Experimental observation of decoherence[*]

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In the 1980s, theoretical estimates showed that on macroscopic scales ▶ decoherence occurs extremely rapidly, thus effectively precluding the observation of nonclassical ▶ superposition states [21–23]. This immediately led to the question of how we may experimentally observe the continuous action of decoherence and thus the smooth transition from quantum to classical. Several challenges have to be overcome in the design of such experiments. The system is to be prepared in a nonclassical superposition of mesoscopically or even macroscopically distinguishable states (▶ Schrödinger-cat state) with a sufficiently long decoherence time such that the gradual action of decoherence can be resolved. The existence of the superposition must be verified, and a scheme for monitoring decoherence must be devised that introduces a minimal amount of additional decoherence. Starting in the mid-1990s, several such experiments have been successfully performed, using physical systems such as:

- Cavity QED (atom–photon interactions) [1];
- Fullerenes (C_{60}, C_{70}) and other mesoscopic molecules [2];
- Superconducting systems (SQUIDs, Cooper-pair boxes) [3].

Other experimental domains are promising candidates for the observation of decoherence; however, the necessary superposition states have not yet been realized:

- Bose–Einstein condensates [24];
- Nano-electromechanical systems [4].

These five classes of experiments are described below (for a more detailed account, see, e.g., Chap. 6 of [21]). Such experiments are important for several reasons. They are impressive demonstrations of the possibility of generating nonclassical states of mesoscopic and macroscopic objects. They show that the boundary between quantum and classical is smooth and can be moved by varying the relevant experimental parameters. For example, by engineering different strengths and types of environmental interactions, wide ranges of decoherence rates can be obtained and the system can be driven into different preferred ("environment-superselected") bases [5]. The experiments also allow us to test and improve decoherence models. Finally, they may reveal deviations from unitary quantum mechanics and thus may be used to test quantum mechanics itself [3]. This would require sufficient shielding of the system from decoherence so that an observed (full or partial) collapse of the wavefunction could be unambigously attributed to some novel nonunitary mechanism in nature, such as that proposed by the ▶ GRW theory. However, this shielding would be

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extremely difficult to implement in practice: The large number of atoms required for the collapse mechanism to be effective also leads to strong decoherence [6]. None of the superpositions realized in current experiments disprove existing collapse theories [7].

Cavity QED

In 1996 Brune et al. at Ecole Normale Supérieure in Paris generated a superposition of radiation fields with classically distinguishable phases involving several photons [1, 8, 24]. This experiment was the first to realize a mesoscopic ▶ Schrödinger-cat state and to observe and manipulate its decoherence in a controlled way.

The experimental procedure is as follows. A rubidium atom is prepared in a superposition of distinct energy eigenstates $|g\rangle$ and $|e\rangle$ corresponding to two circular Rydberg states. The atom enters a cavity C containing a radiation field containing a few photons. The field effectively measures the state of the atom: If the atom is in the state $|g\rangle$, the field remains unchanged, whereas if the state is $|e\rangle$, the ▶ coherent state $|\alpha\rangle$ of the field undergoes a phase shift ϕ, $|\alpha\rangle \longrightarrow |\mathrm{e}^{i\phi}\alpha\rangle$. The experiment achieved $\phi \approx \pi$. The linearity of the evolution implies that the initial superposition of the atom is amplified into an entangled atom–field state of the form $\frac{1}{\sqrt{2}}\left(|g\rangle|\alpha\rangle + |e\rangle|-\alpha\rangle\right)$. The atom then passes through an additional cavity, further transforming the superposition. Finally, the energy state of the atom is measured. This disentangles the atom and the field and leaves the latter in a superposition of the mesoscopically distinct states $|\alpha\rangle$ and $|-\alpha\rangle$.

To monitor the decoherence of this superposition, a second rubidium atom is sent through the apparatus. One can show that, after interacting with the field superposition state in cavity C, the atom will always be found in the same energy state as the first atom if the superposition has not been decohered. This correlation rapidly decays with increasing decoherence. Thus, by recording the measurement correlation as a function of the wait time τ between sending the first and second atom through the apparatus, the decoherence of the field state can be monitored. Experimental results were in excellent agreement with theoretical predictions. The influence of different degrees of "nonclassicality" of the field superposition state was also investigated. It was found that decoherence became faster as the phase shift ϕ and the mean number $\bar{n} = |\alpha|^2$ of photons in the cavity C was increased. Both results are expected, since an increase in ϕ and $\bar{n}$ means that the components in the superposition become more distinguishable. Recent experiments have realized superposition states involving several tens of photons [9].

Fullerenes and other mesoscopic molecules

These experiments were carried out by the group of Zeilinger and Arndt at the University of Vienna [2] and are also described in the entry ▶ Mesoscopic Quantum Phenomena. Basically, they represent sophisticated versions of the ▶ double-slit experiment. Spatial interference patterns are here demonstrated for mesoscopic molecules such as the fullerenes C_{60} and C_{70} (containing $O(1,000)$ microscopic constituents), the fluorinated fullerene $C_{60}F_{48}$ (mass $m = 1632$ amu), and the biomolecule $C_{44}H_{30}N_4$ ($m = 614$ amu, width over 2 nm). Since the de Broglie wavelength of these rather massive molecules is on the order of picometers and since it is impossible to manufacture slits of such small width, standard double-slit interferometry is out of reach. Instead the experiments make use of the Talbot–Lau effect, a true interference phenomenon in which a plane wave incident on a diffraction grating creates an "image" of the grating at multiples of a distance L behind the grating. In the experiment, the molecular density (at a macroscopic distance L) is scanned along the direction perpendicular to the molecular beam. An oscillatory density pattern (the image of the slits in the grating) is observed, confirming the existence of coherence and interference between the different paths of each individual molecule through the grating.

Decoherence is measured as a decrease of the visibility of this pattern. Such decoherence can be understood as a process in which the environment obtains information about the path of the molecule (see also ▶ Which-way experiment). This leads to a decay of spatial coherence at the level of the molecule. As described under ▶ Mesoscopic Quantum Phenomena, controlled decoherence induced by collisions with background gas particles and by emission of thermal radiation from heated molecules has been observed, showing a smooth decay of visibility in agreement with theoretical predictions. These successes have led to speculations that one could perform similar experiments using even larger particles such as proteins, viruses, and carbonaceous aerosols. Such experiments will be limited by collisional and thermal decoherence and by noise due to inertial forces and vibrations [10].

Superconducting systems

See also ▶ Superconductivity. The idea of using superconducting quantum two-state ("qubit") systems for the generation of macroscopic superposition states goes back to the 1980s [11]. The main systems of interest are superconducting quantum interference devices (SQUIDs) and Cooper-pair boxes.

SQUIDs. A SQUID consists of a ring of superconducting material interrupted by thin insulating barriers, called Josephson junctions (Fig. 1a). At sufficiently low temperatures, electrons of opposite spin condense into bosonic *Cooper pairs* (▶ BKS theory). Quantum-mechanical tunneling of Cooper pairs through the junctions leads to the flow of a persistent resistance-free "supercurrent" around the loop (Josephson effect), which creates a magnetic flux threading the loop. The collective center-of-mass motion of a macroscopic number ($\sim 10^9$) of Cooper pairs can then be represented by a ▶ wave function labelled by a single macroscopic variable, namely, the total trapped flux Φ through the loop. The two possible directions of the supercurrent define a quantum-mechanical two-state system with basis states $\{|\circlearrowright\rangle, |\circlearrowleft\rangle\}$. By adjusting an external magnetic field, the SQUID can be biased such that the two lowest-lying energy eigenstates $|0\rangle$ and $|1\rangle$ are equal-weight superpositions of the persistent-current states $|\circlearrowright\rangle$ and $|\circlearrowleft\rangle$. Such superposition states involving μA currents flowing in opposite directions were first experimentally observed in 2000 by Friedman et al. [12] and van der Wal [13] using spectroscopic measurements.

The decoherence of these superpositions was first measured by Chiorescu et al. [14] using Ramsey interferometry [24]. Two consecutive microwave pulses are applied to the system. During the delay time τ between the pulses, the system evolves freely. After application of the second pulse, the system is left in a superposition of the persistent-current states $|\circlearrowright\rangle$ and $|\circlearrowleft\rangle$ with the relative amplitudes exhibiting an oscillatory dependence on τ. A series of measurements in the basis $\{|\circlearrowright\rangle, |\circlearrowleft\rangle\}$ over a range of delay times τ then allows one to trace out an oscillation of the occupation probabilities for $|\circlearrowright\rangle$ and $|\circlearrowleft\rangle$ as a function of τ (Fig. 1b). The envelope of the oscillation is damped as a consequence of decoherence acting on the

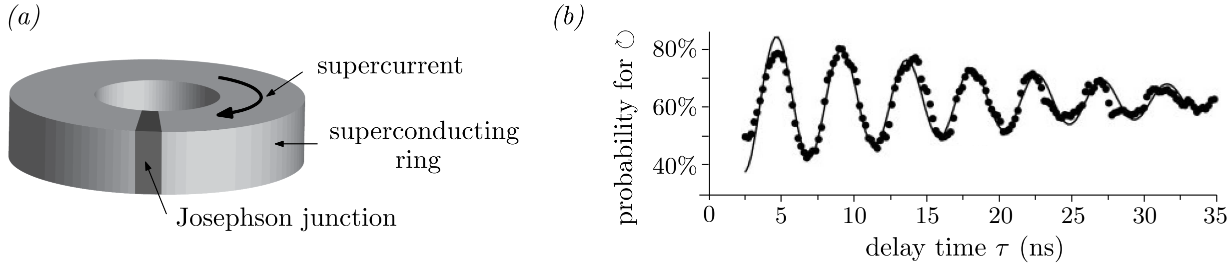

FIG. 1: *(a)* Schematic illustration of a SQUID. A ring of superconducting material is interrupted by Josephson junctions, which induce the flow of a dissipationless supercurrent. *(b)* Decoherence in a superconducting qubit. The damping of the oscillation amplitude corresponds to the gradual loss of coherence from the system. Figure adapted with permission from [14]. Copyright 2003 by AAAS.

system during the free evolution of duration τ. From the decay of the envelope we can thus infer the decoherence timescale. Chiorescu et al. [14] measured a characteristic decoherence timescale of 20 ns. Recent experiment have achieved decoherence times of up to 4 μs [15].

Cooper-pair boxes. Superpositions states and their decoherence have also been observed in superconducting devices whose key variable is charge (or phase), instead of the flux variable Φ used in SQUIDs. Cooper-pair boxes consist of a tiny superconducting "island" onto which Cooper pairs can tunnel from a reservoir through a Josephson junction. Two different charge states of the island, differing by at least one Cooper pair, define the basis states. Coherent oscillations between such charge states were first observed in 1999 [16]. In 2002, Vion et al. [17] reported thousands of coherent oscillations with a decoherence time of 0.5 μs. Similar results have been obtained for phase qubits.

Prospective experimental domains

Bose–Einstein condensates (BECs). In ▶Bose-Einstein condensation, a macroscopic number of atoms undergoes a quantum phase transition into a condensate in which the atoms lose their individuality and occupy the same quantum state [24]. While quantum effects such as interference patterns—created by the overlap of different condensates or by coherently splitting and recombining a single condensate—have been experimentally observed, the preparation of superposition states involving macroscopically distinguishable numbers of particles have to date been unsuccessful. Theoretical studies of decoherence in BECs have played an important role in qualitatively and quantitatively understanding the challenges and conditions for the generation of such superpositions (see, e.g., [18]). The dominant source of decoherence was found to be collisions between condensate and noncondensate atoms. Decoherence models have suggested improved experimental procedures that may soon enable production of the desired superposition states. Existing proposals include: Modified condensate traps for faster evaporation of the decoherence-inducing thermal cloud of noncondensate atoms; creation of superpositions of relative-phase (instead of number-difference) states; environment engineering to shrink the thermal cloud; and faster generation of the superposition.

Nano-electromechanical systems (NEMS). NEMS are nanometer-to-micrometer–sized crystalline mechanical resonators, such as a cantilever or beam, coupled to nanoscale

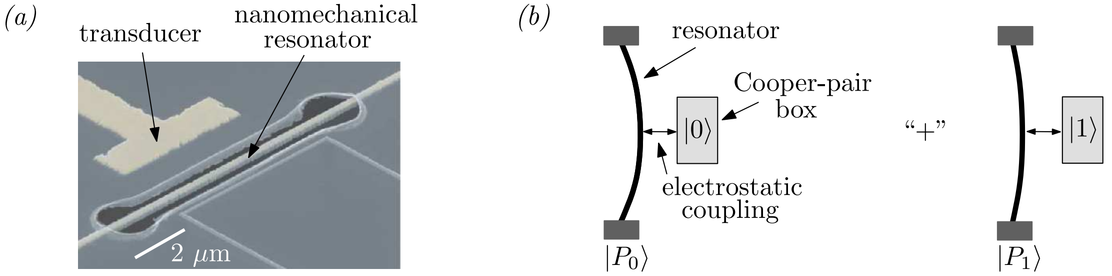

FIG. 2: *(a)* Nano-electromechanical system built by the Schwab group at Cornell University. Figure reprinted with permission from [19]. Copyright 2004 by AAAA. *(b)* Proposed scheme for creating a superposition of two displacements of the resonator (see text).

electronic transducers that detect the high-frequency vibrational motion of the resonator (Fig. 2a) [4]. Despite their macroscopic size, the resonators can be effectively treated as one-dimensional quantum harmonic oscillators (representing the lowest, fundamental flexural mode). NEMS are interesting systems from both applied and fundamental points of view and offer many opportunities for a study of quantum behavior at the level of macroscopic mechanical systems. In particular, Armour, Blencowe, and Schwab [20] have proposed a scheme for the experimental generation of superpositions of two well-separated displacements of the resonator and a measurement of the decoherence of this superposition (Fig. 2b). Here, a Cooper-pair box (prepared in a superposition of two charge states $|0\rangle$ and $|1\rangle$) is electrostatically coupled to the displacement of the resonator. This creates an entangled box–resonator state of the form $\frac{1}{\sqrt{2}}(|0\rangle|P_0\rangle + |1\rangle|P_1\rangle)$, where $|P_0\rangle$ and $|P_1\rangle$ are distinct center-of-mass states of the resonator. Existence of the superposition may subsequently be confirmed through interferometric techniques. Due to strong decoherence, no such superpositions have yet been experimentally realized. Theoretical models of decoherence in NEMS are currently being developed to suggest improvements to experimental structures that could lead to sufficiently long-lived spatial superposition states.

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