

Analysis of the famous experiment of Grangier, Roger, and Aspect supposedly establishing the existence of the photon

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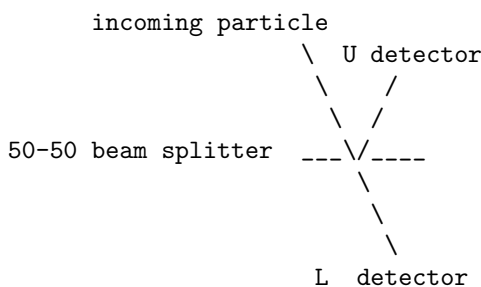
Everything on this website is copyrighted, but I am particularly sensitive to the present document due to the possibility of errors. I shall be questioning a historic experiment. It is easy to make an arithmetic mistake or misinterpret something, particularly for a mathematician like me who is not very familiar with the experimental literature.

If you want to quote this document, please quote the latest version with its date and when it was retrieved, along with a link to the current document. (The current link, which is not expected to change, is www.math.umb.edu/sp/papers/gracom.pdf.) That way, if any errors turn up, I will have the chance to correct them. And of course, I shall be grateful for any suggestions or notification of errors.

1 Introduction

This essay is a product of a posting to the Internet discussion group `sci.physics.research`. It can be accessed through `google.groups.com`, as well as other ways.

The posting asked what happens when a single quantum particle enters a Mach-Zehnder interferometer containing detectors in both arms, as pictured in the following diagram. Only part of the interferometer is shown because we shall be concerned only with that part.



The nature of the quantum particle is unspecified, but the experiments to be discussed use photons. The U detector “fires” if it senses a particle in the “upper” arm, and similarly for the L detector in the “lower” arm.

It is sometimes said that quantum theory implies that *exactly one of the detectors will register* (“fire). This is not so much a prediction of quantum theory as of the concept of “particle” as an indivisible entity. For example, this would be true of a billiard ball which had 1/2 probability of taking each path.

Another way to say this is that the detectors will be perfectly anti-correlated. I had seen statements suggesting this in the literature, but never one which stated it unequivocally. My posting asked if there were any experimental evidence of this. If there were, it could be taken as further evidence of the “photon” concept that light is sometimes best described as consisting of particles.

One person very helpfully replied with two references. One is a famous 1985 experiment of Grangier, Roger, and Aspect [1], to be called GRA below. The other is a 2004 updating of the GRA experiment using technological improvements which had been developed in the meantime [2]. The latter [2] will often be identified simply as “Thorn”, after its lead author. It is too distracting to reference “Thorn, *et al.*” repeatedly, and Thorn has too many authors to form a convenient acronym.

I want to make clear that “Thorn” *always* refers to the paper [2], and not to its lead author J. J. Thorn. Wherever I feared any possibility of misinterpretation, I reverted to “Thorn, *et al.*”.

I initially thought that the citations of GRA and Thorn fully answered my question. But on studying these papers, I realized that neither convincingly demonstrated anti-correlation. This essay will explain why.

2 General discussion of GRA and Thorn

The discussion of GRA is rather condensed, but it does include enough raw data to enable a statistical analysis. By contrast, the discussion of Thorn is generally more extensive, but unfortunately omits some critical discussion and data.

A casual reader might well obtain from GRA the impression that it demonstrates perfect anticorrelation. For example, its first paragraph states:

“During the past fifteen years, nonclassical effects in the statistical properties of light have been extensively studied from a theoretical point of view [1], and some have been experimentally demonstrated [2-7]. . . . However, there has still been no test of the conceptually very simple situation dealing with single-photon states of the light impinging on a beam splitter. In this case, quantum mechanics predicts a perfect anti-correlation for photodetections on both sides of the beam splitter (a single-photon can only be detected once!), while any description involving classical fields would predict some amount of coincidences. In the first part of this letter, we report on an experiment close to this ideal situation, since we have found a coincidence rate, on both sides of a beam splitter, five times smaller than the classical lower limit.”

However, we shall argue that it does *not* demonstrate perfect anti-correlation!

To explain what it *does* demonstrate, we need a brief detour into classical photodetection theory. Classical theory treats light as a classical wave described by a complex electric vector function of space and time \vec{E} . The power per unit area perpendicular to the direction of travel transferred by the wave is called the *intensity* I , and is proportional to $|\vec{E}|^2$. The probability of a light wave of intensity I exciting a photodetector (i.e., causing it to “fire”) in a small time interval $[t, t + \Delta t]$ is given by the theory of classical photodetection as $I(t)\Delta t + O(\Delta t^2)$.

When a light wave (treated classically) impinges on a beam splitter, the electric fields in the upper and lower arm have the same magnitude, but differ by a multiplicative phase (complex function of modulus 1). Thus classical theory predicts that the firings of the two detectors will be positively correlated with the intensity of the electric field and hence with each other.

Suppose a succession of particles, N in all, are sent into the beam splitter. Let N_L and N_U , denote the number of firings of the L and U detectors, respectively, and let N_{LU} denote the number of simultaneous firings. “Simultaneous” firings are defined relative to a small “window of time” of length w surrounding each firing. Firings at times t_L and t_U are considered “simultaneous” if $|t_L - t_U| < w$. Then N_L/N , N_U/N , and N_{LU}/N are experimental approximations to the probabilities p_L , p_U , and p_{LU} of L firings, U firings, and simultaneous firings, respectively.

Because classical theory expects U and L firings to be positively correlated, it expects that $p(U|L) := p_{LU}/p_L$ should be at least as large as p_U . That is, it predicts that

$$p_{LU} \geq p_L p_U \quad . \quad (1)$$

An experimental version of (1) is

$$\frac{N_{LU}}{N} \geq \left(\frac{N_L}{N} \right)^2 \quad . \quad (2)$$

A quantity called the *second-order coherence*, often denoted $g^{(2)}(0)$, is defined as

$$g^{(2)}(0) := \frac{p_{LU}}{p_U p_L} \approx \frac{N_{LU}/N}{(N_L/N)(N_U/N)} = \frac{N_{LU}N}{N_L N_U}.$$

Thus classical theory predicts that

$$\frac{N_{LU}N}{N_L N_U} \approx g^{(2)}(0) \geq 1 \quad . \quad (3)$$

An experiment which measures $g^{(2)}(0)$ sufficiently smaller than 1 will show that the classical theory cannot adequately describe that experimental situation. But of course, that will not prove some alternative theory, such as that U and L should be perfectly anticorrelated!

If U and L *are* perfectly anticorrelated, then $g^{(2)}(0) = 0$. The GRA experiment measures $g^{(2)}(0)$, (which it calls α), obtaining $g^{(2)}(0) = \alpha = 0.18 \pm 0.06$. < 1 . This suggests that the classical photodetecton model cannot explain GRA’s

experimental results and also suggests (though perhaps less strongly since α is closer to 0 than to 1) that U and L might not be perfectly anticorrelated.

Detailed statistical analysis is necessary to decide if the evidence is strong enough to reject either the classical theory or perfect anticorrelation. A statistical analysis to be presented in the next section will indicate that the GRA observations are very improbable under the hypothesis of perfect anticorrelation.

The experiment of Thorn, *et al.*, is conceptually the same as that of GRA, but the experimental techniques are significantly different. The reported results are also significantly different: Thorn obtains $g^{(2)}(0) = .0188 \pm .0067$, which is an order of magnitude smaller than GRA's result.

Thorn, *et al.*, does not mention this discrepancy. It does, however, remark that $g^{(2)}(0) = 0$ is expected.

3 A statistical analysis of the GRA data

3.1 The Poisson model for events occurring randomly in time

This section reminds the reader of the Poisson model for "events" which occur randomly in time. Here "event" is used in the everyday sense of "something which happens", not in the technical sense of "subset of a sample space".

Suppose events occur randomly at a rate of an average of λ per time unit. This will be called a *Poisson process*. The Poisson distribution states that the probability $p(k, T)$ of exactly k events ($k = 0, 1, 2, \dots$) in a time interval $[t, t+T]$ of length T is

$$p(k, T) = \frac{(\lambda T)^k}{k!} e^{-\lambda T} \quad .$$

This is derived by dividing the time interval into a large number n of small subintervals, using the binomial distribution to give the probability that exactly k subintervals contain at least one event, and taking the limit $n \rightarrow \infty$. The natural nature of the derivation under very conservative assumptions (principally that for sufficiently small subintervals, one can ignore multiple events in a subinterval) almost guarantees that the Poisson distribution will have wide practical significance.

It is routine to calculate that the average number of events (i.e., expectation of the number of events) in an interval of length T is λT , as expected from the definition of λ . In practice, the rate λ is estimated by counting the number of events some interval $[t, t + T]$ and dividing by T . Of course, larger T are expected to yield better estimates of the rate.

3.2 Summary of data from GRA

For the reader's convenience, we collect here the relevant data from the GRA experiment. These are somewhat scattered over the first five pages of GRA, with most appearing on p. 177.

The experiment includes an “alarm” which “sounds” whenever a photon enters the interferometer. This is done by generating two photons at the same time (“twin” photons), one of which is channeled to the alarm detector (where it is destroyed upon triggering the alarm), and the other to the input of the interferometer. GRA and Thorn, *et al.*, generate the twins in different ways.

The alarm is triggered at a rate of 8500 counts per second (cps),¹ which is determined by counting the number of times the alarm is triggered. When the alarm “sounds”, the upper and lower detectors are monitored for a time “window” of 9.4 ns (nanoseconds, 9.4×10^{-9} seconds), presumably centered on the time that a photon triggering the alarm would arrive at a detector.

In the upper arm of the beam splitter, the rate of detections is only 5 per second. Of every 10,000 photons triggering the alarm, only about 6 are detected in the upper arm.² Statistics for the lower arm are not explicitly given, but we will take them to be the same.

We will assume that detections in the upper arm are described by a Poisson process with rate of 5 counts per second, and the same for the lower arm. We do not expect the two Poisson processes to be independent; indeed we would expect the opposite if upper and lower detections are perfectly anti-correlated.

The experiment ran for 18,000 seconds (five hours), which implies about 90,000 detections in each arm. However, only 9 coincidences (i.e., simultaneous U and L detections) were observed in the five hour run. A “coincidence” is defined as both U and L detectors firing in the 9 ns window triggered by an alarm.

Initially, only 9 coincidences in 90,000 “trials” sounded to me like good evidence for anti-correlation. One expects some coincidences due to “accidental” counts. One source of accidental counts is two photons arriving almost simultaneously in the interferometer beam and coincident with an alarm, with one directed by the beam splitter into the upper arm and the other into the lower arm. But back-of-envelope calculations indicated that the probability of such accidentals could be low enough that careful analysis would be needed.

Following is a summary of the relevant data from the GRA experiment.

Duration of experiment = 18,000 seconds (five hours)

Rate of photons triggering the alarm = 8500/sec

¹The actual rate was 8800 cps but the reported rate 300/s of “dark counts” has been subtracted. That is, a detector is observed to fire at a rate of 300 firings per second even when no photons impinge on it, and the 8800 cps presumably includes these dark counts.

²Only photons in the arms which are coincident with the alarm are counted. Assuming negligible loss in the beam splitters (a reasonable assumption for modern beam splitters and one which is explicitly confirmed by Thorn, *et al.*), this implies that the beam incoming to the interferometer contains roughly 1000 unpaired photons for every alarm-coincident photon eventually detected in the arms.

The proportion of false alarms to detected coincidences will be about the same. Assuming perfect components, false alarms could simply be ignored. But detectors and/or associated time-to-amplitude converters sometimes have significant “dead time”—a time after a detection during which further detections are impossible. According to [3], dead time can significantly affect the measured value of $g^{(2)}(0)$. GRA contains no discussion of such potentially confounding effects, nor is enough raw data reported to allow the reader to estimate their importance.

Rate of photon detections (heralded by alarm) in upper (lower) arm = 5/sec
Width of time window for detection = 9.4 nanoseconds
Number of coincident detections during the five hour experiment = 9

3.3 Hypothesis testing

This subsection reminds the reader of the protocols of statistical hypothesis testing. In our case, the hypothesis to be tested will be that the upper and lower detectors are perfectly anti-correlated.

Having formulated a hypothesis, one does an experiment to test it. Usually, there is no experiment whose results will definitively confirm a hypothesis, but it is often possible to reject it as implausible.

Under the assumption of the hypothesis, sometimes one can calculate the probability that the experiment will produce the result that it did. If this probability is sufficiently small, then one is tempted to reject the hypothesis. The smaller the probability, the more one is tempted. Since “sufficiently small” implies an arbitrary cutoff, instead of arbitrary rejection some prefer to use the calculated probability as a measure of degree of disbelief in the hypothesis: the lower the probability, the stronger the disbelief.

We shall calculate that the probability of observing nine or more coincidences assuming that the detectors are perfectly anti-correlated is no more than 10^{-26} . This can hardly be taken as good evidence for perfect anti-correlation!

3.4 A simple statistical analysis

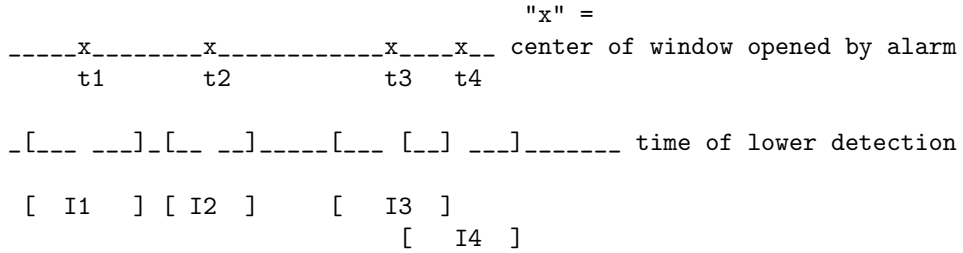
Let AC denote the hypothesis that if there is a photon in the upper arm, then a perfect detector in the lower arm will never fire, and vice versa. i.e., perfect anti-correlation. This is the hypothesis which we shall try to reject.

This subsection will present a simple statistical analysis showing that assuming hypothesis AC, the probability of obtaining the observed nine coincidences or more is less than 10^{-26} , i.e., negligible.

Imagine two parallel lines of time, one above the other. The upper line will refer to the U detector and the lower to the L detector. Below is a crude diagram.

Suppose it takes S seconds for a photon to get from the alarm to the upper detector, and the same for the lower detector. Each time a that the alarm sounds, *and* that a photon triggers the upper detector in the time window opened by the photon at a , make a mark (an “x” in the diagram) at time $t = a + S$ on the upper line. That is, the x’s are the centers of the 9.4 ns time windows during which both U and L detectors are enabled *and* in which U fires. The time corresponding to the j ’th “x” is denoted t_j .

On the lower line directly below each “x”, indicate an interval centered at the time t of width 9.4 ns. The endpoints of the interval are denoted by brackets in the diagram.



Some of the intervals will overlap. Because of the overlapping, the diagram of the lower time line can be ambiguous. To resolve the ambiguity, the intervals are also drawn staggered below the lower line rather than on it. There seems no way to produce subscripts in “diagram mode”, so the intervals are named “I1, I2”, etc. instead of I_1, I_2, \dots in the diagram. However, elsewhere they will be called I_1, I_2, \dots , and similarly for t_1, t_2, \dots

Imagine that the intervals I_1, I_2, \dots on the lower line are lifted directly up to the upper line. These lifted intervals are the windows in which a U photon was observed. They are not drawn on the upper line to avoid cluttering the diagram. A photon was detected in each upper interval, but not necessarily in the corresponding lower interval.

Given a U detection, GRA considers an L detection as “coincident” if it lies in the 9.4 ns interval on the lower line corresponding to the interval on the upper line in which the U detection occurred. Under our anti-correlation hypothesis AC, *all* coincidences are “accidental” coincidences. They may be caused by stray photons. Another possibility is that photon 1 may trigger a U detection in interval I_k (which was opened by the alarm) and another photon triggers an L detection in the same interval. This last possibility is unrelated to experimental imperfections, so we must be careful to account for it. The accounting will be done in such a way that foreseeable experimental imperfections are also accounted for.

We are assuming throughout the hypothesis AC that when a single photon exits the beam splitter, if it triggers the L detector, it never triggers the U detector and vice versa, i.e., perfect anti-correlation. (We are assuming it to try to show that it implies that the experimental results are very improbable.)

Under this hypothesis, one would expect the events of a particular U detection in a particular window I_k and an L detection in same window to be independent. Such a simultaneous detection in both arms would be impossible under the ideal conditions and perfect anti-correlation, but could be experimentally observed if given a U detection, a photon somehow accidentally showed up in L for the reasons given above or some other reason. A photon showing up in L would be a random event, which would have occurred independently of the U detection. If the reader can think of any likely experimental imperfection which could reasonably call the independence into question, I would be grateful for the information.

This independence is the key assumption necessary for our analysis so we

state it explicitly:

Independence Assumption: Under the hypothesis of perfect; anti-correlation, for any time window I_k ,

$$p(\text{L detection in } I_k \mid \text{U detection in } I_k) = p(\text{L detection in } I_k) \quad .$$

We emphasize that our expectation of independence rests on the anti-correlation hypothesis AC. For example, it certainly would not be expected if perfect correlation were assumed instead of perfect anti-correlation.

When I first wrote down the Independence Assumption, it seemed so reasonable as to be almost beyond dispute. (For example, it seems to be an implicit assumption of Thorn’s Appendix A, so obvious as to be unworthy of mention.) But further consideration made me uneasy. I still can’t think of any grounds on which it could be seriously disputed, but though still reasonable, it somehow seems less inevitable than originally.

For the benefit of readers who may share such unease, it may be helpful to remark that the analysis will not actually require the Independence Assumption, but only the weaker assumption that

$$p(\text{L detection in } I_k \mid \text{U detection in } I_k) \leq p(\text{L detection in } I_k) \quad .$$

This weaker assumption does seem almost beyond dispute. It says that when U and L are perfectly anti-correlated under ideal conditions, the information that U has fired in an experiment cannot make one give greater odds that L has simultaneously fired than one would give without that information.

The probability p_I of an L detection in any one of the intervals I_k is given by the Poisson model as:

$$\begin{aligned} p_I &:= p(\text{L detection in } I_k) \\ &= 1 - p(\text{no L detection in } I_k) = 1 - e^{-5 \times 9.4 \times 10^{-9}} \approx 4.7 \times 10^{-8}. \end{aligned}$$

We are interested in the rate of coincident detections, in order to determine how likely under the anti-correlation hypothesis AC are the 9 coincidences that were observed in 5 hours. Waiting for a coincidence is waiting for an event that occurs randomly in time, i.e., a Poisson process.

At some starting time, we wait for the alarm to sound. The alarm opens a 9.4 ns. window in which both U and L detectors are enabled for detection. If U does not detect a photon, we ignore the alarm event and wait for the next alarm. If U does detect a photon, we ask if L detected a photon in the same window. If L did not detect a photon, we ignore the alarm event and wait for the next alarm. If L did detect a photon, we record a “coincidence” event.

More abstractly, we are waiting for an event in the Poisson process which the upper detector monitors. When one occurs, we perform a binary experiment with probability p_I of “success” (defined as detection by L in the 9 ns window I_k in which the U detector fired). If “success” does occur, we record a coincidence, otherwise not. This compound experiment is also described by a Poisson process.

The rate λ_C for this for this new “coincidence” Poisson process is the rate for the original upper arm process times p_I , i.e., $\lambda_C = 5 \times p_I \approx 2.35 \times 10^{-7}$ coincidences per second.

The expected number of coincidences N_{LU} in the entire 5 hr (18,000 sec) experiment is $\lambda_C \times 18,000 \simeq .0042$ which tells us immediately that nine or more will likely be extremely improbable. In fact,

$$\begin{aligned} p(9 \text{ or more coincidences in } 18,000 \text{ sec}) &= \sum_{k=9}^{\infty} \frac{(18,000\lambda_C)^k}{k!} e^{-18,000\lambda_C} \\ &= 1 - \sum_{k=0}^8 \frac{(18,000\lambda_C)^k}{k!} e^{-18,000\lambda_C} \\ &\simeq 1.19 \times 10^{-27} < 10^{-26}, \end{aligned}$$

i.e., vanishingly small. Thus not only does the experimental data not support the anti-correlation hypothesis AC, but strongly suggests that it should be rejected.

That does not imply that the hypothesis is almost surely false, but only that the data presented in GRA do not support it. Of course, the problem may lie with the data rather than with the hypothesis.

3.5 General remarks on Thorn, *et al.*

The Introduction describes how the present work was motivated by citations of the experiments of GRA and Thorn, *et al.*, in sci.physics.research (s.p.r.), as demonstrating perfect anti-correlation. The person citing these papers is a Professor of Physics at the University of California at Davis.

After studying GRA and Thorn in detail, I don’t agree that they can be taken as the definitive evidence which the poster seems to think that they are. The results of Thorn, *et al.*, are directly comparable to GRA’s, but differ by an order of magnitude. It seems very strange that Thorn, *et al.*, does not mention that.

One of the two has to be wrong. If I had to bet, I would bet that it is GRA which is wrong, but the writeup of Thorn, *et al.*, is not sufficiently definite (e.g., some critical raw data is missing) to conclude that its results are definitive.

I have noticed what seem to me questionable points in the experimental setup of Thorn, *et al.*, points which are not addressed in the writeup. (However, a later paper [3] of one of the authors does address some of them.) My guess is that a careful analysis would confirm the experimental conclusions of Thorn, *et al.*, but that is only a guess.

When I began this essay, I planned to describe in detail my doubts about Thorn, *et al.* But upon careful study, my main doubt evaporated. The remaining doubts are sufficiently technical and detailed that they will probably be meaningful only to those who have carefully studied Thorn. I will be happy to discuss them privately with anyone with a serious interest in the matter,³ but I have decided that posting them at this time might invite misinterpretation.

³I would expect anyone who inquires to recognize an obligation to be familiar with Thorn,

Thorn, *et al.*, was published in the American Journal of Physics, a widely read expository journal. Its very title suggests that its intent is pedagogical, to help other small physics departments set up similar experiments. Judged by the standard of that intent, it is excellent. It may not have been intended as a research paper, and to question its methods in detail might appear as nitpicking.

All I will say here is that I don't think that either GRA or Thorn, *et al.*, definitively settle the issue of perfect anticorrelation. If I had to bet, I would bet on perfect anticorrelation, but I wouldn't bet more than I could afford to lose.

4 Final thoughts: A near-paradox resolved by the minimalist interpretation?

My original question amounted to: If a single quantum particle enters a beam splitter, is it ever detected at both outputs?

The wording of the question almost presupposes the answer. The very concept of "particle" as an indivisible entity suggests that it cannot be split between the two arms of the beam splitter.

If a wave description is used, then splitting would be expected, but GRA does seem to rule out that description for this experiment. However, if the beam splitter is completed to form a Mach-Zehnder interferometer, (as GRA actually did), then the wave description explains the experimental results while the particle description fails.

In principle, the arms of the beam splitter could be so long that communication at the speed of light would be impossible between the U and L detectors. Seemingly, whether L fires or not should depend only on the local conditions around L, and similarly for U. But the symmetry of the situation seems to imply that the local conditions should be the same for L as for U.

This glosses over the subtlety that the situation is not truly symmetric because the L detector is in the transmitted beam, whereas the U detector is in the reflected beam. However, all analyses of optical beam splitters known to me claim that there is a phase shift of i (90°) in the reflected beam (relative to the transmitted beam). For a photon described by a classical complex electromagnetic field, this phase shift would multiply the field by the imaginary unit i . If we allow the photon to be described by a quantum wave function $\Psi = \Psi(x)$ (which may be controversial but is frequently assumed, at least implicitly),⁴ the phase shift replaces Ψ by $i\Psi$.

If the incoming quantum particle (e.g., a neutron) is indisputably described *et al.*, and to be willing to discuss it. In the past, I have received inquiries, sometimes anonymous (!), of the nature of: "Tell me what you think is wrong with it." If I do invest hours writing up a critique, I may never hear from the person again.

⁴ Such an assumption is often hidden by denoting the upper and lower beams by notation such as $|U\rangle$ and $|L\rangle$, respectively, with the totality denoted as $(|U\rangle + |L\rangle)\sqrt{2}$. This differs in no essential respect from assuming that the photon is described by a wavefunction $\Psi = \Psi(x)$ which is nonzero only close to the locations x_U and x_L of the U and L detectors, respectively.

by a wave function Ψ , then the argument below requires that a beam splitter for such a particle behaves like an optical beam splitter in that the reflected beam differs from the transmitted beam by a phase.

Let x_U denote the position of the U detector and x_L the position of the L detector. Then the symmetry just discussed suggests that for small w , $|\Psi(x_U + w)|^2 = |\Psi(x_L + w)|^2$. This says that the local conditions are the same near the U and L detectors.⁵

According to quantum mechanics, the probability of U firing should be proportional to $|\Psi(x_U)|^2 = |\Psi(x_L)|^2$, which is the same as the probability of L firing.⁶ Moreover, the firing of L should be independent of the U firing because of their spacelike separation.

In summary, the argument states that the local conditions at U and L are the same, so each has the same probability $p = 1/2$ of firing. The firings are independent, so the probability p_{UL} of simultaneous firings is nonzero (specifically, $p_{UL} = (1/2)^2 = 1/4$).

One poster to sci.physics.research addressed this question, though in such a roundabout way that I doubt that many readers realized that he was doing it. There is a “minimalist” interpretation of quantum mechanics which holds that the quantum wave function Ψ is nothing more than a mathematical tool for predicting experimental results. No “reality” should be ascribed to it.

According to this interpretation (as I understand it), it is wrong to imagine that Ψ might be associated with triggering the detectors. If we ask what *does* trigger the detectors if neither Ψ nor a particle nor an electromagnetic wave, a “minimalist” would presumably reply that the question is meaningless. (The argument above disposes of the possibility that local conditions trigger the detectors.) I agree that this “minimalist” interpretation is logically consistent (at least in the context of the experiments we are discussing), but I have to wonder if it is the best that can be given.

It reminds me of an old joke about the boy who was afraid of kreplachs. A *kreplach* is a pastry that goes in a soup, associated with Jewish cooking. It is made by placing a bit of ground meat in the middle of a square of dough and folding over the corners.

To cure the boy of his phobia, his mother demonstrates how a kreplach is made. She puts the meat in the center of the square of dough and asks him if that makes him afraid: he says not. Then she folds over three of the four corners and asks again: he says he is not afraid. Finally she folds over the fourth corner and he screams in terror: “Aagh, kreplach!”

How does this relate to our beam splitter experiment? Suppose we close off the lower arm and just consider the detector in the upper arm. As I understand it, a typical single photon detector consists of a vacuum tube with several conducting plates inside maintained at an electrical potential difference with

⁵Locally, a phase shift between upper and lower beams cannot be distinguished from an irrelevant global phase shift $\Psi \mapsto c\Psi$, c constant.

⁶This is slightly oversimplified, but the reader should know how to expand the argument. It may look more natural in notation like $\Psi = (|U\rangle + |L\rangle)/\sqrt{2}$ in which there are effectively only two positions U and L . See footnote (4).

respect to each other. An incoming “photon” or electromagnetic disturbance of some kind, kicks an electron off the first plate, which is accelerated by the field toward the next plate. When it hits the next plate, it kicks off several more electrons to be accelerated toward the next plate. This chain reaction continues until the current in the last plate is sufficient to be detected. It is hard to imagine that anyone would question that the initial electromagnetic disturbance (whether one calls it a “photon” or something else) causes the detector to fire.

This description would seem to be completely acceptable. Presumably, whoever invented the detector would have relied on something like it.

Of course, the same applies to the lower detector if the upper arm is blocked. But if both arms are unblocked, suddenly the description is perceived as meaningless, similar to the completion of the kreplach. If the description of firing as determined by local conditions were accepted as meaningful, then it would either contradict usual interpretations of quantum mechanics or would imply the possibility that the spacelike separated U and L can communicate, i.e., that L “knows” when U has fired so that it must not fire.

Granted, there are some assumptions in the above argument that could be questioned. Perhaps it is illegitimate to associate a wave function with photons, even though this is commonly done as explained in the footnotes. Perhaps beam splitters for massive particles like neutrons have different properties than optical beam splitters, invalidating the above phase shift arguments.⁷ But the assumptions do seem reasonable and similar to assumptions commonly made. I would not have the hubris to call this a “paradox”, but to me it seems close.⁸

I think that the value of the minimalist interpretation may be that it reminds us how carefully we must use classical language to avoid contradictions with experiment. But to take it as the last word seems premature. If we don’t look for interpretations which go beyond minimalism, then we surely will not find any. Perhaps there is nothing to find, so looking is a waste of effort. And perhaps not.

5 Comments and credits

July 29, 2014 I thank Dan Riley for pointing out that in the analysis of the GRA experiment, a statement that 8500 photons per second enter the

⁷If readers spot any other questionable assumptions, I would be grateful for the information.

⁸It is similar to an objection to quantum mechanics which I have seen attributed to Einstein. (I can’t remember where I saw it.) That version considers a quantum particle which passes through a single pinhole in a wall. The wall is taken as the x - y plane, and before passing through the pinhole, the particle is traveling along the z axis.

On the other side of the wall, the pinhole is at the center of a sphere covered with particle detectors. The symmetry of the situation suggests that local conditions on the sphere should be invariant under rotations about the z -axis. Local conditions should be the same for any two detectors at the same polar angle θ to the z -axis.

Some of the detectors with the same polar angle will be spacelike separated, but according to most interpretations of quantum mechanics, only one detector can fire. If firing is determined by local conditions, how can two spacelike separated detectors “know” that only one of them can fire?

interferometer should instead say that the alarm is triggered by photons 8500 times a second. (The text has been corrected.)

The original statement overlooked that the efficiency of the alarm detector may be low. The essay's analysis never used the 8500/s rate and is unaffected.

References

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