interlaced D, S pulsed beam .

That pulsed beam is "received" at a 1000 mm distant 0.7 transmissive beam splitter $BS\,3$. An independent 3 mW HeNe laser generates a constant irradiance beam R that enters a

beam expander, $L\,5$ ($f = 100\ mm$) and $L\,6$ ($f = 200\ mm$). Passage of R is controlled by a shutter before reaching a common incidence point with the pulsed D, S beam on $BS\,3$. The trajectory of the reflected R is adjusted by $BS\,3$ to very nearly coincide within $\lesssim 1$ mrad with that of the transmitted pulsed D, S beam such that at the terminus of a 3000 mm "coupling" path, the R beam spot is displaced to one side of the common D, S beam spot as shown in the detail on Fig. 1. The $L\,5, L\,6$ beam expander is deliberately set to give R a slight convergence that positions the minimum waist at the coupling path terminus. These settings are intended to maximize irradiance equilibration of the D and S pulses with R over the 3000 mm coupling path while reducing the R beam spot on the common D, S beam spot at the path terminus. This facilitates selective positioning of the beam spots across the edge of the (Edmund Optics G54-038) detector's 100 mm^2 Si photodiode such that a large fraction of the common D, S beam spot is incident on the photodiode but the R beam spot is largely excluded.

At the terminus, with the beam spots temporarily shifted to the center of the photodiode, the observed power of the total non-pulsed D beam spot is $\int I_{Di}\,da \approx 20\ \mu W$. Here the subscript "$i$" denotes I_{Di} as the initial D irradiance, i.e. before coupling with R. The variable attenuator allows the S beam spot to be adjusted to a comparable power. Additionally, the $L3, L4$ beam expander is set so that the S beam spot has the same irradiance profile as that of the D beam spot. The total observed R beam spot power is $\int I_R\,da \approx 180\ \mu W$. However, when acquiring the experimental data, selective positioning of the beam spots on the edge of the photodiode, as shown in the Fig. 1 detail, results in interception of fractions $F_D \approx 0.4$ of the pulsed D (and S) beam spot power and $F_R \approx 0.02$ of the constant R beam spot power. The amplified detector output is routed to an oscilloscope (Tektronix TDS 1002). The S_1, S_2 interference maxima are centered on the G_c transmissive bands by adjusting the micro-translation stage to give maximum detected irradiance of the D beam with the chopper wheel stationary and the R beam blocked by the shutter.

The chopper wheel is then set into rotation repetitively transmitting a sequence of an 8 msec S pulse, a 4 msec blank, a 4 msec D pulse, a 4 msec blank, a 4 msec S pulse, and an 8 msec blank. The longer, first S pulse provides for oscilloscope triggering based on pulse width. The oscilloscope is operated with a 128 trigger cycle averaging to increase measurement precision. Pulse width triggering is set to ≥ 6 msec to ensure synchronization with the 8 msec. S pulses. The measured pulse heights of the 4 msec D and S pulses are

denoted as P_{Di} and P_{Si}, respectively. The shutter is then opened, unblocking R, and after a 30 sec. interval to allow for equilibrium of the 128 averaging, pulse heights denoted as P_{Df} and P_{Sf} are measured. Each complete trial consists of a set of these four pulse height measurements, P_{Di}, P_{Si}, P_{Df} and P_{Sf}. An experimental "run" consists of a series of these trials. As a final calibration procedure before each such run, R is blocked and the variable attenuator is adjusted to give $P_{Si} = P_{Di}$.

IV.   RESULTS AND ANALYSIS

The essential data of each experimental trial resolves to pulse height ratios P_{Di}/P_{Df} and P_{Si}/P_{Sf}. We can identify

$$\Omega_{Di} = P_{Di}/P_{Df} \tag{7}$$

as a single trial occupation value of the D pulses prior to their equilibration with the R beam. This follows from $P_{Di}/P_{Df} = I_{Di}/I_{Df}$ where $I_{Df} = W_D$ assuming that the D pulses are fully equilibrated after coupling with the R beam. For the S pulses in each trial, the ratio $P_{Si}/P_{Sf} \approx 1$ serves as an "experimental control" for the accompanying D pulse height ratio P_{Di}/P_{Df}. (The pulse heights of the 8 msec S trigger pulses were not distinguishable from those of the accompanying 4 msec S pulses used to provide trial values.) The P_{Si}/P_{Sf} ratios are typically tightly clustered about unity consistent with expected detector measurement error and laser power fluctuations. Initially setting $P_{Si} = P_{Di}$ ensures that the detector response is highly linear in measuring P_{Di} relative to P_{Df} despite the presence of an R-produced baseline in the latter measurement provided that the control condition $P_{Si}/P_{Sf} \approx 1$ is satisfied.

Results are given here for a representative experimental run consisting of a series of 40 trials. With the oscilloscope operating on 128 trigger cycle averaging, this run comprises a total of $\sim 10^4$ D pulses. The trial-averaged ratio $\langle P_{Di}/P_{Df} \rangle = \langle \Omega_{Di} \rangle = \Omega_{c-exp}(2) = 0.96 \pm 0.01$ where $\Omega_{c-exp}(2)$ is the experimental counterpart to $\Omega_{c-th}(2) = 0.92$, theoretically predicted by local realism. The accompanying trial-averaged control ratio $\langle P_{Si}/P_{Sf} \rangle = 1.00 \pm 0.01$ is consistent with both quantum mechanics and local realism.

The results for the pre- and post-coupling configurations are schematically shown in the Fig. 1 pulse sequences where the irradiance I and the wave intensity W are respectively depicted as dashed and solid lines. Quantum mechanically, the transmitted D pulses should

not acquire net irradiance from coupling with the R beam. However, for local realism an $\Omega_{c-exp}(2) = 0.96$, i.e. $\approx 4\%$ depletion, is well within the range of expected values.

It is of some particular corroborative interest that experimental data acquired with the grating G_c replaced by the "idealized" grating G_u yields an $\Omega_{u-exp}(2)$ not statistically different from unity. This result is consistent with the Eq. (4) theoretical prediction of $\Omega_{u-th}(2) \approx 1$ and constitutes a significant experimental control.

Potential sources of errors have been examined to determine their impact on the measurement of $\Omega_{c-exp}(2)$. With regard to local realism, the assumption implicit in Eq. (7) that the final irradiance I_{Df} of the D pulses is completely equilibrated constitutes one probable source of error. In general, local realism predicts an equilibration between two transiently coupled beams of different Ω that results in a net transferrence of irradiance. That irradiance transferrence is directly analogous to the charge transferrence of coupled capacitances. An initial and final Ω and $\int I \, da$ (power) of these beams with total relative probabilities $\int W_D \, da$ and $\int W_R \, da$ on beams D and R respectively are calculationally equivalent to the initial and final V and Q of two capacitances C_D and C_R transiently coupled $+$ to $+$ and $-$ to $-$. Following this analog, the final beam power on D is

$$\int I_{Df} \, da = (\int I_{Di} \, da + \int I_{Ri} da) \frac{\int W_D \, da}{\int W_D \, da + \int W_R \, da}$$
$$\approx \int W_D \, da \tag{8}$$

if $\int W_R \, da \gg \int W_D \, da$, $\int I_{Ri} \, da \gg \int I_{Di} \, da$, and where arbitrary units provide $\int I_{Ri} \, da / \int W_R \, da = \Omega_{Ri} = \Omega_o = 1$. Consequently,

$$\Omega_{Df} = \frac{\int I_{Df} \, da}{\int W_D \, da}$$
$$\approx \Omega_o$$
$$= 1 \tag{9}$$

with the R beam serving as a nearly infinite irradiance "source" negligibly altered from its initial ordinary beam occupation value by the transfer of irradiance in the coupling process. These conditions should be reasonably approximated given the ratio of total beam powers $\int I_{Ri} \, da / \int I_{Di} \, da \approx 180\mu W / 20\mu W$.

Completeness of equilibration is also dependent upon the coupling efficiency. Statistically significant $\langle P_{Di}/P_{Df} \rangle < 1$ are measured when the mutual divergence angle of the pulsed D, S

and R beams is ~ 0.8 mrad. As this angle is increased to $\gtrsim 1.2$ mrad, the resultant $\langle P_{Di}/P_{Df}\rangle$ plateaus at ≈ 1. Accordingly, the mutual divergence angle on the ~ 3000 mm overlapping D, S and R beam paths must be carefully aligned and maintained for the duration of a series of trials. Mechanical instability, transiently increasing this angle, is expected to produce trials for which $P_{Di}/P_{Df} \to 1$ while concurrently the control value P_{Si}/P_{Sf}, remaining at ≈ 1, would not provide an indication of these transient angular increases. A minimal dispersion of $\langle P_{Di}/P_{Df}\rangle$ is probably the most reliable indicator of stable coupling alignment for a given series of trials.

In any case, regardless of the origin of incomplete equilibration, the experimentally measured $\Omega_{c-exp}(2)$ would be closer to unity than the actual occupation value and, equivalently, the actual depletion would be underestimated.

We next consider a source of error associated with the fractional presence of the R beam spot on the detector during coupling. Eq. (7), aside from equilibration assumptions, further assumes that P_{Di} and P_{Df} are proportional measures of the respective D beam irradiances I_{Di} and I_{Df} incident on the detector. (The proportionality would also extend to the incident powers $\int F_D I_{Di}\, da$ and $\int F_D I_{Df}\, da$.) The assumption of proportionality is certainly reasonable for P_{Di} and would seem to be equally reasonable for P_{Df} since the latter quantity is measured relative to the baseline generated by the constant R beam. However, on closer inspection the proportionality is not exact from the viewpoint of local realism and we need to examine the magnitude and sign of the discrepancy.

During coupling, the D beam power increases by

$$\Delta = \int (I_{Df} - I_{Di}) da \tag{10}$$

but this gain must equal the loss of power on the R beam

$$\Delta = \int (I_{Ri} - I_{Rf}) da. \tag{11}$$

Then during coupling, i.e. while the D pulse is actually present on the beam path, the supposedly constant baseline of the R power incident on the detector actually drops by $F_R\Delta$ and the apparent pulse height

$$P_{Df} \propto \int F_D I_{Df}\, da - F_R\Delta \tag{12}$$

is reduced since P_{Df} is measured from the pulse peak to the R baseline adjacent to the peak. Accordingly, the true pulse height of the D beam itself should be larger than P_{Df}.

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The impact of this discrepancy on Ω_{Di} can be estimated by inserting approximate values of $F_D \approx 0.4$, $F_R \approx 0.02$, $\int I_{Di} \, da / \int I_{Df} \, da \approx 0.92$ into Eq. (7)

$$\begin{aligned}
\Omega_{Di} &= \frac{P_{Di}}{P_{Df}} \\
&= \frac{\int F_D I_{Di} \, da}{\int F_D I_{Df} \, da - F_R \Delta} \\
&= 0.924.
\end{aligned} \tag{13}$$

Consequently, the trial value Ω_{Di} is increased by a systematic error of $\approx +0.004$ and an actual depletion of $\sim 8\%$ would be underestimated as $\sim 7.6\%$.

The detector itself presents an additional potential source of error. A systematic measurement error of the relative P_{Di}, P_{Df} pair values potentially might arise from non-linearity of the detector output since these values are acquired at different parts of the detector's photodiode response curve because of the absence and presence of the fractional R beam. However, a comparable error would also be present in the P_{Si}, P_{Sf} pair values. Accordingly, the observed $\langle P_{Si}/P_{Sf} \rangle = 1.00 \pm 0.01$, closely distributed about unity, provides verification of detector linearity.

For individual trials, excursions of P_{Si}/P_{Sf} significantly differing from expected random variations of laser power output are indicative of transitory mechanical instabilities of the apparatus. This has demonstrated by temporarily re-positioning the S beam spot to the center of the photodiode and reducing the S irradiance with the variable attenuator to $\sim 40\%$. The measured power fluctuations over 30 sec. intervals is a reasonably stable $\pm 0.5\%$ exceeded by the observed $\pm 1\%$ fluctuations of P_{Si}/P_{Sf} for which the S beam spot is fractionally incident across the edge of the photodiode. From this we conclude that the larger deviation of the P_{Si}/P_{Sf} trial ratios is primarily associated with increased detection sensitivity to transient mechanical deflections of a fractionally intercepted beam spot combined with a long optical beam path of $\sim 4000mm$. An equivalent mechanical stability sensitivity is expected for the accompanying P_{Di}/P_{Df}. Accordingly, the modest dispersion of $\langle P_{Si}/P_{Sf} \rangle = 1.00 \pm 0.01$ is interpreted as a validation that deviations of P_{Di}/P_{Df} from unity are not significantly caused by mechanical instability during the course of data acquisition.

As an additional means of eliminating systematic error, substitution of a different detector (Hamamatsu S2386-8K 41 photodiode and a reverse bias network) produced results equivalent to those obtained with the original detector. This substitution is tantamount

to verification of the experimental results with a totally separate apparatus since quantum mechanics does not allow for irradiance gain of the D pulses upon coupling with the independent R beam regardless of how those D pulses are generated.

The present apparatus is readily reproducible. In this regard, virtually all components are widely available. An apparent exception is the diffractive beam splitter, DBS in Fig. 1, but any one of multiple alternative devices could be used in substitution to split an incident beam into two beams of equal irradiance. However, G_c clearly emerges as a critical component since local realism predicts that this grating, unlike an idealized grating, will produce output beam occupation values in conflict with quantum mechanics.

In the present experiment, setting $P_{Di} = P_{Si}$, which provides for intrinsic control values, suggests a useful application. This setting effectively encodes the D pulses with a higher wave intensity than those of the S pulses, but a receiver consisting of a simple energy-sensitive detector measures the D, S pulsed beam only as an unremarkable set of constant irradiance pulses. However, a receiver additionally equipped with restorative coupling decodes that higher wave intensity as an increased irradiance on the equilibrated D pulses. It is of some further practical interest that the coupling of the D pulses to the constant R beam constitutes a direct photonic amplification of those pulses.

V.   CONCLUSIONS

From the perspective of local realism, exceptions to the invariance of relative wave intensity (probability density) and energy flux density (irradiance) are very subtle, and the formulation of the probabilistic interpretation of quantum mechanics can be attributed to a presumed universality of that invariance. That formulation necessarily abandons reality and elevates the apparent wave-energy duality of photons to the status of the central proposition of the probabilistic interpretation. The resultant compact interpretation is compelling but nevertheless troubling given the abandonment of reality and the imposition of non-locality. However, combined with Bell's Theorem [8] and associated experimental results [9], that interpretation is widely accepted.

The representation of local realism presented earlier [1, 2] provides a plausible contradictory interpretation not constrained by Bell's Theorem [8] and in agreement with experimental results [9]. The question of quantum mechanical completeness [10, 11] is addressed

in that representation by proposing that wave entities and energy quanta are independent variables, a proposition experimentally tested here. The results of this test show a statistically significant $\sim 4\%$ energy gain consistent with local realism and in conflict with quantum mechanics.

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