Heisenberg’s Introduction of the ‘Collapse of the Wavepacket’ into Quantum Mechanics

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January 23, 2002

Abstract

Heisenberg in 1929 introduced the “collapse of the wavepacket” into quantum theory. We review here an experiment at Berkeley which demonstrated several aspects of this idea. In this experiment, a pair of daughter photons was produced in an entangled state, in which the sum of their two energies was equal to the sharp energy of their parent photon, in the nonlinear optical process of spontaneous parametric down-conversion. The wavepacket of one daughter photon collapsed upon a measurement-at-a-distance of the other daughter’s energy, in such a way that the total energy of the two-photon system was conserved. Heisenberg’s energy-time uncertainty principle was also demonstrated to hold in this experiment.

1 Introduction

In this Symposium in honor of Heisenberg’s Centennial, it is appropriate to begin by recalling the fact that in the spring of 1929, during his lectures at the University of Chicago, Heisenberg introduced the important concept of the “collapse of the wavepacket” into quantum theory [1]. This idea, which he referred to as the “reduction of the wavepacket,” was closely related to the idea of the “collapse of the wavefunction,” which was introduced into the standard Copenhagen interpretation of quantum mechanics in connection with the probabilistic interpretation of the wavefunction due to Born [2]. In the context of a remark concerning the spreading of the wavepacket of an electron, Heisenberg stated the following [1]:

In relation to these considerations, one other idealized experiment (due to Einstein) may be considered. We imagine a photon which is
represented by a wave packet built up out of Maxwell waves [3]. It will thus have a certain spatial extension and also a certain range of frequency. By reflection at a semi-transparent mirror, it is possible to decompose it into two parts, a reflected and a transmitted packet. There is then a definite probability for finding the photon either in one part or in the other part of the divided wave packet. After a sufficient time the two parts will be separated by any distance desired; now if an experiment yields the result that the photon is, say, in the reflected part of the packet, then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment at the position of the reflected packet thus exerts a kind of action (reduction of the wave packet) at the distant point occupied by the transmitted packet, and one sees that this action is propagated with a velocity greater than that of light. However, it is also obvious that this kind of action can never be utilized for the transmission of signals so that it is not in conflict with the postulates of the theory of relativity.

At the heart of Heisenberg’s (and, earlier, Einstein’s) conception of the “collapse of the wavepacket,” was the indivisibility of the individual quantum, here of the light quantum – the photon – at the beam splitter [4]. Ultimately, it was the indivisibility of the photon that enforced the collapse of the wavepacket, whenever a detection of the particle occurred at one of the two exit ports of the beam splitter (for example, whenever a “click” occurred at a counter placed at the reflection port); because the photon was indivisible, it had either to be reflected, or to be transmitted at the beam splitter, but not both. Remarkably, a non-detection by a 100%-efficient detector will also collapse the state, so that the photon is definitely in the other arm [5].

Heisenberg believed that the reduction or collapse of the wavepacket was indeed a physical action, and not just a convenient fiction which was useful in the interpretation of quantum phenomena but which had no physical reality attached to it. It is an irony of history that although Heisenberg attributed this idea to Einstein, it was later totally rejected by Einstein along with all of its consequences, as unexplained, “spooky actions-at-a-distance (spukhafte Fernwirkungen).” The “collapse” idea, and its later developments, culminated in Einstein’s ultimate rejection of quantum theory as being an incomplete theory of the physical world.

In contrast, von Neumann embraced the idea, and further sharpened it by introducing the notion of “projection of rays in Hilbert space” upon measurement, in the last two chapters entitled ‘Measurement and Reversibility’ and ‘The Measuring Process’ of his book Mathematical Foundations of Quantum Mechanics [6]. The physics of the “collapse postulate” introduced by Heisenberg was thereby tied to the mathematics of the “von Neumann projection postulate.” In this way, the Copenhagen interpretation of quantum mechanics, or at least one version of it, was completed.
Figure 1: Color photograph (an end-on view) of the spontaneous parametric down-conversion from an ultraviolet ($\lambda = 351$ nm) laser beam which has traversed a KDP crystal. (Some of the UV laser light, which has leaked through an UV rejection filter, caused the irregular splotches near the center). By means of Pinhole 1 and Pinhole 2, correlated pairs of photons emitted near the same red wavelength ($\lambda = 702$ nm) were selected out for coincidence detection. This picture illustrates yet another striking aspect of the “collapse” idea, which is different from the one discussed in the text. Although the angular distribution of the probability amplitude for the emission of the photon pair starts off as an azimuthally isotropic ring around the center, once a “click” is registered by a detector placed behind one of the pinholes, there is the sudden onset of a type of “spontaneous symmetry breaking,” in which the probability for detection of the other photon suddenly vanishes everywhere around the ring, except at the other pinhole, where the probability of finding it suddenly becomes unity. (Adapted from A. Migdall and A. V. Sergienko’s original photo).
Here we shall review an experiment performed at Berkeley on another aspect of the “collapse of the wavepacket,” as viewed from the standard Copenhagen viewpoint. This experiment involved a study of the correlated behaviors of two photon wavepackets in an entangled state of energy. The two entangled photon wavepackets were produced in the process of spontaneous parametric down-conversion, in which a parent photon from an ultraviolet (UV) laser beam was split inside a nonlinear crystal into two daughter photons, conserving energy and momentum during this process. One can view this quantum nonlinear optical process as being entirely analogous to a radioactive decay process in nuclear physics, in which a parent nucleus decays into two daughter nuclei. We shall see that a measurement of the energy of one daughter photon has an instantaneous collapse-like action-at-distance upon the behavior of the other daughter photon.

2 The entangled photon-pair light source: Spontaneous parametric down-conversion

We produced pairs of energy-entangled photon wave packets by means of spontaneous parametric down-conversion, also known as “parametric fluorescence,” in an optical crystal with a nonvanishing $\chi^{(2)}$ nonlinear optical susceptibility [7]. In our experiment, we employed a crystal of potassium dihydrogen phosphate (KDP) [8]. The lack of inversion symmetry in crystals such as KDP breaks the usual parity-conservation selection rule, so that it is not forbidden for one photon to decay into two photons inside the crystal.

There are many ways in which a single, monoenergetic, parent photon (conventionally called the “pump” photon, originating in our experiment from an argon ion UV laser operating at $\lambda = 351$ nm) can decay into two daughter photons (conventionally called the “signal” and the “idler” photons), while distributing its energy between the two in a continuous fashion. There is therefore no reason why the daughter photons would necessarily be monoenergetic. In fact, as a result of the normal dispersion in the linear refractive index of the crystal, it turns out that the conservation of energy and momentum in the two-photon decay process results in the production of a rainbow of conical emissions of photon pairs with a wide spectrum of colors, which is shown in Figure 1. Two photons on diametrically opposite sides of the rainbow are emitted in a pairwise fashion, conserving energy and momentum in the emission process.

By means of two pinholes, we selected out of the rainbow for further study two tightly correlated, entangled photons, which were emitted around the same red wavelength (i.e., $\lambda = 702$ nm, at twice the wavelength of the pump photon). For millimeter-scale pinholes, which span a few percent of the full visible spectrum, the resulting photon wavepackets typically have subpicosecond widths [9]. Thus, two photon counters placed behind these two pinholes would register tightly correlated, coincident “clicks.”

The KDP crystal which we used was 10 cm long, cut such that its c-axis was
50.3° to the normal of its input face; the UV laser beam was normally incident on the KDP crystal face, with a vertical linear polarization. The correlated signal and idler photon beams were both horizontally polarized. The two pinholes were placed at +1.5° and at −1.5° with respect to the UV laser beam, so that degenerate pairs of photons centered at a wavelength of 702 nm were selected for study. Thus, in this parametric fluorescence process, a single parent photon with a sharp spectrum from the UV laser was spontaneously converted inside the crystal into a pair of daughter photons with broad, conjugate spectra centered at half the parent’s UV energy.

The photon pair-production process due to parametric down-conversion produces the following entangled state [10]:

\[ |\psi\rangle = \int dE_1 A(E_1) |1\rangle_{E_1} |1\rangle_{E_2 = E_0 - E_1}, \]  

where \( E_0 \) is the energy of the parent UV photon, \( E_1 \) is the energy of the first member of the photon pair (the “idler” daughter photon), \( E_2 = E_0 - E_1 \) is the energy of the second member of the photon pair (the “signal” daughter photon), and \( A(E_1) \) is the probability amplitude for the emission of the pair. The first (second) photon is in the one-photon Fock state \( |1\rangle_{E_1} \) \((|1\rangle_{E_2}\)\). Energy must be conserved in the pair-emission process, and this is indicated by the energy subscript of the one-photon Fock state for the second photon \( |1\rangle_{E_2 = E_0 - E_1} \). The integral over the product states \( |1\rangle_{E_1} |1\rangle_{E_2 = E_0 - E_1} \) indicates that the total state \( |\psi\rangle \) is the superposition of product states. Hence, this state exhibits mathematical nonfactorizability, the meaning of which is physical nonseparability: It is an entangled state of energy. Therefore, the results of measurements of the energy of the first photon will be tightly correlated with the outcome of measurements of the energy of the second photon, even when the two photons are arbitrarily far away from each other. There result Einstein-Podolsky-Rosen effects, which are nonclassical and nonlocal [11],[12].

3 Apparatus for the detection of entangled photon pairs: Michelson interferometry, spectral filtering, and coincidence counting

In Figure 2, we show a schematic of the apparatus. Entangled photons, labeled “signal” and “idler,” were produced in the KDP crystal. The upper beam of idler photons was transmitted through the “remote” filter F1 to the detector D1, which was a cooled RCA C31034A-02 photomultiplier tube. Horizontally polarized signal photons in the lower beam entered a Michelson interferometer, inside one arm of which was placed a pair of zero-order quarter-wave plates Q1 and Q2. The fast axis of Q1 was fixed at 45° to the horizontal, while the fast axis of Q2 was slowly rotated by a computer-controlled stepping motor, in order to scan for fringes. After leaving the Michelson, the signal photon impinged on a second beamsplitter B2, where it was transmitted to detector D2 through
Figure 2: Schematic of apparatus to demonstrate another aspect of Heisenberg’s “collapse of the wavepacket,” in which a sharp measurement of the energy of one member of an entangled state results in a collapse in the width of the wavepacket of the other member. A photon pair selected by means of pinholes shown in Figure 1 (not shown here), is emitted from the KDP crystal in parametric down-conversion of a parent photon from the UV laser. One member of the pair (the “idler”) is sent through the “remote” interference filter F1 before detection by a photomultiplier D1. The other member of the pair (the “signal”) is sent through a Michelson interferometer, whose optical path length difference is scanned by means of two quarter-wave plates Q1 and Q2. The beam splitter B2, filters F2 and F3, photomultipliers D2 and D3, coincidence gates $N_{12}$ and $N_{13}$, all serve to select out only those photons which are members of entangled pairs, for observation. The triple coincidence gate $N_{123}$ serves to check that only single-photon Fock states are detected, so that no classical explanation of the results would be possible. (From Reference [8].)
filter F2, or reflected to detector D3 through filter F3. Filters F2 and F3 were identical: They both had a broad bandwidth of 10 nm centered at $\lambda = 702$ nm. Detectors D2 and D3 were identical to D1.

Coincidences between detectors D1 and D2 and between D1 and D3 were detected by feeding their outputs into constant fraction discriminators and coincidence detectors after appropriate delay lines. We used EGG C102B coincidence detectors with coincidence window resolutions of 1.0 ns and 2.5 ns, respectively. Also, triple coincidences between D1, D2, and D3 were detected by feeding the outputs of the two coincidence counters into a third coincidence detector (a Tektronix 11302 oscilloscope used in a counter mode). The various count rates were stored on computer every second.

The two quarter-wave plates Q1 and Q2 inside the Michelson generated a geometrical (Pancharatnam-Berry) phase, which was proportional to the angle between the fast axes of the two plates. Here, one should view the use of the quarter-wave plates as simply a convenient method for scanning the phase difference of the Michelson interferometer. For the details concerning the geometrical phase, see [8] and [11].

We took data both inside and outside the white-light fringe region of the Michelson (i.e., where the two arms have nearly equal optical path lengths), where the usual interference in singles detection occurs. We report here only on data taken outside this region, where the optical path length difference was set at a fixed value much greater than the coherence length (or wavepacket width) of the signal photons determined by the filters F2 and F3. Hence, the fringe visibility seen by detectors D2 and D3 in singles detection was essentially zero.

4 Theory

We present here a simplified analysis of this experiment. For a detailed treatment based on Glauber’s correlation functions, see [11]. The entangled state of light after passage of the signal photon through the Michelson is given by

$$|\psi\rangle_{\text{out}} = \frac{1}{2} \int dE_1 A(E_1) |1\rangle_{E_1} |1\rangle_{E_2=E_0-E_1} \left(1 + \exp(i\phi(E_0 - E_1))\right), \quad (2)$$

where $\phi(E_0 - E_1)$ is the total phase shift of the signal photon inside the Michelson, including the Pancharatnam-Berry phase; the factor of $1/2 = (1/\sqrt{2})^2$ comes from the two interactions with the Michelson 50/50 beam splitter B1. The coincidence count rates $N_{12}$ between the pair of detectors D1 and D2 (and $N_{13}$ between the pair D1 and D3) are proportional to the probabilities of finding at the same instant $t$ (more precisely, within the detection time, typically 1 ns) one photon at detector D1 and also one photon at detector D2 (and for $N_{13}$, one photon at detector D1 and also one photon at detector D3). When a narrowband filter F1 centered at energy $E_{10}$ is placed in front of the detector
D1, $N_{12}$ becomes proportional to

$$|\psi'_{\text{out}}(r_1, r_2, t)|^2 = |\langle r_1, r_2, t | \psi'_{\text{out}} \rangle|^2 \propto 1 + \cos \phi,$$

(3)

where $r_1$ is the position of detector D1, $r_2$ is the position of detector D2, and the prime denotes the output state after a von-Neumann projection onto the eigenstate associated with the sharp energy $E_{i_0}$ upon measurement. Therefore, the phase $\phi$ is determined at the sharp energy $E_0 - E_{i_0}$. In order to conserve total energy, the energy bandwidth of the collapsed signal photon wavepacket must depend on the bandwidth of the filter $F_1$ in front of D1, through which it did not pass. Therefore, the visibility of the signal photon fringes seen in coincidences should depend critically on the bandwidth of this remote filter. For a narrowband $F_1$, this fringe visibility should be high, provided that the optical path length difference of the Michelson does not exceed the coherence length of the collapsed wavepacket (recall that due to the energy-time uncertainty principle, collapsing to a narrower energy spread actually leads to longer wavepacket). It should be emphasized that the width of the collapsed signal photon wavepacket is therefore determined by the remote filter $F_1$, through which this signal photon has apparently never passed! If, however, a sufficiently broadband remote filter $F_1$ is used instead, such that the optical path length difference of the Michelson is much greater than the coherence length of the collapsed wavepacket, then the coincidence fringes should disappear.

## 5 Results

In Figure 3, we show data which confirm these predictions. In the lower trace (squares) we display the coincidence count rate between detectors D1 and D3, as a function of the angle $\theta$ between the fast axes of the wave plates $Q_1$ and $Q_2$, when the remote filter $F_1$ was quite narrowband (i.e., with a bandwidth of 0.86 nm). The calculated coherence length of the collapsed signal photon wavepacket (570 microns) was greater than the optical path length difference at which the Michelson was set (220 microns). The observed visibility of the coincidence fringes was quite high, viz., $60\% \pm 5\%$, indicating that the collapse of the signal photon wavepacket had indeed occurred.

In the upper trace (triangles) we display the coincidence count rate versus $\theta$ when a broadband remote filter $F_1$ (i.e., one with a bandwidth of 10 nm) was substituted for the narrowband one. The coherence length of the collapsed signal photon wavepacket in this case should have been only 50 microns, which is shorter than the 220 micron optical path length difference at which the Michelson was set. The observed coincidence fringes have now indeed disappeared, indicating that the collapse of the signal photon wavepacket (this time to a shorter temporal width) has again occurred.

In addition to the above coincidences-counting data, we also took singles-counting data at detector D3 (where are not shown here), at the same settings of the optical path length of the Michelson for the traces shown in Figure 3. We observed no visible fringes in the singles-counting data during the scan of
Figure 3: Data demonstrating the phenomenon of the “collapse of the wavepacket.” The visibility of the fringes from the Michelson interferometer seen in coincidence detection for the signal photon (see Figure 2), depends on the bandwidth of the remote filter F1, through which it has apparently never passed. In the lower trace, F1 is narrowband, which results in the collapsed signal photon wavepacket having a long coherence length, and thus in the observed high-visibility fringes. However, when the remote, narrowband filter F1 is replaced by a broadband one, the collapsed signal photon wavepacket now has a short coherence length (shorter than the optical path length difference of the Michelson), so that the fringes disappear, as is evident in the upper trace. (Data from Reference [8]).
θ, with a visibility less than 2%. This indicates that we were well outside of the white-light fringe of the Michelson. More importantly, this also demonstrates that only those photons which are detected in coincidence with their twins which have passed through the narrowband filter F1, exhibit the observed phenomenon of the collapse of the wavepacket upon detection. In other words, only entangled pairs of photons detected by the coincidences-counting method show this kind of “collapse” behavior.

Heisenberg’s energy-time uncertainty principle was also demonstrated during the course of this experiment [13]. The width $\Delta t_2$ of the collapsed signal photon wavepacket, which was measured by means of the Michelson, satisfied the inequality

$$\Delta E_2 \Delta t_2 \geq \hbar/2,$$  

where the energy width $\Delta E_2$ of the collapsed signal photon wavepacket, was determined by the measured energy width $\Delta E_1$ of the idler photon, in order to conserve total energy. Hence, the energy width $\Delta E_2$ of the signal photon, which enters into the Heisenberg uncertainty relation (4), was actually the width $\Delta E_1$ of the remote filter F1, through which this signal photon did not pass.

6 Discussion

Any classical electromagnetic field explanation of these results can be ruled out. We followed here the earlier experiment of Grangier, Roger, and Aspect [14], in which they showed that one can rule out any classical-wave explanation of the action of an optical beam splitter, by means of triple coincidence measurements in a setup similar to that shown in Figure 2. Let us define the parameter

$$a = \frac{N_{123}N_1}{N_{12}N_{13}},$$

where $N_{123}$ is the count rate of triple coincidences between detectors D1, D2, and D3, $N_{12}$ is the count rate of double coincidences between detectors D1 and D2, $N_{13}$ is the count rate of double coincidences between detectors D1 and D3, and $N_1$ is the count rate of singles detection by D1 alone. From Schwartz’s inequality, it can be shown that for any classical-wave theory for electromagnetic wavepackets, the inequality $a \geq 1$ must hold [14]. By contrast, quantum theory predicts that $a = 0$.

The physical meaning of the inequality $a \geq 1$ is that any classical wavepacket divides itself smoothly at a beam splitter, and this always results in triple coincidences after the beam splitter B2, in conjunction with a semi-classical theory of the photoelectric effect. By contrast, a single photon is indivisible, so that it cannot divide itself at the beamsplitter B2, but rather must exit through only one or the other of the two exit ports of the beam splitter, and this results in zero triple coincidences (except for a small background arising from multiple pair events).
For coincidence-detection efficiencies $\eta$ less than unity, this inequality becomes $a \geq \eta$. We calibrated our triple-coincidence counting system by replacing the photon-pair light source by an attenuated light bulb, and measured $\eta = 70\% \pm 7\%$. During the data run of Figure 3 (lower trace), we measured values of $a$ shown at the vertical arrows. The average value of $a$ is $0.08 \pm 0.04$, which violates by more than thirteen standard deviations the predictions based on any classical-wave theory of electromagnetism.

It is therefore incorrect to explain these results in terms of a stochastic-ensemble model of classical electromagnetic waves, along with a semi-classical theory of photoelectric detection [15]. Pairs of classical waves with conjugately correlated, but random, frequencies could conceivably yield the observed interference patterns, but they would also yield many more triple coincidences than were observed.

One might be tempted to explain our results simply in terms of conditioning on the detection of the idler photons to post-select signal photons of pre-existing definite energies. And in fact, such a local realistic model can account for the results of this experiment with no need to invoke a nonlocal collapse. However, in light of the observed violations of Bell’s inequalities based on energy-time variables [12], it is incorrect to interpret these results in terms of a statistical ensemble of signal and idler photons which possess definite, but unknown, energies before measurement (i.e., before filtering and detection). Physical observables, such as energy and momentum, cannot be viewed as local, realistic properties which are carried by the photon during its flight to the detectors, before they are actually measured.

We have chosen to interpret our experiment in terms of the “collapse” idea. However, it should be stressed that this is but one interpretation of quantum measurement. Other interpretations exist which could possibly also explain our results. They include the Bohm-trajectory picture [16], the many-worlds interpretation [17], the advanced-wave or transactional model by Cramer [18] (and related ideas by Klyshko [19]), the “non-collapse” quantum-cosmology picture [20], and others.

An obvious follow-up experiment (but one which has not yet been performed) is a version of Wheeler’s “delayed-choice” experiment [21], in which one could increase, as much as one desires, the distance from the source to the filter F1 and the detector D1 on the “remote” side of the apparatus, as compared to the distance to detectors D2 and D3, etc., on the “near” side. The arbitrary choice of whether filter F1 should be broadband or narrowband could then be delayed by the experimenter until well after “clicks” had already been irreversibly registered in detectors D2 or D3. In this way, we can be sure that the signal wavepacket on the near side of the apparatus could not have known, well in advance of the experimenter’s arbitrary and delayed choice of F1 on the remote side of the apparatus, whether to have collapsed to a broad or to a narrow wavepacket.

However, there is no paradox here since the determination of coincident events can only be made after the records of the “clicks” at both near and remote detectors are brought together and compared, and only then does the
appearance or disappearance of interference fringes in coincidences become apparent. The bringing together of these records requires the propagation of signals through classical channels with appropriate delays, such as the post-detection coaxial delay lines leading to the coincidence gates shown in Figure 2. Classical channels propagate signals with discontinuous fronts, such as “clicks,” at a speed limited by $c$. Hence there is no conflict with the postulates of the theory of relativity.

It is therefore incorrect to say that the experimenter’s arbitrary choice of the filter $F_1$ on the remote side of the apparatus somehow caused the collapse of the signal photon wavepacket on the near side. Only nonlocal, instantaneous, uncaused correlations-at-a-distance are predicted by quantum theory. Clearly, the collapse phenomenon is nonlocal and noncausal in nature.

In conclusion, we have demonstrated that the nonlocal collapse of the wavefunction or wavepacket in the Copenhagen interpretation of quantum theory, which was introduced by Heisenberg in 1929, leads to a self-consistent description of our experimental results. Whether or not fringes in coincidence detection show up in a Michelson interferometer on the near side of the apparatus, depends on the arbitrary choice by the experimenter of the remote filter $F_1$ through which the photon on the near side has evidently never passed. This collapse phenomenon, however, is clearly noncausal, as a “delayed-choice” extension of our experiment would show.

7 Acknowledgments

This work was supported in part by the ONR. We thank Charles H. Townes for a careful reading of this manuscript. RYC would like to thank John C. Garrison for helpful discussions, and Aephraim M. Steinberg for pointing out to me once again Reference [1].

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[3] Heisenberg added the following footnote here: “For a single photon the configuration space has only three dimensions; the Schrödinger equation of a photon can thus be regarded as formally identical with the Maxwell equations.”

[4] It is interesting to note here that much earlier, Newton, in connection with his experimental studies of the optical beam splitter (or what Heisenberg called a “semi-transparent mirror”), and in particular, of the phenomenon
of Newton’s rings, struggled with the problem of how to reconcile his concept of an indivisible “corpuscle” (i.e., a particle) of light, with the fact that these corpuscles were coherently divided into transmitted and reflected parts at air-glass interfaces, in such a way that these parts could later interfere with each other, and thus produce Newton’s rings.

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