Unveiling the Invisible System-Bath Coupling Dependence in Microscopic System

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Microscopic systems are significantly affected by system-bath coupling, as shown by their highly fluctuating motions. However, the dynamics of microscopic systems are surprisingly well described by the Langevin equation which includes no system-bath coupling-dependent terms. We investigate why microscopic systems can exhibit coupling-independent dynamics even with significant coupling strengths. Starting from an explicit microscopic description of a composite system with an arbitrary interaction Hamiltonian, we derive the reduced system dynamics by applying time-scale separation. We find that the obtained equation contains coupling-dependent terms, which disappear regardless of the coupling strength under two specific conditions: (i) the translational invariance of the bath and (ii) the mutual independence of the system-bath interaction forces on each system particle. Our findings explain why the Langevin equation can successfully describe experimental observations, as these conditions are typically met in usual experimental setups. Finally, we validate our results both theoretically and numerically using toy models and molecular dynamics simulations.

[1] J.-M. Park, H. Park, J. S. Lee, arXiv:2309.15359 (2023).