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MULTIPARTICLE INTERFEROMETRY AND THE SUPERPOSITION PRINCIPLE

We're just beginning to understand the ramifications of the superposition principle at the heart of quantum mechanics. Multiparticle interference experiments can exhibit wonderful new phenomena.

Daniel M. Greenberger, Michael A. Horne and Anton Zeilinger

Discussing the particle analog of Thomas Young's classic double-slit experiment, Richard Feynman wrote in 1964 that it "has in it the heart of quantum mechanics. In reality, it contains the *only* mystery."[1] That mystery is the one-particle superposition principle. But Feynman's discussion and statement have to be generalized. Superposition may be the only true quantum mystery, but in multiparticle systems the principle yields phenomena that are much richer and more interesting than anything that can be seen in one-particle systems.

The famous 1935 paper by Albert Einstein, Boris Podolsky and Nathan Rosen pointed out some startling features of two-particle quantum theory.[2] Erwin Schrödinger emphasized that these features are due to the existence of what he called "entangled states," which are two-particle states that cannot be factored into products of two single-particle states in any representation. "Entanglement" is simply Schrödinger's name for superposition in a multiparticle system. Schrödinger was so taken with the significance of multiparticle superposition that he said entanglement is "not *one* but rather *the* characteristic trait of quantum mechanics."

Until the mid-1980s, the quintessential example of an entangled state was the singlet state of two spin-½ particles,

$$|\psi> = (1/\sqrt{2})(|+>_1|->_2 - |->_1|+>_2)$$

or its photon analog. The subscripts 1 and 2 refer to the two particles (distinguished, for example, by their flight directions), and the plus and minus signs refer to spin up or down with respect to any specified axis. This state of two spatially separated particles was introduced into the Einstein–Podolsky–Rosen discussion by David Bohm[3] in 1951. It inspired a spate of experiments in the 1970s and '80s.

Since the mid-1980s there has been a revolution in the laboratory preparation of new types of two-particle entanglements. Various experimental groups started doing interferometry with down-conversion photon pairs. Down-conversion is a process in which one ultraviolet photon converts into two photons inside a nonlinear crystal.[4] This process allows one to construct "two-particle interferometers" that entangle the two photons in a way that needn't involve polarization at all. Many experimental groups independently came up with this idea, but the first explicit proposal was made by two of us.[5]

Real experiments commenced when Carroll Alley and Yan Hua Shih[6] at the University of Maryland first used down-conversion to produce an entangled state and when Ruba Ghosh and Leonard Mandel[7] at the University of Rochester first produced two-particle fringes without using polarizers. Since these pioneering efforts, many increasingly sophisticated experiments have been performed, with important lessons for quantum theory.

In all of these two-particle experiments, the source of the entanglement has been down-conversion. We will discuss a small sampling of recent developments, with particular emphasis on the fundamental ideas. Three-particle interferometry is even richer, and we shall say something about it. But it is mostly unexplored territory, both experimentally and theoretically.

One of our motivations for writing this article was to make the point that one doesn't have to be a quantum optics expert to understand or analyze such experiments. They illustrate beautifully the general principles of quantum mechanics, and they can be understood, both qualitatively and quantitatively, in those terms. Calculations based on detailed nonlinear quantum optics Hamiltonians do describe specific mechanisms. But they tend to obscure the generality of the conclusions, which depend primarily on the fact that if one cannot distinguish (even in principle) between different paths from source to detector, the amplitudes for these alternative paths will add coherently.

Two-particle double-slit interferometry

Figure 1 is a sketch of an idealized two-particle interference experiment that nonetheless exhibits some intriguing phenomena which have been verified experimentally. Consider a particle Ω near the center that can decay into two daughter particles. If the original particle is essentially at rest, then the momenta of its two daughters will be approximately equal and opposite. Now imagine that there are screens on both sides of the center, each with

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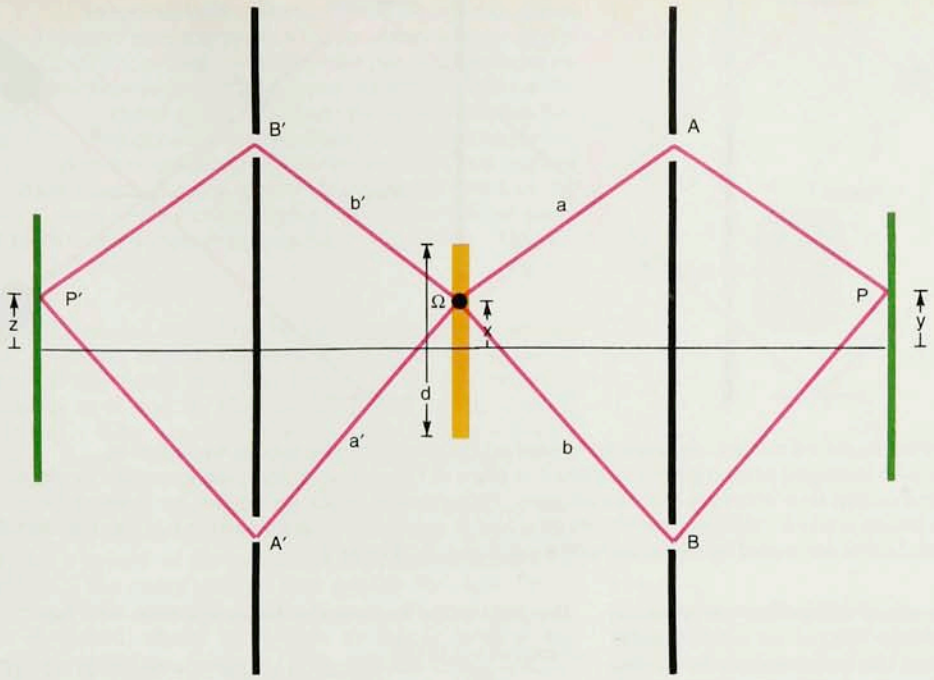


Idealized two-particle interferometer has two detecting screens (green) flanking two collimating screens, each with a pair of holes, that bracket a source (orange) of decaying particles at the center. The vertical extension of the source is d. A particle Ω decays at height x above the center line into two particles (trajectories in red) that hit their respective detecting screens at heights y and z. Because one can't tell whether the pair passes through holes A and A' or B and B', these alternatives can interfere. **Figure 1**

two holes in it, as shown in the figure. These holes confine the escaping decay particles to either of a pair of opposite directions. The decay particles can pass either through holes A and A' or through holes B and B'. We can then write the state of the two-particle system as

$$|\psi> = (1/\sqrt{2})(|a>_1 |a'>_2 + |b>_1 |b'>_2)$$

where the letter in the state-vector bracket denotes the escape direction defined by the corresponding holes. Beyond the two perforated screens are two scintillation screens that record the positions of particles landing on them.

Because each of the particles can reach its detecting screen by way of two different paths, one might expect these screens to show interference patterns. But they don't. That's where the two-particle interferometer differs from a single-particle interferometer based on Young's classic double-slit experiment. There is no interfence pattern at either screen in these two-particle experiments because, for reasons that will become clear, the vertical position of the decaying particle is unknown to within some source size d that is considerably larger than λ/θ, where θ is the angle subtended by the hole pairs at the source, and λ is the relevant wavelength—optical or de Broglie, as the case may be. Thus the initial position uncertainty d washes out any interference fringes.

In the single-particle case, by contrast, the geometry is so determined, usually by lenses, that the source is effectively a point. Its positional uncertainty is much smaller than λ/θ, so that the waves arrive at the two holes with a definite phase relation and therefore interfere. The experimenter produces a diffraction pattern by controlling the geometry of the emission process.

In the two-particle case, something like the opposite of this process happens. With a large source, if one looks at either particle *separately*, one sees no interference pattern. But there is a *two*-particle interference pattern! If one monitors the arrival positions P and P' at the two scintillation screens *in coincidence*, then one sees that the two particles are much more likely to land where the alternative paths $PA\Omega A'P'$ and $PB\Omega B'P'$ differ in length by an integral multiple of the wavelength and so interfere constructively. Note that one cannot catch such two-particle interference patterns on film at either screen; one has to record coincidences.

One may well ask how one particle could have any knowledge of where the other can land, especially when the source position is unknown and therefore the first particle doesn't even know where it itself will land. The answer is that by landing at a specific point, one particle actually creates a sinusoidal amplitude of possible positions where the source is likely to have been—a sort of "virtual crystal." This crystal in turn creates the two-particle diffraction pattern. Virtual slit systems can be exploited in actual experiments.[8]

To see how this works here, let us for simplicity consider only the vertical degree of freedom x for the source position relative to the horizontal center line in figure 1. And let us say that the decay particles are photons. If y and z are the corresponding vertical distances above center of the landing points P and P', respectively, then the quantum mechanical amplitude for landing at P is

$$\psi \sim \exp(ikL_a) + \exp(ikL_b) \sim \cos\frac{2\pi\theta}{\lambda}(y+x)$$

where k is $2\pi/\lambda$ and the L's are the alternative path lengths for the photon on the right side of the apparatus. Similarly the amplitude for the other photon to land at P' is

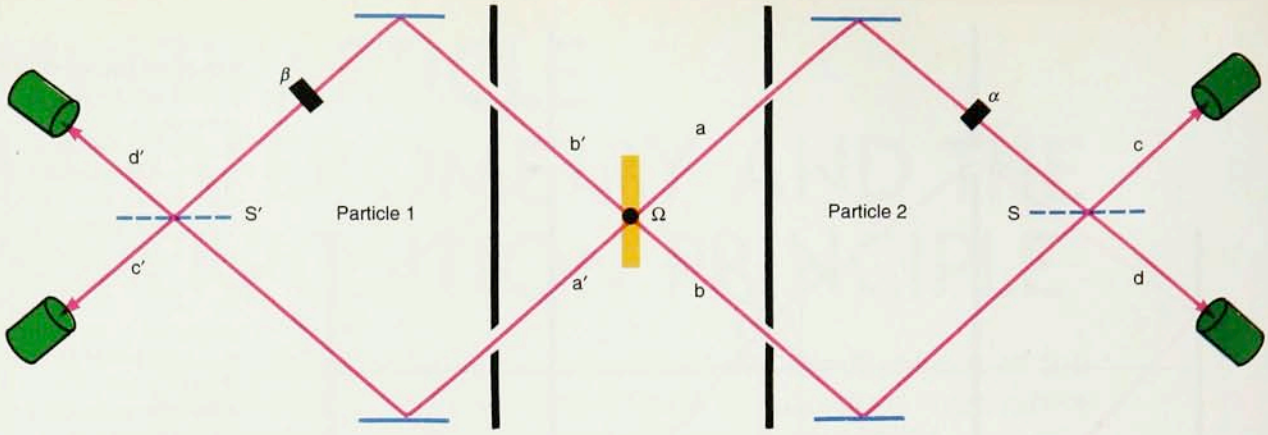
$$\psi' \sim \cos\frac{2\pi\theta}{\lambda}(z+x)$$

Then the total amplitude for the two photons to land at heights of x and y, respectively, above center will be

$$\psi(y,z) \sim \frac{1}{d}\int_{-d/2}^{d/2} dx \cos\frac{2\pi\theta}{\lambda}(y+x)\cos\frac{2\pi\theta}{\lambda}(z+x)$$

If d is much larger than λ/θ, this integral becomes $\frac{1}{2}\cos(2\pi\theta(z-y)/\lambda)$, and one gets 100% visibility for "conditional fringes" between the two photons on opposite sides.

At the other extreme, if d is much smaller than λ/θ, the integral gives $\cos(2\pi\theta y/\lambda)\times\cos(2\pi\theta z/\lambda)$.



Beam splitters (half-silvered mirrors, represented by dashed blue lines) can be used in two-particle interferometry with localized photon detectors (green) in place of the extended detecting screens of figure 1. Particle Ω in the central source decays into two photons. Phase shifters (black rectangles) are inserted into decay-photon beams a and b', shifting their phases by α and β, respectively. Before arriving at the detectors the alternative-path beams are mixed by the beam splitters at S and S'. **Figure 2**

That's a product of independent diffraction patterns, so we actually see single-particle fringes on each screen. The condition $d \ll \lambda/\theta$ is just the requirement for seeing fringes in a usual single-particle diffraction experiment. So there is a sort of complementarity between one- and two-particle fringes: The conditions for seeing one *preclude* the possibility of seeing the other.

One can make the same argument in momentum space. Momentum p is related to wavenumber by $k = p/\hbar$. If $d \gg \lambda/\theta$, the uncertainty principle tells us that the fractional transverse momentum spread $\delta k/k$ of each emitted photon will be much less than θ. That's too little to illuminate both pinholes simultaneously, so there can be no single-particle interference. On the other hand, if the source is small, then $\delta k/k \gg \theta$ and the particle can pass through either hole. The two paths can then interfere, and one will see fringes at the individual screens. But then one can no longer guarantee that if one photon goes through pinhole A, the other will go through A'. That destroys the two-particle entangled state. Once again, the two conditions are mutually exclusive.

The gedankenexperiment we have just described is essentially what Ghosh and Mandel did in their pioneering down-conversion experiment.[7] Its main difference from our description is that their originating ultraviolet photon strikes the nonlinear crystal with a substantial momentum, so that the two down-converted photons it generates both emerge together from the back of the crystal. Thus Ghosh and Mandel were able to catch both photons on a single screen.

Beam splitters

Most subsequent down-conversion experiments have used a different technique, replacing the scintillation screens with beam splitters. Figure 2 is a schematic illustration of such an interferometer. Beam splitters at S and S' have replaced the two detector screens of figure 1. Small detectors beyond the beam splitters monitor the counts in the four photon beams labeled c, d, c' and d'. To detect interference, one inserts a phase shifter of phase α into beam a, and one of phase β into b'.

We assume that each beam splitter transmits precisely half of each incident beam and reflects the other half. (Without loss of generality we can take the transmitted and reflected beams to be 90° out of phase.) Then the joint state beyond the beam splitters will be

$$\frac{i\exp(-i(\alpha+\beta)/2)}{\sqrt{2}}\left[\sin(\Delta/2)\,|c\rangle_1|c'\rangle_2 + \cos(\Delta/2)\,|c\rangle_1|d'\rangle_2 + \cos(\Delta/2)\,|d\rangle_1|c'\rangle_2 - \sin(\Delta/2)\,|d\rangle_1|d'\rangle_2\right]$$

where $\Delta = \alpha - \beta$ is the difference between the parameters of the two phase shifters. To see two-particle interference effects one must simultaneously monitor beam detectors on the left and right sides of the apparatus (c and c', for example) for coincident counts while varying Δ. In any single detector, by contrast, one sees no interference; the counting rate is a constant independent of the variable phase shifters. Each detector on its own is seen to record at random half of all events. For example,

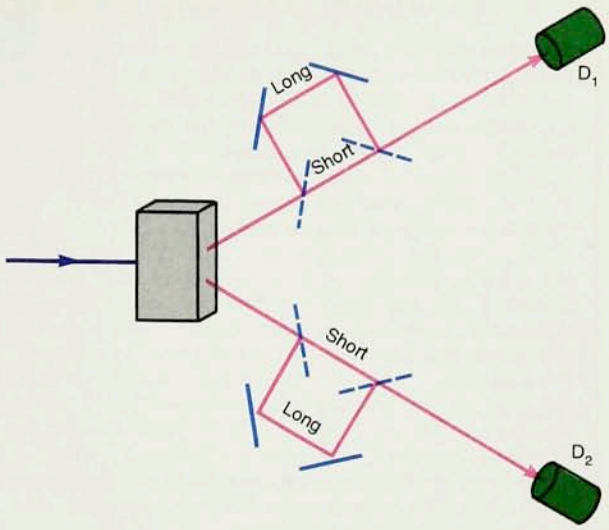
$$P(c) = P(c,c') + P(c,d') = \frac{1}{2}\sin^2\frac{\Delta}{2} + \frac{1}{2}\cos^2\frac{\Delta}{2} = \frac{1}{2}$$

independent of Δ, where $P(c,c')$ is the joint probability of simultaneous counts in c *and* c'. One can also use this setup to perform an Einstein–Podolsky–Rosen experiment. We assign a value of +1 to a detection at either detector c or c', and −1 to d or d', and take the product of the appropriate values for a pair of simultaneous counts at left and right. Simultaneous counts in detectors c and d', for example, get a score of $(+1)\times(-1) = -1$. One can then take the expectation value over a long series of counts to confirm the quantum mechanical prediction:

$$E(\alpha,\beta) = P(c,c') - P(c,d') - P(d,c') + P(d,d') = -\cos\Delta$$

This cosine form is identical to what one gets for Bohm's version of the Einstein–Podolsky–Rosen experiment, with its two spin-½ particles in the singlet state.[9] The phase shifters play the role of the spin polarizer angles in that experiment. Variants of Bohm's version have been performed many times, generally using photon polarization rather than the spin of massive particles. The first such experiment was done by John Clauser and Stuart Freedman at Berkeley, and the most famous is the experiment of Alain Aspect and his coworkers at Orsay, near Paris.[10] With the advent of the parametric down-converter, the new version without polarization that we've been describing has also been done.[11]

The fact that these experiments exhibit two-particle correlations but not single-particle interference has some important (if poorly understood) ramifications, of which



Temporal double-slit experiment proposed by James Franson[13] produces two-photon interference because one doesn't know *when* the pair was produced by down-conversion of an incident ultraviolet photon in the crystal (gray). The down-conversion photons (red trajectories) arrive simultaneously at their respective detectors (green), so one knows that both took paths of equal length. But one doesn't know whether both took the long or the short alternative paths offered by the beam splitters and mirrors in each arm of the apparatus. **Figure 3**

we shall mention two. One is that it is impossible to use such a system to communicate faster than the speed of light. If the value of α had any effect on the counting statistics at c' and d', that would clearly violate special relativity. Why quantum theory, a specifically nonrelativistic theory, should conspire to be consistent with relativity in this way is a deep mystery.

To illustrate the other particularly interesting feature of the experiment sketched in figure 2, consider keeping a record of the results of repeated outcomes for particle 1, the decay product that goes to the right. Such a string of 1's and −1's (depending on whether detector c or d clicked) would be useless by itself, because the numbers would be random. It is not until the lists for the left and right decay particles are brought to the same place for comparison, possibly weeks later, that the correlations between them can be seen. So these correlations, necessarily nonlocal in character, are worthless until they are locally compared.

In England, John Rarity and Paul Tapster[11] have performed such an experiment by means of down-conversion. The converted photons emerge from the crystal with a broad range of colors and directions, but they can be accurately selected by filters and other optical devices. Rarity and Tapster employed a folded version of the configuration in figure 2, with both photons coming out on the same side of the crystal. Although several other groups[6,7] have done tests of Bell's inequality with the new techniques, the experiment of Rarity and Tapster was the first one that did not rely at all on the polarization of the photons. Their data reflect the transverse correlation of the two photons beyond the beam splitters.

Interference of emission times

Ten years ago Mandel pointed out[12] that one could get two-photon fringes when two independent and spatially separate single-atom sources produce coincident photon counts in a pair of detectors. He traced this idea back to the 1950s. Interference occurs because, as Mandel put it, "one photon must have come from one source and one from the other, but we cannot tell which came from which."

An ingenious alternative was proposed by James Franson at Johns Hopkins.[13] He pointed out that two-particle fringes can also arise because we don't know *when* the particles were produced. Several groups[14] have successfully produced interference fringes using Franson's scheme, and it is becoming an efficient way to produce such fringes. We will describe a recent experiment by Raymond Chiao and colleagues at Berkeley,[15] which is the first to produce high-visibility fringes in this way.

Figure 3 illustrates the novel type of superposition in Franson's proposal. A pair of down-conversion photons register at detectors D_1 and D_2 within a coincident-time window (1 nsec in the newest experiment) that is small compared with the travel-time difference (4 nsec) between the short and long alternative routes in each arm of the interferometer. Which route did each photon take? Because the down-conversion photon pairs are produced together and arrive together (within the coincidence window) at detectors D_1 and D_2, they must *both* have taken either the long way or the short way. But because we can't know at what time the down-conversion took place, we must use the quantum-state superposition

$$(1/\sqrt{2})(|s\rangle_1\,|s\rangle_2 + |l\rangle_1\,|l\rangle_2)$$

where, for example, $|s\rangle_1$ denotes the short route for particle 1. Because we don't know whether the photon pair was produced at the earlier or later time consistent with the coincidence observation, this device is in effect a "temporal double slit." It is easy to see how this kind of arrangement could be generalized from a two-time slit to a multitime grating.

By changing the length of one of the long paths and thus altering the relative phase of the two terms, one can produce sinusoidal oscillations ("fringes") in the coincident count rates. But the singles rate in each separate detector is constant.

Why is there no interference in the individual detectors, even though each particle passes through a self-contained interferometer? Well, one could completely remove the half-silvered mirrors from one of these interferometers and monitor the short route, thereby ascertaining whether the particle in the other one took the short or long route. That is, if the counts are nearly simultaneous, both must have taken the short (straight) route, but if the photon in the intact interferometer arrives 4 nsec late, it must have taken the long route. Thus one can use one particle to obtain path information about the other one, even though the latter passes through an interferometer, and hence no single-detector oscillations are possible. But when both interferometers are intact and both particles have been detected within a 1-nsec window, the opportunity to obtain path information is lost forever. Then the two-particle oscillations appear!

This explanation stresses an aspect of the interpretation of the wavefunction that is not often emphasized: The wavefunction contains all information about the system that is potentially available, not just the information actually in hand. It is the mere possibility of obtaining path information for the individual photon in a particular experimental configuration that guarantees that the amplitudes along those paths will not interfere. It is what the experimenter can do, not what he bothers to do, that is important. Changing the configuration to

A Mind-Boggling Experiment

We present here a more detailed analysis of the experiment of Zou and coworkers,[16] illustrated in figure 4a, to show that the phenomena involved are understandable by elementary quantum mechanics; you don't need the full machinery of quantum optics. (In our description, $|a\rangle_1$ simply denotes particle 1 in beam a. It does not represent the field of beam a. The particle could just as well be an electron.[24]) We want to encourage nonexperts to enter the game.

At A, the first beam splitter, we have $|a\rangle \rightarrow (|b\rangle + i|c\rangle)/\sqrt{2}$. At B, $|e\rangle \rightarrow (T|g\rangle + iR|f\rangle)$, where T and R are the (real) transmission and reflection amplitudes at the second beam splitter. (The reflected and transmitted parts are 90° out of phase to conserve probability.) At C, the third beam splitter, $|h\rangle \rightarrow (|l\rangle + i|m\rangle)/\sqrt{2}$ and $|d\rangle \rightarrow (|m\rangle + i|l\rangle)/\sqrt{2}$. At P, the phase shifter, $|h\rangle \rightarrow e^{i\varphi}|h\rangle$. At the down-conversion crystals, $|b\rangle \rightarrow \eta|d\rangle_1|e\rangle_2$ and $|c\rangle \rightarrow \eta|h\rangle_1|k\rangle_2$, where η, on the order of 10^{-6}, is the amplitude for down-conversion. Finally, by perfectly lining up the beams we get $|g\rangle \rightarrow |k\rangle$.

Combining all these terms gives

$$|a\rangle \rightarrow \frac{1}{\sqrt{2}}(|b\rangle + i|c\rangle) \rightarrow \frac{\eta}{\sqrt{2}}(|d\rangle_1 |e\rangle_2 + i|h\rangle_1 |k\rangle_2)$$

$$\rightarrow \frac{\eta}{2}[(T - e^{i\varphi})(|m\rangle + i(T + e^{i\varphi})|l\rangle]_1 |k\rangle_2$$

$$+ i\frac{\eta}{2} R(|m\rangle + i|l\rangle)_1 |f\rangle_2$$

By counting coincidences at detectors D_1 and D_2 one measures the square of the amplitude of the $|l\rangle_1 |k\rangle_2$ term,

$$\frac{\eta}{2}(1 + T^2 + 2T\cos\varphi)$$

That gives a fringe contrast $v = 2T/(1 + T^2)$ for coincident counts at D_1 and D_2. This contrast increases with T, which is the amplitude ratio of the two contributions to beam $|k\rangle$. If instead of recording coincidences one only monitors beam $|l\rangle$ at D_1, there are contributions from the $|l\rangle_1 |k\rangle_2$ and $|l\rangle_1 |f\rangle_2$ terms, yielding

$$\frac{\eta^2}{2}(1 + T\cos\varphi)$$

so that the contrast is reduced to $v = T$. Thus the degree of coherence of beam 1 is controlled by beam 2, even though beam 2 isn't even in the coherence path. The only purpose the second beam serves is to make it impossible to tell in which crystal the down-conversion occurred.

eliminate the path information can restore the interference fringes.

Path distinguishability and coherence

To show some of the possibilities inherent in two-particle superpositions, we will describe a truly mind-boggling experiment by Mandel and his Rochester colleagues Xin Yu Zou and Li Jun Wang.[16] Their experiment, schematically illustrated in figure 4a, marvelously vindicates Feynman's dictum that states interfere with each other only when they cannot physically be distinguished in a particular experimental setup.

Consider a single photon in beam a entering the Zou–Wang–Mandel apparatus. After the beam splitter A, this particle's wavefunction illuminates *both* of the down-conversion crystals X_1 and X_2. But because there is only one photon, it can down-convert at only one of the two crystals, creating the entangled state $(1/\sqrt{2})(|d\rangle_1 |e\rangle_2 + |h\rangle_1 |k\rangle_2)$. If one recombines the beams h and d at beam splitter C, will they interfere? Normally they will not, because one could catch the companion photon (in beam e or k) and thus know in which crystal the down-conversion occurred. But Zou and company, following a suggestion of their colleague Zhe Yu Ou, cleverly overlapped the beams e and k (the crystals being transparent) to erase that potential information. Thus the state $|e\rangle$ evolves into the state $|k\rangle$, and the entangled state now becomes $(1/\sqrt{2})(|d\rangle + |h\rangle)_1 |k\rangle_2$, which is no longer entangled. Consequently one can get ordinary single-particle interference fringes at detector D_1 by varying the phase φ at the phase shifter P.

It is important to note several things here. First, as opposed to the two-particle fringes discussed earlier, in this experiment the second photon does not actually need to be detected. The fringes at the detector looking at photon 1 are there in any case because the detection of photon 2 in beam k cannot provide information about where photon 1 was created. Second, if beam e is blocked, the fringes at detector D_1 will *disappear*, because in that case the detection of a photon in beam k would tell you that it was created in crystal X_2. Zou and his collaborators demonstrated this by inserting a beam splitter at B and showing that the visibility of the fringes in D_1 varied with the transmission coefficient of the splitter.

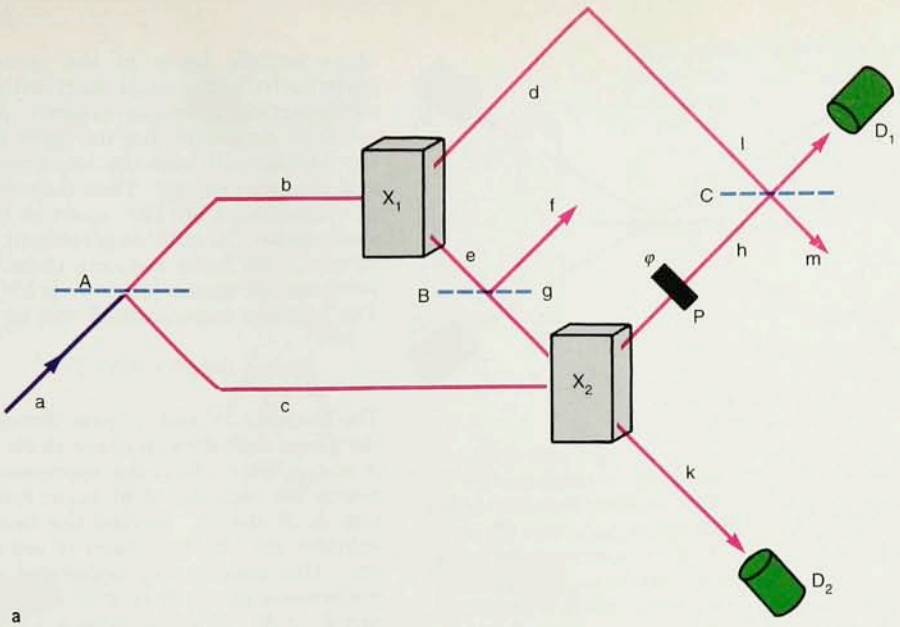
The mind-boggling feature of this experiment is that the beams e and k are not even in the two alternative coherence paths that run from A to D_1! The only role they play in the experiment is that, by overlapping, they prevent us from determining in which crystal the down-conversion occurs.

One might be tempted to think that beam e contributes to the amplitude leading to beam h through some nonlinear coupling. That would make the effect seem less amazing. Be that as it may, note that if we placed an additional phase shifter γ into beam e, the state created in crystal X_1 would become $e^{i\gamma}|d\rangle_1 |e\rangle_2$. The consequent phase shift in beam d would produce a modulation of the form $\cos(\varphi - \gamma)$ at detector D_1. So it is a mistake to think that beam e is contributing to beam h in any direct way, in which case one might have expected $\cos(\varphi + \gamma)$.

This experiment is a prime example of how one could certainly interpret the same result in terms of some nonlinear Hamiltonian mechanism that couples the two-photon state to the vacuum. But one is then in danger of missing the point that *any* such mechanism will produce the effect, if and only if the beams are experimentally indistinguishable.

The experiment also reinforces the point that it is potential information, not actual information, that destroys coherence. Furthermore we have to generalize Dirac's famous dictum that a photon can only interfere with itself. In this experiment the original photon in beam a is not even present to interfere at D_1. Its down-converted progeny are doing the interfering. We prefer to think of the down-converted pair as a single entity, a "two-photon." It is this two-photon, created at either X_1 or X_2, that is interfering with itself. More generally, it is the time-evolved continuation of the photon state that is interfering with itself. (See the box at left.)

Figure 4b is a photograph of an interesting variant of this exeriment very recently carried out by Thomas Herzog and coworkers in Zeilinger's Innsbruck laboratory.[16] They use only one crystal, but the continuation of the original beam and its down-converted progeny are reflected back through the crystal so that one can't tell whether the down-converted pair was created during the the first pass of the incident photon or on its return. Therefore these two possibilities interfere and one can, in



Manipulating one photon can alter the interference pattern of another. The arrangement[16] sketched in **a** can produce an interference pattern at detector D_1 when the phase shifter P is varied. An entering ultraviolet photon a is split at beam splitter A so that both down-conversion crystals (X_1 and X_2) are illuminated. One of the resulting pair of down-conversion photons can reach D_1 by way of beam path d or h. If one could monitor beams e and k separately, one would know in which crystal the down-conversion occurred, and there would be no interference. But merging beams e and k in this configuration lets the alternative paths of the other photon interfere. A new variant of this scheme, shown in **b**, uses only one crystal (at the center). The ambiguity here is created by reflecting the originating beam (blue, from the top of the photo) and its down-converted progeny (red and green) back through the crystal from mirrors (at the bottom of the photo), so one can't know on which pass the down-conversion occurred. **Figure 4**

effect, enhance or suppress the atomic emission process in the crystal by small movements of mirrors that are several feet away!

The quantum eraser

Figure 5 shows an experimental arrangement first used by Alley and Shih,[6] and recently exploited by Paul Kwiat and coworkers at Berkeley[17] to demonstrate Marlan Scully's notion of a "quantum eraser." Others have called it "haunted" or "phantom" measurement.[18] To appreciate the basic idea, first suppose that only the beam splitter is in the path of the two beams emerging from the down-converter crystal. This arrangement produces an interesting and very basic two-particle effect: Both particles must end up in the same detector.[19]

The reason is simple. To get coincident counts at the two detectors, either particle 1 (the photon that ultimately lands in detector 1) takes route a and particle 2 takes route b, or vice versa. In the former alternative, both photons are reflected by the beam splitter, each reflection contributing a 90° phase shift to the overall amplitude. The latter alternative, by contrast, involves *no* phase-shifting reflections. Thus the two alternative amplitudes are 180° out of phase with each other, and they cancel.

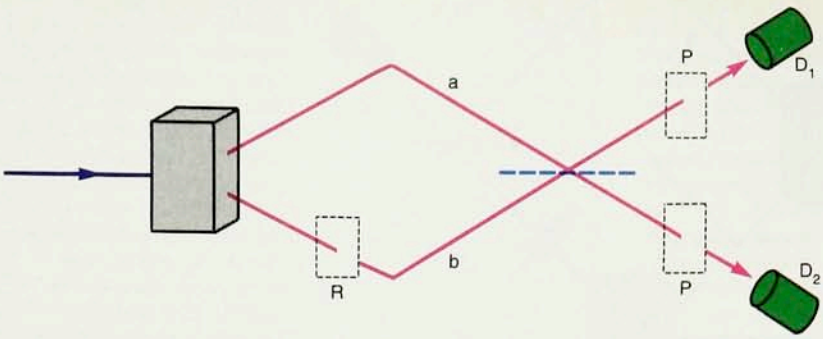
So if both beams are, for example, horizontally polarized, they will remain so, and there will be no coincident counts in detectors 1 and 2. But if we now insert a 90° polarization rotator into beam b, it will become vertically polarized and the two amplitudes will no longer interfere because one can tell which path a photon took to its detector by measuring its polarization. Thus there will now be no superposition of the two amplitudes, and therefore coincidence counts between the two detectors will be observed.

But it is still possible to "erase" this path information and recover the interference by placing a linear polarizer in each beam, as shown in the figure. If both polarizers are either horizontal or vertical there will be path information present. But if they are oriented at 45° to the horizontal, either route, a or b, can now lead to either detector. The coherence is restored and there are, once again, no coincident counts.

The idea here is that one can seem to destroy information about a system without actually doing so. The information remains subliminally present; it can be recaptured. Or, as Chiao has put it, "Nothing has really been erased here, only scrambled!" Helmut Rauch's Vienna group performed a conceptually identical experiment in 1982 with a neutron interferometer, but that involved only single-particle interference.[17]

Generalization to many states

Experiments with entangled particles have generally been confined to two-state systems, either spin-½ particles or photons. One way to generate superpositions



Polarizers can serve as quantum erasers.[17] A single ultraviolet photon entering a down-conversion crystal (gray) produces two optical photons that mix at a beam splitter (dashed blue line) before arriving at detectors D_1 and D_2. If there are no polarizers (P) or polarization rotator (R) in the beams, both photons must end up in the same detector. Inserting a 90° rotator into beam b provides information that renders the beams incoherent and thus produces coincidence counts in the two detectors. Inserting the polarizers oriented 45° to the horizontal after the beam splitter erases that information and recovers the coherence that prevents coincidence counts. **Figure 5**

involving more than two states is to use systems of higher spin. An easier alternative is to generalize the beam splitter to provide more than two paths for each photon. We call such systems "multiports."[20] The half-silvered mirror that serves as a beam splitter is a four-port; it has two input ports and two output ports. The output beams in such devices are mathematically related to the input beams by a unitary transformation.

A simple generalization of the beam splitter, shown in figure 6, is the six-port, with three input beams and three output beams. We call it a "tritter." (An eight-port would be called a "quitter.") If the beam splitters A, B and C in the figure are chosen to have reflectivities $1/\sqrt{2}$, $1/\sqrt{3}$, $1/\sqrt{2}$, respectively, and the phase shifters α, β and γ are chosen appropriately, this device will yield three equally intense output beams if any one of the three input ports is illuminated. That's a straightforward generalization of the symmetric beam splitter. But by varying all these parameters one can induce a range of unitary transformations. Multiports provide a practical method for investigating such transformations in an N-dimensional Hilbert space.

Three-particle interferometry

Figure 7 shows an idealized three-particle interferometer.[21] No such device has been been built, but a number of models have been proposed.[22] This particular configuration was inspired by David Mermin's Reference Frame column in PHYSICS TODAY, June 1990, page 9. Imagine a three-particle decay at the center. (Alternatively one could start with a three-particle down-conversion.) Assume for simplicity that the three decay particles all have the same mass and the same energy. Then they will, of course, come off 120° apart in the decay plane. A suitable placement of screens with holes restricts them to two possible states: $|abc\rangle$ or $|a'b'c'\rangle$. The coherent superposition will be

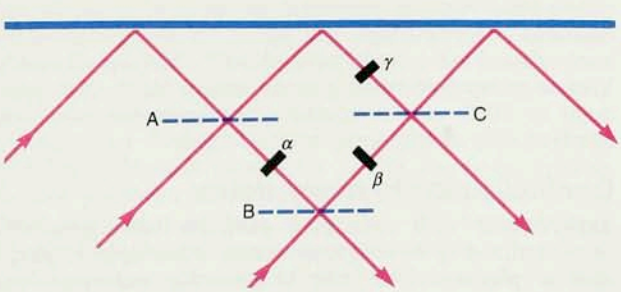
$$\psi = \frac{1}{\sqrt{2}}(|abc\rangle + |a'b'c'\rangle)$$

The beams a', b' and c' pass through the phase shifters with phase shifts α, β and γ, after which the appropriate beams are recombined at beam splitters A, B and C. Beyond the beam splitters are the three pairs of counters. One records only triplets of simultaneous counts at G or G', H or H' and K or K'. If one assigns a +1 (or −1) to a count in an unprimed (or primed) counter, then the probability that a triplet of counts will give the product +1 (for example, GHK or $GH'K'$) will be $(1+\sin\Delta)/2$, where $\Delta = \alpha + \beta + \gamma$. The probability for a product −1 (for example, $G'H'K'$ or $G'HK$) will be $(1-\sin\Delta)/2$. Then the expectation value over a large number of counts is simply $\sin\Delta$.

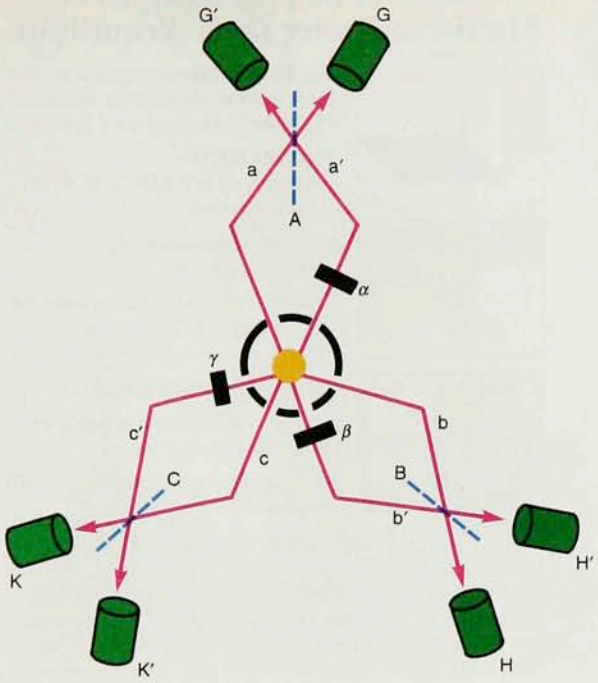
This result is remarkably similar to the case of the two-particle interferometer, but the implications are entirely different. In the three-particle case a perfect correlation occurs when $\Delta = \pi/2$ or $3\pi/2$. Then if one knows at which counter two of the particles have landed, one can predict with certainty the counter at which the third particle will land, without having disturbed it at all. Hence there exists what Einstein, Podolsky and Rosen called an "element of reality" associated with the path from the beam splitter to the counter. Elements of reality are those entities to which, from the Einstein–Podolsky–Rosen point of view, the concept of an objective reality most clearly applies. They are natural entities for discussions of local, realistic descriptions of quantum events.

In the two-particle interferometer, measurements involving only perfect correlations are uninteresting, in the sense that they cannot violate Bell's inequality. (This famous inequality is a statement of the limits of correlation allowable between separated events in any theory that preserves local reality.) But from the Einstein–Podolsky–Rosen viewpoint these perfect correlations are essential for the introduction of elements of reality.

In the three-particle interferometer, however, if one assumes the existence of these elements of reality, one already runs into a contradiction even if the correlations are perfect.[21] If the particles are perfectly correlated in the two-particle case, their spin directions are precisely opposite. But perfect correlation in the three-particle case yields a continuum of possibilities, a condition that is impossible to satisfy within the classical restrictions.



A six-port, or 'tritter,' is made with three beam splitters. If the reflectivities of the beam splitters A, B and C and the phase angles α, β and γ of the phase shifters (black) are properly chosen, this configuration yields three output beams of equal intensity when any one of the three input ports is illuminated. **Figure 6**



Three-particle interferometer. A particle at the center decays into three daughters of equal mass and momentum. Collimation restricts the decay state to beams *a*, *b* and *c* or *a′*, *b′* and *c′*. The primed beams pass through phase shifters (black rectangles) with phase shifts α, β and γ, respectively, after which the alternative paths are mixed at beam splitters *A*, *B* and *C* before arriving at three pairs of detectors (green). **Figure 7**

Therefore one can disprove the existence of elements of reality by observing just one event. (Of course one can never attain perfect correlations, so the situation will be more complicated in any realistic experiment.) Clearly correlations among three particles are even richer than two-particle correlations.

Another interesting feature of the three-particle interferometer is that *only* three-particle correlations show up. When one looks at only one particle or at coincidence counts between two particles, one gets random results. One has to look at all three particles to see any correlations.

We have tried to point out here that the superposition principle, the source of much of the strangeness in one-particle quantum theory, has proved to contain even more mysteries when several particles are involved. In addition to the new experimental techniques we have discussed, other new directions are being explored. One of these goes by the name of quantum cryptography. That's rather a poor name, because this new field has very general implications for quantum theory. (Reference 23 gives a sampling of recent papers; see also PHYSICS TODAY, November 1992, page 21.) For example, the paper by Charles Bennett and collaborators points out that quantum cryptographic techniques can be used to "teleport" a quantum state from one observer to another. This futuristic scheme does not violate relativity, because the receiver cannot decipher the quantum state without additional information that comes through conventional channels.

The superposition principle is at the very heart of quantum theory. It seems funny, therefore, to say that this central idea is just beginning to be explored in depth. Our guess is that many more surprises await us in multiparticle interferometry.

References

1. R. P. Feynman, R. B. Leighton, M. Sands, *The Feynman Lectures on Physics*, Addison–Wesley, Reading, Mass. (1963).
2. A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. **47**, 777 (1935); reprinted in J. A. Wheeler, W. H. Zurek, *Quantum Measurement Theory*, Princeton U. P., Princeton (1983).
3. D. Bohm, *Quantum Theory*, Prentice–Hall, New York (1951).
4. D. C. Burnham, D. L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).
5. M. A. Horne, A. Zeilinger, in *Proc. Symp. on Foundations of Modern Physics*, P. Lahti, P. Mittelstaedt, eds., World Scientific, Singapore (1985), p. 435. M. A. Horne, A. Shimony, A. Zeilinger, Phys. Rev. Lett. **62**, 2209 (1989).
6. C. O. Alley, Y. H. Shih, *Proc. 2nd Int. Symp. on Foundations of Quantum Mechanics in the Light of New Technology*, M. Namiki *et al.*, eds., Phys. Soc. Jpn., Tokyo (1986), p. 47. Y. H. Shih, C. O. Alley, Phys. Rev. Lett. **61**, 2921 (1988).
7. R. Ghosh, L. Mandel, Phys. Rev. Lett. **59**, 1903 (1987).
8. P. Storey, M. Collett, D. Walls, Phys. Rev. Lett. **68**, 472 (1992).
9. J. S. Bell, Physics **1**, 195 (1964). All of Bell's basic writings on the subject are reprinted in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, Cambridge U. P., New York (1987).
10. J. Clauser, S. Freedman, Phys. Rev. Lett. **28**, 938 (1972). A. Aspect, J. Dalibard, G. Roger, Phys. Rev. Lett. **47**, 1804 (1982). For an analysis, see F. Selleri, *Quantum Paradoxes and Physical Reality*, Kluwer Academic, Dordrecht, The Netherlands (1990).
11. J. G. Rarity, P. R. Tapster, Phys. Rev. Lett. **64**, 2495 (1990).
12. L. Mandel, Phys. Rev. A **28**, 929 (1983).
13. J. D. Franson, Phys. Rev. Lett. **62**, 2205 (1989).
14. Z. Y. Ou, L. J. Wang, L. Mandel, Phys. Rev. Lett. **65**, 321 (1990). P. G. Kwiat, W. A. Vareka, C. K. Hong, H. Nathel, R. Y. Chiao, Phys. Rev. A **41**, 2910 (1990).
15. P. G. Kwiat, A. M. Steinberg, R. Y. Chiao, Phys. Rev. A **47**, 2472 (1993).
16. X. Y. Zou, L. J. Wang, L. Mandel, Phys. Rev. Lett. **67**, 318 (1991). L. J. Wang, X. Y. Zou, L. Mandel, Phys. Rev. A **44**, 4614 (1991). T. Herzog, J. Rarity, H. Wienfurter, A. Zeilinger, in Proc. Workshop on Quantum Optics, Ulm, April 1993 (to be published).
17. P. G. Kwiat, A. M. Steinberg, R. Y. Chiao, Phys. Rev. A **45**, 7729 (1992). J. Summhammer, G. Badurek, H. Rauch, U. Kischico, Phys. Lett. A **90**, 110 (1982).
18. M. O. Scully, R. Shea, J. D. McCullen, Phys. Rep. **43**, 485 (1978). M. O. Scully, B.-G. Englert, H. Walther, Nature **351**, 111 (1991). D. M. Greenberger, A. YaSin, Found. Phys. **19**, 679 (1989).
19. C. K. Hong, Z. Y. Ou, L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).
20. A. Zeilinger, H. J. Bernstein, D. M. Greenberger, M. A. Horne, M. Zukowski, in *Proc. 4th Int. Symp. on Foundations of Quantum Mechanics in the Light of New Technology*, H. Ezawa *et al.*, eds., World Scientific, Singapore (1993).
21. D. M. Greenberger, M. A. Horne, A. Zeilinger, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, M. Katafos, ed., Kluwer Academic, Dordrecht, The Netherlands (1989), p. 173. D. M. Greenberger, M. A. Horne, A. Shimony, A. Zeilinger, Am. J. Phys. **58**, 1131 (1990). N. D. Mermin, Am. J. Phys. **58**, 731 (1990).
22. D. M. Greenberger, H. J. Bernstein, M. A. Horne, A. Zeilinger, in *Proc. 4th Int. Symp. on Foundations of Quantum Mechanics in the Light of New Technology*, H. Ezawa *et al.*, eds., World Scientific, Singapore (1993). B. Yurke, D. Stoler, Phys. Rev. Lett. **68**, 1251 (1992). L. Wang, K. Wodkiewicz, J. H. Eberly, in *Tech. Digest Annu. Mtg. of the OSA*, Albuquerque, September 1992, abstr. MUU4.
23. A. K. Ekert, J. G. Rarity, P. R. Tapster, G. M. Palme, Phys. Rev. Lett. **69**, 1293 (1992). C. H. Bennett, G. Brassard, N. D. Mermin, Phys. Rev. Lett. **68**, 557 (1992). C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, W. Wooters, Phys. Rev. Lett. **70**, 1895 (1993).
24. R. J. Glauber, Phys. Rev. **130**, 2529 (1963); **131**, 2766 (1963). E. C. G. Sudarshan, T. Rothman, Am. J. Phys. **59**, 592 (1991). D. Walls, Am. J. Phys. **45**, 952 (1977). ■