Multicomponent Loschmidt Echo and Mixing in Quantum Evolution Dynamics of Systems with Discrete Dense Spectra

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We investigate quantum evolution of a system coupled to a reservoir with dense discrete spectrum. Under assumptions (equidistant spectrum of the reservoir and system-reservoir coupling independent of the reservoir states) proposed long ago by R.Zwanzig (Lectures in Theor. Phys., **3**, 106 (1960)) we find exact analytic solution of the model, which is a simplified version of the Legget-Caldeira Hamiltonian. We show that there are possible three dynamic regimes of the evolution: (I) - almost coherent oscillations governed by transitions from the system to the resonance reservoir state; (II) - multicomponent Loschmidt echo, when the system is exchanged its energy with many states of the reservoir; (III) - mixing of recurrence cycles. (I)-(II) transition corresponds to the transition from coherent to incoherent dynamics. It occurs when the coupling matrix elements C equals reservoir level spacing. (I)-(III) transition occurs for the recurrence cycles higher than $k_c^{I-III} \simeq 2C^{-3}$, and the critical cycle number for (II) - (III) transition is $k_c^{II-III} = \pi^2 C^2$. In the cycle mixing regime (III) due to inevoidably in any real system coarse graining of time or energy measurements, or initial condition uncertainty, the system loses invariance with respect to time inversion. In such conditions dynamic evolution of the system can not be determined uniquely from the spectrum, and in this sense long time system dynamics looks as a random-like. Our model can be applied to rationalize experiments on femtosecond range vibrational relaxation of a specially selected state (the system) coupled to all other states (the reservoir) of nano-particles. Our main results (e.g., three different regimes of the evolution, varying from exponential decay to irregular oscillations) are in the agreement with spectroscopic experimental data of nano-systems with characteristic inter-level spacing of the order of 10 cm^{-1}, and with recurrence cycle periods within the window $10^{-13} - 10^{-11}\, s$.