CAVITY CARVING OF ATOMIC BELL STATES

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Cavity Carving of Atomic Bell States

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Research Interest

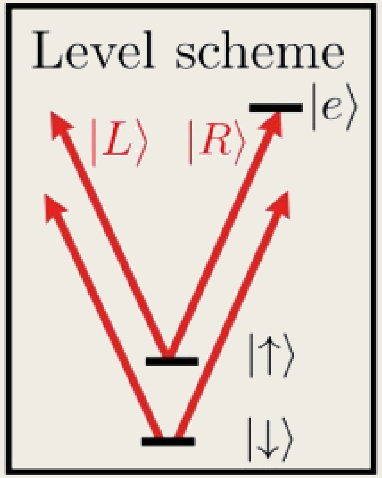
- Cavity Quantum Electrodynamics
- Quantum Information Processing
- Bose Einstein Condensation (BEC)
- etc.

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
$|A\rangle = (|R\rangle - i|L\rangle)/\sqrt{2}$

$|\uparrow\uparrow\rangle$
$|\uparrow\downarrow\rangle$
$|\downarrow\uparrow\rangle$
$|\downarrow\downarrow\rangle$

superpositioned

$|\uparrow\rangle$ 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!

$|\uparrow\uparrow\rangle$
$|\uparrow\downarrow\rangle$
$|\downarrow\uparrow\rangle$

new superposition

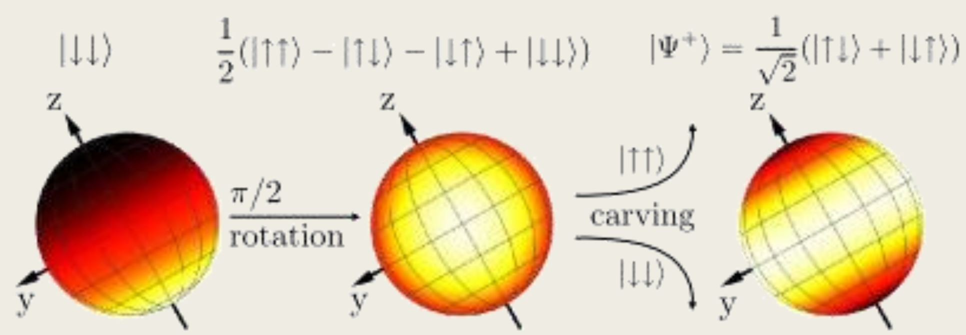


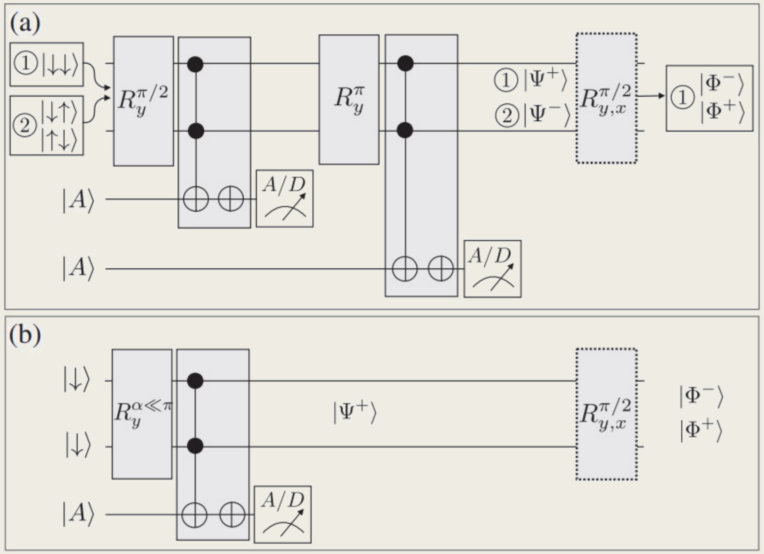
Figure: Husimi Q distribution of states

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

$$|\downarrow\downarrow\rangle \xrightarrow{R_y^{\pi/2}} \frac{1}{2}(|\uparrow\uparrow\rangle - |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle + |\downarrow\downarrow\rangle) \xrightarrow{|A\rangle} \frac{1}{\sqrt{3}}(|\uparrow\uparrow\rangle - |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \xrightarrow{R_y^{\pi}} \frac{1}{\sqrt{3}}(|\downarrow\downarrow\rangle + |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

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

$$\xrightarrow{|A\rangle} |\Psi^+\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

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

total 32% probability
(1/2 for ideal cavity)

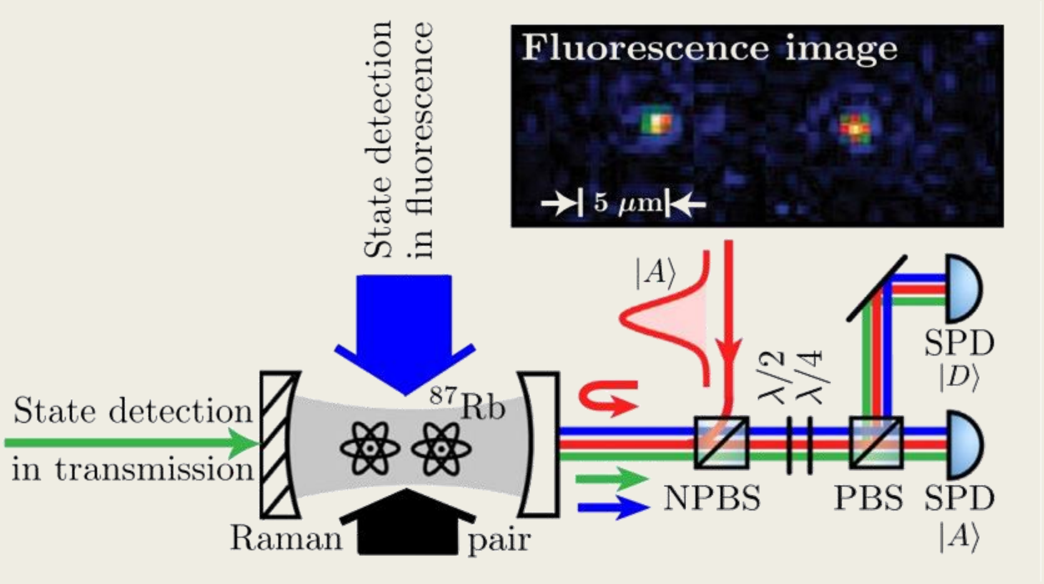
$$\left\{ \xrightarrow{R_{x/y}^{\pi/2}} \begin{matrix} |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \\ |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) \end{matrix} \right\}$$

- Single-carving scheme

$$|\downarrow\downarrow\rangle \xrightarrow{R_y^{\alpha}} sin^2\frac{\alpha}{2}|\uparrow\uparrow\rangle - \frac{1}{2}sin\alpha(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) + cos^2\frac{\alpha}{2}|\downarrow\downarrow\rangle \xrightarrow{|A\rangle} sin^2\frac{\alpha}{2}|\uparrow\uparrow\rangle - \frac{1}{2}sin\alpha(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \simeq |\Psi^+\rangle$$

$$\left\{ \xrightarrow{R_{x/y}^{\pi/2}} \begin{matrix} |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \\ |\Phi^+\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle) \end{matrix} \right\}$$

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: $(g, \kappa, \kappa_{out}, \gamma) = 2\pi(7.8, 2.5, 2.3, 3.0)$
  - κ: total decay rate, κ_{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
  - $|\uparrow\rangle = |F = 2, m_F = 2\rangle, |\downarrow\rangle = |F = 1, m_F =$

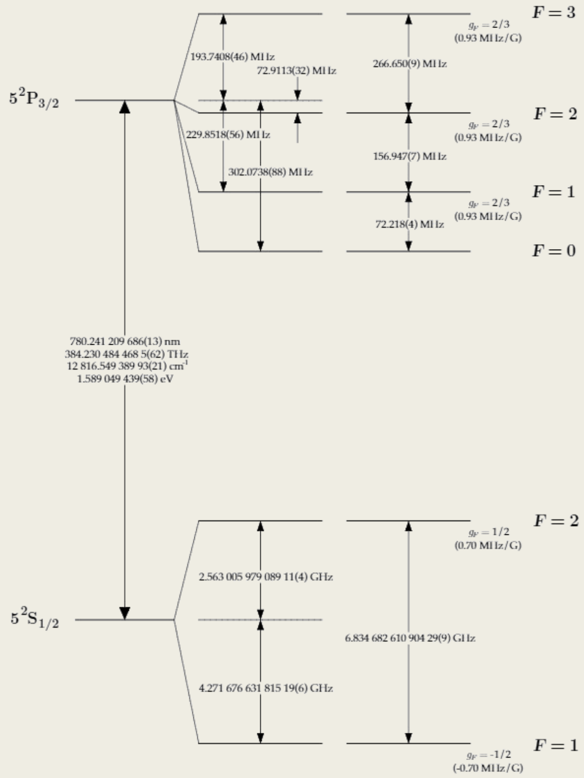


Figure 2: ^{87}Rb D_2 transition hyperfine structure, with frequency splittings between the hyperfine energy levels. The excited-state values are taken from [6], and the ground-state values are from [16]. The approximate Landé g_F-factors for each level are also given, with the corresponding Zeeman splittings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

Experimental Set Up

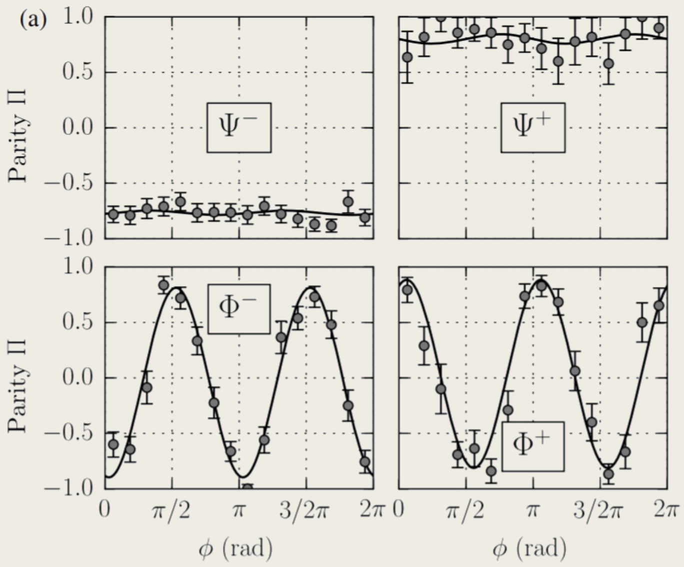
- State detection
  - Use fluorescene, the protocol consists of two successive measurements on two atoms with an interleaved π-pulse -> able to distinguish between $|\uparrow\uparrow\rangle$, $|\downarrow\downarrow\rangle$, $|\uparrow\downarrow\rangle/|\downarrow\uparrow\rangle$
- Rotation
  - Use Raman laser with beam waist 35μm to make initial state to coherent spin state $|\theta,\varphi\rangle = \otimes_{j=1}^{2}\left[\cos\left(\frac{\theta}{2}\right)|\uparrow\rangle_j - e^{i\phi}\sin\left(\frac{\theta}{2}\right)|\downarrow\rangle_j\right]$ where θ and φ can be adjusted by Raman laser power, duration, detuning, phase

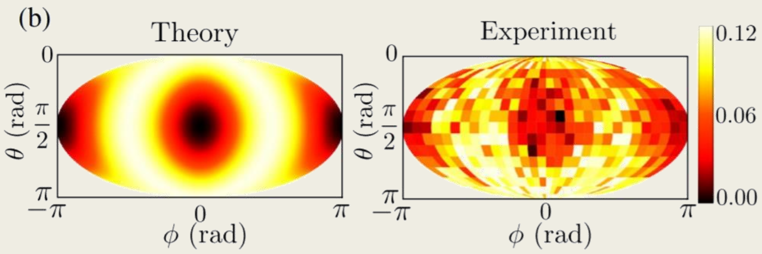
Experimental Set Up

- Double carving scheme
  - Use pulse with average photon number = 0.33
  - Distinguish states with parity oscillation
  - Rotate state with π/2 and φ in bloch sphere and calculate parity $\Pi(\phi) = P_{\uparrow\uparrow} + P_{\downarrow\downarrow} - (P_{\uparrow\downarrow} + P_{\downarrow\uparrow})$ and investigate its dependence on φ
  - Perform experiment scanning φ from 0 to 2π in 750 times and measure probabilities
  - Experiment repeated at a rate of 1kHz with 180 μs being used for optical pumping and 740 μs for cooling between each experiment
- Single carving scheme
  - Measure fidelity through manipulating α from 0 to 0.63π
  - Average photon number of the pulse is 1.2

Result

- Distinguishing states through Parity Oscillation





Husimi Q distribution (= $(3/4\pi\langle\theta,\phi|\rho|\theta,\phi\rangle)$ of $|\Phi^-\rangle$ state in theoretical and experimental data

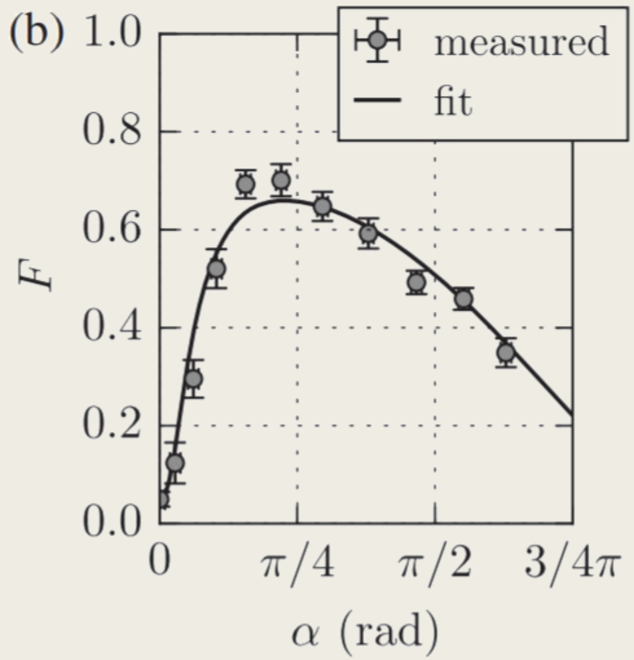
Result

- Double-carving scheme
  - Measure fidelity $\mathrm{F} = \langle\psi|\rho|\psi\rangle$, ($|\psi\rangle$: 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