Philosophica 83 (2010) pp. 117-137

QUANTUM MECHANICS, CHANCE AND MODALITY

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ABSTRACT

The thesis of this article is simple: even if it is accepted that quantum mechanics is a fundamentally probabilistic theory, this provides us with no special reason to believe in "chances" in the sense of objectively existing factors that are responsible for the relative frequencies we encounter in experiments. More in general, quantum mechanics gives us no special reason to believe in the actual existence of modalities. We may intuitively be inclined to believe in chances as a kind of causes, just as in classical mechanics we are inclined to think of forces as causal powers that produce accelerations. It might even be the case that intuitions of this kind can be developed into a coherent metaphysical scheme (something which has yet to be done, I think). But as I shall argue, a sober Humean perspective on quantum mechanics is certainly possible as well, and has much to recommend it. In short, the thesis of the present paper is that for a Humean, quantum mechanics introduces no reasons to abandon his position.

1 Introduction

The thesis of this article is simple: even if it is accepted that quantum mechanics is a fundamentally probabilistic theory, this provides us with no special reason to believe in "chances" in the sense of objectively existing factors that are responsible for the relative frequencies we encounter in experiments. More in general, quantum mechanics gives us no special reason to believe in the actual existence of modalities. We may intuitively be inclined to believe in chances as a kind of causes, just as in classical mechanics we are inclined to think of forces as causal powers that produce accelerations. It might even be the case that intuitions of this kind can be developed into a coherent metaphysical scheme (something which has yet to be done, I think). But as I shall argue, a sober Humean perspective on quantum mechanics is certainly possible as well, and has much to recommend it. In short, the thesis of the present paper is that for a Humean, quantum mechanics introduces no reasons to abandon his position.

In spite of the controversy surrounding the interpretation of quantum mechanics, there is a universally agreed upon "cash value" of the quantum state Ψ: the square of the modulus of Ψ, $|\Psi|^2$, yields *probabilities of measurement outcomes*. Although interpretations differ concerning what goes on behind the scenes of measurement, the experimental meaning of the quantum state in terms of possible outcomes of experiments and their probabilities is thus clear and uncontroversial. Consider, for example, the case of a single particle. In this case we can write down the state in the form of a wave function $\Psi(x)$, a continuous function of position; $|\Psi(x)|^2$ has the empirical meaning of the probability of finding the particle at x in a position measurement. This probability interpretation is well supported empirically and the enormous empirical success of quantum mechanics partially rests on it.

This simple example already illustrates one of the features of quantum theory that are essential for our theme: the state Ψ contains information about *all possible* measurement outcomes. Now, if we assume that Ψ characterizes an individual situation (a natural assumption, since a more detailed representation of the individual case is not available in the standard mathematical framework of the theory), it seems plausible to conclude that this individual situation in some way comprises all such possibilities. This then may be conceived as pointing into the direction of a *modal realism*: possibilities exist no less than what is actual. There is plenty of room for further elaboration and specification of this idea, in which different interpretations may lead to different details. But the main suggestion is that quantum mechanics makes possibilities as ontologically serious as actualities (see for discussions of different forms of this suggestion, e.g., De Witt and Graham, 1973; De Witt, 1979; Everett, 1957; Redhead, 1987; Skyrms, 1976; Saunders, 1998; Thompson, 1988; Wallace, 2003; Wilson, 2006). This in turn suggests that quantum mechanics supports a non-Humean analysis of laws of nature: the possible worlds that are allowed by the quantum mechanical laws are not mere thought constructions, but are as ontologically robust as the world we live in. According to this line of thought laws have a status that transcends the status of regularities in our own world: they describe what is common to a huge collection of equally real worlds.

The second feature of quantum mechanics that is important for our discussion is its indeterminism: in any experiment that we perform only one result will be obtained, whereas the theory does not contain anything that determines which possibility will be singled out for our actual experience. Although the latter fits in with the symmetry between the actual and the possible that we just discussed, the uniqueness of outcomes awakens the intuition that somehow a fundamental chance process forces transitions from possibility to actuality after all. This then leads to the thought that an objective factor, perhaps a propensity or disposition, nudges the outcomes one way or another; and that quantum mechanics is to be considered a theory that describes objective chance.

These ideas (modal realism and objective chance) have a confusing relation to each other and each of them raises complicated questions of its own. In the following we shall argue that quantum mechanics had better do without them, and in this way steer free from metaphysical confusion.

2 Superpositions of possibilities

Suppose that a measurement will be performed on a quantum object in a state Ψ, and that the quantity that is going to be measured is represented by an observable with eigenstates $|\psi_n>$. The state Ψ can be written as a *superposition* of these eigenstates: $\Psi = \sum c_n |\psi_n>$, where the c_n are numerical coefficients (complex numbers). If we denote the initial state of the measuring device by $|A_0>$, the linearity of the Schrödinger equation tells us that an ideal (i.e. non-disturbing) measurement interaction is to be represented by the following transition from the initial to the final state of the combined system "object plus measuring device": $\sum c_n |\psi_n> |A_0> \rightarrow \sum c_n |\psi_n> |A_n>$. In the final state, at the right-hand side of this equation, the different states $|A_n>$ in the superposition correspond to different possible indications of the measuring device (different "pointer positions"); that is, to different possible outcomes of the measurement. Clearly, all possible outcomes occur on an equal footing in the superposition of the final state, so that there is no sign that any one of them is more real than any other. This is the situation alluded to in the Introduction.

Now, in the older literature it is often said that at some stage during the measurement interaction the state "collapses": that all terms suddenly disappear except the one corresponding to the actually realized outcome. Such a collapse *would* single out the actual from the merely possible. Collapses constitute, however, a process of evolution that conflicts with the evolution governed by the Schrödinger equation. And this raises the question of exactly when during the measurement process such a collapse could take place or, in other words, of when the Schrödinger equation is suspended. This question has become very urgent in the last couple of decades, during which sophisticated experiments have clearly demonstrated that in interaction processes on the sub-microscopic, microscopic and mesoscopic scales collapses are never encountered. The presence of a macroscopic measuring device must therefore apparently be assumed in order for collapses to happen. But according to all we know, the transition from the microscopic realm to the macroscopic is completely gradual, without any specific point where things could become qualitatively different. So it is difficult to see how the notion of macroscopicity could serve to justify the essential difference between processes in which collapses do occur and processes in which they are absent. Moreover, recent experiments have extended the domain in which the absence of collapses has been established to situations that are virtually macroscopic (very big molecules etc., so-called "macroscopic superpositions"). Accordingly, there is a growing consensus that it is most implausible that collapses really occur. All evidence points into the direction of universal validity of the (unitary) Schrödinger evolution, which leads to a description of interactions and measurements as illustrated in the above equations.

What is more, even if collapses *did* occur, we still had to countenance the situation that immediately *before* the collapse *all* possibilities would be present in the superposition, on a completely equal footing. The erasure of most of them in a collapse, with the result that only the actual remains, would not annihilate the fact that there was no distinction between the actual and the possible in the quantum state until the instant of the collapse.

In accordance with what was just said about the implausibility of collapses, most modern treatments of quantum mechanics do without them. In these no-collapse interpretations (e.g., decoherence approaches, many worlds interpretations, modal interpretations) states that are superpositions of different possibilities are endemic. But as we have just observed, even if one does accept the occurrence of collapses one must acknowledge that quantum states generally contain the actual and possible alike. This is therefore a typical feature of quantum mechanics.

What is the physical significance of these superpositions? To answer this question it is important to realize that there is an essential difference between situations represented by the superposition $\sum c_n |\psi_n>$ and situations in which *one* of the $|\psi_n>$ obtains, but we do not know which one. This difference has empirical consequences, for the single case. Consider, to see this, the famous double-slit experiment (Figure 1). When quantum particles, for example electrons, from the left approach a screen with two slits, the state of these particles at the right-hand side of the screen will be a superposition of two terms, each corresponding to a transition through a single slit. Each individual particle, in each individual run of the experiment, will be represented by this same superposition state. Now, if the position of the individual electrons is measured on the right hand side, for example by positioning a photographic plate at some distance from the screen with the slits, the probability distribution of the possible outcomes will be given by $|\Psi|^2 = |\Psi_1 + \Psi_2|^2$, with Ψ_1 and Ψ_2 the two states corresponding to a transition through the upper and lower slit, respectively. This probability distribution will become visible on the photographic plate if we repeat the experiment many times: in the long run, the number of electrons found at a particular spot will become proportional to the probability that an electron is found at that spot. The pattern that will manifest itself in this situation is a so-called *interference* pattern. It is not the mere sum of a contribution coming from Ψ_1 and one coming from Ψ_2, respectively, but it contains an additional "cross term" that expresses how these two terms work together and interfere. The result is shown in Figure 1.

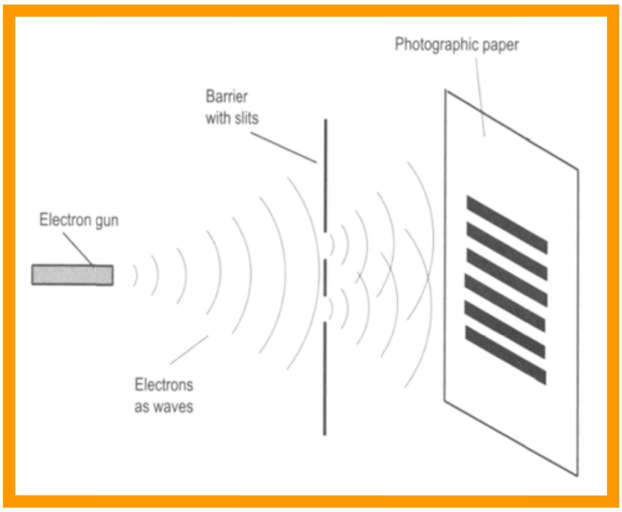

Figure 1. The double slit experiment. The "waves" represent the state Ψ.

What is more, even if collapses An essential characteristic of this interference pattern is that at some places the probability vanishes: at these places no electrons will be found on the photographic plate. This means that *each individual* electron must “know” that it is being represented by the superposition $\Psi = \Psi_1 + \Psi_2$; each individual electron must have information about which places are forbidden. The situation in which the state is not a superposition but a case of ignorance (*either* Ψ_1 *or* Ψ_2, but we do not know which) is completely different. This latter situation is experimentally realized if only one of the slits is open in each individual run of the experiment, but we do not know which one. Also in this case we can make the corresponding probability distribution visible in a long series of experiments, now by opening the slits alternatively in random fashion. The resulting pattern is shown in Figure 2.

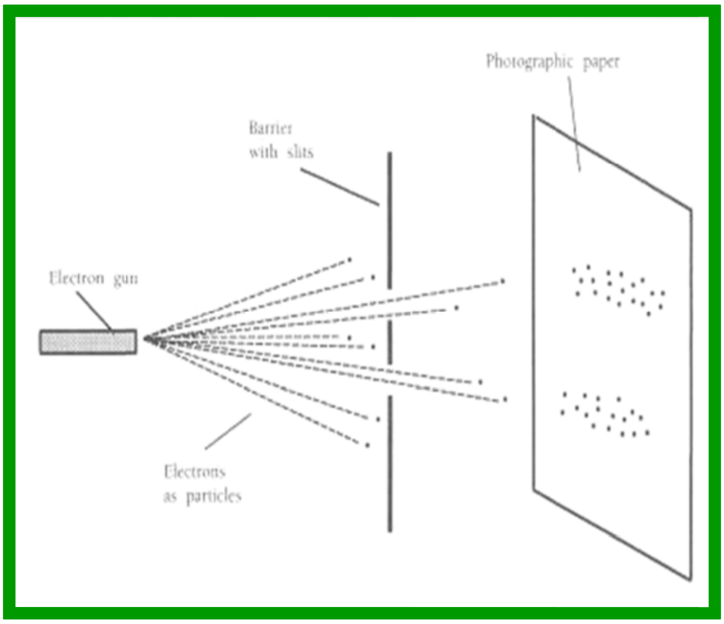

Figure 2. One slit or the other. The resulting pattern can be understood on the basis of a particle picture of the electrons, each particle going through one slit.

Again, it should be stressed that in each *individual* run of the experiment the difference between the superposition and the either-or situation (the situation of a so-called “mixture” of possibilities) is essential. The spots on the photographic plate that are forbidden according to the superposition are not forbidden if there is a mixture. Each individual electron must “be aware” of its state in order to know whether it can hit the forbidden spots or not.

Each term in the superposition plays an indispensable role in bringing about the measurement result. Both components are needed for the interference pattern; removing one of them, by changing the experimental set-up (e.g., by blocking one of the slits) will result in a change in the observable pattern on the photographic plate. One could perhaps say that each term represents a part of the total cause of the final result. As we have seen, this result cannot be regarded as the sum of what would be brought about by the partial causes separately: there is interference, so the “causes” apparently interact with each other. Anyway, it can be concluded that both Ψ_1 and Ψ_2 refer to aspects of what actually exists – indeed, something that does not exist cannot be causally relevant.

Since Ψ_1 and Ψ_2 separately describe situations in which only one slit is open, we might be tempted to say that these situations are both in some way present and interfere to bring about the result. If we translate this thought to our earlier case, the measurement of properties of a quantum object by a measuring device, we arrive at the picture that all individual terms in the superposition $\sum c_n |\psi_n> |A_n>$ refer to something actually existing. Since these individual term correspond to different possible measurement outcomes, the conclusion seems plausible that according to quantum mechanics the possible must be as real as the actual. Think, to make the idea more concrete, of Schrödinger’s notorious cat. Its paradoxical state is $\Psi = \Psi_{dead} + \Psi_{alive}$, with Ψ_{dead} and Ψ_{alive} corresponding to a dead and a living copy of the cat, respectively. If it is measured whether the cat is dead or alive, one of these possibilities will be found, with a probability given by the relative weight of the corresponding component in the total state. But according to quantum mechanics it is also possible to measure other properties, in which the Ψ_{dead} and Ψ_{alive} interfere. According to the above argument, it follows that in some sense both the dead and the living cat are parts of the overall reality.

This situation is specific to quantum mechanics. In classical physics the most fundamental description of a physical system (a point in phase space) reflects only the actual, and nothing that is merely possible. It is true that sometimes states involving probabilities occur in classical physics: think of the probability distributions ρ in statistical mechanics. But the occurrence of possibilities in such cases merely reflects *our ignorance* about what is actual. The statistical states do not correspond to features of the actual system (unlike the case of the quantum mechanical superpositions), but quantify our lack of knowledge of those actual features. This relates to the essential point of difference between quantum mechanics and classical mechanics that we have already noted: in quantum mechanics the possibilities contained in the superposition state may interfere with each other. There is nothing comparable in classical physics. In statistical mechanics the possibilities contained in ρ evolve separately from each other and do not have any mutual influence. Only one of these possibilities corresponds to the actual situation. The above (putative) argument for the reality of modalities can therefore not be repeated for the case of classical physics.

3 Do the laws of quantum mechanics transcend actuality?

The quantum mechanical state Ψ is the central quantity in quantum mechanics and plays a pivotal role in the quantum mechanical laws (like the Schrödinger equation). Now if it is true that Ψ refers to the actual and the possible in a symmetrical way, and if both the actual and the possible are equally causally effective, and if the laws of quantum mechanics are about how Ψ behaves, then it seems inevitable to conclude that the laws of quantum mechanics are more than representations of regularities in *our* world. Rather, they appear to be about everything that is possible, conceived of in an ontologically robust way. This line of thought leads us to the idea that quantum mechanical laws refer to regularities in the collection of all possible worlds, with the understanding that these possible worlds are ontologically on a par with our actual world. Indeed, there is one interpretation of quantum mechanics in which this idea is made explicit: the "many worlds" interpretation. An alternative idea is to enlarge our ordinary actual world and to populate it with new entities: real modalities or dispositions that exist in addition to ordinary things.

This issue about the status of quantum mechanical laws connects to a well-known debate in the philosophy of science, about the status of laws of nature. There are two main positions in this debate. The first one, the "Humean" view, is typically empiricist (see, e.g., Lewis, 1986; van Fraassen, 1989). It says that laws of nature represent regularities in the pattern of events in our actual world – the actual pattern of events realized during the history of our universe. According to this empiricist viewpoint it is true that once we have formulated such laws, we can use them to discuss counterfactual statements: about what *would* have happened if the conditions in our world *had* been different. The laws serve to fix the truth conditions for such statements. For example, I can ask myself what would have happened if I had made a wrong move a moment ago; the law of gravity convinces me that in this case I would have lost my balance. But according to the Humean analysis this does not commit me in any way to thinking that these counterfactual possibilities are real, or to the view that laws transcend the actual world. The Humean maintains that we need to assume the existence of only one world, namely the ordinary actual one; that the regularities of this world are expressed in our laws and theories; and that we introduce possible other worlds and counterfactual circumstances purely as thought constructions, in order to bring out the peculiarities of the laws we have formulated. Possible worlds are mental tools and not really existing entities.

Modalities, like necessity and possibility, are concepts we introduce on the basis of our theories and do not correspond to features of reality that transcend the ordinary description in terms of actual events.

An anti-Humean counterargument is that the laws of nature we in fact use can hardly be interpreted as referring to actual regularities in our own world. Take the law of inertia as an example: this law says that bodies on which no forces are exerted move with constant velocity in a straight line. Such force-free bodies do not exist in our world (gravitational forces are present everywhere), and it therefore follows that there is no actual regularity that corresponds to the law of inertia. Rather, the argument continues, the law tells us how bodies should and would behave *if* they were force-free. In other words, the law is there independently of what is going on in actuality; it "stands above" the world and *governs*, together with the other laws, the processes occurring in our world. This leads to a non-Humean conception of natural laws that can be worked out in several ways (e.g. in a Platonic fashion: Armstrong, 1983; Dretske, 1977; Tooley, 1977). The essential difference with the Humean view is that according to this alternative conception laws are not depending on and representing what happens in our actual world, but possess an independent mode of existence.

In summary, laws, according to the Humean, only arise ***after*** our study of the patterns in the phenomena; a Humean thinks of the actual phenomena as being primordial. Our thinking about modalities (possibility, necessity, etc.) is informed by our theorizing and is therefore also *a posteriori*. By contrast, according to the non-Humean views mentioned here laws exist independently of the phenomena and endow modalities with a corresponding independent status.

The arguments we have explained above led to the conclusion that quantum mechanics supports a non-Humean analysis of natural laws. The reason adduced was that the quantum mechanical laws seemed to commit us to belief in more than pure actuality; they involved really existing possibilities, perhaps in the form of other possible worlds or perhaps in the form of dispositions that exist in addition to ordinary actual things. If this argument is correct, it would follow that developments within physics have been capable of deciding a traditional metaphysical debate. The distance between physics and metaphysics, and the flexibility there usually is in the interpretation of scientific theories, should make one already suspicious of such a conclusion. Indeed, in the following I shall argue that there is no compelling reason coming from quantum mechanics to reject a Humean analysis of laws.

4 The empiricist conception refined

Let us first reconsider the traditional objection to the Humean regularity view, namely that the typical laws of theoretical science do not correspond to regularities actually found in nature. The objection is not only that these laws deal with systems that do not actually occur (like the force-free body from the law of inertia), but also that they are about all possible circumstances in which physical systems can find themselves. The ideal gas law, for example, stipulates functional relations between pressure, temperature and volume of gases for all possible values these quantities can assume. It is evident that even if ideal gases existed, they would not be actually instantiated in all these uncountably many circumstances. So, the argument continues, laws tell us more than what actually is the case.

However, this objection is taken care of in modern versions of the regularity view. Let me focus here on the analysis proposed by David Lewis. As in more traditional accounts, the starting point and motivation of this analysis is the idea that laws encode information about actual regularities. As Lewis puts it, the “mosaic” of actual events in the world (both in the future and in the past) constitutes the basis on which laws “supervene”. But the way this mosaic of actual events and the laws of nature are supposed to interrelate is more sophisticated than in older Humean accounts. The idea is that science looks for a *theoretical system* that *fits* the mosaic of events. This theoretical system is not a mere reproduction of all events that happen in the history of the universe – such a reproduction would be an infinite list that we would not recognize as a scientific theory. Rather, we look for a compressed representation, using a finite set of axioms. In other words, we want a deductive system that is both simple and able to reproduce the actual regularities – at least approximately. Now, *laws* are defined as the axioms of our *best* theoretical description of our world. Of course, this raises the difficult question of how to judge what the best theoretical system is. Theories differ, among other things with respect to simplicity and information content. The best theoretical system must possess some kind of balance between these virtues, which may conflict with each other. For example, systems that are very simple tend to be less informative; and very informative systems tend to be complicated. A precise characterization of choice criteria for scientific theories, and their relative weights, is obviously a very difficult task; quite plausibly, there does not exist a general objective and context independent solution of this problem of theory construction. Fortunately, however, this is a problem that need not detain us here. For our purposes it is sufficient to acknowledge that the broad outlines of this picture of scientific theories are faithful to actual science. That is, scientific theories in fact aim at saving the actual empirical phenomena, while also taking into account such super-empirical virtues as simplicity, mathematical elegance and explanatory power. Now, if laws of nature are identified with axioms of such a theory, it is clear that they do not have to directly represent instantiated regularities. To revert to the example of the law of inertia again, it is sufficient that this law *together* with the force laws and law of motion leads to equations that to a high degree of approximation and in a simple (etc.) way represent the way objects actually move. It is only the *complete* theoretical system that supervenes on the mosaic of actual facts.

Now, what does this imply for the notion of objective chance? Can an empiricist account even make sense of this notion? Doesn’t one have to assume the existence of other worlds, real modalities or dispositions even to give *meaning* to objective chance? The Humean answers that it may happen that our best theory operates with a probability ***p***, without positing underlying variables in terms of which the theory becomes deterministic again. This occurs if we thus achieve the best statistical fit with the actual relative frequencies occurring in the world, while satisfying the non-empirical criteria; and while there is no additional gain in prediction or non-empirical virtues connected with the introduction of additional deterministic variables. In this situation we may call ***p*** "objective chance". But note that this definition does not in any way suppose the existence of things transcending actuality. Most importantly, here ***p*** is not reified as something that exists in its own right, independently of the events in the world (and perhaps *governing* these events in some way). In this empiricist analysis the introduction of objective probability merely serves the purpose of accommodating actual regularities, in the best theoretical way available.

In summary, according to the Humean view on laws, only actual things and events exist. This is true even in indeterministic theories in which the notion of probability is essential.

5 The regularities on which quantum mechanics supervenes

The paradigm case of a quantum phenomenon is the double slit experiment of Figure 1, in which in a long series of repetitions an interference pattern of dark spots arises on the photographic plate. This interference pattern is markedly different from the pattern that results when only one slit is open in each run of the experiment (Figure 2). However, the exact interference pattern of Figure 1 will not be fully realized in a real experiment: an infinite sequence of experiments would be needed for that. The actual experimental findings are more or less similar patterns in finite series of repetitions; and of course there are countless other similar non-classical interference phenomena. Quantum mechanics is our best theoretical system fitting the collection of all these phenomena.

Actually, this account is a bit quick. There is some controversy surrounding the question what the best theoretical system is: in particular, according to some philosophers not standard quantum mechanics but the Bohm version of the theory fits best. This exemplifies what we already mentioned above, namely that finding an optimum balance between the different requirements imposed on theories is a non-trivial task and may well be a problem that cannot be solved in a completely objective manner. However, here we focus on standard quantum mechanics, and accept that this theory constitutes the best theoretical system fitting the phenomena and satisfying non-empirical requirements à la Lewis.

What about the argument mentioned in the section on quantum possibilities, namely that the different terms in a quantum mechanical superposition are all causally active and must therefore represent something real? For the concrete case of the double slit experiment: if both slits are open the state is a superposition of two terms, $\Psi = \Psi_1 + \Psi_2$ and both terms are indispensable for making correct empirical predictions. Does this mean that there is something real corresponding to each of these individual terms?

First of all, it should be noted that the states Ψ, Ψ_1 and Ψ_2 are defined as elements of a mathematical state space. It does therefore not make immediate sense to speak about causal interactions between them: only physical systems can causally affect each other, whereas numbers, functions or mathematical entities in general, do not have causal effects. The states have the role of representing regularities in the phenomena but are not physical entities themselves. So in order to make the causal efficacy argument work, we should provide an interpretation of the formula $\Psi = \Psi_1 + \Psi_2$ in physical terms. However we do this, from a Humean viewpoint it is clear from the outset that the states can only refer to *actual* situations. This is so because the complete theoretical system of which Ψ is a part supervenes on the mosaic of actual events. The notion that $\Psi = \Psi_1 + \Psi_2$ would stand for the causal interaction of two possible states of affairs, two modalities or possible worlds, is therefore unintelligible. It is only the actual that enters into a Humean analysis of theories and laws; and as we have seen there is no reason to suppose that such an analysis cannot be given in the case of quantum mechanics.

A further point to observe is that there is no ground whatsoever to suppose that the plus-sign in our superposition equations stands for simultaneous physical existence; that $\Psi = \Psi_1 + \Psi_2$ means that in the situation described by Ψ the situations described by Ψ_1 and Ψ_2 are physically present as well. In fact, making this assumption would lead to a boundless multiplication of realities, in view of the fact that Ψ can be written as the sum of two other states in an uncountable infinity of ways. Interpreting the + sign as indicating co-presence would be tantamount to assuming that $10 = 9+1 = 8+2 = \ldots$, implies that all integers from 1 to 9 are present, in relevant pairs and cooperating to form 10, as soon as 10 appears on the scene. Or, to take a more physical example, like assuming that the fact that a force can be written as the sum of two other component forces in infinitely many ways implies the simultaneous real presence of all these component forces. Clearly, the fact that Ψ_1 and Ψ_2 by themselves, in isolation, represent other situations – in our case situations in which only one slit is open – does not have the consequence that these situations are also present in the case represented by $\Psi_1 + \Psi_2$. It is the full Ψ that characterizes the situation, in the sense that it corresponds to what actually is the case.

Consider, to make the same point in a perhaps more vivid way, the Schrödinger cat case again. Here we encounter a total cat state that has the form $\Psi = \Psi_{\text{dead}} + \Psi_{\text{alive}}$, with Ψ_{dead} and Ψ_{alive} by themselves corresponding to situations in which there is a dead or a living cat, respectively. According to what we just have said, this situation should not be thought of as the simultaneous effort, or the struggle for hegemony, or the causal interaction, of a dead and a living animal. Ψ is a state of its own, neither describing a dead nor a living cat. It refers to a situation in which there is a cat with typically quantum properties, not describable in classical terms. That in a subsequent measurement in which "dead" and "alive" are the properties that are probed one of these two outcomes will actually be found should not confuse us into believing that these results already had some kind of limbo existence before the measurement took place. Rather, the situation is simply that the pattern of phenomena is such that each time the situation represented by Ψ is present, subsequent measurements will result in "dead" or "living" with frequencies (approximately) fixed by Ψ.

6 Non-Humean alternatives.

Of course, one is not compelled to subscribe to empiricism. Once an indeterminstic theory involving a probability ***p*** as described above is proposed, one may feel it desirable to interpret this ***p*** in a realist fashion, for example as referring to a really existing disposition. But one should be aware that this adds to the metaphysical baggage of the theory, which should be justified by an increase in explanatory power or some other enhanced theoretical virtue. However, I think it is unclear how a realist interpretation of ***p*** as some kind of ontologically objective chance can help our understanding of what is going on in nature. Clearly, such an interpretation cannot change the empirical content and predictive power of the theory that is involved. But also with regard to explanations nothing seems to be gained by introducing ontologically real chance or real modalities, because the notion of a real modality is in need of explanation itself. For example, we do not really know what kind of things dispositions are, and it is obscure exactly how a disposition could take care of the task of arranging for the right relative frequencies to occur in long series of experiments. Indeed, the very content of the notion of disposition does not seem to go beyond "something responsible for the actual relative frequencies found in experiments". But if this is indeed the case, the introduction of dispositions is very similar to the attribution to classical particles of properties like “love for uniform motion” or “inertiality” in order to explain the law of inertia. Since the Scientific Revolution it has been generally accepted that *virtus dormitiva*-like properties of this kind – that *label* law-like behavior rather than explain it – should be shunned in science.

It is not right to object that realism with respect to unobservable entities occurs across the board in science, and that realism with respect to modalities is just another instance. The realist interpretation of not-directly observable entities like atoms and molecules arguably enhances the coherence of a theory, because it leads to a unifying account of the macroscopic and microscopic domains. Moreover, in the historical development of statistical mechanics realism with respect to submicroscopic particles has led to new predictions (e.g., fluctuation phenomena). Something similar does not appear to be in the cards in the case of chance, dispositions or propensities. Therefore, it is questionable whether reification of chance can be seen as being on a par with a realist stance with respect to unobservable (but actual!) entities.

Something similar can be said for the case of the reification of modalities in the form of possible worlds. The added metaphysical burden is enormous here, while the theoretical virtues that should compensate this remain obscure. In particular, although it is true that the notion that all possibilities are equally real and that there is no ontological distinction between the actual and the possible (the central tenet of the now popular many worlds interpretation) resonates well with the democracy of the terms making up a quantum mechanical superposition, this same symmetry makes it difficult to explain and even to accommodate the indeterministic character of the theory. If all possibilities are realized in the same way, it appears there can be no room for probability considerations. There have been interesting attempts to introduce such probabilities nevertheless, and even to derive them as a natural consequence of the many worlds scheme (see Wilson, 2006;

Wallace, forthcoming). The probabilities in these accounts are introduced as subjective uncertainties about the world one will end up in after a measurement; but uncertainties of this type remain difficult to square with the certainty that all worlds are to be considered as equally real and actual. There obviously exists a tension between on the one hand the reification of all possibilities and on the other hand the explanation of the indeterminism we encounter in the actual practice of physics. The derivations of the probabilistic rules of quantum mechanics that have been proposed in the literature accordingly posit the applicability of probabilistic concepts rather than deriving this applicability, and therefore do not dissolve the just-mentioned tension (cf. Dieks, 2007). It is consequently far from obvious whether the many worlds solve more conceptual problems than they raise, and their role in explaining our actual experience remains obscure.

7 Conclusion

The Humean view is a sober one: it recognizes only one world, namely our actual one. According to this view laws are descriptions of regularities exhibited by the events in the actual history of our universe. Laws supervene on what happens in our world, in the sense that they are the axioms of the theoretical system that best fits the pattern of actual events. This view harmonizes with the empiricist tradition according to which laws are descriptive instead of normative: they do not govern the world but merely *represent* the way the world is. By definition then, laws, theories and the concepts occurring in them deal only with what is actually the case. Modalities, like possibility and necessity, and counterfactual statements, are accordingly introduced *a posteriori*, as conceptual tools that enable us to deal theoretically with the actual world; they do not have an independent life of their own. This general empiricist viewpoint can be maintained in quantum mechanics no less than in classical physics. In fact, as we have seen, the Humean viewpoint provides a consistent and self-sufficient stance, whereas non-Humean alternatives introduce additional metaphysical commitments without clearly improving the explanatory capacities of the theory. The Humean point of view has therefore much to recommend itself.

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