

Can repeated interactions show more about a photon than current theory allows?

Neil Bates

Newport News, VA

nfb222@email.vccs.edu

We explore whether it is possible in principle to find the “circularity” (amount of circular polarization) of a single photon to a degree not allowed in conventional quantum theory. The thought experiment involves passing the same photon many times through a half-wave plate (with intermediate correction) so the tiny “spin” interaction of the photon is amplified enough to transfer measurable angular momentum to the detector HWP. HWPs invert coefficients for RH and LH states instead of “collapsing” the photon into a circular basis. Because passing one photon many times through a HWP should be like passing many photons once each through the plate, the transferred angular momentum would be revealed on a continuum. Such a measurement would violate the “projection postulate” (which says that only yes/no answers to probabilistic detection questions can be found for a single particle.)

“A paradox is a situation which gives one answer when analyzed one way, and a different answer when analyzed another way, so that we are left in somewhat of a quandary as to actually what should happen.”

Richard Feynman [1], *The Feynman Lectures on Physics*, Vol. II

Acknowledgments: I thank Drs. Geoffrey Krafft and Michelle Shinn of TJNAF/CASA, Dr. Kevin Beard, business owner and independent theorist Dr. Martha Harrell, Physics grad student Jenny Lorraine Nielsen of KU, Steven Colyer, and any others who enabled the writing of this article with their instruction, answers, and critiques.

The challenge to quantum measurement theory

Presented here is a challenge to our understanding of light and measurement in quantum mechanics. The proposition: it is possible to learn more about the polarization state of a single photon than current theory allows. The projection postulate (built around single interactions with measuring devices) says we can get only probabilistic yes/no answers from attempts to measure certain states of a quantum particle. This thought experiment builds on three factors to escape that limitation. First, we utilize the *known* atypical properties of half-wave plates (HWP/s.) HWPs collect angular momentum when they “flip” the spin of a photon. However, unlike familiar “detectors” they still preserve the photon’s superposed character. The second factor is to have one particle interact many times with this other kind of detector, instead of familiar one-shot measurement. The third factor is the principle of indistinguishability: individual particles have no special hidden extra features or individual identity (*i.e.* no hidden variables), beyond the quantum state description itself. (Entanglement does involve extra correlative factors, but does not contradict the POI.)

Combining these three, we summarize the basis for transcending the projection postulate in a sentence: one properly-maintained photon passed through a HWP one million etc. times should act just like a million identical photons passing through a HWP, once each. We effectively bypass the PP and the “no-cloning” theorem by arranging for a single photon to act like an ensemble. An ensemble of photons of a particular polarization transfers angular momentum to a HWP along a continuum, according to the relationship of their circular states. Based on what we know: a lone photon should retain its individual circular “mix” during *multiple* interactions with such a HWP. The puny spin of one photon is thereby amplified through many transmissions to detectable, yet continuous-range levels. This method may reveal how much circular polarization (difference between squared amplitudes of right-hand and left-hand components) comprised that photon – a trait ostensibly hidden by an impenetrable veil. This proposal is also a “paradox” in that we cannot be sure it would work as postulated. Yet, in any case it poses a worthy and insightful challenge to standard quantum theory.

I call this hypothetical system a “photon circularity spectrometer” or PCS. We could learn other polarization traits on a one-dimensional range by conversion to circularity. If such enhanced measurements are possible, even in principle, it has profound consequences for quantum mechanics. It could enable confounding and problematical phenomena like faster-than-light communication. Sadly, such an experiment is not yet practical for various reasons, although the work of Tigran Galstian of Laval University on tiny clusters of chiral nematic molecules may show a way. Galstian’s work led to US Patent No. 6,180,940; “Light-driven molecular rotational motor.” [2] More traditional nanomachinery may also be useful.

This proposal bears some relation to “weak measurements,” which in concert report

information about the system without effectively disturbing it. A classic paper by Aharonov and Vaidman [3] outlines basics of WM as applicable to their example. A recent work by Lundeen *et al.* [4] addresses “directly measuring the transverse spatial wavefunction of a single photon, a task not previously realized by any method.” Pride *et al.* [5] discuss polarization measurement. The current proposal goes well beyond such work, attempting to circumvent accepted trade-offs (even using WM) in possible knowledge.

This is an argued proposition, and a paradox: not a proof. This challenge might even be answered within the conventional framework. Yet paradoxes are worthwhile even if conventionally resolved, because of the insights and advances they can provide. Purely theoretical challenges are relevant: e.g. the infinities in quantum field theory, even though that isn’t the actual result. For example, we may have to adjust other postulates to preserve the PP (such often happens.) This proposal will still have constructively stimulated good discussions about the measurement problem. On the other hand, something major may have to bend, which would be very exciting. (The Afshar experiment [6], involving wave-particle duality, is a possible empirical example.)

A historical “media” note: in November 2000, I started a discussion [7] on “Usenet” in the moderated and respected newsgroup *sci.physics.research*. It was titled “New quantum measurement paradox?” and proposed a concept of same name and similar to that described here. This post ignited much debate and many comments, and professionals such as John Baez (a moderator) and Jacques Mallah weighed in. Few agreed with my core thesis, but several said it was a clever try and worth delving. (Much of the response was relevant only to that different proposal.) A side issue generated extra interest: how to maintain conservation if the transferring photon has less energy than what its angular momentum should add to the energy of a spinning disk? That thread and related posts in my blog (a recent description of this paradox may be found here [8]) generated enough linkings to bounce around in the top five or so hits of Google search for “quantum measurement paradox.”

Background: measurement, photons, spin, and wave plates.

First, let’s consider what’s “wrong” with ordinary quantum measurement. A (ideal) linear polarization filter is a type of conventional “measuring device.” Have a LP filter set to pass the component of a photon state orientated at zero degrees (“H”). This filter does not, for example, pass a LP photon based on whether it is oriented to say, $\pm 5^\circ$ of that mark. Instead, the squared projection $\cos^2\theta$ of the photon state onto the filter axis determines the chance the photon passes the filter. Hence, a LP photon prepared to 20° has ≈ 0.883 chance of passage, and other rules govern passage of elliptical and circular states. Passing versus being absorbed (binary testing) are the only options. Furthermore, the passed photon state is now in horizontal orientation. It has been “collapsed” to the H state, not just “checked.” To say the photon was “detected as H” is misleading: all other

orientations except the orthogonal state V at 90° , have some chance of passing this “test.” This is the essence of the projection postulate. Must everything work this way? Many would suppose, “yes” - but this outcome is essentially based on a certain type of detector, operating once upon an incident particle. Perhaps we should try other kinds of interactions, and more of them as well, between particle and detector.

Now, consider a normalized photon state $a|R\rangle + \beta|L\rangle$ in the *circular* basis, where β includes coefficient b as well as phase angle $e^{i\theta}$. The simple (Born Rule) probability of measuring this superposed state as right hand equals a^2 , and the probability of measuring it as left hand equals b^2 . (Phase angle does not matter for this, a feature helpful to the success of the PCS.) Each pure state R or L expresses (per our convention) a unit of spin \hbar or $-\hbar$, respectively. The expectation value $\langle S \rangle$ of the photon’s spin angular momentum is the average value per photon, also providing the total spin angular momentum for n photons. We can usefully define a circularity $C = a^2 - b^2$, and $\langle S \rangle = \hbar C$. If n such photons strike an absorbing surface, they impart a twist $n\hbar C$ to the surface.

Transmission through angle-dependent phase retarders such as half-wave plates is more complicated. The photon can also be considered a superposition of orthogonal linear states. The HWP retards one such axis by an angle π relative to its perpendicular. This changes the sign of C for a transmitted photon (hence, swaps a and b , with various changes to phase angle, and $C' = -C$.) The polarization angle (as applicable) is reflected relative to the fast axis (axis of least retardation.) Phase difference depends on wavelength (however, not in principle), so we presume matched photons. N.B., a HWP is not like a filter! The photon exits with its original information (changed but recoverable) intact. Yes, wave plates really are “special.” This property is key to enabling possible violation of the PP.

Historical note: Vikings may have used birefringent materials like iolite and the common and famous Iceland spar (calcite) to navigate. These “sunstones” showed them the directional polarization of the sky, useful at twilight. As I pass his gallant bronze statue near the Mariners Museum in Virginia, I wonder: Did Leifr Eiriksson use polarized light to reach North America long before Columbus?

The inversion of $\langle S \rangle_{\text{photon}}$ requires reciprocal (and doubled) transfer of angular momentum to the plate. However, this is meaningful only if the plate is free to rotate (including torque measurement.) (For comparison: we can use a “wobbly mirror” to test for recoil linear momentum from an originally separated photon component. If so, the photon is localized at the WM. Later attempts to recombine states can’t cause interference.) Also, a lesser-known uncertainty relation $\Delta S \Delta \theta \geq \hbar/2$ governs our ability to measure plate angular momentum S_{plate} . Here ΔS is uncertainty in S , and $\Delta \theta$ is uncertainty in plate orientation. However, regardless of this condition, C simply changes sign within observational limits (as explained later.) If we pass n photons through the plate, we can expect a change ΔS in S_{plate} , now considered macroscopically:

$$\Delta S_{\text{plate}} = 2n\hbar C. \quad (1)$$

A similar experiment [9] was done by Richard Beth in 1936. It confirmed that polarized photons do indeed carry real, mechanically effective angular momentum.

It is curious and interesting that HWPs interact with photons in a way that alters both the photon and the plate. It seems this should constitute a “measurement” of photon spin. If so, by the PP, each photon should collapse into a circular basis R or L with respective probabilities a^2 and b^2 . However, we know this does not happen. A reasonable explanation may be: the increase in angular momentum of a HWP caused by a single photon pass, is smaller than the spread of uncertainty in S_{plate} . Hence each passage simply adds $2\hbar C$ to $\langle S \rangle_{\text{plate}}$, equivalent to shifting the spread by that amount. (See technical note for further explanation.)

Constructing and justifying the circularity spectrometer

Now we are ready to conceptually construct a PCS and see why it should beat the PP. (See diagram in Figure 1.) We use a “photon gun” to send a single photon into our system, and existing knowledge to predict the results. (Coherence length of the photon is enough to clear any component before interaction with another component.) The PCS consists of one free-rotating (*i.e.*, measurable) HWP₁ used to measure torque (spin), a rigid HWP to serve as “corrector” (as needed, depending on how we recirculate the photon), mirrors to direct the photon around a course, and a gate for initial photon entry (not shown.) First, we send the photon through the torque-measuring plate HWP₁. One

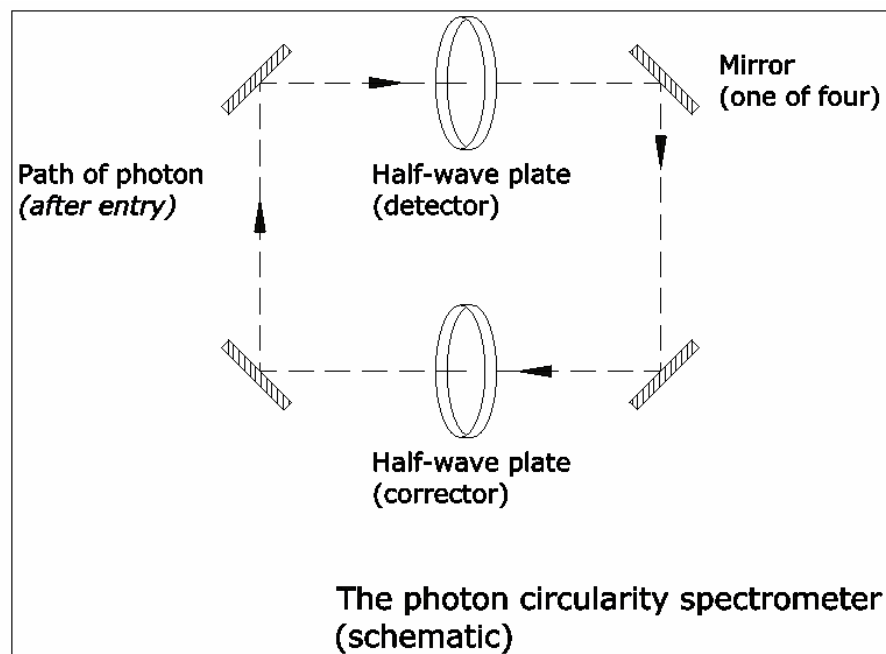


Fig. 1

passage reverses the sign of C . Then we direct the exiting photon through a second, rigid “corrector” plate HWP_2 . HWP_2 restores the sign of C . Then we’ll direct that photon back through HWP_1 again, and so on. We use mirrors to make a circuit. (Mirrors can affect polarization, but we can arrange to return the photon to HWP_1 with its entering circularity.) Basic arguments tell us the circularity should continue to flip-flop, although long-term behavior is debatable. The very interesting question motivating this article is: what happens to the first plate after the same photon passes through it many, many times?

If we believe in indistinguishability, then photons have no identity like persons: they are fully defined by their properties. Each time that photon enters HWP_1 , all the plate should “feel” is “photon” with a given circularity. (Perhaps article-less Russian is better for particle physics? The Sapir-Whorf hypothesis deserves more attention.) Hence, each pass of “that photon” might as well be a new photon, just like successive ones in a straight stream of light.

If C simply keeps changing sign, then n passes of the cycling photon should affect HWP_1 just as would the passage of n identical photons in a beam. Unless return circularity changes during the course of many transits, the result should be the same! Each pass of that single photon ticks the average angular momentum of HWP_1 up or down, by a little bit $2\hbar C$. So, “ n ” in Equation (1) must interchangeably mean “number of photons passing once each” or “number of passes by a photon” (*i.e.* “passes” is independent of identity.) We make an “ensemble” from a single photon. This partly, at least, defies no-cloning rules!

The implications of this equivalence for quantum measurement theory are staggering. We can *e.g.* create an elliptical photon with $C = 0.8$ and direct it enough times through the circuit to be mechanically measurable. Then we could in principle measure the circularity of a single photon along a range, and violate the PP. It is “quantum tomography” of a single wavefunction. Realistically, absorption, scattering, phase mismatch etc. will likely occur before then, but thought experiments can be ideal. More important: any ability to test photon polarization better than binary inquiry would be a breakthrough. Example: finding which third of the C scale (leaning R, low or zero C , or leaning L).

Possible objections to the PCS

Are there good objections to the PCS proposal? The tempting avenues have problems, although attempts to “visualize” the quantum process are daunting regardless of one’s perspective. Raw application of the POI says that one repeated photon is like many photons – but that may be inadequate. At present we do not (?) have a contravening theory of “serial cumulative entanglement” etc. to keep *adding* new correlated values to the plate in reference to one photon. (Another thought experiment [10] with HWPs may provide insight into the problem of photon-plate correlations.)

First, we could extrapolate from ordinary, one-shot measurements – just ignoring directly predicted interactions. After many photon passes, the HWP is effectively

measurable. S would “jump” to either $2n\hbar$ or $-2n\hbar$, indicating measurement of the photon as either “R” or “L”. This model requires *sudden shifts of perhaps millions or trillions etc.* of \hbar . A quantum “jump” is supposed to be quantum-sized, correlating spin at the level of \hbar itself.

Another thought experiment may shed light on multiple interactions and macroscopic changes. Reflect a photon many times between mirrors to impart macroscopic recoil linear momentum. A particularly intriguing version, first divides the photon state with a beam splitter. Each portion separately, repeatedly, reflects between a rigid and a moveable mirror. Interference is lost, but due to multiple interactions we can still wonder: would both moveable sides gain some measurable momentum? Or, would only one of them “collapse” to show by its momentum which way the photon went, despite having to manifest more than the original momentum of the photon in a potentially discontinuous way?

Another option is to explicitly keep C evolving towards a pure R or L state, resulting in eventual detection as if R or L. Literal photon evolution faces various hurdles. The evolution must be unidirectional. Its increments must be small enough to explain our failure to detect them, but large enough to lead to a distinct RH or LH outcome - even if the photon starts out linear. Shifting of polarization angle might provide “cover” for such changes, but the PA is not relevant to C . For each pass HWP-photon system must consistently “remember” the same photon is returning, and to give ΔC the same sign as before! Random evolution (*i.e.*, not correlated between passes) of almost any kind can’t lead to the conventional result either, due to “random walk” problems. A state starting near $C = 0$ would likely stay “hung up” in that region. Such “reasonable” evolution wouldn’t fully thwart the PCS, perhaps yielding tripartite results of the sort noted. Finally, we can challenge correlation schemes by inserting more than one serial photon, with differing C . Then what happens?

There is another way to think of photon “evolution.” We imagine the state becoming a sort of mixture due to decoherence of the relative phase angle between R and L states. Since $\Delta S \Delta \theta \geq \hbar/2$, polarization angle (and hence, phase angle between R and L components) must unpredictably shift a bit, each pass through a measurable HWP. In this sense, the originally coherent photon develops ever more the density matrix of a mixture of R and L photons. (Yet, *must* a state not be “coherent” because we don’t *know* the phase angle?) The angle uncertainty is the right order of magnitude, since $n\Delta\theta \geq \hbar$ is needed for our measurement to transcend binary attribution. (Here, $\Delta\theta$ is *uncertainty*.) Following the decoherence interpretation, we imagine the superposition eventually becoming “sometimes a R photon and sometimes a L photon.” So either a RH or LH photon “eventually” manifests in the PCS, and the result is simply detection of a circular eigenstate under Born probability.

This concept is probably not viable. The DI considers ensembles of actual one-shot measurements on each of many particles, not situations like the PCS. In order to

preserves the PP: sometimes a given *run* is like “same RH photon passing” over and over, and others are like “same LH photon passing.” Yet “a photon” is not really an ensemble. Each PCS test is not a true ensemble of *separate explicit measurements*. We aren’t building up a “pattern” of readings to compare, as with interference experiments. Also, per the POI each entry of “photon” is just a DM of R and L. Each separate pass becomes like “either” instead of “both.” Each *individual pass* becomes like “sometimes a RH photon and sometimes a LH photon,” building up the same result predicted before. Finally, the DI has conceptual problems and possibly an experiment [11] can disprove its key thesis: that decoherence effectively turns superpositions into mixtures.

Validity, implications, and prospects

If the argument holds up, we must revise our views of quantum measurement, because the projection postulate forbids this level of knowledge about one photon. It would treat this entire process as one “measurement.” With the PP, a^2 and b^2 strictly represent the respective chances of detection as if either RH or LH photon. A violation would be big news, with a major ripple effect on other issues, and maybe on technologies. Examples include complementarity, photon cloning; quantum information, computing, and cryptography; quantum-state engineering, entanglement correlations, etc. Indisputable “news” means empirical evidence. A real PCS faces a major hurdle: keeping a photon intact during the many passes likely required to make spin measurable to at least a three-value outcome. However, the proposal is still worth much consideration as a theoretical problem and conceptual tool.

One exciting possible implication of a working PCS is faster-than-light communication. Briefly: having detailed polarization knowledge of “entangled photons” might allow instant signaling between the famous partners Alice and Bob. (See Nick Herbert [12] for a good discussion.) Many problems, such as for foundations of causality and equality of inertial frames, would arise from successful FTL communication. Hence, perhaps measuring C would not really allow superluminal signaling – an intriguing line of study.

The paradox we’ve just explored may or may not revolutionize physics, but it is certainly worth investigating further. The projection postulate is in jeopardy. It can’t (as far as I know) be demonstrated compulsory by ground-up reasoning of the sort employed by the Noether theorem to assert conservation laws. Also, all the other things we know or think we know and Occam’s razor say this cascading of an established interaction should allow measuring C for a single photon. However, the importance of this paradox does not depend on overthrowing the projection postulate. Even if we find a way to solve the PCS paradox, accommodation may involve substantial or even radical transformation of quantum theory anyway. Will we need to jettison other principles like indistinguishability to save the PP, or will the projection postulate fall like the conservation of parity and other rules we expected to be true? The prospects for saving traditional theory look challenging,

and anyone is welcome to try. The road ahead is unknown, which makes for compelling science.

References:

- [1] R. Feynman, R. Leighton, M. Sands; Eds: *The Feynman Lectures on Physics, Vol. II* (Addison-Wesley, Reading MA, 1977), p. 17-4.
- [2] Tigran Galstian, "Light-driven molecular rotational motor." *U.S. Patent No. 6,180,940*. USA (2001).
- [3] Y. Aharonov and Lev Vaidman, "Measurement of the Schrödinger Wave of a Single Particle," *Phys. Lett. A* 178, 38-42 (1993).
- [4] Jeffrey S. Lundeen *et al.*, "Direct Measurement of the Quantum Wavefunction," *Nature*, 474, 188 (2011) [arXiv:1112.3575v1 [quant-ph]].
- [5] G. J. Pryde, *et al.*, "Quantum weak values," *Phys. Rev. Lett.* 94:220405 (2005) [arXiv:quant-ph/0412204v2].
- [6] Shahriar S. Afshar, *et al.*, "Paradox in Wave-Particle Duality," *Found. Phys.* 37, 295 (2007) [arXiv:quant-ph/0702188v1].
- [7] Neil Bates, "New Quantum Measurement Paradox?" (http://groups.google.com/group/sci.physics/browse_thread/thread/5c8a16b3893a1814, posted 10/31/2001, verified last page update 08/31/2012).
- [8] Neil Bates, "Proposal summary: can we find circularity of a single photon along a range of values?" (<http://tyrannogenius.blogspot.com/2010/01/proposal-test-can-we-find-circularity.html>, posted 01/10/2010, verified last page update 08/31/2012).
- [9] Richard A. Beth, "Mechanical Detection and Measurement of the Angular Momentum of Light," *Phys. Rev.* 50, 115-125 (1936).
- [10] Neil Bates, "Can We Distinguish Supposedly "Indistinguishable" Quantum Mixtures?" (<http://tyrannogenius.blogspot.com/2011/03/can-we-distinguish-supposedly.html>, posted 03/21/2011, verified last page update 08/31/2012).
- [11] Neil Bates, "Our Non-Deterministic Reality Is Neither Digital Nor Analog: Experimental Tests Can Show That Decoherence Fails to Resolve the Measurement Problem" (<http://fqxi.org/community/forum/topic/949>, posted 02/17/2011, verified last page update 08/31/2012).
- [12] Nick Herbert, *Faster than Light: Superluminal Loopholes in Physics* (New American Library, New York, 1988).

Technical Note: explaining gradual incrementation of angular momentum in the half-wave plate.

A reasonable explanation for interaction between a polarized photon state and a HWP not causing collapse may be: the increase in angular momentum of a HWP caused by a single photon pass, is below the critical threshold of measurability that would force a collapse and projection of the photon to a definite state. The idealized, unmeasured angular momentum of the HWP is presumed as a superposition (“spread”) of various specific values of angular momentum, a condition we may write as

$$|\psi\rangle_{\text{plate}} = u|S_1\rangle + v|S_2\rangle + w|S_3\rangle + \dots \quad (2)$$

with normalized coefficients for the various superposed amounts of rotational angular momentum. In a realistic macroscopic plate, the spread of values would be many millions of \hbar , likely incorporate essentially all intermediate values, and resemble a normal distribution. From application of superposition and linearity to the HWP state, we consider that passage of a photon $\alpha|R\rangle + \beta|L\rangle$ results in the plate shifting to a new state given by

$$|\psi\rangle'_{\text{plate}} = \alpha (u|S_1 + 2\hbar\rangle + v|S_2 + 2\hbar\rangle + w|S_3 + 2\hbar\rangle + \dots) + \beta (u|S_1 - 2\hbar\rangle + v|S_2 - 2\hbar\rangle + w|S_3 - 2\hbar\rangle + \dots). \quad (3)$$

Note, the change in each component is by an amount $\pm 2\hbar$ due to inversion of photon states. This alters the plate’s expectation value by the amount $\Delta\langle S \rangle = 2\hbar C$ needed for the correct measurable change in a case of large n . Yet from interaction with any one photon, this tiny quantity is hidden within the huge overall uncertainty of the plate’s AM. Since it is not a distinct and detectable “jump” for the plate, it does not represent a corresponding collapse for the interacting photon. If spin states are not “tagged,” there is no distinction between pairs of states initially separated by $4\hbar$, that became equal when incremented respectively by R and L input. The coefficients for that particular value of spin would simply combine. (The plate’s other interactions with the environment are constantly “monitoring” and shifting its configuration of angular momentum, but this process is a relevant approximation of the effect of a single photon.)