Generation of squeezed vacuum with hot and ultra-cold Rb atoms

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Left to right: Arturo Lezama, Eugeniy Mikhailov, Mark Havey, Salim Balik, Travis Horrom, and Irina Novikova
Heisenberg uncertainty principle

Optics equivalent

$\Delta \phi \Delta N \geq 1$

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa.

Optics equivalent strict definition

$\langle \Delta X_1^2 \rangle \langle \Delta X_2^2 \rangle \geq 1$

$$X_1 = \frac{a + a^\dagger}{\sqrt{2}}$$

$$X_2 = \frac{a - a^\dagger}{\sqrt{2}i}$$
Coherent states of light

unsqueezed

amplitude-squeezed

phase-squeezed

angle-squeezed
Probe transparency dependence on its detuning.

Storage and retrieval of single photon squeezed state (Furusawa and Lvovsky PRL 2008)

Squeezed state requirements for a quantum memory probe:
- Squeezing carrier at atomic wavelength (780nm, 795nm)
- Squeezing within narrow resonance window at frequencies (< 100kHz)

Traditional nonlinear crystal based squeezers are capable of it, but they are extremely technically challenging especially at short wavelength.
Quantum memory with atomic ensembles

Probe transparency dependence on its detuning.

\[ |b\rangle \xrightarrow{\omega_{bc}} |a\rangle \xrightarrow{\omega_p} |b\rangle \]

\[ |c\rangle \xrightarrow{\omega_d} |c\rangle \]

Squeezing with Rb vapor

Storage and retrieval of a single photon with a squeezed state (Furusawa and Lvovsky, PRL 2008).

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\[ |a\rangle \]

\[ |b\rangle \]

\[ \omega_{bc} \]

\[ \omega_p \]

\[ \omega_d \]

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Quantum memory with atomic ensembles

Storage and retrieval

- single photon
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Self-rotation of elliptical polarization in atomic medium

A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

\[ a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in}) \]  \hspace{1cm} (1)
Will something so simple work?

Yes! J. Ries, B. Brezger, and A. I. Lvovsky, Experimental vacuum squeezing in rubidium vapor via self-rotation, PRA 68, 025801 (2003). Observed 0.85dB of squeezing at bandwidth 5-10MHz.

No! M. T. L. Hsu et al., Effect of atomic noise on optical squeezing via polarization self-rotation in a thermal vapor cell, PRA 73, 023806 (2006). Observed 6dB of excess noise after the cell.

Possible. A. Lezama et al., PRA 77, 013806 (2008).


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1.4 dB of squeezing

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- **Definitely** Philippe Grangier et al. Optics Express, 18, Issue 5, pp. 4198-4205 (2010)
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Setup

PBS

RB87

LOV Sq

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Noise contrast vs detuning in hot $^{87}\text{Rb}$ vacuum cell

$F_g = 2 \rightarrow F_e = 1, 2$

Noise vs detuning

$F_g = 1 \rightarrow F_e = 1, 2$

Noise vs detuning

Noise vs quadrature angle

Transmission  PSR noise

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Squeezing vs detuning in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 2.5Torr Ne

(a) $P=1.0$ mW, (b) $P=1.5$ mW, (c) $P=4.2$ mW, (d) $P=6.6$ mW

![Graphs showing self-rotation angle, transmission, and noise power versus frequency for different power levels.](image-url)
Low frequency squeezing vs noise sidebands frequency in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 2.5Torr Ne, T=63.3°C
(a) P=1.0 mW, (b) P=1.5 mW, (c) P=4.2 mW, (d) P=6.6 mW
Low frequency squeezing vs noise sidebands frequency in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 2.5Torr Ne, $T=63.3^\circ$C $P=1.5$ mW

Low frequency squeezing vs noise sidebands frequency in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 5Torr Ne, $T=63.3^\circ$C

$P=0.5$ mW

![Graph showing noise vs frequency](image-url)
Excess noise and the source of the controversy

No buffer gas near $F_g = 2 \rightarrow F_e = 2$ transition

Squeezing occurs in the rather narrow parameters space
MOT squeezer

\[ T = 200 \, \mu K, \, N = 2 \times 10^{10} \, 1/cm^3, \, OD = 5, \, \text{beam size} = 0.1 \, \text{mm} \]
Noise contrast in MOT with $^{87}$Rb $F_g = 2 \rightarrow F_e = 1$
Squeezing in MOT with $^{87}\text{Rb}$ $F_g = 2 \rightarrow F_e = 1$
Theoretical prediction for MOT squeezing with $^{87}\text{Rb}$

$F_g = 2 \rightarrow F_e = 1, 2$ high optical density is very important
Summary

- Self-rotation based squeezing is possible in hot and ultra-cold $^{87}$Rb vapor
- Squeezing is generated in the range from 10 kHz to several MHz
- Such vacuum squeezing is suitable for atomic quantum memory tests

Advantages of the PSR squeezing
- Requires very little optical power (< 100 mW)
- Generated at atomic transition wavelength
- Potentially can be generated at any wavelength where the suitable transition exists
  - think blue or even ultraviolet