Quantum-Enhanced Optical lattice Clock

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Outline

• Entanglement-Enhanced Optical Clock Phase Measurement

• Time-Reversal-Based Quantum Metrology
  - ArXiv: 2106.03754 (2021)
Quantum Projection Noise

\[ \sigma^2 = p(1 - p)/N \]

Standard Quantum Limit (SQL)

\[ \sigma_{SQL} = \frac{1}{2\pi f_0 C \sqrt{N T_{Ramsey}}} \sqrt{\frac{T_{Ramsey} + T_{preparation}}{\tau}} \]

Entanglement on Optical Clock Transition

One Axis Twisting Hamiltonian

\[ H = \hbar \chi S_z^2 = (\hbar \chi S_z)S_z \]
Cavity Feedback Squeezing

Hamiltonian

\[ H = \hbar \mu_B S_z + N_\uparrow \frac{c^\dagger c g^2}{\Delta} \]

Cooperativity \( \eta = \frac{4g^2}{\kappa \Gamma} = \frac{24F}{\pi k^2 w^2} \)

\[ \sqrt{\kappa \Gamma N_\uparrow \eta} \]

\( \Delta_z \)

\[ I = 1/2 \]

\[ F = 3/2 \]

\[ | \downarrow \rangle \]

\[ | \uparrow \rangle \]

\( \omega_a \approx \omega_c \)

\[ m \quad -1/2 \quad +1/2 \quad +3/2 \]
Theoretical simulation

\[
\xi^2 = \frac{\xi'^2}{\mathcal{C}^2}
\]

\[
F = \xi_+^2 \xi_-^2 - 1
\]
Entanglement on Optical Clock Transition

Time-Reversal-Based Quantum Metrology with Many-Body Entangled States

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Time-Reversed Evolution

\[ H = \chi S_z^2 \]

\[ H = -\chi S_z^2 \]

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Backward Evolution

$+H$

$-H$

$\langle N \rangle = 220$

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Signal Amplification
Signal Amplification
Signal Amplification
Quantum-Enhancement

a. SATIN Ramsey

b. Phase Allan dev. (mrad) vs. number of measurements

- SQL: $\Delta \varphi = 1/\sqrt{N}$
- $\times 15$

Heisenberg limit: $\Delta \varphi \propto 1/N$

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Conclusion and Outlook

• Quantum entanglement on optical clock transition.
• 15x quantum improvement with time-reversed quantum metrology.

• Improve clock laser coherence
• Squeezing-while-rotating
• Multi-ensemble clocks.
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