Quantum repeaters with individual rare-earth ions at telecommunication wavelengths

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Abstract

We present a quantum repeater scheme using individual Erbium and Europium ions. Entanglement between distant erbium ions is created by photon detection. Entanglement is then transferred to nearby Eu ions for storage. Gate operations between nearby ions can be performed using electric dipole-dipole coupling in order to perform entanglement swapping and therefore to establish long-lasting entanglement between distant ions. We describe preparation strategies that allow us to design quantum repeaters. We also propose a multiplexed version of our scheme to enhance the entanglement distribution rate.

Entanglement distribution over long distances enables us to transfer information securely using quantum repeaters across quantum networks. However, due to unavoidable transmission losses, the distances for an efficient entanglement distribution via direct state transfer are limited to a few hundred kilometers. To overcome this limitation, the use of a quantum repeater has been suggested.

Among different rare earth (RE) ions, erbium (Er) is attractive due to its well-known optical transition (around 1540 nm) which is in wavelength window, where absorption losses in optical fibers are minimal. Europium (Eu) is another RE ion that is attractive due to its long nuclear spin coherence time.

Motivated by these properties, we propose and analyze a quantum repeater protocol based on single RE ions doped into a high finesse cavity [1]. First, we use Er ions to generate entanglement between the nodes of an elementary link of length L_0 by creating a local entanglement between the spin state and a spontaneously emitted single photon for each ion and then detecting these emitted photons. Next, using control logic gates between nearby ions within each crystal through the permanent electric dipole-dipole interaction, the quantum state of each Er ion maps to its nearby Eu ion. Once entangled pairs are generated in neighboring links, we perform a joint measurement on both ions at each intermediate node to distribute entanglement. As a result, we have an entangled pair between the outer nodes.

We show that for a dipole interaction strength of $\Delta\nu = 2\pi \times 46$ kHz corresponding to an Er-Eu separation of about 6 nm, the CNOT gate time can be as small as $T_{\mathrm{CNOT}} = 94\ \mu$s, and the fidelity of the gate would be $F_{\mathrm{CNOT}} = 0.986$. We also calculate the success probability and the average time for the distribution of an entangled pair over the entire distance.

Moreover, to significantly enhance the entanglement distribution rate, we propose to use a multiplexed version of our protocol. More precisely, we consider an array of m cavities in which each cavity emits a photon that features a distinguishable resonance frequency from the rest. In Fig.1, the performance of our scheme as a function of distance is compared with the direct transmission of photons and the well-known DLCZ protocol [2].

[1] Kimiaee Asadi, F., Lauk, N., Wein, S., Sinclair, N., O'Brien, C., and Simon, C. *Quantum repeaters with individual rare-earth ions at telecommunication wavelengths*, Quantum **2**, 93 (2018).

[2] Duan, L. M., Lukin, M. D., Cirac, J. I., and Zoller, P., *Long-distance quantum communication with atomic ensembles and linear optics*, Nature **414**, 413–418 (2001).

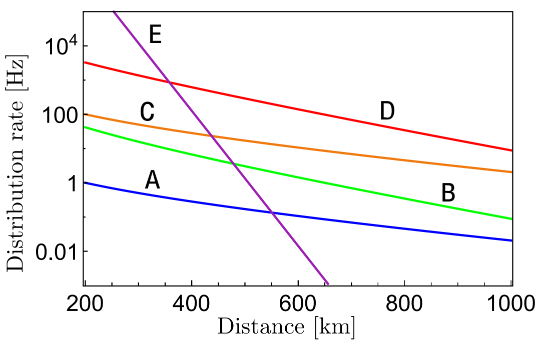

Figure 1: The entanglement distribution rate as a function of distance. Direct transmission scheme using a 10 GHz single-photon source (E) is compared with original DLCZ protocol (A) and our scheme (B) using 8 elementary links. Also shown are the rates that correspond to the multiplexed versions of DLCZ (C) as well as our scheme (D) with $m = 100$ using the same number of elementary links.