Report on the Scientific Exchange Project Ultra-fast Dynamics of Quantum Dots

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ESF Network Arrays of Quantum Dots and Josephson Junctions
Host: Prof. F. Kusmartsev, Loughborogh University, 06/12/2004-12/03/2005

1. Aims of the visit

The purpose of the visit, as was formulated in the proposal application, was an application of functional integral formalism to investigate the ultra-fast dynamics of optically driven quantum dots and a subsequent comparison of obtained results with results obtained by other approaches. The three specific goals of the visit were:

1. *formulating the dynamics of the relevant physical quantities in terms of the functional integral,*
2. *reproducing the result of the simple models like the pure dephasing of the Independent Boson model, and*
3. *developing a numerical algorithm for evaluation of the functional integral.*

The investigation carried out during the visit fully accomplished all three goals of the proposal.

2. Desription of the work during the visit

Using the coherent states representation for the phonon subsystem I derived the Feynmann-Vernon memory functional in a form suitable to account for discrete carrier states of a strongly confined quantum dot. The expression for the functional integral with the Feymnann-Vernon action has been transformed into a form suitable for a subsequent numerical calculation. I developed a representation of the functional integral on finite time mesh that avoids a familiar problem of a non-unitary evolution. This problem arises in numerical calculation of the functional integral in real times and usually prevents from obtaining a long time dynamics. The representation was based on a time separation of the coupling with the external field and the phonon subsystem. One possible way is to represent the field as sequence of ultra-short (delta) pulses, each of small amplitude, that strike the system periodically. The advantage of this representation is that one can easily compare the result of the functional integral approach with the exact results for the delta pulses obtained by the generating functions method by Vagov et al. [Phys. Rev. B 66, 165312 (2002)]. Comparing results for a single delta pulse demonstrated equivalence of both approaches. Dynamics obtained by the generating function formalism for the two-level Independent Boson model was subsequently used to test the numerical algorithm to evaluate the numerical functional integration.

For numerical calculations of the functional integral I have employed a numerical procedure of finding the optimal paths for the time evolution of the system. Similar algorithm was previously introduced to study quantum dissipative systems in chemistry [E. Sim, J. Chem. Phys. 115, 4450 (2001)]. I demonstrated that the algorithm can be successfully used for strongly confined quantum dots, although its implementation requires considerable adaptations when the number of dot levels is more than two. A particular advantage of this algorithm is that it reduces the evolution of the essentially non-Markovian system with the memory kernel to a Markovian evolution of the enhanced density matrix tensor, the evolution of which to a next time step is governed by a transfer matrix.

The algorithm is efficient and its first draft implementation was compiled using a relatively slow Mathematica programming language. This allowed calculations for the two level Independent Boson model, for which a number of new results has been obtained. A more efficient C++ code, with a ten time speed increase, is being developed.

3. Summary of main results

Main result of the current work is the developing of an efficient numerical procedure to calculate the time evolution of the few body-few strongly confined quantum dots, strongly coupled with phonons and driven by external field. Developed algorithms will help to initiate further systematic studies of the dynamics of the relevant physical systems.

Some preliminary results for the dynamics of the Rabi rotations in the dots have already been obtained. For example, it has been demonstrated that the Rabi oscillations decay faster for stronger driving field and that they will not revive at a later time. Furthermore, a considerable temperature dependence of the Rabi frequency is demonstrated in the current calculations. As an example, in Figs. 1, 2 I have plotted the Rabi rotations in the 00 and 01 components of a density matrix for a two level InGaAs quantum dot of approximately 10nm diameter, driven by a constant amplitude external laser field, at temperatures T=0K, 100K and 300K.

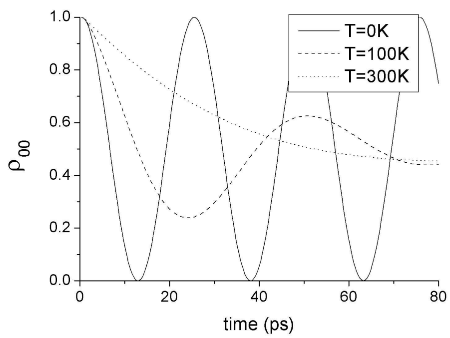

Fig. 1

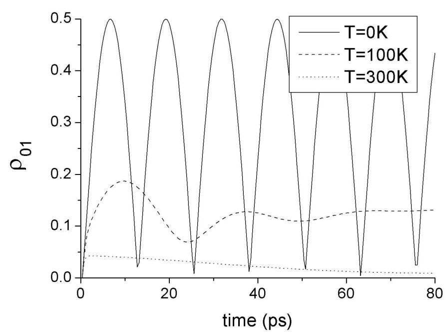

Fig. 2

This result already substantially improves the earlier findings by Machnikowski et al in Phys. Rev. B 69, 193302 (2004) obtained by perturbation analysis. Although, no publication of the results has been prepared yet, some preliminary results have been reported on a series of seminars in Loughborough.

4. Future collaboration with host institution

The research group of Prof. Kusmartsev in Loughborough is involved in the projects requiring a detailed knowledge of the dynamics of quantum systems such as backyballs and Josephson junctions. During the visit extensive exchange of ideas with the members of the group took place in a form of seminars and informal discussiona. It appears that the methods for the numerical functional integration developed during the visit can be also applied to study the dynamics in such systems. Together with Prof. Kusmartsev we formulated future research directions and applied for funding to the EU Marie Curie Fund and EPSRC. An immediate plan is a more scientific visits of involved scientists to Antwerp and Loughborough for further collaboration.

4. Projected publications

Although more programming is needed to create an efficient code for the calculations, the results obtains so far are very promising and undoubtedly constitute a basis for a publication in an international journal, like PRB. Given a wide spread interest to the topic of ultra-fast dynamics of quantum dots in the context of quantum information and communication a publication in PRL is also plausible.