Uncertainties about uncertainty principle

Is the notion that successive measurements on an isolated quantum system will yield the same result an axiom of the quantum theory or a consequence of it? This old argument has now resurfaced.

THE paradoxical nature of the quantum theory has since the mid-1920s been neatly encapsulated in Heisenberg's uncertainty principle. For why should it be that, in the real world, it is impossible to make simultaneous measurements of, say, the linear momentum and the position of a particle? Or of all three components of its angular momentum? The simple and familiar answer to all such questions is flatly to assert that this is what the quantum theory has shown the real world to be like, but this, of course, is unconvincing. The uncertainty principle is paradoxical because it conflicts with expectations derived from experience with macroscopic systems with the result that discussion of the uncertainty principle has always been embedded in a rich matrix of explanation, or at least of *post hoc* justification. And the process continues.

De Broglie's argument is the oldest and that most often found in elementary textbooks: once it is accepted on the basis of, say, electron diffraction phenomena that particles can also be represented as trains of waves, it is natural to expect a trade-off between the localization of a particle represented by a wave-packet and the spread of wave-number (representing momentum) of which it is constituted. In the 1920s, however, Dr Broglie's argument was too slight to banish the sense of paradox, while the need for understanding these problems was urgent. This was the task undertaken by Niels Bohr and the Copenhagen school, with its doctrine of complementarity, the definition of what is meant by a quantum state and the whole vocabulary in which quantum theory is even now discussed.

Inevitably, the Copenhagen school has become the focus of the discontent of those who may be called the dissidents. Out and out dissenters, those like the later Einstein who held that the uncertainties of the quantum theory will at some stage melt away regard the whole Copenhagen episode as a gigantic aberration, as when there were popes based at Avignon.

M. Cini, of the University of Rome (*Il Nuovo Cimento* **73**, 27; 1983) has a more subtle but more interesting complaint against the Copenhagen legacy What, he asks, is the logical status of the belief that if you make a measurement of some physical property of a quantum system, supposed to be at the outset in some uncertain stage, and discover some specific value of the physical variable concerned, then (other things being equal) the system will be found to persist in a condition in which the physical property remains unchanged? Cini's question goes to the root of the Copenhagen argument. His answer is comforting — complementarity survives — but some puzzling features of the argument about the effects of measurements on quantum systems are neatly clarified.

Here is an example, one of Bohr's *Gedankenexperimenten*. Take a screen in which two parallel slits A and B have been cut and conceal a source of electrons behind it, symmetrically in relation to the slits. If the source emits photons, to which the argument equally applies, the result is Young's apparatus for the demonstration of optical interference. In other words, detectors on the side of screen opposite from the source can be used to show that there are some points at which the chance of the arrival of an electron is literally zero and in a statistical sense, the standard interference pattern is recovered by the detector even when particles (or photons) are emitted singly, one by one. So here is another paradox: since the interference pattern is destroyed if one slit or the other is covered up, there is a sense in which each particle reaching the detector must be held to have passed through *both*.

How can this be accomplished? Formally the procedure is straightforward. One definable state of the system is that in which the particle travels through slit A, another is that in which it travels through slit B and, if each of these is represented by some symbol (ψ_A and ψ_B after Schrödinger or $|A>$ and $|B>$ after Dirac), then the state in which the particle travels through both slits is that represented by the sum of the two symbols multiplied by some number (generally complex). The outcome is that it is possible to record the arrival of single particles in the plane of the detector, and indeed by repeated measurement to reconstruct an interference pattern from which the momentum of the particles can be derived, but only at the price of being entirely uncertain about the routes, slits A or B, by which the particles have travelled. But why not cheat by equipping slit A, say, with another detector that will tell whenever a particle passes through? Because that measurement will disturb the state of each particle, so that each will finish up in a state represented by some other linear combination of the separate slit-state symbols than the simple sum, whence the notion that measurements affect the states of quantum systems as if they were operators operating algebraically on the individual states.

Even in retrospect, it is quite remarkable that in the 1920s the entire algebra of the quantum theory was reconstructed from such simple considerations. But Cini's complaint centres on an assumption made then and afterwards — that the effect of trying to cheat as described above is to convert the composite state of a particle into one or other of the elementary states of which it is composed. Thereafter, the argument goes, further measurements designed to tell which slit has been traversed will yield the same result.

Cini's argument is that this assumption, while in practice valid, is logically unnecessary. Rather, he says, the almost but not quite exact projection of the composite state vector onto just one of the components of which it is composed is a consequence of the way that measurements are made. For this purpose, he has devised a *Gedanken*-detector for particles, a model of a proportional counter made of idealized ionizable atoms which are mathematically simple enough for the detector and the particle to be treated as a whole. The objective is to calculate the time evolution of the combined system. Predictably, when the number of atoms is large (or the counter macroscopic), there can be only small departures from the rule that performing a measurement on a quantum system forces it into a state corresponding to the measured value.

So what? Bohr in the 1920s was fully aware of the need that an effective measuring device should be a macroscopic system, while much of what Cini has to say is for practical purposes contained in the formulation of quantized statistical mechanics by people like Leon Rosenfeld in the 1930s. Cini, however, has two axes to grind. He wants the projection postulate eliminated from the quantum theory because it is logically unnecessary, and he wants to deny descriptions of the quantum theory that take forms such as "measurement disturbs the system measured". Not a bit of it, he says; the system and the instrument are part of a system that may be self-contained, and which is evolving under the influence of their mutual interaction. A simple conclusion? Not all of Cini's referees have shared this view, with the result that the editor of *Il Nuovo Cimento* has given him the luxury of a "note added in proof" that runs to more than 2,000 words to defend himself against his silent critics. □

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