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Magnetic resonance at the quantum limit, and beyond

The detection and characterization of paramagnetic species by electron-spin resonance (ESR) spectroscopy has numerous applications in chemistry, biology, and materials science [1]. Most ESR spectrometers rely on the inductive detection of the small microwave signals emitted by the spins during their Larmor precession into a microwave resonator in which they are embedded. Using the tools offered by circuit Quantum Electrodynamics (QED), namely high quality factor superconducting micro-resonators and Josephson parametric amplifiers that operate at the quantum limit when cooled at 20mK [2], we report an increase of the sensitivity of inductively detected ESR by 4 orders of magnitude over the state-of-the-art, enabling the detection of 1700 Bismuth donor spins in silicon with a signal-to-noise ratio of 1 in a single echo [3]. This sensitivity can be enhanced even further by using squeezed microwave fields to reduce noise below the vacuum fluctuations level [4]. We also demonstrate that the energy relaxation time of the spins is limited by spontaneous emission of microwave photons into the measurement line via the resonator [5], which opens the way to on-demand spin initialization via the Purcell effect. These results constitute a first step towards circuit QED experiments with magnetically coupled individual spins. [1] A. Schweiger and G. Jeschke, Principles of Pulse Electron Magnetic Resonance (Oxford University Press, 2001) [2] X. Zhou et al., Physical Review B 89, 214517 (2014). [3] A. Bienfait et al., Nature Nanotechnology 11, 253 (2015) [4] A. Bienfait et al., in preparation (2016) [5] A. Bienfait et al., Nature 531, 74 (2016)

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