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京都大学
7. 消耗とマクロスコピック量子システムの動力学

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1. Introduction

In the dynamics of macroscopic systems, the dissipative effect is
unavoidable. Owing to the recent development of microfabrication technique, the quantum effect is being observed in the dynamics of macroscopic degrees of freedom such as the magnetic flux in SQUID which also obeys the dissipative dynamics. Caldeira and Leggett\(^1\)) have given a theoretical formulation to include the Ohmic dissipation in the dynamics of macroscopic variables. Here we review their result and some examples of its applications. In the following, the explicit formulae are not given due to the limitation of length. For the details, see the references given at the end of the paper.

2. Quantum Tunnelling with Dissipation

In the single junction SQUID, the dynamics of the magnetic flux \(\phi\) confined in the ring is described by the equation of motion equivalent to that for the damped motion of a particle in the nonlinear potential.\(^1\)) If the external magnetic flux is increased from zero to a certain finite value, the state with \(\phi = 0\) becomes metastable. It decays into the true ground state by thermal activation or quantum tunnelling. At low temperatures, the quantum tunnelling is dominant if the size of the junction is small enough. This tunnelling process is accompanied by dissipation. Caldeira and Leggett\(^1\)) treated this process theoretically introducing the heat bath consisting of infinite number of harmonic oscillators linearly coupled to \(\phi\). Using the imaginary time path integral formalism and eliminating the heat bath variables, they obtained the path integral expression for the thermodynamic quantities in terms of the effective action which is the functional only of \(\phi\).

Using this action, the tunnelling rate \(\Gamma\) is calculated. It is shown that \(\Gamma\) is always reduced by dissipation. The recent experiments using small junctions of submicron size confirm their result quantitatively\(^2\).

3. Quantum Coherence and Dissipation

If \(\phi\) is equal to \(\phi_0/2\) (\(\phi_0\): flux quantum), the states with \(\phi = 0\) and \(\phi_0\)
are doubly degenerate ground states in the absence of tunnelling. In the usual quantum mechanics with tunnelling, the true ground state is the coherent superposition of the two states above. It is shown, however, that for sufficiently strong damping the coherence is destroyed and tunnelling probability vanishes. As a result, the system stays in one of the localized states. The theoretical treatment is given in 3). The experimental detection of coherent behavior is not yet successful and is one of the most challenging experiments in this field.

4. Dissipation and Chaos in Quantum Systems

While the chaotic orbit can attain a fine structure of any complexity in the classical systems, it is destroyed by the interference of wave function in the corresponding quantum systems, and the quantum-classical correspondence holds only for the rather short time scale $\tau_c \sim \ln h^{-1}$ 4). The dissipative coupling with the heat bath can destroy the interference helping the recovery of the chaotic dynamics 5).

In the real time path integral representation of the quantum dynamics of the density matrix, two exponential factors appear corresponding to the time developments along forward and backward paths $q_1$ and $q_2$. In the absence of dissipation, these paths can be arbitrarily apart and contribute to the integral with equal weight and various phase factors resulting in interference. The dissipative contribution to the action, however, suppresses the fluctuation in $y = q_1 - q_2$ reducing the interference between widely separated paths. The amplitude $\delta y$ of the fluctuation in $y$ is bounded by $\sqrt{\hbar C}$ (C: a constant determined by the heat bath). If C is finite, $\delta y$ is bounded uniformly with respect to time and the interference is suppressed for arbitrary time in the limit $\hbar \to 0$. For the Ohmic heat bath, C is logarithmically divergent with respect to time. This divergence, however, is so weak that the convergence is uniform within practical time scale.

If $\delta y$ is much smaller than the typical variation scale of nonlinear
potential, the interference is well reduced and the distribution of the paths is equivalent to that of the Brownian motion with the c-number quantum noise with colored time correlation\(^5,6\)). This noise is the main quantum effect in the semiclassical dissipative system. Although the chaotic orbit is sensitive to the noise, the structure of the chaotic attractor would not be strongly affected by the noise if it is structurally stable enough. If it is not the case, however, the noise has dominating effect on the dynamics\(^7,8\)).

5. Bloch Wave Oscillation in Josephson Junction

The oscillation corresponding the Bloch oscillation of a quantum particle in a ideal crystal is realized in Josephson junction in which the phase corresponds to the displacement of the particle and the charge to its momentum. For details, see 9)(theory) and 10)(experiment).

References

As reviews on the subjects in sections 1 - 3:


For section 2:


For section 3:


10) K. Yoshihiro, J. Kinoshita, K. Inagaki and C. Yamanouchi: same as A) 298.