

## Why the quantum? “It” from “bit”? A participatory universe? Three far-reaching challenges from John Archibald Wheeler and their relation to experiment

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### Introduction

First a word of thanks. When I first came across the papers of John Archibald Wheeler on the foundations of quantum mechanics, most of them reprinted in Wheeler and Zurek (1983), I could not believe what I read. Finally here was a colleague of worldwide reputation, given his many contributions to theoretical physics, who was not afraid to discuss openly the conceptual problems of quantum mechanics. The outstanding feature of Professor Wheeler’s viewpoint is his realization that the implications of quantum mechanics are so far-reaching that they require a completely novel approach in our view of reality and in the way we see our role in the universe. This distinguishes him from many others who in one way or another tried to save pre-quantum viewpoints, particularly the obviously wrong notion of a reality independent of us.

Particularly remarkable is Professor Wheeler’s austerity in thinking. He tries to use as few concepts as possible and to build on this the whole of physics. A fascinating case in point is the title of one of his papers “Law without law,” the attempt to arrive at the laws of nature without assuming any law *a priori*.

For me personally his work on fundamental issues in quantum mechanics has been particularly inspiring. The questions he raises are exceptionally far-reaching and some of his concepts in the foundations of physics are so radical that calling them revolutionary would not do them justice. Such radically new concepts are certainly needed in view of such challenges as the measurement problem, the Schrödinger cat paradox, the conceptual nature of quantum entanglement, or the transition from quantum to classical.

In his discussions of the foundations of quantum mechanics Wheeler uses thought-experiments a number of times. In this way he continues the beautiful tradition which was set in quantum mechanics from the very beginning, for example by Heisenberg's gamma microscope and culminating in the Bohr-Einstein dialogue, showing that thought-experiments are the vehicle of choice to demonstrate counterintuitive features of quantum theory or even to challenge it. In the last two to three decades technological progress has made it possible for many of these thought-experiments to be realized in the laboratory, and this has led to a perfect confirmation of all the counterintuitive predictions of quantum mechanics. It has also led to the invention of novel experiments which the forefathers did not even dream of in their *gedanken* version, and, most recently, this work on the foundations of quantum mechanics has brought into existence a new field of information science signified by such interesting topics as quantum cryptography, quantum teleportation, and quantum computation.

This experimental development is now giving rise to new thinking about the foundations of quantum mechanics, having increasingly freed the minds of physicists, particularly of young physicists, from the prejudices about how the world ought to work, prejudices that are based on pre-quantum classical concepts. In search of the final understanding of quantum mechanics, John Archibald Wheeler's far-reaching questions provide bright beacons for illuminating the abysses of prejudice, of preconceived notions, and of complacency with seemingly satisfactory yet immature partial solutions.

### **A participatory universe?**

Quantum physics has raised the question of the role of the observer in a novel way, at least for physics. In classical physics the observer has a role that is essentially passive. It is certainly legitimate within that world-view to assume reality as existing prior to and independently of our observation. The situation might be compared with that of actors on a stage, in the sense that the stage with its objects and features, including the other actors, is essentially present and we just move through it. There is clearly some influence by the observer on the world even in classical physics; for example the actor can certainly move objects around on stage, but this influence can be understood, at least in principle, on the basis of an unbroken causal chain. The most essential point here is the view that we are dealing with features of an outside world, a world in which, while it might be changed somehow by the observer through the act of observation or through other acts, any such change is a change of features pre-existing before observation.

Not so in quantum physics. Already in the famous double-slit experiment it depends on which question we ask whether the particle passing through the

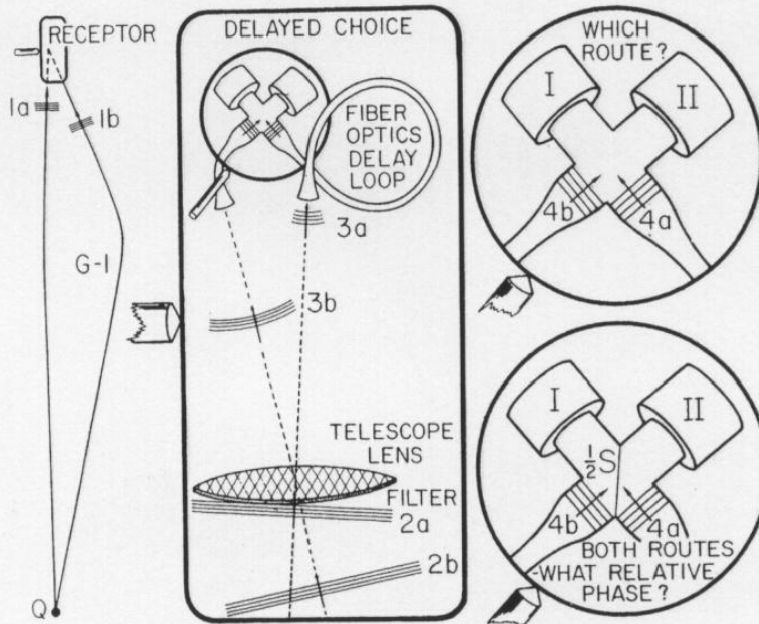


Figure 11.1. Proposed delayed-choice experiment extending over a cosmological reach of space and time. Left, quasar Q recorded at receptor as two quasars by reason of the gravitational lens action of the intervening galaxy G-1. Middle, schematic design of receptor for delayed-choice experiment: (a) filter to pass only wavelengths in a narrow interval, corresponding to a long wave train, suitable for interference experiments; (b) lens to focus the two apparent sources on to the acceptor faces of the optic fibers; (c) delay loop in one of these fibers of such length, and of such rate of change of length with time, as to bring together the waves traveling the two very different routes with the same, or close to the same, phase. Right, the choice. Upper diagram, nothing is interposed in the path of the two waves at the crossing of the optic fibers. Wave 4a goes into counter I, and wave 4b into counter II. Whichever of these photodetectors goes off, that – in a bad way of speaking – signals “by *which* route, a or b, the photon in question traveled from the quasar to the receptor.” Lower diagram, a half-silvered mirror,  $\frac{1}{2}S$ , is interposed as indicated at the crossing of the two fibers. Let the delay loop be so adjusted that the two arriving waves have the same phase. Then there is never a count in I. All photons are recorded in II. This result, again in a misleading phraseology, says that “the photons in question come by both routes.” However, at the time the choice was made whether to put in  $\frac{1}{2}S$  or leave it out, the photon in question had already been on its way for billions of years. It is not right to attribute to it a route. No elementary phenomenon is a phenomenon until it is a registered phenomenon.

apparatus can be viewed as a particle or as a wave. This has been brought into focus by Wheeler’s proposal of a delayed-choice experiment (Fig. 11.1). Wheeler considers the ultimate interferometer, which is of the size of the universe. The essential starting point is the observation of more than one image of one and the same quasar at two spots in the sky which are close to each other. The explanation is that light from these quasars is deflected in some way by an intervening galaxy which is placed along the path of the light from the quasar to us. Wheeler then argues that the light



which has come along the two (or more) routes must be coherent as it comes from the same source, so it should be possible to bring the light which has come along the two routes to interference, as is shown by the middle part of Fig. 11.1. In order to achieve this, Wheeler chooses to couple the light into optical fibers and to bring it to interference at a fiber-optic coupler. The two routes are certainly not of equal length because the geometrical arrangement of quasar, galaxy, and our position is rarely a symmetric one, so the light along one of the two routes will have arrived earlier, meaning that we have to store it until the light from the other route also arrives. Considering the cosmic differences this could be a very long time and thus beyond any practical feasibility, but that is not the point here. Then Wheeler makes the interesting suggestion that it is up to the observer to decide at the last instance just before the photon is measured whether it behaved like a particle or like a wave. The observer is free to decide to either detect the photons having propagated on their separate paths separately or to insert a semi-reflecting beam-splitter (the right-hand part of Fig. 11.1), in which case the waves which have come from the two routes are coherently superposed. It is clear that it is a decision at the disposal of the experimentalist whether or not to insert the semi-reflecting mirror at the time after the light has already propagated to us. This choice then decides whether or not the light has come to us as a particle or as a wave. In Wheeler's own words, "One decides whether the photon should have come by one route or by both routes after it has already done its traveling."

In an experiment a few years ago in my group we brought Wheeler's thought-experiment into the laboratory and carried it a step further (Dopfer 1998; Zeilinger 1999a). The idea was to demonstrate that it can be decided after the photon has been registered already whether the phenomenon observed can be understood as a particle or as a wave. Let us first contemplate the relationship of path information and interference pattern in the two-slit experiment.

Consider a double-slit experiment with electrons (Fig. 11.2). We have an electron gun which emits electrons at such low intensity that they come one by one. The electrons then pass through a diaphragm with two slit openings and are collected on an observation screen. On the observation screen we will observe an interference pattern consisting of bright and dark stripes. This fringe pattern can easily be understood on the basis of waves which came through both slits and which interfere constructively at the maxima of intensity on the observation screen and destructively at the minima. Evidently the interference pattern only forms because of the wave having come along two routes. Let us then also consider some light source which produces photons with energy  $h\nu$ . These photons may be scattered by the electrons and we view the scattered photons using a Heisenberg microscope. This microscope assembly had been invented by Heisenberg (1927) in order to demonstrate the position-momentum uncertainty relation for electrons.



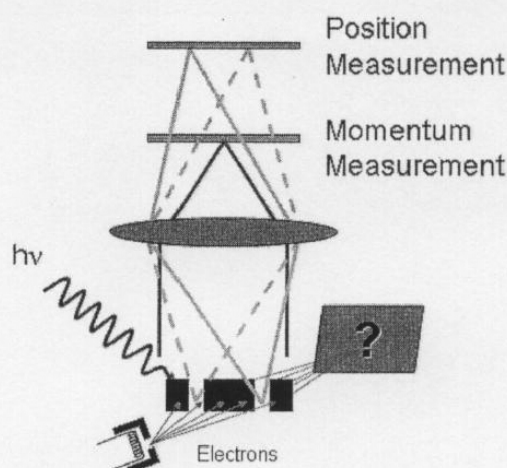


Figure 11.2. The Heisenberg microscope in a double-slit experiment for electrons. Photons with energy  $h\nu$  are scattered off electrons passing one by one through a double-slit assembly. The scattered photons are then imaged using a Heisenberg microscope. The experimentalist has the choice to position the observation screen for the scattered photons at any distance behind the Heisenberg lens. If the observation screen is placed in the focal plane, detection of a photon there collapses the incoming wave of the photon onto a momentum eigenstate containing no position information, hence double-slit electron interference should appear in that case. If the observation screen is placed at the image plane of the microscope lens, the position where the scattering took place can be determined and thus the slit through which the electron passed. In that case no double-slit electron interference should appear.

There are clearly various choices in which observation plane we detect our photons behind the microscope. Let us assume that we use a position-sensitive photon detector which for each photon gives us the position where it arrives. At first we consider the detector being placed at the image plane of the microscope. Each position on the detector plane corresponds to a unique position in the plane of the two-slit assembly. Therefore, by registering where the photon arrives we can find out which path the electron took through the assembly. Therefore no interference pattern can arise as it is well known that any interference pattern disappears as soon as we have path information.

Yet we also have other alternative choices available as to where we place our single-photon detector. For example, if we place our detector in the focal plane of the lens then each incident direction is imaged onto one spot of the detector. Therefore detection of the photon now gives us the momentum of the photon after it has been scattered by the electrons and no path information for the electrons whatsoever, which therefore must show an interference pattern. The conceptual problem now arises that we can easily consider a situation where the electrons are detected in the observation plane earlier than the photons are detected. Therefore, we

could consider the choice as to whether a momentum measurement or a position measurement is made through the photon to be done at the last instant after the electron has already been measured. This possibility has actually been remarked upon for the Heisenberg microscope by C. F. von Weizsäcker (1931).

So what does the poor electron then do, when it arrives on the observation screen? Does it behave like a wave forming an interference pattern, as would be necessary if a momentum measurement is made on the photon, or does it behave like a particle arriving randomly somewhere on the observation plane, allowing for the possibility that the detector be placed at a location for position measurement? Let us therefore refer to the real experiment.

In the experiment, instead of using an electron and a photon, we use entangled photon pairs created in the process of type-I parametric down-conversion, in a  $\text{LiIO}_3$  crystal, with an optical nonlinearity, pumped by a UV laser beam (Fig. 11.3). This results in rare spontaneous creation of entangled photon pairs. These pairs are entangled in the sense that neither of the two photons carries any well-defined momentum or well-defined energy on its own but all that is defined is that their momenta and their energies have to add up to the momentum and energy of the incident photon. Experimentally this means that as soon as one of the two photons is measured it spontaneously assumes some energy and momentum and then the other photon, no matter how far away it is, immediately assumes the corresponding energy and momentum such that they add up to the energy and momentum of the original photon. Here we only consider the momentum entanglement. One of the two photons is then sent to a double-slit set-up and detected behind its double-slit using a movable single-photon detector. The other photon passes through the Heisenberg lens and is detected in the single-photon Heisenberg detector D1. The Heisenberg detector may be placed at any position behind the lens including the two positions considered above. As we will now see, photon 1 passing through the Heisenberg lens plays exactly the same role as the photon in our previous considerations.

We expect that if the detector is placed at the focal distance  $f$  behind the lens, the incoming photon is projected on a well-defined momentum state, and thus it cannot carry any position information. Therefore, we have no information where photon 2 passes through the two-slit assembly, as it also is projected onto a momentum eigenstate and thus it should exhibit a two-slit interference pattern. On the other hand, if we place the detector at the distance  $2f$ , the plane with the two-slit assembly is exactly imaged, as this is  $2f$  in front of the lens measuring the distance from the lens via the crystal to the slits. Then we can get position information and no interference pattern should arise for the second photon. This is exactly what we have seen in the experiment (Fig. 11.4). Does this now mean that the distribution of the photons in the observation plane behind the two-slit assembly changes depending on what we

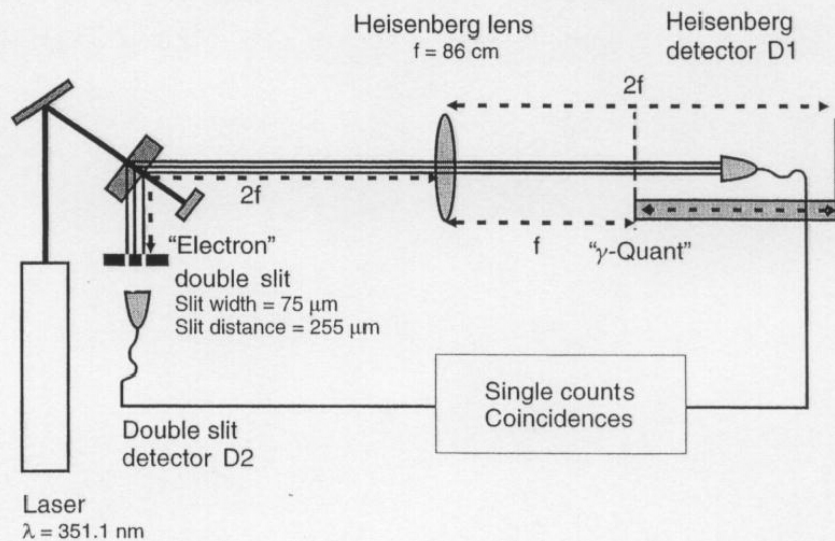


Figure 11.3. Experimental realization of the Heisenberg microscope double-slit experiment. In the  $\text{LiO}_3$  crystal an incoming UV photon may spontaneously convert into two red photons which are momentum-entangled. One of the two photons plays the same role as the photon in the thought-experiment of Fig. 11.2. It passes through a Heisenberg lens and then the Heisenberg detector can be placed at any position behind the lens. The other photon plays the role of the electron of the thought-experiment passing through a double slit. Using proper electronics, one can determine both the individual counts in the detectors and the coincidences.

do with photon 1? Obviously this is impossible, as photon 1 is detected at a time after photon 2 has been registered already. The solution is that we have to register the two photons in coincidence. Thus whether we obtain the two-slit pattern or not depends on whether the possible position information carried by the other photon has been irrevocably erased or not.

The important conclusion here is that the distribution of events in the observation plane behind the two-slit assembly is independent of what we do with photon 1. Yet the interpretation of that distribution is crucially dependent on whether we place the detector for photon 1 in the focal plane or at the distance  $2f$ . In the first case we can consider each photon that has already passed through the two-slit assembly and has already been registered as a wave having passed through both slits. In the second case we have to consider each photon as a particle having passed through only one slit. The important conclusion is that, while individual events just happen, their physical interpretation in terms of wave or particle might depend on the future; it might particularly depend on decisions we might make in the future concerning the measurement performed at some distant spacetime location in the future. It is also evident that the relative spacetime arrangement of the two observations does not matter at all. We could carry out the two registrations in a spacelike separated manner, in which case the relative time ordering of the two events is not



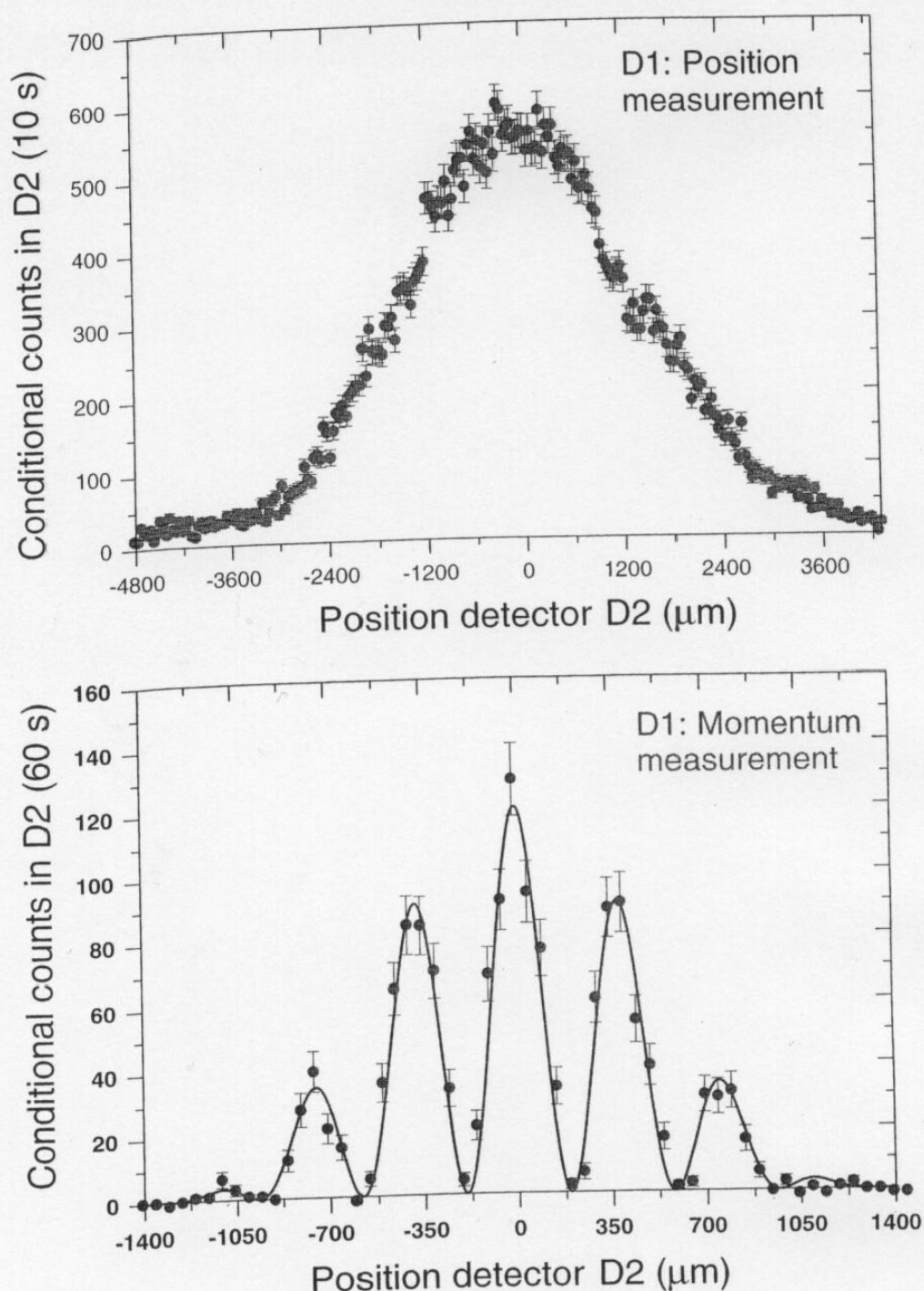


Figure 11.4. Experimental result of the experiment of Fig. 11.3. If the Heisenberg detector is placed at a distance suitable for position measurement (top), no interference fringe results as path information for the second photon passing through the double slit is available. If the detector for the first photon is placed in the focal plane behind the Heisenberg lens, no position information is available and hence for those photons arriving behind the double slit in coincidence, with the other photon being registered behind the lens, beautiful interference fringes result (bottom). The reader should also check the intensity, which clearly demonstrates that we have single-photon interference.

well defined. Depending on the relative motion of an observer and the apparatus, either one might precede the other or they might appear to be simultaneous. Or we might arrange the two detections in a timelike separated manner, having a clear temporal sequence between the two. In any case this experiment, besides being a manifestation of Wheeler's delayed-choice proposal, can also be viewed as supporting Niels Bohr's famous dictum, "No phenomenon is a phenomenon unless it is an observed phenomenon." Here it means that we are not allowed to talk about photon 2 as a particle or as a wave, even at a time when it has been registered already, unless the respective experiment has actually been carried out by also registering photon 1.

The experiment just discussed also provides a clear illustration of the role of the experimentalist. By choosing the apparatus the experimentalist determines whether the phenomenon observed can be seen as a wave or as a particle phenomenon and once the observer has made this choice, Nature gives the respective answer and the other possibility is forever lost. Thus, we conclude, by choosing the apparatus the experimentalist can determine which quality can become reality in the experiment. In that sense, the experimentalist's choice is constitutive to reality, yet one should be warned strongly against a subjective interpretation of the role of the experimentalist or of the observer. It is clear that the consciousness of the observer does not influence the particle at all, in contradiction to a widespread but unfortunate interpretation of the quantum situation.

### **"It" from "bit"?**

This is the second far-reaching question raised by John Archibald Wheeler which we will discuss here, the question concerning the role of information. What is the relation between material existence and knowledge, between reality and information?

As scientists, indeed as human beings, we look at the world and, from the information streaming in on us, we construct some kind of reality. Probably science began when the first person looking up to the sky and wondering at its beauty asked the question of how to interpret the small bright points up there. Prehistoric humans had very little information at their disposal to answer this question and thus they had to invent additional information in order to construct a consistent picture. Therefore we have scores of different explanations as to what the stars really are. Today, due to modern technology, we have much more information available and therefore we have very refined yet in general less romantic pictures of the stars, of the galaxies, and of the universe.

We would now like to address an important question, namely that of the relation between the size of a system and the amount of information it can carry. Clearly a huge system like a galaxy needs an immense number of bits of information in order

to be characterized completely. But how do we expect the information to scale with the size of a system? Apparently, if we split a system into two, it is reasonable to assume that each half needs about half the information to be characterized on its own. So we continue to split our system into smaller ones and smaller ones and smaller ones, and therefore the number of bits necessary to characterize one of these partial systems will be further and further reduced. Evidently we will arrive at a fundamental limit if we keep continuing in this way, and the limit is reached when one system carries only one bit of information. Less is obviously not possible (Zeilinger 1999b). So it is suggestive to define the most elementary system in the following way: the most elementary system carries one bit of information.

As a word of caution we point out that an elementary particle in physics might in general not be a most elementary system in every sense, as it might carry electrical charge, spin, position information, energy, etc. In that sense the definition of a most elementary system pertains to the observation in the specific experimental context.

Our observation that the most elementary system carries only one bit of information simply means that it can carry only the answer to one question or the truth value of one proposition only. We can now show how this simple, innocuous observation leads to an understanding of such basic notions as complementarity, of the randomness of individual quantum events, and of entanglement. Complementarity is one of the most fundamental conceptual notions in quantum mechanics. We might quote Niels Bohr here: "Phenomena under different experimental conditions must be termed complementary in the sense that each is well defined and that together they exhaust all definable knowledge about the object concerned." The most basic situation where complementarity arises is the one between the path and the interference pattern (Fig. 11.5). In the most simple version we have two paths available, *a* and *b*, which are superposed at a semi-reflecting beam-splitter, and finally two detectors, I and II. If we consider our most elementary system passing through this set-up, how would we use the one bit of information available? Clearly there are at least two different possibilities. On the one hand we can use the one bit of information to define whether the particle passes along path *a* or path *b*. This is done by preparing the particle in the appropriate quantum state. Or, alternatively, we can prepare the state such that the system represents the information defining whether detector I or II will fire. In either case we have completely exhausted the one bit of information available and therefore there is no information present at all to define the other quantity. Therefore, once the one bit of information is used to define which-path information, no information is available any more to determine if detector I or II will fire. Alternatively, once the one bit of information is used to define whether detector I or II will fire, no information is available to define the particle's path, *a* or *b*. In both cases, the property for which no information is



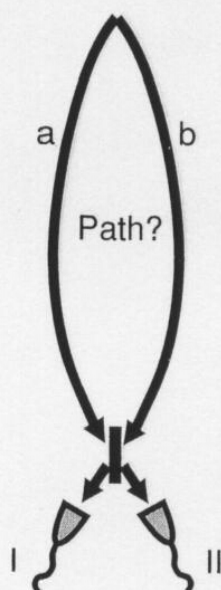


Figure 11.5. Complementarity and information in quantum interference. An incoming particle can propagate along path a or path b to a semi-reflecting mirror. Behind the mirror detectors I and II can observe the particle: either which-path (a or b) information can be defined or which-detector (I or II) information.

available any more must therefore be completely undefined, so such a quantity must be objectively undefined. Therefore, for that very simple reason, there is no room for considerations about hidden variables.

For completeness we point out that one can also choose to define either information partly, so it is possible (see, e.g., Wootters and Zurek (1979)) to have both partial information about the path taken and partial information about which detector will fire. But this can only be done in such a way as not to exhaust the total one bit of information available. It is interesting that this alone already points to a measure of information different from Shannon's (Brukner and Zeilinger 2001).

As stated above, the definition of the most elementary system pertains only to a specific experimental context. Therefore there is no limit in principle to the internal complexity of a system to show quantum interference. All that is needed is an experimental set-up where the way of reasoning just exposed can be applied. In that sense quantum interference has been realized with many different kinds of particles, the largest ones being the fullerenes  $C_{60}$  and  $C_{70}$  (Arndt *et al.* 1999). These molecules (Fig. 11.6) are extremely complex systems, containing a huge amount of information. Not only do they consist of a number of individual atoms, each atom already being a complex arrangement by itself. In the experiments performed so far the fullerenes are at high temperatures, typically around 900 K. This means that they are highly excited in many internal quantum states. Nevertheless, with respect to external motion they clearly exhibit an interference pattern, as seen in Fig. 11.7.

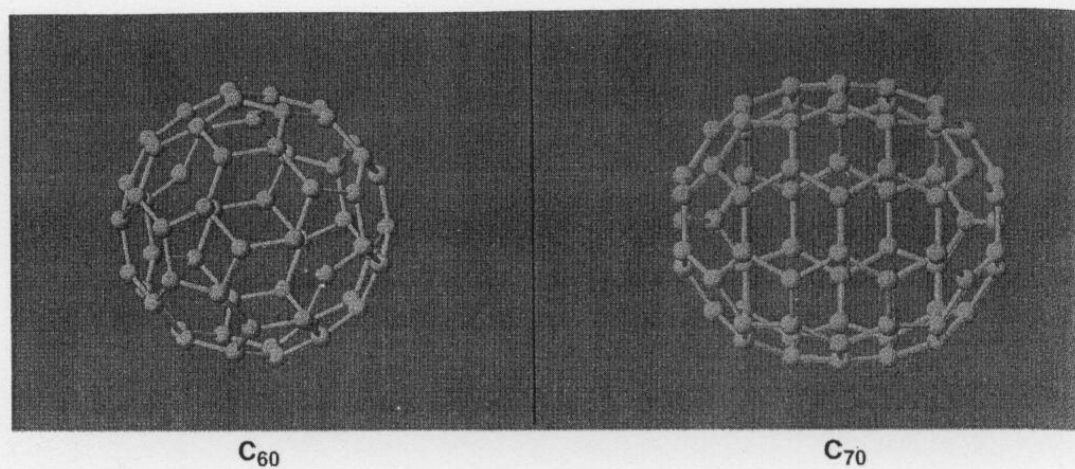


Figure 11.6. The fullerenes  $C_{60}$  and  $C_{70}$ , the largest individual objects for which quantum interference has been demonstrated hitherto.

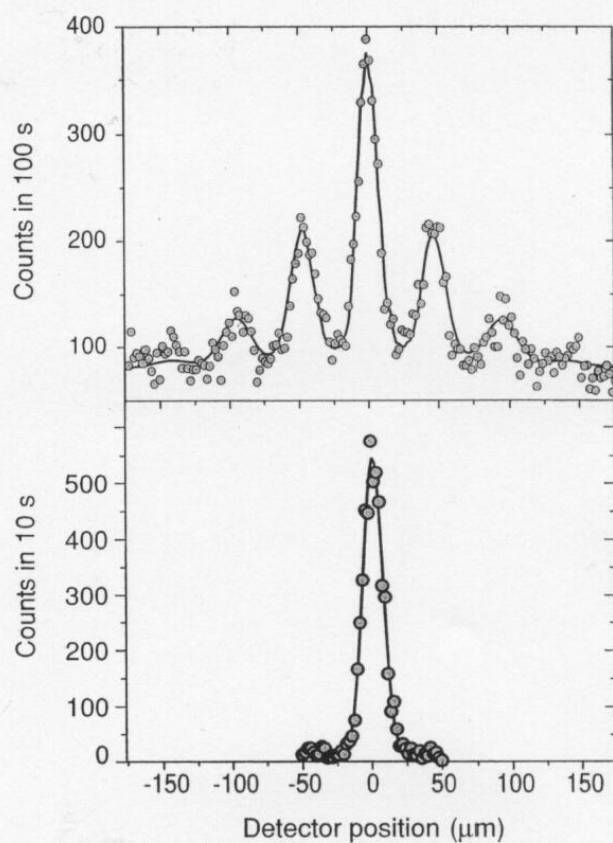


Figure 11.7. Interference pattern of  $C_{60}$  molecules after passage through a multi-slit assembly (Arndt *et al.* 1999) (top). The bottom shows the fullerene distribution without the diffraction grating present.

We note that in principle nothing in quantum physics limits the size of objects for which such interference phenomena might be observed some day. It is a safe bet that no limit for the validity of quantum superposition will ever be found in experiments. Therefore it is just an experimental challenge to further develop and refine these techniques in order to extend the realm of systems for which quantum interference has been experimentally observed to larger and larger systems, perhaps one day all the way to small viruses or maybe even larger living systems. Clearly in that case the challenge of isolation of the system from the environment becomes more and more serious. Yet we note that, already in our present experiments, the fullerene molecules were not completely isolated from the environment, as at these temperatures the fullerene molecules can already be viewed as small objects emitting black-body radiation (Mitzner and Campbell 1995). The reason why interference was observed in our experiments is simply the fact that the photons emitted have such a long wavelength that observation of the photon does not reveal any which-path information. Therefore for biological systems, perhaps tiny bacteria, one might hope that they emit such long-wave radiation that the coupling to the environment does not deteriorate quantum interference. Yet even if that were so, one could even contemplate to provide such small bacteria with a micro-life-support system, thus sufficiently isolating it from the environment. In any case, there is ample space for fantasy and creativity for experimentalists.

Another consequence of our observation that the most elementary system carries only one bit of information is an immediate understanding of the nature of quantum randomness. Let us consider again our basic interference set-up in Fig. 11.5. Suppose we use up the one bit to define which-path information. Thus, the answer to one question we might ask the system, namely the question as to which path is taken, *a* or *b*, is well defined. Then, by the mere fact that information is limited to one bit, no information is left for the particle to "know what to do" when it meets the detectors I and II, and therefore by necessity the click at detectors I and II must be random and they must be irreducibly random with no hidden possibility of explanation. This randomness therefore is an objective randomness, as opposed to the subjective randomness in classical physics and in everyday life, where we assume that any random event has an explanation in terms of its individual causal chain, where we assume that such an interpretation is at least in principle possible and not in contradiction with any other concepts. Since that randomness is subjective, it is the ignorance of the subject describing the situation that leads to apparent randomness. Not so in the quantum situation. It is not just subjective ignorance but there is objectively no information present to define which detector will fire in the situation just discussed.

This randomness of individual events in quantum mechanics has been used to create physical random number generators. A specific example is our random-number



generator (Jennewein *et al.* 2000a), which is based on the randomness of the path taken by photons after meeting a semi-reflecting beam-splitter, exactly the situation just discussed.

Our point of view that the most elementary system carries one bit of information only also leads to a natural understanding of entanglement. The notion of entanglement was coined by Erwin Schrödinger (1935a) (in German *Verschränkung* (Schrödinger 1935b)) and he called it the most essential feature of quantum physics. A quintessential entangled state is

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 - |1\rangle_1|0\rangle_2) \quad (11.1)$$

where we have two quantum bits, or qubits, carrying the bit value “0” or “1”. The entangled state presented above means that if qubit 1 (the first ket in either product state) carries the bit value “0” or “1”, then the other qubit, the second one, carries the other bit value, “1” or “0”, so there is perfect correlation between the two. Physically a qubit could be any dichotomic, that is, two-valued, observable, for example an electron’s spin, a photon’s polarization, or a particle’s path taken in an interferometer (Horne and Zeilinger 1985). Most importantly, the state (11.1) represents a coherent superposition of the two possibilities and not just a statistical mixture. This implies that interference takes place. For the state of eqn (11.1) it means that it has the same mathematical form in any basis, whichever one might choose. This would not be the case for a statistical mixture.

To see the relation of eqn (11.1) to information it is suggestive to assume that two elementary systems just carry two bits of information. One way to view this is simply by assuming that each bit of information represents a possible measurement result for each elementary system on its own. This we would like to call local coding. In that case any relations between the possible measurement results on both sides are just a consequence of the information carried by each individual system. For example, should we elect to use the two bits, one each to define the spin along the *z*-axis, then we also definitely know how the spin measurements along that axis relate to each other. This apparently is one further bit of information but it is not independent information, it is a direct consequence of how the information is encoded into the two systems on their own.

But there could also be completely different situations. Instead of defining the information carried by each system separately, we could use up both bits of information to represent just how measurement results on the two systems relate to each other. For example, state (1) is uniquely defined by the two statements “the two qubits are orthogonal in the basis chosen” and by “the two qubits are orthogonal in

a conjugate basis," where a conjugate basis is defined as

$$|0'\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad \text{and} \quad |1'\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \quad (11.2)$$

Thus we used up the two bits of information, the propositions are clearly independent of each other, and there is no information left to define measurement results on the individual systems on their own. As there is no information left to define the properties of the systems on their own, the measurement result on each individual system on its own must be completely random, as prescribed by quantum mechanics. This is the puzzle of entanglement exactly as expressed by Schrödinger. How can it be that measurement results are perfectly correlated without individuals carrying any information whatsoever? We just saw that our principle of finiteness of information, together with the new way of distributing the information between two systems, leads to a direct intuitive understanding of entanglement.

We have thus seen that three of the most fundamental conceptual notions or consequences of quantum mechanics can readily be understood on the basis of our identification of a most fundamental system being the basic element of information, the bit. We have, finally, to analyze the notion of "system" used so far. One might be tempted to assume that a system in the sense we are talking about is something which exists with all its features in its own right independent of observation. Yet if we take our notion of elementary system carefully it cannot be more than, in the concrete experimental situation, that which is characterized by information. Therefore the system is not anything more than that to which the information relates; in other words, there is no more than this information. To ascribe to a system more reality would mean to assign it more information, in contradiction with our fundamental assumption.

While entanglement is one of the most counterintuitive notions in quantum mechanics and while it has been investigated for this very reason with increasing intensity over the last three decades (Freedman and Clauser 1972), a surprising new development has set in, namely applications of entanglement in novel quantum information protocols. All these are just based on the property that entangled systems can carry information in a nonlocal way (Zeilinger 1998).

As one example let us consider first quantum teleportation. There Alice would like to teleport a qubit in a state unknown to her over to Bob. It has been well known for a long time that the most basic procedure is not possible, namely that Alice simply measures her qubit, determines its quantum state, sends all the information obtained over to Bob, and he reconstructs the original system. The problem here is that no measurement is possible to reveal the quantum state of an individual system, yet

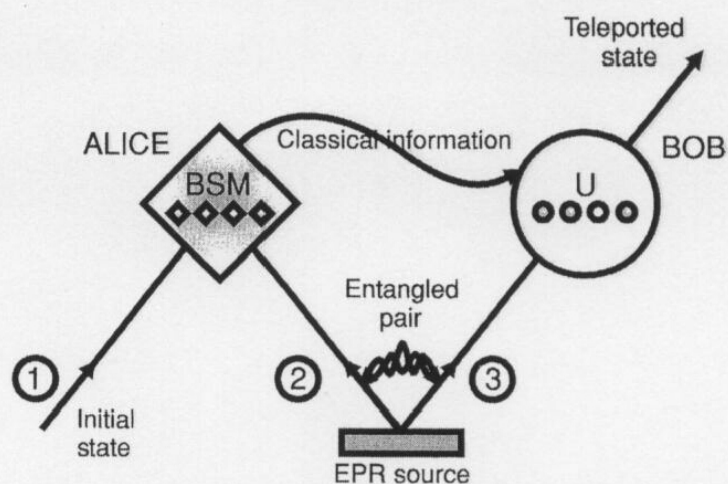


Figure 11.8. Principle of quantum teleportation of qubits. A qubit in an arbitrary initial state unknown to Alice is teleported to Bob. Alice performs a joint Bell-state measurement (BSM) on her initial qubit and on one of the two qubits of an auxiliary entangled pair emerging from an Einstein–Podolsky–Rosen source. Bob, after receiving the classical information about the result of the Bell-state measurement through a simple rotation can transform his qubit into an exact replica of the original.

we wish to teleport individual systems. Therefore it seems that quantum mechanics puts a fundamental limitation on all aspirations to achieve quantum teleportation some day.

Yet quantum mechanics itself comes to the rescue (Bennett *et al.* 1993). The basic idea there is to use entanglement to transfer quantum information over large distances. Alice and Bob (Fig. 11.8), anticipating the need for teleportation, share an entangled pair of qubits. Alice then performs a Bell-state measurement on her qubit to be teleported and on her member of the entangled pair. A Bell-state measurement projects the two qubits into an entangled state. For qubits there are four different Bell states, the state of eqn (11.1) being one of them. All these Bell states can be understood as representing any combination of the two possible truth-values of the two propositions mentioned above. We thus by a simple chain of logical reasoning know exactly how, after the Bell-state measurement, the quantum state of Bob's particle relates to Alice's original. In one of the four cases, Alice obtains a Bell-state measurement with exactly the result that corresponds to the state originally shared by Alice and Bob. Then Bob's particle is immediately projected into the state of the original qubit. In the other three cases this is not the case and Bob has to perform a rotation on his qubit, depending on the specific result Alice has obtained. This rotation is completely independent of the state of the original qubit to be teleported. In particular, the results for the Bell-state measurement occur



randomly, each with 25% probability, completely independent of what the initial incoming state was.

It has been conjectured that quantum teleportation might beat the speed of light limit imposed on us by Einstein's special theory of relativity. True, it is necessary that Alice transmits to Bob which of the four Bell states was obtained and these two classical bits can at most travel at the speed of light. Yet, as we noticed above, the possibility arises that Bob's particle is immediately projected into an exact replica of the original whenever by chance a specific one of the four Bell states results appears in Alice's measurement. So, we are faced with the possibility that in one of the four cases, Bob's particle instantly becomes identical with the original. Can this now be implied to demonstrate a violation of Einstein locality? The answer, which evidently is in the negative, rests on a very subtle curiosity. This is that Bob cannot know immediately whether or not the system he receives has been projected into a state such that it is an exact replica of the original. Thus, while it might very well happen that Bob's particle is instantly projected into the same state as Alice's original, this cannot be used to transfer information faster than the speed of light. Bob has to wait for the classical message from Alice to arrive at his location and that can only happen at the speed of light. In a sense, to put it more succinctly, it can very well be argued that while quantum systems appear to be able to communicate faster than the speed of light, this cannot be utilized in a practical way by humans.

We will now briefly analyze the teleportation experiment (Bouwmeester *et al.* 1997) from our information theoretical approach to quantum mechanics. The situation is rather simple. From the initial preparation of the auxiliary entangled state we know how its two qubits relate to each other, should they be measured. Then Alice's Bell-state measurement does nothing else than provide us with the two bits of information necessary to tell us how the photon to be teleported and Alice's member of the entangled pair relate to each other. Therefore we know how both the photon to be teleported relates to Alice's entangled photon and how Alice's entangled photon relates to Bob's entangled photon, and thus finally by a simple logical chain of reasoning we know how the original relates to Bob's. This is a very simple chain of reasoning and gives us a unique state for Bob.

There are other important applications of quantum entanglement in the science and technology of information. Technically most advanced is quantum cryptography (Jennewein *et al.* 2000b; Naik *et al.* 2000; Tittel *et al.* 2000), where entanglement is used to circumvent a standard problem in conventional cryptography, namely the necessity to transfer the key for encryption from one place to another. Using entanglement, the key is generated at two distant locations at the same time. Finally quantum computation relies on the superposition of very complex states consisting of many qubits. This, evidently, immediately leads to the entanglement of information just discussed above.

### Why the quantum?

*In the beginning was the word.*

*(The Gospel according to John 1.1)*

The quest for the reason for quantum mechanics is one of the most fundamental ones advocated by John Archibald Wheeler. He simply asks whether there is any possibility to arrive at the fundamental understanding of why we have quantum mechanics at all. What is the simple, basic reason for the existence of quantum physics? What is the underlying principle? Thus the point of view and context of these questions simply is that while the counterintuitive properties of quantum mechanics, such as for example Schrödinger's cat paradox (Schrödinger 1935b), most likely will stay with us forever, we would at least like to have an understanding why we are forced to accept these counterintuitive properties. We will now attempt such an explanation.

A guide in our consideration is again Niels Bohr, who, according to J. P. Petersen once remarked, "There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out what Nature is. Physics concerns what we can say about Nature." It is suggestive to assume that this implies that what can be said at all limits our possible knowledge about the world. So what we are doing both as scientists and in our daily lives is that we collect information about the world, information which always can be structured as a series of answers to questions or a series of truth-values of propositions. The way one constructs the world out of such a series of propositions has been beautifully illustrated by John Archibald Wheeler in his version of the game of "Twenty Questions." In the standard way of playing the game, one person leaves a room and the remaining persons then agree on some object or concept. The other person then comes back and has to find out by successively questioning the others through questions which can only be answered by "yes" or "no" what the object or concept the others agreed upon is. Usually, and interestingly, this can often be found out in less than 20 questions. John Archibald Wheeler's version is an amusing one. He suggests that the persons remaining in the room do not agree at all upon the object. Indeed, all they agree upon is that everyone is free to give whatever answer she or he wants but any answers have to be consistent with previous ones. So, the object or concept is then constructed together by all persons present following the course of questioning. This is a beautiful example of how we construct reality out of nothing.

But still, one may be tempted to assume that whenever we ask questions of nature, of the world there outside, there is reality existing independently of what can be said about it. We will now claim that such a position is void of any meaning. It is obvious that any property or feature of reality "out there" can only be based

on information we receive. There cannot be any statement whatsoever about the world or about reality that is not based on such information. It therefore follows that the concept of a reality without at least the ability in principle to make statements about it to obtain information about its features is devoid of any possibility of confirmation or proof. This implies that the distinction between information, that is knowledge, and reality is devoid of any meaning. Evidently what we are talking about is again a unification of very different concepts. The reader might recall that unification is one of the main themes of the development of modern science. One of the first unifications was the discovery by Newton that the same laws apply to bodies falling on earth and to the motion of heavenly bodies. Other well-known unifications concern the unification of electricity and magnetism by Maxwell or the later unification of electromagnetism and the weak force.

In other words, it is impossible to distinguish operationally in any way reality and information. Therefore, following Occam's razor, the notion of the two being distinct should be abandoned, as the assumption of the existence of such a difference does not add anything that could not also be obtained without it.

Therefore, if we now investigate fundamental elements of information, we automatically investigate fundamental elements of the world. We have already seen earlier that any representation of information is based on bits. Any object is representing a huge number of bits. If we go to smaller and smaller objects we necessarily arrive at the fact that such objects can be characterized by one bit, two bits, three bits, etc., that is, information is quantized in truth-values of propositions. In view of our proposal that information and reality are basically the same, it follows that reality also has to be quantized. In other words, the quantization in physics is the same as the quantization of information. To conclude, it is worth mentioning that this idea can be turned into a research program developing the structure of quantum physics from first principles (Brukner and Zeilinger 1999, 2001, 2003; Baeyer 2001).

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# SCIENCE AND ULTIMATE REALITY

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