Nanoscale Systems for Optical Quantum Technologies

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D2.6 Ion-ion interactions readout

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Version history

Version	Date	Author(s)	Description
V1	21/08/2019	A. Walther (ULUND), A. Kinos (ULUND)	First draft
V2	30/08/2019	David Hunger	Added content
V3	20/09/2019	Klaus Mølmer	Added content, final version submitted to EU

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Deliverable Description

This deliverable describes the results of task 2.4, which focuses on interactions between different rare-earth (RE) ions for quantum computation applications. We discuss the basic principle of an interaction-based CNOT gate between two ions and estimate the expected performance that can be achieved for the current experimental parameters, and the effect of resonant cavity coupling is considered. Further, we characterize unwanted interactions shifts due to non-qubit ions for both single-qubit and two-qubit gates. Finally, we evaluate new protocols for preparation, multi-ion addressing and gate-schemes for quantum computing.

Results

Two-ion gates with Eu^{3+}:Y_2O_3 for quantum computing

The possibility to isolate closely spaced dopant ions in frequency space due to the combination of narrow homogeneous and broad inhomogeneous linewidths is promising to realize multi-qubit nodes. In crystals with low symmetry, the ions possess permanent dipole moments which differ in ground and excited states, enabling controllable ion-ion interactions that are suitable for the realization of quantum gates. Notably, the interaction is to a very high degree common mode for the qubit states, which are defined in Hyperfine ground states, such that a qubit is essentially independent of the interaction as long as it is not optically excited [Macfarlane]. This is a beneficial aspect for scalability.
The frequency shift of ion i due to interaction with ion j is given by

$$\Delta\nu_{ij} = \frac{\Delta\mu_i \Delta\mu_j}{4\pi h \epsilon \epsilon_0 r_{ij}^3}\left[(\hat{\boldsymbol{\mu}}_i \hat{\boldsymbol{\mu}}_i) - 3(\hat{\boldsymbol{\mu}}_i \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\mu}}_j \cdot \hat{\boldsymbol{r}})\right],$$

where $\Delta\mu = \left|\mu_e - \mu_g\right|$ is the dipole moment difference of the ground and excited state, and r_{ij} the distance between the ions

For Eu^{3+}, the dipole moment difference has been measured by CNRS by Stark spectroscopy of Eu^{3+}:YSO, and recently also for Y_2O_3 ceramic crystals and Y_2O_3 nanoparticles with the following results:

Eu^{3+}:YSO (D1)	27 kHz/V cm [Macfarlane]
Eu^{3+}:Y_2O_3 (ceramic)	30 kHz/V cm [Fossati]
Eu^{3+}:Y_2O_3 (nanoparticles)	50 kHz/V cm [Fossati]

Linear optical Stark shifts were measured on transparent ceramics and nanoparticles in the form of powders using a photon echo sequence (Figure 1). Samples of 500 µm thickness were placed between two transparent electrodes allowing applying voltages of a few volts across them. The frequency shift induced by the electric field causes a dephasing that accumulates during the electric pulse length T_S. Since this dephasing is not

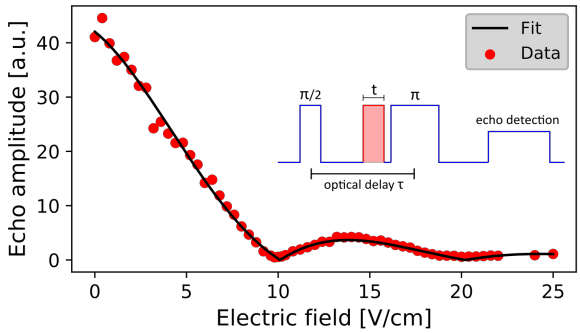

Figure 1: Photon echo amplitude as a function of applied electric field for Stark coefficient measurement in Eu^{3+}:Y_2O_3 nanoparticles. The electric pulse length is 1 µs.

refocused by the π pulse in the sequence, the echo amplitude oscillates with increasing electric field. Both ceramics and nanoparticle powders have random orientations with respect to the electric field, which results in an additional damping of the echo amplitude as a function of the electric field, as shown in Fig. 1. The field E_S at which the echo vanishes allows determining the Stark coefficient along the two-fold axis of Eu crystallographic site as $k = 1/2T_SE_S$. Indeed, in C_2 symmetry, all electric dipole moments are oriented along this axis. The nanoparticle Stark coefficient appears larger than the ceramic one, which we attribute to a smaller electric field on the particles because of the porosity of the powder.

The measured Stark coefficient corresponds to a dipole moment difference of $\Delta\mu = 3 \times 10^{-31}\ Cm$ for the nanoparticle case, and for ions with aligned dipoles at a distance of 1nm, this corresponds to a shift $\Delta\nu_{ij} = 600$ MHz. Figure 2 shows the interaction shift as a function of the ion separation. For distances smaller than about 20nm, the interaction shift remains larger than the expected homogeneous linewidth (<100kHz) of the currently available material and achievable sample temperature. Ions inside this sphere will be fully shifted out of resonance with a probe laser and can thus be controlled by the center ion. For the used doping concentration of 0.5%, about 1500 dopant ions in the relevant C_2 symmetry site reside inside this blockade sphere, where 1/3 of the ions will have aligned dipoles. By frequency selective excitation with a narrow-band laser, strongly coupled ion pairs are expected to be well resolvable.

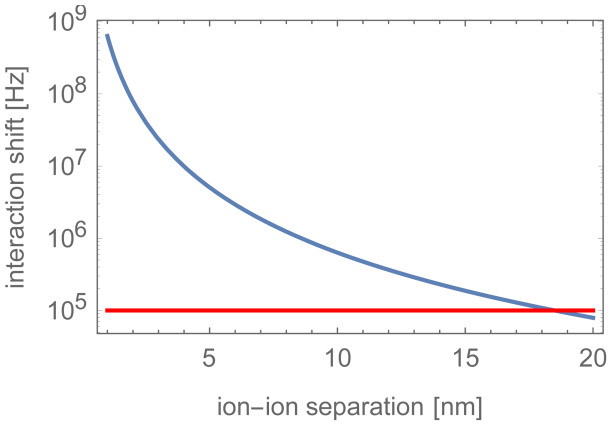

Figure 2: Interaction shift for Eu3+:Y2O3 nanoparticles as a function of ion-ion separation (blue line). The homogeneous linewidth (red line) is shown for comparison.

This interaction can be harnessed to realize entanglement and a CNOT gate [Ohlsson]. The required optical pulse sequence is shown in Figure 3. In brief, pulse 1 excites ion *j* to inhibit transitions on ion *i*, dependent on its logic state $|0\rangle, |1\rangle$ encoded in hyperfine ground states. Pulses 2-4 perform a swap operation of the logic state of ion *i*, and pulse 5 finishes the sequence by bringing population in the excited state of ion *j* back to the ground state.

In the following, we estimate the achievable fidelity of the CNOT operation given the current experimental parameters. The main limiting factor is the dephasing time of the optical transition, which can't be circumvented since the control ion needs to be prepared in general in a superposition state that involves the excited state for the gate. For the Eu^{3+}:Y_2O_3 nanoparticles optimized within NanOQTech that is suitable for cavity experiments, an optical coherence time of $T_2 = 4.8$ µs has been achieved. In contrast, hyperfine coherence lifetimes of up to $T_{2n} = 3$ ms have been observed in this material, contributing negligibly to dephasing during the pulse sequence. Similarly, the unperturbed excited state lifetime of $T_1 = 1.4$ ms will have negligible influence. To minimize dephasing, pulses with minimal duration should be used, while the maximal Rabi frequency for pulses should not exceed ~1/10 of the hyperfine level splitting of 30 MHz to avoid off-resonant excitation. This yields $T^\pi = 170$ ns and a corresponding dephasing factor $\exp(-T^\pi/T_2) = 0.97$ per pulse duration. Note that the high Rabi frequency requires an interaction shift >3 MHz and thus restricts to ions closer than 6 nm, leading to about 50 ions within the blockade sphere.

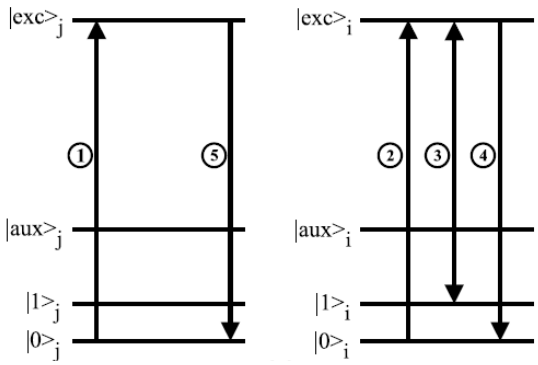

Figure 3: Pulse sequence for a dipole-blockade based CNOT two-qubit gate.

Assuming perfect optical π −pulses and initialization, the optical dephasing is dominated by the time needed for the pulses and will limit the fidelity $F = \langle\psi|\rho|\psi\rangle$, where ρ is the density matrix of the two-qubit system and ψ a target state such as $\psi^+ = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. Assuming an overall duration of the gate of 5 π pulses plus 1.5 π pulses for the initial state preparation of qubit j, a fidelity $F = 90\%$ is expected.

Ion-Ion gate in the presence of Purcell enhancement

For ions resonantly coupled to the cavity, the lifetime of the excited state will be reduced by the Purcell effect according to $T_1 = T_1^0/(C+1)$. Furthermore, the homogeneous linewidth is broadened if the effective Purcell factor becomes larger than the ratio between the homogeneous and the lifetime-limited linewidth. Purcell broadening is not expected to be disadvantageous since the effective broadening due to the desired high Rabi frequencies will dominate. However, the lifetime reduction can become a limiting factor for the gate operation. For the currently targeted parameters with a cavity finesse $F = 100000$ and mode volume $V_c = 3\lambda^3$ (currently realized parameters are $F = 20000$ and $V_c = 4\lambda^3$), we expect an effective Purcell factor $C = 100$ (currently 15), leading to an

excited state lifetime $T_1 = 10\mu s$ (70µs). In particular for improved materials with T_2 approaching T_1, this will become a relevant effect.
To avoid lifetime reduction, we propose to keep the cavity off resonance during the gate and drive the ions without use of resonant enhancement. Detuning the cavity from the ions by a few linewidths will turn off the Purcell enhancement and can lead even to a small lifetime increase. After the gate operation, the cavity can then be dynamically tuned on resonance for readout.
To estimate the available bandwidth of cavity length modulation, we have studied the response of the cavity positioning platform. While the lowest mechanical resonance frequency of the setup is between 5 and 10 kHz depending on details of the mounting, modulation at much higher frequencies was observed to be possible. Figure 4 shows the measured cavity transmission for a sinusoidal piezo voltage modulation at a frequency of 420 kHz and an amplitude of 80 pm. The cavity length follows the piezo actuation linearly without noticeable excitation of mechanical modes. From this we deduce that the cavity can be tuned on/off resonance within ~1µs.

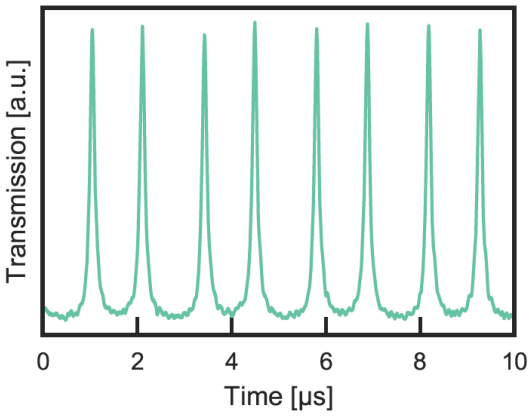

Figure 4: High frequency cavity length modulation for controlled switching on/off resonance.

In a different experiment, we have furthermore explicitly studied the controlled switching on and off resonance of an ensemble of Er^{3+} ions to modulate the Purcell enhancement (see also D2.7 for more details). Figure 5 shows time delayed fluorescence coupled to the cavity that is modulated by the cavity. Here, the setpoint of the active cavity length stabilization was switched to achieve frequency tuning while maintaining the lock. Here, time constants of 210 µs and 160 µs could be achieved. When considering qubit coherence lifetimes of $T_{2n} = 3$ ms, this switching speed would already be sufficient to allow for shifting the cavity on resonance after a gate operation for state tomography by Purcell-enhanced fluorescence readout.

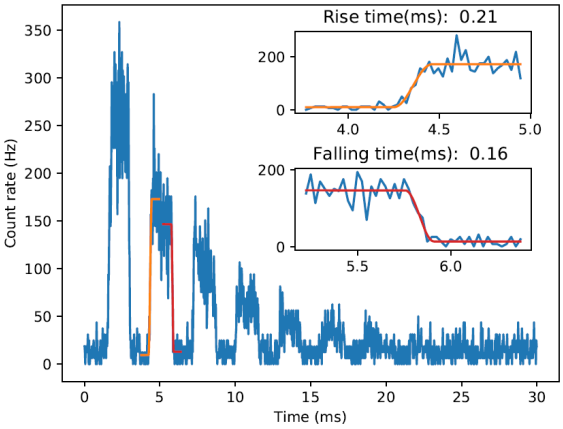

Figure 5: Dynamic modulation of Purcell enhancement of Er^{3+} ions coupled to a cavity that is switched on/off resonance while maintaining active stabilization.

Parasitic ion coupling

This section aims at evaluating the potential decrease in gate operation fidelities due to undesired ions causing instantaneous spectral diffusion on qubit ions. This investigation is important since the current quantum computing scheme requires high dopant concentrations which increase the risk that undesired ions have similar frequencies as the qubit ion and cause unwanted dipole-dipole interaction shifts. The high dopant

concentrations are needed in order to increase the qubit chain length, i.e., increase the number of total qubits in the quantum computer.

In order to investigate this topic a two-ion simulator was set up, where both ions have two ground states and one excited state. The simulator is using the Lindblad master equation which tracks the evolution of the density matrix of the two-ion states, $|00\rangle$, $|01\rangle$, $|0e\rangle$, etc., in total resulting in 9 states in the simulator.

In the simulation, a single qubit gate is applied to the first ion, the qubit ion, while the second ion, the undesired ion, may also be excited if it is sufficiently close in frequency, in which case it would disturb the gate operation on the qubit. In Fig 6, the fidelity of the gate operation is examined as a function of the detuning of the second ion and as a function of the frequency shift caused by the disturbing excitation of the second ion. The gate operation consists of four two-color sechyp pulses [Rippe], each having a duration of either 4.4 µs or 400 ns.

Several conclusions can be drawn from this figure: (i) if the detuning is large compared to the pulse bandwidth the fidelity is hardly affected, except for when the shift is equal to the detuning but with opposite sign. This is because the undesired ion is then shifted into resonance with the laser as soon as the qubit ion is excited (the diagonal line). (ii) The fidelity is highly affected if the detuning is small compared to the pulse bandwidth, even if the interaction shift is rather low. (iii) How high the shift can be while still maintaining a high qubit gate fidelity scales inversely with pulse duration, and is in the order of 10 kHz for the long pulse and 100 kHz for the short pulse.

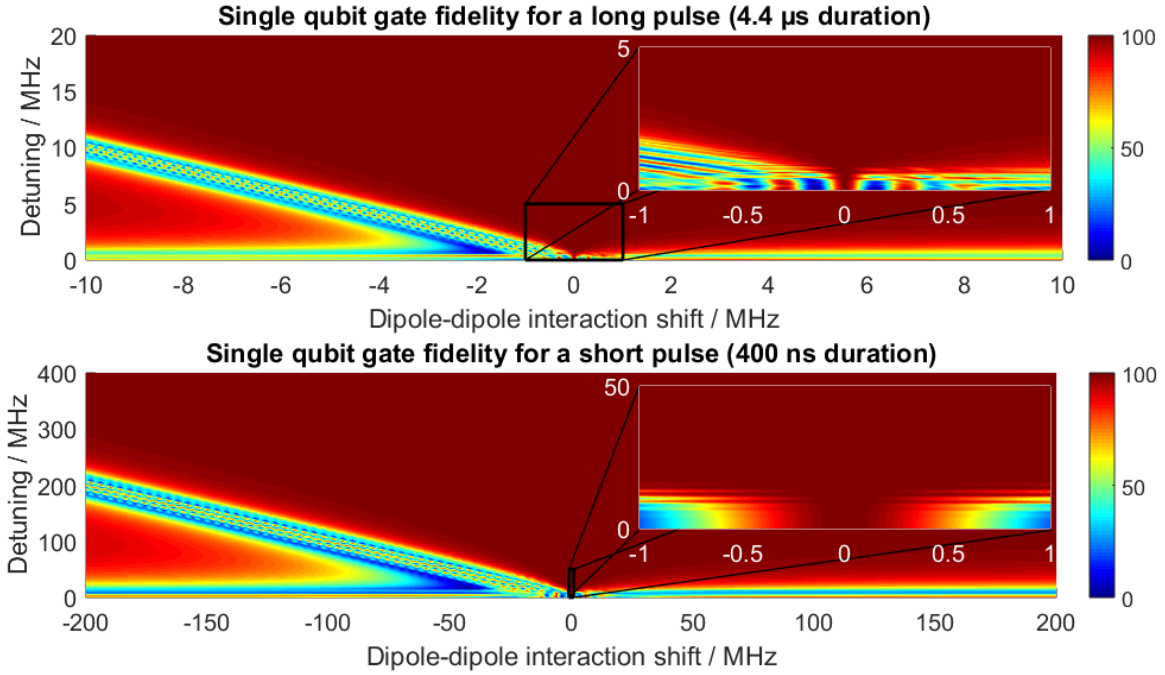

Figure 6: Fidelity (color) of a single qubit gate operation as a function of the optical detuning (y-axis) of an undesired ion causing instantaneous spectral diffusion, where the strength of the dipole-dipole interaction shift is shown on the x-axis. The single qubit gate operation consists of four two-color sechyp pulses each with a duration of 4.4 µs (top part) and 400 ns (bottom part), respectively. The insets show a zoomed-in view over the regions of low interaction shifts. Note that both the x and y axes use different scales for the two parts.

Making the pulse duration shorter thus decreases the sensitivity toward interaction shifts, but at the same time a larger interval of detunings affect the fidelity since the pulse bandwidth is increased. These two effects scale similarly, and the fidelity drop due to instantaneous spectral diffusion is therefore insensitive toward pulse duration. This can be understood by going through how the different properties scale: the probability of an undesired ion having a certain detuning is similar for all detunings; a certain interaction shift is equivalent to a certain distance r between the qubit ion and the undesired ion, and scales with $1/r^3$. If the pulse duration is scaled down by a factor of ten, the interaction shift can be ten times larger, meaning that the undesired ion must be located in a volume that is ten times smaller compared to before. In that volume the number of ions are ten times lower, but since the shorter pulse is less sensitive toward detunings it is ten times more likely that an ion is within the bandwidth of the pulse, leading us to the result that the two effects cancel out. Additionally, the number of ions within a certain frequency interval and with a certain shift remains fairly constant as a function of dopant concentration as long as it exceeds a critical concentration (~0.1% for Eu:YSO), thus allowing experimentalists to choose the concentration freely with respect to this issue.

An approximate solution to the fidelity as a function of the dipole-dipole interaction shift and pulse duration, t_{dur}, can be seen in the equation below and is valid if the detuning is low compared to the bandwidth of the pulse.

$$\text{Fid} = \frac{1}{2}(1 + \cos(2\pi \cdot shift \cdot t_{dur}))$$

Note that this expression only describes the fidelity loss due to the interaction shift. In Figure 7, the fidelity is shown as a function of the pulse duration for a few different values of the interaction shift. Note that it is equally likely for a 400 ns pulse to have an undesired ion giving a shift of 10 kHz as it is for a 4 µs pulse to have an undesired ion giving a shift of 1 kHz.

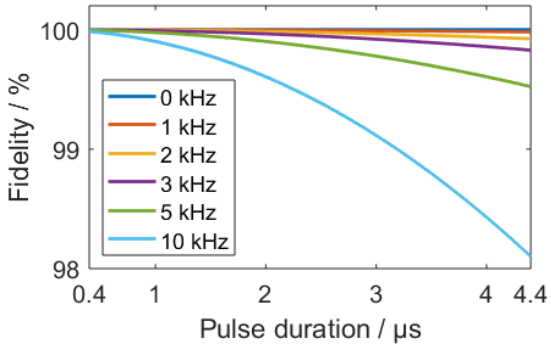

Figure 7: Approximate fidelity as a function of pulse duration for a few different interaction shifts. Valid if the detuning is small compared to the bandwidth of the pulse. It also disregards any fidelity loss due to limited coherence- and lifetime.

Thus, we conclude that the fidelity loss due to interaction shifts is approximately independent of both pulse duration and ion concentration, and furthermore sufficiently small that high fidelity gates are feasible. Although note that shorter pulses are still preferred since they have lower fidelity loss from a limited coherence time.

Finally, we briefly discuss the implications of instantaneous spectral diffusion when considering two qubits and one undesired ion. Since the two qubits must lie close to each other in order to perform the two qubit gate, and it is much more likely that the undesired ion is far away, it will interact with both qubits and with similar interaction shifts. We can thus conclude that the error will at least be of the same magnitude as for the single qubit case discussed above, possibly larger. Fortunately, the addition of one extra qubit ion provide us with an opportunity, since only the two qubits interact strongly with each other. It should thus be possible to apply an optical pumping scheme that uses this strong interaction in order to move the undesired ion into an auxiliary state where it no longer

interacts with the incoming laser pulse, and therefore no longer reduce the fidelity of the single or two-qubit gates.

New protocols for preparation, addressing and gates

We have theoretically had a focus on the use of adiabatic passage for one-qubit quantum gates, and we have proposed a novel scheme using two-atom dark states for precise and fast gate operation. So far we developed this gate for the situation of Rydberg interacting atoms (not NanOQTech), but it has potential for application with the dipolar interaction among ion dopants. As follow-up on our adiabatic gate efforts, for NanOQTech, we have particularly proposed a new "gate scheme" for rapid hole burning in situations where the excited state lifetimes are very long, prohibiting rapid preparation of spectral holes by optical pumping. The idea is simply to transfer population towards an initially unpopulated state by a resonant STIRAP process. For ions with different frequencies, the transition is non-resonant, and for large detuning the condition of adiabaticity is violated (when the process is very off resonant, the population remains in the initial state rather than following the adiabatic eigenstates). This process surprisingly gives rise to a very flat and uniform spectral hole, with the possibility to transfer absorbing peaks back at selected frequencies [Debnath1]. We have further investigated the robustness of the scheme to decay and dephasing mechanisms.

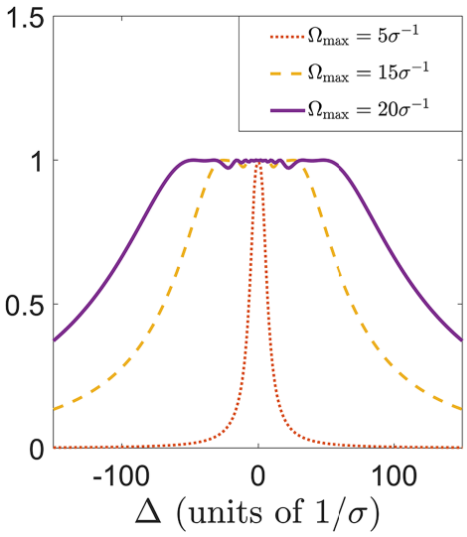

Figure 8: Efficiency of optical hole burning by a single STIRAP pulse pair as a function of detuning. A flat hole is obtained and characterized by the pulse duration σ, and Rabi frequency Ω.

We have investigated the prospects of separately addressing ions with light pulses through driving of a cavity with a linewidth including both ions. The cavity mediates interactions between the ions, but with suitable control pulses it is possible to obtain separate control. The problem is easier to avoid by selecting ions with large frequency splitting, but in the long run, our scheme may be used to reduce the remaining weak perturbation also in that case [Debnath2].
Planned efforts to obtain improvement in gate operations by use of ancilla ions fail in their most simple implementations, while more elaborate multi-ion schemes for encoding and processing of few qubits, remain a possibility with a hybrid use of error correcting codes and dissipative stabilization of Hilbert subspaces. This work demands more attention than anticipated and is still in preparation [Debnath3].

Conclusion

In conclusion, we have studied several aspects of ion-ion interactions for quantum computation applications. With current experimental parameters we expect that two-qubit gate fidelities up to 90% can be achieved. The impact of resonant coupling to a cavity during the gate operation was discussed, and a scheme based on dynamic switching is reported and substantiated with first experimental results that suggest that cavity enhancement for readout can be combined with state protection during gate operation. Further, we have studied parasitic interactions shifts due to non-qubit ions and found that for first experiments with a dilute ion spectral distribution, this effect is uncritical. For future high qubit density integration, we find that a proper choice of the ion's spectral distribution can also allow high fidelity gates. Finally, we describe a new protocol for ion ensemble preparation based on a STIRAP process. This can be useful for initializing high-density single-qubit registers faster than by conventional optical pumping. Finally, ongoing efforts to develop schemes for multi-ion addressing in a cavity and improved multi-ion gate-schemes for quantum computing are briefly sketched.
Overall, our results show that rare-earth ions could be a powerful platform for the realization of quantum gates and quantum computation, with the potential of a high qubit integration density. This motivates that additional experimental and theoretical effort is devoted to develop this promising direction further.

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