Hans von Briesen Jr.
St. John's College, Santa Fe Campus
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A BACKGROUND FOR PERPLEXITY: SOME FUNDAMENTALS OF QUANTUM THEORY

Prelude:

I recall a statement in a published formal lecture to the College that to learn quantum mechanics would take about six years.(1) My goal tonight is to impart to you some of its fundamentals in less than sixty minutes, clearly a risky enterprise. I risk on the one hand being utterly obscure, and on the other hand being utterly shallow. At best I shall be neither, and at worst, both. My aim is to introduce a minimum of fundamentals and to show how the conventional interpretation of quantum theory, that of Niels Bohr, defies common sense, abandons physical intuition to paradox, and with experiment casts a deep shadow upon the concept of objective reality. I hope in the process to provide a corrective to our shallowest view of science as an edifice of fact.

This lecture is a result of the inspiration, scholarship, and perservering curiosity of Mr. Ralph Swentzell, who invited me to look over certain papers in quantum theory with him. He hoped that my training in physics would help his understanding. You will appreciate that I thought I knew these things until he asked me what certain passages meant, say in a paper by Niels Bohr, or by Einstein. These exchanges continued naturally into the faculty study group in quantum mechanics last year, led by Mr. Swentzell. I shall not even try to enumerate my vast debt to other colleagues for my learning in this community.

Introduction:

There is an epistemological question that has tagged along with quantum theory ever since it was judged by most physicists to be consistent and complete. One form of the question has to do with the distinction between object and subject; another form asks about the reality of objects. Touched by experiment in recent times is the question, What do we mean by physical reality? To the philosophically literate, these are well-worn questions. At one extreme is the skeptical response that nothing exists independently of my perception of it; at the other extreme is a realism in which every object of my experience exists independently of my observation.

This latter point of view, that of extreme realism, holds that my observation of something has little or nothing to do either with its existence or with its properties. This room, these chairs, these people are really here whether or not you, I, or anyone else is aware of them. This realism is also unequivocally the point of view of working science and technology, the epistemological questions of quantum theory notwithstanding: Objects, systems of things, phenomena in general are both observable and analysable in terms that ignore the role of the observer.(2) We must assume this in order meaningfully to engage in observation, yet how seriously do we mean it? And how seriously shall we question it?

For me, an interesting twist of quantum theory is that these questions, which challenge this working view, arose within a discipline whose practice has since flourished without asking them. Practicing physicists have no need in their study of experiment and theory to wonder to what degree an experimental setup is but a manifestation of their form of mind, or to what degree a successful theory is a reflection of mind as much as of matter. In fact, such questions are likely to interfere with professional success, and had best follow upon it. To the practical, working scientist or technologist, these questions must seem a bit frivolous, of the kind for which philosophers deserve a bad name.

This being St. John's College, the questions, whether the subject and the object are separable, and whether separate objects have independent reality, come up without quantum theory. It would behoove us to see how our own philosophical excursions are fundamentally related to an enormously successful physical theory whose application has literally changed our world.(3)

In what follows, I shall pretend that you know what the words "wavelength", "frequency", and "energy" mean. It is not necessary to understand their meanings in full technical detail. Your intuitive sense of what they might mean will be enough for this lecture. In the same spirit, I shall also use the word "momentum". Intuitively, momentum is a measure of how hard it is to stop something that is moving, but its direction is also important. I shall also use the term "angular momentum" which is the momentum of turning. If parts of this lecture seem too technical for you, please just ride them out.

Waves and Superposition:

The fundamentals I shall talk about have very much to do with vibrations and waves. We all have extensive experience with these -- for example: musical strings; the resonant tone of an organ pipe, or a clarinet, or a shower stall, or a beer bottle; the propagation of sound through air, through water, through the ground, or through steel; ocean swell, and the ripples on a pond; the motion of a car with worn out shock absorbers; the collective motion of ripe grain in a wind-swept field; or more abstractly, radio waves that we neither see nor hear, our power to manifest them being based on an electromagnetic wave theory; and finally, light, evidently an electromagnetic wave like radio waves.

The most important property of waves and vibrations that we shall be concerned with for quantum theory is the principle of superposition. Let me introduce it quite primitively. If someone shoves me hard enough to move me two feet over, and someone else at the same time shoves me equally hard, how far was I shoved? Four feet? Only if the shoves were in the same direction. Had they shoved in opposite directions, I would be sore but physically unmoved. The shoves would cancel out if measured, not by my pain, but by the gross motion of my body. Had they shoved at right angles to one another, my net movement would roughly be two feet times the square root of two. This is an example of the superposition of vectors, meaning that the result of a combination of separate motions must take direction into account.

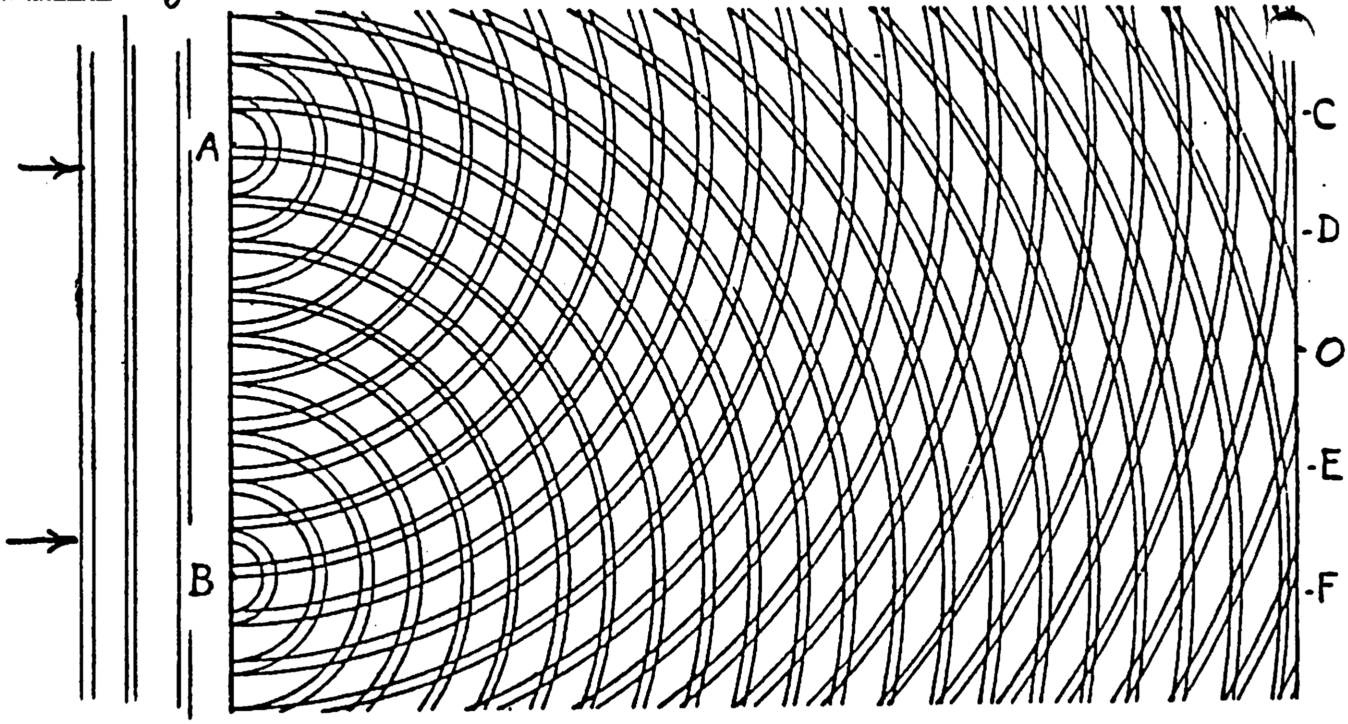
Something similar happens with waves to yield interference patterns in which here waves may add to one another and there they may tend to cancel one another out. Consider the sound from two musical strings almost but not quite in tune. The sounds from the separate strings propagate independently of one another, but their combined effect is such that the ear or a microphone picks up periodic variations in volume, called beats. A musician will reduce the beat frequency to zero for perfect, identical tuning. During the loud part of the beat cycle, I will hear the waves reinforcing each other, and during the soft part of the cycle, I will hear the waves tending to cancel one another.

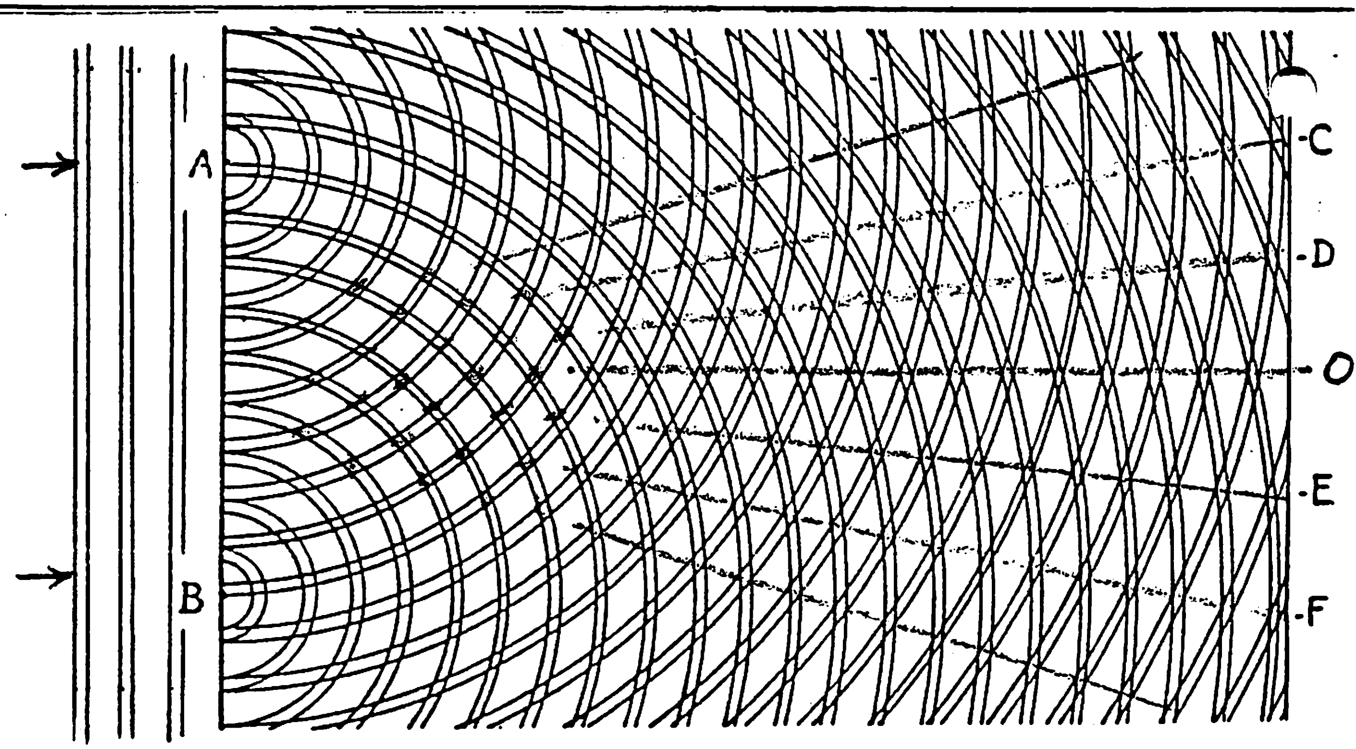
Another example is the so-called "killer wave" of sailing lore, a freak reinforcement of separately moving sea swells much higher than any of the swells already terrorizing the sailor. A counterpart to this would be momentary patches of relatively calm water in which cancellation is taking place.

The superposition we shall be most interested in is the interference of light. <Figure 1> If light from the same source is made to pass through slits A and B, the light radiates from each slit as if from a new source. But the light from both slits has a common source, and so the waves passing through the two slits are synchronized with one another. In this illustration, we show only two slits, but the effect is more pronounced for a diffraction grating which has many slits. The result for light of a single wavelength is that an eye or a detection screen will reveal a pattern with reinforcement at points O, C, D, E, F, and so on, and cancellation at points in between.(4) The light from

Figure 1.

Wave diffractio





each slit travels independently of the light from another slit, but their effect on a detector is a combined one, an effect of superposition. This is diffraction. <Projector off>

Other examples of superposition of light can be seen in thin oil slicks on water, in interferometers, and even in the wings of a butterfly. In the latter, striking visual effects come about by the reinforcement and cancellation of different wavelengths of light, since wavelength corresponds to color.

It turns out that any wave can be analysed as if it were a superposition of other waves. This is connected with powerful analytical tools, one of them called Huygens's principle for the analysis of wave paths,(5) and another called Fourier analysis for the analysis of wave frequencies and shapes. Neither of these shall I discuss tonight, although I invoked Huygen's principle in saying that the diffraction slits act as new sources of the light; and a generalized Fourier analysis is central in the superpositions of quantum theory.

The Wave-Particle Duality for Light:

Now that I've told you that light is a wave phenomenon, I also have to tell you that light is evidently also a particle phenomenon. One of Einstein's two famous 1905 papers, that on the photoelectric effect,(6) proposes this and gives evidence for it, but this contradicted the electromagnetic wave theory, with its enormous predictive success, beauty, and elegance. It took precise measurements years later by Millikan for Einstein's conclusions to be generally accepted by the physics community.(7)

The photoelectric effect has to do with the ability of light to release electric charge from a metallic surface, giving rise to measurable electrical effects. Our seniors perform measurements of the photoelectric effect, using a diffraction grating to separate different colors of light produced in a Mercury discharge lamp. This separation is exploiting the wave properties of light. And then with a photoelectric cell and some other equipment they perform measurements which support the interpretation of the light as consisting of discrete energy packets highly localized in space, like a particle.(8)

Your experience with waves will verify that the very concept of wave implies some extension in space, and that the energy carried by waves is spread out. Light is manifestly a wave phenomenon. But it is also evidently a particle phenomenon.

Now this is just the sort of thing that superposition should be made for: If superposition yields "killer waves" among sea swell, why cannot it yield a particle like wave packet from light waves? In principle, this is right thinking for quantum theory, but a technical argument shows that in this case it doesn't work.

In the first place, the localization we are talking about is comparable with the size of an atom, about one hundred-millionth of a centimeter, ten thousand times smaller than both the spacing of slits in the diffraction grating and the wavelenth of the light. These localized packets are clearly too small to pass through more than one slit of the diffraction grating at a time. In the second place, such a wave packet would have to be a superposition of waves having a range of different wavelengths in order that there is cancellation outside the packet and reinforcement within. But the smaller the packet, the wider the range of wavelengths required for the superposition, and in this case the range would have to be so great that we are certainly not talking about light of a single color.(9)

To summarize, then, if light is a wave, then light of one color cannot be sufficiently localized to account for the photoelectric effect. So light is not a wave, but is particulate. On the other hand, if light is particulate, its packets of energy are far too small to be passing through more than one slit of a diffraction grating, and hence cannot give the interference patterns or the color separation that we observe. So light is not particulate, but must be a wave. Evidently, we have here to be very careful about what we take to be contradiction. This paradoxical situation is referred to in physics as the wave-particle duality as it applies to light.

Particles in Quantum Theory:

I have introduced the wave-particle duality through a discussion of light, but it also occurs for what we might call "real particles", to the extent that there is such a thing as a "real" particle, one that has mass or weight and is very, very small. In discussing the quantum theory of matter, I shall introduce just enough to get by. My task is to give an intellible, bare-bones account while minimizing the interpretation of it until I am ready to address that explicity. There are five features:

First, atoms are rather small, and their components, such as electrons or nuclei, are smaller still. This means that although we can still treat them as objects indirectly observable, there is no way to observe them that will not affect them. Even if there is never observation without interaction, we can often successfully ignore the interaction; but it is unavoidably significant on the atomic and subatomic scale. For example, to locate an electron by means of shining light on it is to measure the interaction of the light and the electron, and the electron is significantly affected by any light that is adequate for the observation.(10)

Second, not only does the absorption and emission of light by matter seem to require the localization of light in discrete, particle-like packets, as in the photoelectric effect; but the absorption and emission seem to be describable by a mathematical theory only if the energies of the absorbing or emitting matter are limited to definite, discrete, discontinuous values with no energies in between. We say that energy in atomic systems is quantized, meaning that it takes only certain discrete values.(11)

Third, the mathematics discovered and developed adequately to describe the phenomena of atomic interactions with light is a mathematics that attributes wave-like periodicity to its objects. But its objects include electrons, normally known as particles. This leads to a wave-particle duality for particles. Theoretically and experimentally, an electron can have wave-like properties. For instance, a beam of electrons can be made to diffract in a crystal which acts as a diffraction grating for atom-sized wavelengths. Particles have wavelength in this description, and this implies extension in space in agreement with our concept of waves, but contrary to our concept of particles.(12)

Fourth, the most successful interpretation of this mathematics says that it yields the probabilities of certain events, but it cannot determinately predict single events. For example, used to compute the location of the one electron in a hydrogen atom, it can only yield a probability distribution. Were one to test such predictions, one could only do so by many identical measurements of many similarly prepared individual systems such as hydrogen atoms.(13)

And fifth, one can measure a certain magnitude for, say, an electron, with indefinitely high precision, but only at the expense of sacrificing precision in the measurement of a different, complementary magnitude for that particle. This is the Heisenberg Principle of Indeterminacy which even Einstein finally accepted as firmly established. If I measure position accurately, I affect the electron by imparting an indeterminate and irreducible change in its momentum.(14) This is of no consequence in the physics of everyday life, because it can be important only in the very small, where the quantum of action, Planck's constant, is significantly different from zero. Planck's constant is about 10-27 erg seconds, or one thousandth of one trillionth of one trillionth of an erg second, quite small in units appropriate to everyday life. Only in extremely small or extremely special systems is the difference from zero of any consequence.

However unimportant in the physics of everyday life it may be, quantum theory subverts the most extreme ambitions of classical physics, that is, to "write down the universe". The above features of quantum theory suggest that the claims of mechanical determinism are wrong in principle, because, in principle, not just in practice, it is impossible to know all details exactly.

<Figure 2> The next illustration summarizes the five features of quantum theory that I've chosen to tell you about. What I've said is likely to have strained not just your powers of attention, but your credulity. I want now to take a one- min break in order that all of us can mentally and physically regroup before I deliver the second half of this lecture. Please feel free to stand and stretch.

<Projector on during pause, but off at end.>

Questions of Interpretation:

These features describe a mathematical formalism arrived at through both physical and mathematical reasoning. The theory is stunningly successful as a mathematical characterization of empirical data. It is accepted as such by all physicists. But when we try to develop consistent, intuitively sensible pictures of what the theory describes, we have problems such as the wave-

FIGURE 2

Five features of Quantum Theory:

1. The medium of observation affects the observed.

2. Energy is quantized into discrete values. Waves are quantized into localized energy packets.

3. Material particles have attributes of periodicity, e.g., wavelength.

4. Predictions are probabilistic.

5. Heisenberg's Principle of Indeterminacy ("Uncertainty" principle):

$$\Delta x \Delta p \sim \hbar \simeq 10^{-27}\ \text{erg} \cdot \text{sec.}$$

$$\Delta t \Delta E \sim \hbar$$

particle duality. If we could be satisfied with the mathematical prescriptions and their results, and avoid attributing reality to intuitive pictures, we would avoid much confusion. The harshest characterization of this view is, "Ask me no questions and I'll tell you no lies." More reasonably, let us put it, "Ask me no naive questions, and I'll tell you no naive lies."

A defense of this view is to assert that the universe is essentially mathematical but not in a way that is commensurate with ordinary, physical intuition. In a Platonic spirit, one can assert that the intelligible universe is inaccessible to my poor, primitive, physical intuition of the way things are, and I must instead develop and extend my mathematical intuition to approach what truly is. I feel this to be the easiest way around our difficulties, but I'm not satisfied with it. I believe this view is implicit in the working view of most physicists.

Einstein felt that quantum theory was incomplete. He constructed a number of ingenious thought experiments to challenge the limits imposed by the Heisenberg principle of indeterminacy, although he finally admitted that the principle was established. He felt also that because the predictions of quantum theory were probabilistic, the theory was valid only for ensembles, that is, collections of identical systems. Einstein hoped that the descriptions of single systems and single events were yet to come in a better theory, a complete theory. He asserted that "God does not play dice with the universe."(15)

To the contrary, Niels Bohr and physicists of his school held that quantum theory was complete, meaning that it said as much about individual systems as could be known. Furthermore, the theory had the virtue of specifically not saying what could not be known. Their interpretation, which became the conventional interpretation, held that not only were complementary variables such as position and momentum not amenable to simultaneous, perfect measurement, but that they could not meaningfully and simultaneously be assumed even to have perfectly defined values, measurement or no measurement. It was not only that, given a perfect momentum measurement, one could not simultaneously have a perfectly measured position; but moreover, given a perfectly defined momentum, there was no real meaning to the concept of perfectly defined position; and vice versa.(16)

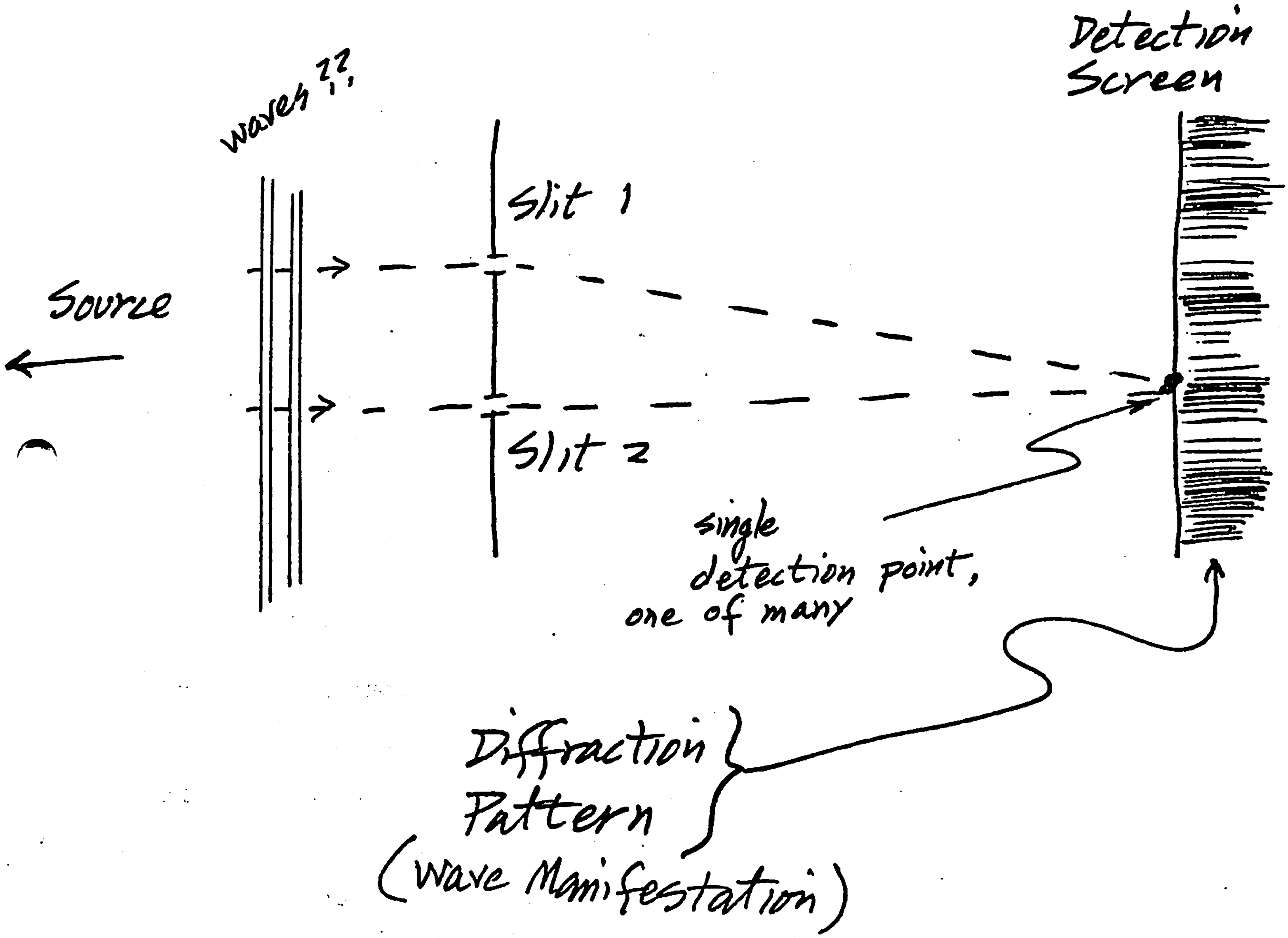
Furthermore, if quantum theory can only predict probabilities, what can it say about individual events? Under this interpretation, it says that individual events are in nature indeterminate. The theory's failure exactly to predict them means that our notion of determinate exactness is in principle inappropriate to subatomic reality. For an example, take radioactive decay: since theory can predict only the statistical lifetime of a particular radioactive decay, there in fact is no predetermined decay time for any individual atom among a sample of radioactive atoms. At any given time, the prediction is one of probability -- of a potential decay -- each atom actualizing the decay at a definite time, individually and unpredictably.

By way of another thought experiment, I want to describe further Bohr's interpretation. We shall invoke the superposition principle as a sixth feature of quantum theory. The superposition principle states that it is possible to take any quantum state function, a mathematical description of the state of a quantum system, and reexpress it as a superposition of other quantum state functions. How one chooses to do this has very much to do with the convenience of getting certain predictions rather than others.(17) As I've said, the predictions will be probabilities.

The result of any individual measurement, however, will be a definite value for the variable measured. Since the superposition may include many values for a measured magnitude, and only one value emerges from each measurement, physicists sometimes speak of the "collapse" of the superposition from a state of many values to a state of one value. This is like describing one throw of a pair of dice as a superposition of possible scores which collapses to one score as the dice come to rest. This so-called "collapse of the state function" could be termed a seventh feature of quantum theory, necessitated by taking the theory as complete and applicable to individual events. In analogy, we should take this description of our dice throw as literally true and complete. A major difference from our dice, however, is that the different component states of a quantum superposition can interfere with one another as waves do, giving constructive and destructive interference.(18)

<Figure 3> Let us go back to diffraction, setting up a thought experiment of two slits diffracting a beam of either light or electrons. It doesn't matter which, because both can manifest wave-like superposition by yielding an interference pattern, yet both upon actual detection manifest particle-like

Figure 3: Diffraction



qualities in their localization. Being here indifferent to whether they are photons, that is, quanta of light, or electr , let's call these energy packets quanta. Let us admit that the theory of their behavior is complete and that therefore superposition is literally appropriate for each single quantum: that is, the state of each quantum is a superposition of two states, one state corresponding to passage through one slit, and the other state corresponding to passage through the other slit, and that the two component states interfere just as waves interfere. The quantum will manifest at the screen at a point whose location is predicted in terms of a probability distribution. Enough such quanta will reveal a diffraction pattern, predicted by the probability distribution.

That's how the theory describes our thought experiment. However, we may in our naivete ask, Which slit did each quantum really pass through? Surely you don't mean it passed through both! Fortunately, this can be tested by placing detectors at each slit. The result, according to the theory, will show that each quantum passed through one slit only, with about half going through each. So our naive assumption is valid. However, in the presence of these detectors, there is no interference pattern. In trying to measure the particle-like properties of the quantum state, we evidently sacrificed the wave-like properties. To manifest wave-like properties, we evidently have to refrain from the measurement of the particle property, namely, which slit did it pass through. Here is our wave-particle duality seen in the light of a quantum theory assumed to be complete.(19) <Projector

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Bohr's explanation of this was that the two pictures of our quantum state, wave picture and particle picture, are complementary to one another, neither by itself being adequate. Furthermore, it was essential to include the measuring apparatus in the description, meaning in our case that our effort to detect each quantum as a particle was an essential component of any adequate description, and so also for our measurements of the diffraction pattern corresponding to a wave picture. To ask whether the quantum was a wave or a particle was, according to Bohr, not meaningful independently of some specification of the observing apparatus.(16) In a surprisingly literal sense, what you look for is what you get. If now you should rise up in exasperation and say, "Enough of this nonsense! Is it a wave or a particle?" I could respond, "Well, yes, I believe so." But Mr. Steadman's answer is more complete. It goes, "Who wants to know?"

I already pointed out that in Bohr's view the meaningfulness of position or momentum was intimately connected with our measurements of them. Together, these were part of Bohr's Principle of Complementarity, still the basis for the conventional interpretation of quantum theory.(16) An additional part of this principle was the assertion that all of our observations must be describable in classical, non-quantum- mechanical terms, terms that use words like 'position', 'length', 'time duration', 'angle', 'momentum', and so forth, unambiguously. Although we could question whether these concepts have meaning in the subatomic world independently of observation, and Bohr held that they did not, our observations necessarily had to be described in terms in which their meaning is assumed. In Bohr's view, it meaningful to speak of a precise measurement of position, or of a particle-like attribute, but only by foregoing definiteness of meaning in the concept of momentum, or of wave-like attributes, respectively.

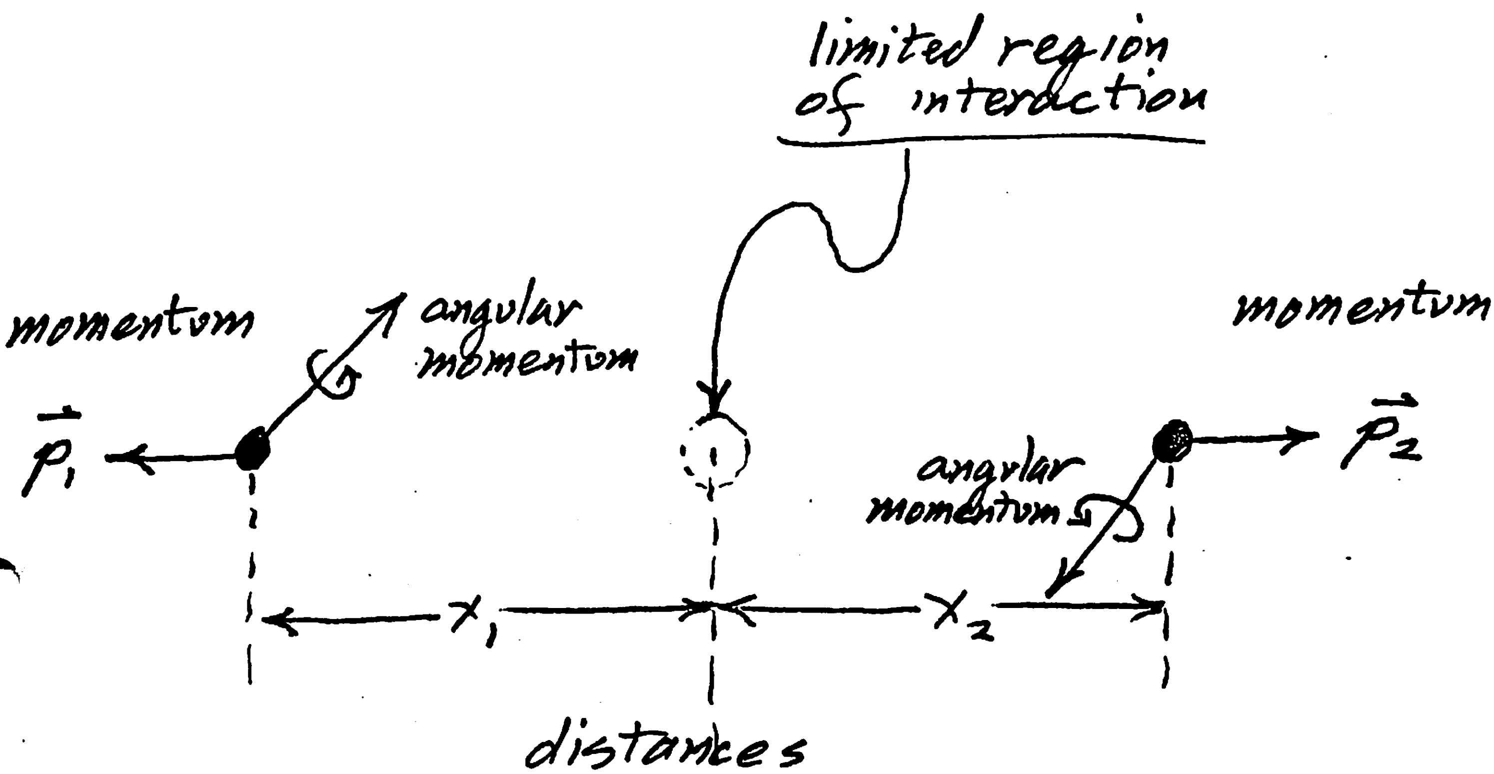
Einstein challenged this point of view in 1935 with two coauthors, Podolsky and Rosen, collectively referred to as EPR, in an article entitled, "Can Quantum- Mechanical Description of Reality be Considered Complete?"(20) EPR began by distinguishing between objective reality, independent of any theory, and the physical concepts of a theory. They introduced as a criterion of completeness that every element of physical reality should have a counterpart in the physical theory. They then introduced a reasonable definition of physical reality which is as follows:

> If, without in any way disturbing a system, we can predict with certainty (i.e., with a probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

They then presented a thought experiment in which quantum theory, assumed to be complete, fails to predict what are elements of physical reality by this definition.

EPR imagined two quantum systems that had interacted and had then separated and were no longer interacting. Let them be, for instance, particles, equal halves of some combined system that had disintegrated. <Figure 4> In such a case, the interaction has conserved certain physical quantities as required by accepted physical law. For instance, in both classical and

Figure 4. EPR's Thought Experiment



Total momentum is zero. $\therefore \vec{p}_1 = -\vec{p}_2$
Total angular momentum is zero.

quantum physical theory, both momentum and angular momentum must be conserved in any isolated interaction. This means that they must be correlated between the two separate systems even though the systems are no longer in interaction.

Now quantum theory provides for the precise measurement of only one of a pair of complementary variables, according to the Heisenberg principle; and under the Bohr interpretation, the other of the pair of variables would then not even have either definite meaning or a definite value. If I measure the one, the other cannot be an element of physical reality, and vice versa. As we shall see, combining this with the required correlation between the separated particles implies the existence of elements of physical reality not accounted for in the quantum theory. Einstein had the genius to find a situation in which quantum theory interpreted as complete not only failed to satisfy his criterion of completeness, but also seemed more clearly unacceptable to reason as illuminated by common sense. Let me digress just a moment. <Projector off>

The affront to common sense was not news to Bohr, who had already experienced, years before, his share of anguish about the meaning of quantum theory. As Heisenberg wrote,(21)

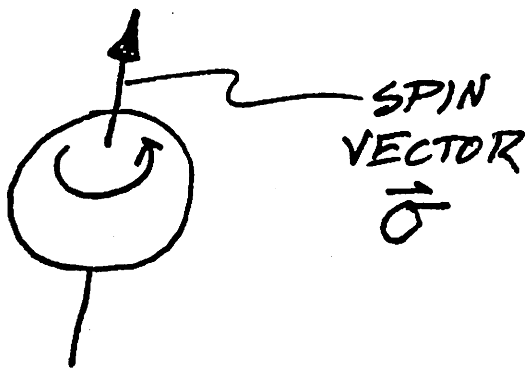
> "During the months following these discussions an intensive study of all questions concerning the interpretation of quantum theory in Copenhagen finally led to a complete and, as many physicists believe, satisfactory clarification of the situation. But it was not a solution which one could easily accept. I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighboring park I repeated to myself again and again the question: Can nature possibly be as absurd as it seemed to us in these atomic experiments?"

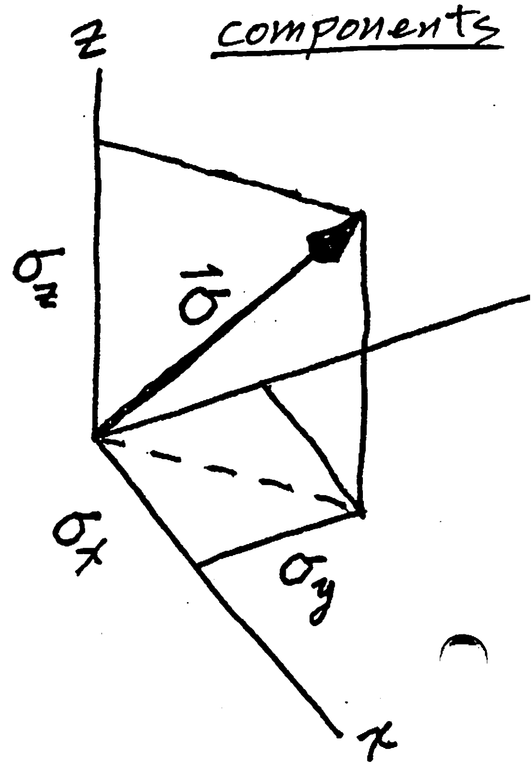
Bohr felt that the interpretation was as responsible as one could be, however crazy, and he suggested that quantum physics had lessons in thought and language that we had yet to discover.(16)

Let's return to the EPR experiment: <Figure 4 again> Instead of position and momentum, discussed by EPR, I shall present their argument in terms of spin angular momentum, a formulation that allowed some physicists at least to think about experimental tests.(22) Angular momentum can be thought of as a measure of the difficulty of stopping the turning of something. A turning bicycle wheel and a planet have angular momentum. So also do the elementary particles of physics. But in the case of elementary particles, spin seems by ordinary standards to be a little weird, and so our version of EPR's argument must unfortunately share that weirdness. <Figure 5> I wish position in EPR's own argument were less weird, but here we go.

Spin has discreteness. Furthermore, only one component of the angular momentum vector can be defined, the three perpendicular components being a trio of complementary variables subject to the Heisenberg principle. Changes in angular momentum can only occur in integral multiples of Planck's constant. We shall take the simplest case where a particle has spin up or spin down, along any chosen direction, the difference being one unit.(23) We shall take our two separated systems, formerly interacting, to be particles of spin like this. We shall also assume the combined state, during the interaction, was of zero angular momentum.

Figure 5. Angular momentum in Quantum Theory



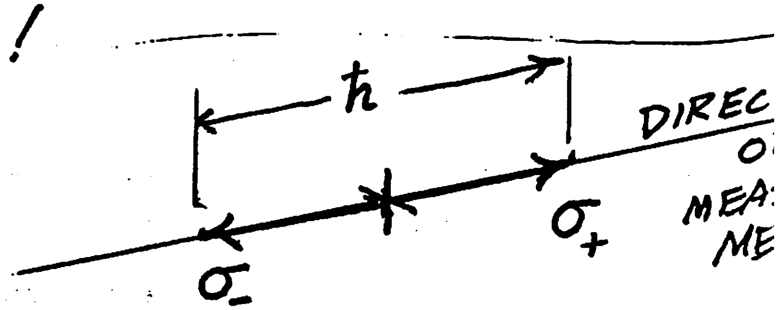


EITHER $\sigma_x = +$ or $-$

OR $\sigma_y = +$ or $-$

OR $\sigma_z = +$ or $-$

BUT NO TWO!

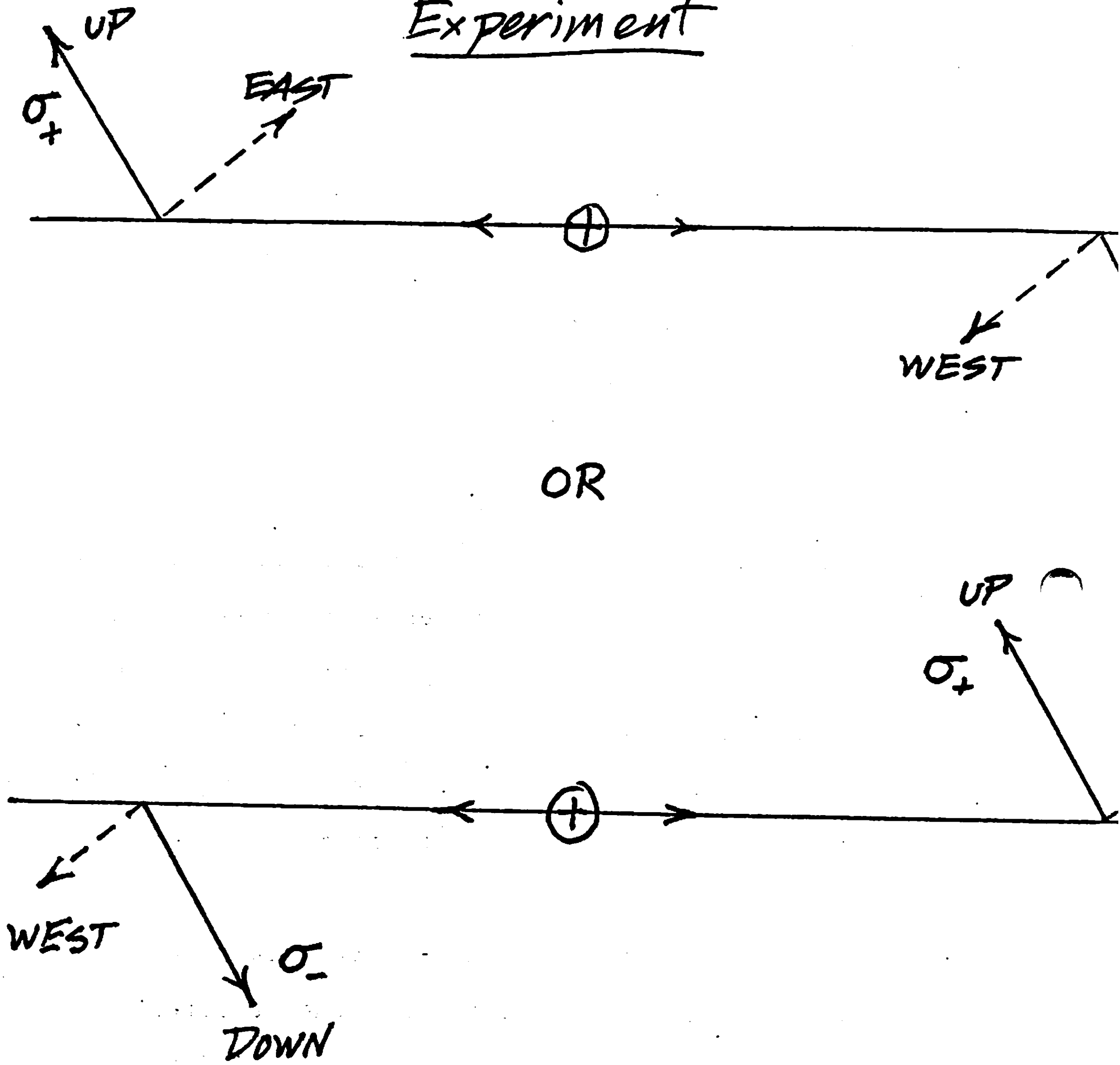


Under these assumptions, a measure of the spin of either particle can be made in any direction, but the result, experimentally and theoretically, will be either plus or minus in that direction. <Figure 6> Physical law requires that if we measure the spin of both particles in the same direction, for example, vertically, there must be perfect correlation, that is, if one measures up, the other must measure down. Choosing another direction, the same for both particles, if one spin measures east, the other must measure west. And so forth. This correlation is required by the law of conservation of angular momentum, a law that stands outside this controversy.

If we measure the two spins with reference to two different directions, their relation is a probabilistic one predicted by quantum theory. But how does the left-hand particle "know" whether the right hand measurement was in the same direction as its own measurement? For in principle, these particles could already be light-years separate. The right-hand spin could be measured along any direction, yet if the left hand spin should be measured in a direction parallel to it, there must be perfect correlation, whatever the common direction.

Thus a measurement in the vertical on the right-hand particle yielding an up spin yields a certainty that a later, vertical measurement on the left-hand particle will yield a down spin. Therefore, the down spin of the left-hand particle is an element of physical reality by EPR's definition. But the same is true if the directions are horizontal, or in any orientation. Thus, our freedom to choose direction in first measuring the spin

Figure 6. Spin Measurements in Modified EPR Thought Experiment



of the right-hand particle implies that the spin in any direction of the left-hand particle is itself an element of physical reality or is determined by one. But because quantum theory cannot attribute simultaneous reality to these components of spin, the theory must therefore be incomplete.

Here is the way this situation can be described, technically, according to the conventional quantum theory: The first measurement collapses a superposition of spin states, each of which conserves angular momentum, and each of which must therefore describe the two particles as one system. The collapse is into a well-defined spin state in the measured direction. If, then, the second measurement is in the same direction, its result is perfectly determined in accordance with the results of the first measurement. If the second measurement direction is different, the definite spin state established by the first measurement can be reexpressed as a superposition of spin states along the second measurement direction in conformity with the results of the first spin measurement. Thus the first measurement on one particle collapses the general superposition of spin states into a more limited one; so that the remaining particle is likely to respond differently to a spin measurement than it would have if the first measurement had not been made. That's the quantum theoretical description, assuming the theory to be complete. How far apart the particles are is of no consequence.

Recall that the two systems are no longer interacting in any ordinary sense. We are also presuming that signals are not being sent between the measuring apparatuses. We have said then, with EPR, that the particles must therefore carry something with them that enables their spins to be correlated according to both quantum theory and general law. The failure of the quantum theory to describe these somethings is an incompleteness. So goes a modified EPR argument. <Projector off>

Almost thirty years after the EPR paper, which had been largely ignored or forgotten in the exhilarating technical success of quantum theory, John S. Bell in the early 1960's demonstrated theoretically that the separated particles could carry no signals, no elements of physical reality, no hidden variables, that could fully emulate the accepted quantum theoretical results. He was able to find a potential experimental test wherein the conflict between quantum theory and Einstein's concept of physical reality could be evaluated. If indeed there were somethings carried by the two particles that determined their correlated behavior, it would be possible, at least in principle, to observe the failure of the quantum theoretical prediction. His results are referred to as Bell's inequalities.(24)

A few other physicists picked up the challenge, worked with Bell's inequalities, and constructed feasible experiments, the combined results of which suggest strongly that quantum theory, but not EPR's definition of physical reality, is adequate to the situation.(25) Either these particles can communicate by some signal that exceeds the speed of light, or they cannot be truly separated, being part of an indivisible combined system.

To say that an influence can travel faster than the speed of light is to challenge a cherished physical principle, that of Einstein's special theory of relativity, the content of his other famous 1905 paper.(26) The formalism of quantum theory makes no challenge to special relativity. On the contrary, it would be thought to fail if it could not incorporate it.

The alternative is to say that these objects, once joined, are indivisible to the extent that their separate behaviors are correlated with one another. This is a sensible description of what the quantum theoretical formalism says. Recall that they may be separated by light-years.

If we reject communication faster than the speed of light, and if we have indeed found our two systems incapable of separately carrying the information which would allow their correlation: How, then, the results? What cause, and how the effect? We have only metaphysics to turn to, because all our physically intuitive explanations fail.

Not only must the ideal of objective reality be carefully rethought, if not abandoned, nothing new to philosophy, but so also must our physically intuitive notions of efficient cause be questioned. Also in question is the principle that efficient cause only can provide scientific explanation.(27) For although the EPR experiment is abstract and technically sophisticated, it should take only a single instance of a violation of assumed principles of natural science in order to bring those principles into question in the minds of others besides speculative philosophers. The stunning technical success of quantum theory and its transformation of our world only highlight how little we understand of what we think we know.

Thank you.

Footnotes:

(1) I recalled wrongly. The time mentioned is six months. C. Wilson, "The Archimedean Point and the Liberal Arts," The St. John's Review, Annapolis, St. John's College Press, Summer, 1984, v.35, n.3, p.40ff.

(2) The devotion required for excellence in scientific research is not particularly enhanced by epistemological scruples.

(3) In mind are solid state and microelectronics, and of course nuclear weaponry.

(4) Thomas Young, "On the Nature of Light and Colors," A Course of Lectures on Natural Philosophy and the Mechanical Arts, London, Jos. Johnson, 1807, v.1, pp.457-72. Included in part in the Junior Laboratory Manual, Second Semester, St. John's College, Santa Fe, 1986, pp. 55-61.

(5) Christian Huygens, Treatise on Light, S.P. Thompson, Trans, London, MacMillan, 1939. Included in Junior Laboratory Manual, Second Semester, pp.1-22. Also included in The World of the Atom, H.A. Boorse & L. Motz, New York, Basic Books, 1966, v.1, pp.62-85.

(6) There are three papers, not two. That on the photoelectric effect is, A. Einstein, Annalen der Physik 17 (1905), 132-148. Trans in The World of the Atom v.1, pp.544-57.

(7) Inferred from The World of the Atom, pp.535,539-40.

(8) Senior Laboratory Manual, Atoms and Measurement, St. John's College, Annapolis, 1981, pp.73-82.

(9) Atoms and Measurement, footnotes to Schroedinger and Heisenberg readings, pp.111,151.

(10) See, for example, W.K. Heisenberg, "Critique of the Physical Concepts of the Corpuscular Theory of Matter," Trans in Principles of Quantum Theory, Eckart & Hoyt, Chicago, Univ. of Chicago Press, 1930, p.13ff. Included in Atoms and Measurement, p.150ff, and in The World of the Atom, v.2, pp.1094-1122.

(11) Planck's work on the cavity spectrum of radiation: The World of the Atom, v.1, pp.462-501; Atoms and Measurement, Appendix I, p.159ff. The Bohr model of the hydrogen atom: See The World of the Atom, v.1, pp.734-765; Atoms and Measurement, pp 83-94. Schroedinger's wave mechanics: The World of the Atom, v.2, pp.1060-1076; Atoms and Measurement, pp.107-119.

(12) deBroglie: The World of the Atom, v.2, pp.1041-1059; Atoms and Measurement, pp.105-107. Schroedinger: see note (11).

(13) Max Born: The World of the Atom, v.2, pp.1077-1093.

(14) See note (10).

(15) See Albert Einstein: Philosopher-Scientist, Ed., P.A. Schilpp, La Salle, Illinois, Open Court, 1970, in particular, N. Bohr, "Discussion with Einstein on Epistemological Problems with Atomic Physics," pp.201-241, and A. Einstein, "Remarks to the Essays Brought Together in this Co-operative Volume," pp.665-688. The quotation, "God does not play dice with the universe," remains uncited -- apocryphal?

(16) N. Bohr, see note (15) and "Can Quantum Mechanical Description of Physical Reality be Considered Complete?", Phys. Rev. 48 (1935), 696-702. The latter paper is a response to the EPR paper cited below.

(17) For instance, a superposition of photon angular momentum states can be reexpressed as a superposition of photon polarization states. See, for example, P.A.M. Dirac, The Principles of Quantum Mechanics, 4th Edition, Oxford, Clarendon Press, 1958.

(18) The formalism doesn't require the word "collapse", but provides for the computation of the probability of a particular value of a measurement, given a superposition. See Dirac, note (17). Note that probabilities have precise meaning in the everyday world only in the context of large numbers of events, e.g., many throws of a pair of dice.

(19) Another description of quantum diffraction is given by R.P. Feynman, The Feynman Lectures on Physics, Volume III, Chapter 1.

(20) EPR: A. Einstein, B. Podolsky, N Rosen, Phys. Rev. 47 (1935), 777-780.

(21) W. Heisenberg, Physics and Philosophy: The Revolution in Modern Science, New York, Harper & Row, 1962, p.42.

(22) D. Bohm and Y. Aharonov, Phys. Rev. 108 (1957), 1070. Cited by J.S. Bell (see below). David Bohm is one of the few physicists who took seriously Einstein's challenges to the conventional interpretation of quantum theory.

(23) See for example, the textbook of Dirac, note (17).

(24) J.S. Bell, "On the Einstein Podolsky Rosen Paradox", Physics 1 (1964), 195-200. Also "Introduction to the Hidden-Variable Question", in Foundations of Quantum Mechanics, Ed, B. d'Espagnat, New York, Academic Press, 1971, pp.171-181.

(25) J.F. Clauser & A. Shimony, "Bell's Theorum: Experimental Tests and Implications", Rep. Prog. Phys. 141 (1978), pp.1881-1927. This is a full review article. For a later experiment attempting to rule out inter-apparatus communication, see A.

Aspect, J. Dalibard, & G. Roger, "Experimental Test of Bell's Inequalities Using Time-Varying Analysers", Phys.Rev 49 (1982), 1804-1807.

(26) See note (6). The special relativity paper is A. Einstein, "On the Electrodynamics of Moving Bodies", Annalen der Physik 17 (1905). Included in The Principle of Relativity, a collection by Lorentz, Einstein, Minkowski, and Weyl, notes by A. Sommerfeld, New York, Dover, 1952.

(27) I am not including the "action at a distance" of the inverse-square laws of gravity and electrostatics under the heading of efficient cause. Perhaps our difficulty is more simply stated, Is there action at a distance, meaning action without a medium?