

Dissipative Quantum Tunneling

Samuel Défago

The problem of validity of quantum mechanics at the macroscopic level, emphasized by Schrödinger's question about some dead-and-alive cat, was the subject of many physical interests. Among quantum mechanical effects physicists dreamt to find at the macroscopic level, tunneling kept a place of choice. With the discovery of the Josephson effect, macroscopic quantum systems seemed feasible, and the first experimental realizations were made in the early 80's. A few years later, Caldeira and Leggett studied quantum tunneling in dissipative systems, an approach reluctant for both microscopic and macroscopic systems. By their very nature, the last ones are inherently dissipative, since the system interacts with its environment. The results obtained by Caldeira and Leggett, who applied the so-called system-plus-bath model to introduce dissipation, could later be observed in Josephson junctions, confirming the relevance of their predictions for macroscopic systems.

Physically motivated by phenomena like electron or defect tunneling in solids, where the system (an electron, respectively a defect) is coupled to phonons, the idea of the system-plus-bath model is to couple the system to its environment (here the phonons), assumed to be in thermal equilibrium, and modeled as a set of quantum harmonic oscillators. Under certain assumptions, the system exhibits Ohmic dissipation, which is relevant in a large number of practical cases, like in Josephson junctions.

By applying this model, we then discuss tunneling of the system in the special case of Ohmic dissipation. We assume the system to live in a quadratic-plus-cubic potential, presenting one metastable position, which the system can leave either by thermal decay or by quantum tunneling, depending on the temperature. Since we are only interested in the typically quantum mechanical phenomenon of tunneling, we choose to work at zero-temperature, and initially prepare the system in the ground state at the bottom of the potential well, corresponding to the metastable position. The decay rate of the system then reduces to the tunneling rate out of the ground state, for which we will find an explicit expression. To achieve this goal, the path integral formalism and the imaginary-time formulation will be helpful tools. Finally, we apply the formula we have established for the tunneling rate to the special cases of weak and strong dissipations, showing that, in both cases, dissipation tends to suppress quantum tunneling.

As an application of the theory, we present an experimental device living at the macroscopic scale, the SIS Josephson junction, which exhibits quantum mechanical behavior. Such a device consists in two superconductors separated by a thin insulating barrier. By using the so-called RCSJ-model, which describes the dynamics of such a device by a circuit where the junction is in parallel with an effective Ohmic resistance and a capacitance, we find an equation of motion for the macroscopic variable describing the system, in the case of a SIS junction the difference between the two superconducting phases. By applying an external current to the junction, the potential in which the system lives can locally be approximated by a quadratic-plus-cubic potential, and the system can leave the potential well by quantum tunneling (at temperatures close to zero), so that the junction physically travels between two macroscopically distinct states. Having presented the principles of the device, we end with the discussion of an experimental method used to observe the tunneling of the junction.