

Coherent quantum dot spectroscopy

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An InAs self-assembled quantum dot embedded in GaAs confines both electrons and holes to the nanoscale and has a strong optical dipole transition connecting the first valence and conduction levels. The physics is dominated by quantum confinement. On the one hand, the quantized states allow quantum dots to mimic atoms. In particular, by exploiting the possibilities of a semiconductor heterostructure, quantum dots as artificial atoms are highly tunable via a voltage applied to a semiconductor device. On the other hand, the complex environment leads to rich physics, some of which lies at the very heart of condensed matter physics: the electron-phonon interaction, the central spin problem, and the Kondo effect.

An overview of spectroscopy experiments carried out over the past five or six years will be presented, experimental work carried out with the group of Khaled Karrai at the Center for NanoScience, Munich using state-of-the-art wafer material from the group of Pierre Petroff at University of California Santa Barbara with theoretical support from Alexander Govorov at Athens. A key step was the development of laser spectroscopy applied to single quantum dots [1,2]. By measuring the transmission coefficient in a cryogenic microscope at low laser power, detection of the resonant excitation of the optical transitions became possible. This allowed initially the application of concepts from two-level atomic physics to quantum dots, for instance power broadening and the ac Stark effect. Subsequently, some new atomic physics was discovered: the non-linear Fano effect [3]. A Fano scheme was established using electron tunneling to couple the quantum dot exciton level to an empty continuum. The striking result is that the “visibility” of the Fano interference becomes stronger as the laser power increases, providing an exquisitely sensitive probe of the coherent coupling of the quantum dot to a continuum. Quantum interferences within a 3-level system were also explored, initially with a three-level ladder system, and while the atomic physics may also be new, the quantum interferences are rather weak on account of spontaneous emission [4]. Instead, a single spin was probed with the goal of probing a system with two highly coherent ground states. An InAs/GaAs quantum dot is sufficiently small to exhibit a pronounced Coulomb blockade at 4 K, allowing a single electron to be confined to a single quantum dot simply by dialing up a gate voltage applied to a vertical tunneling device. Laser spectroscopy on a single electron spin provides a powerful means of probing the decoherence mechanisms, spin leakage to the Fermi sea for instance, or spin leakage to the nuclear spins via the hyperfine interaction. In particular, an optically-detected spin resonance scheme provides a striking example of the apparent dephasing of the electron spin via noise in the nuclear spins [5]. As an alternative, we have also developed controlled hole charging and laser spectroscopy on a single hole spin [6,7]. In this case, we were able to demonstrate a very clear quantum interference in the laser spectroscopy, coherent population trapping [7]. The experiments show that with unprepared nuclei spins in an in-plane magnetic field of a few Tesla, the hole spin coherence time is one to two orders of magnitude larger than that of a single electron spin in the presence of nuclear spin noise.

Pointers to the future will be provided: the possibility of highly coherent spins, entangled states, and sophisticated functionality with GHz bandwidth electronics and tunable microcavities.

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