LETTER

doi:10.1038/nature14293

Entanglement with negative Wigner function of almost 3,000 atoms heralded by one photon

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QFLL Journal club
2015/09/22
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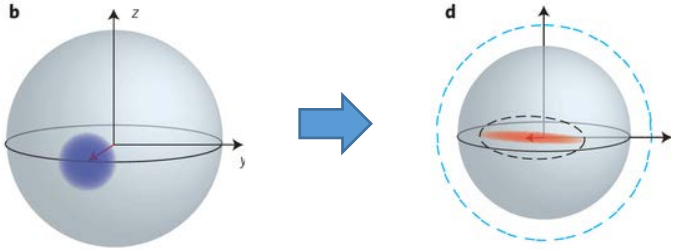
- Professor of physics – MIT (2011~)
- Former position
  - 2004~ associate professor @ MIT
  - 2000~ assistant professor @ Stanford
  - 1997~ Lynen fellowship @ Stanford
  - 1997 ph.D @ Universitat Munchen, T. Hänsch
- Current research interest
  - **C-QED with atomic ensembles**
  - Cavity Doppler cooling & sideband cooling
  - Spin squeezing for atomic clocks

Introduction

- Non-classical entangled state generation with atomic spin ensembles
  - Spin-squeezed state



J.G. Bohnet et al, Nature photonics (2014)

  - Non-Gaussian entangles state
    - Greenberger-Horne-Zeilinger (GHZ) state

$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|0\ldots0\rangle + |1\ldots1\rangle)$$

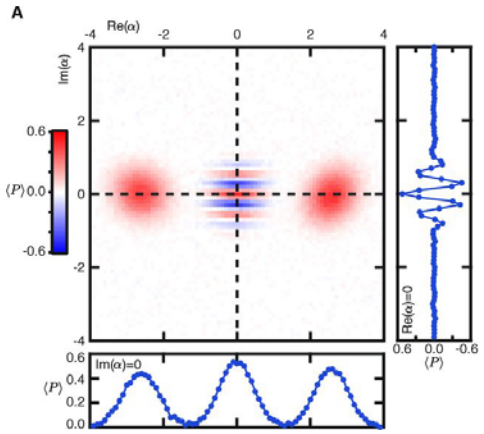
      - *Nature* **438**, 639 (2005) (Wineland group), *PRL* **106**, 130506 (2011) (Blatt group)
    - W state (first dicke state)

$$|1_N\rangle \equiv \frac{1}{\sqrt{N}}(|10\ldots0\rangle + |010\ldots0\rangle + \ldots + |00\ldots1\rangle)$$

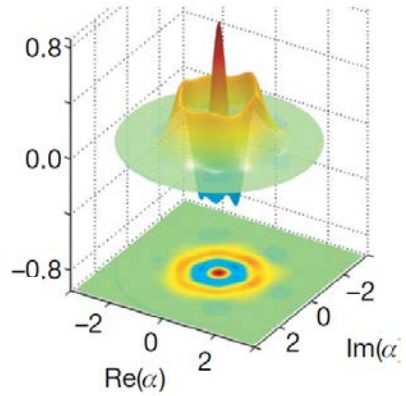
      - *PRL* **112**, 155304(2014), *Science* **344**, 180 (2014) – 41 atoms

Entanglement criteria

- Negative-valued wigner function



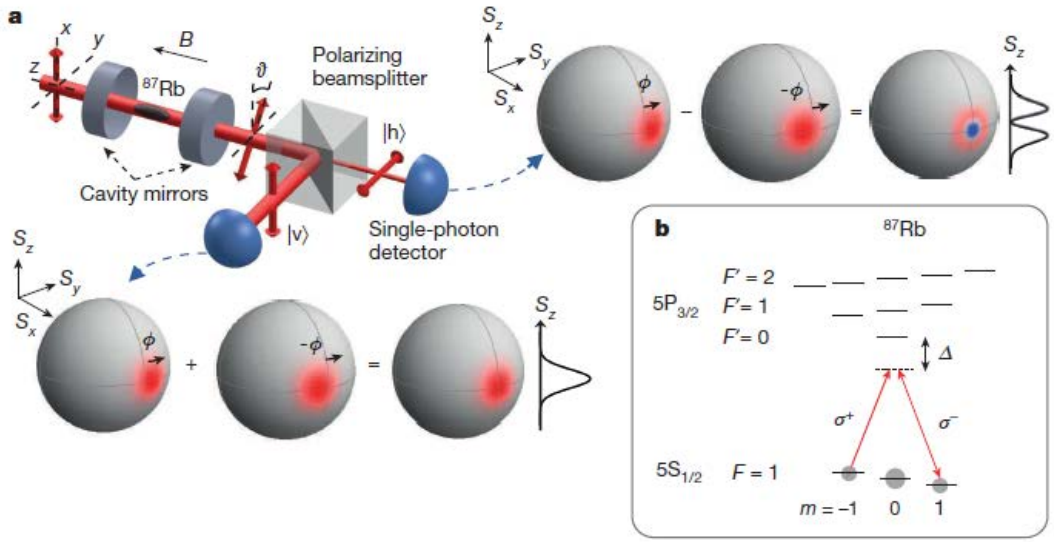
Cat state of microwave photon (n~7) (*Science* **342**, 607 (2013))



Fock state of photon with n=3 (*Nature* **455**, 510 (2008))

- Entanglement depth : minimum number of atoms entangled with one another
  - 170 of 2300 (spin-squeezed state, *Nature* **464**, 1165 (2010))
  - 13 of 41 (W state, *Science* **344**, 180 (2014))
- Entropy of entanglement, concurrence, etc. – not mentioned here.

Experimental scheme & setup

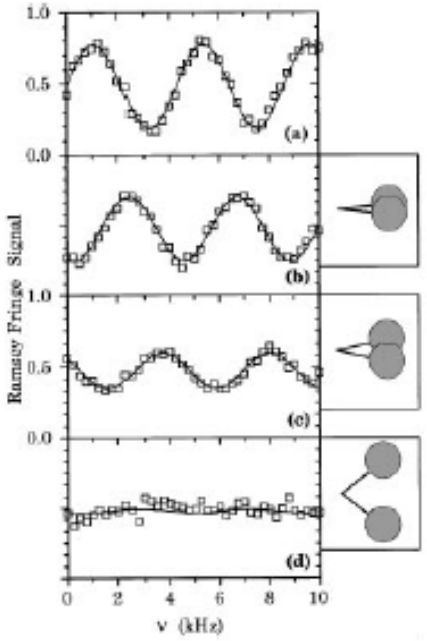


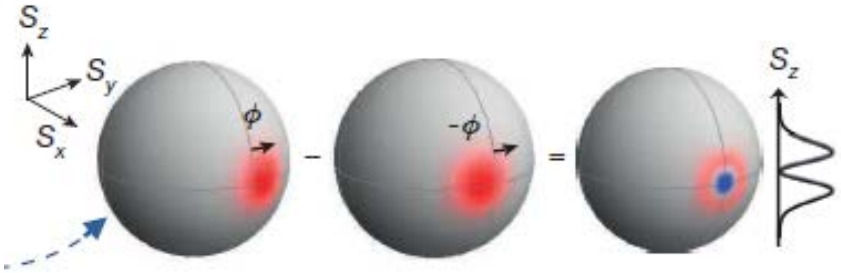
Far detuned field interaction → AC stark shift of atom level → Larmor precession of atomic spin → phase shift

$$|\psi\rangle \propto |\sigma^+\rangle|+\phi\rangle + |\sigma^-\rangle|-\phi\rangle$$

- ^{87}Rb atoms of 3100 atoms in optical cavity
  - T=50uK, Trap depth 20MHz (ODT)
  - Cavity finesse 5600, linewidth 1MHz * 2π, cooperativity 0.2
  - Effective atom # = 2/3 * total atom#
  - Effective cooperativity = 3/4 * cooperativity at antinode
- Probe light detuning = -200MHz * 2π, photon number of light pulse ~ 210

Analogy to Haroche's experiments





$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|e, \alpha e^{i\phi}\rangle + |g, \alpha e^{-i\phi}\rangle\right)$$

Coherent state (photon) + superposition state (atom)

$$|\psi\rangle \propto |\sigma^+\rangle|+\phi\rangle + |\sigma^-\rangle|-\phi\rangle$$

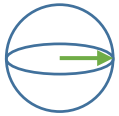
Coherent state (atom ensemble) + superposition state (photon, polarization)

Experimental step

preparing step

Atom preparation on ODT trap, optical pumping to m=1 state

→ Radio-frequency π/2 pulse $|S_x=N\rangle$ state (CSS, coherent spin state)



Heralding step

→ Probe pulse injection (vertical polarization) → Polarization-selective detection of cavity transmission

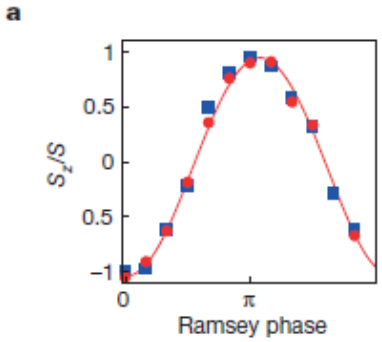
Measurement step

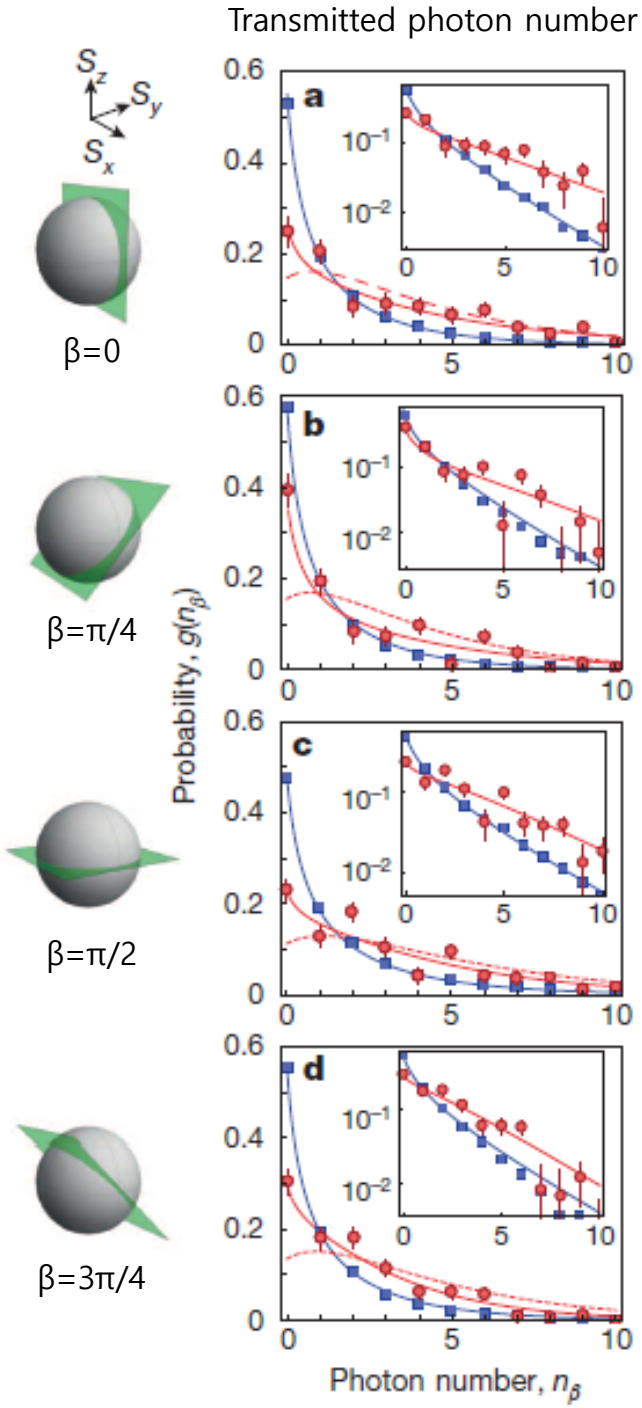
→ Spin-rotation about x-axis → State measurement by strong probe injection ($n_h \propto S_z^2$)

Result

- After heralding event, reconstruct the collective spin state
- To measure S_β distribution, rotate the collective-spin by RF pulse and measure S_z
- Strong probe pulse of vertical polarization
  - Faraday rotation angle $\theta \propto S_z$
  - Transmission of horizontal polarization $\propto \theta^2$
  - Large number of photon detection means non-zero S_z
  - In ideal case, $\langle n_{her} \rangle / \langle n_{css} \rangle = 3$ for any β
  - Exp. data : 2.7(0.2), 2.2(0.2), 2.4(0.2), 2.1(0.1) for $\beta = \{0, \pi/4, \pi/2, 3\pi/4\}$

- Ramsey interferometry shows fringe contrast change is negligible (state remains near equator of Bloch sphere)





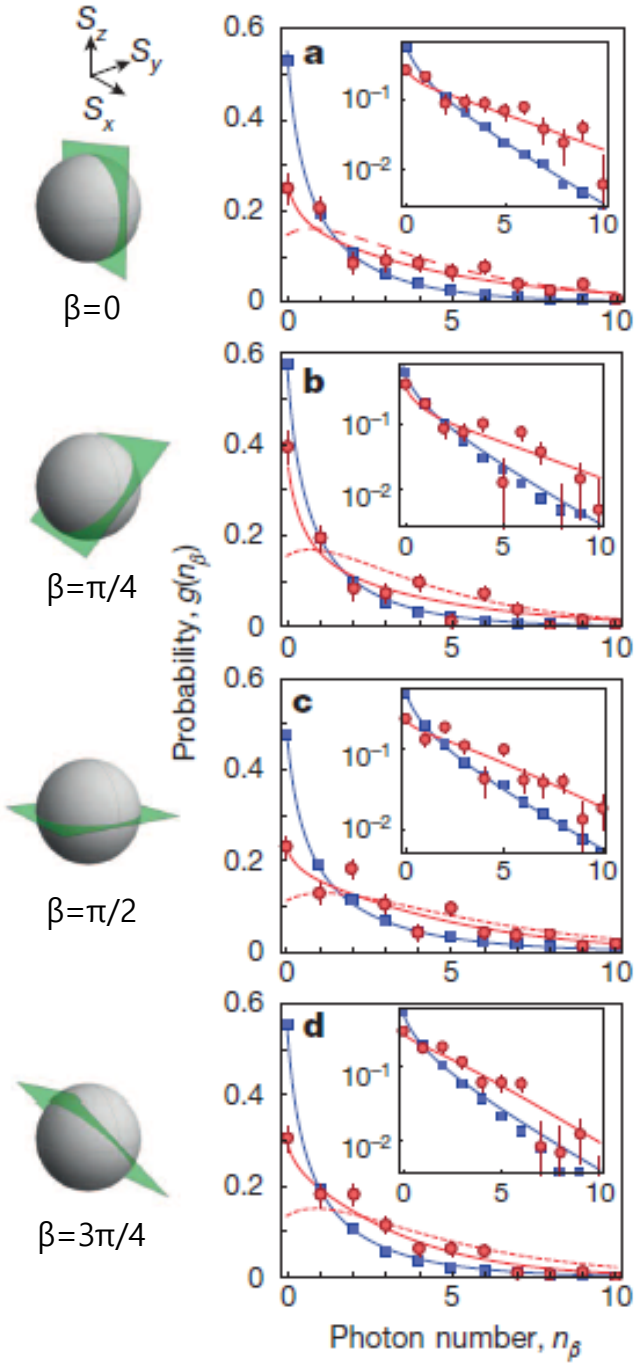
Result

- Blue solid curve, red dashed curve : theoretical expectation without free parameter for CSS, first dicke state
- Red solid line : fit to data

$$g(n_\beta) = \sum_{S_\beta} f(S_\beta) P(n_\beta, S_\beta) = \sum_{S_\beta} f(S_\beta) \exp\left[-q n_{\text{in}} (\phi S_\beta)^2\right] \frac{\left[q n_{\text{in}} (\phi S_\beta)^2\right]^{n_\beta}}{n_\beta!}$$

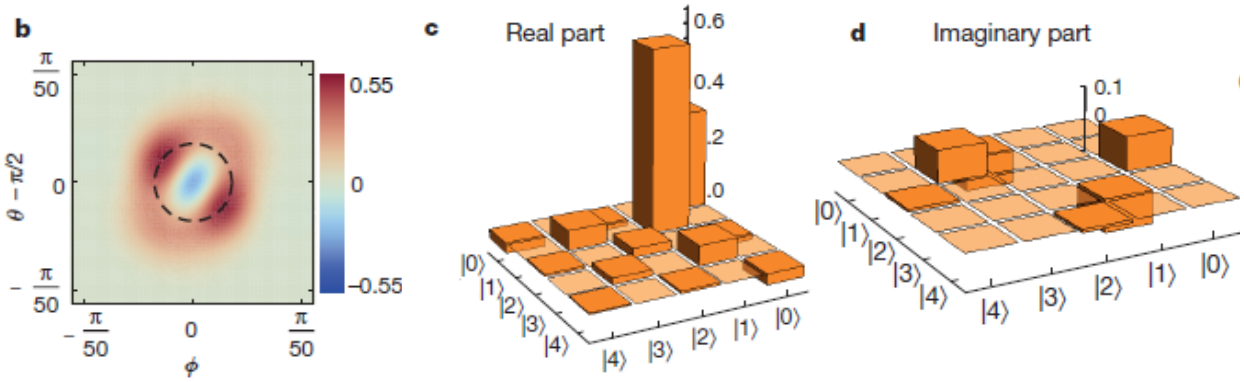
$$f(S_\beta, \rho, N) = \langle S_\beta | \rho | S_\beta \rangle$$

- imperfection makes small admixture of
  - Two photon heralded state ~ 10%
  - False heralding event due to polarization impurity ~ 10%

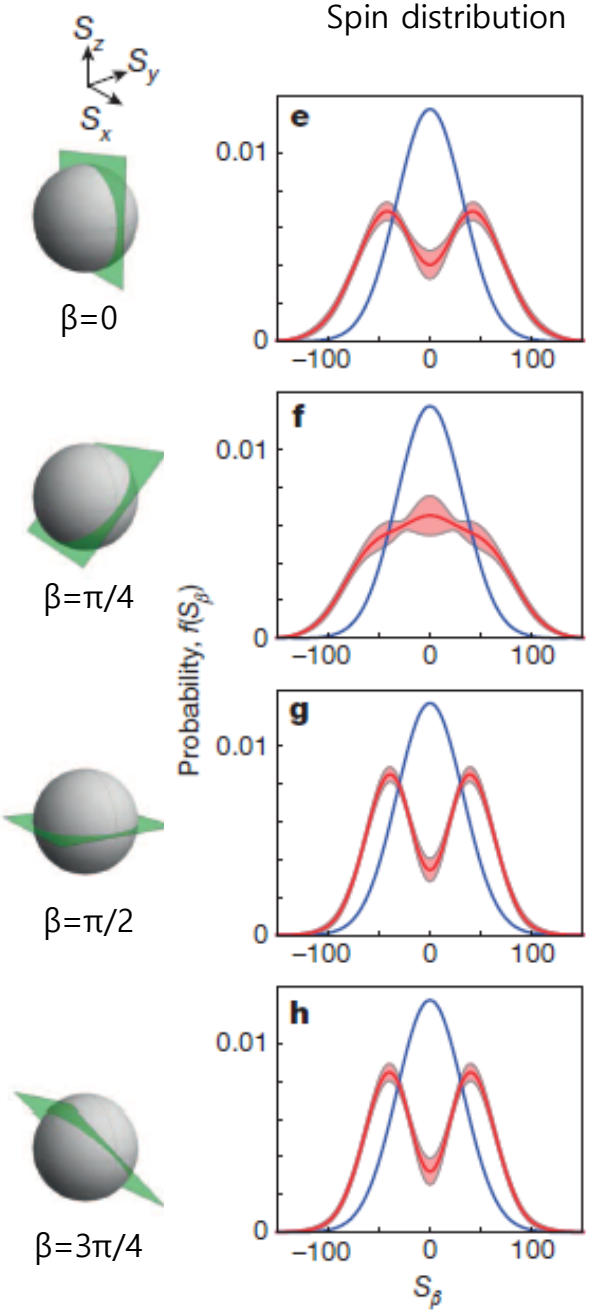


Result

- From the data, they reconstructed density matrix and wigner function
  - Ideal first dicke state : W(π/2,0) = -1
  - Neglecting off-diagonal components, ρ_{00} = 0.32(0.03), ρ_{11} = 0.66(0.04) → W(π/2,0) = -0.36(0.08)
  - Fit with whole density matrix components, W(π/2,0) = -0.27(0.08)



Spin distribution



Result

- Entanglement depth
  - Minimum number of entangled particles

$$|\varphi\rangle = \left|\varphi_1^{1,\ldots,k_1}\right\rangle \otimes \ldots \otimes \left|\varphi_M^{1,\ldots,k_M}\right\rangle$$

  - $k_i < k, \sum_i k_i = N$
  - Minimum k = entanglement depth

- 2910±190 inseparable atoms out of 3100 total atoms

- In region plot, red region shows 1-stdev. confidence region of heralded state.