PhD THESIS DEFENSE: Detection of a Single Erbium Ion in a Nanoparticle

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Encoding information into quantum mechanical properties of a system can lead to applications many fields, including computing and communication. Devices that will enable these applications could be part of a quantum network in the future. Quantum networks can be implemented using nodes that have the ability to generate and store entanglement efficiently for long durations as well as to process quantum information. The nodes also need to be interfaced with photons, which can faithfully carry information over long distances. Single rare-earth ions doped in crystals offer all these capabilities. The main goal of this thesis was to detect a single erbium ion, which operates in the telecommunication wavelength, and to investigate its feasibility as a spin-photon interface.
Detecting a single erbium is challenging due to its low emission rate, but it can be aided by Purcell-enhancing its emission via coupling to an optical cavity. In this thesis, we utilize

erbium ions doped into nanoparticles, which facilitates their integration into cavities with small mode-volumes. In addition, nanoparticles provide the confinement required to individually manipulate spatially close-by single ion qubits, which is required for dipolar quantum gates. We hence first study the optical coherence properties of Er:Y2O3 nanoparticles at cryogenic temperatures. We identify the limiting mechanisms and identify avenues for improvement in the future. We also study the optical and spin coherence properties of Pr:Y2O3, which is a promising alternative to erbium.
Fiber-based microcavities can achieve high Purcell factors as they can simultaneously realize high finesse and small mode-volume. They are also ideally suited to be coupled to nanoparticles due to their tuning capabilities. However, stabilizing such a cavity inside a cryogenic environment is challenging. We hence first describe the construction of a custom setup, which enables us to stabilize the cavity while being coupled to a suitable nanoparticle. Utilizing the first iteration of this setup, we then report on the coupling of Er:Y2O3 nanoparticles to a fiber-based high finesse microcavity. We achieve an average Purcell factor of 14 for a small ensemble of ions, while a small subset of ions show Purcell factor up to 70. We explain the obtained multi-exponential decay behaviour using a detailed model. Furthermore, we demonstrate dynamic control of the Purcell-enhanced emission by tuning the cavity resonance on a time-scale faster than the spontaneous emission rate of the ions. This allows us to extract the natural lifetime of the ions as well as to shape the waveform of the emitted photons. However, we conclude that the achieved signal-to-noise ratio is not high enough to resolve single erbium ions.
For the final experiment, we operate the second iteration of the setup, which improves our sensitivity to single erbium ions by more than a factor 50. This enables us to demonstrate the first detection of a single erbium ion in a nanoparticle. The ion exhibits a Purcell factor of 60, leading to a cavity enhanced lifetime of 225 us, and a homogeneous linewidth of 380 MHz. The counts received from the ion show a clear saturation and we measure the second-order auto-correlation of the emitted photons to be 0.59, which reduces to 0.29 after background-subtraction. This is strong evidence that the photons are emitted by a single erbium ion. Our work opens the path for exploring single rare-earth-ions doped into nanoparticles as spin-photon interfaces for quantum information processing.

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