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Engineering distant cavity fields entanglement through Bragg diffraction of neutral atoms

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ABSTRACT

We propose various schemes for the generation of cavity field entangled states including Bell states, W-state and GHZ states. The fundamental ingredient of all such engineering schematics is a simple, state of the art cavity field off-resonant, first order Bragg diffraction of the neutral two-level atoms. The proposal can be extended to generate any arbitrarily large multipartite state forming a quantum web. The proposal is comparatively decoherence resistant and is quite experimentally feasible with high enough success probability and fidelity under prevailing cavity QED research scenario.

1. Introduction

The phenomenon of the quantum entanglement, marked as the characteristic trait of the quantum theory [1,2], is serving best of the frontiers of the theory, i.e., exploration of the philosophical foundations and related counterintuitive issues of the theory [3–5], as well as the application of the theory in the rapidly growing field of the informatics [6]. Therefore, keeping the vitality of the subject in view, various diverse technologies including NMR, Squids, photonics and cavity QED based atom-field systems have been extensively utilized for the generation of such entangled states [7]. Specifically relevant are the examples of cavity-atom entanglement by Haroche's group [8] and the similar work by Walther's group [9]. In this regard, Bragg-regime atom–field interactions have also been employed to address various quantum informatics issues including entanglement engineering among cavity fields along with external as well as the internal degrees of freedom of the atoms [10–13], quantum state measurement [14,15], quantum teleportation [16,17], information distribution over quantum networks [18] and the explorations in the delayed choice quantum eraser [19]. Similarly, Bragg diffraction of atoms has also been invoked to experimentally tackle the foundational issues [20,21]. More recently Haq et al. [22] have published a protocol for cavity field Bell state generation based on entanglement swapping through atomic momenta. The proposal involved two atoms and four high-Q cavities; here two cavities were field entangled after performing Bell basis measurement over the rest of the cavities. We, however, present a much simpler and versatile scheme for engineering of various bipartite as well as multipartite entanglement among distant cavity fields including Bell state, W-state and GHZ state through just off-resonant Bragg diffraction of a single, neutral two-level atom through the respective cavity fields. The schematics can be straightforwardly extended to generate any arbitrary multipartite entangled state among spatially separated cavity fields in a fashion much akin to photonics's Bell multiport setups [23,24], and hence to formulate a multitasking quantum network [25–29]. The proposal presented in the paper has an evident and stringently needed advantage over the rest of its counterparts being executed under cavity QED based atom–field interactional scenario: here the mediator, a Bragg diffracted atom carrying quantum information and traversing in between the distant high-Q cavities is a ground state, neutral two-level atom posing minimal decoherence threat during execution of the protocol [30]. The claim is further fortified because atom also interacts with the cavity fields off-resonantly leading to virtual Rabi cycles and hence the decoherence that comes through spontaneous emission can be ignored completely.

The paper is organized as follows. Section 2 furnishes a brief review of the atom-field interaction under Bragg regime cavity QED. Section 3 then elaborates the engineering schematics for the generation of Bell, W- and GHZ states among spatially disjoint,

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distant cavity fields. Finally in Section 4, we summarize our work while comprehensively mentioning its merits and experimental feasibility along with the *envisionable* generalization of the protocol over multi partite, multi-nodal quantum web.

2. Bragg regime atom–field interaction

The de Broglie atomic wave diffraction via Bragg regime atom–field interactions is an energy as well as momentum conserving, multiphoton, elastic Raman scattering phenomenon that follows general Bragg diffraction conditions with the role of light and matter duly interchanged for the present case [31,32]. In this regard, the atomic momentum change occurs only in the discrete initial atomic momenta values, evidently in the direction parallel to $\mathbf{k}$ vector, i.e., along the cavity axis. The conditions for momentum and energy conservation are [14,15]

$$p_{out} = p_o + l\hbar\mathbf{k} \quad (1)$$

$$\frac{|p_o|^2}{2M} = \frac{|p_{out}|^2}{2M}. \quad (2)$$

Here $p_o = l_o\hbar\mathbf{k}/\mathbf{2}$ is the initial quantized momentum of the incoming atom with l_o being an even integer and designating the order of Bragg diffraction. Moreover, p_{out} stands for the final momentum acquired after l interactions. It is worth noting that each interaction, i.e., a complete Rabi cycle, imparts a momentum of either zero or $2\hbar\mathbf{k}$ along the direction of the standing wave field [11,13]. Simultaneous solution of the energy and momentum conservation expressions, i.e., Eqs. (1) and (2) yields $l\left(l + l_o\right)\hbar^2\mathbf{k}^2/2M = 0$ implying two equally valid results; (i) $l=0$ corresponding to un-deflected atom with no momentum change, and (ii) $l = -l_o$ marking a momentum change linked with l_o interactions. Later case describes a deflected atom with an acquired momentum being exactly equal to the initial value [33]. Thus we note that, in Bragg diffraction, the magnitude of atomic momentum stays unaltered while its direction is reversed. The order of the Bragg diffraction l_o therefore has values 2, 4 and 6 corresponding to the first, second and third order diffraction. Corresponding orderwise momenta imparted to the atom are $\left(\left|p_o\right\rangle = \left|\hbar\mathbf{k}\right\rangle, \left|p_{-2}\right\rangle = \left|-\hbar\mathbf{k}\right\rangle\right)$, $\left(\left|p_o\right\rangle = \left|2\hbar\mathbf{k}\right\rangle, \left|p_{-4}\right\rangle = \left|-2\hbar\mathbf{k}\right\rangle\right)$ and $\left(\left|p_o\right\rangle = \left|3\hbar\mathbf{k}\right\rangle, \left|p_{-6}\right\rangle = \left|-3\hbar\mathbf{k}\right\rangle\right)$ in accordance with the so-called Bragg resonances [34]. We consider an initial two-level ground state, i.e., $|g\rangle$ atom, travelling along the z-axis with transverse quantized momentum $\left|p_o\right\rangle$ along the x-axis, i.e., in the direction of cavity field, that interacts with the cavity Fock field $\left|n_c\right\rangle$ as depicted in Fig. 1. The governing interaction picture Hamiltonian, formulated under dipole and rotating wave approximations, may be expressed as follows [13–15]:

$$H_I = \frac{p_x^2}{2M} + \frac{\hbar\delta_c}{2}\sigma_z + \hbar\mu\cos\left(k\hat{x}\right)\left(\hat{a}\sigma_+ + \hat{a}^\dagger\sigma_-\right). \quad (3)$$

Here μ designates the coupling constant for the atom–field interaction, $\hat{a}\left(\hat{a}^\dagger\right)$ is the field annihilation (creation) operator while $\sigma_+ = |e\rangle\langle g|(\sigma_- = |g\rangle\langle e|)$ and $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$ are the related atomic raising (lowering) and inversion operators, respectively. The system's detunning with the cavity field is marked as δ_c and $p_x^2(\hat{x})$ stands for momentum (position) operators for the center-of-mass motion of the atom. The state vector describing such an interaction lasting for any arbitrary time t may be written as follows:

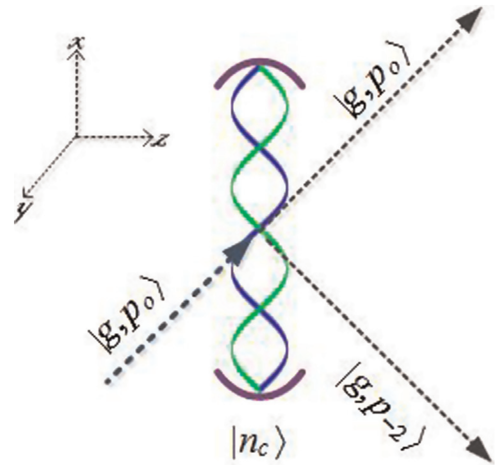

Fig. 1. Cavity field interaction of an atom with quantized momenta in Bragg regime.

$$\left|\Psi_{a-f}^{p}(t)\right\rangle = e^{-i(p_o^2/2M-\delta_c/2)t}$$

$$\times\sum_{l=-\infty}^{\infty}\left[C_{nc,g}^{pl}\left(t\right)\left|n_c, g, p_l\right\rangle + C_{(n-1)c,e}^{pl}\left(t\right)\left|(n-1)_c, e, p_l\right\rangle\right]. \quad (4)$$

In the above expression $C_{nc,g}^{pl}\left(t\right)\left[C_{(n-1)c,g}^{pl}\left(t\right)\right]$ stands for the probability amplitude when the cavity field is in Fock state $\left|n_c\right\rangle\left[\left|(n-1)_c\right\rangle\right]$ while atom is in ground $|g\rangle$ [excited $|e\rangle$] state having quantized transverse momenta $\left|p_l\right\rangle$ after l interactions. The running summation over l marks the accumulated transverse atomic momenta acquired through successive Bragg's order bounded number of Rabi's interactional cycles. Schrödinger's equation implies the following set of infinite coupled first order differential equations (ICDE) as the solution for the respective probability amplitudes under l_oth order Bragg diffraction:

$$\frac{\partial C_{nc,g}^{pl}(t)}{\partial t} = -i\left[\frac{l(l_o+l)\hbar k^2}{2M}\right]C_{nc,g}^{pl}(t) + \frac{\mu\sqrt{n_c}}{2}\left(C_{(n-1)c,e}^{pl+1}(t) + C_{(n-1)c,e}^{pl-1}(t)\right), \quad (5)$$

$$\frac{\partial C_{(n-1)c,e}^{pl}(t)}{\partial t} = -i\left[\frac{l\left(l_o+l\right)\hbar k^2}{2M} + \delta_c\right]C_{(n-1)c,e}^{pl}(t) + \frac{\mu\sqrt{n_c}}{2}\left(C_{nc,g}^{pl-1}(t) + C_{nc,g}^{pl-1}(t)\right). \quad (6)$$

Now in order to eliminate decoherence linked with spontaneous emission from an excited atom, we select off-resonant Bragg diffraction such that $\delta_c \gg \omega_r$, with $\omega_r = \hbar k^2/2M$ denoting the recoil frequency. Furthermore, we also invoke adiabatic approximation, i.e., $\omega_r + \delta_c \gg \mu\sqrt{n_c}/2$ and select first order Bragg diffraction with $l_o = 2$. Selection of this specific order therefore reduces the ICDE set to only five significant equations contributed by $l \in \{-3, -2, \ldots 1\}$ [14,15,31,32,35]. Now $l\left(l_o+l\right)\hbar k^2/2M$ is ignored in large detunning limit and adiabatic approximation when applied for an initially ground state atom, implies $\partial C_{(n-1)c,e}^{p+1}(t)/\partial t = \partial C_{(n-1)c,e}^{p-1}(t)/\partial t = \partial C_{(n-1)c,e}^{p-3}(t)/\partial t = 0$. Same approximations also suggest us to ignore $C_{nc,g}^{p+2}(t)$ and $C_{nc,g}^{p-4}(t)$ as being insignificantly small [14,33,36].