Universal scaling of adiabatic tunneling out of a shallow confinement potential

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The ability to tune quantum tunneling is key for achieving selectivity in manipulation of individual particles in quantum technology applications. The exponential sensitivity of tunneling rates to the barrier shape of the confining potential provides discriminative power for quantum state initialization, read out, or quantum logic operations. High-speed operation of tunneling devices is however limited by the maximal tunneling rate set by the minimal barrier height. Here we explore the shallow confinement limit in microscopic tunneling of single electrons from tunable-barrier semiconductor quantum dots, realized in a GaAs/AlGaAs heterostructure.

We utilize the capture probability of the last-to-escape electron in a time-dependent confinement potential to probe the dependence on the decoupling speed of a quantum dot from the source lead. Using a clock-controlled charge detection scheme, electron escape events are accurately counted, independent of the chosen barrier rise time. This enables the variation of decoupling speed over orders of magnitude. A minimal microscopic model of ground state tunneling from an anharmonic confinement potential predicts a universal scaling curve down to the limit of shallow confinement, in excellent agreement with the empirical scaling observed in experiment. Crossover to thermally activated transport provides an estimate for the single time-energy scale of the model. The robust validation of the scaling relation over several experimental realizations establishes a technique to infer the ground state escape rate up to a regime, where confinement is eventually lost. For quantum metrology applications that rely on the escape of excess electrons and capture of the target number of electrons, this work provides a method to validate the generic quantization mechanism over greatly extended parameter range. The scaling of speed and potential depth provides a practical benchmark for characterization of shallow quantum dots.