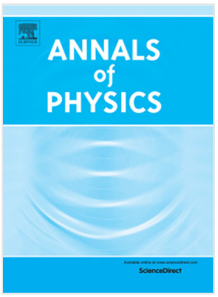
Accepted Manuscript



Quantum-classical transition in the Caldeira-Leggett model

J. Kovács, B. Fazekas, S. Nagy, K. Sailer

PII: S0003-4916(16)30281-0
DOI: http://dx.doi.org/10.1016/j.aop.2016.12.010
Reference: YAPHY 67272

To appear in: *Annals of Physics*

Received date: 24 March 2016
Accepted date: 5 December 2016

Please cite this article as: J. Kovács, B. Fazekas, S. Nagy, K. Sailer, Quantum-classical transition in the Caldeira-Leggett model, *Annals of Physics* (2016), http://dx.doi.org/10.1016/j.aop.2016.12.010

Quantum-classical transition in the Caldeira-Leggett model

J. Kovács[a,b], B. Fazekas[c], S. Nagy[a], K. Sailer[a]
[a]Department of Theoretical Physics, University of Debrecen, P.O. Box 5, H-4010 Debrecen, Hungary
[b]Institute of Nuclear Research, P.O.Box 51, H-4001 Debrecen, Hungary
[c] Institute of Mathematics, University of Debrecen, P.O. Box 12, H-4010 Debrecen, Hungary
(Dated: September 6, 2016)

The quantum-classical transition in the Caldeira-Leggett model is investigated in the framework of the functional renormalization group method. It is shown that a divergent quadratic term arises in the action due to the heat bath in the model. By removing the divergence with a frequency cutoff we considered the critical behavior of the model. The critical exponents belonging to the susceptibility and the correlation length are determined and their independence of the frequency cutoff and the renormalization scheme is shown.

I. INTRODUCTION

The Caldeira-Leggett (CL) model is a simple semi-empirical model to treat a quantum mechanical anharmonic oscillator which is linearly coupled to a heat bath consisting of a set of noninteracting or independent harmonic oscillators. The model enables us to investigate dissipation phenomena in the framework of quantum mechanics [1–3]. Although the model is relatively simple, it enables us to reproduce several properties of realistic dissipative systems without running into difficulties that can appear in the usual way of quantization. Furthermore, the interaction-independent construction of the model opens up the possibility of application to a wide range of physical systems exhibiting dissipative phenomena [15]. The heat bath can be considered as the environment of the physical system, which now corresponds to the anharmonic oscillator. As is known the environment plays a crucial role in the appearance of the decoherence phenomenon, the manner by which a quantum system turns effectively into a classical one. Its coupling to the environment makes the physical system an open quantum system in which quantum dissipation and entanglement may occur, so that the CL model may provide a good framework to discuss such phenomena, too.

The microscopic interaction between the oscillator and the heat bath is quadratic in the frequency therefore it can be integrated out, giving an additional nonlocal term into the action. The resulting effective theory can be investigated by several techniques. Here we apply the functional renormalization group (RG) method which enables one to eliminate the degrees of freedom systematically [4–11]. The method starts from a high-energy ultraviolet (UV) microscopic action, and gives its evolution into the infrared (IR) region. Thus the method can treat how the physical system changes throughout several orders of magnitude of the energy scale into the low energy regime. Furthermore, the RG method is very powerful in treating phase transitions, therefore we expect that this method can give a proper description for the quantum decoherence in the CL model [12–14].

The description of the dissipative systems is highly nontrivial [15]. Certain versions of the CL model is applicable to describe the dissipation of spin-boson model, where one has a two-level system [16, 17]. Another important application of treating dissipative systems with the CL model is the examination of the Josephson junction [18]. The traditional RG method is suitable to treat equilibrium processes, and one needs to improve or at least modify it in order to consider the dynamics of the dissipative phenomena with nonequilibrium RG technique. There are several possible ways to cure this problem, e.g. to use real time RG method [19], numerical RG [20], time dependent density matrix RG [21], or further ideas and techniques [22–24]. The RG method can be used to consider the nonequilibrium description of the Kondo model [25]. The Schwinger-Keldysh or closed time path (CTP) formalism of the RG method can be used to describe the gravitational and cosmological problems [26]. The CTP technique can give a proper formalism to handle the dissipative phenomena and the dynamics of open systems [27], where the physical system interacts with its environment. In the framework of the RG method using the CTP formalism, the environment can be identified by the modes which are removed during the RG blocking step [28], uncovering the entanglement between the system- and the environmental modes.

The quantum mechanical one-dimensional anharmonic oscillator can be considered as the $d = 1$ dimensional version of the $O(1)$ model in quantum field theory. Generally the $O(N)$ model has a Wilson-Fisher (WF) fixed point which separates two phases, the symmetric and the spontaneously broken (or simply broken) ones. Away from the 4-dimensional case the local potential approximation (LPA) needs to be improved by higher order terms in the gradient expansion [29–32]. More precise results can be obtained without expanding the potential in Taylor series [33]. In the case of $d = 1$ the model has a single phase, since there is no spontaneous symmetry breaking due to the quantum tunneling effect [34–39]. The RG treatment runs into difficulty when the initial double-well potential meets a weak anharmonic coupling. The numerical solution of the Schrödinger equation for the anharmonic oscillator shows up a convex effective potential, independently of the strength of the anharmonic coupling. In the case of the RG method