Synchronization of Photons in a Quantum Network Via a Quantum Memory

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Interfacing Ions with Neutrals

Practical implementation of quantum networking requires interfacing different quantum systems (trapped-ions [2], SiV [3], neutral-atoms [4], etc…) utilizing each qubits strengths to form a hybrid quantum network [5].

For example, trapped ions excel at high-fidelity single- and two-qubit gates [2] and neutral-atoms excel at single-photon manipulation [4]. Here, extend our previous work [6] to show our plan to demonstrate temporal synchronization of two quantum nodes in a network (see Fig 3) for a proposed 100x increase in two-node entanglement rates [7].

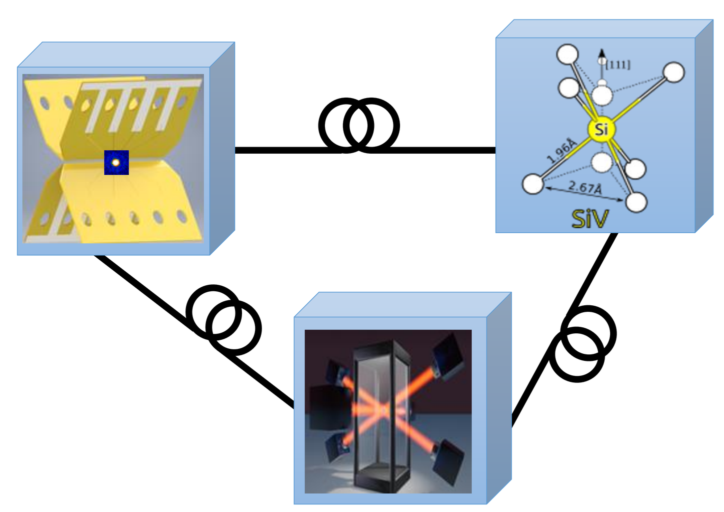

Fig 1. Vision of a 3-node hybrid quantum network transmitting flying qubits.

Ion-Photon Entanglement, Photon Collection & Qubit Detection

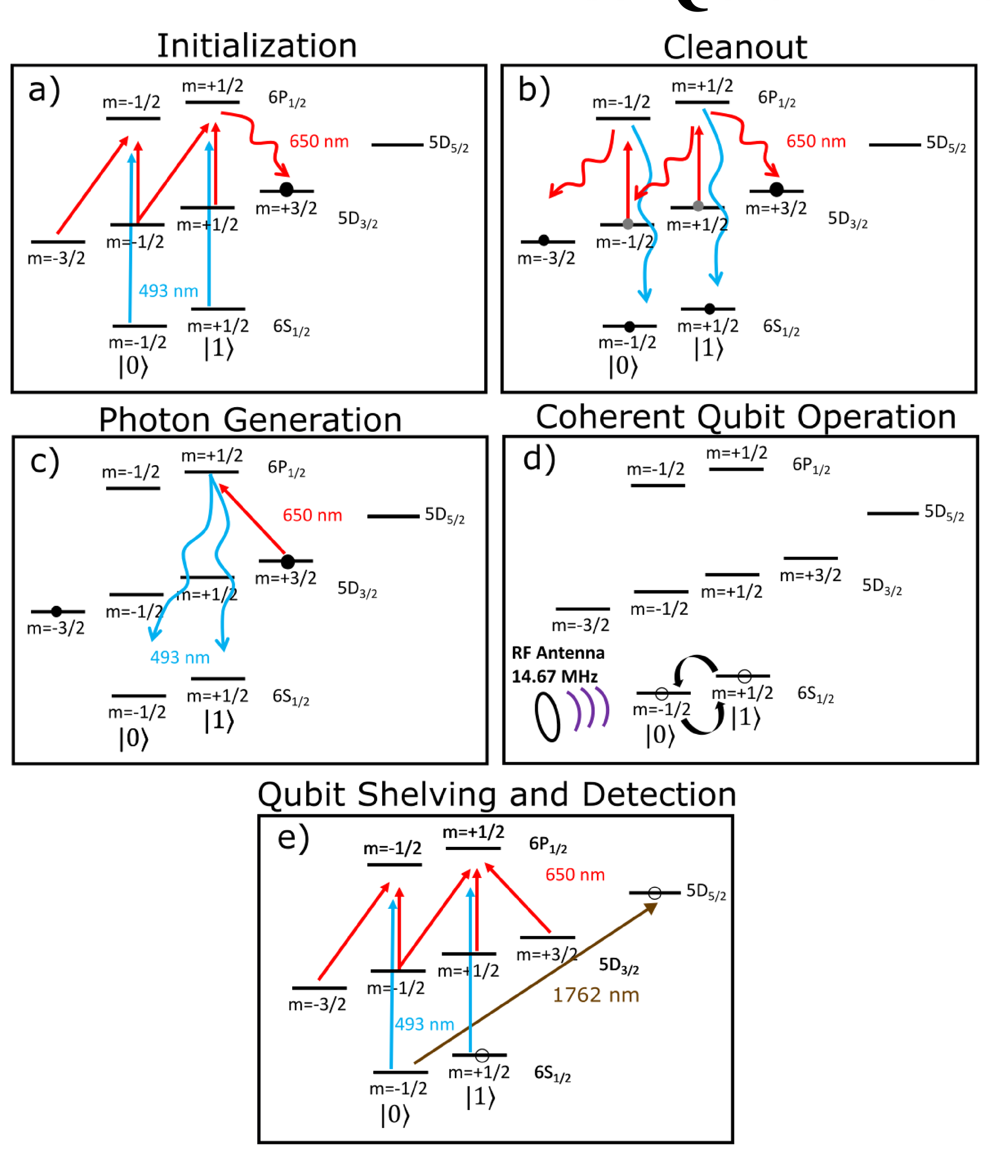

Fig 2. Trapped $^{138}Ba^{+}$ ion operations [8].

- Generate ion-photon Bell state (see Fig 2):

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0V\rangle + |1H\rangle\right)$$

- 493 nm ~10% photon collection (0.6 NA lens)
- Entanglement generation rate @ 780 nm: 45 s^{-1} w/ 48 x 10^3 attempts/s [8]
- Ion-photon entanglement fidelity bounds @ 780 nm: 84% < F < 94% [8]
- The 780 nm photon subsequently stored via quantum memory (see Fig 4).

References

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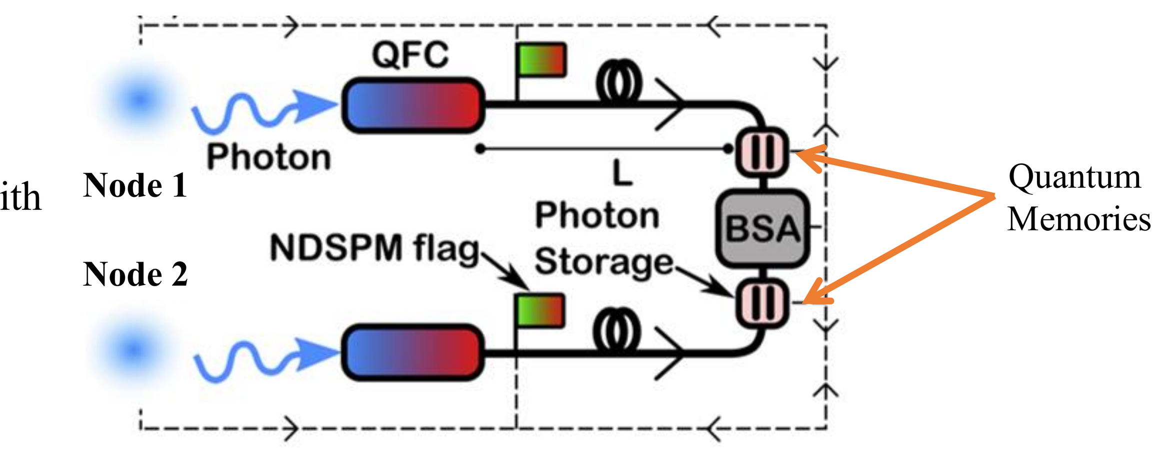
Preserving Ion-Photon Entanglement in ^{87}Rb

Motivated by our previous work (Fig 3) [7]:
Higher entanglement rates via a quantum memory!
- Temporal synchronization
- Increased entanglement rates

Fig 3. Protocol for increased network entanglement rates with photon storage [7].



Proposed method (Fig 4):

(I) Ion-photon flying qubit generation @ 780nm
1. Prepare ion-photon polarization entangled Bell state with flying qubit @ 493 nm via spontaneous emission (Fig 2).
2. Frequency-convert 493 nm flying-qubit to 780 nm via polarization-preserving quantum frequency conversion (QFC) [8].

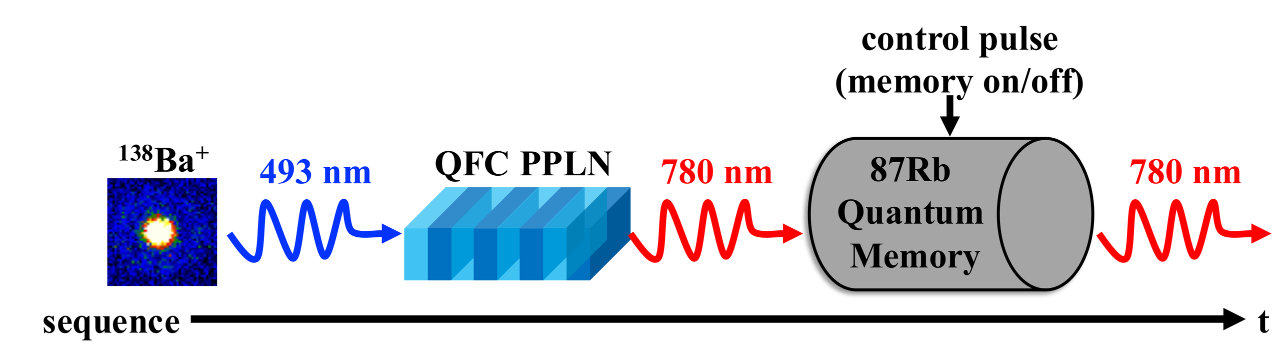


Fig 4. Flying qubit photon storage (quantum memory).

(II) Flying qubit @ 780 nm mapped onto ^{87}Rb spin-wave
1. Initialize ^{87}Rb atoms by optically pumping to $|g\rangle = |F = 1, mF = 0\rangle$ (Fig 5) using electromagnetically-induced transparency (EIT).
2. Coherently map flying qubit quantum-state @ 780 nm to spin-wave in ^{87}Rb vapor cell using EIT (Fig 5).
3. Retrieve from ^{87}Rb and analyze flying qubit quantum-state fidelity and efficiency.

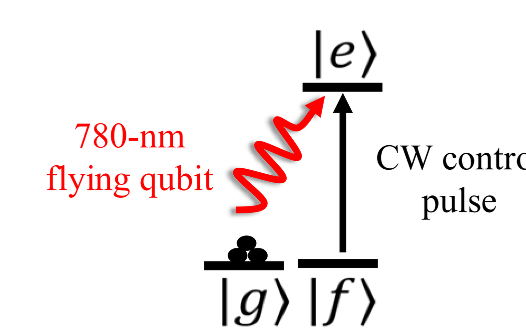


Fig 5. EIT energy-level diagram.

Projected EIT Retrieval Efficiency & Entanglement Fidelity of Ion's Photon @ 780 nm

photonic flying qubit state ⟺ neutral-atom spin wave

Custom-designed ^{87}Rb vapor cell
➔10 Torr Neon + Paraffin + cold finger + 2° wedged windows + AR coating
➔3-layer μ-metal shielding

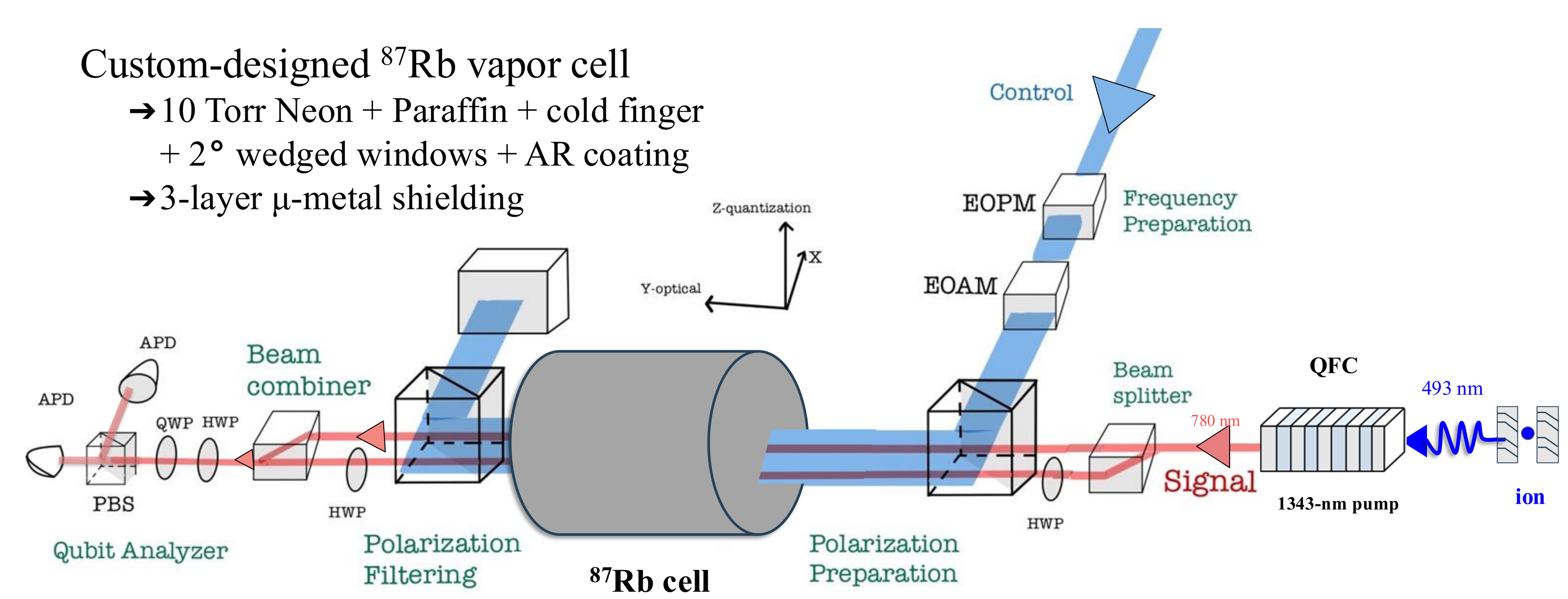


Fig 6. Entanglement swapping between ion/spin-wave and then back to ion-photon after storage.

- *(status)* Setup built completed May 2025
- *(upcoming)* Calibration data on ^{87}Rb cell, testing with CW light
- *(future)* Read-out spin-wave.

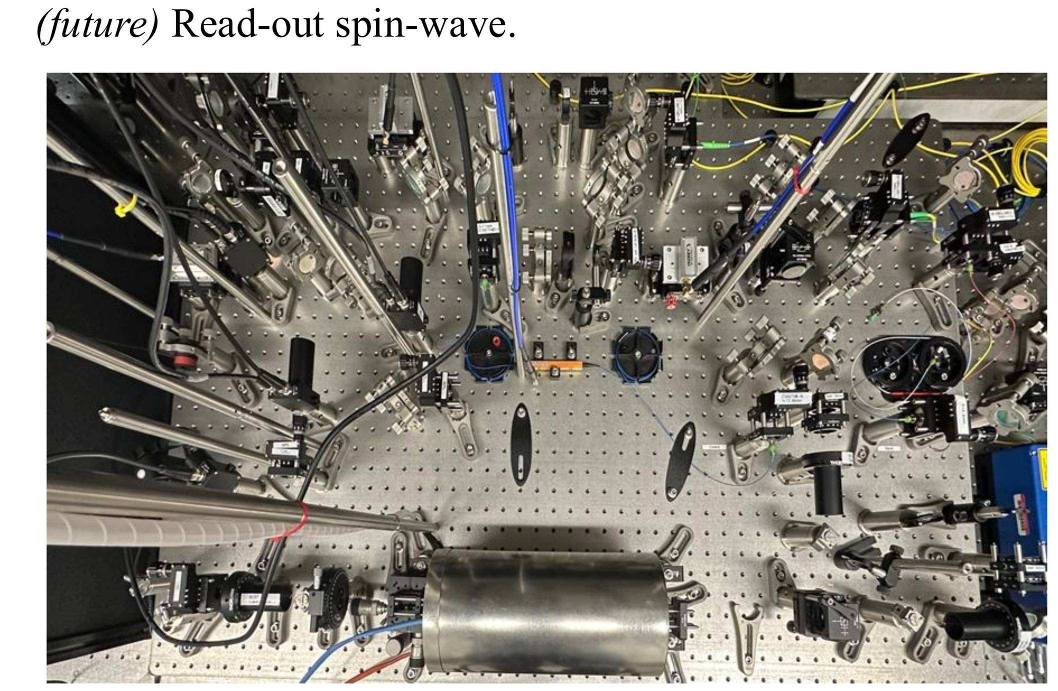


Fig 7. Actual quantum memory setup.

QM Figures of Merit

1. Store for a "long" time ⟶ Storage Duration
2. Retrieve signal ⟶ Efficiency
3. Preserve state ⟶ Fidelity

We project a storage efficiency: ~ 50%

$$\eta = \frac{\int |\Psi_{out}(t)|^2\,dt}{\int |\Psi_{in}(t)|^2\,dt}$$

We project ion-photon entanglement fidelity after storage: ~ 71-89%

Derived from: $F_{I\text{-}P,B} \times F_{QM} = (0.84 - 0.95) \times 0.95$

$F_{I\text{-}P,B}$: ion-photon entanglement fidelity before quantum memory [8]

F_{QM} : flying qubit storage fidelity projecting