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Cavity-Enhanced Ion-Ion Remote Entanglement

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Trapped ions are a promising platform for quantum information processing. However, it is difficult to scale up the number of qubits in a single trap. One potential scaling approach lies in building multiple traps and entangling ions from different traps through quantum channels. Such entanglement mediated by photons has been demonstrated experimentally. In this scheme, the polarization of each photon is entangled with the spin state of each ion. The two photons are then mixed by a beamsplitter to erase which-path information, followed by polarization-sensitive detection on the two output ports. Coincidence detection of the two photons projects the ion-photon state onto an ion-ion Bell state. However, this isotropic spontaneous emission has low capture probability due to the limited optical access offered in many ion traps, resulting in a very low entanglement rate (5 Hz is state-of-the-art [1]). One way to increase the photon collection efficiency is to couple the ion to a high-finesse optical cavity, which enhances photon emission into the cavity mode. Much work has been done towards the experimental demonstration of ion-cavity coupling, most of which use a cavity-enhanced Raman process in calcium to achieve ion-photon entanglement. The cavity-enhanced Raman scheme has the general advantage of coherent control, high photon collection, and detection efficiencies. However, no cavity-enhanced ion-ion remote entanglement has been shown. It is currently not clear whether the photons thus produced are suitable for mediating ion-ion entanglement.

We propose an ion-ion entanglement protocol based on a coherent Raman-cavity process similar to reference [2]. We choose Sr$^+5D_{3/2}$, $m_J = 1/2, 3/2$ as the spin states, which are entangled with the polarizations of the cavity photon. The longer wavelength (1092 nm) of these photons makes cavity coupling easier as well as lying in the telecom band. We argue that the temporal-mode purity of the photon plays a crucial role in achieving high fidelity remote entanglement. Cavity photons generated by cavity-enhanced Raman scheme have imperfect temporal-mode purity due to the spontaneous decay of the intermediate state Sr$^+5P_{1/2}$ to initial state Sr$^+5S_{1/2}$. However, this spontaneous decay can be reduced by clever choices of the cavity parameters and the temporal shape of the Raman field. We model this process taking into account common experimental errors, such as Raman laser phase noise, Raman laser light path fluctuation, cavity mirror misalignment, photon light path fluctuation and detection time jitter. Our research has laid a theoretical foundation for achieving ion-ion remote entanglement with good fidelity and high entanglement rate. We designed a micro 3-D Paul trap integrated with micro-cavity and based on this model, we predict that with current mirror fabrication technology, ion-ion remote entanglement with a fidelity of 96% at a rate of 100 kHz may be achieved.

[1] D. Hucul, et.al., Nature Physics 11,37 EP (2014).
[2] A. Stute, et.al., Nature 485, 482 EP (2012).

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