STOCHASTIC PROCESSES APPLIED TO PHYSICS

Proceedings of the International School held in
Santander, Spain, 10-14 September 1984

Editors: L Pesquera & M A Rodriguez

World Scientific

Published by

World Scientific Publishing Co Pte Ltd.
P. O. Box 128, Farrer Road, Singapore 9128
242, Cherry Street, Philadelphia PA 19106-1906, USA

Library of Congress Cataloging in Publication Data

Main entry under title:

Stochastic Processes Applied to Physics.

Papers presented at the International School on Stochastic Processes Applied to Physics sponsored by the Universidad Internacional Menéndez Pelayo and the Grupo Interuniversitario de Física Teórica.
1. Stochastic Processes — Congresses. 2. Mathematical Physics — Congresses. I. Pesquera, L. II. Rodriguez, M. A. III. International School on Stochastic Processes Applied to Physics (1984: Santander, Spain) IV. Universidad Internacional Menéndez Pelayo. V. Grupo Interuniversitario de Física Teórica (Spain)

QC20.7.S8S74 1985 530.1'592 85-14499
ISBN 9971-978-20-2

Printed in Singapore by Singapore National Printers (Pte) Ltd.

CONTENTS

DISSIPATIVE QUANTUM DECAY AT FINITE TEMPERATURES

Peter Hanggi, Department of Physics
Polytechnic Institute of New York
333 Jay Street, Brooklyn, NY 11201, USA

and

Hermann Grabert and Ulrich Weiss
Institut für Theoretische Physik, Universität Stuttgart
Pfaffenwalding 57, D-7000 Stuttgart-80

In various experiments performed over the last four years a typical quantum behavior of macroscopic variables of Josephson systems has been observed. Those experiments spurred a rapid development of the theory which accounts for the effects of damping upon the quantum behavior including tunneling, coherence and fluctuations. In the following, the discussion is confined to the topic of dissipative quantum decay.

We consider a quantum system, interacting with a thermal environment at temperature T, which can decay out of a metastable state. The metastable state is rendered unstable via both, thermal activation over the barrier and quantum tunneling. Kramers' classical theory of the activation rate becomes modified at lower temperatures when quantum fluctuations and tunneling prevail. An efficient technique to calculate the decay rate Γ in presence of dissipative quantum effects (damping) is given by Feynman's path-integral approach. To determine the decay rate Γ, which is proportional to the imaginary part of the free energy, the Euclidian time version of Feynman's path-integral is used advantageously, and the so-called "bounce" technique originally introduced by Langer and beautifully popularized by Coleman, is employed. Within the WKB approximation, there occurs a crossover temperature T_0

$$T_0 = \frac{\hbar}{2\pi k_B} \alpha \qquad (1)$$

where a transition between classical and quantum behavior takes place. T_0 is characterized by the fact that the "bounce" solution at low temperatures ceases to exist. The quantity α occurring in the expression for the crossover temperature T_0 denotes the memory-renormalized reactive frequency which enters the classical prefactor of the activation rate $\Gamma_{c\ell}$ in presence of generally frequency dependent damping. At $T = T_0$, the classical Arrhenius factor, $\exp - U_b/k_BT$ (with U_b denoting the barrier height) matches smoothly with the one-bounce contribution, $\exp - S_B(T)/\hbar$, where S_B is the effective Euclidian action evaluated along the "bounce"-trajectory with period $\hbar/k_BT$.

For temperatures $T > T_0$, the classical prefactor of the rate becomes modified due to quantum fluctuations in order $\hbar^2$. The behavior very close to $T = T_0$ is complicated by the fact that the fluctuation modes about the bounce trajectory include, besides an unstable (negative eigenvalue) mode, two dangerous modes; an exact zero-mode, which describes phase fluctuations of the "bounce" and a quasi zero-mode describing amplitude fluctuations. Below T_0, the fluctuation modes about the "bounce"-trajectory include the zero-mode of the "bounce" phase and an unstable mode. In this temperature range, the thermal enhancement of the rate is different from the classical enhancement inherent in the Arrhenius factor. For a dissipative quantum system the effective action $S_B(T)$ near $T = 0$ shrinks algebraically with increasing temperature, i.e.

$$S_B(T) = S_B(T=0) - cT^n \qquad (2)$$

The exponent n is independent of the particular form of the metastable potential and is a distinctive feature of the dissipative mechanism at low frequencies.

For the important case of "Ohmic-like" dissipation, i.e. a damping mechanism $\gamma(\omega)$ that becomes independent of frequency, at low frequency, $\gamma(\omega) \rightarrow \gamma_0$ $(\omega \rightarrow 0)$, the enhancement near $T \geq 0$ takes on an universal dependence on temperature as

$$\Gamma(T) = \Gamma(T=0) \exp cT^2/\hbar \qquad (3)$$

with a coefficient c depending on the damping coefficient γ_0 and the form of the metastable potential. For an undamped system, $\gamma(\omega) = 0$, the thermal enhancement is exponentially small. Obviously, a precise measurement of the temperature dependence near $T = 0$ would render a crucial test of currently discussed theories modeling the thermal heat bath interaction.

The following bibliography is given in order to help the interested reader to fill in the details and to get additional information on this research topic.

For a general introduction into the subject matter and further references see:

Caldeira, A.O. and Leggett, A.J., Ann. Phys. (NY) 149, 374 (1983); 153 445 (1984) (E).

Larkin, A.I., Likharev, K.K., Ovchinnikov, Yu.N., Secondary Quantum Macroscopic Effects in Weak Superconductivity, LT-17 Conference proceeding, Karlsruhe 1984, North Holland 1984.

Path Integrals:

Feynman, R.P., Hibbs, A.R., Quantum Mechanics and Path Integrals, McGraw Hill, New York 1965.

Feynman, R.P., Statistical Mechanics, Benjamin, New York 1972, Ch. 3.

B. Felsager, Geometry, Particles and Fields, ed. C. Claussen, 2nd edition, Odense University Press 1981, Ch. 5.

Bounce-Technique:

Langer, J.S., Ann. Phys. (NY) 41, 108 (1967).

Coleman, S., Phys. Rev. D15, 2929 (1977).

Callan, C.G., Coleman, S., Phys. Rev. D16, 1762 (1977).

Classical Activation Rate Theory and Influence of Memory:

Kramers, H.A., Physica 7, 284 (1940).

Grote, R.F., Hynes, J.T., J. Chem. Phys. 73, 2715 (1980).

Hanggi, P., Mojtabai, F., Phys. Rev. A26, 1168 (1982).

Hanggi, P., J. Stat. Phys. 30, 401 (1983).

Carmeli, B., Nitzan, A., Phys. Rev. A29, 1481 (1984).

Hanggi, P., Weiss, U., Phys. Rev. A29, 2265 (1984).

Quantum Decay Rate at T = 0:

Caldeira, A.O., Leggett, A.J., Phys. Rev. Lett. 46, 211 (1981); Ann. Phys. 149, 374 (1983); 153, 445 (1984) (E).

Chang, L.D., Chakravarty, S., Phys. Rev. B29, 130 (1984); B30, 1566 (1984) (E).

Quantum Decay Rate at Finite T and Crossover to the Classical Activation Rate

Affleck, I.K., Phys. Rev. Lett. 46, 388 (1981).

Wolynes, P.G., Phys. Rev. Lett. 47, 968 (1981).

Melnikov, V.I., Meshkov, S.V., J.E.T.P. Lett. 38, 130 (1983).

Grabert, H., Weiss, U., Hanggi, P., Phys. Rev. Lett. 52, 2193 (1984).

Grabert, H., Weiss, U., Z. Physik B56, 171 (1984).

Larkin, A.I., Ovchinnikov, Yu.N., Zh. Eksp. Teor. Fiz. 86, 719 (1984) - Sov. Phys. JETP.

Grabert, H., Weiss, U., Phys. Rev. Lett. (in press).

Dissipative Quantum Coherence and Energy Loss

Chakravarty, S., Phys. Rev. Lett. 49, 681 (1982); see also LT-17 Conference proceeding, Karlsruhe 1984, North Holland 1984.

Bray, A.J., Moore, M.A., Phys. Rev. Lett. 49, 1545 (1982).

Chakravarty, S., Leggett, A.J., Phys. Rev. Lett. 52, 5 (1984).

Hakim, V., Muramatsu, A., and Guinea, F., Phys. Rev. B30, 464 (1984).

Chakravarty, S., Kivelson, S., Phys. Rev. Lett. 50, 1811 (1983); 51, 1109 (1983) (E).

Weiss, U., Riseborough, P., Hanggi, P., Grabert, H., Phys. Lett. 104A, 10 (1984).

Experiments

Boer, W. den, Bryn Ouboter, R. de, Physica 98B, 185 (1980).

Voss, R.F., Webb, R.A., Phys. Rev. Lett. 47, 265 (1981); Phys. Rev. B24, 7447 (1981).

Jackel, L.D., et. al., Phys. Rev. Lett. 47, 697 (1981).

Bol, D.W., Weelderen, R. van, Bryn Ouboter, R. de, Physica 122B, 1 (1983).