Chapter 6
Quantum Paradoxes and Applications of the TI

The Copenhagen Interpretation brings with it a certain baggage. In particular, Heisenberg's knowledge interpretation and positivism have led Einstein, Schrödinger, Wigner, Wheeler, and many others to focus on situations in which the conventional Copenhagen interpretational tools seem to fail, to lead to counter-intuitive conclusions, or to paradoxes. In this Chapter we will consider some of these, and we will also show examples applying the Transactional Interpretation to clarify quantum interpretational problems.

In the sections that follow, we will distinguish between *gedankenexperiments* that, for one reason or another have not been performed or cannot be performed, and actual experiments that have been performed and analyzed in the quantum optics laboratories by placing an asterisk (*) at the end of the section headings of the latter. The starred experiments have actually been performed.

6.1 Thomas Young's Two-Slit Experiment (1803)*

Thomas Young (1773–1829) presented the results of his two-slit experiment to the Royal Society of London on November 24, 1803. A century and a half later, Richard Feynman [1] described Young's experiment as "a phenomenon that is impossible …to explain in any classical way, and that has in it the heart of quantum mechanics. In reality, it contains the only (quantum) mystery."

The experimental arrangement of Young's two-slit experiment is shown in Fig. 6.1. Plane waves of light diffract from a small aperture in screen A, pass through two slits in screen B, and produce an interference pattern in their overlap region on screen C. The interference pattern is caused by the arrival of light waves at screen C from the two slits, with a variable relative phase because the relative path lengths of the two waves depends on the location on screen C. When the path lengths are equal

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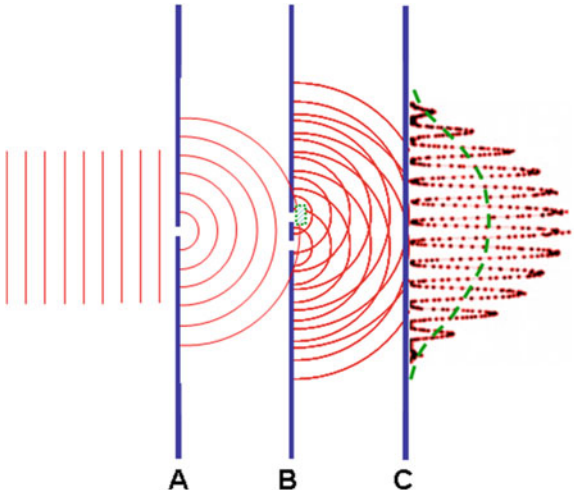

Fig. 6.1 Young's two-slit experiment. Light waves diffract from the aperture in screen *A*, pass through two slits in screen *B*, and produce a "comb" interference pattern in their overlap region on screen *C*. The *green/dashed line* at *C* shows the diffraction pattern that would be observed if the two paths through the slits were made distinguishable, e.g., put in different states of polarization by a half-wave plate, shown behind the upper slit at *B*

or differ by an integer number of light wavelengths λ, the waves add coherently (constructive interference) to produce an intensity maximum. When the path lengths differ by an odd number of half-wavelengths $\lambda/2$, the waves subtract coherently to zero (destructive interference) and produce an intensity minimum.

One can "turn off" this interference pattern by making the two paths through slits *distinguishable*. In this case, the "comb" interference pattern is replaced by a broad diffraction "bump" distribution, as shown by the green/dashed line at *C* in Fig. 6.1. This might be accomplished by arranging for the waves on the two paths to be in different polarization states, thereby "labeling" the wave paths with polarization. For example, one could use a light source that produces vertically polarized light, and one could place behind one slit a small optical half-wave plate, shown in Fig. 6.1 behind the upper slit at *B*, set to rotate vertical to horizontal polarization. This would eliminate the previously observed two-slit interference pattern, because the light waves arriving at screen *C* from the two slits are now in distinguishable polarization states, with the waves from the lower slit vertically polarized and waves from the upper slit horizontally polarized. The *intensities* of the waves will now add instead of their amplitudes, and there can be no destructive cancellation. This interference suppression occurs even if no polarization is actually measured at *C*.

In the 19th century Young's experiment was taken as conclusive proof that light was a wave and that Newton's earlier depiction of light as a particle was incorrect. Einstein's 1905 explanation of the photoelectric effect as caused by the emission of photon particles of light cast doubt on this view. In 1909, a low-intensity double-slit experiment performed by Sir Geoffrey Taylor [2] demonstrated that the same interference pattern is obtained, even when the light intensity is so low that the interference pattern must be accumulated one photon at a time. The emergence of the interference pattern from individual photon events is illustrated in Fig. 6.2, in which we see the build-up of the two-slit interference pattern as single photon events (green points) are accumulated, one at a time. Based on Taylor's experimental results,

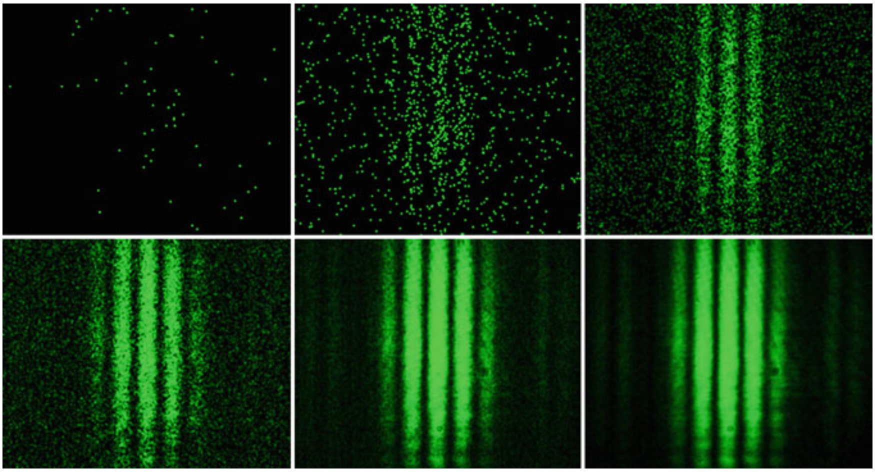

Fig. 6.2 Build-up of a two-slit interference pattern in a Young's two-slit experiment at low illumination intensity as more and more single-photon events (*green points*) are accumulated [4]

in 1926 G.N. Lewis [3] reasoned, in a remarkable precursor to the Transactional Interpretation, that "an atom never emits light except to another atom …I propose to eliminate the idea of mere emission of light and substitute the idea of transmission, or a process of exchange of energy between two definite atoms or molecules."

The emergence of the interference pattern from individual photon events is the "quantum mystery" to which Richard Feynman referred: How is it possible that an ensemble of single photons, arriving at the screen one at a time, can produce such a wave-like interference pattern? It would appear that each individual photon particle must pass through *both* slits and must interfere with itself at the screen.

The Transactional Interpretation explains the puzzling build-up of a wave interference pattern from photon events as follows: in Fig. 6.1 the source emits plane offer waves moving to the right that are diffracted at screen *A*, pass through both slits at screen *B*, and arrive at any point on screen *C* from two directions. At locations along screen *C* where the two components of the offer wave interfere constructively there is a high probability of transaction, and at locations where the two components of the offer wave interfere destructively and cancel there is zero probability of a transaction. Confirmation waves propagate to the left, moving back through the slits at *B* and the aperture at *A* to the light source. There the source, which is seeking to emit one photon, selects among the confirmation offers, and a transaction delivers a photon to screen *C*. The position at which the photon arrives is likely to be where the offer waves were constructive and unlikely to be where the waves were destructive. Therefore, the interference pattern made of many single photon transactions builds up on screen *C* as shown in Fig. 6.2.

The interference suppression from labeling can also be explained by the TI. Screen *C* receives offer waves that have passed through both slits and returns corresponding confirmation waves to the source. However, the vertically polarized offer wave will cause the return of a vertically polarized confirmation, and likewise for the horizontally polarized offer wave. The confirmation wave echo arriving at the source will only match the vertical polarization of the source if it returned through the same slit that the corresponding offer had passed through, so the transaction that forms will pass through only one of the two slits. Therefore, there will be no two-slit interference pattern for this case.

6.2 Einstein's Bubble *Gedankenexperiment* (1927)

Quantum nonlocality is one of the principal counterintuitive aspects of quantum mechanics. Einstein's "spooky action-at-a-distance" is a real feature of quantum mechanics, but the quantum formalism and the orthodox Copenhagen Interpretation provide little assistance in understanding nonlocality or in visualizing what is going on in a nonlocal process. The Transactional Interpretation provides the tools for doing this. Perhaps the first example of a nonlocality paradox is the Einstein's bubble paradox, previously mentioned in Sect. 1.1. It was proposed by Albert Einstein at the 5th Solvay Conference in 1927 [5, 6].

A source emits a single photon isotropically, so that there is no preferred emission direction. According to the Copenhagen view of the quantum formalism, this should produce a spherical wave function ψ that expands like an inflating bubble centered on the source. At some later time, the photon is detected, and, since the photon does not propagate further, its wave function bubble should "pop", disappearing instantaneously from all locations except the position of the detector. Einstein asked how the parts of the wave function away from the detector could "know" that they should disappear, and how it could be arranged that only a single photon was always detected when only one was emitted?

At the 5th Solvay Conference, Werner Heisenberg [6] dismissed Einstein's bubble paradox by asserting that the wave function cannot be depicted as a real object moving through space, as Einstein had implicitly assumed, but instead is a mathematical representation of the knowledge of some observer who is watching the process. Until detection, the observer knows nothing about the location of the emitted photon, so the wave function must be spherical, distributed over the 4π solid angle to represent his ignorance. However, after detection the location of the photon is known to the observer, so the wave function "collapses" and is localized at the detector. One photon is detected because only one photon was emitted.

The Transactional Interpretation provides an alternative explanation, one that permits the wave function to be, in some sense, a real object moving through space. This is illustrated in Fig. 6.3. The offer wave ψ from the source indeed spreads out as a spherical wave front and eventually encounters the detector on the right. The detector responds by returning to the source a confirmation wave ψ^*. Other detectors (i.e., potential absorbers) also return confirmation waves, but the source randomly, weighted by the $\psi\psi^*$ echoes from the potential absorbers, selects the detector on the right to form a transaction. The transaction forms between source and detector, and

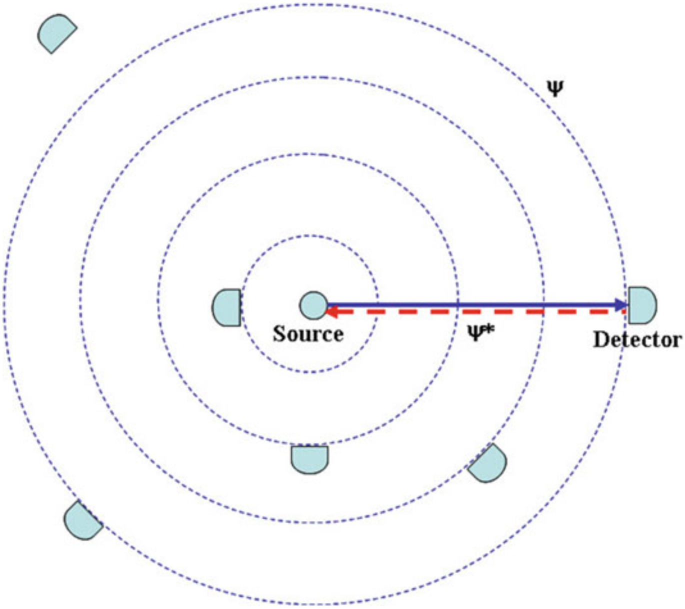

Fig. 6.3 Schematic of the transaction involved in the Einstein's bubble paradox. The offer wave ψ (*blue/solid*) forms a spherical wave front, reaching the detector on the right and causing it to return a confirmation wave ψ^* (*red/dashed*), so that a transaction forms and one photon's worth of energy $\hbar\omega$ is transferred. Other detectors also return confirmation waves, but the source has randomly selected the detector on the right for the transaction

one $\hbar\omega$ photon's worth of energy is transferred from the source to the detector. The formation of this particular transaction, satisfying the source boundary condition that only one photon is emitted, prevents the formation of any other transaction to another possible photon absorber, so only one photon is detected. This is an illustration of a simple two-vertex transaction in which the transfer of a single photon is implemented nonlocally. It avoids Heisenberg's assertion that the mathematical solution to a simple second-order differential equation involving momentum, energy, time, and space has somehow become a map of the mind, deductions, and knowledge of a hypothetical observer.

In this context, we note that there is a significant (but untestable) difference between Heisenberg's knowledge interpretation and the Transactional Interpretation as to whether the outgoing state vector or offer wave changes, collapses, or disappears at the instant when knowledge from a measurement is obtained. The knowledge interpretation would lead us to expect, without any observational evidence and with some conflict with special relativity, that Einstein's bubble "pops" when the detector registers the arrival of a photon and that other parts of the outgoing wave disappear at that instant. The bubble needs to pop in the knowledge interpretation because the state of knowledge changes, and also because this prevent multiple photon detections from a single photon emission.

In the analogous description by the Transactional Interpretation, the parts of the offer wave away from the detection site, because they represent only the *possibility* of a quantum event, do not disappear, but instead continue to propagate to more distant potential detection sites. These sites return confirmation echoes that compete with the echo from the detector of interest for transaction formation. The consequence of this difference is that the TI does not have to explain how wave functions can change in mid-flight, how the *absence* of a detection can change a propagating wave function, or what "instantaneous" means in the context of special relativity. See the discussions of Renninger's and Maudlin's *gedankenexperiments* in Sects. 6.6 and 6.16 for further examples of this important interpretational difference.

6.3 Schrödinger's Cat (1935)

In 1935, Erwin Schrödinger presented his Cat Paradox, a problem that focused on the situation that occurs when the strange procedures of quantum mechanics in acting on microscopic systems are projected into the macroscopic world [7]. It is illustrated in Fig. 6.4. Suppose, he said, that we have a box that is completely and perfectly

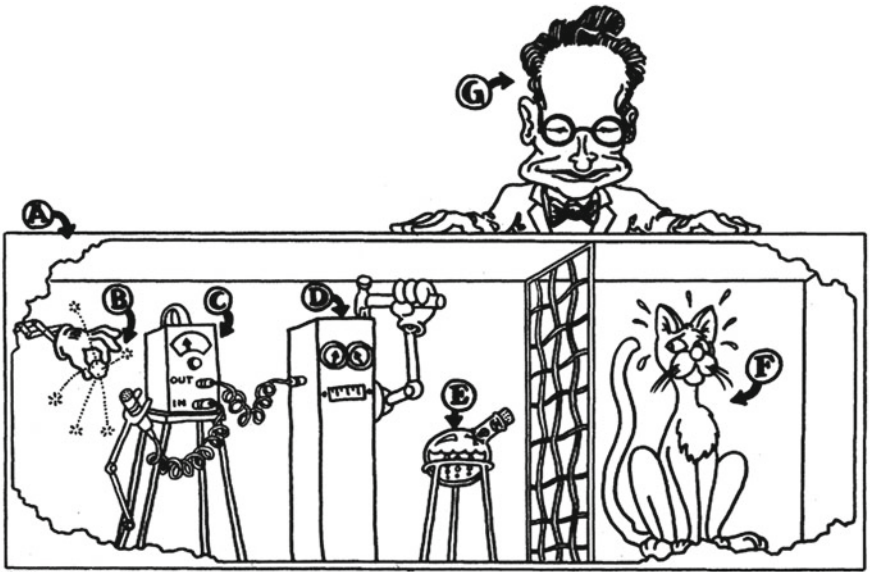

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Fig. 6.4 The Schrödinger's Cat *gedankenexperiment*: A sealed and insulated box (*A*) contains a radioactive source (*B*) that has a 50 % chance during the course of the"experiment" of triggering Geiger counter (*C*) that activates a mechanism (*D*) causing a hammer to smash a flask of hydrocyanic acid (*E*) killing the cat (*F*). In the Copenhagen view, the observer (*G*) must open the box in order to collapse the wave function of the system into one of the two possible states: $|\,\text{alive}\rangle$ or $|\,\text{dead}\rangle$, and before that, the cat's wave function was $(1/\sqrt{2})\;|\,\text{alive}\rangle + (1/\sqrt{2})\;|\,\text{dead}\rangle$

isolated from the outside world and has its own air supply. In the box is a radioactive source, a Geiger counter, and a mechanism that will smash a flask of hydrocyanic acid (a lethal poison) if the Geiger counter should detect a single radiation event. The radioactive source is very weak, with a strength adjusted so that the probability of the Geiger counter detecting a single radiation event in one hour is just 50 %.

Now we place a cat in the box, seal the lid, and wait for an hour. The question is, what is the quantum mechanical wave function describing the state of the cat at the end of an hour? There is a probability of $1/2$ that the cat will be alive at the end of an hour and a probability of $1/2$ that it will be dead. According to the procedures and formalism of standard quantum mechanics, the wave function of the cat is therefore $\Psi_{cat} = (1/\sqrt{2}) \mid \text{alive}\rangle + (1/\sqrt{2}) \mid \text{dead}\rangle$. In other words, the cat is predicted to be in a state that is half alive and half dead, two inconsistent states, as Schrödinger put it, that are mixed or smeared out in equal parts. He expressed an unwillingness to accept as valid such a "blurred model" for representing reality.

I have not been able to determine whether Heisenberg ever addressed the Schrödinger's Cat paradox directly, but his response is fairly predictable. The wave function of the cat is a mathematical representation of the knowledge of an observer. Since the observer does not know the state of the cat after an hour, of course a wave function representing his state of knowledge would have to include both dead and alive possibilities, and would be a mixture of the two until the box was opened.

The central focus of the problem posed by Schrödinger's Cat is the question of *when* the wave function actually collapses. The Transactional Interpretation avoids this implicit dilemma because in the TI the wave function collapse, i.e., the formation of the transaction, is two-way in time and atemporal. During the entire one hour period that the box is closed the radioactive source B of Schrödinger's apparatus sends out a very weak offer wave ψ. This offer wave and its confirmation wave may or may not, with equal 50 % probabilities, be selected to produce a detection by the Geiger counter C, so that a completed transaction is formed. If a transaction is formed, then the count is recorded, the flask shattered, and the cat killed. If such a transaction is not formed then the cat remains alive. The initial wave function (or offer wave) does indeed have implicit in it both live cat and dead cat possibilities, but the completed transaction (or lack thereof) allows only one of these possibilities to become real. Because the collapse does not have to await the arrival of the observer, there is never a time when "the cat is 50 % alive and 50 % dead". And the need for consciousness, permanent records, thermodynamics, or alternate universes never arises. If the "buck stops" anywhere, it stops at the radioactive source at the start of the process, which receives advanced wave echoes from potential radiation absorbers and must select from among them transactions that can lead to only one of the two possible outcomes to be projected into reality, a live cat or a dead cat.

To put this another way, Schrödinger's question is: When can a quantum event be considered finished? Is it when the gamma ray leaves the radioactive nucleus? Is it when it interacts with the Geiger counter? When the flask is smashed? When the cat dies? When the observer looks in the box? When he tells a colleague what he observed? When he publishes his observations in the *Physical Review*? When …? A billiard shot is over when the billiard balls stop colliding and come to rest. But the atomic "billiard balls" of a quantum billiard game continue to collide forever, never coming to rest so that the shot can be considered finished.

The source of confusion here is that the wrong question is being asked. The Copenhagen view has led us to ask *when* the wave function collapses instead of *how* it collapses. But there is not a "when", not a point in time at which the quantum event is finished. The event is finished when the transaction forms, which happens along a set of world lines which include all of the event listed above, treating none of them as the special conclusion of the event. If there is one particular link in this event chain which is special, it is not the one which ends the chain. It is the link at the beginning of the chain when the emitter, having received various confirmation waves from its original offer wave, reinforces one (or more) of them in such a way that it brings that particular confirmation into reality as a completed transaction. The atemporal transaction does not have a "when" at the end.

6.4 Wigner's Friend (1962)

In 1962 Eugene Wigner elaborated on the knowledge issue with his Wigner's Friend paradox, an expansion of the Schrödinger's Cat problem [11]. Wigner replaced the cat with a "friend", i.e., an intelligent observer and at the same time replaced the hydrocyanic acid mechanism with a less lethal piece of apparatus, e.g., a light bulb that is switched on when a count is recorded. The experimenter then performs the experiment, which can be considered as two experiments: (a) treating friend+box as a system, the experimenter makes an observation, and (b) treating the counter mechanism as a system, the friend makes an observation that is subsequently reported to the experimenter (Fig. 6.5).

We will not reproduce Wigner's detailed analysis of this *gedankenexperiment* here, but will state his conclusion: consciousness must have a special role in the collapse of the wave function, for otherwise one must deal (at least on the philosophical level) with un-collapsed wave functions containing conscious observers in a multiplicity of alternative states.

The discussion in Sect. 6.3 also applies to the Wigner's Friend paradox. From the viewpoint of the Transactional Interpretation, there is nothing special about one observer observing another one. Transactions involving observers, like other transactions, form atemporally, and asking *when* the transaction forms is asking the wrong question.

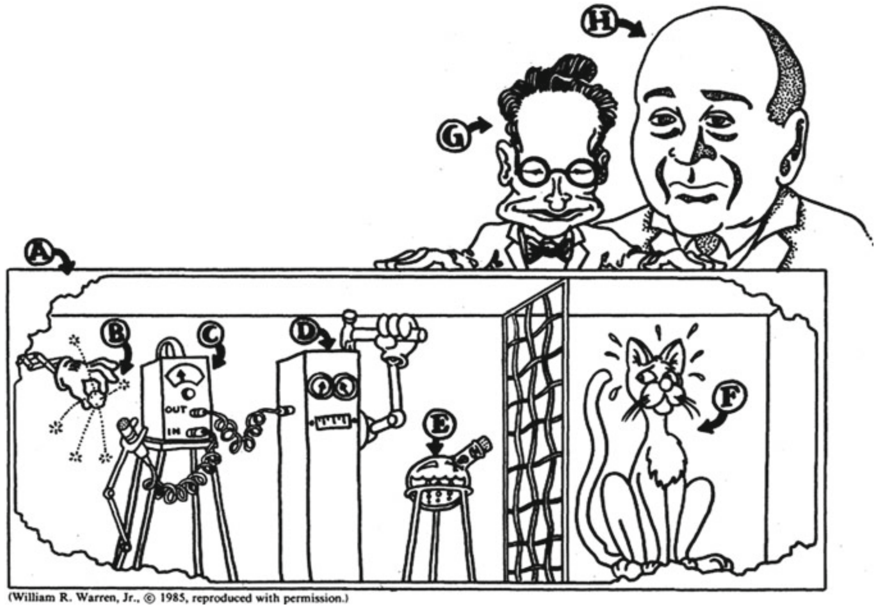

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Fig. 6.5 The Wigner's Friend *gedankenexperiment*: In the Schrödinger's Cat setup, a second observer (Wigner's Friend H) may be needed, according to the Copenhagen view, to collapse the wave function of the larger system containing the first observer (G) and the apparatus (A–F). And another observer may be required to collapse *his* wave function, and so on …

6.5 Renninger's Negative-Result *Gedankenexperiment* (1953)

This is a *gedankenexperiment* focusing on the collapse of the wave function produced by the *absence* of an interaction of the system measured (an alpha-particle) with the measurement apparatus. It was suggested by Renninger [8] and was featured by de Broglie [9] in his book on the interpretation of quantum mechanics. The experimental arrangement is shown in Fig. 6.6.

Source S is located at the center of a spherical shell E_2 of radius R_2. The interior of E_2 is lined with a scintillating material that will produce a detectable flash of light that will be seen by the observer if E_2 is struck by a charged particle, e.g., an alpha particle. Inside E_2 is a partial concentric sphere E_1 of radius R_1, also lined with scintillator viewed by the observer. Partial sphere E_1 subtends solid angle Ω_1 as viewed from the position of source S. The portion of E_2 that is not shadowed by E_1 therefore subtends a solid angle $\Omega_2 = 4\pi - \Omega_1$. The source S is arranged so that in the time interval of the experiment it will emit exactly one alpha particle with velocity v, which has an angular dependence that is completely isotropic.

A reminder about notation: in the discussions that follow we will explicitly indicate offer waves ψ using the Dirac bra/ket state vector notation; a *ket* is a bar and angle bracket that enclose some symbol that distinguishes one retarded offer wave function

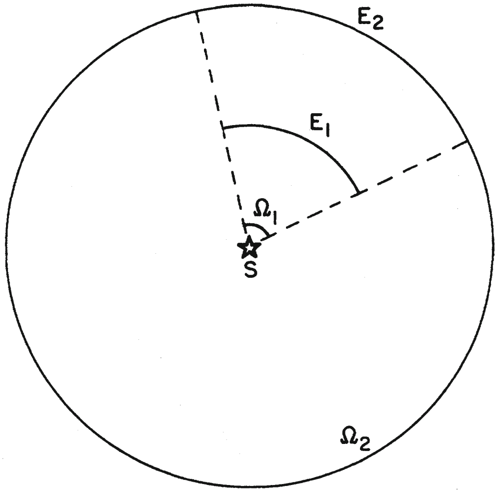

Fig. 6.6 Schematic diagram showing Renninger's negative-result *Gedankenexperiment*. Source S isotropically emits an alpha particle that is detected by the scintillator on spherical surfaces E_1 and E_2, depending on respective solid angles Ω_1 and Ω_2

from another. For example, a wave that is terminated at partial sphere E_1 can be represented by $\psi_{E_1} = \mid E_1\rangle$. The corresponding confirmation waves $\psi^*_{E_1}$ will similarly be indicated by a Dirac *bra* state vector $\psi^*_{E_1} = \langle E_1 \mid$, which reverses the bar and angle bracket to indicate an advanced confirmation wave.

Now let us consider the state vector $\mid S(t)\rangle$ as a function of time t, where t is the time that has elapsed since the source S has been commanded to emit an alpha particle. At time t before the alpha particle has traversed the distance R_1, i.e., for $0 < t < (R_1/v)$, the probability that the particle will produce a scintillation at E_1 is $P_1 = \Omega_1/4\pi$, and the probability that it will produce a scintillation at E_2 is $P_2 = \Omega_2/4\pi$. Thus the state vector might be written as:

$$\mid S(t)\rangle = p_1 \mid E_1\rangle + p_2 \mid E_2\rangle \tag{6.1}$$

where $\mid p_1 \mid^2 = P_1$ and $\mid p_2 \mid^2 = P_2$.

But now let us suppose that time t becomes greater than (R_1/v) and that the observer does not observe a scintillation from E_1. Then according to the knowledge interpretation the state vector must collapse, with the result that the probabilities become $P_1 = 0$ and $P_2 = 1$, and the state vector becomes $\mid S(t)\rangle = \mid E_2\rangle$ for $t > (R_1/v)$. The interpretational problem as stated by Renninger and de Broglie is that the state vector has collapsed abruptly and non-linearly, and yet "the observer sees nothing at all on screen E_1, where nothing has happened". Thus, it would appear that the absence of an interaction with the measurement apparatus leading to the absence of an observation can collapse the state vector as readily as a positive and definite observation.

This *gedankenexperiment* helps us to understand the knowledge interpretation logic that led von Neumann [10] and Wigner [11] to stress the need for a conscious and intelligent observer as the triggering agent for the collapse of the state vector.

The change in "knowledge" when no scintillation is observed at E_1 when $t = R_1/v$ requires a deduction on the part of the observer as to what should have happened if the alpha particle had been aimed at E_1. It correspondingly casts some doubt on Schrödinger's principle of state distinction [7] and on Heisenberg's irreversibility criterion [12], since no state-distinguishing record is made at $t = R_1/v$ and no irreversible process is initiated. Furthermore, one could imagine a more elaborate version of this experiment with a very large number of partial spheres inside E_2, so complicated that no human observer could possibly keep track of all the times and expectations of flashes that would signal the occurrence or elimination of various possible outcomes. And one could speculate on how the state vector collapse might occur in that situation. We also note that Neumaier [13] posted a *gedankenexperiment* on the quantum physics arXiv that he named the "Collapse Challenge" and that is the equivalent of the Renninger *gedankenexperiment*. He points out the deficiencies of the Copenhagen Interpretation in analyzing the system and says that the decoherence interpretation "only fakes the real situation".

The Transactional Interpretation avoids the conceptual problems implicit in this experiment by eliminating any state vector collapse that occurs at some definite instant such as $t = R_1/v$. In the TI, the state vector does not change at $t = R_1/v$, as the knowledge interpretation would imply. Instead, the TI employs an atemporal four-space description implicit in the transaction model: the state vector is emitted from the source at $t = 0$ as a retarded offer wave that grows as a spherical wave front, part of which encounters E_2 at $t = R_2/v$ and the remainder encounters E_1 at $t = R_1/v$. The boundary condition of S that only a single alpha particle is emitted permits one and only one transaction to occur between S and E_1 or E_2. The transaction will occur with a probability proportional to the confirmation wave echoes that S receives from the two possible absorbers. These echoes will be proportional to the solid angles subtended by the two possible absorbers, i.e., Ω_1 and Ω_2 as expected. A single transaction forms in accordance with these probabilities through the exchange of advanced and retarded waves characterizing the transition of an alpha particle from S to E_1 or to E_2.

As in Sect. 6.2, we note in this experiment the Copenhagen knowledge interpretation predicts an in-flight change in the wave function moving towards E_2 after it reaches the radius of E_1 (because an observer could deduce that the particle did not hit E_1), while the Transactional Interpretation predicts *no such change* in the wave function. This is a significant difference in the two interpretations, but it leads to no observable consequences that could be tested.

6.6 Transmission of Photons Through Non-Commuting Polarizing Filters*

The behavior of quantum systems in response to measurements of non-commuting variables is often cited as one of the interpretational problems of quantum mechanics and has been used as a justification for the development of quantum logics.

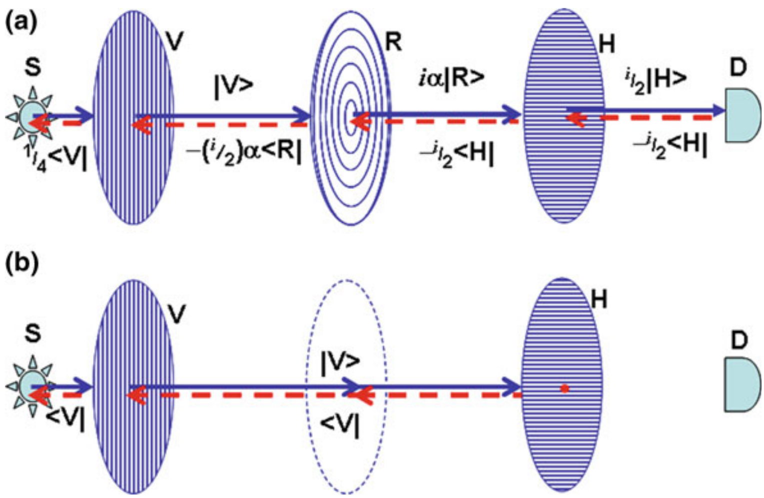

Fig. 6.7 Schematic diagram showing **a** the passage of a single photon through successive non-commuting polarizing filters V, R, and H (see text), and **b** Same diagram with filter R removed. Offer waves are shown as *blue/solid* and confirmation waves as *red/dashed*

However, one can usually find excellent classical analogs of such measurements, e.g., the Fourier time-frequency complementarity of electrical pulse wave-forms (see Sect. 2.4) and the transmission of light through successive polarizing filters.

Therefore, it is instructive to consider the QM treatment of the transmission of light through polarizing filters as an illustration of the application of the TI. We will specifically select a case where the handling of complex amplitudes is required so that this aspect of the TI can be demonstrated. Figure 6.7 shows the system to be considered: A single photon of light is emitted by source S and travels along an optical bench to the single-quantum detector D. In traversing this path, it passes through three polarizing filters, which we will call V, R, and H to indicate that, respectively, they transmit with 100 % efficiency light which is in a pure state of vertical linear polarization, right circular polarization, and horizontal linear polarization, respectively, while completely absorbing light that has the orthogonal polarization. Right circular polarization means that an observer viewing an oncoming wave will see its electric vector as rotating in the counter-clockwise direction, and the trajectory of the tip of the electric field vector would trace the threads of a right-handed screw. Similarly, the observer would see electric vector of a left circularly polarized wave as rotating in the clockwise direction, and the trajectory of the tip of the electric field vector would trace the threads of a left-handed screw.

This example is chosen because the operators characterizing linear polarization eigenstates do not commute with the operators characterizing circular polarization eigenstates, and so linear and circular polarization are non-commuting variables. The two descriptions (linear vs. circular) represent two related bases. In particular, if $|H\rangle$, $|V\rangle$, $|R\rangle$, and $|L\rangle$ represent pure states, respectively, of horizontal linear, vertical linear, right circular, and left circular polarization, then they are related by the basis transform equations:

$$| R\rangle = \alpha(| H\rangle - i \,| V\rangle) \tag{6.2}$$
$$| L\rangle = \alpha(| H\rangle + i \,| V\rangle) \tag{6.3}$$
$$| H\rangle = \alpha(| R\rangle + | L\rangle) \tag{6.4}$$
$$| V\rangle = i\alpha(| R\rangle - | L\rangle) \tag{6.5}$$

where $\alpha = \sqrt{1/2}$ and $i = \sqrt{-1}$. Here, multiplication by i means that the wave is shifted in phase by 90°, so that its maximum arrives $1/4$ of a period early.

The Transactional Interpretation provides the following description of the transmission of a photon from S to D: The source S produces a retarded offer wave (OW) in the form of a general state vector including all possible states of polarization. This wave then passes through filter V. The filter transmits only $| V\rangle$, i.e., that component of the state vector that corresponds to a state of pure vertical linear polarization (VLP). This wave then travels to filter R, which transmits only that component of $| V\rangle$ that is in a pure state of right circular polarization (RCP). From Eq. 6.5 this is $i\alpha \,| R\rangle$. This RCP wave then travels to filter H, which transmits only the component in a pure state of horizontal linear polarization (HLP). From Eq. 6.2, this will be $\alpha(i\alpha \,| H\rangle) = (i/2)\,| H\rangle$. This HLP offer wave then strikes D as an offer to be absorbed and detected.

But according to the transaction model this is only half of the story. To confirm absorption of the incident retarded wave, the detector must produce a "time-mirrored" advanced confirmation wave (CW). This wave will be the complex conjugate of the incident offer wave and will have the form:

$$CW = OW^* = [(i/2)\,| H\rangle]^* = -(i/2)\langle H \,| \tag{6.6}$$

This advanced CW travels back along the track of the incident OW until it encounters filter H, where it is fully transmitted since it is already in a state of pure horizontal linear polarization.

The CW then proceeds back along the track of the OW until it reaches filter R, where only its RCP component is transmitted. We can use Eqs. 6.2–6.5 for changing the basis of advanced waves by taking the complex conjugates (i.e., the time reverse) of both sides of the equations to obtain a new set of transformation equations. Employing that procedure, Eq. 6.4* shows us that the transmitted CW will have the form:

$$(\alpha)[-i/2\,\langle R\,|] = -(i/2)\alpha\langle R\,| \tag{6.7}$$

The CW then proceeds until it reaches filter V, where only its VLP component is transmitted. Eq. 6.2* shows us that the transmitted wave will be:

$$CW = i\alpha[-(^{i}/_{2})\alpha\langle V\ |] = {}^{1}/_{4}\langle V\ | \tag{6.8}$$

Thus the source has sent out an OW of unit amplitude and has received back a CW in state ${}^{1}/_{4}\langle V\ |$. This then is a concrete example of the assertion that the probability of a transaction is proportional to the amplitude of the CW echo from a potential absorber and is also an illustration of the operation of the Born probability law $P = \Psi\Psi^*$. The transaction will be confirmed and the photon transmitted from S to D with a probability of 1/4 and will arrive at D in a state of pure horizontal polarization. There will also be a probability of 3/4 that the photon will not be transmitted to D, but instead will be absorbed by one of the filters. These are the same transmission and absorption probabilities that are given by classical optics for the transmission of an initially horizontally polarized beam of light from S to D.

Now consider the modification of the apparatus shown in Fig. 6.7b, in which the second filter R has been removed. Now the OW is placed in a pure state of VLP by filter V, so that when it travels to filter H it cannot be transmitted. Therefore, no OW reaches the detector D and no transaction from S to D takes place. With filter R removed, the transmission of the apparatus drops from 25 to 0 %.

The TI description of other experiments involving non-commuting variables can be constructed by employing the same procedures used above (see Sect. 6.10, for example). In each case it will be found that the probability of the quantum event under consideration is just the real and positive amplitude of the echo CW response to the OW from the emitter.

6.7 Wheeler's Delayed Choice Experiment (1978)*

In 1978, John A. Wheeler raised another interpretational issue [14] that is now known as Wheeler's Delayed-Choice Experiment (Fig. 6.8). Suppose that we have a Young's two slit interference apparatus as discussed in Sect. 6.1, with photons produced by a light source that illuminates two slits. The source emits one and only one photon in the general direction of the slits during the time interval chosen by the observer who is operating the apparatus. Downstream of the slits are two different measuring devices. One of these is a photographic emulsion σ_1 that, when placed in the path of the photons, will record photon's positions as they strike the emulsion, so that after many photon events, the emulsion will show a collection of spots that form a two-slit interference pattern characteristic of the photon's wavelength, momentum, and the slit separation. The other measuring device consists of a lens focusing the slit-images on photographic emulsion σ_2 at image points $1'$ and $2'$. A photon striking either image point tells us that the photon had passed through the slit that is imaged at that position. Therefore, detection at σ_2 constitutes a determination of the slit (1 or 2) through which the photon passed.

Such an apparatus is often used to illustrate the wave-particle duality of light. The light waves that form the interference pattern on the emulsion must have passed through both slits of the apparatus in order to interfere at the emulsion, while the

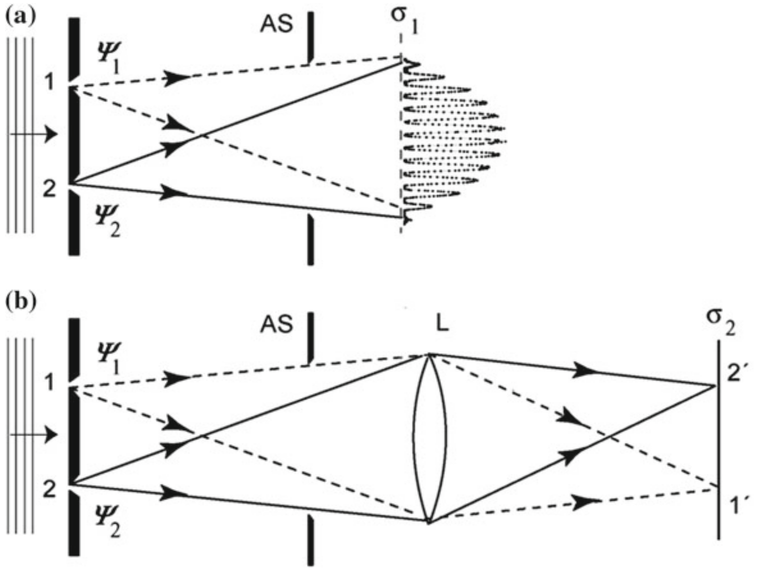

Fig. 6.8 Wheeler's delayed choice experiment: Light from a single-photon source can either **a** produce an interference pattern on photographic emulsion σ_1 or **b** be imaged by lens L to produce images of the two slits on photographic emulsion σ_2 at points $1'$ and $2'$. The experimenter waits until *after* the photon has passed through the slits to decide whether to lower photographic emulsion σ_1 so that photographic emulsion σ_2 provides which-slit information, or to leave it place so that the two-slit interference pattern characteristic of passage through both slits is observed at σ_1

photon particles that strike the photographic emulsion σ_2 can have passed through only one slit, the one imaged by the lens L at image point $1'$ or $2'$. The photographic emulsion σ_1 measures momentum (and wavelength) and the photographic emulsion σ_2 measure position, i.e., conjugate variables are measured. Thus, the two experimental measurements are "complimentary" in Bohr's sense. The uncertainty principle is not violated, however, because only one of the two experiments can be performed with a given photon. But Wheeler is not done yet.

The emulsion σ_1 is mounted on a fast acting pivot mechanism, so that on command it can almost instantaneously either be raised into position to intercept the photon from the source or rapidly dropped out of the way so that the photon can proceed to σ_2. Thus when the emulsion σ_1 is up, we make an interference measurement requiring the photon to pass through both slits, and when the emulsion σ_1 is down, we make a position measurement requiring that the photon pass through only one slit.

Wheeler's innovative modification of this old *gedankenexperiment* is this: We wait until a time at which the photon has safely passed the slits but has not yet reached the emulsion apparatus σ_1. Only at that time do we decide whether to place the σ_1 emulsion up or down. The decision is made after the photon must have passed through the slit system. Therefore, the photon has already emerged from the slit system when the experimenter decides whether it should be caused to pass through one slit (emulsion down) or both slits (emulsion up). Wheeler concluded that the delayed-choice experiment illustrated his paradigm about quantum mechanics: "No phenomenon is a real phenomenon until it is an observed phenomenon."

It might be argued that there would not really be time enough for a conscious observer to make the measurement decision. However, Wheeler has pointed out that the light source might be a quasar, and the "slit system" might be a foreground galaxy that bends the light waves around both sides by gravitational lensing. Thus, there would be a time interval of millions of years for the decision to be made, during which time the light waves from the quasar were in transit from the foreground galaxy to the observer. The delayed choice experiment, since it seems to determine the path of the photon after it has passed through the slit system, has been used as an illustration of retrocausal effects in quantum processes.

The *gedankenexperiment* does not lead to any explicit contradictions, but it demonstrates some of the retrocausal implications of the standard quantum formalism. In particular, the cause (emulsion σ_1 down or up) of the change in the photon's path has come after the effect (passage through one or two slits). There have been several experimental implementations of this experiment, the most recent (2007) performed by the Aspect group in France [15]. All have shown the expected results, i.e., the predictions of standard quantum mechanics.

The Transactional Interpretation is able to give an account of the delayed choice experiment without resort to observers as collapse triggers. In the TI description the source emits a retarded OW that propagates through slits 1 and 2, producing offer waves ψ_1 and ψ_2. These reach the region of screen σ_1, where either (a) they find the screen σ_1 up and form a two-path transaction with it as illustrated in Fig. 6.8a or; (b) they find the screen σ_1 down and proceeds through lens L on separate paths to screen σ_2 where they strike the screen at image points $1'$ and $2'$ and create confirmation waves that return through the lens and slits to the source. In case (b), the source receives confirmation wave echoes from two separate sites on screen σ_2 and must decide which of them to use in a one-slit competed transaction, as shown by the solid and dashed lines in Fig. 6.8b.

For case (a) in which the photon is absorbed by σ_1, the advanced confirmation wave retraces the path of the OW, traveling in the negative time direction back through both slits and back to the source. Therefore the final transaction, as shown in Fig. 6.8a, forms along the paths that pass through both slits in connecting the source with the screen σ_1. The transaction is therefore a "two-slit" quantum event. The photon can be said to have passed through *both* slits to reach the emulsion.

For case (b) the offer wave also passes through both slits on its way to σ_2. However, when the absorption takes place at one of the images (not both, because of the single quantum boundary condition), the lens focuses the confirmation wave so that it passes through only the slit imaged at the detection point. Thus the confirmation wave passes through only one slit in passing back from image to source, and the transaction which forms is characteristic of a "one-slit" quantum event. The source, receiving confirmation waves from two mutually exclusive one-slit possibilities, must choose only one of these for the formation of a transaction. The photon can be said to have passed through *only one* slit to reach σ_2.

Since in the TI description the transaction forms atemporally, the issue of *when* the observer decides which experiment to perform is not significant. The observer determined the experimental configuration and boundary conditions and the transaction formed accordingly. Further, the fact that the detection event involves a measurement (as opposed to any other interaction) is not significant and so the observer has no special role in the process. To paraphrase Wheeler's paradigm, we might say: "No offer wave is a real transaction until it is a confirmed transaction".

6.8 The Freedman–Clauser Experiment and the EPR Paradox (1972)*

Another quantum puzzle is the Freedman–Clauser experiment [16], previously discussed in Sect. 2.8. An atomic 2-photon cascade source produces a pair of polarization-entangled photons. If we select only entangled photons emitted back-to-back, then because of angular momentum conservation, both photons must be in the same state of circular or linear polarization. In the linear basis, their wave function should be in the Bell state of Eq. 2.1. Measurements on the photons with linear polarimeters in each arm of the experiment show that when the planes of the polarimeters are aligned, independent of the direction of alignment, the two polarimeters always measure HH or VV for the two linear polarization states, i.e., both photons are always in the same linear polarization state.

When the polarization plane of one polarimeter is rotated by an angle θ with respect to the other polarization plane, some opposite-correlation HV and VH events creep in. If θ is increased, the fraction of these events grows proportional to $1 - \cos^2(\theta)$, which for small values of θ is proportional to θ^2. As discussed in Sect. 2.8, this polarization correlation behavior produces a dramatic violation of the Bell inequalities [17], which for local hidden variable alternatives to standard quantum mechanics require a growth in HV and VH events that is *linear* with θ. The implication of the Bell-inequality violations is that quantum nonlocality is required to explain the observed quadratic polarization correlations.

How are the nonlocality-based polarization correlations of the Freedman–Clauser experiment possible? The Transactional Interpretation provides a clear answer, which is illustrated in Fig. 6.9. The source of the polarization-entangled photons seeks to emit the photon pair by sending out offer waves ψ_L and ψ_R to the left and right detectors. The detectors respond by returning confirmation waves ψ_L* and ψ_R* back to the source. A completed three-vertex transaction can form from these echoes, however, only if the two potential detections are compatible with the conservation of angular momentum at the source. This requirement produces the observed polarization correlations. The transaction does not depend on the separation distance of the polarimeters or on which of the polarization detection events occurs first, since

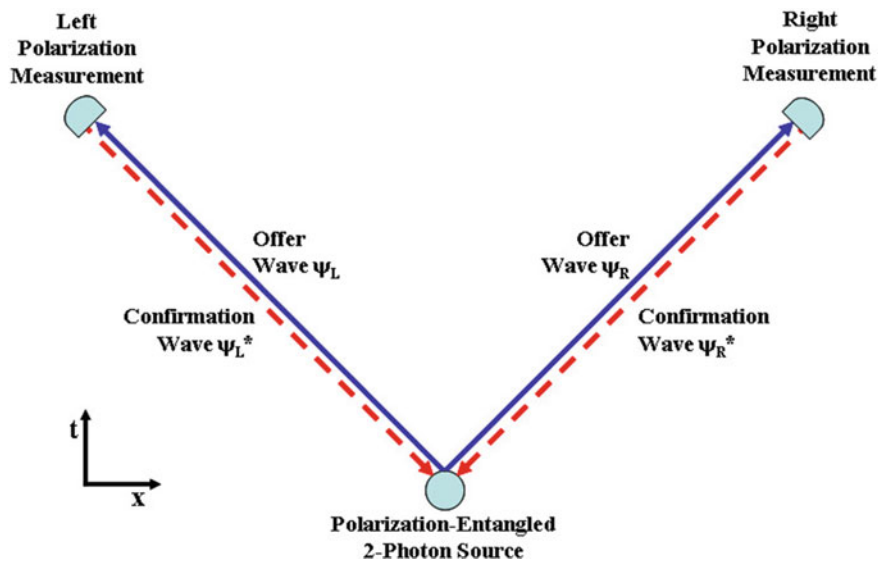

Fig. 6.9 Space-time schematic of a nonlocal "V" transaction for visualizing the polarization-entangled Freedman–Clauser EPR experiment. Offer waves ψ_L and ψ_R (*blue*/*solid*) move from source to linear polarization detectors, and in response, confirmation waves ψ_L* and ψ_R* (*red*/*dashed*) move from detectors to source. The three-vertex transaction can form only if angular momentum is conserved by having correlated and consistent measured linear polarizations for both detected photons

the transaction formation is atemporal, and it even-handedly treats any sequence of detection events. Appendix C describes two "quantum games" that produce correlations analogous to those present in the Freedman–Clauser experiment.

6.9 The Hanbury Brown Twiss Effect (1956)*

The Hanbury-Brown-Twiss effect (HBT) is an example of the interference of radiation sources that are incoherent [18, 19]. It has been applied to the measurement of the diameters of nearby stars with radio interferometry and to investigation of the dimensions of the "fireball" developed in relativistic heavy ion collisions in which a large number of π-mesons (pions) are produced in each collision [20–23]. The HBT effect applies equally well to classical radio waves and to particle-like quanta such as pions.

A simplified version of a HBT interference measurement is illustrated in Fig. 6.10. Sources 1 and 2 are separated by a distance d_{12}. Both sources emit photons of the same energy $\hbar\omega$ but are completely incoherent. The radiation from the two sources is detected by detectors A and B, which are separated by a distance d_{AB}. The line of

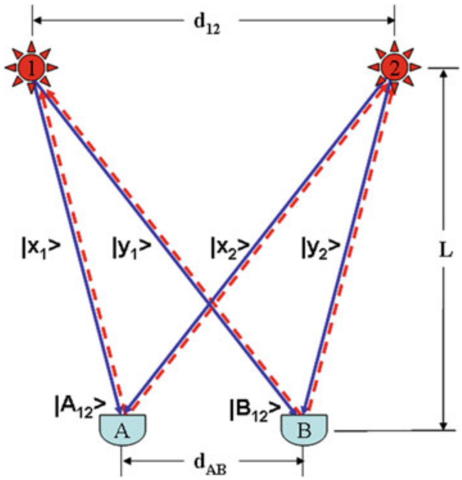

Fig. 6.10 Schematic diagram of the Hanbury-Brown Twiss experiment demonstrating coherent interference between light or particle waves from incoherent sources. Sources 1 and 2 are separate by distance d_{12}, and emit offer waves $|\, x_{1,2}\rangle$ and $|\, y_{1,2}\rangle$ (*blue/solid*) of identical wavelengths λ. Detectors A and B located a distance d_{AB} apart and a distance L from the sources return confirmation waves (*red/dashed*), and 4-vertex transaction forms in which two photons are transferred and detected. A product or coincidence between detector outputs results in a composite signal exhibiting an interference effect depending on L, λ, d_{12}, and d_{AB}, allowing d_{12} to be determined from measurements

centers of the sources is parallel to the line of centers of the detectors, and the two lines are separated by a distance L.

It will not be demonstrated here, but a signal that is a product of (or coincidence between) the signals received at A and B (indicating that photons have simultaneously triggered both detectors) reflects the coherent interference of the two sources and depends on the source separation d_{12} as well as the detector separation d_{AB}. Measurements made at a number of values of d_{AB} can therefore be used to determine d_{12}, in a manner analogous to moving a single detector in an interference pattern to determine the separation of a pair of coherent sources. This is the HBT intensity interference effect.

There is a lesson for applications of the Transactional Interpretation in this kind of interference phenomenon: particles like photons and pions cannot be consistently described as little blobs of mass-energy that travel from point A to point B, as the Bohm–de Broglie interpretation would like us to believe. In the HBT effect, a whole photon is assembled at each detector out of partial-photons contributed by each of the two sources. Consider a transaction in which photons are emitted by 1 and 2 and detected by A and B so that their product signal exhibits HBT interference. In the TI description of such an HBT event, retarded OW's $|\, x_1\rangle$ and $|\, y_1\rangle$ are emitted by the source 1 and travel to detectors A and B, respectively. Similarly, OW's $|\, x_2\rangle$ and $|\, y_2\rangle$ are emitted by the source 2. Detector A receives a composite OW $|\, A_{12}\rangle$ which is a linear superposition of $| x_1\rangle$ and $| x_2\rangle$ and seeks to absorb the "offered" photon by producing advanced CW $\langle A_{12} |$, the time reverse of that superposition. Detector B similarly responds to composite OW $| B_{12}\rangle$. These advanced waves then travel back to the two sources, each of which receives a different linear superposition of $\langle A_{12} |$ and $\langle B_{12} |$.

An HBT 4-vertex transaction is formed that removes one energy quantum $\hbar\omega$ from each of the two sources 1 and 2 and delivers one energy quantum $\hbar\omega$ to each of the two detectors A and B. For many combinations of source and detector separation distances, the superimposed OW's and/or CW's are nearly equal and opposite, so that the composite wave is very weak and the transaction is very improbable. For a few ideal combinations of source and detector separation distances all of the composite waves are strong because their components coherently reinforce, and in this case the transaction is much more probable. The transaction probability depends on the separation distances in just the way predicted by quantum mechanics. Thus the HBT effect is completely explained by the Transactional Interpretation.

However, there is an interesting point here: neither of the photons detected by A or B can be said to have uniquely originated in one of the two sources. Each detected photon originated partly in each of the two sources. It might be said that each source produced two fractional photons and that fractions from two sources combined at a detector to make a full size photon. Particles transferred have no separate identity that is independent from the satisfaction of the quantum mechanical boundary conditions. The boundary conditions here are those imposed by the HBT geometry and detection criteria.

This two photon event may be viewed as a simple case of more general multiphoton (or multiparticle) events, which may involve many sources and many detectors. Such transactions can be viewed as assembling particles at a detector from contributions derived from an number of sources, with no one-to-one correspondence between particles emitted and particles detected except in the overall number. One way of stating this is to emphasize that the spatial localization of the emitter (or the absorber) may be very fuzzy and indefinite, so long as all boundary conditions are satisfied. Likewise the time localization of the emission event (or absorption event) can be made very indefinite by a choice of experimental conditions, e.g., very low emission probability as in the Pflegor–Mandel experiment [24].

6.10 The Albert–Aharonov–D'Amato Predictions (1985)

The predictions of Albert, Aharonov, and D'Amato [25] (AAD) clarify an old problem, the question of retrospective knowledge of a quantum state following successive measurements of non-commuting variables [26]. The assumption of contra-factual definiteness (CFD) plays an important role in the AAD predictions because these concern the retrospective knowledge of the observer about the outcome of experiments that might have been performed on the system in the time interval between one of the measurements and the other. We need the CFD assumptions that the various alternative possible measurements that might have been performed on the system would each have produced a definite (although unknown and possibly random) observational result and that we are permitted to discuss these results. Under the assumption of CFD, the AAD predictions provide a challenging interpretational problem.

As a simple example of the AAD predictions, consider the experiment illustrated in Fig. 6.11. A photon is emitted from source *S* and is transmitted through a filter *V* that passes only vertical linearly polarized (VLP) light. It then travels a distance *L* and is transmitted through a second filter *R* that passes only right circularly polarized (RCP) light. The photon is then detected by a quantum sensitive detector *D*, which generates an electrical signal registering the arrival of the photon. The questions that are addressed by AAD are: (1) What is the quantum state of the photon in the region L, which lies in the region between *V* and *R*, and (2) What would have been the outcome of measurements on the photon that might have been performed in that region?

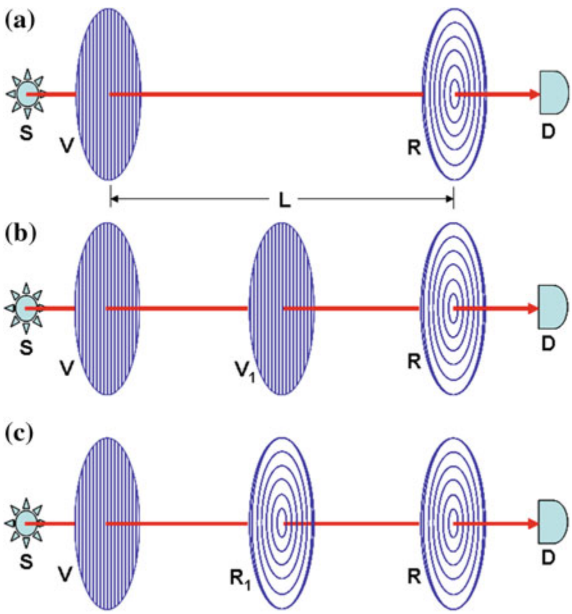

Fig. 6.11 Schematic diagram showing the three experimental situations considered in the AAD predictions. **a** The photon emerges from the source *S*, passes through a vertical linear polarizing filter *V*, and then through a right circular polarizing filter *R* before being detected by a photomultiplier tube *D*. **b** An intermediate vertical linear polarizing filter V_1 is inserted. **c** An intermediate right circular polarizing filter R_1 is inserted. These additional measurements (**b** and **c**) are said [25] to demonstrate that the photon is simultaneously in a state of linear and circular polarization in the intermediate region

The authors of AAD use the formalism of quantum mechanics as applied to the joint probability of a series of measurements [26] to demonstrate a remarkable pair of predictions (here applied to the present example): (1) if a linear polarization measurement had been performed (Fig. 6.11b) in region L the photon would have been found to be in a VLP state, and (2) if a circular polarization measurement (Fig. 6.11c) had been performed in region L the photon would have been found to be in a RCP state. In other words the intermediate measurement of polarization appears to be equally influenced by the past linear polarization measurement that was performed at V and by the future circular polarization measurement that will be performed at R, in that both seem to equally prepare the system in a definite state that "forces" the outcome of the intermediate measurement.

This completely valid application of the QM formalism appears to be in at least interpretational conflict with the uncertainty principle and with complementarity, which assert that since RCP and VLP states are eigenstates of noncommuting variables, a photon cannot have been in both of these eigenstates simultaneously. The authors of AAD, on the other hand, interpret their result as indicating that "without violating the statistical predictions of quantum mechanics, it can be consistently supposed …that non-commuting observables can simultaneously be well defined" and that indeed, "given those statistical predictions, … it is inconsistent to suppose anything else". The AAD result was summarized in a popular science account as indicating that: "The measurement on Friday caused, in some sense of the word "cause", the smeared-out values of spin on Wednesday to collapse into some definite configuration. The logical puzzle about time and causality that this development engenders has not yet been fully explored."

It is therefore of considerable interest to apply the Transactional Interpretation to this interpretational puzzle, both as a means of gaining insight into the problem and as a test of the utility of the TI for resolving the interpretational paradoxes of quantum mechanics. The TI analysis of this problem follows that of Sect. 6.6, which also dealt with the transmission of a photon through polarizing filters. The three experimental configurations considered are illustrated in Fig. 6.11a–c, and Fig. 6.12a–c show diagrammatically the corresponding state vector (SV) descriptions that will be discussed. These experimental configurations must be treated as separate (but related) quantum mechanical systems and each must be analyzed separately with the TI. Let us first consider Fig. 6.11b.

The TI provides the following description of the transmission of the photon from S to D with an intermediate VLP measurement: The source S produces a retarded offer wave (OW) in the form of a general SV including all possible states of polarization. This wave then passes through filter V. The filter transmit only $\mid V\rangle$, i.e., that component of the SV that corresponds to a state of pure vertical linear polarization (VLP). This wave then travels to filter V_1, which transmits $\mid V\rangle$ unchanged. This VLP wave then travels to filter R, which transmits only that component that is in a pure state of right circular polarization (RCP). From Eq. 6.5, this will be $i\alpha \mid R\rangle$, where $\alpha = {}^1\!/\!\sqrt{2}$. This RCP wave then strikes the detector D and produces the advanced confirmation wave (CW) $-i\alpha\langle R \mid$, the complex conjugate of the OW at D, which travels back along the track of the incident OW to confirm the transaction. When the

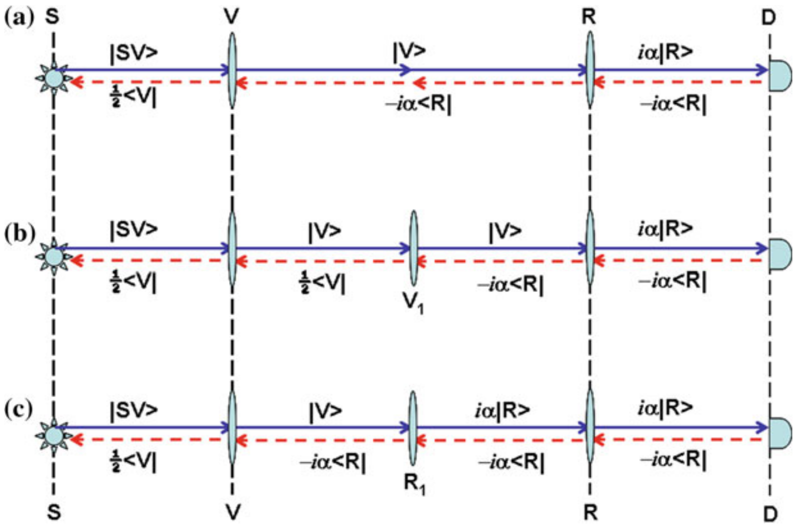

Fig. 6.12 Schematic diagram showing the Transactional Interpretation descriptions of the three AAD experiments. Offer waves are *blue/solid* and confirmation waves are *red/dashed*. Note the differences in quantum states in the intermediate region in (**b**) and (**c**). Here $\alpha = 1/\sqrt{2}$

CW reaches R it is transmitted without modification because it is already in a state of RCP. However, when it reaches V_1, only its VLP component is transmitted, so from Eq. 6.2* it becomes $i\alpha(-i\alpha\langle V\ |) = \frac{1}{2}\langle V\ |$. As discussed in Sect. 6.6, we use the complex conjugates of the basis transform Eqs. 6.2–6.5 when dealing with the filtering of advanced waves. The CW retains the same form as it passes through the filter V and back to the source S.

The description of the transmission of the photon from S to D with an intermediate RCP measurement illustrated in Fig. 6.12c is very similar: The source S produces a retarded OW in the form of a general SV including all possible states of polarization. This wave then passes through filter V, which transmits only $|\ V\rangle$. This wave then travels to filter R_1, which transmits only that component that is in a pure state of right circular polarization (RCP). From Eq. 6.5, this will be $i\alpha\ |\ R\rangle$. This RCP wave then travels to filter R, which transmits $i\alpha\ |\ R\rangle$ unchanged. It reaches detector D and produces the advanced CW $-i\alpha\langle R\ |$, the complex conjugate of the OW, which travels back along the track of the incident OW to confirm the transaction. When the CW reaches R and R_1, it is transmitted without modification because it is already in a state of RCP. However, when it reaches V, only its VLP component is transmitted, so from Eq. 6.2* it becomes $i\alpha(-i\alpha\langle V\ |) = \frac{1}{2}\langle V\ |$. It retains this form as it passes back to the source S.

In cases (b) and (c) the insertion of the intermediate polarizing filter does not alter the statistical aspects of the measurement from that of case (a) where there is no intermediate measurement, and so the three cases are equivalent in the observational sense. However, the TI gives us the opportunity to examine the intermediate quantum states in each case, and when this is done we find that the transaction that is confirmed is quite different in each of the three cases. This is illustrated in Fig. 6.12. In case (a) where there is no intermediate measurement the state in the intermediate region between V and R is in an indeterminate quantum state, in that the OW is $| V\rangle$ while the CW is $-i\alpha\langle R|$. This is also the case for the region between V_1 and R for case (b) and for the region between V and R_1 for case (c). However, we see that for case (b) the CW in the region between V and V_1 is in a state of pure VLP, while for case (c) the CW between R_1 and R is in a state of pure RCP.

The TI resolution of the riddle posed by the AAD predictions is that the uncertainty principle is not compromised, nor can non-commuting observables simultaneously be well defined, as the AAD authors have suggested. However, as was suggested above in another context, the circular polarization measurement that occurs later at R does cause, in some sense of the word cause, the smeared-out values of circular polarization between R and V to earlier "collapse into some definite configuration". The transactions that form in the three cases are not identical, even though they lead to the same observables, because each transaction is a separate self-consistent solution to the wave equation. Each satisfies a different set of boundary conditions. The insertion of the intermediate filter, while not altering the statistics of the measurement, brings into being a different transaction that has different characteristic eigenstates in the intermediate region between V and R. Thus, the two predictions of the AAD calculation concern intrinsically different quantum systems and cannot be construed as implying the presence "simultaneously" of the eigenstates of no-commuting variables, as was incorrectly asserted.

6.11 The Quantum Eraser (1995)*

A more elaborate delayed-choice variation is the quantum eraser experiment, a high-tech descendant of Wheeler's delayed choice concept. The experiment used a new (in 1995) trick for making "entangled" quantum states. If ultraviolet light from a 351 nanometer (nm) argon-ion laser passes through a $LiIO_3$ crystal, non-linear effects in the crystal can "split" the laser photon into two longer wavelength photons at 633 nm and 789 nm in a process called "down-conversion". The energies of these two "daughter" photons add up to the energy of their pump-photon parent, as do their vector momenta, and they are connected non-locally because they constitute a single "entangled" quantum state. They are required to be in correlated states of polarization, and under the conditions of this down-conversion they will be vertically polarized. As in other EPR experiments, a measurement performed on one of these photons affects the outcome of measurements performed on the other.

In a version of the experiment performed by Anton Zeilinger's group in Innsbruck, Austria, [27] the laser beam is reflected so that it makes two passes through the non-linear crystal, so that an entangled photon pair may be produced in either the first or the second pass through the non-linear crystal. As shown in Fig. 6.13, the experiment has the configuration of a six-pointed star formed of three beam paths intersecting

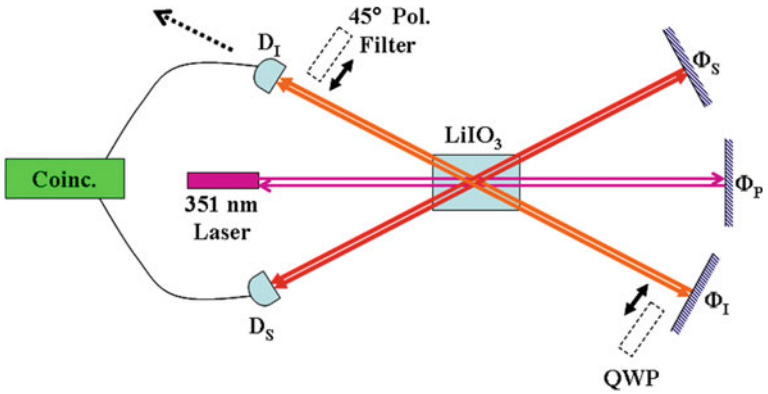

Fig. 6.13 Schematic diagram of the quantum eraser experiment. A $LiIO_3$ nonlinear crystal is pumped by a 351 nm laser beam (*violet*) and produces by down-conversion vertically polarized 633 nm (*orange*) and 789 nm (*red*) photons that can be made in either pump-photon pass through the crystal. A quarter-wave plate (QWP) and 45° polarizing filter may be inserted in the I path and the path to D_I may be lengthened (see text)

at a point inside the crystal. The laser beam first passes through the crystal moving horizontally downstream, is reflected by a downstream mirror Φ_P, and then passes through the crystal again moving horizontally upstream. Along the two diagonal branches downstream of the laser the two down-converted photons made in the first laser-pass travel to mirrors Φ_S and Φ_I (S for signal and I for idler), where they are reflected back to their production point and travel past it to upstream detectors D_S and D_I. The laser beam, in making its second pass through the crystal has a second chance to make a pair of down-converted photons. If these are produced, they travel directly to the upstream detectors along the two upstream diagonal branches.

The net result is that a photon arriving in coincidence at the two upstream detectors may have been produced in either the first laser pass through the crystal and then reflected to the detector, or in the second pass and traveled directly to the detector. There is no way of determining which "history" (direct vs. reflected) happened, so the states are superimposed. Therefore, the quantum wave functions describing these two possible production histories must interfere. The interference may be constructive or destructive, depending on the interference phase determined by the downstream path lengths (all about 13 cm) to the three mirrors of the system. Changing the path length to one of the mirrors (for example, by moving the laser-beam reflector Φ_P) is observed to produce a succession of interference maxima and minima in the two detectors.

This experimental setup is governed by the same physics as the delayed-choice experiment of Sect. 6.7, but, because there are two coincident photons and well separated paths for the two possible histories, it is easier to play quantum tricks with the system. Initially, all polarizations are vertical. Now the experiment is modified to remove the quantum interference by placing distinguishing polarization labels on the two possible photon histories (direct vs. reflected). A transparent optical element called a “quarter-wave plate” (QWP) is placed in front of the photon reflection mirror Φ_I. The QWP is set to rotate the polarization state of the reflected photons from vertical to horizontal polarization as they pass twice through it. This polarization modification allows the reflected and direct “histories” to be quantum-distinguishable, because one of the reflected photons is horizontally polarized while the direct photons are vertically polarized. The two superimposed quantum states are now distinguishable (even if no polarization measurement is actually made), and the interference pattern is eliminated, both in the *I* arm of the experiment in which the QWP is placed and also in the other *S* arm, where no modification was made.

Finally, the “quantum eraser” is brought into use. Any vertically or horizontally polarized light beam can be separated into a light component polarized 45° to the left of vertical and a light component polarized 45° to the right of vertical. Therefore, for the photons with the QWP in front of their mirror, placing just in front of their detector a filter that passes only light polarized 45° to the left of vertical “erases” the label that had distinguished the two histories by making the polarizations of the two waves reaching detector D_I the same. When this is done, it is found that interference is restored.

Further, the paths to the two detectors can have different lengths, with the path through the 45° filter to D_I made much longer than the path to detector D_S. This has the effect of erasing the path-distinguishing label on the *I* photon *after* the *S* photon had already been detected. This modification is observed to have no effect on the interference. The *post-facto* erasure still restores interference. The path label can be erased retroactively and has the same effect (retroactive or not) on the quantum interference of the waves. Effectively, the quantum eraser has erased the past!

The Transactional Interpretation can easily explain the curious retroactive erasure of “which-way” information. When which-way information is present, separate transactions must form for each of the paths, and no interference is observed. When the which-way information is erased, the overall transaction that forms involves both paths, and interference is observed. Modifying the polarizations causes a different type of transaction formation, resulting in different observations. The retroactive erasure of the which-way information is irrelevant, because the transaction forms atemporally, connecting the source and detectors in one or two advanced-retarded TI handshakes across space-time.

6.12 Interaction-Free Measurements (1993)*

In 1993, Elitzur and Vaidmann [28] (EV) showed a surprised physics community that quantum mechanics permits the non-classical use of light to examine an object without a single photon of the light actually interacting with the object. The EV experiment requires only the *possibility* of an interaction.

In their paper [28] Elitzur and Vaidmann discuss their scenario in terms of the standard Copenhagen Interpretation of quantum mechanics, in which the interaction-free

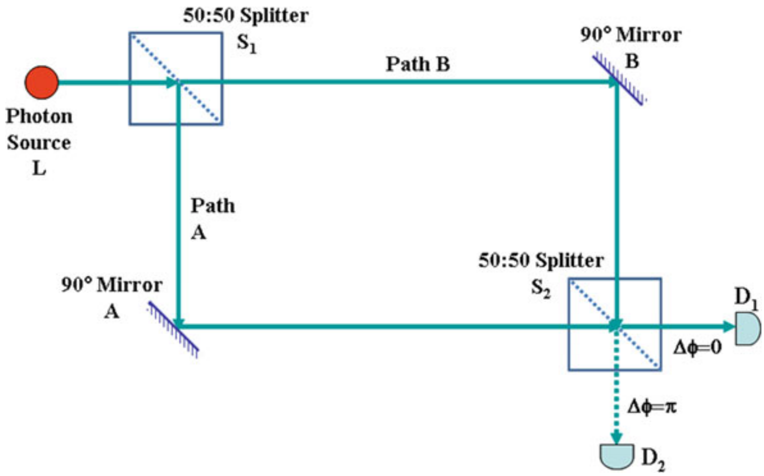

Fig. 6.14 Mach Zehnder interferometer with both beam paths open. All photons go to D_1 because of destructive interference at D_2

result is rather mysterious, particularly since the measurement produces "knowledge" that is not available classically. They also considered their scenario in terms of the Everett–Wheeler or "many-worlds" interpretation of quantum mechanics [29, 30]. Considering the latter, they suggest that the information indicating the presence of the opaque object can be considered to have come from an interaction that had occurred in a separate Everett–Wheeler universe and was transferred to our universe through the absence of interference. Here we will examine the same scenario in terms of the Transactional Interpretation and will provide a more plausible account of the physical processes that underlie interaction-free measurements.

The basic apparatus used by EV is a Mach–Zender interferometer, as shown in Fig. 6.14. Light from a light source L goes to a 50:50 % beam splitter S_1 that divides incoming light into two possible paths or beams. These beams are deflected by 90° by mirrors A and B, so that they meet at a second beam splitter S_2, which recombines them by another reflection or transmission. The combined beams from S_2 then go to the photon detectors D_1 and D_2.

The Mach–Zehnder interferometer has the characteristic that, if the paths A and B have precisely the same path lengths, the superimposed waves from the two paths are in phase at D_1 ($\Delta\phi = 0$) and out of phase at D_2 ($\Delta\phi = \pi$). This is because with beam splitters, an emerging wave reflected at 90° is always 90° out of phase with the incident and transmitted waves [31]. The result is that all photons from light source L will go to detector D_1 and none will go to detector D_2.

Now, as shown in Fig. 6.15 we place an opaque object (Obj) on path A. It will block light waves along the lower path after reflection from mirror A, insuring that all of the light arriving at beam splitter S_2 has traveled there via path B. In this case

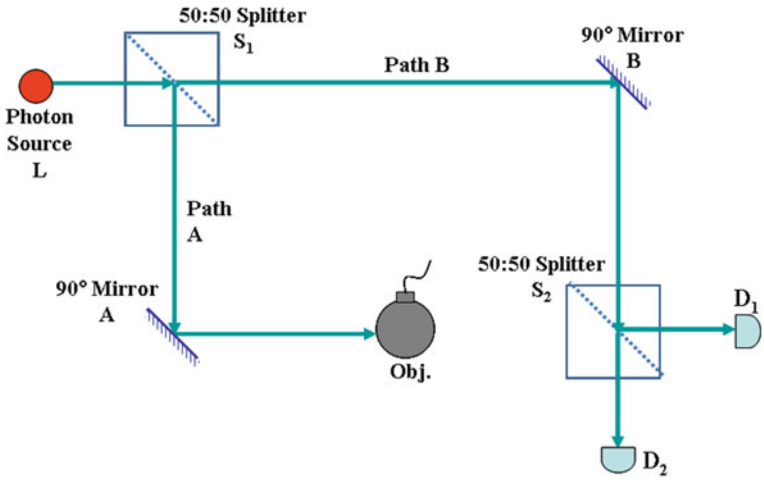

Fig. 6.15 Mach Zehnder interferometer with one beam path blocked. Half of the photons are absorbed by the blocking object, 25 % go to D_1, and 25 % go to D_2

there is no interference, and beam splitter S_2 sends equal components of the incident wave to the two detectors.

Now suppose that we arrange for the light source L to emit only one photon within a given time period. Then, if we do the measurement with no opaque object on path A, we should detect the photon at D_1 100 % of the time. If we perform the same measurement with the opaque object *Obj* blocking path A, we should detect a photon at D_1 25 % of the time, a photon at D_2 25 % of the time, and should detect no photon at all 50 % of the time (because it was removed by *Obj* in path A). In other words, the detection of a photon at D_2 guarantees that an opaque object is blocking path A, although no photon had actually interacted with object *Obj*. This is the essence of the Elitzur and Vaidmann interaction-free measurement.

Note that if a photon is detected at detector D_1, the issue of whether an object blocks path A is unresolved. However, in that case another photon can be sent into the system, and this can be repeated until either a photon is detected at D_2 or absorbed by *Obj*. The net result of such a recursive procedure is that 66 % of the time a photon will strike the object, resulting in no detection signal, while 33 % of the time a photon will be detected at D_2, indicating without interaction that an object blocks the A path. Thus, the EV procedure has an efficiency for non-interactive detection of 33 %.

As before, in analyzing interaction-free measurements with the Transactional Interpretation, we will explicitly indicate offer waves ψ by a specification of the path in a Dirac *ket* state vector $\psi = |\, path\rangle$, and we will underline the symbols for optical elements at which a reflection has occurred. Confirmation waves ψ^* will similarly be indicated by a Dirac *bra* state vector $\psi^* = \langle path\, |$, and will indicate the path considered by listing the elements in the time-reversed path with reflections underlined.

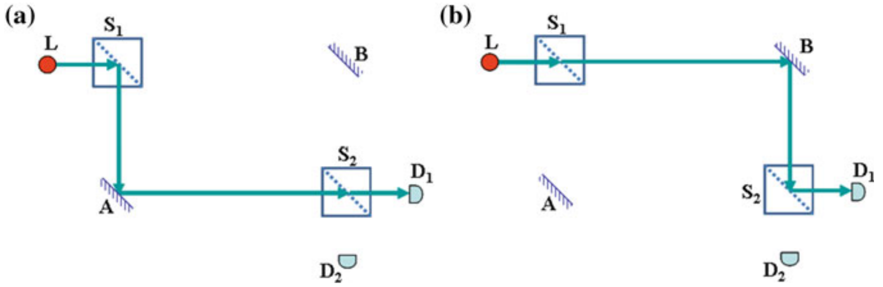

Fig. 6.16 Offer waves **a** $|\ L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}S_2\text{-}D_1\rangle$ and **b** $|\ L\text{-}S_1\text{-}\underline{B}\text{-}\underline{S_2}\text{-}D_1\rangle$

Consider first the situation in which no object is present in path A as shown in Fig. 6.16. The offer waves from L to detector D_1 are $|\ L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}S_2\text{-}D_1\rangle$ and $|\ L\text{-}S_1\text{-}\underline{B}\text{-}\underline{S_2}\text{-}D_1\rangle$. They arrive at detector D_1 in phase because the offer waves on both paths have been transmitted once and reflected twice. The offer wave from L initially has unit amplitude, but the splits at $^1/_{\sqrt{2}}$ each reduce the wave amplitude by $^1/_{\sqrt{2}}$ so that each wave, having been split twice, has an amplitude of $^1/_2$ as it reaches detector D_1. Therefore, the two offer waves of equal amplitude and phase interfere constructively, reinforce, and produce a confirmation wave that is initially of unit amplitude.

Similarly, the offer waves from L to detector D_2 are $|\ L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}\underline{S_2}\text{-}D_2\rangle$ and $|\ L\text{-}S_1\text{-}\underline{B}\text{-}S_2\text{-}D_2\rangle$. They arrive at detector D_2 180° out of phase, because the offer wave on path A has been reflected three times while the offer wave on path B has been transmitted twice and reflected once. Therefore, the two waves with amplitudes $\pm^i/_2$ interfere destructively, cancel at detector D_2, and produce no confirmation wave.

The confirmation waves from detector D_1 to L are $\langle D_1\text{-}S_2\text{-}\underline{A}\text{-}\underline{S_1}\text{-}L\ |$ and $\langle D_1\text{-}\underline{S_2}\text{-}\underline{B}\text{-}S_1\text{-}L\ |$. They arrive back at the source L in phase because, as in the previous case, the confirmation waves on both paths have been transmitted once and reflected twice. As before the splits at S_1 and S_2 each reduce the wave amplitude by $^1/_{\sqrt{2}}$, so that each confirmation wave has an amplitude of $^1/_2$ as it reaches source L. Therefore, the two offer waves interfere constructively, reinforce and have unit amplitude. Since the source L receives a unit amplitude confirmation wave from detector D_1 and no confirmation wave from detector D_2, the transaction forms along the path from L to D_1 via A and B. The result of the transaction is that a photon is always transferred from the source L to detector D_1 and that no photons can be transferred to D_2. Note that the transaction forms along *both* paths from L to D_1. This is a transactional account of the operation of the Mach–Zender interferometer.

Now let us consider the situation when the object blocks path A as shown in Fig. 6.17. The offer wave on path A is $|\ L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}Obj\rangle$. As before an offer wave on path B is $|\ L\text{-}S_1\text{-}\underline{B}\text{-}\underline{S_2}\text{-}D_1\rangle$, and it travels from L to detector D_1. The wave on path B also splits at S_2 to form offer wave $|\ L\text{-}S_1\text{-}\underline{B}\text{-}S_2\text{-}D_2\rangle$, which arrives at detector D_2. The splits at S_1 and S_2 each reduce the wave amplitude by $1/\sqrt{2}$, so that the offer wave at each detector, having been split twice, has an amplitude of $^1/_2$. However,

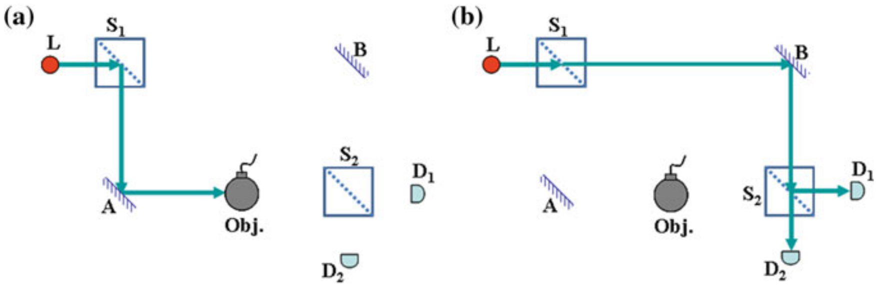

Fig. 6.17 **a** Offer waves $|\,L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}Obj\rangle$ and **b** $|\,L\text{-}S_1\text{-}\underline{B}\text{-}\underline{S_2}\text{-}D_1\rangle + |\,L\text{-}S_1\text{-}\underline{B}\text{-}S_2\text{-}D_2\rangle$

the offer wave $|\,L\text{-}\underline{S_1}\text{-}\underline{A}\text{-}Obj\rangle$ to the object in path A, having been split only once, is stronger and has amplitude of $1/\sqrt{2}$.

In this situation, the source L will receive confirmation waves from both detectors and also from the object. These, respectively, will be confirmation waves $\langle D_1\text{-}\underline{S_2}\text{-}\underline{B}\text{-}S_1\text{-}L\,|$, $\langle D_2\text{-}S_2\text{-}\underline{B}\text{-}S_1\text{-}L\,|$ and $\langle Obj\text{-}\underline{A}\text{-}\underline{S_1}\text{-}L\,|$. The first two confirmation waves started from their detectors with amplitudes of $1/2$ (the final amplitude of their respective offer waves) and have subsequently been split twice. Therefore, they arrive at source L with amplitudes of $1/4$. On the other hand, the confirmation wave from the object initially has amplitude $1/\sqrt{2}$, and it has been split only once, so it arrives at the source with amplitude $1/2$.

The source L has one photon to emit and three confirmations to choose from, with round-trip amplitudes ($\psi\psi^*$) of $1/4$, to D_1 $1/4$ to D_2, and $1/2$ to object Obj. In keeping with the probability assumption of the Transactional Interpretation and Born's probability law, it will choose with a probability proportional to these amplitudes. Therefore, the emitted photon goes to D_1 25 % of the time, to D_2 25 % of the time, and to object Obj in path A 50 % of the time. As we have seen above, the presence of the object in path A modifies the detection probabilities so that detector D_2 will receive $1/4$ of the emitted photons, rather than none of them, as it would do if the object were absent.

How can the transfer of non-classical knowledge be understood in terms of the transactional account of the process? In the case where there is an object in the A path, it is probed both by the offer wave from L and by the aborted confirmation waves from D_1 and D_2. The latter are 180° out of phase and cancel. When we detect a photon at D_2, (i.e., when a transaction forms between L and D_2), the object has not interacted with a photon (i.e., a transaction has not formed between L and the object Obj). However, it has been *probed* by an offer wave from the source, which "feels" its presence and modifies the interference balance at the detectors, providing non-classical information. Thus, the Transactional Interpretation gives a simple explanation of the mystery of interaction-free measurements.

6.13 The Quantum Zeno Effect (1998)*

P.G. Kwiat et al. [32], a collaboration based at Los Alamos National Laboratory and the University of Innsbruck, have demonstrated both theoretically and experimentally that the efficiency of an interaction-free measurement can be increased from 33 % in the EV scheme to a value that is significantly larger. In fact, the efficiency can be made to approach 100 %, depending on how many times N it is possible to cycle the incident photon through the measurement apparatus. Their scheme is shown in Fig. 6.18.

Here a light source L supplies photons that are horizontally (H) polarized. These are injected (*In*) into an optical "racetrack" that is capable of cycling a photon around in a closed rectangular loop N times before extracting it (*Out*) to an analyzing system. After injection, the photon passes through an optical polarization rotator element (R) that changes its direction of linear polarization by an angle $\theta = \pi/2N$. Note that if N is large, this rotation is small.

The photon then travels to a polarizing beam splitter (S_1) that transmit horizontally polarized (H) light and reflects vertically polarized (V) light. The object (*Obj*) to be measured may (or may not) be placed in the V beam path. Downstream of the object position, the H and V photon components enter a second polarizing beam splitter (S_2) that recombines them into a single beam. The recombined photon then cycles back through the apparatus. After N cycles, the photon is extracted and sent to a third polarizing beam splitter (S_3) that, depending on the photon's polarization, routes it to a pair of photon detectors D_H and D_V. This detection is, in effect, a measurement of whether the photon's final polarization is horizontal or vertical.

If no object is in the V path, the polarization split and recombination has no net effect. The polarization rotator rotates the plane of polarization N times, each time by an angle of $\pi/2N$. The cumulative rotation is therefore a rotation of $\pi/2$. Therefore,

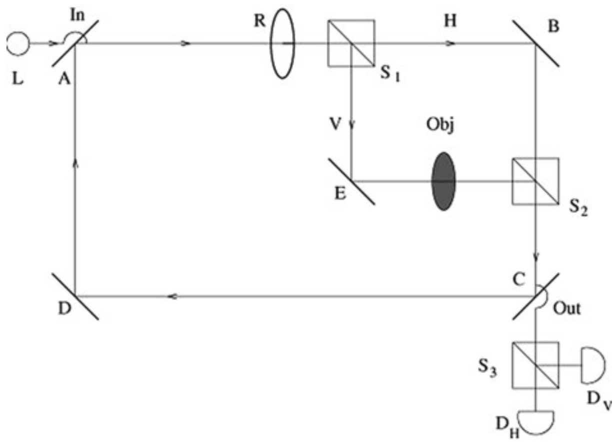

Fig. 6.18 Quantum Zeno arrangement for high efficiency interaction-free measurements

a photon that was initially polarized horizontally (H) will emerge from the apparatus with vertical (V) polarization and will be detected by photon detector D_V only.

On the other hand, if an object is placed in the V path, the H and V beams are not recombined, so the split at the first polarization beam splitter (S_1) is in effect a polarization measurement. From Malus' Law, there is a probability $P_E = \cos^2(\pi/2N)$ that the photon will survive each such horizontal polarization measurement and emerge in a pure state of horizontal (H) polarization. After each cycle in which the photon survives, it is reset to its initial state of horizontal (H) polarization, so that when it is extracted after N cycles it will be detected by photon detector D_H only. In each cycle, there is a small probability $(1 - P_E)$ that the photon will be projected into a state of pure vertical (V) polarization, will travel on the V path, will interact with the object, and will be removed from the process.

In summary, if the object is not present, the emerging photon will be detected by the D_V detector 100 % of the time. If the object is present, the emerging photon will be detected by the D_H detector with a probability $P_D = P_E^N = \cos^{2N}(\pi/2N)$, and the photon will interact with the object and be removed with a probability $P_R = 1 - P_E^N = 1 - \cos^{2N}(\pi/2N)$. We note that when N is large, $P_D \approx 1 - (\pi/2)^2/N$ and $P_R \approx (\pi/2)^2/N$. Therefore, the probability of removal decreases as $1/N$ and goes to zero as N goes to infinity. Therefore, the procedure greatly improves the efficiency of interaction-free measurements. For example, when the number of passes N is equal to 5 the measurement is 60 % efficient. With $N = 10$ it is 78 % efficient, and with $N = 20$ it is 88 % efficient. Figure 6.19 shows an unfolding of the quantum-Zeno interaction-free measurement, for the case where no object is placed in the V beam.

The recycled path is represented as a linear sequence of incremental rotations, beam splittings, and beam recombinations. It should be clear from the diagram that the successive splittings and recombinations have no net effect. On the other hand, the N successive rotations have the cumulative effect of a $\pi/2$ rotation that converts the initial horizontally polarized photons into vertically polarized photons by the time they reach the final beam splitter and the detector D_V.

From the point of view of the Transactional Interpretation, the initial offer wave leaves the light source L and is then successively rotated, split, and recombined. These operations do not reduce the amplitude, so the offer wave reaches detector D_V at full strength. The confirmation wave from D_V travels back along the same path and arrives back at L at full strength, thereby completing the transaction.

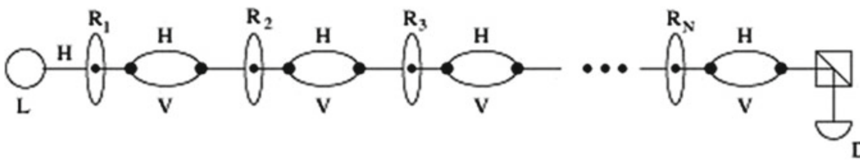

Fig. 6.19 Unfolding of the Quantum Zeno measurement (no object) for high efficiency interaction-free measurements

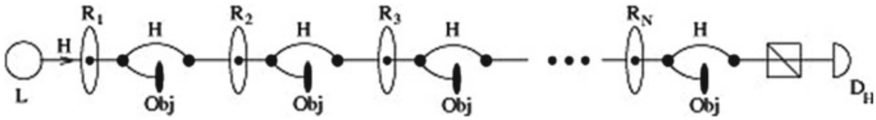

Fig. 6.20 Unfolding of the Quantum Zeno measurement with an object present

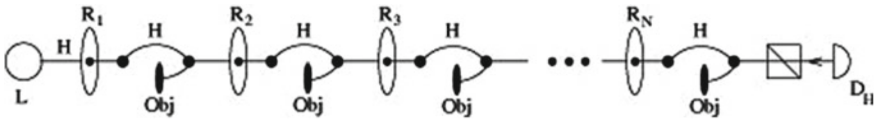

Fig. 6.21 Paths of detector confirmation waves in the unfolded Quantum Zeno measurement with an object present

The situation when an absorber is present and there is no interaction is shown in Fig. 6.20.

Now the object *Obj* blocks the path V of the vertically polarized beam after the splitter, so only the photons on the H path can reach the detector system. The net effect of this is that after each incremental rotation, the beam is reset to the H state and passes straight through the final splitter without deflection to reach detector D_H.

From the point of view of the Transactional Interpretation, the initial offer wave leaves the light source L and at each rotation and splitting the intensity of the offer wave that will reach detector D_H is reduced by $\cos(\pi/2N)$, so that the net intensity at the detector is $\cos^N(\pi/2N)$. At the mth split (for m = 1 to N), an offer wave of intensity $\cos^{m-1}(\pi/2N)\sin(\pi/2N)$ travels to the object *Obj* and may interact with it. The confirmation wave from each of these potential interactions will travel back to the light source L with the same reduction factor, so that the net probability of an interaction following the mth split is $\cos^{2(m-1)}(\pi/2N)\sin^2(\pi/2N)$.

The path of confirmation waves from the detector D_H is shown in Fig. 6.21. The confirmation wave leaves detector D_H with an amplitude of $\cos^N(\pi/2N)$, the final amplitude of the offer wave. As the confirmation wave travels back to the light source L, at each of the N splits it is reduced in intensity by a factor of $\cos(\pi/2N)$. Thus its net intensity at L will be $\cos^{2N}(\pi/2N)$, which is just the probability that the detection event will occur. At each split, there is a component of the confirmation wave that takes the lower path in Fig. 6.21 and ends at object *Obj*. However, these components cannot form a transaction, since they cannot connect back to the light source L.

As before, the object *Obj* in the V path is probed both by the offer wave from L and by the aborted confirmation wave from D_H. When we detect a photon at D_H, (i.e., when a transaction forms between L and D_H), the object *Obj* has not interacted with a photon (i.e., a transaction has not formed between L and *Obj*), but the object has been probed repeatedly by weak offer and confirmation waves from both sides. As the number of passes N is increased and the efficiency of the measurement approaches 100 %, the amplitudes of these probe waves grows weaker as their number increases. It also becomes clear why, even when the object does not interact with a photon, the *possibility* of interactions is required. If the interaction probability were zero, the offer and confirmation waves would not be blocked by the interposed object and the measurement would not have been possible.

6.14 Maudlin's *Gedankenexperiment* (1996)

In a book publication of his PhD Thesis in 1996, Tim Maudlin [33] constructed a *gedankenexperiment* that he claimed cast doubt on the validity of the Transactional Interpretation.[1]

Figure 6.22a shows Maudlin's *gedankenexperiment*. A particle source S is configured to emit a single slow particle ($v \ll c$) that has a 50 % chance of being emitted in the direction of particle detector A on the right and a 50 % chance of being emitted in the direction of particle detector B on the left. However, particle detector B is initially positioned behind A on the right, and only if A *does not detect the particle* is B moved to its final position on the left, where the emitted particle will be detected. Maudlin claims that there cannot be the a transactional "echo" competition between the two possible outcomes because the second outcome (detection at B) is causally connected to the first outcome (non-detection at A). He also claims that the process is deterministic rather than stochastic and that after a non-detection at A, the wave function for detection at B must have an increased amplitude, not provided by the Transactional Interpretation, because it will then have a 100 % probability of being detected. Lewis [35] has subsequently made the same latter claim.

We will dispose of Maudlin's last point first. For the purposes of evaluating probabilities including a non-detection event, his experiment is the same as that of Renninger, which is discussed in Sect. 6.6. Renninger's *gedenkenexperiment* was also discussed in some detail in Sect. 4.1 of the 1986 TI paper [36], the target of Maudlin's critique. The claim by Maudlin and Lewis that the left-going wave function should change at the instant when detector A can, but does not, detect a particle. This expectation is an unverifiable prediction of Heisenberg's knowledge interpretation. It is not suggested by either the Transactional Interpretation or the standard quantum formalism. In the TI description, the left-going wave function does not magically change in mid-flight, nor does it need to. In the TI the amplitude of the left-going wave and its echo remain unchanged after a right-going particle should have reached detector A, and they correctly predict that 50 % of the particles will be detected by detector B

[1] Ruth Kastner [34] states that "Maudlin's Challenge" was taken as fatal to the Transactional Interpretation by philosophers of science for over a decade. My initial reaction to his paradox, after obtaining Maudlin's book by inter-library loan, was that before the assertions could be taken seriously, he needed to provide a mathematical description of his *gedankenexperiment* using the formalism of quantum mechanics, and then to use that formalism with the Born rule to calculate probabilities, etc., since it is the formalism, not the interpretation, that should be used to make predictions. However, at a meeting is Sydney in 2005, Kastner convinced me that Maudlin did have a point worth considering (and discussed here). This resulted in my realization that the concept of *hierarchy* needed to be added to the transaction model (see Sect. 5.5) to deal with the problem that he had raised.

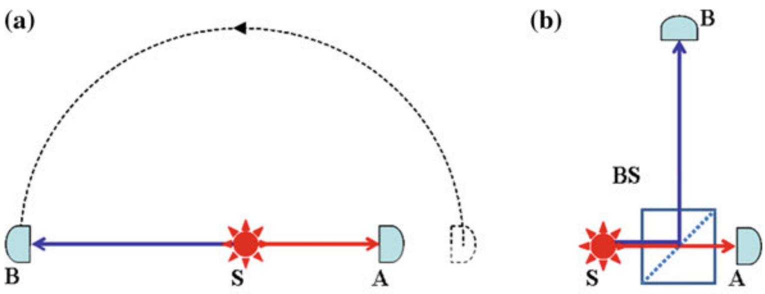

Fig. 6.22 **a** Maudlin's *gedankenexperiment*: Slow particle source S emits one particle that either goes to detector A on the right (*red*) or to detector B on the left (*blue*), with a 50 % probability of each. However, detector B is initially positioned behind A and is only moved to it final position on the left if A does not detect a particle. **b** Related experiment: Single photon source S sends one photon through a 50:50 splitter BS to detectors A and B

(See Sect. 6.6 for further discussion of this point.). Maudlin and Lewis have provided another example of the dangers of swallowing whole the knowledge interpretation, with its disappearing waves.

Now let's consider the Maudlin experiment and its implications. Maudlin's specifications for the source seem innocent enough, but in the real world they present a problem. Real sources in the quantum optics laboratory do not emit single particles "on command", like a gun when the trigger is pulled; they emit at a rate that is adjusted so that, in a given time interval, the probability of emitting one particle is greater than that of emitting zero or two particles, in keeping with the time-energy constraints of the uncertainty principle. Therefore, there is always a non-zero probability that no particles at all will be emitted by the source, and that possibility cannot be switched off. Thus, in the real world there are three possible outcomes for Maudlin's setup: detection at A, detection at B, and no detection at all.

How is Maudlin's experiment described with the quantum formalism? The state vector can be written as:

$$| S(t)\rangle = \frac{1}{\sqrt{2}}(| 1\rangle_A \, | 0\rangle_B + e^{i\phi} \, | 0\rangle_A \, | 1\rangle_B) \tag{6.9}$$

where ϕ is a phase that depends on relative path length, $| 1\rangle_A$ indicates detection of one photon at A, $| 1\rangle_B$ indicates detection at B, $| 0\rangle_A$ indicates no detection at A, and $| 0\rangle_B$ indicates no detection at B. This is the same wave function that could be used to describe the related experiment shown in Fig. 6.22b. In both experiments the external world can be undergoing irreversible changes during the time interval between the potential A and B detections, but only in Fig. 6.22a do these changes affect the B detection configuration. In both experiments, applying the Born probability rule to Eq. 6.9 leads to 50:50 detection probabilities, in contradition to Maudlin's assertion.

Interestingly, Eq. 6.9 is a Bell-state wave function (see Sect. 2.8 and Eq. 2.2) describing the entanglement of detection at one detector with the non-detection at the other detector. The difference between the two experiments, despite the fact that they share the same wave function, is that in Fig. 6.22a a causal connection has been implemented between non-detection at A and the position of B, while in Fig. 6.22b there is no such connection. The point of this comparison is that the QM formalism is indifferent to whether there is a causal connection or not.

However, Maudin has a valid point. There would seem to be a problem in the situation in which some early possible outcomes of a transaction can change the physical configuration of later possible outcomes. This problem is solved by the assumption of *hierarchy*. The hierarchy part of the 3D transaction model discussed in Sect. 5.5 asserts that in selecting a transaction from among the advanced-retarded wave echos, the emitter makes an ordered separate decision to select or not select each particular echo for transaction formation. Thus, each echo is successively in competition with the decision to form no transaction, not with the other echos. The emitter evaluates echos propagating back from small space-time intervals before proceeding to those echoes from larger intervals. In this way, the time structure of the future universe is in some sense built into the transaction selection process.

The hierarchy assumption resolves the problem that Maudlin had pointed out. The echo from A is considered first, and only if it is rejected is the echo from B considered. The rejection of the A detection triggers the movement of B, which then is in place to intercept the left-going wave and produce the echo received and selected by the source. In both cases, the possibility of no detection (and no emission) is a competing possibility. The 50 % probability in the setup is a statement of the relative probabilities of the two detections, and does not include the probability that no particle will be emitted at all in the time interval of the experiment. We note that the physics literature contains several other analyses and resolutions of Maudlin's *gedankenexperiment* [37–40], none of which is identical to the analysis presented here.

Maudlin also claimed that the Transactional Interpretation was deterministic rather than stochastic because it provided no mechanism for randomness. This claim too is incorrect. The intrinsic randomness of the Transactional Interpretation comes in the third stage of transaction formation, in which the emitter, presented with a sequence of retarded/advanced echoes that might form a transaction, hierarchically and randomly selects one (or none) of these as the initial stage of transaction formation, as described in Sect. 5.5. Mead's TI-based mathematical analysis of a quantum jump [41], discussed there, describes a process in which the perturbations between emitter and absorber create a frequency-matched pair of unstable dipole resonators that either exponentially avalanche to a full-blown transaction with the transfer of energy or else disappear due to boundary conditions when a competing transaction forms. In a universe full of particles, this process does not occur in isolation, and both emitter and absorber will be bombarded with perturbations from other systems that can randomly drive the instability in either direction. This is the source of randomness in the Transactional Interpretation.

In this context, it is interesting that Boisvert and Marchildon [40] have suggested that if one assumes determinism and a block universe, the hierarchy described above is not needed. We, however, prefer hierarchy and randomness to determinism, as discussed in Sect. 9.2.

6.15 The Afshar Experiment (2003)*

The Afshar experiment [42] shows that, contrary to some of Niels Bohr's pronouncements about complementarity and wave particle duality, it is possible to see the effects of wave-like behavior and interference, even when particle-like behavior is being directly observed. In Bohr's words [43]: " … we are presented with a choice of either tracing the path of the particle, or observing interference effects, … we have to do with a typical example of how the complementary phenomena appear under mutually exclusive experimental arrangements." In the context of a two-slit experiment, Bohr asserted [44] that complementarity in the Copenhagen Interpretation dictates that "the observation of an interference pattern and the acquisition of which-way information are mutually exclusive."

The Afshar experiment, shown in Fig. 6.23 was first performed in 2003 by Shariar S. Afshar and was later repeated while he was a Visiting Scientist at Harvard. It used two pinholes in an opaque sheet illuminated by a laser. The light passing through the pinholes formed an interference pattern, a zebra-stripe set of maxima and zeroes of light intensity that were recorded by a digital camera. The precise locations of the interference minimum positions, the places where the light intensity went to zero, were carefully measured and recorded.

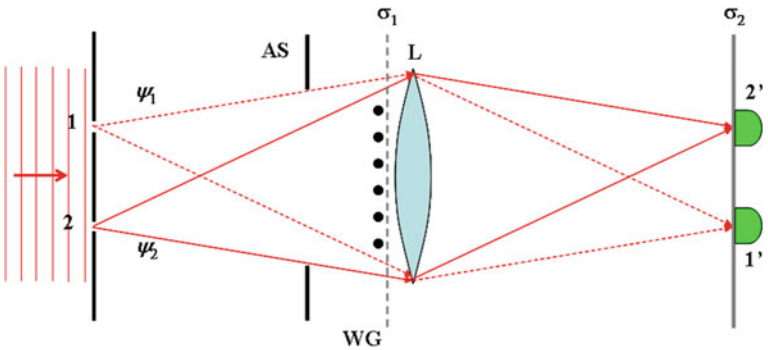

Fig. 6.23 In the Afshar experiment, a version of Wheeler's delayed-choice experiment (Sect. 6.7) is modified by placing vertical wires (WG) at the locations at which the interference pattern has interference minima on screen σ_1. High transmission of light through the system when the wires are present and σ_1 is absent implies that the interference pattern is still present, even when which-way information is available from the downstream detectors $1'$ and $2'$

Behind the plane where the interference pattern formed, Afshar placed a lens that formed an image of each pinhole at a second plane. A light flash observed at image $1'$ on this plane indicated unambiguously that a photon of light had passed through pinhole 1, and a flash at image $2'$ similarly indicated that the photon had passed through pinhole 2. Observation of the photon flashes therefore provided particle-path which-way information, as described by Bohr. According to the Copenhagen Interpretation, in this situation all wave-mode interference effects must be excluded.

However, at this point Afshar introduced a new element to the experiment. He placed one or more vertical wires at the previously measured positions of the interference minima. In such a setup, if the wire plane was uniformly illuminated the wires absorbed about 6 % of the light. Then Afshar measured the difference in the light intensity received at the pinhole image detectors with and without the wires in place.

We are led by the Copenhagen Interpretation to expect that when which-way information is obtained the positions of the interference minima should have no particular significance, and that the wires should intercept 6 % of the light, as they do for uniform illumination. However, what Afshar observed was that the amount of light intercepted by the wires is very small, consistent with 0 % interception. This implies that the interference minima are still locations of zero intensity and that the wave interference pattern is still present, even when which-way measurements are being made. Wires that are placed at the zero-intensity locations of the interference minima intercept no light. This observation would seem to create problems for the complementarity assertions of the Copenhagen Interpretation. Thus, the Afshar experiment is a significant quantum paradox.

The Transactional Interpretation explains Afshar's results as follows: The initial offer waves pass through both slits on their way to possible absorbers. At the wires, the offer waves cancel in first order, so that no transactions to wires can form, and no photons can be intercepted by the wires. Therefore, the absorption by the wires should be very small ($\ll$6 %) and consistent with what is observed. This is also what is predicted by the QM formalism. The implication is that the Afshar experiment has revealed a situation in which the Copenhagen Interpretation has failed to properly map the standard formalism of quantum mechanics.

We note that the many-worlds interpretation of quantum mechanics [29, 30] asserts that interference between its "worlds" (e.g., paths taken by particles) should not occur when the worlds are quantum-distinguishable. Therefore, the Many-Worlds interpretation would also predict that there should be no interference effects in the Afshar experiment. Thus, the Many-Worlds interpretation has also failed to properly map the standard formalism of quantum mechanics.

6.16 Momentum-Entangled 2-Slit Interference Experiments (1995–1999)

The Freedman–Clauser and quantum-eraser experiments described in Sects. 6.8 and 6.11 above use conservation of angular momentum and the entanglement of the polarization states of a photon pair to demonstrate EPR correlations and switchable interference patterns. Although the entanglement of linear polarization is a very convenient medium for EPR experiments and Bell-inequality tests, in many ways the alternative offered by momentum-entangled EPR experiments provides a richer venue, and we will consider some of these here.

*6.16.1 The Ghost-Interference Experiment (1995)**

Perhaps the earliest example of a momentum-entangled EPR experiment is the 1995 "ghost interference" experiment of the Shih Group at University of Maryland Baltimore County [45]. Their experiment is illustrated in Fig. 6.24.

Here a nonlinear BBO (β-BaB_2O_4) crystal pumped by a 351 nm argon-ion laser produces co-linear pairs of momentum-entangled 702 nm photons, one (*e* or extraordinary) polarized vertically and the other (*o* or ordinary) polarized horizontally. These are directed to separate paths by a polarizing beam splitter (PBS).

The experimenters demonstrated that when the pair of photons is examined in coincidence, passing the *e*-photon through a double slit system before detection at

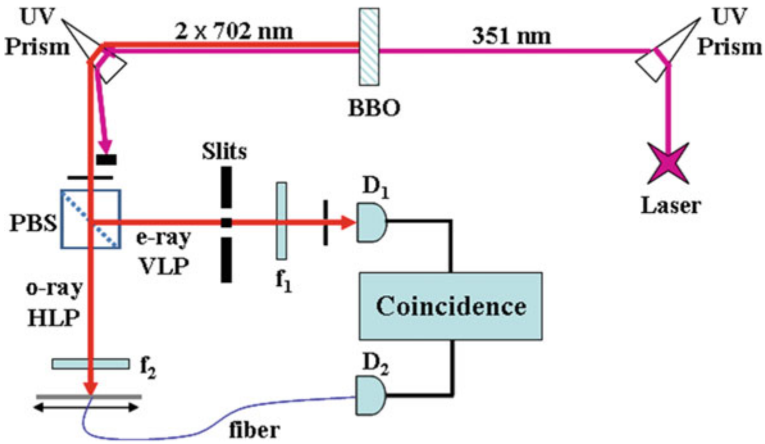

Fig. 6.24 The "ghost interference" experiment of the Shih Group/UMBC. A BBO crystal produces a momentum-entangled photon pair with orthogonal polarizations, which are split and sent along two paths. Covering one slit in the *e* path switches off the 2-slit interference pattern observed in the *o* path

D_1 produced either (1) a "comb" 2-slit interference distribution or (2) a "bump" diffraction distribution in the position X_2 of the e-photon detected at D_2, depending on whether (1) both slits were open so the o-photon could take both paths through the slits or (2) one of the slits was blocked, so that which-way information was obtained about the path of the e-photon.

Thus, one can make the interference pattern of the o-photon observed at D_2 appear or disappear, depending on what is done to the e-photon. If the e-photon is made to exhibit particle-like behavior by passing through only one slit, the e-photon also exhibits particle-like behavior. If the e-photon is made to exhibit wave-like behavior by passing through both slits and interfering, the o-photon also exhibits the wave-like behavior of an interference pattern. This suggests a paradox: that in a system with a momentum-entangled photon pair, a nonlocal signal might be sent from one observer to another by controlling the presence or absence of an interference pattern. To send such a signal, however, one would have to be able to see the interference in singles, without a coincidence with detection of the other member of the photon pair. The Shih Group reported that no interference pattern was observed in singles. See Chap. 7 for a detailed discussion of the possibility of nonlocal signaling.

The Transactional Interpretation explains the ghost interference effect as follows: the e and o photon are momentum entangled, so that any transaction involving them must conserve transverse momentum, because the transverse momenta of the pair must add up to the near-zero transverse momentum of the pump photon that produced them. Therefore, if the e photon deviates to the right of its beam center-line, the o photon must deviate a corresponding amount to the left of its beam center-line. Therefore, a two-photon transaction involving detection at D_1 of e offer waves that have passed through both slits must be accompanied by detection at D_2 with o offer waves matching the two paths of the e waves. Both sets of offer waves will coherently interfere and produce two-slit interference patterns. However, if one of the slits is blocked, the new transaction that forms will involve only one path for each photon, and no two-slit interference will be observed.

*6.16.2 The Dopfer Experiment (1999)**

Another momentum-entangled EPR experiment was the 1999 PhD thesis of Dr. Birgit Dopfer at the University of Innsbruck [46], performed under the direction of Prof. Anton Zeilinger. The Dopfer experiment is illustrated in Fig. 6.25.

Here a nonlinear $LiIO_3$ crystal pumped by a 351 nm laser produces momentum-entangled pairs of 702 nm photons and selects pairs that emerge from the crystal at angles of 28.2° to the right and left of the pump axis. The lower photon in the diagram passes through 2-slit system S_1 and is detected by single-photon detector D_1. The upper photon passes through a lens of focal length f and is detected by single-photon detector D_2. The system geometry is arranged so that the distance from S_1 to the crystal plus the distance from the upper lens to the crystal add to a total distance of

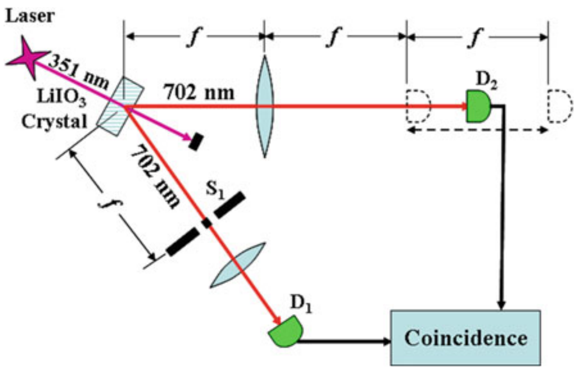

Fig. 6.25 The Dopfer experiment of the Zeilinger Group/Innsbruck. Here the distance $2f$ (twice the focal length) is the "bent" distance from the lens to the slits S_1, and also the distance from the lens to the extreme position of detector D_2

$2f$. Beyond the upper lens, detector D_2 can be positioned either (Case 1) at a distance of $2f$ from the lens or (Case 2) at a distance of f from the lens. It is observed that for Case 2 an interference pattern is observed at D_2, while for Case 1 there is no interference pattern, but only a broad aperture-diffraction distribution.

Dopfer demonstrated that for Case 1, the position distribution measured by detector D_2 showed two sharp spikes, which were interpreted as "ghost" images of the slits at S_1 that provided which-way information. The slit-lens-detector geometry was such as to produce a 1:1 image, and momentum entanglement caused a right-going photon in the lower system to be mirrored by a left-going photon in the upper system. Thus, in Case 1 detector D_2 in effect was measuring which path the lower photon took through the slit system S_1 and forcing particle-like behavior in both photons that suppressed the two-slit interference pattern.

In Case 2 the distributions measured by detectors D_1 and D_2 were both two-slit interference patterns. Detector D_2 was placed in the "circle of confusion" region of the lens where no image was formed and virtual rays from both slits would overlap, resulting in interference. Thus, in Case 2 both photons of the entangled pair exhibited wave-like behavior and formed interference patterns.

Therefore, one can make the interference pattern at detector D_1 appear or disappear, depending on the location of detector D_2. Again, this suggests that in a system with a momentum-entangled photon pair, a nonlocal signal might be sent from one observer to another by controlling the presence or absence of an interference pattern.

The Transactional Interpretaton handles the Dopfer experiment in the same way as the ghost interference experiment discussed in Sect. 6.16.1. When which-way information is available, a 3-vertex transaction can form between D_1, the crystal, and only one of the slit images at D_2. When D_2 is in the circle-of-confusion region, a 3-vertex transaction can form between D_1, the crystal, and any point on the interference pattern at D_2. Thus, the interference pattern at D_1 is "switchable", depending on the distance of D_2 from the lens.

The question has been raised [47] of whether this switchable-interference-pattern behavior can be preserved if the coincidence requirements in these two experiments are removed to facilitate nonlocal signaling. This issue is addressed in Chap. 7.

6.17 "Boxed Atom" Experiments (1992–2006)

The Stern–Gerlach (SG) effect for measuring atomic spin was first demonstrated in 1922 [48]. It uses the inhomogeneous magnetic field near a wedge-shaped magnetic pole tip to deflect a beam of atoms (in the SG case, spin-$\frac{1}{2}$ silver atoms) either upward or downward, depending on the direction in which the atomic spin was pointing with respect to the vertical axis. The beam splitting is, in effect, a measurement of the spin directions of the atoms along a selected axis perpendicular to the beam. The SG effect is reversible, in the sense that a second inhomogeneous magnetic field can recombine the two beams into a single beam of indeterminate spin direction.

6.17.1 The Hardy One-Atom Gedankenexperiment

In 1992 Lucien Hardy [49, 50] proposed the *gedankenexperiment* shown in Fig. 6.26, which is a modified version of the interaction-free measurement scenario of Elitzur and Vaidmann [28] (see Sect. 6.12) in which their blocking object (or bomb) is replaced by a single spin-$\frac{1}{2}$ atom, initially prepared in an X-axis $+\frac{1}{2}$ spin-projection,

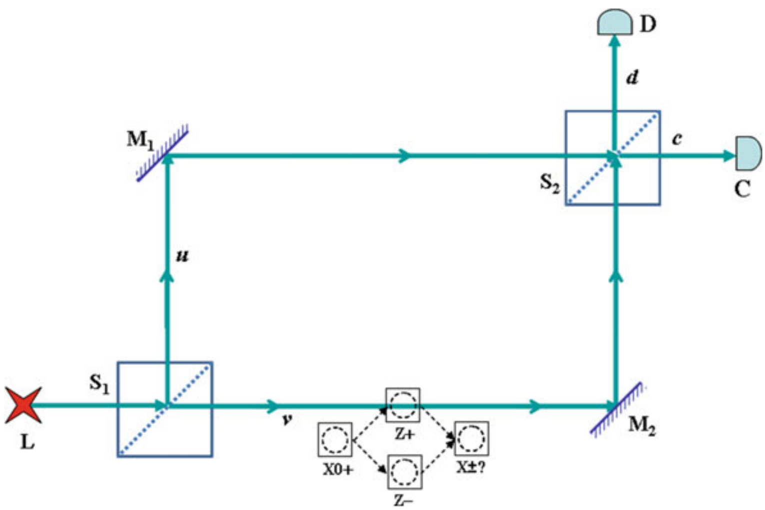

Fig. 6.26 The Hardy single-atom interaction-free measurement

then Stern–Gerlach separated into one of two spatially separated boxes that momentarily contain the atom in its Z-axis $+1/2$ and $-1/2$ spin projections, then transmit their contents to be recombined by an inverse Stern–Gerlach process, so that the X-axis projection of the atom can be measured.

The Z-spin $+1/2$ box ($Z+$) is placed directly in one path of a Mach–Zehnder interferometer, so that if the atom is present in that box during photon transit, it has a 100 % probability of absorbing a photon traveling along that arm of the interferometer.[2] After a single photon from light source L traverses the interferometer, the final X-axis spin projection of the atom is measured.

The non-classical outcome of the *gedankenexperiment* is that, for events in which a photon is detected by dark detector D, the spin measurement of the atom has a 50 % probability of having an X-axis spin projection of $-1/2$, even though the atom had previously been prepared in the $+1/2$ X-axis spin state, and the atom had never directly interacted with the photon.

Hardy analyzes the measurement in terms of the Bohm–de Broglie interpretation/revision of quantum mechanics [51] and concludes that the non-classical outcome of the measurement can be attributed to "empty waves", by which he means de Broglie guide waves that have traversed the interferometer along paths not subsequently followed by the single emitted photon. At least four other papers [52–55] have analyzed the Hardy *gedankenexperiment* using alternative QM interpretations that focus on wave function collapse, notably the "collapse" and the "consistent histories" interpretations.

Appendix D.1 provides a detailed analysis of this experiment using the Transactional Interpretation and explains the transfer of non-classical knowledge in terms of the transactional account of the process. In particular, in the case where there is an atom in the v path, it is probed by the offer wave from L. When we detect a photon at D, (i.e., when a transaction forms between L and D), the object has not interacted with a photon (i.e., a transaction has not formed between L and the atom in box $Z+$). However, the atom has been probed by offer waves from L, which "feel" its presence and modify the interference balance at the detectors and the spin statistics of the atom. Thus, the Transactional Interpretation gives a simple explanation of the Hardy *gedankenexperiment*.

6.17.2 The Elitzur–Dolev Three-Atom Gedankenexperiment

Elitzur and Dolev [56] proposed an elaboration of the Hardy experiment, shown in Fig. 6.27, in which three spin-analyzed Hardy-mode atoms instead of one are placed in boxes intercepting the v interferometer arm. Any of the upper boxes in the v path may be opened, measuring the Z-spin of that atom, or the upper and lower

[2] In the real world, it would be extremely difficult to insure that an isolated trapped atom would intercept a single incident photon with 100 % probability. Thus, Hardy's interesting proposal is doomed to remain a *gedankenexperiment*.

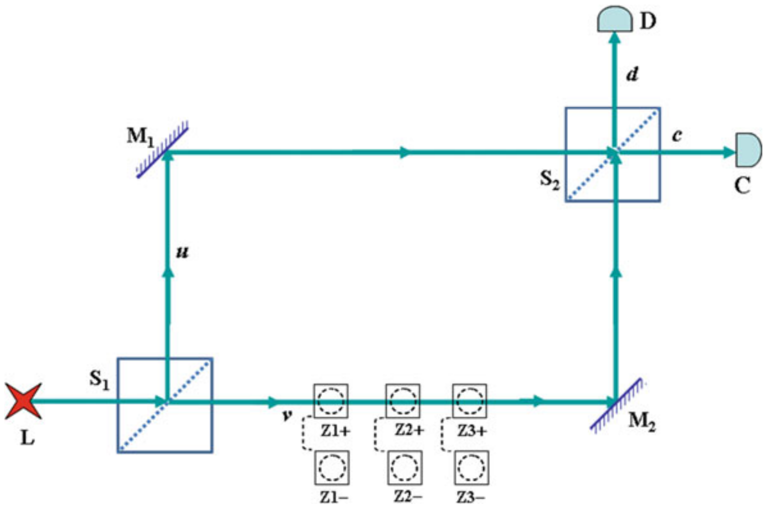

Fig. 6.27 The Elitzur–Dolev three-atom *Gedankenexperiment*

box contents may be recombined in an inverse Stern–Gerlach procedure and a measurement of the atom's X-spin performed. They do a detailed quantum mechanical analysis of the expected results, which will not be reproduced here.

The most surprising outcome of that analysis is for the case in which a photon is detected in dark detector *D* and one of the three atoms is found to be in the Z-spin $+1/2$ state by opening its upper box on the *v* path and finding the atom to be present there. In this situation, the analysis indicates that the other two atoms *must* be found to have remained in their initially prepared state of X-axis spin $+1/2$. This is true no matter which of the boxes is opened. The other two atoms always remain in their original spin state, unperturbed by the photon, and this result is independent of the order of the atoms along path *v*. Further, a larger number of Hardy-mode atoms could be placed along path *v*, and in that situation it would still be the case that finding one atom with a Z-spin of $+1/2$ would leave all the others unperturbed, even though their wave functions all intercept the photon's possible *v* path before or after the selected atom.

Elitzur and Dolev point out that in this situation, Hardy's empty wave analysis [49, 50] fails, as do all other analyses in the literature [52–55]. They suggest that the Transactional Interpretation might be able to account for the expected non-classical results of the *gedankenexperiment*, and they request that such an analysis, along the lines of the author's previous analysis of interaction free measurements [57], be performed for this *gedankenexperiment*.

The paradoxical aspects of this *gedankenexperiment* arise partly from the fact that there are really four *gedankenexperiments* to be analyzed, one in which all boxes remain closed and three in which one of the boxes is opened. A transactional analysis, as in the case of the AAD *gedankenexperiment* discussed in Sect. 6.10, needs to be performed separately for each of the four experimental configurations.

Following Elitzur and Dolev, we will focus on only those events in which a photon is detected in dark detector D, indicating the presence of at least one atom in a $+1/2$ Z-spin state along path v. In the box positions, the three atoms may be in 2^3 or eight different state combinations, which are:

$$|\,s\,\rangle \equiv |\,Z_{1+}\rangle\,|\,Z_{2+}\rangle\,|\,Z_{3+}\rangle \tag{6.10}$$
$$|\,t\,\rangle \equiv |\,Z_{1-}\rangle\,|\,Z_{2+}\rangle\,|\,Z_{3+}\rangle \tag{6.11}$$
$$|\,u\,\rangle \equiv |\,Z_{1+}\rangle\,|\,Z_{2-}\rangle\,|\,Z_{3+}\rangle \tag{6.12}$$
$$|\,v\,\rangle \equiv |\,Z_{1+}\rangle\,|\,Z_{2+}\rangle\,|\,Z_{3-}\rangle \tag{6.13}$$
$$|\,w\,\rangle \equiv |\,Z_{1-}\rangle\,|\,Z_{2-}\rangle\,|\,Z_{3+}\rangle \tag{6.14}$$
$$|\,x\,\rangle \equiv |\,Z_{1+}\rangle\,|\,Z_{2-}\rangle\,|\,Z_{3-}\rangle \tag{6.15}$$
$$|\,y\,\rangle \equiv |\,Z_{1-}\rangle\,|\,Z_{2+}\rangle\,|\,Z_{3-}\rangle \tag{6.16}$$
$$|\,z\,\rangle \equiv |\,Z_{1-}\rangle\,|\,Z_{2-}\rangle\,|\,Z_{3-}\rangle \tag{6.17}$$

For all of these possibilities except $|\,z\,\rangle$, one (or more) of the atoms will block an offer wave on path v, suppressing the destructive interference and enabling a possible photon detection at dark detector D. In the experimental configuration in which no boxes are opened, the box contents are recombined, and the X-spin states of the atoms are measured, the atom transactions superimposing states $|\,s\,\rangle$ to $|\,y\,\rangle$. Because of the slight 4 to 3 preference for the Z-axis $+1/2$ spin state in the superposition, the observer will find each atom in the prepared X-spin $+1/2$ with a slightly higher probability than finding other combinations.

Now we assume that box Z_{2+} is opened, and the second atom is found to be in the Z-axis $+1/2$ spin state. This observation is only consistent with offer waves $|\,s\,\rangle$, $|\,t\,\rangle$, $|\,v\,\rangle$, and $|\,y\,\rangle$, so the offer wave is a superposition of these states. For the other two atoms, this superposition contains equal amplitudes for Z-axis spin of $+1/2$ and $-1/2$ with no alteration of phase, so if the contents of boxes 1 and 3 are recombined and the X-axis spins measured, the resulting transactions will require both atoms have X-axis spins of $+1/2$, as was originally prepared. If we assume that box Z_{1+} or Z_{3+} is opened instead, we will obtain the same result for the other two atoms. Elitzur and Dolev describe this result as: "In other words, only one atom is affected by the photon in the way pointed out by Hardy, but that atom does not have to be the first one, nor the last; it can be any one out of any number of atoms. The other atoms, whose wave-functions intersect the Mach–Zehnder interferometer arm before or after that particular atom, remain unaffected."

In the context of the Transactional Interpretation, is it really true that only one of the Hardy atoms interacts with the photon? No. The offer waves for the photon detected at D have interacted with all of the atoms, but have done so in such a way as to force all remaining atoms into their original state when one selected atom is found to be in the path-blocking Z-axis $+1/2$ spin state. The allowed composite multi-vertex transactions between transaction vertexes L, D, Z_{2+}, X_{1+}, and X_{3+}, or the equivalent for other measurement scenarios, produce this result. The Transactional Interpretation has no difficulty in explaining this counter-intuitive result.

6.17.3 The Elitzur–Dolev Two-Atom Gedankenexperiment

In 2006 Elitzur and Dolev [56] also proposed another revision of the Hardy experiment, shown in Fig. 6.28, in which spin-analyzed atoms are placed in boxes intercepting both of the Mach–Zehnder interferometer arms. In the interest of brevity, we will leave it as an exercise for the reader to repeat the detailed analysis of the previous sections. Instead, we observe that this is a direct extension of Hardy's *gedankenexperiment*, except that there are now nine transaction vertices: L, C, D, $X10_+$, $Z1_+$, and $X1_\pm$, $X20_+$, $Z2_-$, and $X2_\pm$. The same boundary conditions discussed above apply to these photon and atom vertices.

Again focusing on non-classical events involving photon detection at dark detector D, we see that such detection requires that an atom in box $Z1_+$ blocks the v path or an atom in box $Z2_-$ blocks the u path, but not both. Because of the superposition of the two possibilities, the atom detectors $X1_\pm$ and $X2_\pm$ will measure a probability $\frac{3}{4}$ of observing the previously prepared spin state and a probability $\frac{1}{4}$ of observing the opposite spin state.

Elitzur and Dolev, in considering the possibility of a transactional analysis of this *gedankenexperiment*, stated "Once the interaction time with the atom is over and no absorption occurred, two facts need to be addressed: (1) The wave-function is radically changed, now giving probability 1 that the photon is in the other

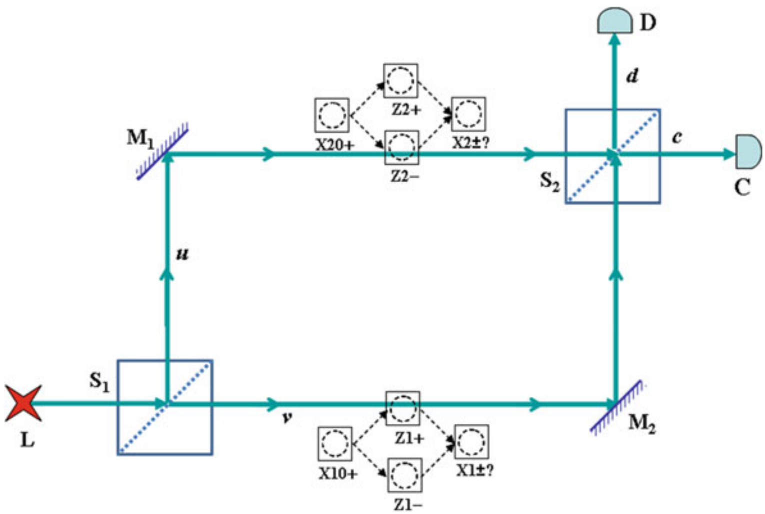

Fig. 6.28 The Elitzur–Dolev two-atom *Gedankenexperiment*

Mach–Zehnder interferometer path and (2) One can remove the second beam splitter and the detectors in a ‘delayed choice experiment’ fashion, preventing the final interaction altogether. Now, if the TI insists that the ‘confirmation waves’ from the atom and from the detectors arrive to the source together, the resulting account cannot properly handle these intermediate stages”. They suggested that some recursive “go-back-and-start-again” structure to the transactions would be required in this case, in the form of a “cancellation wave”. That, however, is not a part of the Transactional Interpretation.

The Elitzur and Dolev account contains a misperception of how the Transactional Interpretation should be applied to multi-vertex quantum events. The emitters receive the ensemble of confirmation waves from potential absorbers and make a hierarchical probabilistic choice, based on their amplitudes, with possible transactions from “near” (small space-time interval) absorbers (in this case, the atoms) confirmed or rejected before transactions involving “far” absorbers (in this case, the detectors) are considered (see Sect. 5.6.). Because of the hierarchy in transaction formation, there is no need for any recursive procedure or the invocation of cancellation waves. Further, probabilities are calculated only for completed transactions. Mid-process reevaluation of probabilities is a peculiarity of the knowledge interpretation (see Sect. 6.6) and is not a part of the TI. Any change in the configuration, such as removal of a beam splitter, represents a separate and distinct configuration from the one being analyzed and must be analyzed as a separate system with its own set of possible transactions that are also selected hierarchially. Thus, the TI, when properly applied, meets the Elitzur–Dolev challenge with no problems.

6.17.4 The Time-Reversed EPR Gedankenexperiment

Elitzur and Dolev went on to propose a variation of the two-atom experiment [56, 58] (Sect. 6.17.3) in which the initial light source and splitter are replaced by two distant light sources S_1 and S_2 that are synchronized to coherently produce light of identical wavelengths. This is shown in Fig. 6.29. The sources are of very low intensity, so that, on the average, only one photon is emitted during a given time interval, and it may be emitted from either source. The probability of emission for each source is $P_\gamma \ll 1$. We note that arranging for two widely separated coherent sources of light can be implemented by sending the sources ultra-fast synchronizing pulses, as discussed in Sect. 6.19 on entanglement swapping.

The two beams cross at a 50:50 beam splitter BS and are then detected by single-photon detectors C and D. The path lengths are arranged so that the coherent waves from the two sources destructively interfere at D and constructively interfere at C. Operationally, this situation differs from the two-atom experiment (Sect. 6.17.3) only in that there is a possibility that two simultaneous photons may be detected or absorbed by the atoms. The probability of such a coincidence is $P_\gamma^2 \ll 1$, which is so small that it can be completely neglected.

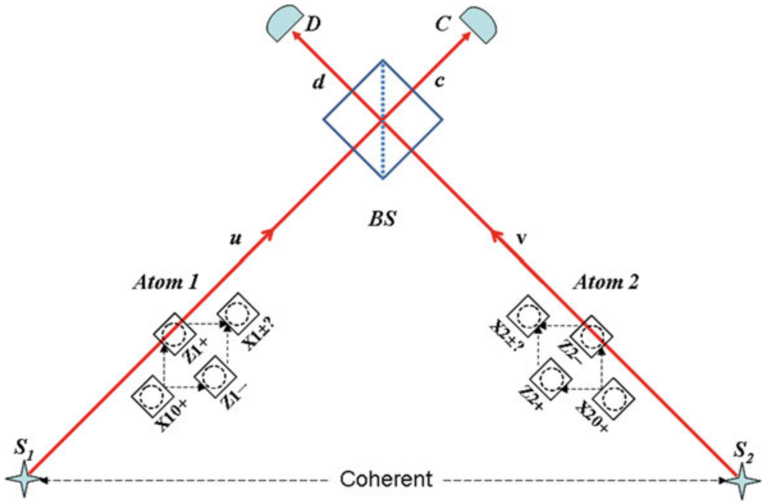

Fig. 6.29 The time-reversed EPR *Gedankenexperiment*. Weak coherent sources S_1 and S_2 send light through Hardy atoms to a beam splitter (*BS*) and detectors *C* (constructive) and *D* (destructive). For detections at *D*, EPR Bell-state correlations are observed

As before, the atoms initially have a positive spin along the x-axis, are SG separated based in their spin projection on the z-axis, and sent to two intermediate boxes, with a probability of 50 % that the atom may reside in each box at the time a photon passes through it. If a box is occupied by an atom when a photon passes through, there is a 100 % probability that the photon will be absorbed, leaving the atom in an excited state, with no light waves transmitted any further along the path.

Elitzur and Dolev focus exclusively on events in which detector *D* detects a photon (and *C* does not). They argue that, in the sense of interaction-free measurements (Sect. 6.12), one of the two boxes, but not both, must have been occupied by an atom just before the detection. This means that the wave function for detection at *D* was:

$$\mid D\rangle = {}^{1}\!/\!_{4}\,(\mid Z_{1+}\rangle \mid Z_{2+}\rangle + \mid Z_{1-}\rangle \mid Z_{2-}\rangle), \tag{6.18}$$

where $\mid Z_{(1,2)\pm}\rangle$ indicates the Z-axis spin projection of atom 1 or 2. Thus, the two atoms, which have never interacted, are entangled in a full-blown EPR Bell state in which their Z-axis spin projections must match. (see Eq. 2.1):

In other words, for *D* detections subsequent tests of Bell's inequality performed on the two boxed atoms, e.g., by rotating the axis of one SG x-axis recombiner with respect to the other, will show the same Bell inequality violations observed in EPR tests like the Freedman–Clauser experiment (Sect. 6.8), and indicating that the spin value of each atom depends on the choice of spin direction measured for the other atom, no matter how distant.

Unlike the more conventional EPR experiments, in which the particles are entangled in a Bell state because they have interacted earlier, here the only common event between the two atoms lies in their *future*. One might argue that the atoms are measured only after the photon’s interference and detection, hence the entangling event still resides in the measurements’ past. However, all three events, namely, the photon’s interference and the two atoms’ measurements, can be performed at large spacelike separations. In that case, by suitable choice of reference frame, the entangling event may be made to reside either in the measurements’ past or its future. Thus, this *gedankenexperiment* is truly a time-reversed EPR experiment.

The Transactional Interpretation analysis of this experiment is similar to previous analyses. One might think that a weak source might only occasionally send out offer waves. However, the proper TI view is that a weak source should continuously emit very weak offer waves, which only occasionally result in the formation of a transaction. Because of destructive interference that has been arranged, detector *D* can receive these offer waves only for the situation in which one of the paths is blocked by the presence of an atom in a Hardy box. For such offers, it returns confirmation waves to the appropriate source, a transaction can form, and a photon can be transferred from that source to detector *D*. Such transactions only occur when one Hardy box is empty and the other occupied, leading to the selection of only Bell-state offer wave functions as those capable of forming a transaction to detector *D*. Thus, the TI easily accounts for the curious time-reversed EPR results.

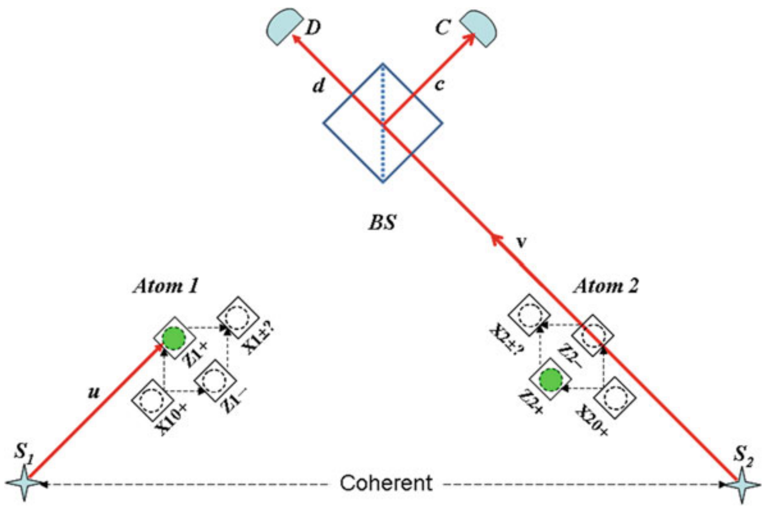

Fig. 6.30 The Elitzur–Dolev Quantum Liar Paradox *Gedankenexperiment*

6.17.5 The Quantum Liar Paradox

Finally, Elitzur and Dolev (ED) consider the implications of the time-reversed EPR experiment for the logic of the spin orientation of one atom affecting the spin orientation of another, when they have neither interacted with each other nor with a passing photon.

In the situation illustrated in Fig. 6.30 we find that after detection at D, discovering, for example a spin-up atom in box 1, has the following implications:

1. Atom 1 is positioned in the intersecting box $Z1^+$.
2. It has not absorbed any photon.
3. Still, the fact that the spin of Atom 2 is affected by the position of Atom 1 means that *something* has traveled the path blocked by Atom 1. To prove that, let an opaque object be placed on path u after Atom 1. No EPR nonlocal correlations will be observed.

ED argue that the very fact that one atom is positioned in a location that seems to preclude its interaction with the other atom is affected by that other atom. They say that this is logically equivalent to the statement "this sentence has never been written." They state that they are unaware of any other quantum mechanical experiment that demonstrates such an inconsistency.

The Transactional Interpretation explains this paradox by observing that Atom 1 is probed by an offer wave from S_1 that it blocks, even if no transaction occurs between S_1 and Atom 1. The absence of this offer wave beyond splitter BS, because it stops at Atom 1, prevents destructive interference in path d and allows a transaction between S_2 and D to form, provided Atom 2 does not block that path. The transactional handshake between S_2 and D is only possible because path u is blocked and path v is open. Placing an opaque object on path u would allow transactions between S_2 and D with Atom 1 in both possible spin orientations and would destroy the Bell-state offer wave selection and EPR correlations. This, however, does *not* prove that "something has traveled the path blocked by Atom 1" as claimed by ED. Thus, the TI has no problem in explaining the Quantum Liar paradox and its underlying logic. We note that Kastner [37] and Boisvert and Marchidon [40] have also published somewhat different Transactional Interpretation analyses of the quantum liar paradox.

6.18 The Leggett–Garg Inequality and "Quantum Realism" (2007)*

Noble Laureate Anthony J. Leggett of the University of Illinois has demonstrated that by focusing on the falloff of correlations with *elliptical* polarization (mixtures of circular + linear polarization), rather than on the linear polarization of the Bell Inequality EPR experiments, one can compare the predictions of quantum mechanics with a class of nonlocal realistic theories [59–61]. The resulting Leggett–Garg

Inequalities can be used in the same way as the Bell Inequalities, but to test nonlocal realism instead of local realism.

A group of experimentalists at Anton Zeilinger's Institute for Quantum Optics and Quantum Information (IQOQI) in Vienna have performed an EPR experiment that is a definitive test of the Leggett–Garg Inequalities [62]. They show that in EPR measurements with elliptically polarized entangled photons, the Leggett–Garg Inequalities in two observables are violated by 3.6 and by 9 standard deviations. This is interpreted as a statistically significant falsification of the whole class of nonlocal realistic theories studied by Leggett.

The group summarizes the implications of their results with this statement: "We believe that our results lend strong support to the view that any future extension of quantum theory that is in agreement with experiments must abandon certain features of realistic descriptions." In other words, quantum mechanics and reality appear to be incompatible and have parted company.

Is the case against objective reality truly so strong? To answer this question, we must examine in more detail the nonlocal realistic theories that Leggett studied. This class of theories assumes that when entangled photons emerge from their emission source, they are in a *definite but random state of polarization*. That is Leggett's definition of "realism". It is well known from the work of Furry [63, 64] that when that assumption (and no other) is made, one does not observe the quantum mechanical prediction of Malus's Law for the correlations of the photon pair.

However, Leggett cures that problem by assuming an unspecified nonlocal connection mechanism between the detection systems that fixes the discrepancy. In effect, the two measurements talk to each other nonlocally in such a way that the detected linearly polarized photons obey Malus' Law and produce the same EPR polarization correlations predicted by quantum mechanics. Leggett then shows that this nonlocal "fix" cannot be extended into the realm of elliptical polarization and that quantum mechanics and this type of nonlocal realistic theories give differing predictions for the elliptical polarization correlations. In other words, the "reality" that is being tested is whether the photon source is initially emitting the entangled photons in a *definite but random state of polarization*. It is this version of reality that has been falsified by the IQOQI measurements.

We can clarify what is going on in these experimental tests by applying the Transactional Interpretation to these Leggett–Garg Inequality tests. From the point of view of the TI and standard quantum mechanics, Leggett's assumption that the entangled photons are emitted in definite states of polarization is simply wrong. The "offer wave" for each photon that emerges from the source includes all possible polarization states. These offer waves travel to downstream detectors, and time-reversed "confirmation waves" travel back up the time-stream to the source, arriving at the instant of emission. As was illustrated for the Freedman–Clauser experiment in Fig. 6.9, a three-way transaction then forms between the source and the two detections that matches the confirmation waves to a mutually consistent overall state that satisfies appropriate conservation laws (in this case, conservation of angular momentum). The final result is a completed transaction with the two photons in definite states, but this definite state was not present in the initial emission of the offer waves, and that is the part of the process described in detail by the wave-mechanics formalism of quantum mechanics. We note that the TI does not in itself make any predictions about the linear or elliptical polarization correlations of the entangled photon pair. It only describes the quantum formalism that is making the predictions that the IQOQI group has observed to be consistent with their experiment, but it clarifies what is going on in those predictions.

Does this mean that the TI (and the quantum formalism it describes) are not "realistic", i.e., inconsistent with an objective reality that is independent of the observer's choice of measurements? I don't think so. The transactions that form in quantum processes arise from a "handshake" between the past and future across space-time, but they are not specifically the result of measurements or observer choices. The latter are only a small subset of the transactions that form as the universe evolves in space-time. The message of the Leggett–Garg Inequality tests, from the point of view of the TI, is that the assumption of emission in a definite polarization state is too restrictive. I would argue that initial emission without a definite polarization state is perfectly consistent with objective reality and is consistent with the quantum formalism. It is just that reality is not fixed by the initial offer wave and does not become "frozen" until the transaction is formed.

The TI description of the quantum formalism is both realistic and nonlocal, in at least some definitions of those terms, and it is completely consistent with the IQOQI results. To put it another way, Leggett has set up a straw man that has been demolished by the IQOQI tests, but that is only an indication that his version of "realism" is too naïve. And this theory and experiment can be viewed as another demonstration of the value and power of the TI in understanding the peculiar predictions and intrinsic weirdness of quantum mechanics.

6.19 Entanglement Swapping (1993–2009)*

In conventional telecommunication systems, transmission of signals over significant distances uses "repeaters", devices that receive incoming signals, reshape and amplify them, and send them along to the next repeater station. If quantum information contained in photon entanglement needs to be sent over long distances and is to be "repeated" in the same way, there is a significant problem in how such a "quantum repeater" might operate while preserving entanglement.

The solution to this problem seems to be *entanglement swapping*, first proposed in 1993 [65]. Briefly, this is accomplished by mixing an entangled photon taken from each of two synchronized entangled photon sources and performing Bell-state measurements on the mixed pair. The consequence is that the two unmixed outgoing photons from the two sources will be entangled, and the type of entanglement can be selected by coincidences with the detected photons of the Bell-state measurements. Interestingly, the technique produces photons that are entangled, even though they have never interacted and they originate in separate locations. Somehow, because

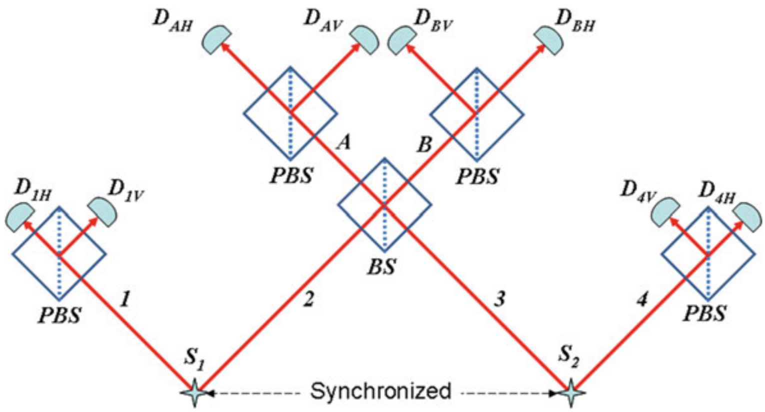

Fig. 6.31 An experimental configuration for producing entanglement swapping. Synchronized sources S_1 and S_2 produce polarization-entangled pairs (*1, 2*) and (*3, 4*). Photons *2* and *3* are mixed at *BS* and their Bell-state detected by polarimeters *A* and *B*. Photons *1* and *4*, which have never interacted, are entangled

their entangled twins interact, the entanglement is "swapped" to the non-interacting pair.

Figure 6.31 shows an experimental configuration [66] for producing this entanglement swapping. Synchronized entangled two-photon sources S_1 and S_2 produce polarization-entangled pairs (1, 2) and (3, 4). The polarization-entanglement is such that if one photon is vertically polarized (V) the other is horizontally polarized (H), and *vice versa*. Photons 2 and 3 are mixed and their Bell-state detected by polarimeters A and B with detectors D_{AH}, D_{AV}, D_{BH}, and D_{BV}, using Hong–Ou–Mandel interference [67]. Only two photons are detected, but they may be detected by any pair of polarimeter detectors. Therefore, in principle the two detections may be in any of 6 combinations: (H_A, V_A), (H_A, H_B), (H_A, V_B), (V_A, H_B), (V_A, V_B), or (H_B, V_B). The result of this is that photons 1 and 4 are entangled so that, in coincidence with the polarimeter detections, they are projected into a Bell state (see Eqs. 2.1 and 2.2) that depends on the detection combination. They will be in the Bell state $\frac{1}{\sqrt{2}}(|\,H_1V_4\rangle - |\,V_1H_4\rangle)$ if they are in coincidence with (H_A, V_B) or (V_A, H_B), and they will be in the Bell state $\frac{1}{\sqrt{2}}(|\,H_1V_4\rangle + |\,V_1H_4\rangle)$ if they are in coincidence with (H_A, V_A) or (H_B, V_B). The polarimeter combinations (H_A, H_B) and (V_A, V_B) do not occur because the sources are set for opposite-polarization entanglement.

The entanglement of 1 and 4 can be eliminated by removing the beam splitter BS, so that there is no mixing and the A polarimeter measures the polarization of 3 and the B polarimeter measures the polarization of 2. In this case 1 and 4 are in unentangled product states. Curiously, the path to the A and B polarimeters can be made much longer than the 1 and 4 paths, so that the decision of whether 1 and 4 should be entangled or not can be made *after* these photons have already been detected.

So far, entangled photon transmission has been limited to distances on the order of 100 km [68–70]. To increase transmission distances beyond this level, quantum repeaters are needed. The entanglement-swapping configuration discussed here has been tested [66] and found to give high quality entanglement that would be suitable for use in a quantum repeater. Imagine that S_1 is the beginning of a quantum transmission line, and path 1 is short while 2 is very long, and that ultra-fast synchronizing pulses and the output of the 1 polarimeter are sent on a path parallel to 2. Source S_2 is synchronized with S_1 and produces photons 3 and 4. Photon 3 is mixed with 2 and analyzed. Photon 4 becomes the "repeated" version of 2 and is sent along the line, along with the polarimeter outputs and the synchronizing pulse. This process can be repeated at suitable transmission length intervals indefinitely, leading, at least in principle, to the development of large scale quantum communication networks.

The Transactional Interpretation makes it easy to understand what is going on in entanglement swapping. One must consider the formation of a transaction for each configuration in which one H and one V photon are detected at polarimeters 1 and 4. Without going into the details of the transactions involved, it is easy to see that, for example, a single transaction that involves dual emissions at S_1 and S_2 and detections at D_{1H} and D_{4V} will require either matching detections at D_{AH} and D_{BV} or detections at D_{AV} and D_{BH}. These involve a network of offer and confirmation waves linking the vertices of the transaction. Similarly, it is easy to see that transactions involving detections at D_{1H} and D_{4H} cannot be completed if the A and B polarimeters detect one H and one V photon, so detections inconsistent with the (1, 4) entanglement are forbidden. Thus, by selecting HV coincidences in the A and B detectors, the wave function for photons 1 and 4 is a Bell state, and the entanglement has been transmitted. One can also see that if the beam splitter BS is removed, only separate and independent transactions will form between polarimeters 1 and B and between polarimeters A and 4, so there will be no (1, 4) entanglement.

6.20 Gisin: Neither Sub- nor Superluminal "Influences"? (2012)

The Gisin group [71] has examined the nonlocality of quantum mechanics from another direction. They consider Bell-type EPR experiments in which entangled pairs of photons are given entangled polarizations by the emission process (through angular momentum conservation) and their polarization states are measured in some selected polarization basis (H/V linear, ±45° linear, or L/R circular) by downstream detectors. Quantum mechanics requires that whenever the detection bases of two such measurements match, the measured values must also match.

The authors assume that they can replace orthodox quantum mechanics by some unspecified semi-classical process in which the "causal influences" have a well defined propagation velocity and travel between measurements to insure that the polarization correlations match. It has already been well established through the work of J. S. Bell and others that any such causal influences traveling at velocities less than or equal to the speed of light cannot account for the EPR correlations observed in Bell-type EPR experiments. The authors extend consideration to include causal influences traveling at velocities *greater than the speed of light*. They show that causal influences traveling at velocities greater than the speed of light can indeed account for EPR correlations, but the assumption of superluminal influences carries with it the inevitable consequence that signaling between observers at the superluminal speed of the causal influences becomes possible.

Special relativity (see Sect. 7.2) forbids such signaling at any well-defined superluminal speed because its existence would allow the discovery of a preferred reference frame and would destroy the even-handedness with which relativity treats all inertial reference frames. Thus, the authors concluded that no semiclassical explanation of quantum nonlocality and EPR correlations is possible, even when superluminal causal influences are allowed.

We note that extensions of the many-worlds interpretation have attempted to deal with quantum nonlocality by hypothesizing a traveling "split" between worlds, i.e., universes, that originates at the site of one measurement and propagates to the sites of other measurements, in order to arrange consistent EPR correlations between measurement results. This moving split is just the kind of moving causal influence with a well defined propagation velocity that has been ruled out by the Gisin group's paper.

The work presents a hypothesis that some have seriously entertained and then demonstrates its unacceptable implications. However, the basic approach, one that has been taken by many other works in the physics literature, seems intended to mystify and obscure quantum mechanics and nonlocality rather than to clarify and understand them.

The Transactional Interpretation, which is not referenced or considered in the Gisin group's paper, describes "causal influences", i.e., the wave functions ψ and ψ^* of the emitted entangled photons, as propagating in both time directions along the allowed trajectories of the particles and handshaking to observe conservation laws by building in the observed EPR correlations. The causal influences are not superluminal, but rather retro-causal. Does this causal link imply that superluminal signaling is possible? Not in the sense considered in the Gisin group's paper. The lines of communication for the entangled EPR photons, as described by the Transactional Interpretation, are all along light-like world lines that transform properly under the Lorentz transformations of relativity, favoring no preferred inertial reference frame and remaining completely consistent with special relativity (see Sect. 7.2).

6.21 The Black Hole Information Paradox (1975–2015)

Stephen Hawking's 1975 calculations [72] predicting black hole evaporation by Hawking radiation described a process that apparently does not preserve information.

This created the Black Hole Information Paradox, which has been an outstanding problem at the boundary between general relativity and quantum mechanics ever since. Lately, gravitational theorists have focused on pairs of quantum-entangled particles, in part because the particle pair involved in Hawking radiation should be entangled. They have considered ways in which the quantum entanglement might be broken or preserved when one photon of the entangled photon pair crosses the event horizon and enters a black hole.

One recent suggestion is that the quantum entanglement breaks (whatever that means) when the infalling member of the entangled particle pair crosses the event horizon, with each breaking link creating a little burst of gravitational energy that cumulatively create a firewall just inside the event horizon. This firewall then destroys any infalling object in transit [73]. The firewall hypothesis, however, remains very controversial, and there is no apparent way of testing it.

More recently Maldacena and Susskind [74] have suggested an alternative. When two entangled black holes separate, they hypothesize that a wormhole connection forms between them to implement their entanglement. It has even been suggested that such quantum wormholes may link *all* entangled particle pairs. There are, however, problems with this interesting scenario, not the least of which is that such wormholes should have significant mass that is not observed.

The Transactional Interpretation offers a milder, if less dramatic solution to this problem, providing an interesting insight into the Black Hole Information Paradox. One normally thinks that absolutely nothing can break out of the event horizon of a black hole from the inside and escape. However, there is one exception: advanced waves can emerge from a black hole interior, because they are just the time-reverse of a particle-wave falling in. An advanced wave "sees" the black hole in the reverse time direction, in which it looks like a white hole that emits particles. The strong gravitational force facilitates rather than preventing the escape of an advanced wave. Thus, an entangled particle pair, linked by an advanced-retarded wave handshake, have no problem in maintaining the entanglement, participating in transactions, and preserving conservation laws, even when one member of the pair has fallen into a black hole. There is no need for entanglement-breaking firewalls or entanglement-preserving wormholes, just a transactional handshake. Thus, it would seem that the Transactional Interpretation goes some considerable distance toward solving the Black Hole Information Paradox and resolving an issue that divides quantum mechanics and gravitation and providing a mechanism for preserving information across event horizons.

6.22 Paradox Overview

In summary, there is a large and growing array of interpretational paradoxes and puzzles arising from the formalism of quantum mechanics and its peculiar properties and behavior. New quantum optics experiments are published every day that demonstrate the intrinsic counter-intuitive weirdness of the quantum world. Heisenberg's knowledge interpretation, a central part of the Copenhagen Interpretation, had been able to deal with some of these problems, but its focus on observer knowledge appears inadequate to deal with systems involving multiple measurements, multiple observers, and multiple choices that may be made in any time sequence.

The emphasis of the knowledge interpretation on the observer and his knowledge has led us into some philosophically deep waters. It is asserting that somehow, the solutions of a simple second-order differential equation relating mass, energy, and momentum have entered the head of an intelligent observer and are describing his state of knowledge about the outside world. It leads to the conclusion that, in some sense, the observer is "creating" the external reality by his choice of observations, choosing to make one member of a pair of conjugate variables "real" at the expense of the other by deciding to measure it. Quantum mysticism based on such observer-created reality has become a popular theme in books that attempt to sensationalize physics for the general reader, finding tenuous and deceptive connections between the Copenhagen brand of quantum mechanics and the dogmas of exotic religions.

Further, the positivism of the Copenhagen Interpretation frustrates our desire to "view" quantum processes and to understand what goes on "behind the scenes" that can lead to such curious and paradoxical behaviors in the quantum world. The Transactional Interpretation provides a straightforward way of resolving these paradoxes and problems and eliminating the need for appeal to observer knowledge. It also provides the tools for visualizing the underlying mechanisms in quantum processes.

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