On the Direct Generation of Ion-Photon Entanglement at Telecom Wavelengths in $^{171}\text{Yb}^+$

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Quantum network\cite{1}

\begin{itemize}
  \item connect distributed quantum processors
  \item 1. High-performance local processor
  \item 2. Fast entanglement of local and flying qubits
  \item Probabilistic entanglement
  \begin{itemize}
    \item need ion-photon entanglement
      \[ |\phi_{IP}\rangle = a|\psi^+\rangle|\sigma^+\rangle + b|\psi^+\rangle|\sigma^-\rangle \] interfere at PBS
  \end{itemize}
\end{itemize}

$^{171}\text{Yb}^+$ ion: local processor

Excellent local quantum processor:

\begin{itemize}
  \item Long coherence microwave clock qubit
  \item High state preparation fidelity
  \item High fidelity two-qubit gate\cite{2}
\end{itemize}

$^{171}\text{Yb}^+$ ion: quantum repeater

Networking ~1 m distance:

\begin{itemize}
  \item Well-explored: P1/2 $\rightarrow$ S1/2: 369 nm UV photon
  \item Remote entanglement rate (4.5 per second) survives remote decoherence time scale ($\approx 1$ s)
\end{itemize}

Limitations for even longer distance ($>10$ km):

\begin{itemize}
  \item 369nm UV $\rightarrow$ difficulties in optics/cavity enhancement, huge fiber attenuation
  \item Quantum frequency conversion $\rightarrow$ complicated elements, limited fidelity and efficiency (conversion efficiencies to telecom bands in current implementations with ion $<25\%$\cite{3,5})
\end{itemize}

Potential with $^{171}\text{Yb}^+$'s low-lying D states

\begin{itemize}
  \item NIR dipoles transitions (fiber loss)
    \[ 1345 \text{nm (0.3 dB/km)} \]
    \[ 1650 \text{nm (0.25 dB/km)} \]
  \item Quadrupole transitions
    \[ 435 \text{nm, E2} \]
    \[ 1650 \text{nm (0.25 dB/km)} \]
    \[ 1345 \text{nm (0.3 dB/km)} \]
\end{itemize}

Raman scheme isn’t competitive

P to low-lying D states in spin ½ ions ($^{40}\text{Ca}$): Cavity-enhanced bi-chromatic Raman

\begin{itemize}
  \item Large detune to suppress spontaneous emission from P to S
  \item To generate high-fidelity photon by Raman, the ratio $>1$.
  \item For Yb$^+$:
    \begin{itemize}
      \item cavity $g = 500$ kHz
      \item $\Omega_{\text{drive}} = 5$ GHz (10 mW 1650nm)
      \item $\Delta = 500$ MHz
    \end{itemize}
\end{itemize}

Hamiltonian (rotating-frame) $H_{\text{Raman}}$ = $-\frac{\hbar}{2} (|\psi\rangle \langle \psi | + |\sigma\rangle \langle \sigma |)$ $\Delta$ $\Omega_{\text{drive}}$

\[
H_{\text{Raman}} = -\frac{\hbar}{2} \left( |\psi\rangle \langle \psi | + |\sigma\rangle \langle \sigma | \right) \Delta \Omega_{\text{drive}}
\]

Linear drive form master equation

\[
\dot{\rho} = -\frac{i}{\hbar} [H_{\text{Raman}}, \rho] + \gamma_{\text{drive}} \rho + \gamma_{\text{Raman}} \rho
\]

Entangled photon leaving the system through fiber (not measured)

\[
|\psi\rangle \rightarrow |\psi\rangle + |\sigma\rangle \rightarrow |\psi\rangle + |\sigma\rangle
\]

Continuous excitation dynamics: choose $\Omega_{\text{drive}}$ $\approx$ $5$ MHz $\rightarrow$ $t_{\text{seq}} = t_{\text{rep}} + t_{\text{rep}} + t_{\text{cool}} = 17.3 \mu$s

\[
R_{P1} = R_{P1345}/t_{\text{seq}} \approx 0.1/17.3 \approx 5.7 \text{ kHz}
\]

Experimental

\begin{itemize}
  \item Control D states
  \item HOM-depth $g(\gamma)$ measurement
  \item Trap ion in cavity
  \item Moving towards large g, large x regime: fiber cavity
\end{itemize}

Theoretical

\begin{itemize}
  \item Fidelity calculation
  \item Bi-chromatic improved spontaneous scheme $\rightarrow$ maximally entangled states
\end{itemize}

Future plan

Summary of Results

Simulation

\begin{itemize}
  \item Hamiltonian (rotating-frame) $H_{\text{Raman}}$ = $-\frac{\hbar}{2} (|\psi\rangle \langle \psi | + |\sigma\rangle \langle \sigma |)$ $\Delta \Omega_{\text{drive}}$
  \item Lindblad form master equation
    \[
    \dot{\rho} = -\frac{i}{\hbar} [H_{\text{Raman}}, \rho] + \gamma_{\text{drive}} \rho + \gamma_{\text{Raman}} \rho
    \]
  \item Spontaneously emitted photon (measured by the environment):
    \[
    \rho_{\text{env}} = |\psi\rangle \langle \psi | + |\sigma\rangle \langle \sigma | + \gamma_{\text{drive}} \rho + \gamma_{\text{Raman}} \rho
    \]
  \item Continuous excitation dynamics: choose $\Omega_{\text{drive}}$ $\approx$ $5$ MHz $\rightarrow$ $t_{\text{seq}} = t_{\text{rep}} + t_{\text{rep}} + t_{\text{cool}} = 17.3 \mu$s
  \item Tune detune $\Delta$ ($\approx 1$ GHz $\rightarrow$ 5 MHz)
    \[ \approx 7.5 \text{ kHz} \]
\end{itemize}