

Probing quantum mechanics towards the everyday world: where do we stand?

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Abstract

I briefly examine the motivation for experiments designed to test quantum mechanics against an alternative, “common-sense” view of the everyday world which I denote “macrorealism”, and review how far existing experiments go towards settling the issue.

This paper is essentially a much condensed version of a review paper currently in press for *Journal of Physics: Condensed Matter*, [1] to which the reader is referred for details of the arguments given here, not all of which are self-contained.

1 Why should we look?

Let me start with a short quiz. (See note at end). I would like to ask the audience (a) how many of you believe that, in a typical Young’s slits experiment with electrons, each individual electron of the ensemble definitely passes through one slit or the other?

[Two people raised their hands, and there were a few abstentions].

Good. Now let me ask you a second question: How many of you believe that in Schrodinger's thought-experiment on the unfortunate cat (or rather ensemble of cats) each individual cat of the ensemble is definitely either dead or alive before we open the box and inspect her state?

[This time, about half the audience raised their hands, and again there were a few abstentions].

So, it appears that quite a large fraction of you would like to give one interpretation of the formalism of quantum mechanics at the microscopic level, and a quite different one at the macroscopic level. Is this legitimate? As always, I hear people murmur the dreaded word "decoherence". But I claim that this is a major red herring. At the microscopic level, most of you would like to give an interpretation of the quantum formalism which, whatever positive statements you might want to attach to it, at least has the negative feature that it does not allow each electron to choose one alternative or the other. The evidence which forces you to embrace this interpretation is the well-verified phenomenon of interference between the two paths. Now when we go from the level of the electron to that of the cat, what has changed? Certainly the formalism of quantum mechanics itself has not changed one bit (at least if we assume that QM is the whole truth about the world; more on that in a moment). All that the standard "decoherence" arguments tell us is that, at least in a typical and not specially designed experimental situation, by the time we get up to the level of the cat the possibility of observing interference between (e.g.) the living and dead states of the cat is essentially zero. But so what? Does the vanishing of the evidence permit a complete reinterpretation of the meaning of the formalism? I do not believe so. In fact, in my view there are really only two interpretations of the quantum formalism which are internally consistent (most others can either be regarded as variants of one or the other of these, or fall foul of the above argument): One is the what I call the "extreme statistical" interpretation (see e.g. ref.[2]), according to which no physical meaning should be attached to the QM formalism either at the microscopic or at the macroscopic level, but it should be regarded as literally nothing more than a formal calculus whose sole purpose is to calculate the probabilities of various possible directly observed outcomes at the macrolevel (e.g. "cat alive" or "cat dead"). I believe this interpretation is indeed free of internal inconsistencies; however, my experience is that most physicists, and particularly most experimentalists, find it very difficult to take it seriously (as your second vote showed: if you really believe the "extreme statistical" interpretation, then my second question was essentially meaningless and you should have voted "no", or at best abstained!).

In the extreme statistical interpretation, the symbols of QM, in particular the probability amplitudes, correspond to nothing at all in the real world, neither at the microscopic nor at the macroscopic level. The only consistent alternative,

in my opinion, is to attribute to the amplitudes physical significance at both the microscopic and the macroscopic levels. If one does this one is apparently forced to embrace some version of the “relative-state” or “many-universes” interpretation. While the formal theorems underlying this interpretation are unexceptionable, the metaphysics seems to me total nonsense: when an advocate of this interpretation claims that the unobserved branches of the wave function correspond to worlds which are “equally real”, these words sound like English, but for me, at least, they are complete gibberish.

So it seems to me that once we have decided that quantum mechanics is the whole truth about the physical universe, both at the level of electrons and that of cats, there simply is no interpretation of the formalism which is both internally consistent and (to most physicists) psychologically acceptable. Where does that leave us? The only way out is to challenge the premise of the argument, that is to stand back and ask: Is it in fact obvious that QM is the whole truth about the physical universe? In particular, does it follow that because QM describes brilliantly the behavior of electrons and atoms, and everyday matter is composed of electrons and atoms, then QM must describe, in all respects, the behavior of everyday matter? To question this almost universal assumption may no doubt be labelled eccentric, but it offends no laws of logic.

2 What are we looking for?

Once we have decided to take seriously the possibility that QM may not be the whole truth about the physical universe, and in particular that new laws of physics may come into play as we go from the atomic to the everyday level, then at least two approaches are possible. One is to try to conjecture a priori the correct form of the supervening laws and to work out under what circumstances predictions based on them should differ from the standard quantum-mechanical ones. A number of people have tried to develop such specific alternative theories; the most sophisticated and best-developed to date is that associated with the names of Ghirardi, Rimini Weber and Pearle (“GRWP”) (see e.g. ref. [3]). In this theory the mechanism which is responsible for the realization of a definite outcome is a sort of universal noise background which is not itself subject to the laws of QM, and the “trigger” for the reduction is a sufficiently large value of the difference in the center-of-mass coordinate of a large object in the two branches of the wave function. Such an approach has the advantage of making specific predictions about the point at which standard QM should break down; the down side is that it is clearly essential to have guessed correctly the specific features of the situation which will trigger the breakdown.

An alternative approach is not to commit oneself more than one has to on this point, but rather to try to make a very general hypothesis, based on our “common sense” notions about the world at the everyday level, whose pre-

dictions can be shown to be, under appropriate conditions, incompatible with those of QM. Let us attempt a preliminary formulation of such a hypothesis, which I will call “macroscopic realism” or macrorealism (MR) for short, by making the following assertion: Whenever a macroscopic body has available to it two (or more) macroscopically distinct states, then at “almost all” times it is definitely in one or the other. (The “almost all” is a technicality which is necessary to allow for the possibility of finite transition times). The above assertion is independent of whether or not the state of the system is observed.

We will see in section 4 that the hypothesis of MR, when so defined and augmented by a couple of fairly innocuous-looking supplementary assumptions, does indeed make experimental predictions incompatible with those of standard QM. Irrespective of this, it is clear that it is in direct conflict with the QM notion of a superposition of the two states in question, at least so long as we interpret the latter in the way which we were compelled to do at the microlevel. Thus, any confirmation of the predictions of QM based on the existence of such a superposition, while not necessarily formally a refutation of the MR hypothesis, could be regarded as circumstantial evidence against it. Generally speaking, as in the single-electron (Young’s-slits) case, the evidence for the superposition is some form of interference between its branches. Thus, we are led to look for the existence of quantum interference of macroscopically distinct states (“QIMDS”).

In trying to assess how far existing and projected experiments go in this direction, a major headache, historically speaking, has been the question of what exactly we mean by “macroscopically distinct”. Basically, it seems to me that our definition of this concept should reflect our intuitive feeling that there is a qualitative difference between a superposition of two states of an electron corresponding (say) to transit through one hole or the other, and the superposition of the dead and alive states of the cat. In other words, we seek a quantitative measure of the concept which for want of a better name we might call “Schrodinger’s-cattiness”. I want to emphasize that this is a very subjective question; I do not think it matters very much how we decide it, provided that the outcome is not such as to make the search for QIMDS pointless by definition.

My own tentative definition involves the conjunction of two criteria. The first is what I call “extensive difference”: there should exist some extensive variable whose difference in the two states compared is “large” on the scale of typical atomic quantities. One possible example, which makes contact with the GRWP theory, would be the position of the center of mass; but I see no particular reason to give this quantity priority over other extensive variables such as e.g. the magnetic moment.

As formulated this criterion is not sufficient, since it would allow e.g. the intermediate states of a neutron in an interferometer to count as “macroscopically distinct”, something which does not seem (at least to me) to reflect our intuitive notion of “Schrodinger’s-cattiness”. I therefore propose to augment it

with a second criterion which I have christened [4] “disconnectivity”, which is basically a measure of the number of “elementary” particles which are behaving differently in the two branches.

Although the word is no doubt unfamiliar, the basic concept defined in ref. [4] is actually very close to the notion of “degree of entanglement” as developed in the more recent context of quantum information. In fact, it would almost certainly be possible to use modern quantum-information-theoretic ideas to give a more elegant quantitative definition than the rather awkward one originally given in the above reference. In any case, I want to stress that the precise quantitative definition is not to mind of any great importance; what matters is the qualitative idea that not one but a large number of elementary constituents are behaving quite differently in the two branches of the superposition. An important question which may be raised [5], however, is whether this “cooperation” should be achieved in the absence of appreciable interaction between the constituents (as it is in a typical EPR-type situation, for example). For present purposes I shall assume that this is not an essential ingredient, but it should be noted that if we take the opposite view then some of the experiments mentioned in the next section would be disqualified.

3 What have we seen so far?

In the context of the discussion in the last section, we may distinguish three stages of the experimental program ¹:

At stage I, we produce what theory says is a quantum superposition of macroscopically distinct states, but the actual experimental data are equally compatible with a classical mixture.

At stage II, we “demonstrate” the existence of a superposition by performing experiments which, if interpreted according to the standard prescriptions of QM, exclude a “mixture” interpretation.

Finally, stage III is an experiment or experiments which, irrespective of interpretation, must (if it verifies the quantum predictions) exclude the hypothesis of macrorealism.

Stage-I experiments are actually rather commonplace—a typical example of such an experiment is one in which a set of radioactive particles is monitored by a Geiger counter; according to QM, the state of the universe after some time corresponds to a quantum superposition of many different macroscopically distinct states of the counter and the associated recording apparatus. However, it is entirely obvious that all experimental results could equally well be explained by a classical probabilistic model. A rather spectacular variant of this kind of

¹*Note that “stage I” below plays a different role from the “stage 1” described in the J.Phys.C review.

case is the famous MIT interference experiment [6] with Bose condensates (if we believe QM, the initial “Fock” state of the system is a quantum superposition, rather than a mixture, of the states corresponding to the various fringe offsets actually observed).

I will devote the remainder of this section to recent experiments which correspond to stage II of the program, with the definition of “macroscopically distinct” given in the last section (or something close to it). Thus, I will not discuss the very elegant ENS experiments on cavity QED [7] nor the equally elegant ones of Nakamura and co-workers [8] on the “single-Cooper-pair box”, since contrary to a surprisingly widespread misconception neither of these corresponds to a large value of disconnectivity.

The main candidate systems which have been actually used to date for stage-II experiments are (1) molecules in free space, (2) magnetic biomolecules (3) quantum-optical systems and (4) Josephson devices. I will give a very brief summary of the situation with respect to each of these systems; for a more detailed discussion, see ref.[1]. Although I shall usually note explicitly the (order of magnitude of the) disconnectivity realized, that of the extensive difference is in each case comparable (not surprisingly, since all the systems involved are complex many-particle systems).

Although experiments on Young’s-slits type diffraction experiments in free space are almost as old as QM itself, until recently the most complex objects which it had proved possible to diffract were small clusters of hydrogen and helium atoms, with disconnectivity no more than about 30. Very recently, the Vienna group has made [9] a spectacular advance on this front by demonstrating the diffraction of C-60 molecules, a case which corresponds to a disconnectivity of more than a thousand. Two particularly interesting features of this experiment are that the authors were able to use a molecular beam which, while not precisely thermal, was not far from it, and that contrary to what one might at first sight perhaps think, decoherence due to the interaction of the intramolecular modes with the blackbody radiation field is not sufficient to destroy the effects of interference.

The most striking work on magnetic biomolecules is the series of experiments by Awschalom and co-workers on horse spleen ferritin; see for example ref.[10]. In these experiments what was detected was a resonance in the absorption and noise spectra of the molecules in an rf magnetic field, with a frequency which was of the order of 1MHz and appeared to scale exponentially with the size of the magnetic core. This resonance is interpreted by the authors of the experiments as follows: The ferritin has a core of up to 5000 iron atoms, which are coupled mostly antiferromagnetically but with a residual ferromagnetic moment of a few hundred Bohr magnetons. Since the symmetry of the core is biaxial, it is believed that the groundstate of the spin system is classically degenerate in zero external field and can be split by quantum tunnelling into even- and odd-

parity superpositions. The observed resonance is then interpreted as due to transitions between the even-parity groundstate and the odd-parity low-lying excited state. While this interpretation seems to account for several aspects of the data, and in particular for the exponential dependence of the frequency on core size, a number of criticisms have been raised in the literature, and the situation is still controversial. If it is correct, then the degree of disconnectivity would be of the order of several thousand.

In the area of quantum optics, while proposals for stage-II type experiments abound in the theoretical literature, until recently most experiments which had actually been performed involved only small numbers (~ 10) of atoms or photons. Very recently, a group at Aarhus [11] has achieved by optical means a spectacular degree of entanglement of the spins of two macroscopic samples of alkali atoms. Although the main interest in this experiment was the “nonlocal” aspect, the situation achieved does in fact have a fairly large value of disconnectivity, namely about 10^6 . (The total number of atoms in each sample is of order 10^{12} , but the disconnectivity is by any reasonable definition of the order of the square root of this).

The “workhorse” system for the program envisaged in this lecture, and the one where the most spectacular results to date have been achieved, is the system formed by a superconducting device based on the Josephson effect, such as an r.f. SQUID. There is a long history of experimental work on this system, which has shown inter alia that, contrary to many people’s zeroth-order guess, decoherence in them is not necessarily so severe as to preclude the possibility of stage-II experiments. In particular, it was shown that it would make sense to try to detect quantum superpositions of states in which the collective electron current is circulating clockwise (L) and counterclockwise (R) respectively, in each case with a magnitude of the order of a few microamps. Indeed, in the past couple of years two groups, at SUNY Stony Brook and Delft (Netherlands) have independently conducted such experiments [12,13], in which they looked for the avoided crossing of the groundstate and first excited state (or in the SUNY case a corresponding pair of excited states), which are just such quantum superpositions. In each case, had the system been described by a classical mixture of the L and R, the frequency of resonantly absorbed microwave radiation should have gone to zero at the crossing point where L and R are classically degenerate; that the frequency in fact bottomed out at a finite value at this point (“avoided crossing”) is evidence, at least circumstantial, for the existence of the superposition. The disconnectivity in this case is of order 10^9 , several orders of magnitude larger than in the other experiments mentioned (and approaching half way, on a logarithmic scale, between the atom and the real-life cat!).

4 Where do we go from here?

The most obvious extension of the experiments described in the last sections would be simply in the direction of higher values of the two parameters which I have identified as together embodying the concept of “macroscopic distinctness”, namely “extensive difference” and “disconnectivity”. Such an extension should certainly be possible, at least in principle. For example, it has been suggested that one might eventually try to diffract a small virus; similarly, there seem to be no obvious a priori limitations on the size of the loop (and hence effectively the degree of disconnectivity) usable in SQUID experiments of the SUNY-Delft type.

However, on reflection it is not clear that this would necessarily be the optimum direction in which to try to push the experiments. In fact, now that one has verified that “macroscopic distinctness” as such, at least at the level exemplified by SQUIDS, does not lead to a breakdown of QM, it may be more interesting to look at other “dimensions” which in some sense measure the extent to which we are approaching the everyday world. For example, rather than simply trying to superpose two different center-of-mass states of a virus as is done in the standard diffraction experiment, it might be more informative to try to superpose two states of that virus which correspond to different biological functionality. In a similar vein a number of people have suggested trying to look for superposition of functionally different states of the rhodopsin molecule which plays a central role in human vision. It should be pointed out that for such experiments to be fully meaningful in the present context, they would need to be carried out under biologically realistic conditions and in particular at room temperature, and the effects of decoherence under such conditions are expected to be severe in the extreme, so that the prospects for seeing interference are at first sight very dim. However, we may take some consolation from the fact that the SQUID experiments described in the last section, when originally proposed twenty years ago, evoked a similar degree of scepticism!

A second possible direction [5] is to define the concept of “disconnectivity” more severely, so that for instance it would entail that the various “elementary” particles involved do not interact appreciably. (In the case of the real-life cat, it is true that while some of the particles involved (e.g. the atoms of the cat’s body) maintain their mutual interaction throughout, others such as the black-body photons which interact with the cat essentially “go off to infinity” and so reflect the kind of nonlocality which is at the core of modern quantum information theory). Whether such a constraint would make further progress in this direction in practice impossible is a delicate issue which deserves further thought.

Be that as it may, my own view is that the most important direction to go in the near future is from “stage II” to “stage III”. It is impossible to

overemphasize the fact that even the most spectacular of the existing stage-II experiments, while certainly adequately confirming the predictions of standard quantum mechanics and thereby perhaps making alternative hypotheses less psychologically attractive, do not exclude the hypothesis of macrorealism. (If it seems unthinkable that quantum mechanics could get all this right and yet not be the ultimate truth, think about the status of classical physics in say 1880!) .Thus it is of the utmost importance to proceed to stage III,that is,to do an experiment which,if it indeed comes out as predicted by QM, will at the same time definitively refute the whole class of macrorealistic theories.

To make such an experiment possible, one has to supplement the basic definition of a “macrorealistic” theory given in section 2 with a couple of auxiliary assumptions, namely “noninvasive measurability” (NIM) and “induction”; I refer to ref.[14] for a detailed discussion, but note that NIM is essentially the “common-sense” hypothesis that if you look for something in a given place and do not find it, you could not have affected its subsequent behavior,while induction is simply our usual concept of a unidirectional arrow of causality in time. With these supplementary assumptions it turns out that for a simple two-state system such as the SQUID (where the two states are the macroscopically distinct states L and R introduced above) one can prove an analog of Bell’s theorem,but with polarizer setting replaced by time. That is, there exists a combination of experimentally measurable two-time correlations of the operator whose eigenstates are L and R,such that any theory of the MR class must predict it to be less than or equal to 2. On the other hand, (again just as in the Bell’s theorem case), under idealized conditions QM predicts this same combination to have the value $2^{3/2}$. Thus, under idealized conditions one could use a measurement of the quantity in question to discriminate unambiguously between QM and the class of MR theories.

The crunch question is, of course,how far the QM prediction will differ from the “ideal” value $2^{3/2}$ under realistic conditions,when all relevant sources of decoherence are taken into account? The answer is actually quite encouraging: while one certainly does not expect the value to be very close to the ideal limit, it will still exceed the MR upper bound of 2 for quite small values of the Q-factor of the two-state oscillations- certainly a value much smaller than that necessary in order to use such systems as practical qubits, a possibility now being taken very seriously in many laboratories. Until very recently it was not clear that even this rather weak condition could be satisfied (it probably was not in the SUNY or Delft experiments). However,as this goes to press there is an exciting report [15] that a “hybrid charge-flux qubit” (a circuit which for all intents and purposes seems to be equivalent in the present context to the SUNY and Delft ones) has attained a Q-factor larger than 10^4 . This would seem to make progress to stage III very definitely a practical proposition, and I am hopeful that the relevant experiments will be done within the next decade.

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Note added: In my actual lecture in Goteborg,I asked the audience the two questions about the interpretation of quantum mechanics in the discussion period rather than at the beginning of the talk. However, the "votes" were approximately as quoted here.

5 References

1. Leggett, A.J., in preparation for submission to Journal of Physics:Condensed Matter
2. Ballentine, L.E., Revs. Mod. Phys. **42**, 358 (1970).
3. Pearle, P., Phys. Rev. A **39**, 2277 (1989).
4. Leggett, A.J., Prog. Theor. Phys. supp. no. **69**, 80 (1980).
5. Devoret, M.H., private communication
6. Andrews, M.R., Townsend, C.G., Miesner, H-J., Durfee, D.S., Kurn, D.M., and Ketterle, W., Science **275**, 637 (1997).
7. Brune, M., Hagley, E., Dreyer, J., Maitre, X., Maali, A., Wunderlich, C., Raimond, J-M., and Haroche, S., Phys. Rev. Letters **77**, 4887 (1996).
8. Nakamura, Y., Pashkin, Yu. A., and Tsai, J.S., Nature **398**, 786 (1999).
9. Arndt, M., Nairz, O., Vos-Andreae, J., Keller, C., van der Zouw, G., and Zeilinger, A., Nature **401**, 680 (1999).
10. Awschalom, D.D., Smyth, J.F., Grinstein, G., Di Vincenzo, D.P., and Loss, D., Phys. Rev. Letters **68**, 3042 (1992).
11. Julsgaard,B., Kozhekin, A., and Polzik, E.S., Nature **41**,400 (2001)
12. Friedman, J.R., Patel, V., Chen, W., Tolpygo, S.K., and Lukens, J.E., Nature **406**,43 (2000).
13. van der Wal, C.H., ter Haar, A.C.J., Wilhelm, F.K., Schouten, R.N., Harmans, C.J.P.M., Orlando, T.P., Lloyd, S., and Mooij, J.E., Science **290**,773 (2000).
14. Leggett, A. J., in "Time's Arrows Today", ed. Steven F. Savitt, Cambridge University Press, 1995.
15. Vion, D., Aassime, A., Cottet, A., Joyez, P., Pothier, H., Urbina, C., Esteve, D., and Devoret, M.H. submitted to Science, Dec.2001.