Quantum mechanics

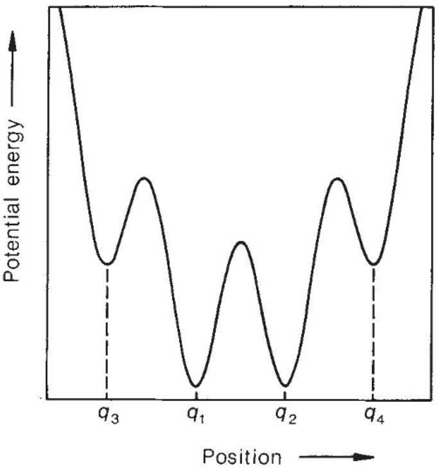
Is the theory applicable to macroscopic objects?

from Ulrich Eckern

DESPITE the fact that quantum mechanics has been used successfully for decades to explain physical processes on an atomic or sub-atomic level, a slight uneasiness has remained about the connection between quantum mechanics and daily life, which is governed by the laws of classical mechanics. This relation is unique: although quantum mechanics contains newtonian mechanics as a limiting case, at the same time it requires this limiting case for its own formulation. The importance of the concept of measurement, that is, the interaction of a quantum object with a classical object (a measuring apparatus) has been elucidated by Niels Bohr. Objections to these ideas have been formulated, perhaps most rigorously by Albert Einstein (see ref. 1). Naturally, the question arises of how quantum theory extrapolates to macroscopic systems: are there interference phenomena associated with the superposition of wavefunctions describing macroscopically distinct states? Is the transition from quantum to classical behaviour continuous or discontinuous? Clearly, these questions have to be answered experimentally.

To demonstrate the principle of superposition, let us consider an object which can be described by a single variable, say q (the coordinate of a 'particle'), with a potential energy $U(q)$ as shown in the figure. Evidently, the potential has two equivalent stable minima, q_1 and q_2, and a classical particle in its ground state (the state of lowest energy) will be located at q_1 or q_2. In the quantum case, because of the uncertainty principle, the energy of these two states is increased to the value $h\nu/2$ (zero point motion), where h is Planck's constant and ν the frequency of classical oscillations of small amplitude (near q_1 or q_2). In addition, the exponentially small overlap of the wavefunctions localized at q_1 and q_2, respectively, leads to the possibility of coherent tunnelling between '1' and '2': The probability of finding the particle in state 1 at a certain time t, $P(t)$, is oscillating between one and zero (with a frequency much smaller than ν). This phenomenon, quantum coherence, is well established for microscopic systems — for example, the oscillations between the two positions of the nitrogen atom in an ammonia molecule (ammonia maser), and the oscillations between the two values of strangeness of a neutral K-meson.

What are the difficulties in applying quantum mechanics to macroscopic objects? Much theoretical[2-7] and experimental[8-12] work has been inspired by the ideas of A.J. Leggett[2]. The important point is that, even if the description of a macroscopic object by a single collective variable, say q, is a good approximation (and this can be justified for specific models[4]), there is always an environment, caused by all the microscopic degrees of freedom, leading to friction in the motion of this variable. Theoretical results[5-7] indicate a behaviour that depends crucially on the value of the dimensionless friction constant, α, as well as on temperature, T. Especially, for $T = 0$, three regimes have to be distinguished. For $0 \leqslant \alpha < \frac{1}{2}$, coherent oscillations are obtained in $P(t)$ (quantum behaviour), whereas for $\alpha > 1$, the system is localized in one of the minima (classical behaviour). The intermediate range (except for $\alpha = \frac{1}{2}$) is an unresolved problem[7]. In addition, for $\alpha < 1$ and at temperatures that are not too low (depending on α), and for all temperatures if $\alpha > 1$, incoherent relaxation is predicted, with $P(t)$ decreasing exponentially with time.



Relevant experiments[8-12] have been performed recently using superconducting quantum interference devices (SQUIDs) and Josephson junctions at very low temperatures (a few millidegrees from absolute zero). For example, the SQUID is a superconducting ring interrupted by a weak link, in which case the collective variable q is the magnetic flux through the ring, and oscillations of q correspond to an alternating current. The figure shows the potential relevant to this case, provided a certain external magnetic field is applied. In addition, α is equal to R_0/R, where R is the resistance of the SQUID and R_0 is close to $h/4e^2 \simeq 6{,}453$ ohms (e is the charge of an electron). But macroscopic quantum coherence has not yet been observed. Instead, experimental investigations have focused on the tunnel effect, a separate but related aspect of quantum mechanics.

Suppose that the particle is initially localized in an unstable minimum of the potential (at q_3 or q_4). The probability of finding the particle close to that minimum then decreases in time, and the decay time can be determined by monitoring the change of the magnetic flux. In agreement with the theoretical prediction[3], it is found that the decay rate at low temperatures is larger than the rate predicted by thermal activation theory and approaches a temperature-independent value for $T \rightarrow 0$. This value is thought to be caused by quantum tunnelling. In addition, the $T = 0$ decay rate decreases with increasing dissipation, which agrees with the expectation that the width of a wavefunction (for example, a harmonic oscillator in its ground state) is reduced by contact with an environment.

However, experiments have gone one step further: if the decay rate out of the metastable state is small, then, for a quantum variable, the energy levels for states localized near the unstable minimum have to be quantized and, by irradiating the system with microwaves, the particle can be excited into higher states. Thus, the decay rate (which is larger for higher energy levels) has to increase if h times the microwave frequency equals the energy difference (of, for example, the transition from the lowest to the first excited level). This has been confirmed in an elegant experiment by J.M. Martinis, M.H. Devoret and J. Clarke[10], which provides further evidence for the existence of macroscopic quantum phenomena. Although the idea of macroscopic quantum coherence still needs experimental justification, I believe that the experiments described here represent important steps in this direction, and that they may ultimately shed some light on the relationship between classical and quantum physics. ☐

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