Квантовые вычисления на спиновых волнах в атомном ансамбле в одномодовом резонаторе

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OPTICS
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Литература

Linear and continuous variable spin-wave processing using a cavity-coupled atomic ensemble

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(Dated: October 1, 2021)

Spin-wave excitations in ensembles of atoms are gaining attention as a quantum information resource. However, current techniques with atomic spin waves do not achieve universal quantum information processing. We conduct a theoretical analysis of methods to create a high-capacity universal quantum processor and network node using an ensemble of laser-cooled atoms, trapped in a one-dimensional periodic potential and coupled to a ring cavity. We describe how to establish linear quantum processing using a lambda-scheme in a rubidium-atom system, calculate the expected experimental operational fidelities. Second, we derive an efficient method to achieve linear controllability with a single ensemble of atoms, rather than two-ensembles as proposed in [K. C. Cox et al. "Spin-Wave Quantum Computing with Atoms in a Single-Mode Cavity", preprint 2021]. Finally, we propose to use the spin-wave processor for continuous-variable quantum information processing and

Spin-Wave Quantum Computing with Atoms in a Single-Mode Cavity

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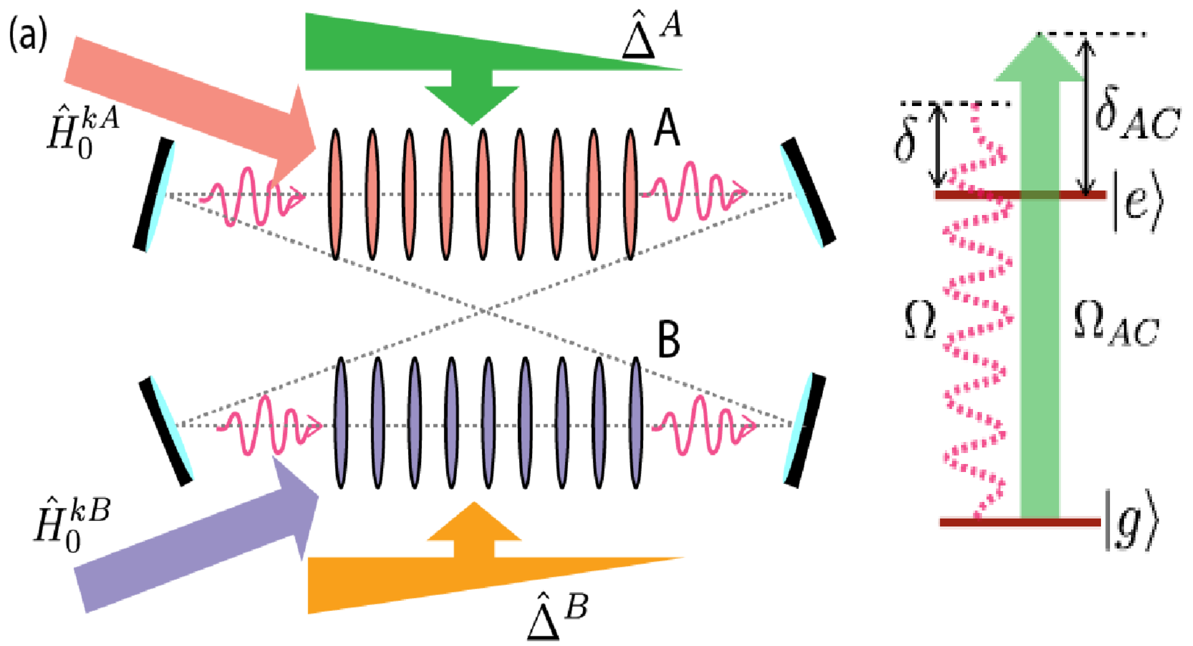
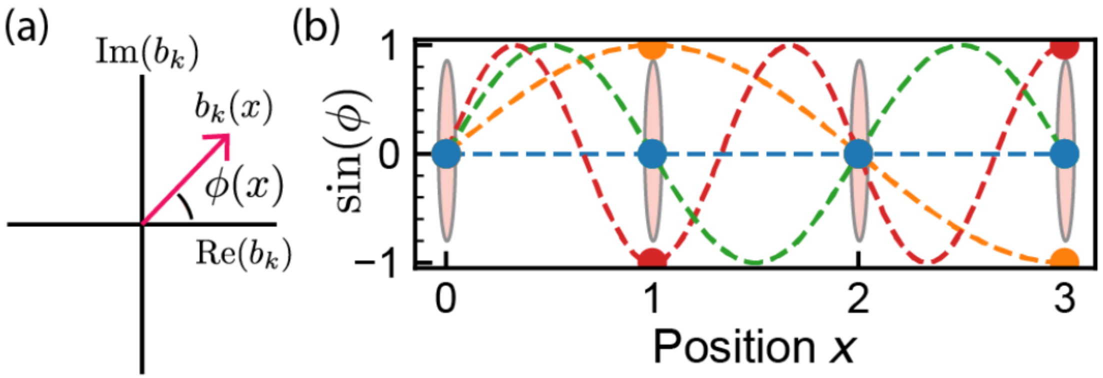
We present a method for network-capable quantum computing that relies on holographic spin-wave excitations stored collectively in ensembles of qubits. We construct an orthogonal basis of spin waves in a one-dimensional array and show that high-fidelity universal linear controllability can be achieved using only phase shifts, applied in both momentum and position space. Neither single-site addressability nor high single-qubit cooperativity is required, and the spin waves can be read out with high efficiency into a single cavity mode for quantum computing and networking applications.

Постановка задачи

- Два ансамбля с атомами, в каждом N атомов разделены на M локализованных подансамблей, n атомов в каждом
- Атомы взаимодействуют с одномодовым резонаторным полем и градиентом оптического потенциала с разными отстройками
- Число коллективных возбуждений мало
- Включение и выключение взаимодействия с резонаторной модой происходит независимо для двух ансамблей через «одевающие поля»





$$\hat{a}_x = \frac{1}{\sqrt{n}} \sum_{l=0}^{n-1} |g_l\rangle\langle e_l|$$

коллективное возбуждение в одном подансамбле

$$\hat{b}_k = \frac{1}{\sqrt{M}} \sum_{x=0}^{M-1} e^{i2\pi xk/M} \hat{a}_x$$

коллективное возбуждение стационарной спиновой волны с определённым импульсом

Взаимодействие

$$\hat{a}_x = \frac{1}{\sqrt{n}} \sum_{l=0}^{n-1} |g_l\rangle\langle e_l| \qquad \hat{b}_k = \frac{1}{\sqrt{M}} \sum_{x=0}^{M-1} e^{i2\pi xk/M} \hat{a}_x$$

Действие оптического градиента:

$$\hat{H}_\Delta = \sum_{x=0}^{M-1} -\hbar \frac{\Omega_{AC}^2(x)}{2\delta_{AC}} \hat{a}_x^\dagger \hat{a}_x. \quad \xrightarrow[\Omega_{AC}^2(x) \;=\; \alpha x]{\tau \;=\; (4\pi|\delta_{AC}|)/(\alpha M)} \quad e^{-i\hat{H}t/\hbar} = \hat{\Delta} = \sum_{x=0}^{M-1} \left[\sum_{l=0}^{n-1} \left(|g_{l,x}\rangle \langle g_{l,x}| + e^{2\pi i x/M} |e_{l,x}\rangle \langle e_{l,x}| \right) \right]$$

Эта операция переводит все спиновые возбуждения из моды с импульсом *k* в моду *k+1:* $\hat{\Delta}\hat{b}_k^\dagger = \hat{b}_{k+1}^\dagger \hat{\Delta}$

Взаимодействие с резонатором (модель Тэвиса-Каммингса + RFA):

$$\hat{H}_c = \hbar\delta\hat{c}^\dagger\hat{c} + \hbar g(\hat{c}^\dagger \hat{J}_- + \hat{c}\hat{J}_+) \qquad \hat{J}_+ = \sum_{i=0}^{N-1} |e_i\rangle\langle g_i| \qquad \hat{J}_- = \sum_{i=0}^{N-1} |g_i\rangle\langle e_i|$$

Динамические уравнения:

$$\dot{\hat{c}} = -i\delta c - ig\hat{J}_-$$
$$\dot{\hat{J}}_- = -igN\hat{c}.$$

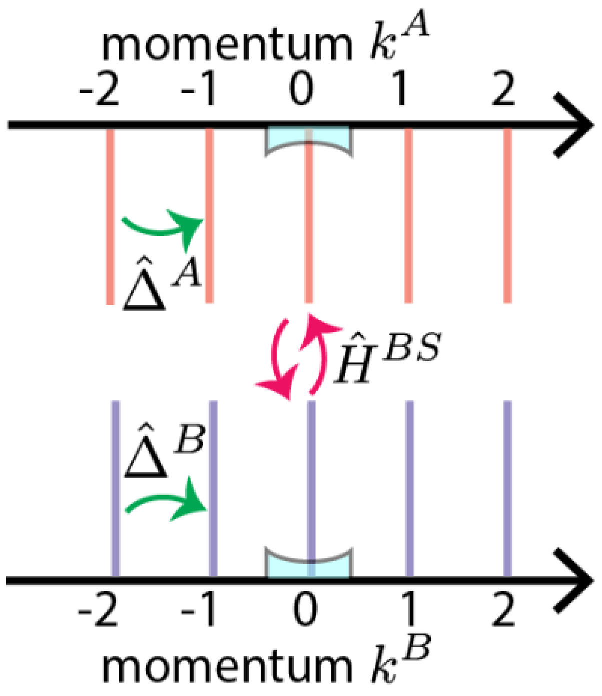
$\Longrightarrow$ Рамановское приближение

$$\hat{c} \approx -\frac{g}{\delta}\hat{J}_- \,, \quad \dot{\hat{J}}_- = i\frac{g^2}{\delta} N \hat{J}_-$$

Эффективный гамильтониан: $\hat{H}_0^k = -\hbar\frac{\Omega^2}{4\delta}\hat{b}_0^\dagger\hat{b}_0.$

$\hat{b}_0 \approx \hat{J}_-/\sqrt{N} \quad \Omega = 2g\sqrt{N}$

$$\hat{H}^{BS} = -\hbar\frac{\Omega^2}{4\delta}(\hat{b}_0^{\dagger A} + \hat{b}_0^{\dagger B})(\hat{b}_0^A + \hat{b}_0^B)$$



Ошибки

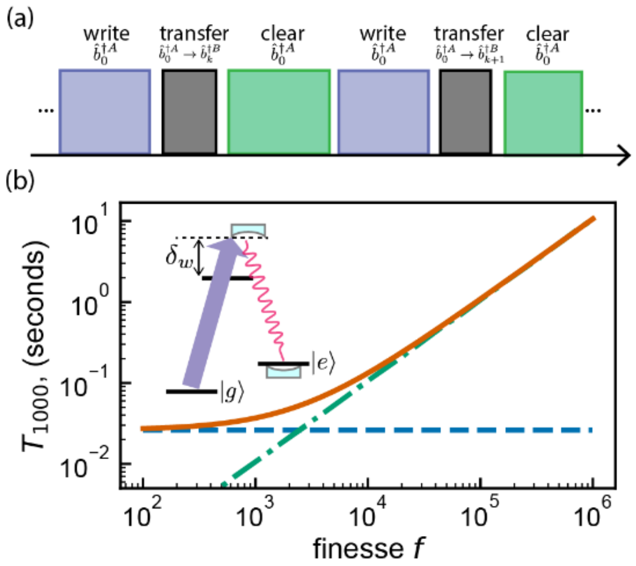
3 источника ошибок *BS* гамильтониана:

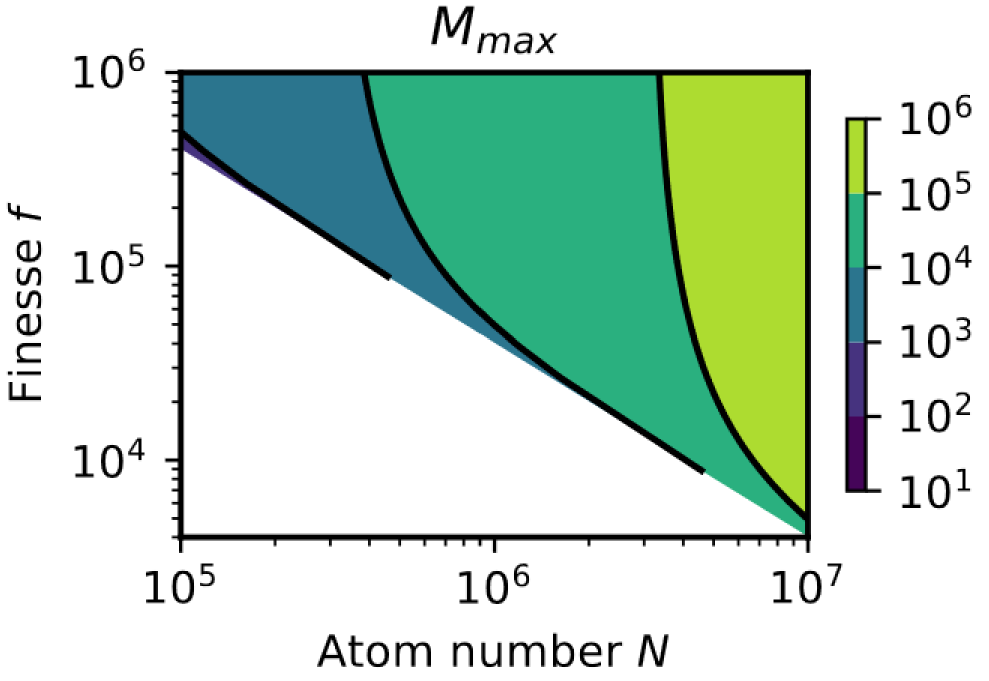
Насыщение атомов: $\hat{J}_+ = \sqrt{N}\hat{b}_0^\dagger\sqrt{1-\frac{\hat{b}_0^\dagger\hat{b}_0}{N}}$, $\hat{J}_- = \sqrt{N}\sqrt{1-\frac{\hat{b}_0^\dagger\hat{b}_0}{N}}\hat{b}_0$

$$\hat{H}_0^k = -\hbar\frac{\Omega^2}{4\delta}\hat{b}_0^\dagger\hat{b}_0. \Rightarrow \hat{H}_0^k \propto \hat{b}_0^\dagger\hat{b}_0 - \frac{\hat{b}_0^\dagger\hat{b}_0^\dagger\hat{b}_0\hat{b}_0}{N} \qquad E_M \sim (m-1)^2/N^2$$

Излучение в свободное пространство: $T \sim \delta/\Omega^2 \quad P = \Gamma T \quad E_{FS} \sim \frac{\Gamma\delta}{\Omega^2} = \frac{\delta}{\kappa NC}$

Излучение в резонатор: $E_c \sim \Gamma_c T \sim \frac{\kappa}{\delta}$





$$\delta_{opt} = \kappa\sqrt{NC},$$

Генерация сжатия и кластерных состояний

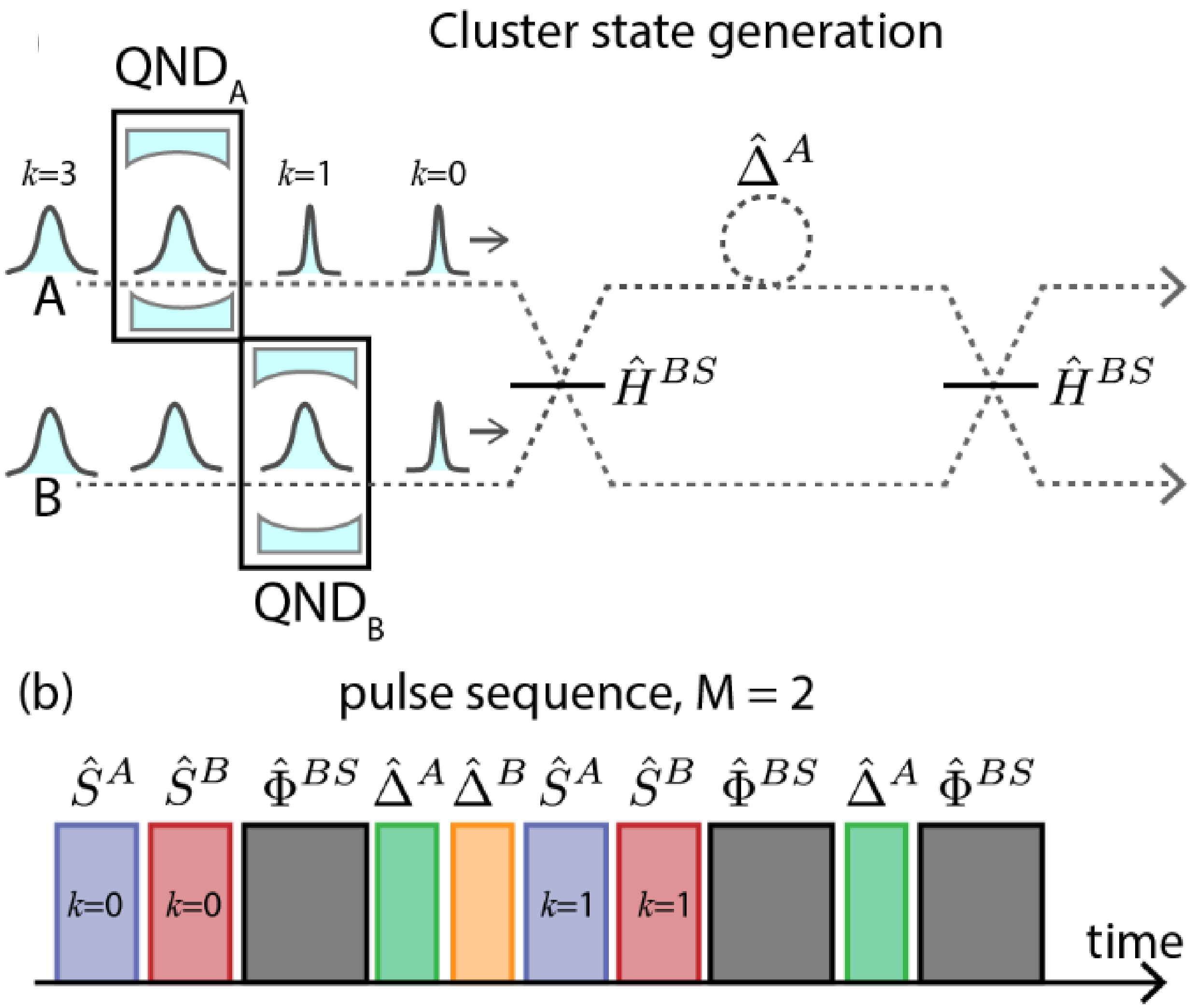
Generation of Spin Squeezing via Continuous Quantum Nondemolition Measurement

A. Kuzmich, L. Mandel, and N. P. Bigelow

Phys. Rev. Lett. **85**, 1594 – Published 21 August 2000

$$\hat{S}(\alpha) = \exp(\tfrac{1}{2}(\alpha \hat{b}_0^2 - \alpha \hat{b}_0^{\dagger 2}))$$

$$\epsilon_k^x = \hat{\mathcal{X}}_k^A + \hat{\mathcal{X}}_k^B + \hat{\mathcal{X}}_{k+1}^A - \hat{\mathcal{X}}_{k+1}^B,$$
$$\epsilon_k^p = \hat{\mathcal{P}}_k^A + \hat{\mathcal{P}}_k^B - \hat{\mathcal{P}}_{k+1}^A + \hat{\mathcal{P}}_{k+1}^B,$$



Спасибо за внимание!