The quantum measurement problem, the role of the observer and the conditions of knowing

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Since the beginning of quantum theory physicists have felt that the classical appearance of the world had something to do with the role of the observer. That is indeed so, but not because the observer's consciousness collapses the wave function, as it was once hypothesized. The classical appearance of the world is connected with the conditions of our knowing in general. The world appears classical to us because, in order to know, we have to be entangled with what we know.

Superpositions and mixtures

It is generally recognized among physicists that on a microscopic scale (the size of molecules, atoms and smaller systems) the world behaves very differently from the macroscopic world we are accustomed to. The microscopic world is a strange landscape, hard to visualize, because the concepts we have evolved to represent objects are appropriate only for things roughly of our order of magnitude, neither too much smaller nor too much larger. Those concepts do not apply on a microscopic scale. Quantum physics, the physics of the microscopic world, had to develop entirely new notions, that do not have equivalents in our everyday language.

One of these strange notions is the idea of *superposition*. In the quantum world a proposition and its opposite, "A" and "not A", are not mutually exclusive. Beside "A" and "not A", quantum physics takes into consideration various superpositions of "A" and "not A", in which both possibilities coexist, so to speak, *in potentia* and one or the other is actualized only when an observation is made on the system. *After the observation* the state of the system is either "A" or "not A", but it is *a priori unpredictable* which one will manifest. *Intrinsically unpredictable*: this kind of unpredictability is not the familiar kind, which we could describe as "this is unpredictable because we don't have enough information to predict". It is a radical kind of unpredictability, describable as "even with maximum information about the system, this is still unpredictable". (How we have been led to consider this different notion of unpredictability is a very interesting topic, but I am not going into it here because it would lead us too far from our subject. You will have to just believe me when I say that in the microscopic world we have to include, beside the ordinary kind of unpredictability, this more radical kind.)

So, in a superposition "A" and "not A" coexist, the system sits astride both possibilities. But the superposition doesn't simply tell us that the outcome of an observation performed on the system can be either "A" or "not A": it is a bit more specific than that. To each possibility it assigns a coefficient, a complex number which determines its probability of actualizing.

Let me explain this with an example. Let's imagine that we have a "quantum coin". If we toss an ordinary coin (a "classical coin"), it will land as either head or tail. If we don't look at it (let's say we immediately cover it up with a piece of cloth), we won't know whether it's head or tail – but still we can confidently say that it is either one or the other. Not so with a "quantum coin". The list of the possible states of the the coin does not consist just of head and tail, but includes all the superpositions

$$\alpha \times \text{head} + \beta \times \text{tail}, \qquad (1)$$

where α and β are complex numbers such that $|\alpha|^2$ is the probability of seeing a head when we look at the coin and $|\beta|^2$ is the probability of seeing a tail when we look at the coin. ($|z|^2$ is the modulus square of a complex number z and is always a positive real number. But don't worry if you don't know what's a complex number. If you know a little bit of math this notation will help you to get a firmer grasp on the argument that follows. But if you don't, you can still grasp the essential. Don't be frightened and persevere.) In math probabilities are positive numbers in the interval between zero and one: zero probability means that something doesn't happen at all, and probability one means that it is certain to happen. Since when we look at the coin we are bound to see either a head or a tail, the sum of the probabilities must be equal to one: $|\alpha|^2 + |\beta|^2 = 1$.

Notice also that when $\beta = 0$ the superposition (1) represents a quantum coin which is certainly a head and when $\alpha = 0$ it represents a quantum coin which is certainly a tail. So "pure heads" and "pure tails" are particular cases of the superposition (1). The general case of (1), on the other hand, is neither head nor tail (or we could say that it is both).

As I said, it is not essential to follow the math. The only thing that it is important to grasp is how the states of a quantum coin differ from the familiar states of an ordinary coin. The two have one thing in common: when we look at the coin, be it quantum or classic, we are bound to see either a head or a tail. But *what is implied in the act of looking* is very different in the two cases. We can consistently assume that a classical coin is already a head or a tail before we look. Our looking doesn't change anything as far as the coin is concerned: it only changes the amount of information in our head. About a quantum coin, on the other hand, we *cannot* consistently assume that it is already a head or a tail before we look. A quantum coin *becomes* a head or a tail when we look. Its state changes when we observe it. Observation has a far more active role in quantum physics than in classical physics.

This is subtle, so it's worth describing more precisely. As I said, when a quantum coin is in the state (1) it is in principle unpredictable whether a head or a tail will show up. A single experiment, therefore, is not very significant. Quantum physics focuses on statistics, it deals with large numbers of trials. Therefore we have to develop a language to talk about large numbers of trials. This is the language of "sets". A set is a collection or group of things. Here we shall consider sets of identical systems (e.g. sets of quantum coins or classical coins) in various states, We shall denote sets by putting curly brackets around the state or the states of the systems included in the set. E.g., a set of coins which are all heads will be denoted by

{head}.

When a set is a mixture of systems in different states, we shall separate the various states with semicolons, and each state will be preceded by its proportion. E.g., a set of coins which are half heads and half tails will be written

{½, head ; ½, tail}.

Then, if we have a set of quantum coins all prepared in the state (1), we shall represent this as

$$\{\alpha \times \text{head} + \beta \times \text{tail}\}. \qquad (2)$$

Now suppose we look at them one by one. We see head in a fraction $|\alpha|^2$ of the cases and tail in a fraction $|\beta|^2$ of the cases. At the end we have in front of us two subsets, heads and tails. We mix them up and we cover them, so that we no longer know whether an individual coin is a head or a tail. At this point we have produced a mixed set, in which heads and tails are present in the proportions $|\alpha|^2$ and $|\beta|^2$, a set we can write

$$\{|\alpha|^2, \text{head} ; |\beta|^2, \text{tail}\}. \qquad (3)$$

This set is of course identical to one of classical coins, of which we have turned a fraction $|\alpha|^2$ head up and a fraction $|\beta|^2$ tail up, mixing them and covering them afterwards. Looking at each coin therefore turns the quantum superposition (2) into the classical mixture (3).

We are now in a position to define more precisely in which sense what is implied in the act of observation in quantum physics is different from the classical case. Looking at a coin in the classical mixture set (3) in order to find out whether it's a head or a tail doesn't change anything in the coin itself. It simply amounts to finding out whether the coin belongs to the heads subset or to the tails subset. That's what is called a mere increase in information. Not so with the quantum superposition (2). In (2) there are no subsets, and finding a head or a tail is no mere increase in information. It actually changes the state of the coin.

There is a whole lot of experimental evidence that the microscopic world cannot be described in terms of classical mixtures. It requires the introduction of the specifically quantum notion of superposition. Atoms and molecules and smaller things are not either-or creatures, they are and-and creatures. They are like quantum coins, not like classical coins.

As a paradox, Erwyn Schrödinger once imagined a famous quantum thought-experiment. Instead of a quantum coin he had a cat and instead of "head" and "tail" he had "alive" and "dead". The experiment would cause the cat to end up in a superposed state of life and death. This was a kind of provocation, something like: if we consistently follow through with the notions of quantum physics, look where we get.

Now we are confronted with a question. In the macroscopic world we inhabit we never see coins being simultaneously head and tail or cats being simultaneously dead and alive. Yet we have good reasons to believe that cats and coins are made of atoms and molecules and that atoms and molecules behave in the strange way that has just been described. The question then is: how does the well-behaved world of cats and coins arise out of the weird world of atoms and molecules?

The quantum measurement problem

This question becomes particularly critical when we analyze in detail what happens in a "quantum measurement", i.e. in the process of observation of a quantum system.

We have no way to observe microscopic systems directly through our senses. The observation always involves a process of amplification. A chain of correlated interactions takes place, starting at the atom and molecule level (or smaller), with the observed system interacting with some microscopic systems in our measuring apparatus and changing their state. These microscopic systems in turn interact with a larger number of microscopic systems, also changing their state, and these with many more – and so on, until the process reaches macroscopic proportions and becomes visible to our eyes.

This chain of interactions involved in a measurement is called a "von Neumann chain" (from John von Neumann, who first mathematically described it). The essential requirement, of course, is the fact that the changes transmitted along the chain should all be correlated, so that they carry information from the microscopic eventually all the way to the macroscopic level.

To see what this means, let's build a little model of a quantum measurement in terms of quantum coins. We shall consider a very simplified von Neumann chain, consisting at one end of a quantum coin (microscopic observed system, or "object system") and at the other end of a measuring apparatus which has only three possible states: NEUTRAL, HEAD and TAIL. NEUTRAL is the state of the apparatus before the measurement. HEAD is the state of the apparatus when it has registered the "head" result, and TAIL is the state of the apparatus when it has registered the "tail" result.

Then the above correlation requirement simply translates into the following. If the initial state of the observed system is head, i.e. the initial state of the whole system object + apparatus is "headNEUTRAL", the interaction must produce the endstate "headHEAD":

headNEUTRAL $\rightarrow$ headHEAD.

If the initial state of the observed system is tail, i.e. the initial state of the system object + apparatus is "tailNEUTRAL", the interaction must produce the endstate "tailTAIL":

tailNEUTRAL $\rightarrow$ tailTAIL.

What happens then if the initial state of the quantum coin is the superposition (1), i.e. the initial state of the system object + apparatus is

$$\alpha \times \text{headNEUTRAL} + \beta \times \text{tailNEUTRAL?} \qquad (4)$$

A fundamental property of the equations of quantum physics is that they are linear, i.e. if we know what happens to each term of a superposition, we know what happens to the whole superposition. In particular the superposition (4) turns into

$$\alpha \times \text{headHEAD} + \beta \times \text{tailTAIL}. \qquad (5)$$

To look at this in statistical terms, i.e. in the language of sets, we only need to wrap curly brackets around (4) and (5):

$$\{\alpha \times \text{headNEUTRAL} + \beta \times \text{tailNEUTRAL}\} \rightarrow \{\alpha \times \text{headHEAD} + \beta \times \text{tailTAIL}\} \qquad (6)$$

The trouble is that this does not resemble at all the result we expect, the result corresponding to laboratory experience, which, as previously mentioned, is that the set separates into two subsets, heads and tails, with probabilities $|\alpha|^2$ and $|\beta|^2$ respectively, a situation that would be described by the classical mixture

$$\{|\alpha|^2, \text{headHEAD} ; |\beta|^2, \text{tailTAIL}\}. \qquad (7)$$

The root cause of the trouble is the linearity of the equations of quantum physics: linear equations are incapable of generating a transition from a superposition to a mixture. They can only turn a superposition into another superposition.

It is interesting to notice here also another characteristics of the superposition (6). It involves the observed system and the measuring apparatus in such a way that their states are inextricably connected: it is what is called an *entangled* state. When two systems are thus entangled, they are like psycho twins, even if they move apart, they are never really separate: whatever is done to one of them instantly affects the other, however far it may be. This is one of the strangest and most powerful notions of quantum physics (it is the notion which at the base of quantum teleportation and the hopes for quantum computing).

Let's take stock of where we have got so far. When we try to describe a measurement process by applying the equations of quantum physics we get a strange result: instead of the classical mixture (7) we get the entangled superposition (6): Schrödinger's cat simultaneously dead and alive… Paradoxically quantum physics is able to describe everything, except the measurements on which the theory itself is built!

How do we deal with that? Quantum physics is eighty years old, and the paradox has been with us for that long. The 'orthodox' or 'Copenhagen' interpretation of quantum theory takes a very practical approach, which basically consists in ignoring the problem. It introduces an *ad hoc* postulate declaring the outcome of a measuring process to be (7) and not (6). This is known as "collapse of the state vector", or "collapse of the wave function". It assumes that something happens in the measurement process which collapses the entangled situation (6) into the classical situation (7).

But of course the theory is fundamentally incomplete unless we are able to say what is that something that collapses the wave function. In other words, what is it that makes the macroscopic world, sitting on top of all this weird quantum stuff, appear classical, either-or, well-behaved, solid (kind of), instead of being an entangled mess of head and tail coins and dead and alive cats?

Proposed solutions

Many proposals have been brought forth. They fall into two broad categories:

(i) either they propose a mechanism to describe the collapse;
(ii) or they state that the superposition (6) and the mixture (7) are in some sense indistinguishable.

Without going into a detailed discussion of the proposed solutions, I will just outline a few of them to give you a glimpse of the variety of philosophical positions implied.

An example of a type (i) proposal is the idealistic solution suggested by Wigner in the 60's. He proposed that the collapse of the state vector is not due to the interaction of the microscopic system with the measuring apparatus, but to the observer's consciousness taking in the measurement's results. The measuring apparatus, after interacting with the microscopic system, does indeed end up in the entangled state (6). And we can assume that the observer's sense organs and brain, after interacting with the measuring apparatus, also end up in an entangled state with all the rest. We can extend the von Neumann chain to include the observer's retina, optic nerve, brain, etc. Let's call all this just "brain", for short, and indicate its state by capital Monotype Corsiva font. Then the resultant entangled state is

$$\{\alpha \times \text{headHEAD}\mathcal{HEAD} + \beta \times \text{tailTAIL}\mathcal{TAIL}\}, \tag{8}$$

(where $\mathcal{HEAD}$ denotes the state of the observer's brain when he/she has read HEAD on the apparatus, and $\mathcal{TAIL}$ denotes the state of the observer's brain when he/she has read TAIL). At this point a non-physical element, i.e. the observer's consciousness comes in. The observer becomes aware that his/her brain has registered HEAD or that it has registered TAIL. Consciosness, says Wigner, cannot be in a superposed state. Therefore it causes the whole chain of correlated systems (observed system-apparatus-retina-optic nerve-brain) to collapse into one or the other possibility. The outcome is therefore the mixture:

$$\{|\alpha|^2, \text{headHEAD}\mathcal{HEAD};\ |\beta|^2, \text{tailTAIL}\mathcal{TAIL}\}. \tag{9}$$

This view of the role of consciousness in quantum measurement is still popular in New Age literature. But it leads to the serious difficulties emphasized by

Schrödinger's cat's thought-experiment, and not many physicists would vouch for it at present (Wigner himself later abandoned this proposal).

A type (ii) proposal is Everett's "many-worlds" idea. Everett assumes that the superposition (6) correctly describes the outcome of a measurement process. But he claims that each term of the superposition exists in a different world. With every quantum measurement the universe branches out and the various measurement results exist simultaneously in different worlds, together with different copies of ourselves. We are unaware of these other replicas of ourselves and of their worlds, and therefore we see only one result. A science-fiction idea, which nevertheless still has a non-negligible following.

Another type (ii) proposal is the so-called "de-coherence" approach, to which many people have contributed. The work of the Milano school, to which I gave a small contribution with my *tesi di laurea*, laid the foundation for it in the late 60's. The idea is that, although the superposition (6) and the mixture (7) represent in principle profoundly different situations, when they are applied to macroscopic systems their difference becomes unobservable. Various factors contribute to this. For one thing all kinds of random processes take place in a macroscopic body. Furthermore a macroscopic body can never be thought of as isolated: it constantly interacts with its environment. These factors have the effect of smearing out the difference between (6) and (7), making it practically unobservable. The actual outcome of a measuring process is still the superposition (6): but it can be replaced FAPP, as John Bell used to say, "for all practical purposes", by the mixture (7).

Is the de-coherence approach a true solution of the measurement problem? How one answers this question depends on one's evaluation of FAPP. The predictions derived from the superposition (6) are never shown to fully coincide with those derived from the mixture (7). The de-coherence results are always approximate – but the approximation is better than any conceivable experimental error.

A new proposal

The approach I am proposing is also of type (ii), i.e. it takes the consequences of quantum physics seriously and assumes that the world is indeed an entangled web of potentialities. Within the framework of our present understanding, i.e. within the model provided by quantum physics, that's the nature of reality. Therefore my question is not how the entangled web of potentialities collapses into a solid, classical world, but how comes that this entangled web *appears* to us as a solid, classical world.
What I am doing is in a way similar to de-coherence, but it is much easier and it is exact. De-coherence is hard work: it finds a difficult answer, and one which

moreover is only approximately true, while I believe that there is a simple and exact answer.
As a first approximation I could make the following statement:

the quantum world appears classical to us not because of the macroscopic nature of our measuring devices, but beacause we, as observers, are part of the world we observe.

Let me now try to make this statement a bit more precise. We are physical beings: our gathering information about the world happens through the interaction of our body with other systems. We can analyze this interaction in terms of the von Neumann chain of systems described in the previous section. The important point is that, in order for us to know something, a trace must remain somewhere along the line of such a von Neumann chain. We know only insofar as such a physical trace exists. About processes that don't leave any trace we cannot say anything, because we never experience them! Our knowing is anchored in traces happening along von Neumann chains of interacting systems. And the way the world appears to us is conditioned by that general condition of knowing.

To explain why that is so is much easier in mathematical terms than in words. That's because our language is not meant to deal with things like superpositions. Our ancestors didn't need them for their survival. An explanation in words is bound to be only a suggestive statement of the argument. But here it goes.

To focus our thoughts, let's stay with the quantum coin measurement described above. In this context I could say that the world appears as classical to us if every possible observation we can make is correctly predicted by the mixture (9) (that guaranrees that the outcomes of the quantum coin measurement can be subdivided into heads and tails, one or the other, no funny in-between business).

But the requirement that *every possible observation* should be correctly predicted by the mixture (9) is unnecessarily restrictive, because it includes also those observations that destroy all traces of the measurement performed on the quantum coin. About these we shouldn't say anything, because nobody ever experiences a "measurement" that leaves no trace. If no trace of the quantum coin measurement is left, it is not really a measurement. It is an ordinary quantum process, which does not involve an observer nor a recording of any kind. For such a process we have strong evidence that the ordinary quantum rules should apply, and we should expect a superposition, not a mixture, to correctly describe the outcome.

As I said, all our knowing is based on interactions which do leave a trace along a von Neumann chain. So, in the context of the quantum coin measurement, when we say that the world appears as classical to us we mean that *every possible observation that preserves a trace of the previous quantum coin measurement* is correctly predicted by the mixture (9). *For that restricted class of observations* we require the superposition (8) to be equivalent to the mixture (9).

Now comes the tricky part, the part that is much more easily explained in mathematical language. It has to do with the notion of entanglement. In the superposition (8) all the systems involved (observed system, measuring apparatus, observer's brain) are entangled together, and, as I said, that means that they are no longer independent: whatever you do to one of them, you do to them all. Now the interesting thing for our purpose is that, in a certain sense, entanglement works also the other way around: if don't do something to one system, that also has consequences for the whole chain. If you leave *a trace of the outcome of the quantum measurement* in one system, i.e. you allow the result of the quantum measurement, head or tail, to be in principle recoverable by an observation performed on that one system, then all the other systems in the chain will behave just as if that observation had actually been made. I.e. the outcome of any observation performed on any of them splits up into a subset corresponding to the head result and one corresponding to the tail result. If you allow the measurement recording to persist in one of the entangled systems, it is as if it it persisted in the whole chain, and the predictions derived from the superposition (8) turn out to be exactly the same as those derived from the mixture (9).

This result is exact and is independent of the microscopic or macroscopic nature of the systems involved. The trace that is preserved can be at any level, microscopic or macroscopic. In simple words, the general statement is: the outcome of any observation process that leaves a trace can be described in classical terms.
But *our knowing happens only through processes that leave a trace, if nowhere else, at least in us*! That's why the world appears classical to us. Not because *it is* classical, in an ultimate sense (ultimate always within the context of our models). But because *the conditions of our knowing make it appear that way*.

Since the beginning of quantum theory physicists have felt that the classical appearance of the world had something to do with the role of the observer. That is indeed so, but not because the observer's consciousness collapses the wave function, as it was once hypothesized. The classical appearance of the world is connected with the conditions of our knowing in general. The world appears classical to us because, in order to know, we have to be entangled with what we know.