8
The Timeless Quantum

Every particle in Nature has an amplitude to move backward *in time . . .*
Richard Feynman (1986, 98)

Note: This chapter is from my book *Timeless Reality: Symmetry, Simplicity, and Multiple Universes* (Amherst, N.Y.: Prometheus Books, 2000). It is copyrighted and should not be further copied or distributed without my permission.

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Seeking a Quantum Arrow of Time

In chapter 4, we learned that three arrows of time are inferred from macroscopic phenomena: the thermodynamic, cosmological, and radiation arrows. We found that these three are essentially the same, and can be understood in terms of the inflationary big bang model of cosmology in a way that maintains overall time symmetry in the universe. In this scenario, we live in the expanding space of the big bang where the entropy at one end of the time scale is much greater than the other, time's arrow then being defined to point in the direction of increased entropy. With $t = 0$ defined as the point at which inflation was triggered by a quantum fluctuation, then the negative t side of the time axis (negative, that is, from our perspective) undergoes an initially identical expansion in which time's arrow points along the $-t$ direction. Thus, an overall time symmetry is maintained at the cosmic scale, as required by all the known fundamental principles of physics.

One of the strong proponents of a time-asymmetric universe is Oxford mathematician and cosmologist Roger Penrose. He has sought an arrow of time in cosmology, and also looked for one in quantum mechanics (Penrose 1989, 250). His cosmological arrow was discussed in chapter 4. Here let us focus on Penrose's quantum arrow.

As I have noted previously, Penrose separates quantum processes into two categories that act in sequence. Firstly, a **U** process describes the ("unitary") evolution of the state of the system as governed by the time-dependent Schrödinger equation. This is completely time-symmetric in all except certain rare processes that we can ignore for the present discussion and, as we will see, can be made time symmetric anyway by including other symmetry operations. The Penrose **R** process provides for the collapse or reduction of the wave function, or state vector, by the act of measurement. As we have noted, state vector collapse is a separate, unwelcome, and probably unnecessary axiom of quantum mechanics. Penrose points out that this part of quantum mechanics is inherently time-asymmetric and the possible source of a fundamental quantum arrow of time.

He illustrates this with a simple example that I have redrawn in figure 8.1. A lamp L emits photons in the direction of a photocell (small photon detector) P. Halfway between is a half-silvered mirror M arranged at forty-five degrees so that the photon, with 50 percent probability, will go either straight through to P or be reflected toward the laboratory wall in the direction W. The paths are indicated by the solid lines in the figure. The lamp and phootcell also contain registersthat count the photons emitted. Penrose then asks: "Given that L registers, what is the probability that P registers?" His answer follows from quantum mechanics: "one-half."

Penrose then considers what he calls the "reverse-time procedure" in which a backward-time wave function represents a photon that eventually reaches P. This wave function is traced backward in time to the mirror where it bifurcates, implying a fifty-fifty chance of reaching the lamp L. He then asks: "Given that P registers, what is the probability that L registers?" His answer: "one." His reasoning is as follows: "If the photo-cell indeed registers, then it is virtually certain that the photon came from L and not the wall!" The conventional application of quantum mechanics Thus, gives the wrong answer in the time-reversed direction and so, Penrose concludes, the **R** process must be time-asymmetric.

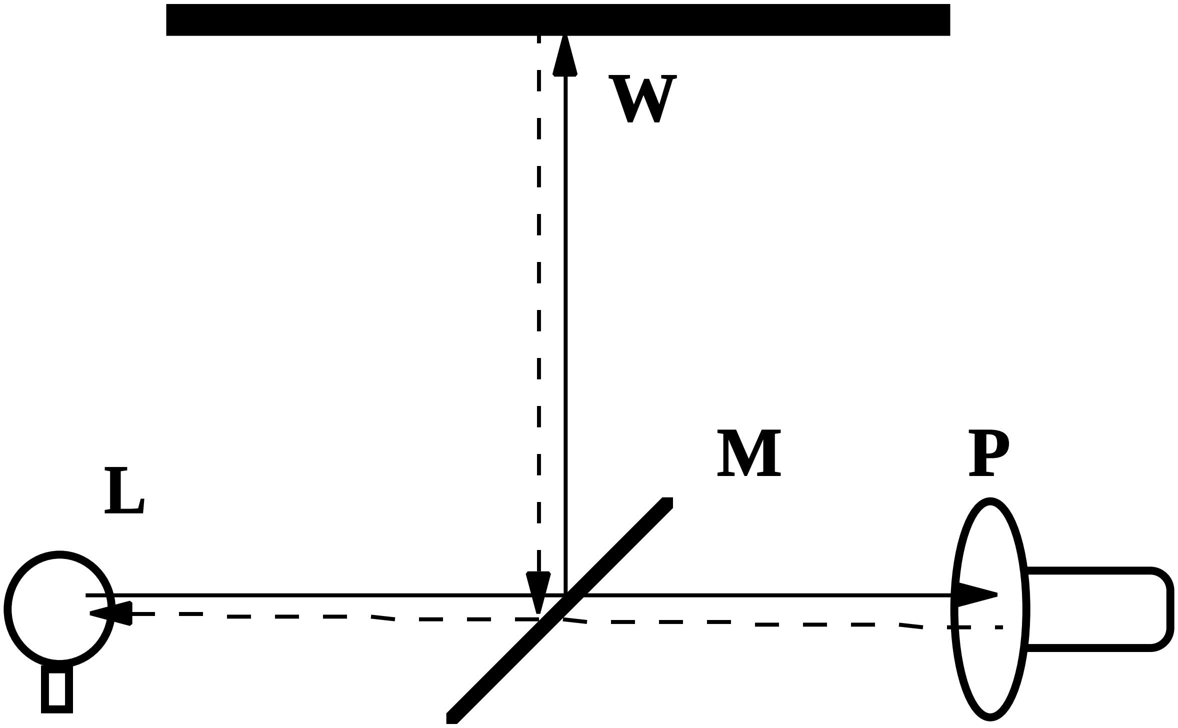

Fig. 8.1. Photons from lamp L have a fifty-fifty chance of either going through the mirror M to the photodetector P or reflecting from M and being absorbed by the wall at W. In the time-reversed process, as imagined in a film run backward through the projector, half the photons are emitted by P and half by the wall, all returning to the lamp at L. At the quantum level, sources can act as detectors or absorbers, and detectors or absorbers as sources. Irreversibility occurs at the macroscopic level because macroscopic sources and detectors are not in general reversible. This figure is based on figure 8.3 in Penrose (1989, 357).

While this is correct for the process Penrose describes, note that this is not what you would actually see watching a film of the event being run backward through the projector. This, more literal reverse-time process is indicated by the dashed lines in figure 8.1. There the photons that are absorbed in the lamp come from two sources, the detector P and the wall. All the photons registered at P also register at L, as in Penrose's example, but the lamp also receives additional photons from the wall.

If the experiment were a purely quantum one, with single atoms as sources and detectors, then it would be completely time reversible. The irreversibility that Penrose sees is exactly the same irreversibility I talked about earlier, an effect of the large amount of randomness in macroscopic many body systems.

Now, Penrose is arguing that the actual experiment is done with a macroscopic lamp L, macroscopic detector P, and macroscopic walls and so it is irreversible. That is, L is not normally a detector and P or the wall is rarely a source. But this is the situation I described in chapter 4 while discussing the arrow of radiation. There I related Price's conclusion that the radiation arrow results from the asymmetry between macroscopic sources and detectors in our particular world. That is, they are part of the "boundary conditions" of the world of our experiences and nothing fundamental. Most lamps are not reversible as detectors, although lasers, being quantum devices, are in principle reversible. As mentioned, the first maser (the precursor of the laser, which worked in the microwave region of the spectrum) was designed as a detector. Most macroscopic detectors, like like photographic film or photomultiplier tubes, cannot be reversed into sources, or, at least, very efficient ones. Furthermore, walls do not emit the kind of narrow beam of visible photons we are assuming in this experiment, although they do emit thermal radiation.

Lamps, detectors, and absorbing walls do not look the same in the mirror of time. However, like the face of the person you see when you look in the bathroom mirror e, which is strangely different from the face you see in a photo, what is seen is not strictly impossible.

Let us peer more deeply into the lamp, detector, and wall. Consider the primary emission and absorption processes that take place at the point where the photon is emitted or absorbed. This was illustrated in figure 4.3 (a), for both time directions. In "forward time," an electron in an excited energy level of an atom in the lamp drops down to a lower energy level, emitting a photon. This photon is absorbed in either the wall at W or the detector P in figure 8.1, with an electron being excited from a lower to a higher level in an atom in wall or detector. In "backward time," either the wall or the detector emits a photon by the same process as the lamp in forward time while the lamp absorbs the photon.

True that, in actual practice, the wall and detector will irreversibly absorb photons, converting their energy to heat and gaining entropy. But if we could do the experiment with a purely quantum lamp, detector, and wall composed of a single atom each with the same energy levels, say a hydrogen atom, then the process would be completely reversible.

As Penrose (1989, 359) says, "the **R** procedure, *as it is actually used*, is *not* time-symmetric." From this he concludes that we have a unique quantum arrow. The first statement is true. But the irreversibility is still statistical and the result of asymmetric boundary conditions imposed on the experiment, not the result of any fundamental principle of physics. This irreversibility does not actually occur for the primary quantum event at the microscopic level. Rather, the arrow appears where the coherent, usually few-body processes of quantum interactions are replaced by the incoherent many-body processes that interface the quantum world with us denizens of the classical world. As with his cosmological arrow, Penrose has not demonstrated any need for a new fundamental law to explain the undoubted time-asymmetry we observe in many body phenomena. The quantum arrow is again the same as the thermodynamic/cosmological/radiation one.

The **U** process as we understand it, is fundamentally time-symmetric. As for **R**, we saw in chapter 6 that this process can be understood in terms of the decoherence that takes place when a quantum system interacts with macroscopic detectors

Robert Griffiths (1984), Yakir Aharonov and Lev Vaidman (1990), Roland Omnès (1994), and Giuseppe Castagnoli (1995), among others, have shown that conventional quantum mechanics can be precisely formulated in a manifestly time-symmetric fashion. Also, Murray Gell-Mann and James Hartle (1992) have demonstrated that a quantum cosmology can be developed using a time-neutral, generalized quantum mechanics of closed systems in which initial and final boundary conditions are related by time reflection symmetry. At the quantum level, we have no evidence for an arrow of time and no unique entropy gradient, other than those discussed previously, to require us to nevertheless adopt an arrow.

Zigzagging in Space and Time

In their book *The Arrow of Time*, Peter Coveney and Roger Highfield (1991, 288) suggest that the macroscopic arrow of time can be used to explain the paradoxes of quantum mechanics. They base this on the attempts by chemist Ilya Prigogine and his collaborators to derive irreversibility at the microscopic level from dynamical principles that they apply first to the macroscopic level. However, Vassilios Karakostas (1996) has shown that these derivations tacitly assume temporal irreversibility. Here we find yet another example of the use of what Price (1996) calls a double standard, in which investigators fail to realize that they have not treated time symmetrically and so fool themselves into thinking they have discovered the source of the arrow of time. Furthermore, contrary to the claims of Prigogine and followers, the recognition that time in fact has no arrow at the quantum level actually helps to eliminate the so-called paradoxes of quantum mechanics. So why should we want to force an arrow back in?

Time symmetry remains deeply embedded in both classical and quantum physics and can be expunged only by making the added, uneconomical assumption that the arrow of normal experience must be applied to both of these areas of basic physics. Why uneconomical? Because it requires an additional assumption not required by the data.

As we saw in the last chapter, Feynman utilized the inherent time symmetry of physics in developing his methods for solving problems in quantum electrodynamics (Feynman 1949a,b). Now, fifty years later, time reversibility still seems indicated by both data and theory. Specifically, it furnishes a way of viewing one of the great puzzles of quantum mechanics: how particles can follow definite paths in space-time and still appear many places at once. Examples include the instantaneous quantum jump of an electron in an atom from one energy level to another, among others.

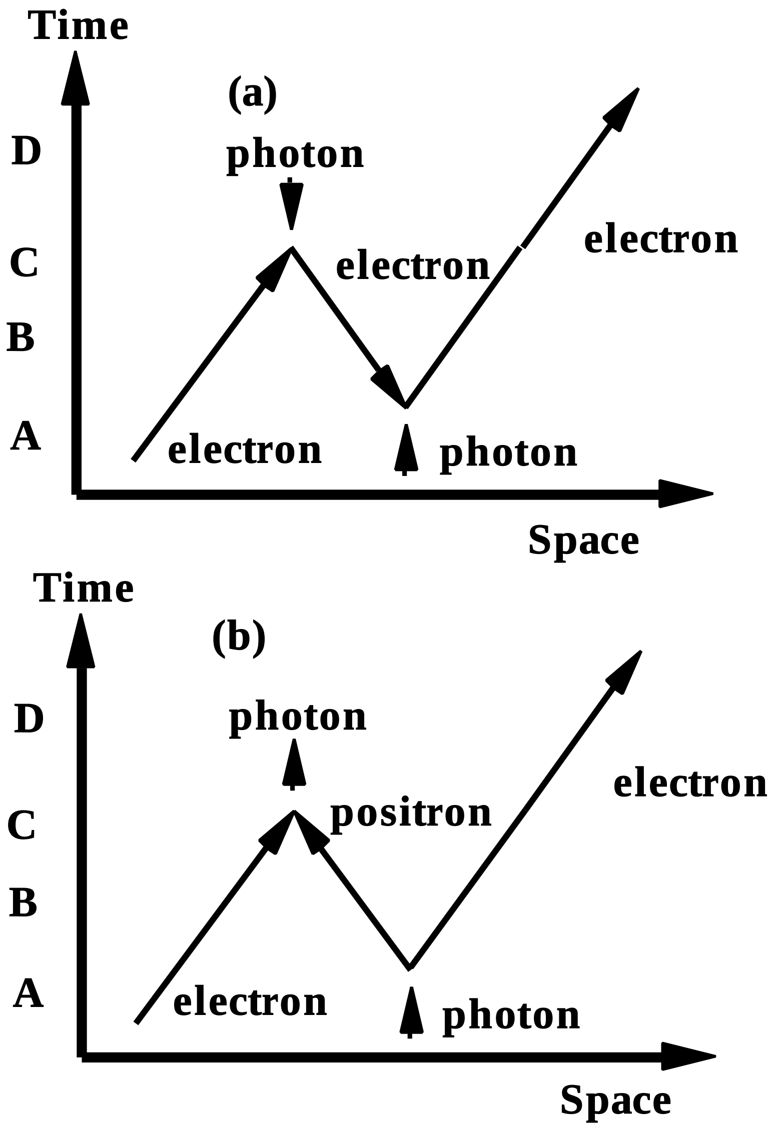

Fig. 8.2 (a) An electron zigzagging back and forth in space-time, thus appearing simultaneously at three different positions at time B and two different positions at time C. (b) The conventional directed-time view in which an electron-positron pair are created by a photon at A, the positron annihilating with an electron into a photon at C. These diagrams can occur "virtually," with zero energy photons in the vacuum, as long as the violation of energy conservation at time C is corrected at time A within a time interval allowed by the uncertainty principle.

To see how time reversibility allows for a particle to follow a definite path, and still be several places simultaneously, consider figure 8.2. In (a), an electron zigzags back and forth in space-time, appearing at one place at time A, three places at time B, then two places for an instant at time C, and back again at one place at time D. The conventional view is shown in (b), where a photon makes an electron-positron pair at A and the positron annihilates with the original electron at C.

This particular phenomenon is observed in experiments with high energy photons (gamma rays), but can also occur "virtually" with the normally undetectable zero energy photons that fill the vacuum (see chapter 7). In this case, the time interval from A to C must be small enough so that the breaking of energy conservation at A is corrected at C. Since an electron-positron pair is being created from "nothing" at A, energy is not conserved by an amount at least equal to the rest energy of the pair, 1.022 MeV. The Heisenberg uncertainty principle applies to measurements of energy and time in the same way it does for measurements of position and momentum. Applying this, the time interval during which an electron zigzag takes place is of the order of 10^{-22} second.[1] The distance over which the zigzag takes place can also be estimated and is easily shown to be of the order of the de Broglie wavelength of the particle.[2] This indicates that the spreading out we associate with the wavelike nature of particles is related to their zigzagging in space-time.

Of course, we do not have direct experience of familiar everyday bodies travelling back and forth in space-time. The time interval for virtual zigzagging is far shorter than anything we can directly measure with our best instruments, and the de Broglie wavelength for the typical macroscopic object is also unmeasurable. Electrons can zigzag over interatomic distances, such as between atoms in a crystal. Particles far less massive than electrons, such as neutrinos and photons, can zigzag over large spatial intervals. Radio photons, for example, can have wavelengths of macroscopic or even planetary dimensions. That is why we don't normally think of them as tiny particles but spread-out waves. But, with space-time zigzagging, we can maintain a single ontological picture of pointlike photons that applies on all scales, from the subnuclear to the supergalactic.

This scheme can also be used to visualize the quantum jump between energy levels in an atom. In the case of excitation to a higher energy level, one photon in figure 8.2 comes in from the outside, the other from interaction with the rest of the atom, as the electron is viewed as jumping instantaneously from one orbit to another at time C.

Feynman's methods for calculating the probabilities of processes such as that shown in figure 8.2 have became basic tools for the in particle physicist. They were heavily utilized in the development of the current standard model of quarks and leptons that agrees with all observations to-date. In applying these methods, most physicists think in terms of the familiar unidirectional time, picture (b) rather than picture (a) in figure 8.2. However, the calculation is the same either way and this simple fact alone demonstrates that time symmetry is evident at the quantum level. Eliminating any preferred arrow of time from our thinking then opens up a new perspective on several of the strange features of quantum mechanics that seem so bizarre in the normal, time-directed convention. Whether or not all the interpretational problems disappear with such a simple expedient will require a more detailed logical and mathematical analysis than I propose to attempt here.

The idea of having particles at different places "at the same time" is not as revolutionary, or as new, as it may seem. Any model of reality we may utilize must take into account the view of time promulgated by Einstein in his theory of relativity that even now, a century later, has not penetrated conventional thinking. As we have seen, Einstein showed that time is not absolute, and so the term "simultaneous" is a relative one. Saying that two events are simultaneous can only refer to the reference frame in which all observers are at rest with respect to one another.[3] Since simultaneity is not absolute, no logical inconsistency exists in describing a particle to be several places at "the same time" as observed in some reference frame.

Note that in the rest frame or "proper" frame of the electron in figure 8.2, the electron is always at a single place in space: "here." This is the same as the understanding that you are always "here" in your own personal reference frame, even when you are hurtling across the sky at 5 miles a minute in a jetliner that places you at well-separated places at different times to an observer on the ground.

If you can be the same place at two different times, why can't you be at two different places at the same time? Only our primitive intuition of absolute, directed time makes this seem impossible. And this intuition is the result of our personal existence as massive, many-particle objects. The zigzagging we do in time is over such small intervals as to be undetectable.

Notice that although the electron seems to jump instantaneously from one point in space to another in figure 8.2, it does not do so by travelling through space at infinite speed. Whether going forward or backward in time, it still moves at less than the speed of light in all reference frames. The electron appears to undergo an infinite acceleration at time A, but that acceleration is not measurable for time intervals smaller than the interval over which the zigzag takes place and is balanced out, just as energy conservation was balanced out at C. Another way to say this is that at one measurable moment the electron is going at a subluminal speed in one time direction, and at the next measurable moment it is moving at a subluminal speed in the opposite time direction.

Still, the violation of Bell's inequality in the Bohm EPR experiment has led to the widespread conclusion that the universe is necessarily "nonlocal," that is, it requires superluminal connections of some type--if not superluminal motion. The conventional wisdom holds that quantum mechanics is complete but nonlocal. But this also has a problem. As I have mentioned, superluminal signals are provably impossible in any theory compatible with the axioms of relativistic quantum field theory. So nonlocality, at least if we read this to mean superluminal motion or signaling, is inconsistent with the most modern application of quantum mechanics. Surely something unfamiliar is going on at the quantum level, but it is not necessarily superluminality.

At the risk of overwhelming the reader with too many unfamiliar terms, I would like to suggest yet another one that I think better describes the situation. David Lewis (according to Redhead 1995) has proposed the term **bilocal** to refer to an object being in two places in space at once. Extending this definition to allow more than two places at once, let me refer to the situation in the quantum world as **multilocal**. While not at one place at one time, a quantum particle is still not everywhere at once but at several well-localized places in space-time. For example, in figure 8.2, the electron is at three localized positions at time B. Again, no superluminal motion is implied because the object goes back in time and then forward again to reach a new position at the same original time. Since we require only localized interactions, no holistic fields need be introduced to provide instantaneous action at a distance.

The EPR Paradox in Reverse Time

The experimental violation of Bell's theorem, discussed in chapter 6 (Aspect 1982), demonstrated that when a system of two particles is initially prepared in a pure quantum state, then those particles retain a greater correlation when they become separated than is expected from either classical physics or more general, commonsense notions of objective reality. In particular, the results of a measurement of some property of one particle are found to depend on the results of a measurement of that property for the other particle, even after they have separated to such a distance that any signal between them would have had to be superluminal.

As mentioned above, no superluminal signal is possible within the framework of standard quantum mechanics and relativistic quantum field theory. The observers cannot determine, with absolute certainty, the outcome of either measurement—if these foundational theories are valid. The observers simply set their detection instruments to a particular configuration and take what nature provides.

Olivier Costa de Beauregard (1953, 1977, 1979) was perhaps the first to suggest that the EPR paradox can be resolved by including the action of signals from the future. Unfortunately, he did not view this idea as a way to economically eliminate the paradox. On the contrary, he claimed a connection with “what parapsychologists call *precognition* and / or *psychokinesis*”(Costa de Beauregard 1978). Others have proposed quantum "theories" of psychic phenomena (Jahn and Dunne 1986, 1987; Goswami 1993). Perhaps as a result of his unnecessary foray into the occult, Costa de Beauregard's original suggestion was not taken as seriously as it should have been.

Nevertheless, time symmetry makes the EPR paradox go away—without occult consequences (see also Sutherland 1983 and Anderson 1988). In the original implementation of the EPR experiment, proposed by Bohm, the two electrons are prepared in an initial state of total spin (angular momentum) zero, the **singlet** state. However, any random pair of electrons will be in either the singlet or the spin one **triplet** state, in statistical proportion of three triplets for each singlet, as the names suggest. The triplet pairs are discarded in the preparation of the experiment, but we must not forget that this operation is part of the experimental procedure.

The electrons go off in opposite directions to detectors that measure their individual spin components along axes that can be set arbitrarily by the observers at the end of each beam line. As noted, measured correlations seem to imply some sort of superluminal connection.

Now, imagine the whole process in a time-reversed reference frame (see figure 8.3). Note: I am not assuming that the experimenters go backward in time or anything of that sort. Just imagine taking a movie of the experiment, and then running it backward through the projector. This is simply another equally legitimate way of observing the experiment. What we see are two electrons emitted from the "detectors" at the beam ends and travelling toward what was the source in the original time direction.

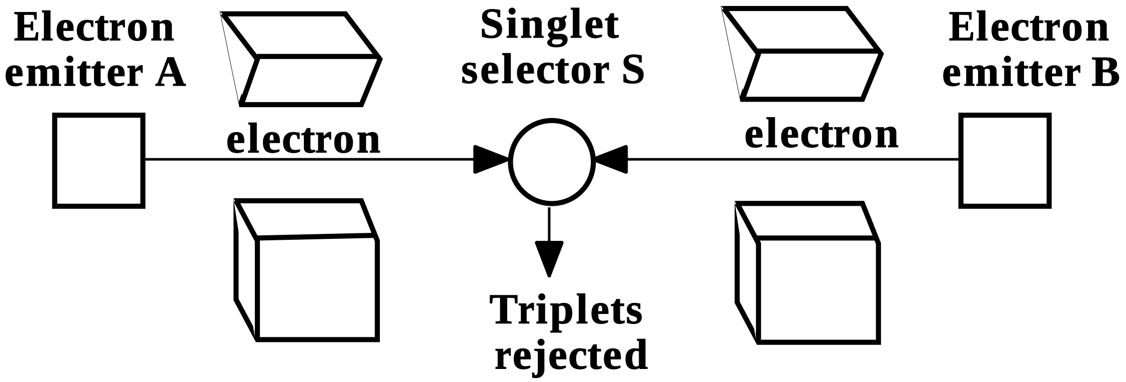

Fig. 8.3. The Bohm EPR experiment viewed in a time-reversed perspective. Electrons with random spin components are emitted by two sources with the triplet states being discarded locally by the singlet selector S.

The emitted electrons can be expected to have random spin components perpendicular to the beam axis. When they come together, the combined two electron system will be either spin one, the triplet state, or spin zero, the singlet state. Again, the statistical ratio will be three-to-one.

In the conventional experiment, only singlet states are accepted and triplet states discarded. Viewing this selection from the time-reversed perspective, we watch the triplet two electron states being discarded while the singlet states are accepted. This action occurs locally, that is, at a single place and time (in the center-of-mass reference frame). Of course, a correlation is then enforced on the system; only the singlet state of the two electrons are allowed in the sample. However, it should be obvious that no superluminal connections of any kind are required.

All other explanations of the EPR paradox require some type of superluminal connections and considerable logic twisting to argue that these are not in fact "signals," which are impossible within the current paradigms of relativity and quantum mechanics, but "influences." Theorems (Stapp 1985) that are purported to prove that quantum mechanics is required to be nonlocal in the light of the Aspect experiment admittedly assume time-directed causality. If they are right, then only time reversibility can rescue us from spooky instantaneous action at a distance in quantum mechanics.

It is important to emphasize that time-reversed pictures are every bit as valid as those drawn with a conventional time direction. That direction is arbitrary. No one viewing the results of an experiment in which electrons of arbitrary polarization are fired at one another and their triplet two-electron states locally discarded would get excited about "nonlocality." So why are so many people excited about the conventional-time EPR experiment, which is indistinguishable from this?

Time Symmetry and Schrödinger's Cat

As we have seen, Schrödinger's cat exemplifies the problem of how a single object in quantum mechanics can exist simultaneously in a mysterious mixture of two states. Unobserved, the cat in the box is somehow a superposition of dead and alive, which I have called "limbo." However, note that no cat is ever seen in limbo—only dead or alive, so no paradox concerning actual observations ever occurs.

Similarly, a photon passed through a left circular polarizer[4] is always found in a single polarized state L. You can verify this by passing the photon through a second left circular polarizer, taking care before doing so not to interact with the photon in any way and possibly change its state.

Let us recall figure 6.7, which shows how the intermediate state of a horizontally polarized photon H (analogous to the cat in limbo) is a superposition of circularly polarized photons L (live) and R (dead). Now suppose we bring time symmetry into the picture. Consider figure 8.4. There I have turned the arrow of the R photon at the bottom around so that it goes into the polarizer instead of out. The L photon at the top is unchanged, still going into the polarizer. The experiment can now be viewed as one in which we have two incoming photons, one spinning along its direction of motion (L) and the other (R) spinning opposite. They combine to form a composite two photon state H.

Alternatively, I could have drawn the two arrows as pointing away from the polarizer. This would be equivalent to the situation where an object disintegrates into two photons. In fact, we know of several such objects, for example, the π^0 meson.

As I mentioned in chapter 6, the quantum formalism contains single photon state vectors for H and V photons, even though these cannot be simply pictured as a single, spinning particle in the same way L and R photons can. Recall that an L photon can be viewed as a particle spinning along its direction of motion while an R photon spins opposite. Because of this easy visualization, I suggested that we might regard circularly polarized photons as the "real," objects and linearly polarized photons as superpositions of two "real" L and R photons. Now bringing time symmetry into the picture, when you send a photon through a linear polarizer that is horizontally oriented, the H photon that comes out is ontologically two photons, an L from the past and an R from the future. That is, it is a "timeless photon."

The point is that at least some of the quantum states that occur in nature can be understood in terms of a superposition of forward and backward time states. This contrasts with the many worlds view in which the superposition is two forward time states in two different worlds. I am suggesting that, with time symmetry, we can get at least these two different worlds into one.

As with the EPR experiment, time symmetry can be utilized to recast our observations into a more familiar form. Based on other observations we have made that exhibit precisely the same phenomenon, nothing is logically inconsistent. The only difference is in the placing of the arrows that specify the time direction. When we are thinking ontologically, we can leave the arrows off. When we must think operationally, as when we consider the results of experiment, we must place an arrow in the direction that is specified by the entropy-generating, or entropy-absorbing, process of our many body experimental setup. This is determined by the boundary conditions of that experiment.

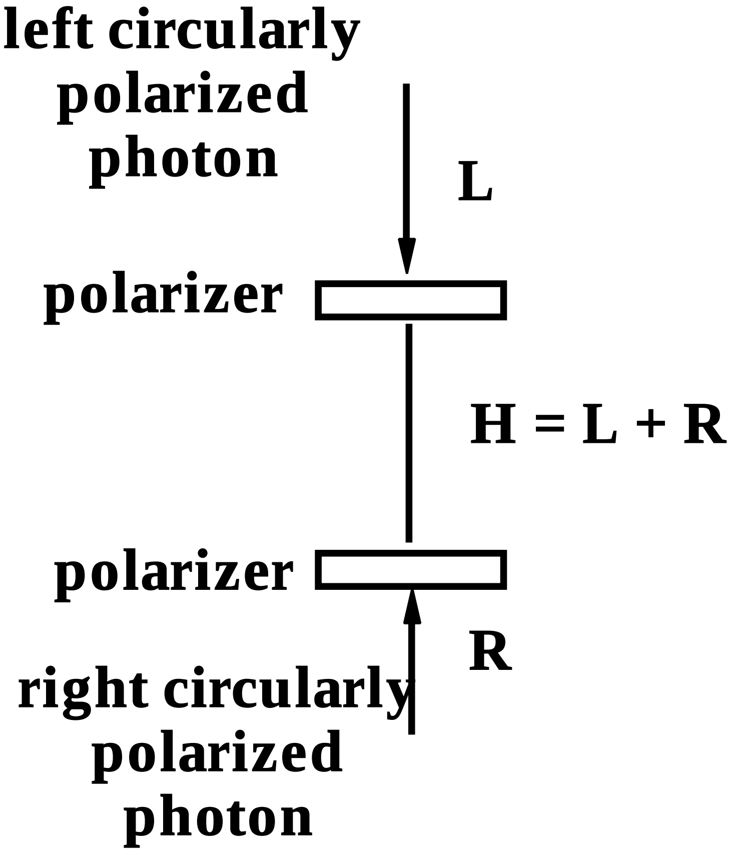

Fig. 8.4. The time-reversible Schrödinger cat experiment as done with photons. The R photon at the bottom is viewed as going into the polarizer rather than coming out. The state in between the two polarizers is then composed of two photons, one coming in and one going out. In the cat experiment, a live cat goes forward in time and a dead one backward in time.

Detection and the Quantum-to-Classical Transition

So, we now see how a time-symmetric reality can provide for a particle existing in a superposition of two quantum states. How, then, do we go from that reality to the one we more directly experience in which time has an unambiguous time asymmetry? We manage this by the same process that takes us from the quantum world to the classical world—the act of observation by a macroscopic system, such as a human eye or a particle detector.

As we have seen, the measurement problem has been at the center of much of the controversy over interpretations of quantum mechanics. In the conventional Copenhagen view, the detector is taken as a classical system and the "collapse of the wave function" occurs during the act of detection. Some interpret this to happen under the control of human consciousness. For good reasons, Einstein called wave function collapse "spooky." It also implies superluminal action at a distance. Bohm and his followers have provided a simple answer to this conundrum: they say that we really have a spooky action at a distance—a mystical, holistic universe in which a quantum potential reaches out instantaneously throughout the universe. Maybe. But we would be wise to rule out less fantastic possibilities first.

In the decoherence interpretation, which has had a number of different formulations, the interaction of the quantum system with macroscopic detectors or the environment itself results in a random smoothing out of interference effects, yielding classical-like observations that do not exhibit these effects. Decoherence provides for wave function collapse in the Copenhagen interpretation, rescuing it from mysticism. It also rescues the many worlds interpretation from incompleteness, by providing a mechanism for selecting out which parallel world is inhabited by a particular observer.

I propose that the quantum-to-classical transition is one and the same with the time symmetric-to-asymmetric transition. As we saw in chapter 4, the arrow of radiation can be traced to the asymmetry between macroscopic sources and detectors, and this in turn is connected to the arrows of thermodynamics and cosmology.

Let us now examine in detail how this asymmetry of detection comes about in an important, specific example.

One of the prime detectors in physics is the **photomultiplier tube**. It provides and excellent prototypical example of a quantum detector since it is sensitive to single photon. Indeed, the photon was first introduced by Einstein in 1905 to explain the **photoelectric effect**, in which light induces an electric current. This played a crucial role in the development of quantum mechanics. The modern photomultiplier tube is an important element of many modern experiments. For example, over 13,000 such tubes provided the primary detection elements in the Super-Kamiokande experiment, on which I worked, that provided the first solid evidence that the neutrino has nonzero mass (see chapter 9).

The detection process in a photomultiplier tube is illustrated in figure 8.5. A photon hits a **photocathode,** which emits an electron into the interior of the evacuated glass chamber that constitutes the tube. The electron is accelerated by the high negative voltage on the cathode to the first **dynode** where it kicks out two or more electrons. This process is repeated, typically ten or so times (only three dynodes are illustrated in the figure), with a multiplication factor of the order of one million. This produces a measurable current pulse that is used to trigger counters and other electronic recording devices.

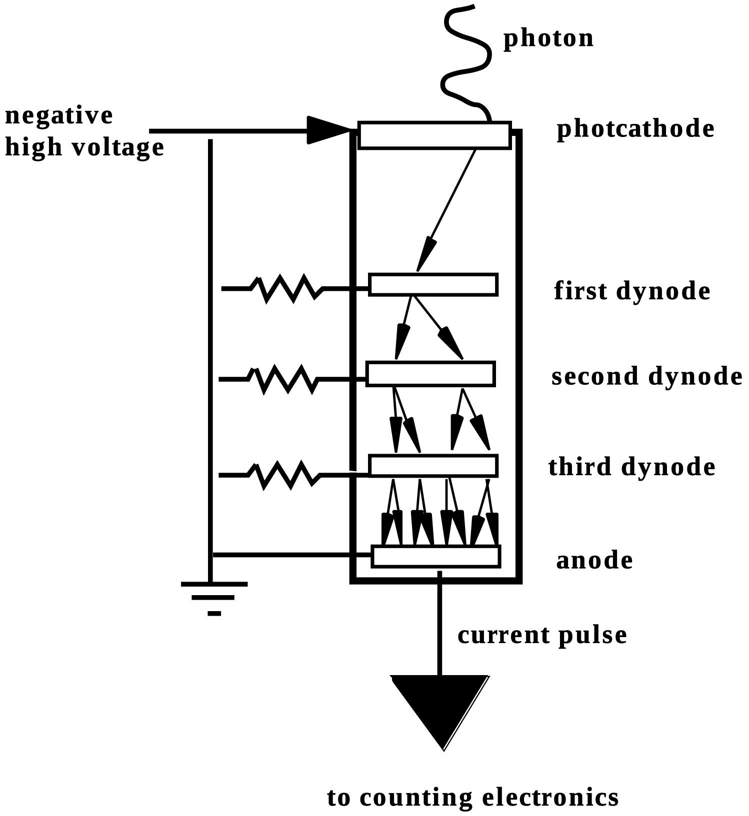

Fig. 8.5. Illustration of the principle of the photomultiplier tube. A photon hits the photocathode which emits an electron into the tube. The electron is accelerated by the high negative voltage to the first dynode, where it kicks out two (or more) electrons. This process is repeated several times (only three dynodes are shown), multiplying the number of electrons and producing a measurable current pulse.

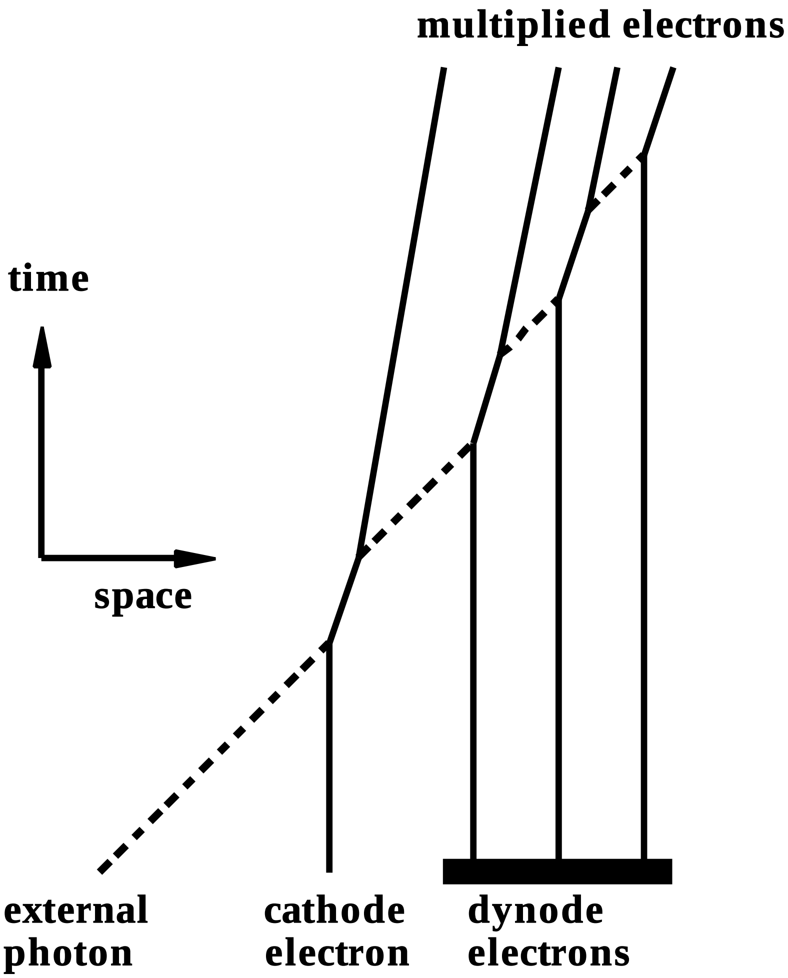

Fig. 8.6. The process of photon detection in a photomultiplier tube as a Feynman diagram. While in principle time reversible, it is very unlikely that the multiplier electrons will interact to produce a single photon.

In figure 8.6, the Feynman diagram for the basic detection process is shown, again in simplified fashion with only single photon exchange interactions indicated. Photons are denoted by dashed lines and electrons by solid lines. The external photon is shown being absorbed by the cathode electron, which then goes on to interact with a dynode electron by virtual photon exchange, kicking it out of the dynode. The struck electron is accelerated to the next dynode, where it interacts with an electron kicking that electron out of its dynode. Thus, the process of multiplication continues. Note that the cathode and dynode electrons all start at rest and so their worldlines run par-allel prior to interaction. However, once scattered outside the metal of the cathode or dynode, their worldlines are more randomly directed.

Now, each of the lines in the Feynman diagram is in principle reversible (hence, no arrows are indicated). Thus, the struck cathode electron can reverse and emit a photon, settling back to its original state inside the cathode. The process is similar to what was illustrated in figure 4.3 (a).

As we move down the dynode chain, however, precise reversibility be-comes increasingly improbable. As noted, the worldlines of the electrons scattered from the cathode and dynode are no longer parallel, meaning they are not at rest relative to one another but flying off in different directions. At the output end where a million or so electrons have produced a macroscopically measurable current, typically a few milliamperes, the probability of them reversing to interact in the exact way needed to result in a single photon being emitted from the cathode is very small. Like a dead cat coming back to life, it is possible but highly unlikely.

Many different Feynman diagrams contribute to the process that converts a photon to a milliampere current. In principle, we would calculate their amplitudes, sum them as complex numbers, and then take the square modulus to get the probability for photon detection. In practice, we simply measure the "detection efficiency" for each tube in the lab and use that to plan our experiments.

In chapter 4, I argued that the three arrows of time—thermodynamic, cosmological, and radiation—were equivalent. In this chapter I have tried to show that no arrow of time exists at the quantum level, but time irreversibility develops during the process of macroscopic measurement. We see that observation is the same decoherent process that makes quantum behavior appear classical, with interference effects being washed out. Indeed, the apparent quantum arrow in what Penrose denotes as the **R** process is just the radiation arrow that results from the built-in asymmetry of macroscopic sources and detectors, and the particular boundary conditions that are imposed on the process of measurement. These boundary conditions are usually those that match the entropy gradient of the apparatus with the cosmological entropy gradient in our part of the universe.

The purpose of measurement is to extract information from a system. Since information is negative entropy, the system under observation must experience an increase in entropy, or disorder. This increase occurs as the entropy of the measuring apparatus decreases, by the very definition of measurement. The reverse process in which a system is made more orderly also can happen, as when you pump up an automobile tire. To measure the pressure with a tire gauge, however, you have to let out a little air and increase the tire's entropy just a bit.

In short, macroscopic measurement processes are irreversible and incoherent by the same mechanism—one that does not apply at the quantum level.

CPT

We have seen how, by changing the time direction of a photon, we can model the superposition of two photon states as a state of two real photons. We need now to generalize this idea to other particles, such as electrons. Let us begin by clearing up something about the process involving photons that was swept under the rug.

Recall that when we time-reflected the L and R photons, we did not change their handedness or chirality. This may seem wrong, because, obviously, the hand of a clock viewed in a film run backward through a projector spins in the opposite direction. But, in fact, we made no blunder. To see why, consider an ordinary clock moving along an axis perpendicular to its front face, as shown in figure 8.7. It is left handed, as can be seen if you place your left thumb in direction of motion of the clock. Your fingers will curl in the direction in which the hand turns on the clock. Now take a film and run in backward through the projector. The direction of motion of the clock will be opposite, but so will be the rotation of the clock hand. The clock is still left handed, as shown on (a). That is, L -> L and R -> R under time reflection.

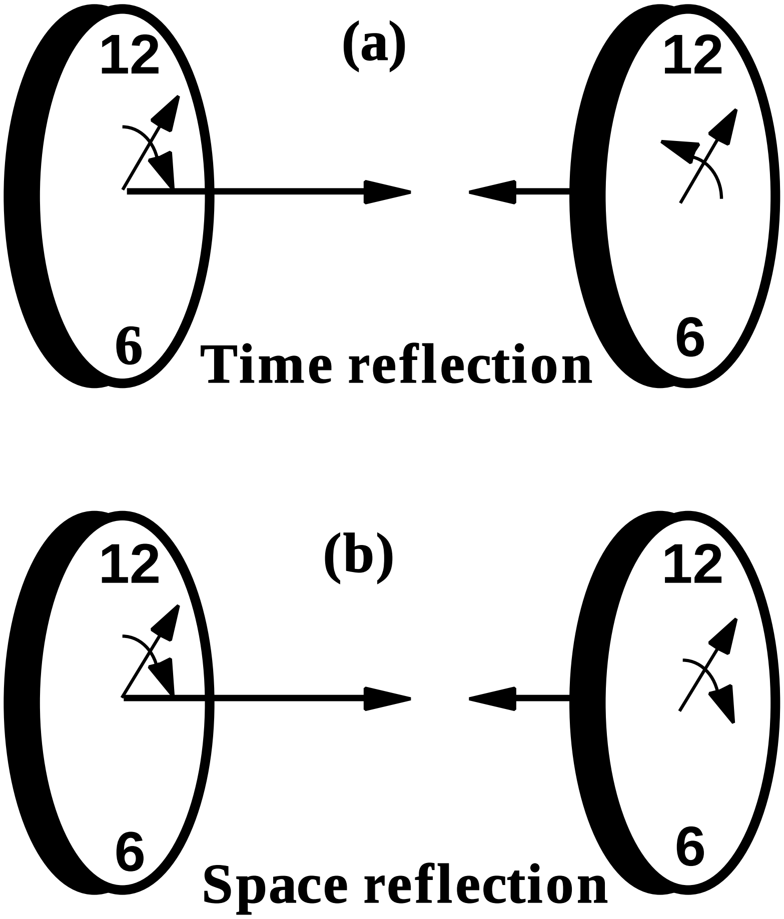

Fig. 8.7. In (a), a clock moving along its axis is left handed in the normal convention and remains left handed upon time reflection. However, it becomes right handed under space reflection (b).

Now let us consider space reflection, as shown in figure 8.7 (b). We see that L -> R and R -> L under space reflection. That is, left goes to right and right to left in a mirror image, a commonsense fact. In physics, we denote time reflection by an operator T and space reflection by an operator P, which stands for **parity**. As we will see, a third operator is also generally involved, denoted by C, which takes a particle into its antiparticle. Photons are their own antiparticles, so this operation did not arise in the above discussion. Later when we deal with electrons in a similar situation, we will combine an electron going forward in time with its antiparticle, the positron, going back in time and viewed in a mirror. The **CPT theorem** has been proved from the most basic axioms of physics; it asserts that every physical process is indistinguishable from the one obtained by the combined operation CPT.

In the case of the photon processes already discussed, time reflection was adequate since those processes are known to be invariant to the T operation. As we will see later, certain fundamental processes, namely, the weak interactions, are not invariant to the P operation. And, a few rare cases of these are not invariant to the combined operation CP. This implies, by the CPT theorem, that these processes violate T. However, we can avoid such complications by being careful to change particles to antiparticles and reflect space as well as time. This will guarantee that the time reflection process will not violate any known principles of physics. That is to say, we can preserve the symmetry of all physical process to time reversal, provided we also change particle to antiparticle and reverse its handedness.

To give a specific example, the CPT theorem says that the interaction between a negatively charged electron and an electron neutrino is indistinguishable from the interaction of a positively charged antielectron, or positron, and an antielectron neutrino, filmed through a mirror with the film run backward through the projector. I realize this is mind-bending, but that's what this book is all about! Please, stick with it. A bent mind is a terrible thing to waste.

Time Symmetry and Interference

Time symmetry can also be used to remove at least some of the mystery of quantum interference. Recall from chapter 6 that photons and other particles produce interference effects that can be easily explained as wave phenomena but become deeply puzzling when we attempt to visualize the par-ticle as following definite paths in space. This was profoundly demonstrated by Wheeler, who showed how the light from a distant galaxy bent by the powerful gravity of an intervening supermassive black hole can be used to do a cosmic double slit experiment in which a choice made by the experimenter seems, somehow, to act hundreds of millions of years back in time.

Interference effects are seen when photons and other particles pass through any number of apertures, or bend around corners. These are conventionally explained in terms of the wave particle duality. Particles have wavelike properties as exhibited by interference and diffraction. In the Copenhagen interpretation, as promulgated by Bohr, this is a consequence of the complementarity of nature, as explained in chapter 6.

In the de Broglie-Bohm pilot wave interpretations, a particle carries along with it a superluminal quantum field that produces these effects. In the many worlds interpretation, the particle picture is retained but the various paths the particle can follow, for example, through two slits, occur in different worlds that can interact with one another to produce the observed interference.

We also found that the consistent histories formulation of quantum mechanics, due to Griffiths, provided a scheme by which a particle can follow a specific path, in a single world, and still exhibit interference effects. This was discussed in terms of the Mach-Zehnder interferometer, which was illustrated in figure 6.1. Instead of the particle being regarded as a superposition of states corresponding to the two paths, the state of the particle, when it is on one path or the other, is a superposition of the two possible detection states. This leads to the same interference effects as the conventional scheme.

Time symmetry can perhaps help us formulate a realistic model of two-path interference that is consistent with this picture. As seen in figure 8.8, we have one photon emitted from S going forward in conventional time and another photon emitted from D1 which goes backward in conventional time, following, as one possibility, the alternative path back to the detector. (If we had used electrons, then a positron would go backward). Of course, the photon can also follow the same path back, but this is indistinguishable from the forward photon. Time symmetry then simply gives us a way to have a photon on each path.

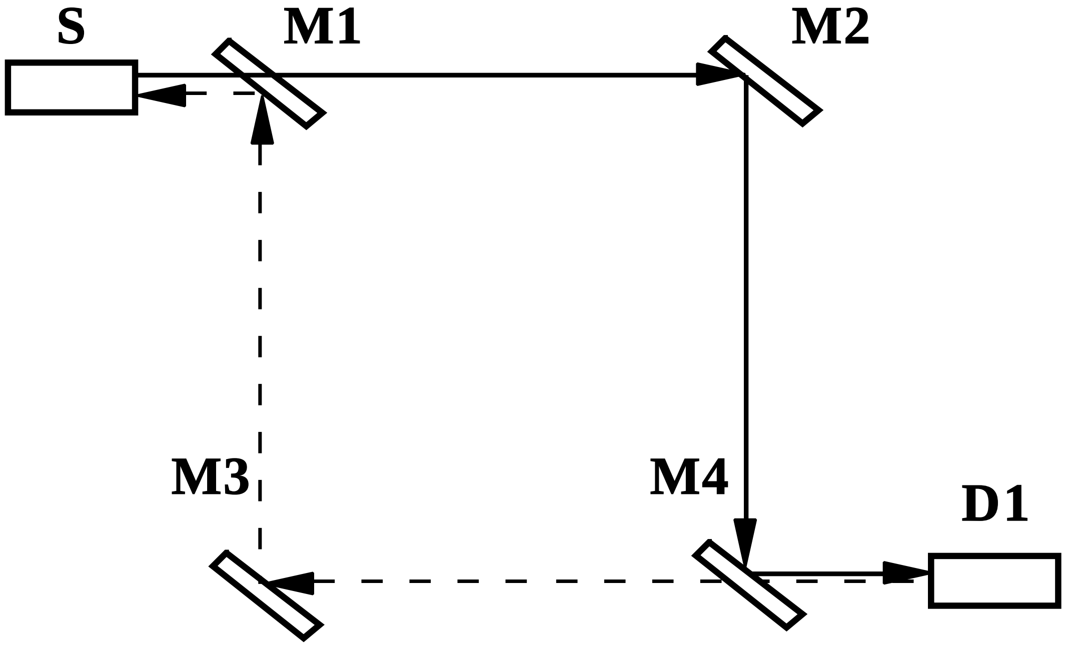

Fig. 8.8. A time-symmetric view of the interferometer. S emits a photon forward in time. When it reaches D1, another photon is emitted by D1 backward in time. It reaches S at the time that S emitted its photon, so the situation is time symmetric.

Let us take another look at the double slit experiment within the framework of time symmetry (see figure 8.9). A single hit is registered at both the source and detector, within a time interval that would allow the particle or antiparticle to propagate the distance between the two, through either slit. This is conceptually the same as the interferometer example above. Included in the possible paths will be pairs in which the particle passes through one slit and the antiparticle passes simultaneously (in the reference frame of the screen) through the other. And so, a correlation exists between the two slits in a given event, without the need of a superluminal signal being sent between the two. (Recall, also, the discussion in chapter 7 with regard to figure 7.2).

Note that the charge balances, as it should. Suppose the particle is an electron.The source loses a negative charge that is gained by the detector some time later, when viewed in conventional time. In reverse-time, the detector loses a positive charge that was *earlier* gained by the source. In either case the net result is the same.

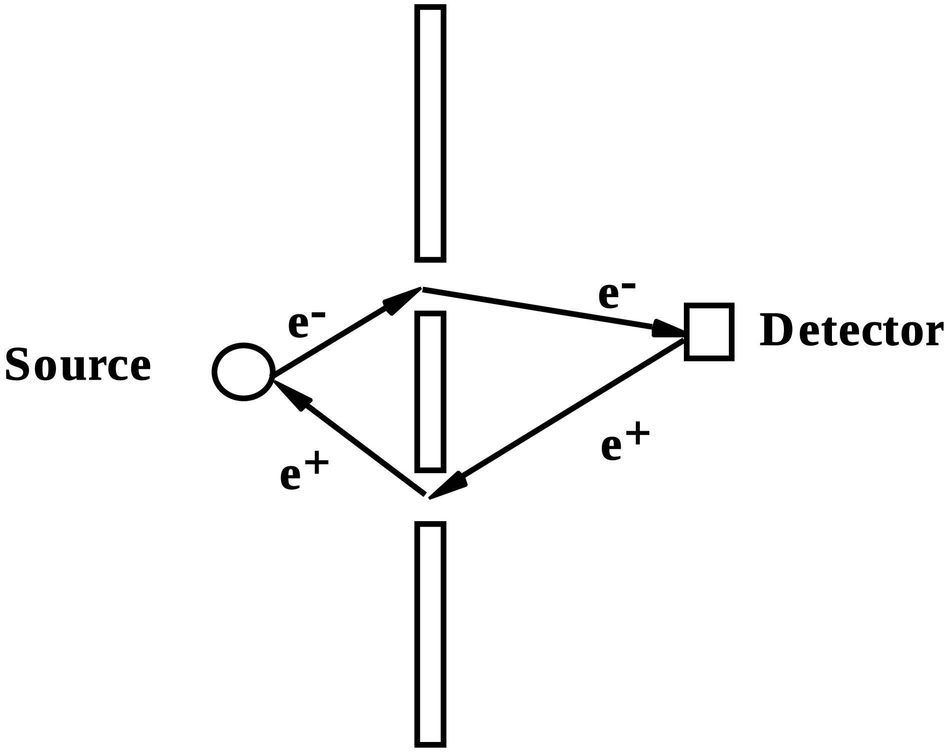

Fig. 8.9. The double slit experiment from a time-symmetric perspective. In conventional time, an electron passes through the top slit. In the time symmetric view, detectors also act as sources and sources as detectors. Here the detector is shown sending a positron back in time through the bottom slit. This is equivalent to an electron going forward in time through that slit. The two electrons pass simultaneously through both slits. Thus, a correlation between the two slits exist that does not require superluminal signals. All the possible paths between source and detector are not shown.

Again, we can see the contrast with the many worlds view, in which the paths through the two slits occur in different worlds. Time symmetry seems to offer an alternative interpretation to the many worlds interpretation of quantum mechanics. This can be extended to multiple slits, or multiple paths. The principle is simply that for every particle following one path in one time direction from point A to point B in space-time, an antiparticle (of opposite chirality) follows the same or another allowed path from B to A in the opposite time direction. In this way all the possible paths between A and B are followed and, as the rules of quantum mechanics require, interfere with one another.

As to "why" the paths interfere, this is basically an axiom of quantum mechanics no matter how it may be formulated or interpreted. I will try to give some idea of its ontological source in Chapter 11, but I make no claim to "derive" this very fundamental feature of quantum phenomena. Nor does any interpretation of quantum mechanics.

Solving the Time Travel Paradox

The time-reversible picture presented here should not be interpreted as implying that macroscopic objects, such as human beings, will ever be able to travel back in time. As with a dead cat being resuscitated, it can happen. But we should not expect to see it in the lifetime of the universe. The familiar arrow of time applies to incoherent many body systems, including the human body, and is defined by the direction of most probable occurrences. Because of the large number of particles involved, this probability is very highly peaked in one direction, which is then defined as the direction of time. The time travel implied by the very unlikely but in principle possible processes that can happen in the opposite direction is not to be confused with some of the other types of macroscopic time travel about which people speculate. For example, cosmological time travel might occur when the time axis is bent back on itself in the vicinity of strong gravitational singularities, or cosmic wormholes are used as time machines (Thorne 1994).

The quantum fluctuations that result in the zigzagging in space-time illustrated in figure 8.2 normally occur only over small distances. Deep inside the nuclei of our atoms, elementary particles are zigging and zagging in space-time, but the aggregate moves in the direction that chance, macroscopic convention, and boundary conditions select as the arrow of time.

Large-scale quantum correlations also exist in the EPR experiment, which has now been performed over kilometer distances. However, we have seen that these do not require superluminal connections in the time-reversible view. Macroscopic, many particle coherent systems such as laser beams, superconductors, and bose condensates also exist. Since these are quantum systems, they should also exhibit time reversibility.

Suggestions have been made that the human brain is a coherent quantum system, and that consciousness is somehow related (Penrose 1989, Stapp 1993, Penrose 1994). These ideas remain highly speculative and highly unlikely, although this has not stopped paranormalists from claiming backward causality in quantum mechanics as a basis for the human mind to reach back and affect the past (Jahn 1986, 1987). Again, I will not repeat what I covered in detail on this subject in *The Unconscious Quantum* (Stenger 1995b).

Still, at least one loose thread needs to be tied up in this chapter. The idea that time reversibility solves the quantum paradoxes has been floating around for about half a century, so no parenthood is being claimed here for that notion. However, time reversibility carries what many people think is paradoxical baggage of its own. This has dissuaded influential figures, like Bell, from incorporating time reversal into interpretations of quantum mechanics.[5] If the time travel paradox can be resolved at the quantum level, then the way is open for time symmetry to be a part of any quantum interpretation.

Human time travel would appear to allow you to go back in time and kill your grandfather when he was a child, thereby eliminating the possibility of your existence. This is the famous time-travel or *grandfather paradox*. Philosophers technically refer to the problem of backward or "advanced" causation as *the bilking problem*. As Price (1996,128) explains it:

> In order to disprove a claim of advanced causation, we need only to arrange things so that the claimed later cause occurs when the claimed earlier effect has been observed not to occur, and vice versa.

Price (1996, 173) discusses in great detail arguments given by philosopher Michael Dummett (1954, 1964) to avoid the bilking problem. As he summarizes Dummett's view:

> Claims to affect the past are coherent, so long as it is not possible to find out whether the claimed earlier effect has occurred, before the occurrence of the alleged later cause.

In other words, if you go back in time you cannot take an action to prevent some effect if you have no way of discovering the causes of that effect.

I will leave it to the philosophers to debate whether or not bilking can be avoided and macroscopic time travel made logically consistent. I kind of doubt it, without recourse to parallel universes, where you end up in a different world from the one in which you started. Let us instead examine the problem on the quantum scale.

The quantum situation is as if you went back in time to look for your grandfather and kill him, but found that he was indistinguishable from all the other men in the world (only two, in the photon example). All you can do is shoot one at random, which you do not have to be from the future to do. Since no information from the future is used, no paradox exists.

Once again, let us illustrate the effect by considering an experiment with coherent photons, rather than macroscopic bodies like cats or grandfathers (see figure 8.10). Suppose we pass initially unpolarized photons through a horizontal linear polarizer H, so that we know their exact state, and thence into a circular polarizing beam splitter. Two beams emerge from the latter, one with left polarization L and the other with right polarization R. We set up the apparatus so that when a photon is detected in the L beam, a signal is transmitted back in conventional time (it need only be nanosecond or so) to insert an absorber that blocks the photon before it reaches the L polarizer. This is analogous to going back in time and killing your grandfather, or yourself for that matter.

Now, each photon that has passed through the H polarizer is in a coherent superposition of L and R states. As a result, we will sometimes block photons that would normally end up in the R beam. That is, we cannot identify an L photon to absorb since that L photon is part of the pure state H. If we act to absorb the photon anyway, we will be killing an H state, not an L state. This action is as if the absorber were randomly inserted in the beam, killing off on average half the photons that will end up in the L and R beams. Since we can achieve the same result without the signal from the future, we do not have a causal paradox. That is, the killing of the photon was not necessarily "caused" by an event in the future.

You might wonder what would happen if, instead of the H polarizer we had an L one. Then we always have L photons and kill them all off. Or, if we have R photons we don't kill any. Again, this can be done without a signal from the future and we have no paradox. The same situation obtains if we try to measure the circular polarization before taking action. To do this we would have to insert a right circular polarizer in the beam, which would produce a beam of pure R. But this can also be done with no information provided from the future.

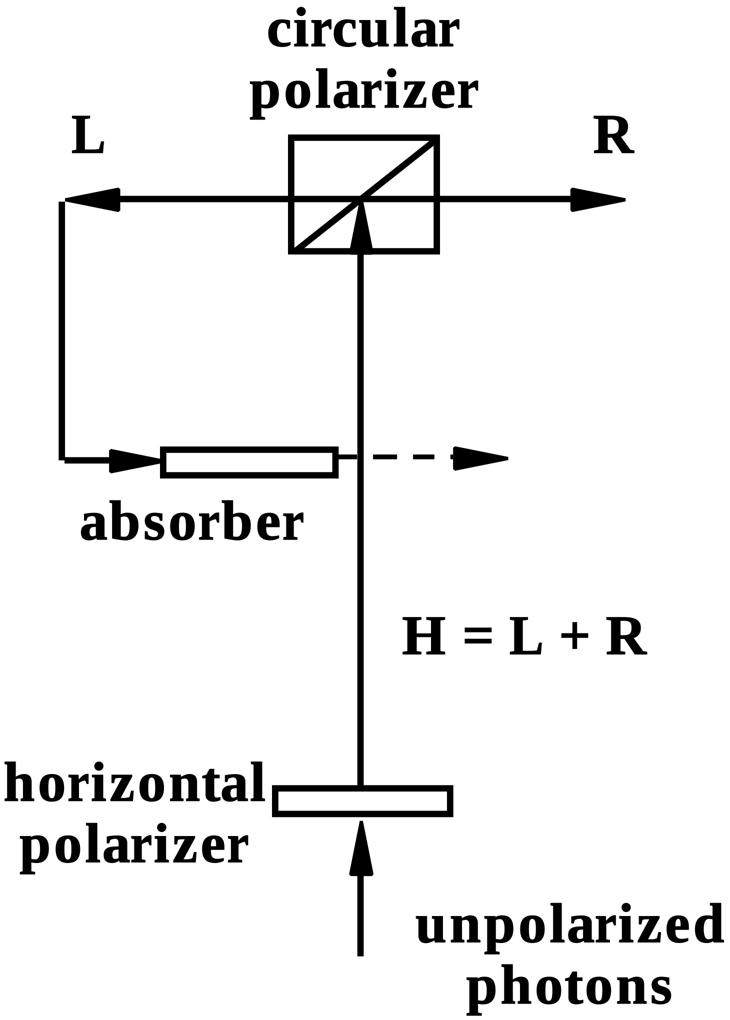

Fig. 8.10. Unpolarized photons are placed in a pure quantum state by the horizontal polarizer. The circular polarizer separates the beam into two circularly polarized beams L and R. When an L is detected, a signal is sent back in time to place an absorber in the beam and prevent the photon from proceeding, thus producing a causal paradox. However, the paradox is not present when the state H is a coherent superposition of L and R, only when it is an incoherent mixture.

To appreciate the role quantum mechanics plays in avoiding paradox, consider what happens when H is removed. Then we have an incoherent mixture of L and R photons from the original source, analogous to a macroscopic system. The absorber will only block the L photons that are destined to be in the L beam. The R photons pass unhindered to the right beam. Now we indeed have a causal paradox, with the signal produced by a particle in the future going back in time and killing the particle. While this example certainly does not exhaust all the possibilities, it strikes me that the causal paradox will be hard to defeat for macroscopic time travel, unless that travel is to a parallel universe.

In the clever *Back to the Future* films, the young time traveller Marty (played by Michael J. Fox) had to take certain actions to make sure his father became his father. He had to watch over him, protect him from bullies, and make sure that he dated Marty's future mother (who found Marty strangely attractive). Time travel may be impossible in the classical world without the parallel universes that these and other films and science fiction tales assume, but time travel in the quantum world appears to remain logically possible.

In this discussion, I have implicitly assumed a direction of time as defined by convention and spoken of "backward" or "advanced" causality from that perspective. However, we have seen that the conventional direction of time is set by the direction of increased entropy, and we might wonder where that enters in these examples.

Actually, it enters in an interesting way. Backward causality involves the use of information from the future that is not available in the past. But this implies that the future has *lower* entropy—more information—than the past, a contradiction. The past is by definition the state of lower entropy. On the other hand, the flow of information from the past into the future is allowed. So no logical paradox occurs when a signal is sent to the future (as it is in everyday experience—far in the future if we send it third class mail), just when it is sent into the past.

In the quantum case, since the same result as backward causality can be obtained without the signal from the future, no information flows into the past and no causal paradox ensues. Indeed, this is exactly what we have discovered; quantum mechanics seems to imply time-symmetric causality, but can be formulated without it. My thesis is not that time reversibility is required to understand the universe, Rather, as happened with the Copernican solar system, once we get over our anthropocentric prejudices time reversibility provides us with a simpler and more economical picture of that universe. And it is on that basis, not proof, that we can rationally conclude that time is reversible in reality. Indeed, with no special present, past, or future, we exist in a *timeless reality*.

Notes

1. $\Delta E \Delta t \geq \hbar / 2$. This can easily be seen using four-vector scheme of relativity, where time and energy are the fourth components of the four-vector position and momentum. Also, in classical mechanics, energy is the generalized "momentum" conjugate to the generalized "position" that is time. For $\Delta E = 2mc^2 = 1.022$ MeV, $\Delta t = 10^{-22}$ second.

2. Distance $\Delta x \approx h / \Delta p \approx h / p = \lambda$, the de Broglie wavelength.

3. In cosmology, we still often talk as if everything across the universe is simultaneous. This works, as long as we limit ourselves to those parts that are moving with respect to us at nonrelativistic speeds.

4. Two kinds of circular polarizers exist. The usual circular polarizer is a quarter-wave plate with an incident linear polarization at 45° from the principal axes, the output will give you either a right circular polarization R or a left circular polarization L, but not both; it essentially depends on the direction of the incident linear polarization with respect to the principal axes. On the other hand, circular polarizing beam splitters give two components, R and L, propagating at right angles.

5. See Price (1996, chapter 9) for Price's attempt to convince Bell of the merits of time symmetry.