Schrödinger Cats

in Atom-Trap BECs

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Microscopic quantum superpositions are routinely observed in experiment. Macroscopic quantum superpositions, on the other hand, are still encountered rarely despite nearly a century of experimentation with quantum mechanics. Fast decoherence of macroscopic states is to blame for this state of affairs (see the articles "Decoherence and the Transition from Quantum to Classical" and "The Emergence of Classical Dynamics in a Quantum World" on pages 86 and 110). And yet, the past few years have witnessed several breakthroughs in the macroscopic regime. To name a few, superposition states of macroscopic numbers of photons and atoms have been produced in cavity quantum electrodynamics, matter-wave interference in fullerene carbon-60 has been observed, and controlled decoherence due to engineered environments has been measured in ion traps. Recently, the first detection of a macroscopic Schrödinger cat state in a radio-frequency (rf) superconducting quantum interference device, or SQUID (a superposition of clockwise and counterclockwise superconducting current flow), was reported. All these achievements tempt one to try similar investigations of basic quantum mechanics in the rapidly growing field of Bose-Einstein condensates (BECs).

In the article "Atom-Trap BECs" on page 136, Eddy Timmermans describes the possible emergence of nonclassical behavior by number squeezing in a dilute BEC. For a double-well configuration, the ground state of the condensate is determined by the competition between the tunneling energy $E_{\text{tun}} = -\gamma E_J \cos\alpha$, which favors states with a well-defined relative phase between the wells, and the interaction energy $E_{\text{int}} = (U/2)(N^2 + m^2)$, which favors number states in each well. When the interaction energy is repulsive ($U > 0$), the ground state corresponds to $m = 0$, and $\alpha = 0$, that is, an equal number of particles in the two wells with zero relative phase. However, for attractive interactions ($U < 0$), the ground state is very different: It corresponds to a superposition of states with $m = +N$ and $m = -N$, namely,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} |N_L = N, N_R = 0\rangle \\ +|N_L = 0, N_R = N\rangle \end{bmatrix} .$$

This state is clearly nonclassical, all N bosons being simultaneously in the left well and in the right well. It corresponds to a macroscopic quantum superposition—a BEC Schrödinger cat—analogous to Schrödinger's Gedanken experiment of a cat in the weird superposition of being both dead and alive.

Various schemes have been proposed for building macroscopic superpositions in BECs. For example, for a BEC in a double-well potential with an attractive interparticle interaction, one can in principle create the cat state through adiabatically cooling down the BEC until the ground state is reached. Another option is to confine bosons that have an attractive interaction between atoms in two hyperfine levels (A and B) in a single potential well. Initially, all atoms in the BEC are in a given hyperfine state, say A, and then a resonant rf pulse is applied to the system to transfer (or rotate) the atoms part of the way between state A and B. The duration of the pulse is much shorter than the self-dynamics of the condensate. At this stage, each atom is in a superposition of levels A and B, and the corresponding many-body quantum state is a product of single-particle superpositions of A and B, that is, it is still a microscopic superposition. However, as this initial state evolves under the nonlinear Hamiltonian that governs the BEC with its attractive interparticle interactions, it reaches a macroscopic superposition in which all atoms are simultaneously in level A and level B, $|\Psi\rangle = (1/\sqrt{2})[|N_A, 0_B\rangle + |0_A, N_B\rangle]$. An even weirder superposition state has been proposed, namely, a coherent superposition of atomic and molecular BECs. It must be stressed that, to date, no experiment has been carried out that attempts to produce any of the aforementioned superposition states.

The condensate is an open quantum system, that is, it is in contact with an environment mainly composed of noncondensed thermal particles. The interaction between that environment and the BEC cat state may cause the loss of coherence between the components of the quantum superposition. If the decoherence time were very small, then the existence of these states in a BEC would be merely of academic interest because there would be no chance of observing them in the laboratory. Therefore, it is important to understand how the thermal cloud affects the longevity of BEC cat states. In principle, a single noncondensed atom colliding with the condensed superposition state and taking away information

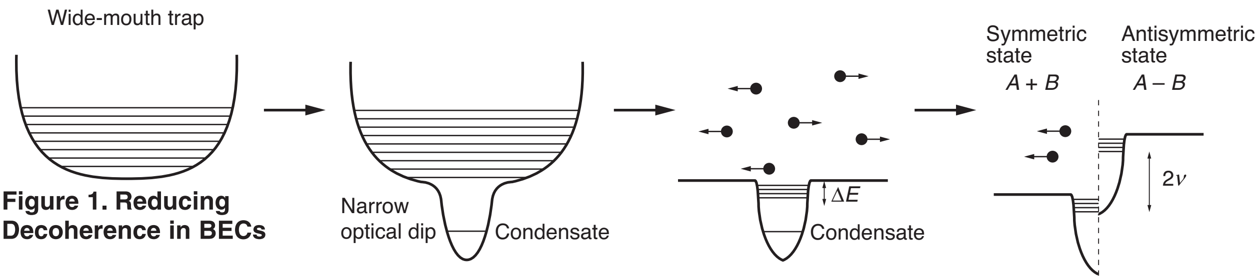

Figure 1. Reducing Decoherence in BECs

about the phase of the state is enough to kill the atomic coherence. Estimated decoherence times for the proposed BEC cat states are inversely proportional to the product of N_E (the number of noncondensed bosons) and N^2 (where N is the number of bosons in the condensate), that is, $t_{dec} \approx 10^5$ seconds/$(N_E N^2)$. For N_E from 10^0 to 10^4 and N from 10^1 to 10^7, the decoherence times can range over 16 orders of magnitude, from 1000 seconds down to 10^{-13} second. Given that macroscopic cats require big values of N, it is clear that, for the sake of the cat's longevity, one must go beyond the standard trap settings.

In what follows, we concentrate on a BEC cat formed with two hyperfine states A and B. We show that, by using a combination of trap engineering and what we call "symmetrization" of the environment, as illustrated in Figure 1, one can decrease decoherence rates. First, one prepares the condensate inside a wide magnetic trap and then superimposes a narrow optical dip. The parameters of the traps are chosen such that only a single bound state lies within the dip. The bosons are forced to adiabatically condense into that state. Then the magnetic trap is opened, and most of the noncondensed atoms are allowed to disperse away. The aim of this procedure is to eliminate as much of the thermal cloud as possible. However, atoms occupying bound states within an energy band of width ΔE at the mouth of the dip may not disperse away, but the occupation numbers of those states before the opening of the wide trap may subsist. Those atoms would stay in contact with the condensate and continue to monitor its quantum state and thereby destroy any chance of the condensate to form a superposition. Even if such a truncated environment is relatively harmless, there are ways to better protect the condensate from it.

What we call "symmetrization" of the environmental states can further reduce the decoherence rate. To produce symmetrization, one applies an rf pulse with frequency ν that induces coherent transitions between states A and B of all atoms, both condensed and thermal ones. On the one hand, the state of the condensate is still a macroscopic superposition but slightly different from the original one $(1/\sqrt{2})[|N_A,0_B\rangle + |0_A,N_B\rangle]$ because the rf pulse produces a small increase in the variance of the number of atoms in each well. On the other hand, the single-particle energy spectrum of the noncondensed bosons is modified. It is now composed of two energy-level ladders shifted with respect to each other by 2ν. One ladder is shifted down, corresponding to states symmetric under the interchange $A \leftrightarrow B$, and the other is shifted upwards, corresponding to states antisymmetric under such interchange. When the energy bandwidth near the mouth of the dip $\Delta E << 2\nu$, only symmetric environmental states are occupied. A collision between atoms occupying those states and the condensate does not affect the phase coherence of the latter because both states and the interaction Hamiltonian are symmetric under the interchange $A \leftrightarrow B$. In other words, a symmetric environmental state affects the components $(|N_A,0_B\rangle$ and $|0_A,N_B\rangle)$ of the BEC cat in exactly the same way, multiplying them by a common phase factor, which obviously does not affect the phase coherence of the condensate. When the relation $\Delta E << 2\nu$ does not hold, some atoms will occupy antisymmetric environmental states and can cause decoherence. However, since that occupation number can be controlled by the intensity of the laser field inducing the coherent transitions between the states A and B, the method of symmetrization can still significantly extend the longevity of the BEC cat. ■

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