4. THE OBSERVER

The decisive move of the founders of quantum mechanics was to bring conscious human observers into the basic theory of physics in a fundamental way. This was a revolutionary step, because it revoked the root cause of the successes of the classical approach that had stemmed from the work of Isaac Newton. The spectacular achievements of that earlier method were due primarily to the exclusion from physics of things such as thoughts and feelings in favor of mathematically described properties attached to points in space-time. The resulting simple conception of the universe as a collection of microscopic properties governed by microscopic laws was dynamically complete: it allowed all physical realities to be determined solely by interactions between tiny neighboring mechanical elements. This meant that our conscious experiences, insofar as they had any influence at all on physical events, were completely fixed by a self-determining micro-local process. Consequently, those experiential aspects of nature could be denied fundamental status in basic physical theory.

The reversal by quantum theorists of the precept of micro-local completeness was due principally to the non-local aspect of nature discussed in the preceding chapter: faster-than-light action at a distance is strictly incompatible with the precepts of classical physics, in the form demanded by Einstein's theory of relativity. On the other hand, our nearby actions can quickly affect *our knowledge* about a faraway physical reality.

For example, if you know that two particles started together at some known faraway point and have moved away from that point in opposite directions at the same speed, with one moving roughly in your direction, then *what you choose to*

find out about the location of the partner that eventually comes into your neighborhood does influence *what you can know* about its faraway mate. Thus if you find out that one of the two particles is currently in the nearby region R then you can determine by simple arithmetic that its partner is in a corresponding faraway region R'. There is nothing mysterious about that quick change in our knowledge *here* about something faraway! But it does mean that "our knowledge" has a faster-than-light feature that superficially resembles the non-locality property described in chapter three.

This trivial observation about sudden changes in "our knowledge" of a faraway reality cannot account for the faster-than-light influences described in chapter 3, unless "our knowledge" is in some sense reality itself. In that case an observation here, by instantly affecting our knowledge of the faraway system, would be instantly affecting faraway reality. However, that literal idealism is not what the founders espoused: their position was more subtle than that.

Yet in a certain way this notion that knowledge is the basic reality is tantamount to what they proposed, which is that we should neither think about nor inquire about the nature of a possible reality lying *behind our experiences*, but should focus our attention instead on the rules that we use to make successful predictions about connections among our experiences. This pragmatic view of science, as a theory exclusively about connections between human experiences, is rationally justified by the observation that, in the final analysis, science is both validated by, and derives its utility from, the success of such rules. What is "actually happening behind the scenes" is irrelevant to science, insofar as science is simply a practical tool for coping with the evolving world of human experience. Yet if the formulas of quantum

theory are just rules connecting the experiences of an entire community of communicating observers then the theory is, in effect, a model in which the reality is knowledge, since the growing collective knowledge of the community is the reality that the theory describes.

Thus the founders of quantum theory did not need to endorse literal idealism. They retreated instead to the more defensible position that science is about *what we can know*, and that all that we really can know is our experiences, and how well our theories account for those experiences. This viewpoint that science is about "our knowledge" allows instantaneous action at a distance to be incorporated into scientific practice in a rationally coherent way, without saying anything at all about what is going on "behind the scenes."

This evasive tactic did not satisfy everyone, Einstein and Schroedinger being the most notable hold-outs, but it did allow the scientists who accepted it to get on with the business of developing, testing, and using this hugely successful practical formulation of what is the basic existing physical theory.

This pragmatic view of science brought the consciousness of the human observers into basic physics in two important ways. The first is as the passive receptacles of the *descriptions* that constitute the database of science. The second is as active participants whose free choices can influence the course of physical events. This second role is the one that this book is about. But to understand this vital second role one must understand the first.

"The observer" that enters the original "Copenhagen" formulation of quantum theory differs from the one of ordinary speech. For one thing, it involves an extension of

the human observer outside his physical body. Bohr mentioned several times the example of a man with a cane: if he holds the cane loosely he feels himself to extend only to his hand. But if he holds the cane firmly then the outer world seems to begin at the tip of his probing cane.

In analogy, the quantum "observer" is considered to extend out to and include the measuring devices that he uses to probe "the observed system", which, however, is not actually seen. This way of splitting things up is unusual: normally one regards the human observer as confined to his body, and what he is observing, in this measurement situation, to be the measuring apparatus, not the unseen atomic system that this device is probing. Yet what is important in quantum physics --- as in all of science --- is that the actual practice involves two different kinds of descriptions. On the one hand, there are descriptions of our conscious experiences, which we can record, remember, and communicate to our colleagues, and which form the empirical database. On the other hand, there is a theoretical structure that we invent for the purpose of extending the range of our experience and reducing it to order. [cf. N. Bohr. Atomic Physics and Human knowledge, p.1]

Copenhagen quantum theory regards the devices as part of the observer because the devices are described not in terms of their atomic constituents but rather in terms of our conscious experiences. Bohr repeatedly points to this key feature of quantum theory, in statements such as:

"The decisive point is that the description of the experimental arrangement and the recording of the observations must be given in plain language, suitably refined by the usual terminology. This is a simple logical demand, since by the word `experiment' we can only mean a procedure regarding

which we are able to communicate to others what we have done and what we have learnt." (Essays 1958/1962….p.3)

Notice that the human observers enter here not as passive receiving "witnesses" but rather as active probing agents, and purveyors of the communicable descriptions of the conscious experiences that result from their probings. This way of viewing science is quintessentially realistic. It takes science to be what it actually is, not some idealized abstraction of the real thing. Human experiences are the basic elements of actual scientific practice.

It might seem that since the key realities in quantum physics are descriptions of experiences pertaining to devices we ought to eliminate the observer and consider instead the devices themselves, regarded as objectively existing realities, and dispense with all the mumbo jumbo about observers. That is not the tack taken by Bohr and his colleagues, for that approach would oblige them to explain how these macroscopic devices could be built out of the atomic entities that obeyed the rules of quantum theory. This theory has well defined rules for building up systems that are conglomerations of the atomic systems that it describes. The problem is that the "devices" constructed in accordance with these rules do not behave like the devices we observe.

For example, in the paradigmatic measuring device, the so-called Stern-Gerlach apparatus, which deflects an ion into either an upper or lower detector according to whether the spin of the ion is pointing up or down, the straightforward solution of the quantum-mechanical equation of motion for the whole system specifies, under certain conditions, that the state of the system consists of two nearly equal contributions that could , if the detectors were removed, be brought back together and interfere, like the light passing through the two

slits of the famous double-slit experiment. But with the two detectors in place either one detector fires or the other, not both. This huge failure of the mathematical laws that work so well at the level of several atomic particles, and even millions of millions of them, to work for the conglomerations that constitute visible devices, is a key problem that the founders of quantum theory had to face.

Because our observations are *wildly* and *irreconcilably* at odds with what arises directly from the basic mathematical equations something obviously needs to be done. The straightforward approach would be to say that the original mathematical rules are not exactly correct, but fail for systems involving huge numbers of atoms, and fail in such a way as to produce the behaviors we observe. That tack must, however, overcome several obstacles. In the first place, the quantum rules have an amazing internal logical cohesion that fits perfectly with the idea of an informational system that is interacting with a collection of probing agents. This beautiful cohesive structure tends to be disrupted by any tinkering with the rules. In the second place, the quantum rules have been tested for systems involving millions of millions of atoms, and no indication of any failure has been observed. In the third place, any such purely physical explanation of the observed facts would require physically real faster than light action at a distance. This third "obstacle" is a purely psychological one: most physicist abhor physically real faster-than-light action more than nature abhors a vacuum. Rather than accepting that unpalatable option the founders of quantum theory chose to change philosophies by shifting to the more realistic conception of science as a human activity that seeks to identify and describe regularities in our streams of conscious experiences. In Bohr's words:

"In our description of nature the purpose is not to disclose the real essence of phenomena but only to track down as far as possible the relations between the multifold aspects of our experience. " (Atomic Physics and Human Knowledge, p.18)

This pragmatic view of the scientific enterprise accommodates any theoretical construction that works in practice. It does not prejudge the nature of the unseen reality, and refuses to take seriously any properties of the theoretical structure outside their ramifications in the realm of human experience.

5. THE UNSEEN.

In quantum theory our knowledge about the unseen system being probed is represented by a mathematical structure called the quantum state. This state normally evolves continuously in accordance with a deterministic law that is closely connected to the "laws of nature" used in classical physics. However, at certain instants this orderly progression is suddenly interrupted by an abrupt "quantum jump". Such a jump occurs each time one of the observers gains new knowledge: the jump brings the quantum state into concordance with the new state of our knowledge. Thus the quantum state of the system being examined continues to represent the expanding knowledge of the community of communicating observers.

But how can a mathematically described state represent dynamic human knowledge?. Our knowledge seems to be a ephemeral and ineffable vagary, whereas the mathematically

described states of quantum theory are precise structures that allow empirically observed numbers to be computed to an accuracy of one part in a hundred million.

To explain this connection I need to introduce two mathematical ideas: "Hilbert space", and "projection operator". These names may sound intimidating, but the ideas are basically simple, and understanding them will allow you to grasp the essence of quantum theory.

A Hilbert space is a collection of *vectors*, and a vector is a displacement by a specified amount in a specified direction. Two vectors, A and B, can be added together to give a vector C, which is formed by adding together the displacements A and B.

Consider, for example, the displacement from the corner of a room where two walls and the floor meet to a point on one of these two walls. That displacement is the sum of a vertical displacement up from the corner plus a horizontal displacement along the wall that contains the point.

If the two vectors A and B that add to give C are perpendicular to each other, as in this example, then the theorem of Pythagoras asserts that the square of the length of A plus the square of the length of B equals the square of the length of C.

This celebrated theorem is tied to the probability rules of quantum theory: If C is a vector of length one (i.e., unity) and A and B are two perpendicular vectors that sum to C, then the square of the length of A plus the square of the length of B is unity (i.e., one). The two perpendicular vectors will correspond to two *alternative possible events*, and the square of the length of A will be the probability for the event

associated with A to occur, and the square of the length of B will be the probability for the event associated with B to occur. The sum of these two probabilities is unity by virtue of the theorem. That the probabilities associated sum to unity is, of course, the basic requirement on probabilities.

In the example of the point on the wall, the space of vectors is two-dimensional: any point on the wall can be reached from the corner by a sum of just two displacements, one in each of the two pre-specified perpendicular directions, vertical and horizontal. We can also easily visualize displacements in a three-dimensional space. But it is possible to consider mathematically an N-dimensional vector space in which there are exactly N mutually perpendicular directions, and each vector in the space is a sum of N vectors, one directed along each of these N directions. We allow null displacements and also negative displacements, which are the same as positive displacements in the reverse direction.

A set of N vectors, each perpendicular to every other one, is not easy to visualize, geometrically, for large N. But if one uses an algebraic approach in terms of sets of numbers, then the examples of vector spaces in one, two, and three dimensions are easily generalized to spaces of arbitrarily large but finite dimension N. With a little more effort one can even go to the case where N is infinite. Hilbert spaces include the infinite-N cases, but that is a technical matter that need not concern us here. It will be enough to think of simple cases where N in finite.

If a vector V is composed of a sum of N perpendicular vectors then a generalization of the theorem of Pythagoras shows that the square of the length of V is the sum of the

squares of the lengths of these N mutually perpendicular vectors that add up to form V.

The second important concept is the idea of a projection operator. A *projection operator* P acts on a vector V to give a new vector PV. The action of P eliminates a specified subset of a set of perpendicular vectors that add up to give the vector V upon which it acts, but leaves unaffected the remaining vectors in the sum. Thus, for example, the vector V from the corner of a room to any point in the interior of the room would be converted by a certain projection operator P to the vector PV that is the displacement from the corner to the point on the floor that lies directly under that point in the room: the vertical vector is eliminated by the action of this particular projection operator P.

That example is a very special case. For one thing the three perpendicular vectors were very special, involving one vertical vector and two particular horizontal ones. But one can imagine replacing the room by a cubic box, and consider the infinity of ways that this box could be oriented relative to the room. For each of these orientations the three edges that meet at a corner define three perpendicular directions. Then one can go from N = 3 to arbitrary N, and select any subset of the set of N perpendicular directions to be the set that is not set to zero. This obviously gives a huge set of logically possible projection operators P.

Given this simple idea of a vector, and how a vector in an N dimensional space can be considered to be a sum of a set of N vectors, each of which is perpendicular to every other one, we can now state the basic idea of quantum theory: Our knowledge about the unseen system, gleaned from earlier experience about things we *can* see, is represented, under

certain ideal conditions, by a vector V of unit length. This vector evolves under the action of the Schroedinger equation, which alters the direction that V points, but leaves its length unchanged.

When a probing event occurs the vector V suddenly jumps to the vector PV or to P'V, where P is the projection operator associated with the probing action. The probability of jumping to PV is the square of the length of PV and the probability that the jump will be to P'V is the square of the length of P'V. These two probabilities add to unity, by virtue of the theorem of Pythagoras.

The big question, however, is: How is P chosen?

According to orthodox quantum theory this choice is made by the probing agent. He must specify P, which means separating the Hilbert space into two parts, one associated with a subset of perpendicular vectors that will not be set to zero to form PV, and the other the complementary subset that will be set to zero to form PV.

The essential point here is that events in nature can be associated with vectors in a Hilbert space, and this association gives simple rules for the probabilities for those events to occur under appropriate conditions of observation. The message of quantum physics is that this idea works with high precision. But then its validity must reflect some deep truth about nature.

We can now return to the question of how our knowledge is represented mathematically.

According to quantum theory the polarization of a photon is represented by a vector in the two dimensional space that is

perpendicular to the photons line of flight. Suppose a photon is allowed to fall on a crystal that splits the beam so that the part polarized along direction V1 is directed to a photon detector D1 and the part polarized in the direction V2, perpendicular to V1, is directed to a photon detector D2. If the detectors are 100% efficient then one or the other of the two detectors will fire, but not both: the vectors V1 and V2 are associated with the *alternative* possible events in the two detectors.

If an observer happens to be watching the detectors --- which are wired up to give off visual signals --- then these alternative possible detection events will be correlated with alternative possible events in the observer's stream of conscious thoughts: he will see either a signal from D1 or a signal from D2. Hence the possible experience of seeing the signal from D1 will be associated with the vector V1, and the alternative possible experience of seeing the signal from D2 will be associated with the vector V2. So a connection exists between two alternative possible experiences and the two perpendicular vectors V1 and V2 in a two-dimensional vector space.

If the incoming photon is associated via some prior experiment with a unit-length vector V that is not directed along either of the two perpendicular directions V1 and V2 but is representable as a sum of vectors in these two directions then this V can be expressed as a sum of a vector directed along V1 and a vector directed along V2. The squares of the lengths of these two component parts will, according to quantum theory, be the probabilities for the alternative possible experiences of seeing the signal from D1 or seeing the signal from D2.

Now it would seem to be clear that in this example the vector V is associated fundamentally with the state of the photon, rather than an experiential event in the mind of a observer, and that the pertinent physical events are the detection events in D1 and D2, not the possible psychological events in the mind of a (possibly not watching) human observer. Yet if one accepts this common sense idea, and tries to give a purely physical description, one is forced, by arguments such as the one given in chapter 3, either to accept the reality of faster-than-light action-at-a-distance or to deny the direct evidence of experience that only D1 or D2 fires, not both.

Physicists are divided about how to cope with this situation. Most side with the injunction of the founders not to get sucked into the question of what is really going on, but to be content with the fact that we have rules that work, and let philosophers squabble about "reality". But a growing minority believes that science should not cop out in that way but should try to dig deeper. Some of these investigators accept the existence of faster-than-light action, and try to devise some purely physical mechanism to explain it. Others hold that the experiential evidence that, for example, D1 and D2 do not both detect the same photon is illusory, and that all of the events that might possibly occur do actually occur in some absolute sense, but that, due to the structure of our brains, our streams of conscious thoughts divide into components that individually recognize only parts of the total objective reality. I shall pursue here a third tack.

6. THE PARTICIPANT

Niels Bohr, the principal architect of quantum philosophy, wrote that we cannot forget "that in the drama of existence

we ourselves are both actors and spectators." [Essays 1958/62 on Atomic Physics and Human knowledge, p.15] This comment succinctly captures a key point of quantum theory: the human observers are no longer passive witnesses to a flow of physical events that they cannot influence. They are essential players in the action, and their "free" choices can influence the flow of physical events.

Quantum theory, in spite of its idealistic content, is formulated in a completely realistic and practical way. It is structured around the activities of human agents, who can probe nature in any of many possible ways. Bohr emphasized this freedom of the experimenters in passages such as:

"The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude."

The point here is that quantum theory, in its original form, is set up in terms of an interaction between conscious human agents and an invisible quantum system. As already discussed, that system is represented in the theory by a vector in Hilbert space. This vector usually evolves according to the quantum law of motion, the Schroedinger equation. But to get information about that system the experimenter must ask specific questions by setting up corresponding probes. For example, the experimenter can orient the crystal in the photon experiment described earlier in any way he chooses. Different choices correspond to different choices of the two perpendicular directions V1 and V2. Moreover, the human agent can choose to do or not do the experiment, or to do it sooner or later. These choices

are, according to our basic physical theory, quantum theory, not fixed by any yet-known laws of nature. Hence these choices are, in that specific sense, "free choices".

We have now arrived at the crux of the matter! Quantum theory, in its orthodox formulation, involves the human observer not as a passive recipient, but as an active agent that enters into natural process in ways that are not controlled by the known physical laws. His specific role, *as it appears in the world of experience*, is to select which experiment is to be performed: i.e., to choose which aspect of nature will be probed. This role, *as it appears in the mathematics*, is to select some one single projection operator P. This P is the projection operator such that the initial vector V will become PV if nature delivers the affirmative answer 'yes' to the posed question, but will become the vector P'V if nature delivers the negative answer 'no'. Here P' is the projection operator that keeps the vectors that P eliminates, and hence satisfies the condition PV+P`V=V for all V.

[Sometimes a complex question involving a combination of several projection operators can be considered. But these can be regarded as a sequence of individual P's, and I shall adopt this simpler way of speaking.]

The essential point here is that, according to orthodox ideas, nature's process of generating the experiences that appear in our streams of consciousness cannot proceed without particular questions being posed. But then the key questions become:

If the known physical laws do not determine the choices that need to be made by the human agents in order for nature's process of generating human experiences to proceed, then

what sort of considerations do influence or determine these choices?

and

What effect do these "free" choices have on the course of physical events?

The evolution of the unseen system involves a sequence of questions with Yes or No answers. Hence the interaction between nature and agent is like a game of twenty-questions: the agent is free to choose a sequence of Yes-No questions, and nature delivers an answer, Yes or No, to each, in the form of an experience that answers the posed question. The choice of question is represented within the mathematical description as the selection of one projection operator P from among an infinite continuum of possibilities. Each possible P corresponds to *particular* way of orienting a set of N mutually perpendicular vectors, and, then, a *particular* choice of which of these N vectors will be eliminated to form PV. The process of making these *particular choices* of P's is not specified by the Schroedinger equation, which controls the *continuous* evolution of the physical state, but neither the agent's choices of the questions nor nature's choices of the answer. In particular, a complete account of the dynamics needs to explain an as-yet-unexplained process that picks a sequence of particular P's from a continuum of possibilities. This selection process is associated, according to orthodox quantum theory, with consciously made free choices on the part of human beings. And, according to the quantum rules themselves, these "free choices" can influence the course of physical events, as we shall presently see.