Propensities in Quantum Mechanics

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Propensities are probabilistic dispositions, and there is a long history of informal appeals to dispositional terms in connection with quantum mechanics, going all the way back to the founding of the discipline. A dispositional account of quantum properties is, for instance, arguably implicit in the early quantum theory in Bohr's model of the atom, since transitions between quantum orbitals can be described as stochastic processes that *bring about* certain values of quantum properties with certain probabilities. Similarly, on the orthodox Copenhagen interpretation, measurements do not reveal pre-existent values of physical quantities, but *bring about* values with some well-defined probability. Then, in addition, starting in the 1950's there has been a succession of attempts to employ explicit dispositional notions, such as propensities, in order to resolve the paradoxes of quantum mechanics. Two stand out: Henry Margenau's *latency* interpretation, and Karl Popper's *propensity interpretation* of quantum probability.

Margenau's *latency* interpretation

Different interpretations of quantum mechanics can be in general fruitfully distinguished in terms of the answers they provide to the paradigmatic question concerning the general interpretation of superposed states. Suppose that the state of a quantum system is Ψ, a superposition of eigenstates of the Hermitian operator that represents the observable Q. The standard interpretational rule within orthodox quantum mechanics, the *eigenstate / eigenvalue link* (e/e link) states that a system in state Ψ can be said to have a value of a property Q if and only if Ψ is an eigenstate of the Hermitian operator that represents the property. The paradigmatic question regarding these states is then the following: *What does it mean – with respect to the property represented by the observable Q – for a quantum system to be in state Ψ which is not an eigenstate of the Hermitian operator that represents Q?* Propensity views of quantum mechanics vary greatly in their details but they all coincide in their answer to the paradigmatic interpretational question: *It means that the system possesses the* propensity *to exhibit a particular value of Q if Q is measured on this system in state Ψ.*

In an excellent pioneering article Henry Margenau (1954) argued in favour of latent quantities, or *latencies*. Margenau's key contribution was the basic *template* for propensity views. Suppose that state Ψ can be written as a linear combination $\Psi = \Sigma_n c_n \,|\, v_n>$ of the eigenstates v_n of the *latent* observable represented by Q with spectral decomposition given by $Q = \Sigma_n a_n | v_n \rangle \langle v_n |$. Margenau then answered the paradigmatic interpretational question very precisely as follows: *a system in state* $\boldsymbol{\Psi}$ *has a latent property Q if and only if it possesses a propensity to manifest eigenvalue* $\boldsymbol{a_i}$ *with probability* $|\boldsymbol{c_i}|^2$ *in a measurement of Q.*

However, Margenau went beyond the basic template in some unhelpful ways. For instance he conflated the possession of a property with the manifestation of a value of the property – a distinction that makes no sense for categorical properties, but is essential in order to understand dispositional property ascriptions in general. A failure to draw this distinction led Margenau to inappropriately link the actualisation of latent properties with their existence. So in the absence of a measurement of position, for instance, an electron has no value of position, and as a consequence it has no position at all. This conflation renders Margenau's attempt to solve the quantum paradoxes largely unsuccessful, and brings about additional difficult issues related to the identity of quantum objects.

The conflation is unfortunately present also in Heisenberg's (1958) well known appeal to Aristotelian potentialities, but can be avoided by distinguishing carefully the possession of a propensity from its manifestation. To be coherent a propensity view must deny a common presupposition behind the (e/e link), namely that it is legitimate to ascribe a property to a system if and only if the system takes a value of the property. It would then follow in accordance with the (e/e link) that a system possesses a property if and only if the system's state is an eigenstate of the operator that represents the property. But any coherent propensity (or more generally dispositional) account must ascribe a property without manifestation. Hence propensity accounts must deny a common presupposition of the (e/e link).

Popper's propensity interpretation of quantum probability

Karl Popper's propensity interpretation of quantum mechanics is surely his most important contribution to the philosophy of physics. Popper conceived the propensity interpretation of quantum mechanics as both a milestone of his philosophical career, and a key to his philosophical system. He defended it in a large number of his writings, and over a very large period of time (for instance Popper 1957, 1982). It was a milestone since it was a consideration of the nature of quantum phenomena that led him to abandon the frequency theory of probability, and adopt instead a propensity interpretation for objective probabilities in general. And it was a key to Popper's philosophical system because the propensity interpretation of probability i) resolved the paradoxes of quantum mechanics; ii) re-established the possibility of a thoroughly realist interpretation of the quantum theory, of physics, and of science in general; and iii) provided strong empirical confirmation in favour of the propensity interpretation of the calculus of probability.

However, Popper's account is subject to three lethal objections, that render it untenable. The first criticism was raised by Neal Grossman (1972), and shows Popper's account to hopelessly confuse quantum mixtures and superpositions. In essence the problem is that for any observable Q every superposed state $\Psi = \Sigma_n c_n \mid v_n>$ can be shown to be statistically indistinguishable from an appropriate mixture $W^{\infty}_{n=1} = \Sigma_n \mid c_n \mid^2 \mid v_n> < v_n \mid$ over the eigenstates $\{\mid v_n> \}$ of the operator that corresponds to Q. Since Popper identifies propensities with probability distributions, he has no option but to identify the propensities generated by both states. Yet both states are different, as is shown in any experiment that measures any observable other than Q on systems in these states.

The second difficulty was first raised by Peter Milne (1985), and is related to the notion of interference of propensity waves invoked by Popper in order to account for the two-slit experiment. Popper's identification of propensities with whole experimental set-ups entails that any small change in the experimental set-up, such as the closing of a slit, essentially brings about a change in the propensity ascribed. Milne employed this fact to refute Popper's account of interference experiments, such as the two slit experiment. Popper's account entails that in each of the experiments *A* and *B* with one or the other slit open a different propensity ascription "A" and "B" is in order. The interference pattern that results in the experiment with both slits open is then just the result of the interference of both propensities "A" and "B". But Milne shows that there is no reason on Popper's account to expect propensities "A" and "B" to be co-present in the interference experimental set-up, since this is distinct from both *A* and *B*.

The final objection to Popper's propensity account is Humphrey's notorious paradox (1985), which shows that propensities are not in general probabilities, and vice versa, since propensities are time-asymmetric but conditional probabilities are not. Together these three objections essentially refute Popper's propensity interpretation of quantum probabilities.

New Prospects for Propensities

The failure of propensity accounts in the past sometimes gives all propensity interpretations a bad name in the philosophy of physics. But this is essentially unfair since, as we have seen, it is not propensities *per se* that have been shown to be inapplicable to quantum mechanics, but rather *particular uses* of them. It remains possible to apply propensities to quantum mechanics in more cunning ways. In particular propensity accounts could abandon the ideal of interpreting probabilities in general. Rather than interpreting probabilities, propensities can be used to *explain* certain probabilities. Some of the presuppositions underlying the (e/e link) will also need to be confronted. Finally, it must be possible to ascribe propensities to quantum systems in the absence of any experimental set-up. Three recent accounts that go some way towards meeting these goals are Maxwell (1988), Thompson (1988) and Suárez (2004).

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