Lecture 6. Principle of indeterminacy*

(Notes on an informal talk to a group of physicists)

The question of indeterminacy is the most sensational [sic] in quantum theory. It really is one of the adventures of the mind.

Werner Heisenberg found that deductively his equations led to a formula: that the consequence of lack of precise prediction leads to a statistical character, and that this statistical character is what is ultimately needed to explain the eigen-states of the atom. Erwin Schrödinger showed this with wave mechanics. Heisenberg said that as a consequence there are very few causal laws for atoms, which is, he said, a refutation of the principle of causality.

Although I also don't believe in a general principle of causality, I do not think Heisenberg is right. A statistical conclusion is derived from a statistical premise – a probability conclusion is derived from a probability premise. A simple consequence of this is that some statistics has to be put in, in order to get statistical laws.

The answer to Heisenberg is to discover from which assumption his formula is deduced. Heisenberg said that if one observes a particle, the observation interferes with the particle, i.e. measurement disturbs. Neils Bohr says that his complementarity principle is involved here [i.e. although the velocity and position of an atomic particle cannot be accurately measured simultaneously, the measurements are complementary in giving a complete description of the behaviour of the particle]. He used a 'screen and spring' picture of measurement [to screen out individual particles and measure the force of their impact, see below]. We also have the same situation with energy and time.

Heisenberg is in a different position from Bohr, as he says one interferes with particle in the measurement. He assumes a causal principle and then says that, by using that principle, one reaches a situation where causality doesn't work.

I consider that the whole thing is derived from statistical assumptions. Both the Bohr interpretation and the Schrödinger wave equation imply that the density or wave amplitude is really the probability that the particle will be at a particular place. My view is that you could not get a super-pure case, i.e. a bundle of particles without a wide range of momenta or locations. However, this limitation to accuracy doesn't obtain for a single particle and therefore you cannot exclude the possibility of a more accurate measurement.

The result of the subsequent discussion was that neither Heisenberg or Bohr raised convincing objections. But Victor Weisskopf said: 'if you can measure the particle to a higher degree of accuracy then you should be able to make an apparatus for measuring a super-pure case, i.e. a contradiction exists between the assumption in making this apparatus and the hypothesis of the quantum theory.

I do not think the Heisenberg assumption of disturbing the particle by measurement is more than a vague popular idea. The present situation is that, from indirect arguments, it is clear that one cannot indeed measure both complementary magnitudes beyond a certain degree of accuracy. From the point of view of measurement this is a consequence of the non-existence of a super-pure case, not only in the scientific sense, but also in the ideal fictitious sense.

The Heisenberg disturbance theory has been developed in some respects. If you attempt measurement, you disturb the particle, and you have a new situation. In the jargon in the Heisenberg–Bohr school the essential word is 'smear'. An additional theory is that, only if one makes an experiment does one force the electron to show its flag and say where in the smear it really is: the particle has not momentum and has not position, but you only force it to show its position by measurement.

Einstein and Schrödinger on the other side now say that something is not yet clarified, as the Heisenberg view does not work in quantum mechanics.

Heisenberg and Bohr always show that the principle of indeterminacy works, but they assume more and are rather dogmatic.

Assume that we have a particle, A, and want to measure it. We collide it with a particle, B, and get something like a Compton effect [transfer of energy between particles]. Einstein said that after the systems A and B separate, there is no interaction at all. By measuring either the position or the momentum of B you can measure either the position or the momentum of A. Thus you have a choice after the event, i.e. nobody any longer interferes with A, and so the Heisenberg and Bohr interference idea cannot work.

Schrödinger shows that in all quantum mechanical situations you have just this sort of situation.

Bohr answered by showing with his 'screen and spring' that, if you measure the impulse of B you have to have screen loose for B, and hence also loose for A. Hence Bohr now transfers the blame for indeterminacy away from the electron smear to a vagueness (or subjectivity) of the coordinate system, i.e. the measurement rather than the properties of elementary physical particles. If the coordinate systems are thus smeared, it fits in excellently with Bohr's fundamental ideas of complementarity. This is the present position [*c.* 1934, in a topical debate among leading atomic physicists].

* *See Popper, K.R. 1934.* Logik der Forschung *p. 181. Berlin, Springer, for a full account.*