A new way of understanding the wave function

Shan Gao: The meaning of the wave function. Cambridge: Cambridge University Press, 2017, x+189pp

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This is a fascinating and important book about how to interpret the wave function of quantum theory. It is clearly written, up to date, and has a wealth of interesting things to say.

In what follows I give a summary of just some of the topics of the book.

It begins with a brief exposition of the formalism of orthodox quantum theory and von Neumann's account of measurement. Shan Gao goes on to discuss the question of whether the wave function can be interpreted ontologically, as specifying the actual physical state of the quantum system, or whether it should be interpreted epistemologically, as encapsulating our incomplete knowledge of the system. After weighing up arguments for and against these two views, Gao rejects the epistemological view, and adopts the ontological view. He then goes on to give an exposition and careful discussion of the modern version of Bohm's interpretation of quantum theory which, after discussion, is rejected. There is also a critical discussion of the Everett or many worlds interpretation of quantum theory.

Gao then gives a sympathetic discussion of Schrödinger's charge density interpretation of the wave function, an interpretation which is, however, rejected because of the problem posed by systems of two or more quantum entangled particles. This leads on to a discussion of the view that a configuration space of 3N dimensions, associated with a system of N quantum entangled particles should be regarded as real. This view, defended by David Albert,[1] is rejected. Gao sensibly adopts the view that a system of N quantum entangled particles should be regarded as having correlated states in three dimensional physical space.

Gao then proceeds to expound the realist interpretation of quantum theory he wishes to defend. A quantum system, such as an electron, is held to exhibit very rapid discontinuous motion, very briefly occupying values of spatial position, momentum and energy in such a way as to accord with what orthodox quantum theory predicts, given relevant measurements. The wave function specifies the state of that which determines, probabilistically, the discontinuous motion of the electron.

Ascribing precise values of position, momentum, energy, and other such physical quantities, to particles at any given instant would seem to contradict a famous theorem due to Kochen and Specker. Gao argues that there are two ways in which this contradiction can be overcome, and he justifies his choice.

Gao goes on to expound in some detail his solution to the quantum measurement problem. A system whose quantum state is in a superposition of energy eigenstates, over time evolves into one or other eigenstate. Imprecise energy becomes precise. The system does this, however, in such a way that, statistically, energy is conserved as far as the ensemble of systems in the same pure state is concerned. Gao argues that the specific postulate he puts forward is such that almost all ordinary experiments performed on quantum systems that are in superpositions of energy eigenstates would not detect deviations from Schrödinger's equation and the predictions of orthodox quantum theory. At the same time, he argues, his collapse postulate predicts that macroscopic measuring instruments, employed in quantum measurements evolve, not into superpositions of macroscopic states (as the Schrödinger equation would imply) but into just one of the macroscopic states that are possible. The proposed collapse postulate provides a potential solution to the measurement problem, in other words!

In a little more detail, Gao's collapse postulate amounts to the following. The quantum state ψ of a system is initially, let us suppose, a superposition of energy eigenstates $|E_i>$, so that:

$$\psi(t_o) = \sum_{i=1}^{m} C_i(t_o)\,|E_i>$$

Gao's idea is that, as time passes, the system - undergoing rapid discontinuous motion from one energy eigenstate to another - will tend to spend more time in some eigenstates than others, the outcome being that those eigenstates that are occupied for slightly longer times will progressively increase in probability, until eventually the probability of the system being in one specific eigenstate is 1, and the probability of it being in any of the other eigenstates is correspondingly 0.

An important feature of Gao's proposal is that time is held to be discontinuous, the shortest nugget of time being the Planck time, t_p, the time it takes for light to travel the Planck distance l_p in a vacuum, the Planck length being defined to be:

$$l_p = \sqrt{\frac{\hbar G}{c^3}}$$

Here, $\hbar = h/2\pi$, where h is Planck's constant, G is the gravitational constant, and c is velocity of light in a vacuum.

Employing the idea that the longer the system remains in the state $|E_i>$, so the more probable it will be for the system to be in that state, Gao arrives at the following formula for the collapse time t_c:-

$$t_c \approx \frac{\hbar E_p}{(\Delta E)^2} \; .$$

Here $E_p = h/t_p$, the Planck energy, and ΔE is the energy uncertainty of the initial state.

As Gao points out, others before him have proposed that probabilistic collapse is to be associated with decrease in energy uncertainty with the passage of time. Specifically, Ian Percival[2] and Lane Hughston[3] have put forward versions of this idea. These have been criticized by Philip Pearle[4] on the grounds that they do not procure spatially localized states of macroscopic objects in the way that is required to solve the measurement problem. Gao argues that his own collapse postulate escapes Pearle's critical strictures because of a crucial difference between his proposal, and the proposals of Percival and Hughston. According to Gao's postulate, the energy uncertainty of a many-body system in a partially quantum entangled state "is not the uncertainty of the total energy of all subsystems, but the sum of the absolute energy uncertainty of every subsystem" (p. 121). It is this feature of the collapse postulate, Gao argues, which enables it to evade Pearle's criticisms of earlier, similar proposals (see pp. 130-132).

Gao calculates that standard quantum mechanical experiments would not detect the different predictions of orthodox quantum theory and his version of the theory. This is because energy uncertainties of quantum micro systems are too small to make the different predictions detectable. The energy uncertainty of a photon emitted from an atom is of the order of 10^{-6} eV, which means that the collapse time, according to Gao's formula, is 10^{25} seconds, which is much longer than the age of the universe, some 10^{17} seconds. But when it comes to macroscopic bodies and phenomena, energy uncertainty can be very much larger, and collapse times correspondingly very much shorter, of the order of 10^{-4} seconds Gao suggests in connection with one example (p. 133).

Gao holds, nevertheless, that his postulate is, at least in principle, testable. The nucleus of the naturally occurring element Tantalum (^{180}Ta) is such that the energy gap between the ground state and the first excited state is 75 keV. This means, according to Gao's postulate, that a superposition of these two states decays into one or other state with a collapse time of some 20 minutes (p. 129).

Gao goes on to discuss rival collapse theories of Ghirardi, Rimini and Weber, Roger Penrose, and others, and concludes with a discussion of the problems of extending the postulate into the relativistic domain.

I may not be the best person to give an impartial assessment of Gao's book. Decades ago I published a paper calling for physicists to stop trying to solve the measurement problem (as then conceived); instead they should remove all references to observables and measurement from the theory, and concentrate on putting forward testable conjectures about the physical conditions necessary and sufficient for probabilistic transitions to occur, formulated in elementary, precise, quantum mechanical terms.[5] And in an attempt to provoke such work, I went on, subsequently, to suggest that quantum theory may have its own entirely new ontology of fundamentally probabilistic entities (propensitons); these might interact probabilistically whenever new "particles" or bound systems are created or destroyed as a result of inelastic interactions. I am therefore predisposed to welcome enthusiastically Gao's book. Even though Gao writes about solving the measurement problem, he nevertheless does just what I think physicists ought to do: put forward precise, testable conjectures concerning probabilistic transitions, formulated in exclusively quantum mechanical terms. (Others, too, of course, have pursued research along these lines. Whereas once upon a time questioning orthodox quantum theory was taboo in physics, nowadays there is a much wider recognition that orthodoxy is untenable, and a better version of the theory needs to be established.)

Does Gao's collapse postulate succeed in evading Pearle's criticism of similar proposals? Does it escape obvious empirical refutation, and at the same time successfully account for the absence of superpositions of macro states of affairs (when these appear not to exist)? Does it successfully account for localization when loss of energy uncertainty almost seems to imply the opposite (an issue Gao discusses explicitly)? Is it acceptable that the universe gradually loses energy uncertainty as time passes? If the answer to all these questions is "yes", the crucial question becomes: Is the basic collapse postulate testable in practice? I do not feel competent to pronounce authoritatively on these matters, but I can say that, in my view, *The Meaning of the Wave Function* makes a courageous and fascinating contribution to understanding the quantum domain. I hope it provokes research from others along similar lines.

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[1] Albert, D.Z., 1992, *Quantum Mechanics and Experience*, Harvard University Press, Cambridge, Mass.

[2] Percival, I.C., 1995, Quantum Spacetime Fluctuations and Primary State Diffusion, Proc. R. Soc. London, Ser. A **451**, 503.

[3] Hughston, L.P., 1996, Geometry of Stochastic State Vector Reduction, Proc. R. Soc. London, Ser. A **452**, 953.
[4] Pearle, P., 2004, Problems and aspects of energy-driven wave-function collapse models *Physical Review* A **69**, 042106.
[5] Maxwell, N., 1972, A new look at the quantum mechanical problem of measurement, *Am. J. Phys*., **40** (10), 1431.