CAVITY CARVING OF ATOMIC BELL STATES

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Cavity Carving of Atomic Bell States

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Research Interest

- Cavity Quantum Electrodynamics
- Quantum Information Processing
- Bose Einstein Condensation (BEC)
- etc.
Introduction

- Bell states: maximally entangled states

$$\Psi^+ = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$, $$\Psi^- = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$
$$\Phi^+ = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$, $$\Phi^- = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$$

- Advantages
  - Fast protocol, time limited only by the duration of the atomic state rotation and the light pulses
  - Focusing and pointing errors of the laser suppressed by the technique
  - No dependence on atomic distance
$|R\rangle$: right circular polarization couples $|\uparrow\rangle$ and $|e\rangle$ atomic state
$|R\rangle|\uparrow\rangle \leftrightarrow |0\rangle|e\rangle$

$|L\rangle$: left circular polarization uncoupled reference with the corresponding atomic transition far off resonant

Linear Polarizations
$|A\rangle = (|R\rangle - i|L\rangle)/\sqrt{2}$
$|D\rangle = (|R\rangle + i|L\rangle)/\sqrt{2}$
General Scheme of Carving

Coherent light pulse
\[ |A\rangle = (|R\rangle - i|L\rangle)/\sqrt{2} \]

\(|\uparrow\rangle\) interact with \(|A\rangle\) (\(|L\rangle\) especially)
reflect \(|D\rangle = (|R\rangle + i|L\rangle)/\sqrt{2}\)
with nonzero probability

\(|\downarrow\rangle\) no interaction whatsoever

even one \(|D\rangle\) photon detected
\(|\downarrow\downarrow\rangle\) state carved off!

new superposition

Figure: Husimi Q distribution of states
Why So Efficient?

- Any light that is not matched to the geometric cavity mode will remain in its original polarization mode & create no heralding signal in the detector.
  → Enhances entangling fidelity significantly and makes the scheme robust against wave front imperfections of the incident light.
Carving Schemes

- **Double carving**
  - Rotate and carve twice to make precise bell states.
  - All four of them can be produced

- **Single carving**
  - Rotate a little bit and carve once to make bell states approximately
  - $|\Psi^-\rangle$ cannot be produced

(a) Double-carving scheme
(b) Single-carving scheme
Carving Schemes

- Double-carving scheme

\[
\begin{align*}
    |\downarrow\downarrow\rangle & \xrightarrow{R_y^{\pi/2}} \frac{1}{2} (|\uparrow\uparrow\rangle - |\downarrow\uparrow\rangle - |\downarrow\downarrow\rangle + |\uparrow\downarrow\rangle) \\
    |A\rangle & \xrightarrow{1/\sqrt{3}} (|\uparrow\uparrow\rangle - |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \\
    |\Psi^+\rangle & = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)
\end{align*}
\]

with 53% probability (2/3 for ideal cavity)

with 61% probability (3/4 for ideal cavity)

\[
\begin{align*}
    R_y^{\pi}/2 & \rightarrow |\Phi^-\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \\
    |\Phi^+\rangle & = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)
\end{align*}
\]

- Single-carving scheme

\[
\begin{align*}
    |\downarrow\downarrow\rangle & \xrightarrow{R_y^\alpha} \sin^2 \frac{\alpha}{2} |\uparrow\uparrow\rangle - \frac{1}{2} \sin\alpha (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) + \cos^2 \frac{\alpha}{2} |\downarrow\downarrow\rangle \\
    |A\rangle & \xrightarrow{\sin^2 \frac{\alpha}{2} |\uparrow\uparrow\rangle - \frac{1}{2} \sin\alpha (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \approx |\Psi^+\rangle}
\end{align*}
\]

\[
\begin{align*}
    R_x^{\pi/2} & \rightarrow |\Phi^-\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \\
    |\Phi^+\rangle & = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)
\end{align*}
\]
Experimental Set Up
Experimental Set Up

- **Cavity environment**
  - Length 486μm mode waist 30μm
  - Use asymmetric cavity, transmission $4.0 \times 10^{-6}, 9.2 \times 10^{-5}$ each
  - Coupling factors: $(g, \kappa, \kappa_{\text{out}}, \gamma) = 2\pi(7.8, 2.5, 2.3, 3.0)$
  - $\kappa$: total decay rate, $\kappa_{\text{out}}$: outcoupling cavity mirror decay rate

- **Atom: rubidium 87**
  - Distance: 2 μm~12 μm
  - Trapped in 3D blue-detuned optical lattice in cavity mode 780 nm
  - $|\uparrow\rangle = |F = 2, m_F = 2\rangle, |\downarrow\rangle = |F = 1, m_F = 0\rangle$

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Figure 2: $^{87}\text{Rb} D_2$ transition hyperfine structure, with frequency splittings between the hyperfine energy levels. The excited-state values are taken from [6], and the ground-state values are from [16]. The approximate Landé $g_F$-factors for each level are also given, with the corresponding Zeeman splittings between adjacent magnetic sublevels.
Experimental Set Up

■ State detection
  - Use fluorescene, the protocol consists of two successive measurements on two atoms with an interleaved \( \pi \)-pulse -> able to distinguish between \(|↑↑\rangle, |↓↓\rangle, |↑↓\rangle/|↓↑\rangle\)

■ Rotation
  - Use Raman laser with beam waist 35μm to make initial state to coherent spin state

\[
|θ, φ\rangle = \bigotimes_{j=1}^{2} \left[ \cos \left( \frac{θ}{2} \right) |↑\rangle_j - e^{iφ} \sin \left( \frac{θ}{2} \right) |↓\rangle_j \right]
\]

where \(θ\) and \(φ\) can be adjusted by Raman laser power, duration, detuning, phase.
Experimental Set Up

- **Double carving scheme**
  - Use pulse with average photon number = 0.33
  - Distinguish states with parity oscillation
  - Rotate state with $\pi/2$ and $\varphi$ in Bloch sphere and calculate parity $\Pi(\varphi) = P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - (P_{\uparrow\downarrow} + P_{\downarrow\uparrow})$ and investigate its dependence on $\varphi$
  - Perform experiment scanning $\varphi$ from 0 to $2\pi$ in 750 times and measure probabilities
  - Experiment repeated at a rate of 1kHz with 180 $\mu$s being used for optical pumping and 740 $\mu$s for cooling between each experiment

- **Single carving scheme**
  - Measure fidelity through manipulating $\alpha$ from 0 to 0.63$\pi$
  - Average photon number of the pulse is 1.2
Result

- Distinguishing states through Parity Oscillation

Husimi Q distribution \(= \left(\frac{3}{4\pi} \langle \theta, \phi | \rho | \theta, \phi \rangle\right)\) of \(|\Phi^-\rangle\) state in theoretical and experimental data.
Result

- Double-carving scheme
  - Measure fidelity $F = \langle \psi | \rho | \psi \rangle$, ($|\psi\rangle$: ideal state) with previously measured probabilities
  - Lifetime measured via measuring the fidelities after various waiting intervals

| $|\psi\rangle$ | $P_{\uparrow\uparrow}$ | $P_{\downarrow\downarrow}$ | $P_{\uparrow\downarrow} + P_{\downarrow\uparrow}$ | $F$          | $\tau (\mu s)$ |
|----------------|-----------------|-----------------|-----------------|-------------|---------------|
| $|\Psi^-\rangle$ | 06(2)%          | 09(2)%          | 84(2)%          | 83.4(1.4)% | 204(26)       |
| $|\Psi^+\rangle$ | 02(2)%          | 15(5)%          | 83(5)%          | 81.9(2.8)% | 134(17)       |
| $|\Phi^-\rangle$ | 40(3)%          | 54(3)%          | 06(1)%          | 89.9(1.7)% | 90(19)        |
| $|\Phi^+\rangle$ | 44(5)%          | 43(5)%          | 13(4)%          | 82.4(3.1)% | ...           |
Result

- Single-carving scheme
Conclusion

- Carving is a fast, efficient method to create an entangled state
- Experiment showed that carving is reasonable method to gain high enough fidelity
Q&A