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Leggett's Program in Philosophy of Science I: Experimental Metaphysics

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Abstract:
Some discussions and developments by John Bell in the context of the 'experimental metaphysics' originally coined by Shimony have motivated a series of experiments to test the standard formulation of quantum mechanics. These continuing efforts could be described as an active preliminary stage for future testable experiments potentially between the standard and Bohmian quantum mechanics.

1. Introduction

Some developments motivated by physicist John Bell led to a series of experiments to test the standard formulation of quantum mechanics. According to philosopher Hagar (2007), the continuing efforts embracing an area of both metaphysical philosophy and experimental physics can be well described as the "experimental metaphysics." He thinks it becomes an active preliminary stage for some future testable experiments between the standard and Bohmian quantum mechanics.

2. Experimental Metaphysics

Amit Hagar (2007) introduces the term 'experimental metaphysics.' The term was originally coined by Abner Shimony to designate 'the remarkable chain of events' that led from (Bohm and then) Bell's re-formalization of the EPR argument, through Bell's famous inequality theorem of EPR, to Aspect's experiments on Bell's theorem. Hagar argues that over the last 30 years of so, condensed-matter physics has matured enough to engage in a research program for the experimental metaphysics. In fact, Hagar and Shimony are not the only ones who acknowledge this chain of events. It is now well known among philosophers of science that Bell was a passionate follower of Bohm's ontological quantum mechanics and insisted on pursuing it as an alternative possible solution to the foundational problems of quantum mechanics. In Bell's mind, higher priorities should have been given to Bohmian corpuscular ontology and its dynamics. Bell was not satisfied with the mathematical simplicity or purity of the minimalists' view of quantum mechanics, the Copenhagen interpretation, which was put into one of the lowest ranked selection options in his decision making. In Giere's terminology, his satisfaction level was certainly higher than the selection option occupied by the bare mathematical formalism of the Copenhagen interpretation.

In his argument for the 'experimental metaphysics,' Hagar (2007), however, did not seem to realize the existence and successful application of the hydrodynamical approach, which has been a separate Bohmian research tradition from Bell's line of the Bohmian ontological developments emphasized by Hagar. That means the two Bohmian quantum mechanics cannot be grouped together in the same discussion of the experimental metaphysics, in a strict sense. However, a parallel argument could also be made in this context toward the hydrodynamical interpretation from Madelung's first idea of stochastic fluid dynamics to the quantum fluid dynamics of electrical engineering. Consequently, this hydrodynamical development can be another successful outcome of the 'experimental metaphysics,' which may already have passed a stage of metaphysics, so to speak, to become a practical stage of computational simulations. In what follows in this section, a particular attention will be paid to physicist Anthony Leggett in great detail and an eventual crucial experiment which could potentially emerge out of the experimental metaphysics.

Nowadays, more and more scientists, especially in experimental condensed matter physics and also in an emerging field of quantum information and computing theory, seem to pursue the foundational problems on quantum mechanics. To them, the issues related with the experimental metaphysics are located among the highest priority options of their ranked selections in their research. As one researcher in this context, Hagar (2007) notes Nobel laureate A. J. Leggett (1980) who aims to verify at a macroscopic level one of the characteristics of microscopic world, the macroscopic linear superposition states. The linear Schrödinger equation in the standard quantum mechanics naturally suggests a linear combination (superposition) of various quantum states as a general solution. For example, the interference patterns in the Young's double slit experiment are usually said to be an outcome of a superposition (and then a interference) of two different waves coming from the two slits.[1] The Schrödinger equation also predicts the same linear superposition states for everyday ordinary objects, assuming it is equally applicable to a

[1] However, a Bohmian particle actually goes through one of the slits following a definite trajectory of motion, guided by a wave (i.e. a pilot wave) through the quantum potential. For an ensemble of particles, thus, all the points in the screen made by the particles collectively form an interference pattern on the screen, although each one of the particle's motion is totally deterministic.

classical domain as a fundamental dynamical equation of physical world. However, macroscopic superposition has never been observed for ordinary objects; there is no linear combination of both dead and live cats (a.k.a. Schrödinger's cat) at a macroscopic level. Therefore, this has been a continuing source of debate.[2]

Apparently, this suggests several possible answers as follow; [1] the Schrödinger equation (and the standard quantum mechanics) is not applicable to a classical world, or [2] something happens in the process called measurement and the process is still unexplained in the standard quantum mechanics (a.k.a. the measurement problem), or [3] something is different at the macroscopic level; only one of the superposition states is already realized at the macroscopic level long before the measurement process is initiated, due to the interactions from the surrounding environment (a.k.a. the density matrix or the decoherence approach).

The first suggestion of [1] further implies that the Schrödinger equation may not be the fundamental equation of nature, not a very acceptable option to most physicists, though.

The second suggestion of [2] implies that before the measurement the cat is in fact in a state of both 'dead' and 'alive' at the same time, but the measurement process initiated by an outside observer somehow destroys the superposition, ending up producing only one state of either 'dead' or 'alive.' However, this raises a further question about the very nature of measurement, i.e. exactly when and how the process intervenes and operates between the object and the outside observer? Without this particular explanation as it is now, can the standard quantum mechanics really be as logically complete as the advocates always claim to be? Thus, this so-called Schrödinger's cat (and the measurement problem in general) has been a constant source of debate since the first standard foundation was established, and arguably still remains to be at the heart of the foundational problems.

Regarding the third suggestion of [3], it is widely accepted that some external environmental disturbances on quantum states should not be ignored. At the macro level, a quantum mechanical system will be interacting with the external environment, and as a result of the interaction with that environment, the relative phases of the (two or several) branches of the superposition will be scrambled up. Thus, from the superposition state of both a dead and live cat, only one state of either 'dead' or 'alive' is realized. So, long before the measurement process begins, macroscopic objects located in some surrounding environment (i.e. Schrödinger's cat in a box) will never exist in a superposition. This so-called 'density matrix' or 'decoherence' approach is currently an active area of research. Nonetheless, this approach still raises a further question, for example, about some possible transitional domain; exactly where in the transition from a quantum to a classical domain do the environmental effects start to appear and actively destroy the superposition? For example, in the Young's two-slit experiment, we already know that there is an interference pattern from a single photon, but no interference pattern was (and quite probably will not be) ever observed from a cat. Then, is there a sharp (or a range of) boundary in which the environmental interactions start to take over? More specifically, as we go up from a quantum to a classical domain, can we expect a sudden disappearance of an interference pattern from an intermediate or mesoscale objects (such as a very big molecule) in the Young's two-slit setting? And, in a case of interference, how precisely can we still make a quantitative measure for macroscopically distinct quantum states in those mesoscale objects? This is a particular line of inquiry Leggett seems to have as one of his prioritized selection options to test the foundational issues under the standard quantum mechanics.

Until recently, the foundation of quantum mechanics was not viewed as proper physics, rather viewed as something completely decoupled from experiment and also as a danger to one's career in physics, according to Leggett. However, according to Hagar (2007), some physicists now believe that the area of the measurement problem is becoming a legitimate field for experiments. Hagar, then, points out that Bohmian quantum mechanics is a viable alternative theory to the standard quantum mechanics, but it has been unfairly mocked as 'bad science' and 'degenerate research program.' Hagar (2007, p.916) continues, "NRQM [non-relativistic quantum mechanics] itself has quite deep foundational problems not only at its most basic level (i.e., the measurement problem), but also for example in its generalizations to both special and general relativity." Hagar (p.917) then concludes,

More than 30 years have passed, but […] we are still far from solving the measurement problem. Agreed, whether or not there exists a problem may depend on one's metaphysical predilection, and Leggett (2002) remarks, condensed-matter physicists continue to conduct beautiful experiments regardless of quantum-information theorists' opinions.

3. Squid

Leggett believes that condensed matter physics in the near future can become mature enough to test the standard quantum mechanics with respect to some alternative forms of it. Here, some technological instruments called the "super-conducting quantum interference devices" (SQUID) could potentailly play a major role for possible experimental tests on quantum mechanics. In particular, according to him, the SQUIDs could experimentally challenge "the measurement problem." Apparently, macroscopic objects do not display any superpositions of multiple quantum states although the linear superposition states have been routinely observed in microscopic objects. Various experimental efforts have been devoted to understand when and how the superposition states cease to exist during the transition from the micro to the macroscopic domain.

4. Leggett's Program

According to Leggett (2005), despite the spectacular success of quantum mechanics over the last 80 years in explaining phenomena observed at the atomic and subatomic level, the conceptual status of the theory is still a topic of lively controversy.[3]

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[2] In Bohmian quantum mechanics, however, each outcome of a quantum system (i.e. whether the cat is dead or live) is completely deterministic, although the outcome depends on the initial condition of the system (i.e. the initial position of a particle determines the fate of the cat). Therefore, there is no linear superposition of a dead and live cat in the first place, and the (measurement) problem is not an issue, here.

Most of his discussion centers on 'the famous (pseudo?) paradox', the quantum measurement problem. He classifies reactions to this problem into three broad classes:[4]

1. QM is complete and represents the physical world at all levels.[5]
2. QM is complete at all levels but only an empirically adequate calculation-recipe-book.
3. QM is neither complete nor empirically adequate at some level.

Leggett notes that the option (a) is widely believed by practicing physicists. He raises two questions regarding this option: (1) In a Young's double slit experiment with electrons, is it the case that each electron either went through slit 1 or slit 2? (2) In a case of Schrödinger's cat, is it the case that the cat realizes "cat alive" or "cat dead" in the absence of inspection by a human agent? A large majority of physicists who believe in the option (a) would answer "no" to the first question and "yes" to the second, according to Leggett.

What Leggett tries to show here is the inconsistency of attitudes (or, in his term, 'a gross logical fallacy') physicists routinely exercise toward two kinds of superposition; at the microscopic level, the presence of superposition is so essential (thus, not even arguable) in understanding quantum mechanics, but at the macroscopic level, physicists suddenly take for granted its absences on ordinary objects. So, at the macroscopic level, they simply interpret superposition as a mathematical measure of the probability of one outcome or the other, one of which is definitely realized for objects. In other words, the adherents of view (a) felt obliged to say that the pattern over the screen in the double-slit experiment can only be explained as the interference of two waves and that, at the microscopic level, it is impossible for a single electron to have an interference pattern from both slits. On the contrary, however, at the macroscopic level of the cat, they somehow try to regain an every day experience of a single cat, either "cat alive" or "cat dead", and no interference of both. The superposition has somehow gone away and no longer appears for the cat. According to this 'orthodox' argument, at the macroscopic level, a superposition is merely a measure of the probability of one outcome or the other.

Leggett, however, believes this 'orthodox' argument embodies a gross logical fallacy. The quantum mechanical formalism is in no way changed from the micro to the macro level, Leggett argues. So, it is simply illegitimate to adopt the option (a) for a microscopic level and the option (b) for a macroscopic level where QM is nothing but a calculation-recipe, designed to predict the probabilities of observed macroscopic outcomes. In Leggett's view, the term 'decoherence' (a.k.a. the density matrix approach) is simply an inconsistent attempt to exploit the vanishing of the interference in an every day object. Without any hesitation, physicists too quickly introduce the phenomenon of environmental coherence at a macroscopic level. So, the phenomenon of decoherence has been designed to made it impossible to see any effects of interference in a macroscopic object, although the standard quantum mechanics still predicts the effects. Leggett believes the phenomenon of decoherence is already experimentally 'refuted', at least, in some mesoscale objects. (This experimental refutation in which mesoscale objects still show a state of superposition will be discussed soon.)

For option (c), he admits that there have been a number of concrete proposals to modify the standard QM at some level. However, Leggett does not specifically take the Bohmian approach under this option. He certainly considers the GRWP (Ghirardi, Rimini, Weber and Pearle) spontaneous collapse theory as one of them (e.g. Pearle 1989; Pearle, Ring, Collar and Avignone 1999). Leggett puts this category of alternative theories under 'macrorealism.' The GRWP theory postulates the existence of a universal stochastic background of some 'noise.' The 'noise' itself is not from any quantum mechanical effects. The theory then adds the extra stochastic term of 'noise' to the standard, linear, time-dependent Schrödinger equation. The effect of this universal 'noise' background is to preserve neither linearity nor unitary nature of the Schrödinger equation, driving a quantum superposition of states into one of its branches. The noise effects also get larger for larger physical objects (for example, greater on cats than electrons). As a result, the superposition disappears (more quickly in macroscopic objects). Therefore, the stochastic background term of noise provides an account for the measurement process.

Now, suppose some experiments have been done on a quantum system. If the experimental outcome appears to conflict with the (standard) quantum mechanical predictions, then immediately a Duhem-Quine objection can be raised. For example, the system is so large and messy that the quantum mechanical prediction is impossible in the first place. A set of similar objections can go on as follow. The exact chemical composition of the system is unknown. The full details of the thermal vibrations of the system and the environment have been neglected. The surrounding blackbody radiation fields should also have been taken into account.

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[3] Strictly speaking, quantum mechanics has not been thoroughly tested in the mesoscale domain, and the semi-classical approach itself is not very spectacular either. The so-called 'quantum leap' between the quantum and the classical world may still be the major conceptual problem.

[4]His original text goes something like as follows.

1. Quantum mechanics is the complete truth about the physical world, at all levels, and describes an external reality.
2. QM is the complete truth (in a sense that it will always give reliable predictions concerning the nature of experiments) but describes no external reality.
3. QM is not the complete truth about the world; at some level between that of the atom and that of human consciousness, other non-quantum mechanical principles intervene.

In a usual philosophical context, however, his "the complete truth about the physical world" and "describes an external reality" should simply be read "complete" and "represents the physical world", respectively. So, it seems that a better exposition of his three different views should now be given as in the main text as (a), (b), and (c) rather than as (A) (B) and (C) in this appendix.

[5] This does not necessarily mean that QM is realistic and ontological as in the Bohmian sense about the physical world it represents.

Consequently, the system's full complexity is too computationally demanding at the present time. And so on and on. This is a familiar territory of the Duhem-Quine thesis. However, Leggett believes there is a way around this (Leggett 2007, p.107);

Could we start from the behavior in a regime where everyone agrees that QM is going to be excellently approximated by classical mechanics? Could we study experimentally the behavior of the system in that regime, work back from there not to the full microscopic Hamiltonian, but to enough of it so that we can now derive from that the quantum behavior? Rather surprisingly and serendipitously, it turns out that apparently the answer to that question is yes. As we will see, that program has been tested, quite severely in some cases, over the last 5 years, and it does appear to work.

Regarding the Duhem-Quine thesis, he appeals to some common background knowledge the condensed matter physics community has widely shared.[6] "We can use the experimentally observed dynamics in the classical regime to make unambiguous and parameter-free predictions of the quantum behavior" (Leggett 2002 p.431). The collection of experiments, well based on reliable modern technology, ranges from traditional Young's double slit experiments, conducted with C_{70} molecules (~ 1300 elementary particles) to SQUID(Super-conducting Quantum Interference Device) experiments in which the two superposed states involved ~ 10^{10} electrons behaving differently. Thus, according to him, the experiments are beginning to impose nontrivial empirical constraints.

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[6] He did not specifically mention the term of the Duhem-Quine thesis on any of his writings.