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Leggett's Program in Philosophy of Science II: Condensed Matter Physics

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Abstract:
Leggett believes that modern condensed matter physics could potentially become mature enough to test the limit on the validity of the standard quantum mechanics with respect to some alternative forms of it. Here, the super-conducting quantum interference devices (SQUID) could soon be sufficiently reliable enough to experimentally challenge, in particular, the measurement problem, although understanding their functions still requires a substantial effort for a generation of physicists to come. However, Leggett is quite confident that, in testing the limit on the validity of the standard quantum mechanics, the SQUIDs could avoid a situation of continuing debate involved in the experiments. Vlentini also believes that the standard quantum mechanics can be tested experimentally with respect to Bohmian quantum mechanics.

1. Josephson Junction

The SQUIDs(Super-conducting Quantum Interference Devices), consisting of two superconductors separated by thin insulating layers to form two parallel Josephson junctions, are very sensitive semiconductors used to measure extremely weak magnetic fields (i.e. small enough to measure the magnetic fields in living organisms), based on superconducting loops containing a Josephson junction. Here, a Josephson junction, a sort of gate, acts as a bottleneck in a superconducting 'bulk' ring.

A Josephson junction will allow electrons to pass but only with some difficulty. So, a large number (about 10^{10}) of electrons form two states of microamp-scale current, flowing clockwise and counter clockwise. The microscopic flows of current carried by those electrons then behave differently in one state from the other, and thus interference can occur between two states of current. People have looked for evidence of the superposition of these two states. They now see the two energy levels split into 'symmetric' and 'anti-symmetric' states with the usual quantum mechanical 'level repulsion' in spectroscopic measurements, instead of a classical case of one state or the other (for some earlier theoretical considerations, Leggett 1984). Consequently, the great sensitivity of the SQUID devices is associated with measuring changes in magnetic field or flux that is quantized in units. If a constant biasing current is maintained in the SQUID device, the measured voltage oscillates with the changes in the magnetic flux. Counting the oscillations allows you to evaluate the quantized magnetic flux change that has occurred.

In 1962, Josephson already proposed that his superconducting junction should show a zero-voltage current due to the tunneling (i.e. tunneling of the wavefunctions of the Cooper pairs through the junction). If two superconductors are separated by a thin insulating layer, then quantum mechanical tunneling can occur for the Cooper pairs without breaking up the pairs. This happens as the wavefunctions for the Cooper pairs on each side of the junction penetrating into the insulating region and "locking together" in phase. Under these conditions, a current will flow through the junction in the absence of an applied voltage (the DC Josephson effect). He also maintained that if a constant voltage were held across the junction, the subsequent current would be oscillating with a frequency depending on the voltage. Initially, these predictions were met with considerable skepticisms. However, these phenomena have since been observed experimentally many times. Nonetheless, there are many questions that need to be answered. What does it mean for a mathematical wavefunction to tunnel through the junction? What exactly is tunneling through it, then? Especially, understanding the processes under various different conditions is still one of the most interesting and debated topics of modern condensed matter physics and thus requires further investigations.

2. Leggett's Program

More specifically, using the effects from QIMDS (the quantum interference between macroscopically distinct states), Leggett has a vision of establishing some (sort of potentially crucial) experiments between the standard quantum mechanics and any non-standard theories from his option (c), the GRWP theory certainly being one. For example, his particular interest in QIMDS includes checking the double-slit interference effects from a macroscopic object ranging from a giant molecule to a cat, eventually. The interference pattern somehow disappears at a macroscopic level well before the level of 'a cat', as is well known from our everyday experience. Leggett then tries to find out exactly where and how this disappearance of the interference happens, and then to check whether the experiment is consistent with the predictions from (the standard or any alternative forms of) quantum mechanics. He is specific enough to suggest three stages of experiments (Leggett 2002). "Stage 1" conducts circumstantial tests to check the applicability (and the standard prescriptions) of quantum mechanics at the mesoscale and macroscopic level. "Stage 2" is a search for direct evidence for QIMDS (i.e. the double-slit interference pattern) in contexts of including some alternative forms of quantum mechanics. "Stage 3" conducts a (potentially 'crucial') experiment which is explicitly designed to see if the results predicted by the standard quantum mechanics are really observed, thereby discriminating various other alternative forms of quantum mechanics.

"Stage 1" of Leggett's tests has been primarily done on quantum devices such as Josephson junctions, as seen already, a key component of the superconducting quantum interference device (SQUID), and some other kinds of the SQUIDs throughout the 80s and 90s (Leggett 2007, p.107). The kind of phenomena involved in these devices are the macroscopic tunneling effects out of the device's meta-stable potential well, the incoherent macroscopic 'hopping' between two potential wells, and possibly the quantized energy level of those wells measured by their radiations. It turns out that some of the Hamiltonians from classical physics pretty well predict the quantum mechanical behavior of those devices. This shows not only the applicability of quantum mechanics to the macroscopic level, but also the soundness of the treatment of 'environmental dissipation', that is, the calculations from classical Hamiltonian can be used to infer enough about the quantum mechanical behavior of the devices.

"Stage 2" of the program is an explicit search for the quantum interference of macroscopically distinct states. The double slit experiments done at the mesoscale (molecular) level by Anton Zeilinger are a beautiful set of such experiments (Arndt *et al.* 1999). They have performed the experiments since the turn of the 21st century, with Carbon-60 (fullerene) molecules, containing about 1000 elementary particles of electrons and neutrons. There are two important features of this experiment, according to Leggett. First, the fullerene molecular beam does not need a special preparation or pre-arrangement to be 'monochromated in velocity' despite the rather large velocity spread in the incoming beam. The uncertainty of initial conditions due to the velocity spread could completely wash out the diffraction patterns in the Young's double slit type experiments. However, the original beam without any pre-arrangement is already monochromatic enough to have a recognizable interference pattern (see figure 2 of Arndt *et al.* 1999). The data are well fitted by a standard quantum mechanical calculation. Second, the ensemble of the molecular beam is produced in an oven at the temperature of as high as 900–1000 K. This is important because this situation is in a sharp contrast to any superconducting experiments that usually require some cryogenic temperature environment. This also means that the molecules are thermally excited, vibrating to produce the infrared radiation. They then strongly interact with the surrounding radiation field. Thus, the interaction of the system with its environment could act as a 'which way' detector, telling that a particular molecular went through slit 1 or slit 2. This will destroy the interference pattern. However, it turns out that the wavelength of the infrared photons each molecule emits or absorbs is too large (compared to the distance between the slits) to destroy the interference pattern. So, it cannot act as a 'which way' detector.

Another example of ongoing "Stage 2" program is on magnetic biomolecules done by Awschalom *et al*. (1992) with a set of molecules from the horse spleen ferritin. These uniform bio-molecules consist of a protein sheath ('apoferritin') surrounding a cavity of about 7.5 nm, which in the naturally occurring species is filled with an iron compound core of containing about 5000 Fe^{3+} ions. They are ferromagnetic and have two states in which the 5000 ion spins are aligned either up or down, giving us an opportunity to see an interference pattern between these two states. This is a program of measurements not just on a single molecule, but on an ensemble of molecules, an ensemble of 10^{23} different molecules. This experiment is still trying to see the quantum interference.

A third interesting case of Leggett's "Stage 2" program by a group at Aarhus (Julsgaard, Kozhekin, and Polzik 2001) is a quantum optical system, prepared by an 'entangling' optical pulse of two spatially separated clusters of cesium (Cs) gas, 10^{12} atoms in total. The original intent of the experiment was to look for the EPR Bell type of correlation, but it may also be in the future the experimental systems of choice in search for QIMDS.

Above all, currently both most ambitious and most systematic workhorse program in this "Stage 2" category has been on Josephson junctions. They were already key components of "Stage 1" program for the last 30 years or so. During this time a variety of painstaking experiments were conducted on aspects of the behavior of the devices such as 'tunneling out of a metastable well,' 'level quantization,' 'resonant activation,' and 'incoherent relaxation of a two-state configuration' etc. Those experiments now become sophisticated enough to level up to "Stage 2," according to Leggett.

These experiments complete "Stage 2" of Leggett's program and confirm the predictions of the standard quantum mechanics for the occurrence and effects of QIMDS. They also push tests of quantum mechanics to a (more macroscopic) level where it is more difficult to display the effects of QIMDS, due to the more severe effects of 'decoherence.' Therefore, according to him, the quantum devices such as the SQUIDs may be becoming part of commonly shared and well-established technology both in the condensed matter physics and in the electrical engineering community.[1] Leggett further seems to believe that the SQUIDs are now reliable enough to avoid the Duhem-Quine complications in his pursuit for the foundational issue on quantum mechanics.[2] He continues (Leggett 2002 p.438) as follows.

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[1] As discussed shortly earlier, in a Josephson junction of the SQUID, quantum mechanical tunneling of the wavefunctions (of the Cooper pairs) can occur. Physicists say the wavefuntions for the Cooper pairs on each side of the junction can penetrate into the layer of the junction and "lock together" in phase. However, although these phenomena are well known, there are many questions remained unexplained. Among them is "what exactly is tunneling through the junction?" Consequently, understanding the SQUID requires further investigations and some still have a skeptical attitude on the physical nature of its functions.

[2] This may seem too dependent on Leggett's own personal opinion as an active 'interested' participant of the on-going experiments. However, strictly speaking, he as a theoretician is not directly part of any on-going developments. Rather, he is just reclassifying these developments into his three categories of stages on his own pursuit for the foundational issues on quantum mechanics. The technical behavior of the SQUIDs is more or less well understood already. However, physicists do not usually

That these devices, in all cases based on the Josephson effect, are promising candidates for the observation of QIMDS has been clear for over 20 years now. Their advantages include that fact that the classical dynamics of the relevant macroscopic variable […] is believed to be excellently understood; that the 'intrinsic' dissipation associated with the motion of this variable can be made extremely weak (by condensed-matter standards, at least!) by going to temperatures which, while low by everyday standards, are nowadays routinely attainable; and that this variable can be addressed by electromagnetic means using technology already familiar to electrical engineers.

3. Testing Quantum Mechanics

Leggett then asks, what if a series of developments in the future as part of "Stage 3" experiments seem to show that QM is neither complete nor empirically adequate at some (mesoscale or macroscopic) level? He thinks, "the first reaction to that is that it has to be a bad experiment. Most people have sufficient confidence in QM that they will not believe that a single experiment has overthrown it" (Leggett 2007, p.114). But, what if the experiment is re-done in half a dozen different labs, and it still comes out negative? This then could potentially become a 'crucial' set of experiments on questioning the foundation of quantum mechanics as it is known of today? His answer is yes (Leggett 2007, p.114),

People will say, "You condensed matter physicists are just too naïve for words. You cannot possible have a good enough description of this messy bit of metal sitting on a lab bench, vibrating like mad, interacting with a radiation field", and so forth. […] That is a very sensible objection I think, but I have tried to emphasize we have been able to meet it to a fair degree over the last 20 years or so. We have been able to show that at least in the first two stages of the program, the prescription we gave for handling these entire unknown does actually seem to work. […] In fact, I think right now we should be worrying in exactly the same sense as with hindsight people in 1875 should have worried about the Gibbs paradox. With hindsight, the Gibbs paradox should have told people that classical mechanics must break at some scale. It could not tell you where or at what point [classical mechanics] would break down or in what way it would break down, but it could tell you that it must break down. I would claim that the same is true today with the formalism of QM: We do not know where it will break down or at what level. That it will break down, I would say, we have much more reason to believe.

Leggett's idea of potentially testing the limits on the validity of quantum mechanics has been clearly noticed by philosophers Hagar who denotes this line of inquiry as the experimental metaphysics in a pursuit for an alternative interpretation of quantum mechanics and a possible future experimental comparison between them. In this respect, the hydrodynamical interpretation of quantum mechanics could also be noticed as a potentially effective computational scheme evolved out of Bohm's metaphysics to become a research tradition in quantum chemistry and engineering.

Whether Leggett's program eventually ends up opening a path for some potentially crucial experiments between the standard and an alternative form of quantum mechanics remains to be seen in the future. It may be argued that one physicist's opinion cannot possibly be very significant in this matter. Science can of course change as a result of one person's new idea, but whether that particular idea will eventually convert a large group of minds or not is still a different question. In this respect, the particular view by Leggett is just as personal as others. However, only a very few actually argued for the limit on the validity of classical electrodynamics and classical mechanics at the turn of the 20th century, but the majority's view was simply not very reliable in the long run. The point is that the number of believers and followers does not guarantee their success of claim in history.

Here, Leggett's program is not necessarily mentioned as a prediction of the inevitable demise of quantum mechanics as we know it today. Rather, it is described in detail to emphasize the future potential of his program on questioning the foundation of the standard quantum mechanics by testing the limits on its validity. The kinds of experimental results Leggett hopes for about the macroscopic superposition would certainly be interesting even if his program fails to predict some potentially crucial experiments and the desired response of the physics community he currently envisions. In fact, crucial experiments are rarely conceived in advance. They are often noticed only in hindsight. Whether a particular set of experiments turn out to play a major role of testing or refuting a scientific theory can only be answered in a historical study of those developments, often long after their actual appearances in history.

4. Bohmian Quantum Mechanics

Interestingly, physicist Antony Valentini and H. Westman (2005) wants to devise a test that could separate the standard quantum mechanics from Bohmian (ontological) quantum mechanics. He first notes that taking a particular particle distribution of so-called 'the Born distribution (i.e. $\rho = |\Psi|^2$) as an initial condition is unjustifiable in a fundamentally deterministic theory such as Bohmian quantum mechanics. In Bohmian mechanics, this Born distribution should not be regarded as an axiom as in the standard quantum mechanics, but rather be dynamically generated or derived to emerge as a statistical feature of some underlying deterministic motions. This situation is similar to the thermal equilibrium as arising from a process of relaxation based on some underlying dynamics. (i.e. if $\rho = |\Psi|^2$ at any t, then it will always remain so under the Schrödinger equation, and $|\Psi|^2$ is only such a distribution with this particular time evolution dictated by the equation.) The relaxation $\rho \to |\Psi|^2$ arises naturally even from a grossly non-equilibrium particle distribution. However, small perturbations drive relaxation over long timescales. In an extreme case of no perturbations at all, an initial nonequilibrium ρ would remain static and far from the equilibrium. Valentini

interpret their functions as a means to investigate the foundational issues. It is Leggett's own view that the behavior of the devices can give us a valuable insight on the validity of quantum mechanics itself.

and Westman(2005) shows, for a free scalar field to model massless particles on expanding flat space of the inflationary universe, relaxation to equilibrium is expected to be suppressed. The suppression in the early universe leads to the detectable temperature fluctuations of the cosmic microwave background radiation in the long wavelength.

In Valentini's view, particles in the Universe today conform to the contingent rules of quantum mechanics called the Born rule because of the quantum equilibrium after the big bang. Immediately after the big bang, however, particles could have existed in states not allowed by the Born rules of the standard quantum mechanics but permitted in Bohmian ontological quantum mechanics. Therefore, "quantum physics is not fundamental; it's a theory of a particular equilibrium state and nothing more," says Valentini in an interview by *Nature News* on 15th May of 2008.[3] He continues in the interview, "to my mind, pilot-wave theory is crying out to us that quantum physics is a special case of a much wider physics, with many new possible phenomena that are just there waiting to be explored and tested experimentally."

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[3] The title of the news article is "Written in the skies: why quantum mechanics might be wrong: Observations of the cosmic microwave background might deal blow to theory."