

## Attempts to Solve the Measurement Problem More About Decoherence and Erasers

The measurement problem described earlier has received much attention. We return now to a description of some of the many attempts that have been made to solve it. There is no general agreement as to where the actual solution lies, so our discussion will not lead to any definite conclusions.

### Small Detectors and Big Detectors: Decoherence

We discussed one form of this effect earlier. Let us return to our analysis of the infinite regress that develops when we attempt to describe a measurement. Recall our comment that, in going from state where ionization did or did not take place to state where detector did or did not catch atom,

$$\begin{aligned} |system\rangle &= a|photon_{low-energy}\rangle|atom_{neutral}\rangle|atom_{straight}\rangle + b|photon_{high-energy}\rangle|atom_{ionized}\rangle|atom_{deflects}\rangle \\ |system\rangle &= a|photon_{low-energy}\rangle|atom_{neutral}\rangle|atom_{straight}\rangle|detector_{catches\ atom}\rangle \\ &\quad + b|photon_{high-energy}\rangle|atom_{ionized}\rangle|atom_{deflects}\rangle|detector_{does\ not\ catch\ atom}\rangle \end{aligned}$$

an important new element has entered the situation, namely, we made a transition from microscopic to macroscopic objects.

Recall also from earlier that large objects, unless they are of a very special sort, are subject to process of decoherence.

A number of physicists have argued that this solves the measurement problem. Their claim is that decoherence does away with need for projection postulate.

Is this claim true?

We now state the essential points of decoherence, with one change from earlier discussion - everywhere we used word **system** before, we use the words **macroscopic detector**.

The essential elements of decoherence are as follows:

- (I) The environment a macroscopic detector is embedded is constantly and irregularly fluctuating.
- (II) If a macroscopic detector is described by a superposition, different terms in superposition will interact differently with environment. In particular, they will have different interaction energies.

Therefore,

- (III) The time evolution of each of the terms in the superposition is constantly and irregularly fluctuating

and

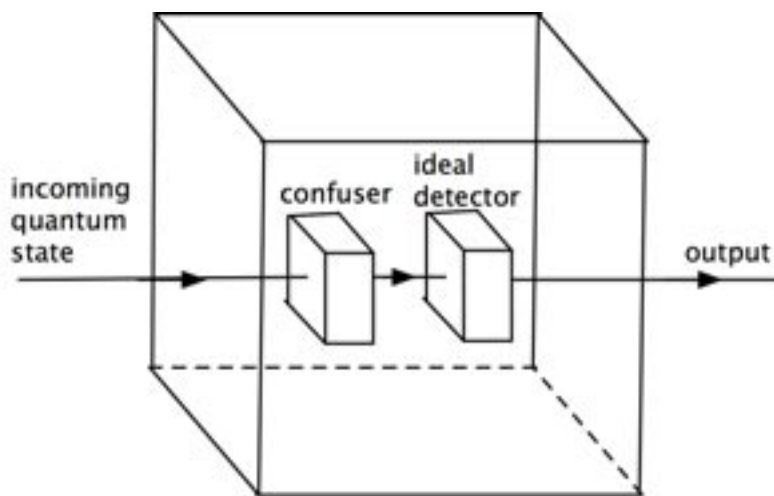
- (IV) This state is indistinguishable from a mixture.

Up to now in our discussion of measurement, we have tacitly assumed that the macroscopic detector behaves in same way as do microscopic objects such as photons and atoms.

But phenomenon of decoherence shows this assumption was unwarranted. Let us now correct this error by repeating our earlier discussion.

We imagine a macroscopic measuring device as being composed of two parts.

The first part describes all the imperfections of a real measurement process, one made by a large-scale object. The second part consists of the sort of absolutely perfect device we have been considering up to now. We will call first part a "confuser," and second an "ideal detector." The figure diagrams configuration we have in mind.



**A Macroscopic Detector**

In the diagram, the confuser represents all the unwanted interactions of the large-scale detector with the environment and with its own internal states, which themselves constitute an irregularly fluctuating intrusion into its behavior(it mimics the coupling between a macroscopic detector and its irregularly fluctuating environment).

We have no information about these interactions, which means that they cannot be included in the quantum-mechanical treatment of the detector's behavior. We can only treat them as unknown and uncontrollable perturbations.

How does such a two-part measuring device work?

As before, the decay photons are emitted by our atoms into a certain state. This can be any of the states we treated in our three cases above:

an eigenstate

a mixture

or

a superposition

In any event, state is well-defined. But now these photons enter the confuser, and at this point everything changes. An element of randomness enters our description, arising from process of decoherence.

Recall that the effect of this randomness is to make a superposition indistinguishable from a mixture. And as case 2 made clear, **if state being measured is a mixture, the projection postulate is not required.**

No matter what input state goes into the confuser, its output will effectively be a mixture.

This state now enters second component of our large-scale measuring device, the perfect detector.

And as we have seen, in this situation we simply do not need projection postulate. In this way, the argument goes, the phenomenon of decoherence solves the measurement problem by eliminating the need for this strange and unsatisfactory postulate.

### **Does Decoherence Really Solve the Measurement Problem? What about the Quantum Eraser?**

Not all physicists agree that decoherence solves the measurement problem. At this time, there is intense debate as to whether the above argument that we have sketched is valid.

There is no debate over fact that macroscopic detectors are intimately connected to a complex and fluctuating environment; and there is no debate over fact that a complex, fluctuating superposition state is indistinguishable from a mixture for certain purposes.

But there is much debate as to whether this state is in principle the same thing as a mixture - and many think that the measurement problem is one of principle, not of practice.

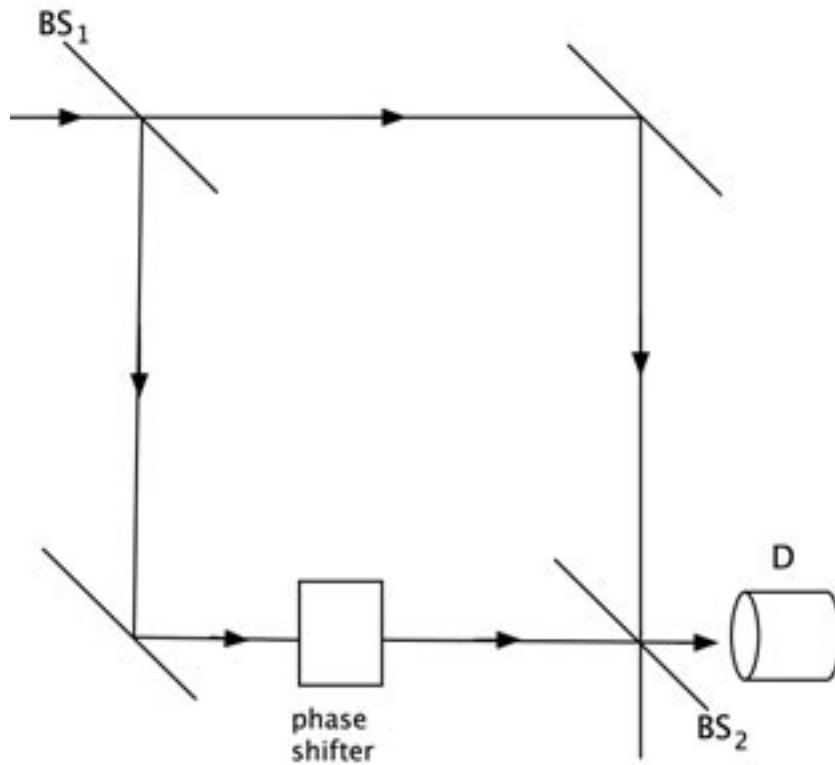
Our earlier discussion of decoherence was somewhat equivocal - it was peppered with phrases such as "equivalent to," "indistinguishable from" and the like, rather than simply "is." This equivocation reflects the lack of consensus in the field at present.

It will not be possible to do justice to the subtle arguments that have been raised in this debate in this seminar.

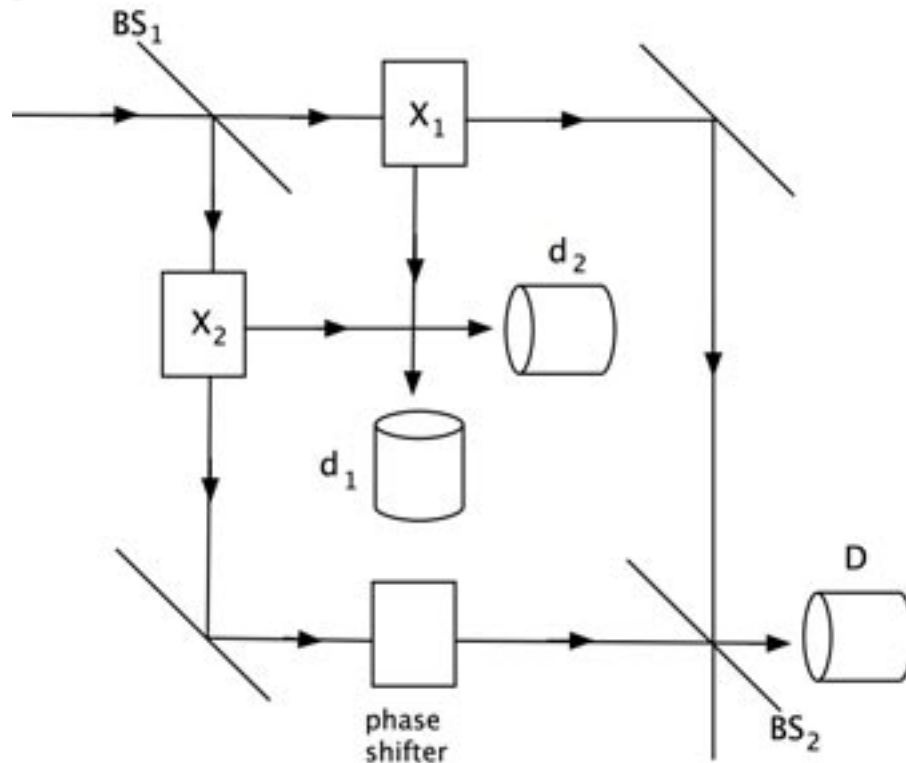
Let us go back to the "quantum eraser", however, which sheds some interesting light on problem.

We begin by describing an experiment that embodies it, after which we will point out its relevance to problem of measurement.

The experimental setup is so complex that we will approach it in a different way than before and in stages, reaching the actual design only in the third stage. In the first figure we illustrate the first step.



It is simple Mach-Zehnder interferometer. A phase shifter which changes the effective path length in one of arms is varied and detector  $D$  records an interference pattern. This is just the double slit experiment in a different form. Now move on to the second stage of the analysis. We insert two nonlinear down-conversion crystals,  $X_1$  and  $X_2$ . Each photon, as it enters a crystal, is split into an entangled pair. These are illustrated in second figure below.



Here the outputs of the nonlinear crystals that have been placed in two arms of interferometer, are monitored by two additional detectors  $d_1$  and  $d_2$ . The two additional detectors,  $d_1$  and  $d_2$ , record the additional photons.

Will initial detector  $D$  still register an interference pattern as the phase shifter is adjusted?

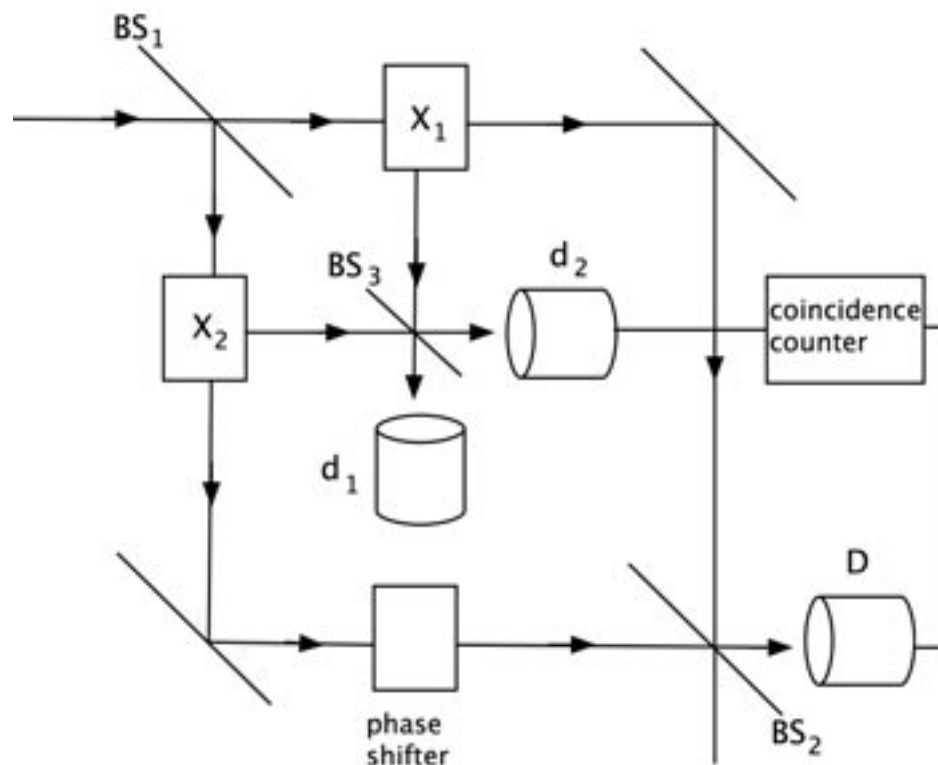
The principles of QM say that it will not.

The apparatus illustrated in the second figure is capable of giving us which-path information; therefore it cannot exhibit interference.

To see how this comes about, suppose that we send a single photon into the apparatus. We know that it is going to split into two photons, because either path it takes leads to a nonlinear crystal. One of the two additional detectors,  $d_1$  and  $d_2$ , is therefore sure to register a count. And if  $d_1$  clicks, we know the initial photon chose upper path. Similarly, if  $d_2$  clicks, initial photon chose the lower path. Thus, whenever  $D$  clicks, we ask which of  $d_1$  or  $d_2$  also clicks. The answer gives which-path information and thus we cannot see an interference pattern at  $D$ .

The essence of concept of quantum eraser is that this which path information can be erased – and when it is, the interference pattern can return.

This is accomplished in the final stage of the experiment in the third figure, in which we place third beam splitter  $BS_3$  into the paths of secondary photons from  $X_1$  and  $X_2$ .



Here the beam splitter  $BS_3$  "erases" the which-path information that had earlier been provided by the crystals, and a coincidence counter between  $D$  and  $d_2$  records an interference pattern.

Now we have lost any means of knowing which photon it was that made  $d_2$  register a count.

By the principles of QM, since we have no which-path information, an interference pattern can now be seen.

But, as we emphasized earlier in our discussion of quantum nonlocality, this interference signal does not show up if we record only counts in detector  $D$ . Rather we must connect  $D$  and  $d_2$  by a coincidence counter, which counts only if  $D$  and  $d_2$  fire simultaneously. It is this coincidence signal that registers an interference pattern as phase shifter is varied.

The experiment we have described has been performed by Mandel and coworkers at the University of Rochester.

Two photon parametric down conversion supplied the secondary photons, in this case twice. Thus, a single ultraviolet photon from a powerful laser was first placed into a one-photon superposition state of the usual kind by passing it through a beam splitter. But then this superposition state passed through two down-conversion crystals,  $X_1$  and  $X_2$ , creating thereby a complex two photon entangled state. Inserting and removing the third beam splitter made this state's interference properties appear and disappear.

What is the relevance of such an experiment to the measurement problem?

It lies in the fact that the interference pattern will only be observed if we look at coincidence counts between two detectors.

Interference, of course, is the characteristic sign of quantum behavior **and this quantum behavior will not be seen if we do wrong experiment.**

Looking at only single detector  $D$  is wrong experiment.

It reveals what appears to be classical behavior - the absence of interference.

In a normal single-photon Mach-Zehnder experiment diagrammed in first figure, the detector  $D$  is "the" detector, and it reveals quantum behavior as phase shifter is varied. But in the more complex two photon experiment of third figure it alone does not.

We might be tempted to argue that this is because the full experiment makes use of nonlinear crystals, which are macroscopic devices, subject to all the fluctuations of the decoherence effect.

The quantum eraser experiment reveals that this, however, is not the case. In reality, full quantum behavior is still present, but it can only be seen by performing a different (the correct) measurement. By asking the right question!!!

Indeed, the effect of the nonlinear crystals here is not to wipe out quantum coherence. It is to entangle a photon arriving at the detector *D* with something else - with another photon arriving at *d2*.

Similarly, the effect of incessant, fluctuating interactions to which all macroscopic detectors are subject is also to entangle them with something else.

In this case, however, the "something else" is far more complex. It is the rest of world.

The lesson of this experiment is that only if the right experiment could be performed, one which detects all multitudinous components of this gigantic entangled state, could quantum behavior be seen all over the apparatus or regardless of the question asked.

In the decoherence model, the conceptual device that we have termed a "confuser" introduces a complex, random disruption of quantum state. This leads to a loss of interference.

But does loss of interference mean that the quantum coherence (ability to see interference effects) has been lost?

This is the key issue addressed by eraser experiment.

If this disruption truly destroys the quantum coherence, destroys it not just in practice but in principle, then it will be impossible to ever recover an interference signal.

On the other hand, if disruption leads rather to the creation of an entanglement, then state has become more complex but its fundamental nature has not altered - it is still a superposition, not a mixture.

In the measurement process, the projection postulate will be unnecessary only if the output of confuser is truly a mixture, i.e., nearly a mixture is not good enough.

At least in this one experiment, it is clear that the quantum behavior has not been destroyed by decoherence.

### **Comments:**

In real world, detailed analysis of a detector with its attendant confuser is beyond our reach theoretically. For this reason, it is difficult to be sure how much relevance this simple model has to the measurement problem.

Complex and subtle arguments have been brought to bear on this issue, with no general agreement at present.

We close by briefly mentioning three other ideas that have been put forward in an attempt to solve measurement problem. These are not the only such attempts, nor are they necessarily the most significant. Rather, our goal in selecting them is simply to indicate how wide is the net that has been cast in the debate on the subject.

Everett, as we have seen, has put forward a re-interpretation of

quantum mechanics, commonly known as the many-worlds interpretation, in which the state vector does not collapse. The entanglement of system and observer is never resolved. Instead, each measurement multiplies the number of branches that the system and observer must simultaneously sustain.

Each branch represents a real option for universe. In Everett's interpretation, all the universes or worlds are simultaneously present with comparable reality.

Ghirardi, Rimini and Weber, on the other hand, modify standard quantum mechanics in a way that has no effect on microscopic objects while at same time changing the quantum dynamics of large objects into a "stochastic" mechanics that displays all features of classical physics. They accomplish this by introducing a term describing a continually fluctuating field whose effect is to cause superpositions to rapidly evolve into mixtures.

Finally, Wigner has proposed that a measurement occurs and state vector collapses, when a person becomes aware of a detector's state. In this view, the brain is described by ordinary quantum mechanics, but the mind is not - it stands outside normal physics, and its workings are not subject to physical law.

The great variety of these suggestions, and the absence of agreement on how the measurement problem is to be solved, are all the more remarkable in that the idea of measurement lies at the very heart of quantum mechanics. It lies at the heart of probability prescription that square of some coefficient evaluated at some point gives the probability that a measurement will find a particle there. It lies at heart of prescription we use in QM to calculate average value of a series of measurements of an observable. Indeed, the concept is essential to every scientific theory for it is through measurements that theory makes contact with experimental reality.

Finally, it is commonplace that measurements take place every day in laboratories throughout the world. Indeed, if Wigner's proposal is wrong and consciousness itself flows from the workings of the human brain, and if quantum mechanics applies to the brain just as well as SQUIDS and macroscopic bits of ferritin - then the very act of looking and seeing is a measurement. How can so prosaic an act be so fraught with difficulty for a theory that has proved so wonderfully successful in every other regard?

This is the area of physics of my own research.