Interaction of a quantum system with its environment: from linewidth of optical transitions to decoherence of qubits

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During the first course on quantum physics one learns only about *pure* states ("wave-functions" in the case of a single electron) of small systems. The same holds most often for the second course on more advanced quantum mechanics. This creates an impression that small quantum systems (for example electrons in quantum dots) are typically in pure quantum states. This is not the case: unless special care is devoted to preparation of the system, its state is typically a *mixed* one, described by a density matrix, not by a state vector. This is due to the fact that pure states can be used to describe only *closed* (i.e. uncoupled from the rest of the world) systems, while it is extremely hard to keep any system (even a single electron) truly closed. All the realistic quantum systems are *open* to some degree, and interaction with their environment (which leads to *decoherence* of pure quantum states) is always relevant for their description. This is an especially salient point when dealing with small quantum systems (e.g. qubits) embedded in a solid-state environment.

In this tutorial I will introduce the basic notions of quantum mechanical description of open quantum systems. I will start with a density matrix of a two-level system (e.g. a spin of a localized electron, or ground and excited state of a quantum dot), and then discuss Rabi oscillations due to external periodic driving, the appearance of Fermi Golden Rule for transition probability due to the openness of the system, spontaneous radiative recombination due to coupling to vacuum fluctuations, Bloch equations (and conditions under which they can be used), and energy relaxation and dephasing due to classical noise. While doing this I hope to explain concepts such as motional narrowing and dephasing due to a quasi-static bath. Examples from experiments on solid state based qubits (mostly quantum dots) will be used for illustration. If time permits, I plan to finish by explaining how a qubit might be turned into a spectrometer of the environmental noise.