Chapter 15

Physical Objects, Retrodiction, Holism and Entanglement

15.1 Physical Objects

In the eyes of most of the founders of quantum mechanics and of their immediate students, the new physics represented a radical departure from tradition in making measurement central not merely at the experimental but at the conceptual level. In their view, Plank's quantum of action makes it impossible to speak about the quantum world without explicitly referring to the experimental setup and, for some, ultimately to one's experiences. Consequently, to the extent they believed quantum mechanics to be complete, many of the founders felt justified in drawing general anti-realist and anti-materialist conclusions from what they took to be the only possible interpretation of the new physics. Often their views were far from restrained and initiated a trend that continued at least into the 1970's.

15.2 Jordan

Pascual Jordan, the author with Heisenberg and Born of one of the fundamental articles in quantum mechanics, was prepared to get quite an amount of mileage from the alleged centrality of measurement. He saw in it the proof that positivism is essentially correct. Quantum mechanics simply connects different experiences (experimental results), telling us nothing about what happens, as it were, in-between measurements: "physical research aims not at disclosing a 'real existence'of things from 'behind' the appearance world, but rather at developing thought systems for the control of the appearance world." (Jordan, P., (1944): 149). In fact, talk of what is 'behind' appearances is bad metaphysics. He also heralded the new physics as the discipline that had brought about the "liquidation" of materialism and the destruction of determinism, thus opening the doors for the possibility of free will and religion not to conflict with science (Jordan, P., (1944): 144; 148-49; 152; 155, 160). More daring than Bohr, he applied complementarity not only to biology but also to parapsychology (an area in which Pauli was interested as well), and analogized between split personality and the position/momentum relation in an electron.[1]

After the war, when the fathers of quantum mechanics, and eventually their direct intellectual heirs, became less active in physical research and more interested in broader cultural issues, this anti-realist and anti-materialist attitude which stresses the role of consciousness became even more marked.

15.3 Heisenberg

Although in the late 1920's Heisenberg and Bohr did not really agree on the interpretation of the new physics, their differences were papered over in order to present a united front against Schrödinger's critical views of quantum jumps and Einstein's idea that the theory is incomplete. Eventually, however, Heisenberg's views came closer to Bohr's, acquiring their final form in his 1958 book *Physics and Philosophy*. Like the other Copenhagen theorists, he emphasized Bohr's claim that in the new physics we are both players and spectators. However, he proposed an analogy between the state of properties in-between measurements and the Aristotelian notion of *potentia* thus characterizing the state of the observables before measurement as an "objective tendency or possibility". Measurement turns the potential O into an actual O, thus bringing about

[1] See Heilbron, J. L., (1988).

an actual value for *O*.[2] More broadly, we could say that the quantum world is one of potentialities that become actual because of their interactions with macroscopic objects or observers.[3] Like Jordan, he opposed 'materialism', even of the blandest sort. By "materialism" he understood the view, common in modern science and everyday life, that *all* material items, including their properties, exist on their own or, as he put it, " the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them." He claimed that

[2] Heisenberg, W., (1971): 38; 41; 46-7; 53-4; 70; 81; 180-81. We may note the analogy with Aristotle's views can be amplified. As for Aristotle potentiality is not mere possibility, but structured possibility that allows some outcomes but not others (the acorn is a potential oak, and therefore it will not develop into a carrot), so the potential observable allows only certain measurement returns, its eigenvalues, and not others. In addition, as for Aristotle the cause of the transition from potentiality to actuality is external to the item undergoing chance, so the potential observable becomes actualized, that is acquires a sharp value, because of measurement which involves an interaction with an external agent, the measuring device.

[3] A similar position can be found in H. Margenau's latency interpretation. While static properties are always present, dynamical properties are only latent in the quantum state of the particle and take on definite values only upon measurement. For an account, see Jammer, M., (1974): 504-05. For Heisenberg, the transition from potentially to actuality occurs at the moment of interaction with the measuring apparatus, not at the registering of the result in the observer's mind, which is represented by the function's collapse. See Heisenberg, W., (1971): 55 and 137.

this view, which at most amounts to nothing more than value determinism, is in conflict with quantum theory (Heisenberg, W., (1971): 129). He viewed quantum mechanics as the discipline that has freed us from the rigid causal materialism of the 1800's, thus providing new room for the mind and religion. Not surprisingly, he rhetorically categorized any opponent of the Copenhagen interpretation such as Einstein as a materialist unable to rid oneself of an antiquated dogma (Heisenberg, W., (1971): 129; 145; 197).

15.4 Pauli

According to Wolfgang Pauli, the general theoretical claims of quantum mechanics are by nature statistical; consequently, they refer to observations on ensembles, not to the observation of an individual system whose outcome is, within certain limits, random (Pauli, W., (1948)). However, contra Einstein, the principled inability to predict individual experimental outcomes is not a sign of the incompleteness of quantum theory, but rather of an irreducible " irrational" aspect of reality. The Schrödinger equation captures the rational aspect of reality by providing a law of temporal propagation of a set of possibilities, one of which is actualized in observation (Pauli, W., (1954)). Such actualization, mathematically expressed by the reduction of the wave function, is the result of a new fact totally absent from classical physics, namely the wholeness of the measured system and the measuring apparatus, as Bohr indicated. Hence, as one may consider measuring instruments as "a kind of prolongation of the sense organs of the observer," the unpredictability of individual measurement outcomes forces on us the abandonment of the ideal of the "detached observer." This ideal, embraced by Einstein and classical physics, and depicting the observer as some kind of spectator ultimately discretely disappearing into the background, has to be rejected as a form of "regressive hope" because quantum theory shows that the observer is not a spectator but necessarily an actor (Letter to Bohr, February 15, 1955, in Laurikainen, K. V., (1988): 164-65; Pauli, W., (1954)).

It is true that at the statistical level, the role of the observer disappears, and one may talk of statistical causality, but at the individual level, causation is not present. Pauli used this claim as a springboard for very speculative and obscure conclusions. As he told Fierz, one of his ex-assistants,

> The physically unique individual is no longer separable from the observer- and for this reason goes through the meshes of the net of physics. The individual case is *occasio* and not *causa*. I am inclined to see in this *occasio* which includes within itself the observer and the selection of the experimental procedure which he has hit upon- a revenue of the *anima mundi* which was pushed aside in the seventeenth century (naturally in "an altered form.") La donna e' mobile- so are the *anima mundi* and the *occasio* (Quoted in Laurikainen, K. V., (1988): 196-97).[4]

[4] "Occasio" is a term of art associated with Occasionalism, a philosophical system developed by N. Malebranche in the second half of the 1600's. What are normally considered causal relations are in reality mere correlations because, in contrast to real causal connections, there is no inconsistency in thinking them severed. When a billiard ball hits another at rest, the former is not the cause of the motion of the latter but only an *occasio* for God to cause the latter to move. Only God can cause anything *at all* because

In spite of his reference to the idea of the world soul (*anima mundi*), or perhaps because of it, Pauli seems at best unclear on what the irrational aspect of reality manifested in individual quantum observations precisely amounts to. He thought that the reduction of nature from a living entity, an organic unity, to a machine that accompanied the development of modern science in the 17th century had produced a schism not only between mind and body, and science and religion, but also among the various aspects of mental life. In opposition to this movement stood the alchemical and hermetic traditions, which emphasized the importance of unity and its experience in a mystical union between the subject and the cosmos. This opposition, present in the conflict between Kepler and Fludd, and Newtonian science and Goethe, (the former ones representing the rational and the latter ones the mystical aspects of human psyche) we should try to overcome.[5] In this context, he emphasized the importance of C. G. Jung's attempt to uncover the psychological content of the old alchemic texts (the only type of alchemy we can accept) and make them accessible to us in psychological terms, in the hope of a "mutual approach of poles in the pairs of opposites" (Pauli, W., (1954a): 147; Pauli, W, (1954b)). Ultimately, then Pauli's position seems to lead to some sort of monism in which the opposites engendered by modern science could be synthesized, a view perhaps not far from Stapp's, as we shall see later.

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the metaphysically unbreakable link required by causation can exist only between God's will and its object: if God wills X, it is absolutely impossible for X not to occur.

[5] And yet, Pauli emphasized the role of archetypal ideas in Kepler's picture of the universe as a system ordered by mystical geometrical relations. See Pauli, W., (1952), reprinted in Entz, C. P., and von Meyenn, K., (eds.) (1994) with a related essay by Jung.

15.5 Wheeler

The trend towards the rejection of the idea of matter fully existing independently of any observer has continued beyond the founders of the orthodox interpretation, as we can see by looking at Archibald Wheeler's views. Consider a Mach-Zehnder interferometer in which the beam splitter S_2 can be inserted or removed at will, as in chapter 12, figure 1. The optical path has been arranged so that when S_2 is in place, all the photons end up at detector C, while when S_2 is not in place half the times a photon arrives at C and half the times at D.

Suppose that S_2 is not in place and the photon is detected by D. Then, we can reasonably infer that the photon went through *d* since, for example, if we remove M_2 no photon arrives at D, and if we lengthen *d* the photon arrives at D with a proportional delay.[6] Suppose now that S_2 is in place, but just before the photon reaches it, S_2 is removed, so that the photon and S_2 do not interact. Then, the situation is the same as before, and if the photon arrives at D, we can infer that it went along *d*. However, this is quite peculiar because had S_2 been left in place, the photon would certainly have arrived at C, which entails that it was in the state of superposition $\frac{1}{\sqrt{2}}\left(|c\rangle + |d\rangle\right)$, which,

[6] Still, the photon is in a state of superposition, and therefore in the orthodox interpretation it is not on either path. Presumably, then, one should interpret Wheeler as pointing out what a denier of EE would consider reasonable. That Wheeler invokes EE later on makes his argument unsatisfactory. The problem here is one of retrodiction, of which more later.

(presumably) together with EE, rules out that the photon went along *d*. Hence, it would seem that a later event, the removal or the presence of S_2, influences an earlier event, whether the photon inside the interferometer was in a state of superposition or moving along *d*.[7] In sum, according to Wheeler, this *delayed choice* experiment seem to show that retro-causation (causation going back in time) is possible, that is, that the present can cause events in the past.

In order to avoid retro-causation, Wheeler proposes that a quantum mechanical items or event exist only when perceived: “No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon” (Wheeler, J. A., (1983): 184).[8] Hence, strictly speaking, the photon was in neither arm, and it acquired the property of being in one only at measurement, which is what an orthodox theorist would say. However, Wheeler seems prepared to go further by claiming that before measurement the photon did not quite exist. The past, Wheeler continues, does not exist in all detail; rather, it exists only as it is recorded in the present (Ibidem, 194). So, the primordial photons that escape our telescopes, and are therefore not observed have some sort of reality but,

[7] The same point can be made with the double-slit experiment. Imagine a device that can insert detectors near the slits between the particle and the screen immediately after the particle has gone though the slits but before it has reached the screen. If the detector near slit A clicks, then the particle went though A even if it was in a superposed state.

[8] In philosophical jargon, a phenomenon is an object of perception, something that has a mental aspect, as it were. So, in a way, Wheeler’s statement is just a tautology. However, both the context in which the statement occurs and the rest of Wheeler’s essay make it clear that by “phenomenon” he means a thing.

Wheeler cryptically claims, “their ‘reality’ is of a paler and more theoretical hue” (Ibidem, 203). Our universe is “participatory” in the sense that only once it produces observers does it acquire “tangible reality…back to the beginning” (Ibidem, 209). What exactly Wheeler is saying is unclear, but perhaps one can somewhat clarify the idea of a “paler” reality by viewing a superposition as an indication that the relevant observable existed as a potentiality to produce the appropriate eigenvalue as a measurement return, thus making Wheeler’s views somewhat close to Heisenberg’s.

15.6 Wigner

While von Neumann, for all his concessions to the centrality of the conscious observer, argued that the cut between measured and measuring systems, with the attendant collapse, is arbitrary, Eugene Wigner explicitly argued that collapse occurs when a conscious being makes an observation. His argument is based on replacing the measuring device with a conscious observer who doubles as a measuring apparatus (Wigner, E., (1961)). Suppose that a system S emits a visible flash of light if in state $|\psi_1\rangle$ and does not if in state $|\psi_2\rangle$. Suppose also that F, a friend of ours, is looking at the system and is in state $|\chi_1\rangle$ if S is in state $|\psi_1\rangle$, and in state $|\chi_2\rangle$ if S is in state $|\psi_2\rangle$. As we know, the state of S+F is given by the linear superposition $c_1|\psi_1\rangle \otimes |\chi_1\rangle + c_2|\psi_2\rangle \otimes |\chi_2\rangle$. Suppose also that if F is in state $|\chi_1\rangle$, he will answer “No” to the question “Have you seen a flash of light?” and that if F is in state $|\chi_2\rangle$ he will answer “Yes” to the same question. In effect, then, F works as a measuring device. So, following von Neumann, one might think that we could place the collapse of the state function at any stage of the measuring process.

However, Wigner claims, this is not so. For, suppose that the question whether F saw the flash or not was already in his mind before we asked. Obviously, by simple introspection he knew what his state of mind was (namely, whether he had seen the flash or not), and therefore the state of F+S could not possibly be the linear superposition $c_1|\psi_1\rangle \otimes |\chi_1\rangle + c_2|\psi_2\rangle \otimes |\chi_2\rangle$, for the linear superposition does not amount to F either having seen the flash of light or not having seen it. Hence, the state of F+S had to be either $|\psi_1\rangle \otimes |\chi_1\rangle$ or $|\psi_2\rangle \otimes |\chi_2\rangle$. In that case, even for us F+S would have to be in a mixed state rather than in a pure state. Hence, the collapse occurred when F made his observation. But why? Wigner's answer is that the only relevant difference between F and other physical systems is that F is *conscious*. Hence, the Wigner friend experiment (as it is sometimes called) allegedly shows that the interaction between quantum and conscious systems breaks the linearity of quantum mechanics.[9]

[9] Note that Wigner's argument crucially assumes that F is not merely conscious but self-conscious: F must know *he* is the one who saw the flash of light. The distinction is important because there is a rather old philosophical tradition, going back at least to Leibniz, of distinguishing the two. For example, humans are self-conscious (they have a sense of the self), and there is good experimental evidence that some primates, chimps, for example, are as well. But while there is little doubt that, say, cats are conscious (they feel pleasure and pain and have a mental life), it is far from clear that they are self-conscious.

Because of the central role of consciousness, materialism is incompatible with quantum mechanics and ought to be replaced by some form of Cartesian interactionism.[10] This theory could associate specific mental states to the bodily states described by $|\chi_1\rangle$ and $|\chi_2\rangle$ and perhaps provide some reason (presumably having to do with the mind's immateriality) why (self-) consciousness brings about such an extraordinary phenomenon as the collapse of the state vector (Wigner, E., (1961) in Wheeler, J. A., and Zureck, W. H., (eds.) (1983): 169; 173; 180). Consciousness, then, is enmeshed in the fabric of the physical world in unexpected ways, and if Wigner is right one could argue that the solution to some fundamental problems of our most successful physical theory lie in an unexpected direction.

15.7 A Brief Criticism

The philosophical conclusions drawn by the founders and their followers hinge on the acceptance of the three main tenets of the orthodox interpretation, namely, state vector completeness, collapse, and EE. As we saw, all have been challenged. It may be instructive to consider the reactions of two views, one (Bohm's) radically opposed to the orthodox spirit, and one (Griffiths') more sympathetic to it. For Bohm, quantum particles exist unconditionally and possess all of their intrinsic properties all the times, even if our knowledge of them is limited by GUP. In addition, state vector completeness and EE are flatly rejected, and collapse is considered a useful computational device at best. Delayed choice situations are treated rather straightforwardly. The particle moves definitely along

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[10] Actually, for Wigner, the main reason against materialism is not its incompatibility with quantum theory but that consciousness is primitive in the sense that its existence cannot be denied while that of the physical world can (Ibidem, 173-74).

c or *d*, although the pilot wave splits, covering both paths. When S_2 is not in place there is no interference, and consequently if C clicks then the particle has gone along *c* and if D clicks then the particle has gone along *d*. By contrast, if S_2 is in place then interference occurs at S_2 and the pilot wave guides the particle to C. To be sure, in this case we cannot tell which path the particle followed, but this is just an epistemological issue, as the particle definitely followed *c* or *d* and not both (Bohm, D., and Hiley, B. J., (1993): 127-30).

Even from the perspective of Griffith's consistent histories interpretation (CH), "Copenhagen done right", as he once put it, the conclusions drawn by the founders are, at best, on shaky grounds. As we saw, for CH collapse is a mere computational device, which rules out lines of argument like Wigner's. To be sure, CH adopts vector state completeness, and quantum particles are certainly not classical items, as they fail to have simultaneous (quantum) incompatible properties and what can be sensibly said about them is limited by the restrictions placed on consistent families. Even so, CH need not accept the more extreme views of the quantum world, as we can see by considering its treatment of delayed choice cases[11].

As we saw in chapter 12, figure 1, when S_2 is not in place, we could employ the family made up of two mutually exclusive histories

$$aCD \otimes \begin{cases} cCD \otimes C^*D \\ dCD \otimes CD^* \end{cases} \tag{15.7.1}$$

so that if the final state of the system is C^*D the particle certainly went along path *c* while if the final state is CD^* the particle certainly followed *d*. Alternatively, we could use the family constituted by

[11] See Griffiths, R., (2002): 273-79, whom we follow.

$$aCD \otimes \frac{1}{\sqrt{2}}[c+d]CD \otimes \begin{cases} C^*D \\ CD^*. \end{cases} \tag{15.7.2}$$

However, (15.7.1) and (15.7.2) cannot be combined because they are mutually inconsistent families. By contrast, when S_2 is in place we could use

$$aCD \otimes \frac{1}{\sqrt{2}}[c+d]CD \otimes fCD^*. \tag{15.7.3}$$

As we know from the discussion of (12.8.7) and (12.8.8), we cannot construct a family exactly analogous to (15.7.1), and consequently, we must resort to

$$aCD \otimes \begin{cases} cCD \otimes \frac{1}{2}(e+f)S^+ \\ dCD \otimes \frac{1}{2}(e+f)S^- \end{cases} \tag{15.7.4}$$

where S^+ is the projector for $\frac{1}{\sqrt{2}}\left(|C^*\rangle|D\rangle + |C\rangle|D^*\rangle\right)$ and S^- for $\frac{1}{\sqrt{2}}\left(-|C^*\rangle|D\rangle + |C\rangle|D^*\rangle\right)$, so that they are orthogonal. Note that for the family (15.7.4) the particle definitely moved along *c* or *d*. The "paradox" of delayed choice is generated by using (15.7.3) when S_2 is in place (the particle is in a superposition of paths) and (15.7.1) when S_2 is not in place (the particle is on a definite path), and concluding that the difference must be due to (caused by) the presence or absence of S_2. However, Griffiths notes, by using the other two families we see that the particle is definitely on *c* or *d* when S_2 is in place (15.7.4) and in a superposition of paths when S_2 is not in place (15.7.2). Hence, whether the particle is definitely on *c* or *d* or in a superposition of paths depends only on the families we choose, that is, on how we decide to describe the events. It follows then that the threat of retrocausation, and what Wheeler builds on it, does not come into the picture at all.

15.8 Retrodiction

In spite of their differences, Bohr, von Neumann, Heisenberg, Pauli, Wigner, Wheeler, just to name a few, agreed that quantum mechanics is primarily about measurement returns, and, as we saw, this is the orthodox view one finds in quantum mechanical texts, at least programmatically. A corollary of this position is that quantum mechanics (eigenstates cases aside) is silent about properties and therefore retrodiction, the determination of the dynamical properties the system had before measurement, or in-between measurements, is misguided. However some critics of the orthodox story, for example Griffiths and Omnés, have claimed that such prohibition is at odds with what physicists actually do. Their point can be understood by looking at a bubble chamber experiment.

Since bubble chambers have played an important role in the discovery of new particles, we may start by saying a few things about them. A bubble chamber is a container from a few centimeters to a few meters across filled with a transparent liquid (typically, Hydrogen) kept at the very low temperature of a few Kelvins and under pressure by a piston.[12] Streams of particles suitably prepared are directed by an array of electromagnets into the bubble chamber, which works both as a detector and as a target. Just as the particles arrive, the pressure is suddenly reduced by expanding the volume by about 1% or so through the lifting of the piston. The liquid then becomes superheated, that is, it has a temperature actually a bit higher than the boiling temperature at that pressure. In that state, any disturbance in the liquid, such as the presence of ions, induces

[12] For an exhaustive account of the economics of bubble chambers and their effect on experimentation, see Galison, P., (1997): ch. 5.

the liquid to boil suddenly. Consequently, a charged particle passing through will ionize some of the liquid's atoms along its path, and they will catalyze the formation of bubbles of hydrogen gas. Typically, particles will move at the speed of light or nearly so, and consequently will cover about one meter in one nanosecond, while the bubbles will take about 10 milliseconds to become visible. Note that as the difference between the two times is of the order of one million, one does not observe the particles but the "ancient" vestigial effects of their passing. Since the passing of the particles will tend to make the liquid boil, it is necessary to recompress it in order to avoid the boiling and complete a cycle by returning to the original condition. The number of cycles varies from one in a few seconds to about 30 per second.[13] The bubble chamber is surrounded by powerful magnets, so that the paths of particles with opposite charges will be curved in opposite directions, with the magnitude of the curvature determined by the momentum and charge of the particles. A set of high-speed cameras takes pictures of the tracks at every cycle, and by studying them, it is possible to determine which type of particle produced which track.

As many particles are neutral (they have no electrical charge), they do not transfer energy to the hydrogen atoms (unless they collide head on with some atomic particle), and therefore they leave no bubble track. In short, they are not detectable. However, by considering what such neutral particles spontaneously decay into and by using conservation laws, particle physicists are able to reconstruct the tracks and to determine

[13] Fast as this is, bubble chambers have been supplanted by different detectors capable producing thousands of sets of pictures per second. Actually, the pictures are computer generated.

the type of particles that produced them. Figure 1 is the photograph and schematic tracing of one of the most famous pictures from a bubble chamber; it was taken in 1964 at Brookhaven National Laboratory, and it shows the path of an Ω^- particle, whose existence had been predicted shortly before. The tracks never observed, but whose existence is retroactively inferred, are represented by broken lines.

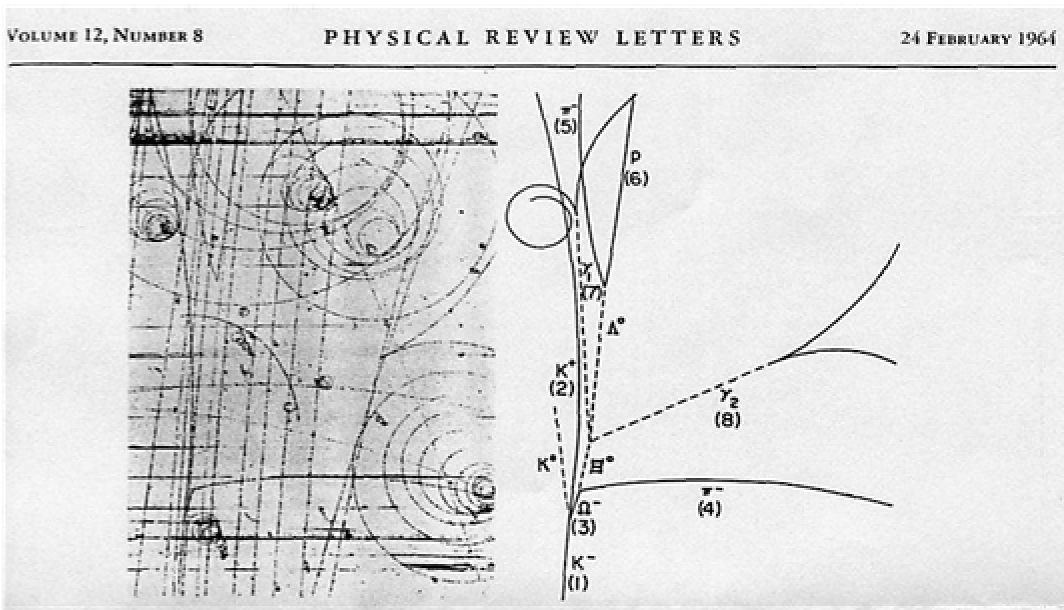

Figure 1

The interpretation is:

$K^- + p \to \Omega^- + K^- + K^\circ$

$\quad\hookrightarrow \Xi^\circ + \pi^-$

$\quad\quad\hookrightarrow \Lambda^\circ + \pi^\circ$

$\quad\quad\quad\quad\hookrightarrow \gamma_1 + \gamma_2$

$\quad\quad\quad\quad\quad\quad\hookrightarrow e + e^-$

$\quad\quad\quad\quad\quad\hookrightarrow e + e^-$

$\quad\quad\quad\hookrightarrow \pi^- + p.$

A stream of K^- mesons (negative kaons) come in from below, and one of them hits a proton (p) in a Hydrogen atom. The two particles are annihilated and three new particles are created, an omega minus, a negative kaon and a neutral kaon: Ω^-, K^-, and K°. Ω^- spontaneously decays into a neutral xi and a negative pion: Ξ° and π^-. The former spontaneously decays into a neutral lambda and a neutral pion, Λ°, and π°. The neutral lambda decays into a negative pion and a proton, while the neutral pion decays into two gamma rays, each decaying into an electron and an anti-electron.[14]

Neutral particles are not the only ones that do not leave a bubble trail. There are also charged particles that are highly unstable and spontaneously decay in about $10^{-23} s$, much too short a time for them to leave any bubble track. Here too, their existence and paths are retroactively inferred by appealing to the particles they decay into and to increased reaction rates. The question is whether the orthodox interpretation can really do this. As a trajectory is a sequence of positions occupied by the particle at successive times, let us concentrate on one such position. In the orthodox story, a particle has no position unless it happens to be in an eigenstate of position. However, since we are interested in the particle's momentum, which is used in determining what happens if the particle hits something in the bubble chamber, we cannot collapse the particles' state

[14] Barnes, V. E., *et al*., (1964). The article makes an interesting read because it gives a sense of the detective work and reasoning that went into the determination of the nature of the invisible particles. To have an idea of the effort involved in finding out a golden event like this, note that about 100,000 pictures were taken containing about 300,000 meters of K^- tracks.

function into a Dirac delta function. By appealing to conservation laws and the experimental setup, one might perhaps argue that with high probability the particle's position could only be within a certain range; however, if we adopt the orthodox interpretation, all we are really entitled to say is that were we to observe the particle as to position (an act that would precipitate collapse onto a Dirac delta function) we would likely find it in such and such a range. But of course, if we have not observed the particle the counterfactual is not satisfied. "Since the particle would have been in a position within a given range R had it been observed, it follows that it was in a position within R if it was not observed" is just as unreasonable as "Since the missile would have been in a position within a given range R had it been fired, it follows that it was in a position within R even if it was not fired." In sum, we face the ontological problem of the existence of unobserved dynamical properties created by EE.

An analogous situation occurs at the level of the standard use of quantum mechanics, even aside from the practices of particle physicists. If there is a constraint on a system imposed by the physical situation, and therefore there is a restriction on the range of property eigenvalues that could be obtained in a measurement, physicists typically assume that the system actually has one of those properties with a value within that range. For example, consider an alpha-particle inside a nucleus. Its being inside imposes a position constraint that is typically exploited to conclude that the magnitude of its momentum cannot be smaller than that allowed by the Uncertainty Principle. One then infers the speed's lower limit, which one can use to figure out the lower limit of how many times per second the particle collides with the potential wall of the nucleus, and so on. In short, run of the mill quantum mechanics is often done in a quasi-property realist way even in textbooks that programmatically adopt the orthodox interpretation and EE.

15.9 Holism and Entanglement

Broadly speaking, holism is the view that the whole is more than the sum of its parts or that it is even ontologically prior to them. Philosophers have traditionally distinguished an analytic whole (*totum analyticum*) from a synthetic whole (*totum syntheticum*). In an analytic whole, the totality is prior to its parts. For example, Newton probably held that the whole of space is prior to its parts because no part of space can be separated from the whole, for doing so would be taking it out of itself, a patent absurdity in his view. Space is not an aggregate of prior parts, and the same is true of time.[15] In a synthetic whole, by contrast, the totality is posterior to its parts. It is this type of totality that we consider here. One must distinguish two cases. In the simplest and paradigmatic case, the parts have ontological priority and exist contemporaneously to their whole. For example, the cogwheels not only existed before the clock but also continue to exist as the clock exists. Alternatively, the parts existed before the whole, but cease to exist as soon

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[15] For the philosophical handling of this, see Clarke's third letter to Leibniz, section 3, his fourth letter, sections 11-12 in Alexander, H. G., (ed.) (1984). However, space and time have a peculiar status in Newton's system because they are divine attributes, and consequently much of what he says about them is colored by theological concerns related to divine simplicity. Since for Newton space and time are *not* part of nature but the framework within which nature is set, it remains true that Newtonian physics is reductionist. More specifically, the physical state and properties of a system are reducible to those of its parts.

as the whole comes into being: they fuse, as it were, losing their individual existence as long as the whole remains. For example, chemical compounds (an acid and a base, say) vanish, resulting in a new compound (a salt).[16]

The counterpart of holism is reductionism, roughly the view that the whole is nothing but the sum of its parts. Let us start by considering a synthetic whole whose parts exist as independent beings contemporaneously with the whole. Suppose we decide to study a mechanical clock. We might start by investigating it as a whole, determining its shape, weight, discovering that it has parts, that the pointers move regularly and that therefore it is a useful device to keep time. If we stopped at that, we would not be diligent. For, a proper study of the clock requires that we determine the nature, motions and spatio-temporal positions of its parts (spring, cogwheels) and how the behavior of the clock as a whole arises from theirs. Upon consideration of what we have done and of our general knowledge about clocks, we may come to the following two conclusions, among others. First, the physical state of the whole is reducible to those of its properly configured parts. We may call this fact "state reductionism." At the theoretical level, state reductionism is reflected by the fact that the state equation of the clock is obtainable from those of its properly configured parts. Second, the properties of the whole are reducible to those of its properly configured parts. We may call this fact "property reductionism." For example, the capacity of the clock to keep time is reducible to the mechanical properties of properly configured springs, cogwheels, and so on; more trivially, the mass of the clock is the sum of the masses of its parts.

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[16] For some recent discussion, see Kronz, F., M., and Tihen, J., T., (2002) and Humphreys, P., (1997).

Exactly defining what one means by "reducible" is difficult. In some cases (mass, for example) the whole is just the arithmetical sum of the parts; in others (velocity, for example) it is the vectorial sum of the parts; in others again (keeping the time, for example), the relation may be more complex. Fortunately, we need not be very specific, and in the present context we assume that minimally B reduces to A only if A uniquely determines B. In other words, that the states (properties) of the properly disposed parts uniquely determine the state (properties) of the whole is a necessary condition for reduction. In what follows, we shall consider whether state and property reductionism obtain in quantum mechanics under the orthodox interpretation.

If a complex system S has a factorizable state (that is, if the component systems have not interacted with each other), then the physical states of subsystems 1 and 2 completely determine that of S, which is simply $|\Psi_S\rangle = |\Psi_1\rangle \otimes |\Psi_2\rangle$. However, if entanglement occurs, things change dramatically. Consider the entangled state of particles 1 and 2 with state

$$|\Psi\rangle = \alpha|e_1 d_2\rangle + \beta|e_2 d_1\rangle. \qquad (15.9.1)$$

Here reductionism seems to fail for the simple reason that in standard quantum mechanics neither 1 nor 2 have independent physical states. This is reflected at the theoretical level by the fact that neither 1 nor 2 have a state vector; only the compound does. Consequently, for the standard interpretation, according to which quantum states are unqualifiedly represented by state vectors, this is the end of the story; state reductionism must fail because there are no states to which the whole state can be reduced to.

Perhaps, however, one might modify the orthodox story by allowing states to be described, albeit not completely, by density operators, and use reduced density operators as representing the states of 1 and 2. Then, one could try to claim that the state vector of the compound is uniquely determined by the density operators of the parts. However, this does not work. As we know, the reduced density operator for particle 1 is

$$\rho_1 = \alpha\alpha^* |e_1\rangle\langle e_1| + \beta\beta^* |e_2\rangle\langle e_2| \tag{15.9.2}$$

and that for particle 2 is

$$\rho_2 = \alpha\alpha^* |d_1\rangle\langle d_1| + \beta\beta^* |d_2\rangle\langle d_2|. \tag{15.9.3}$$

Consider now a system in state

$$|\Psi'\rangle = \alpha|e_1 d_1\rangle - \beta|e_2 d_2\rangle. \tag{15.9.4}$$

If $\alpha = \beta = 1/\sqrt{2}$, $|\Psi\rangle$ and $|\Psi'\rangle$ produce the same reduced density operators for particles 1 and 2. Consequently, ρ_1 and ρ_2 fail uniquely to determine $|\Psi\rangle$ or $|\Psi'\rangle$, different states predicting different measurement returns. Nor are they sufficient uniquely to determine the density operator of the compound. Therefore, even the acceptance of separability, if fleshed out in term of density operators, fails to produce state reductionism.

Perhaps, however, reduced density operators convey too little information, and one might bypass the fact that neither 1 nor 2 have a state vector by making do with Everett's notion of relative state. Since in (15.9.1) $|e_1\rangle$ appears only once, we might say that 1 has state $|e_1\rangle$ relative to 2 having state $|d_2\rangle$, and so on. All we need in order to obtain the state vector of the compound is the expansion coefficients. The price, however, is that we must accept that the state of each part makes an unavoidable reference to those of the other parts. Obviously, this does not apply to paradigmatic cases of reduction such as the clock's. To be sure, the state of the clock depends not only on the state of its parts but also on their spatio-temporal configuration. However, the state of each part makes no reference to that of any other part: it is an intrinsic feature of the part, one might say. By contrast, in the quantum case the state vector of 1 makes essential reference to that of 2, as the former is defined relative to the latter. Still, from the fact that the state of a part must make reference to that of another part it does not follow that it must make reference to the state of the whole: saying that that 1 has state $|e_1\rangle$ relative to 2 having state $|d_2\rangle$ does not involve a direct appeal to $|\Psi_S\rangle$. Nor does the specification of all the relative states trivially provide us with the state vector of the compound (in which case one might suspect that $|\Psi_S\rangle$ has been surreptitiously introduced), as we need to have the expansion coefficients. Whether this is compatible with *bona fide* state reductionism is unclear, as it depends on how broad a notion of part and physical state one is prepared to accept.

In the orthodox interpretation, the discussion of property reductionism is complicated not only by EE but also by the fact that entangled components lack a state vector, and therefore have no individual dynamical properties. For example, in the singlet state the two particles have no individual spin. A further problem is that no-go theorems like KS prevent indiscriminate property ascription to systems and their parts. However, one can bypass the difficulty by abandoning the orthodox story and adopting, for example, a rather close relative, the consistent history interpretation. Then, as the discussion leading to (12.9.3) shows, one can attribute opposite spins to the two EPRB particles, define the total spin of the system S as their sum according to the law of conservation of angular momentum, and obtain the correct result of zero. In short, some properties are in fact reducible. However, in other cases reducibility fails. For example, by appealing to reduced density operators, we could say that particle 1 has the property associated with the Hermitian operator ρ_1 and particle 2 that associated with ρ_2. But as ρ_1 and ρ_2 fail to determine the density operator of S (the whole), their respective associated properties do not determine that associated with the density operator of S.

One can look at entanglement differently and argue that although S is a synthetic whole because it results from the interaction of particles 1 and 2, when the two particles become entangled, they lose their separate existence (they fuse, as it were), and produce a new thing, the entangled system S. That this loss of separate existence persists even when the particles are spatially separated goes against the principle of separability, but this may not bother an orthodox theorist. Hence, one may continue, it is no surprise that 1 and 2 have no quantum state, and therefore no state vector, of their own. The two particles acquire their separate existence again only when the entanglement is destroyed.[17]

[17] Bohm has made much of the non-locality of the quantum potential. If one understands the quantum potential as carrying information about the whole, then each part, insofar as it is affected by the quantum potential, contains within itself information about the whole system and, by extension, the whole universe. Bohm has expressed this idea by saying that there is an *implicate order* in which every part of reality enfolds every other part. He has developed this idea into a rather unclear metaphysical structure. In his view, as the implicate order reveals the dependence of everything on everything else, and in general that of the parts on the whole, so the explicate order reveals the existence of parts that are relatively stable and appear independent of the rest. This is the world of our experience. However, this independence is always limited in that things are aspects, manifestations,

of the organic whole. The whole is a dynamic entity, the holomovement, which our language, based on the primacy of nouns (the linguistic counterpart of things) and not on verbs (the linguistic counterpart of change), has structural difficulties in capturing. Hence, Bohm proposes a new approach to language, the rheomode, emphasizing the role of verbs oven nouns. For a short account of Bohm's metaphysical views, see Sharpe, K. J., (1993), which also contains an ample bibliography. For Bohm explaining his own philosophical views, see Nichol, L., (ed.) (2003).