Nanoscale Systems for Optical Quantum Technologies

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D2.1 Readout/qubit ion candidates

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Version history

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V1	6/3/2017	A. Walther (ULUND)	Writing
V2	27/3/2017	A. Walther (ULUND)	Added input from other WP members, added explanations and references.

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Deliverable Description

This deliverable corresponds to a report on the different options regarding readout and qubit ion combinations. A brief description is given over the most interesting of the different combinations that are available and a summary of what choices that appear to be the best in terms of achieving the later objectives in the NanOQTech project, in particular with respect to single ion readout and ion-ion coupling. The conclusion of this report is also the basis for the decision of Milestone MS1.

Overview of the different choices

Ion-ion coupling schemes

In order to enable ion-ion interactions, there are two different mechanisms that can be considered. The primary mechanism to be investigated is dipole-dipole interactions between two ions. As one ion becomes excited, the permanent dipole moment of that ion changes, which in turn changes the surrounding electric field such that near-lying ions obtain a frequency shift. The requirements for the qubit/readout ion pair is thus that this shift should be larger than the corresponding transition linewidth, and in addition that the readout ion is capable of yielding sufficient fluorescence. These ideas are discussed further in Refs. [1], [2].

A second type of coupling mechanism is possible in the special case when multiple ions are strongly coupled to the same mode of a micro-cavity. In this regime the excitation of one of the ions can affect the ion-cavity interaction in such a way that the excitation of a second ion is blocked. This leads to a case where the ions in the single mode become entangled, with one excitation shared among all indistinguishable ions. An overview of pulsed schemes for this can be found in e.g. Ref. [3], but steady state schemes are also possible[4].

System overview: Table 1

		Qubit ions				
		Eu (best coherence)	**Pr (well known)**	**Nd**	**Er**	**Tm**
Readout with cavity	**Eu**	(1) weak, simple, good coherence				
	Pr	weak as dedicated readout, no overlap	not best at anything, well known			
	Nd (strongest)	strong readout, potential overlap	strong readout, no overlap	(3) strong, simple, is coherence enough?		
	Er (telecom)	no overlap	potential overlap		(4) telecom wavelength	
	Tm (shelving)	weak readout, shelving state, no overlap	weak readout, shelving state, no overlap			weak readout, shelving state
without cavity	**Ce**	spectral overlap	(2) no overlap, already started, trapping state			

Legend: strength, weakness, verification needed, empty box = no reason for this pair

The table presents a simplified view of the core strengths and weaknesses of the different readout ion/qubit ion combinations. *Overlap* refers to spectral overlap on either of the ions' excitation frequencies, which would disqualify that pair. The overlap is in some cases an estimate and is discussed a bit more the section Uncertain factors below. *Strong* and *weak* refers to the fluorescence intensity that can be expected from a cycling transition. The light green background in some cells indicates which approaches that will be in focus during the NanOQTech project. These are also numbered and their relevance for the tasks in WP2 is discussed in more detail in the sections below, summarized in Conclusions.

Qubit candidates

A number of different qubit candidates exist among the rare-earth (RE) ions, and they have different strengths and weaknesses. Pr has been used extensively since it is reasonably strong and has reasonably good coherence properties, while simultaneously being easy to work with in terms of hyperfine level splitting's. In particular, the three hyperfine levels allows efficient schemes of optical pumping, which was used to demonstrate the first rare-earth spin qubit gates[5]. As a pure qubit the Eu system is considered the best due to very good coherence properties, but when scaling down the system to single ion interaction, it has the drawback of having very weak oscillator strength giving low fluorescence. Nevertheless, the approach within the NanOQTech project, to utilize a micro cavity to enhance the strength, should enable enough fluorescence to be emitted to detect single ions.

The other three ions listed as qubit ions, Nd, Er and Tm, all have some favourable readout properties. This means that it can be advantageous to use them as qubit ions specifically in the situation where one also uses them as readout, since those schemes would be simpler than co-doped ones where multiple wavelength etc are required. However, because they do not have better coherence properties than Eu (or Pr as backup), there does not appear to be any reason to use any of these three ions exclusively as qubit ions (with another species as readout). Therefore these choices have been left simply as empty boxes in the table.

Readout strategies

1) Without cavity

Direct 4f readout of single RE ions is difficult due to the weak oscillator strengths. Therefore, all direct readout approaches taken into consideration uses the micro cavity implementation. The only exception to this is Ce that has a reachable short-lived 5d level that can be cycled and can thus act as a readout ion without a cavity. The advantage with this approach is that work has already been ongoing for some time[6], [7], but it has been shown that it does not work well together with Eu as qubit, due to Eu having a spectral overlap with the zero phonon line of the cycling transition of Ce. This means that another ion, like Pr, would have to be used as qubit ion for testing ion-ion interactions in this approach. Another potential issue with Ce is that indications of a long lived trapping state have been found[8], which could be a problem if not taken care of, either by repumping or by removing the trapping state through e.g. annealing or similar methods.

2) With cavity, single species

Eu and Pr are both potential qubit ions, and one could imagine reading them out directly using the enhancement of the cavity, without a co-doped readout species. As mentioned above, the advantage is a simpler setup, but the disadvantage is that they are only weakly fluorescing, so in spite of the cavity enhancement the readout photon rate is still somewhat limited. Further one cannot use the same physical ion for both qubit and readout, since they do not possess a way to make state selective readout through a cycling transition. This is because when a particular qubit state (hyperfine or Zeeman) gets excited and falls back to the ground state, it can fall down into any of the qubit levels, thus destroying the state information after only one cycle. Several possibilities exist for overcoming this problem, such as choosing different physical ions, for example where a readout ion would be resonant with the cavity resonance while qubit ions would be ions sufficiently far away on the inhomogeneous profile that they are outside the cavity resonance. The qubit ions need to be outside the resonance since a long excited state lifetime is required for the readout protocols, even when more advanced protocols such as buffer stages are used[1]. Another approach could be to shift the physical readout ion out of the cavity resonance via electric or magnetic fields.

An interesting exception to the problem of state selective readout is Tm, which has a shelving state ($^3F_4$) below the qubit transition ($^3H_4$) which could be useful. The lifetime of the shelving state is 2.4 ms in Ti:Tm:$LiNbO_3$[9], which would be very long compared to the cycling transition, enhanced by a cavity. In this situation one could transfer one of the qubit states to the shelving state, and use broadband pulses covering both qubit states to cycle them both on the cavity transition. No fluorescence would then mean that the qubit is in the shelving state. This is a similar technique as has been used in ion traps previously.

3) With cavity, co-doped species

In order to get the benefit of both using the best qubit ions and obtain strong readout fluorescence, one could also use a dedicated readout ion species. In this case, each of the listed ions has special advantages:

Nd has the highest oscillator strength. In fact it appears to be the only ion that is strong enough to have a sufficient back-action onto the cavity that the cavity resonance shifts more than the cavity line width, due to the presence of only a single ion. This gives a strong incentive to investigate Nd. In principle one could consider Nd as a single species system, using it for both readout and as qubit ion. Due to simplicity, this approach will be the one used at the start of the NanOQTech project. The coherence properties of Nd in Y_2O_3 are however not known, and there is also a question of which isotope of Nd that would work the best as a qubit. Nd isotopes exist both with and without nuclear spin. Without nuclear spin, the qubit levels would have to be created e.g. using external magnetic fields, but it's not clear if two ground state levels are enough for application protocols. At a later stage one could then use Nd as readout ion and either Eu or Pr as qubit ion, if no spectral overlap is found.

Er is not as strong as Nd, but operates at 1.5 μm, which makes it a natural choice for coupling to existing telecom fiber solutions.

Tm is also weaker but the existence of a shelving state, as described in the previous subsection, is interesting also in this case when it is used as a dedicated readout ion. The shelving level would then act as a built-in buffer stage according to the protocol of[1], simplifying the scheme and potentially freeing up frequency channels to be used as qubits.

Uncertain factors

For the micro cavity approaches the Y_2O_3 host will be used, due to its potential for making nano-sized crystals. However, a lot of data, such as coherence properties and spectral distribution of lines, is not exactly known in this host. This means that some notes in Table 1, comes from extrapolating the values from other hosts. In particular, the coherence properties of Nd in Y_2O_3 at cold temperatures have not been measured, and should be checked before proceeding. When Nd is used as a dedicated readout ion the requirements on coherence time is likely a lot more relaxed.

Another important factor is the spectral overlap between the readout and qubit ions. If the active transitions are spectrally overlapping with each other this could lead to problems such as fluorescence quenching or the qubit state being destroyed. Most of these spectral overlaps have not been measured in Y_2O_3. However, the 4f transitions of RE ions are very robust to their surroundings and typically the lines are narrow and only shift 10-20 nm between hosts. This means that if the overlap is within this range in other hosts (such as through the table by Dieke[10]), it was flagged in the table as a potential overlap that needs to be investigated before proceeding. If no active transitions (the ones that would actually be used either as readout or gate transition) were within 30 nm of each other it was assumed that there would be no overlap, but this may still have to be checked.

Another aspect of spectral overlapping is energy transfer mechanisms. These have not been included in the present investigations, since it has been shown[11] that in most cases it can be avoided by simply choosing ions that are sufficiently far away from each other spatially. This is because energy transfer mechanisms scale with the separation distance to the power of 6, so once the ions are further away than a few nm, this problem is rapidly decreasing.

The oscillator strengths are also not known exactly, and they do vary a bit between hosts. In this investigation, the values for each ion have been estimated from the overviews of ions in different hosts in Refs.[12], [13].

Conclusions and choices for NanOQTech

The cavity enhanced quantum memory of task 2.1, will use only Eu (cell marked 1), and the telecom-based single photon source of task 2.3, will use only Er (cell marked 4), which were both previously decided. The choice of suitable system for demonstrating the ion-ion interactions, task 2.2, was the primary goal of the investigation for this report. Due to the reasons given above, we found that the best strategy is to in parallel implement both the approaches of Ce-Pr without cavity (cell marked 2), and Nd-Nd with cavity (cell marked 3). As a backup plan, primarily in the case the Nd ion has too short coherence time, it should be considered to try the option either Nd-Eu or Nd-Pr in cavity, depending on if any spectral overlap is observed.

Apart from the points that were identified and shown in Table 1 where validation is still a remaining task, these conclusions also serve as the completion of the Milestone MS1.

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