Asymmetric Field Photovoltaic Effect of Neutral Atoms

Wenxi Lai, Jinyan Niu, Yu-Quan Ma, and W. M. Liu
1 School of Applied Science, Beijing Information Science and Technology University, Beijing 100192, China
2 School of Science, Inner Mongolia University of Science and Technology, Baotou, 014010, China
3 Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China and
4 School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100190, China

Photovoltaic effect of neutral atoms using inhomogeneous light in double-trap opened system is studied theoretically. Using asymmetric external driving field to replacing original asymmetric chemical potential of atoms, we create polarization of atom population in the double-trap system. The polarization of atom number distribution induces net current of atoms and works as collected carriers in the cell. The cell can work even under partially coherent light. The whole configuration is described by quantum master equation considering weak tunneling between the system and its reservoirs at finite temperature. The model of neutral atoms could be extended to more general quantum particles in principle.

PACS numbers: 32.80.Qk, 72.40.+w, 67.55.Hc, 03.65.Yz

I. INTRODUCTION

Research on new devices for future atomtronic circuit have attracted great attentions recently, such as atomic clocks [1–3], atom interferometry [4–6], atom transistors [7–10], atom chips [11–13], quantum logic gates [14–17] and atomic batteries [18–21]. They reveal that atoms are well controllable and have substantial degrees of freedom, although they work under critical environments of low temperature at present. Atomic batteries are one kind of these important devices which could be applied to supply power to the others.

Prototype batteries of atoms have been reported both experimentally and theoretically. As far as we know, they include batteries based on chemical potential difference [18, 19], asymmetric trap [20] and artificial gauge fields induced spin-orbit coupling [21]. In the chemical potential difference based atomic battery, the chemical potential difference has been defined as the effective voltage of the cell [18]. Such battery can be charged and discharged using a sweeping barrier of radio-frequency field in a double-well structured magnetic chip trap [19]. In the asymmetric trap configuration, power of the battery comes from the non-equilibrium process between non-condensed thermal atoms and Bose-Einstein condensed atoms with an incoming beam of cold atoms in a highly asymmetric potential [20]. In the spin-orbit coupling induced photovoltaic cell, a coherent light inputs energy into cold atoms due to spin-orbit coupling [21]. Atom population at excited energy level in the double-trap cell can be controlled by the artificial magnetic flux in synthetic dimensional space of atoms.

In this paper, we would demonstrate atomic battery based on asymmetric driving field by trapping atoms in a symmetric potential. Asymmetric field here means two optical fields acting on double traps respectively with different amplitudes, different frequencies or different phases. The phase of light in the present model can be any phase which may be caused by path length of light, initial phase [22], complex dipole moment of atoms [23] or artificial magnetic flux induced by spin-orbit coupling [24–28]. Therefore, it would be naturally proved in the following that the artificial gauge field induced photovoltaic effect in which phase effect has been considered [21] is just one particular case of the present model. In fact, current caused by the amplitude and frequency difference is much larger than the current created due to the phase difference. It indicates that amplitude and frequency of light can play more important role than the phase in this kind of photovoltaic cell.

II. THEORETICAL MODEL

The model that we consider here is a double-trap opened system which is coupled to the left and right leads via atom tunneling as conceptually illustrated in Fig. 1(a). Atoms from the leads occupy the ground state of two traps at the same probability due to potential energy difference. Inhomogeneous external lights excite atoms in the traps into their excited states and rearrange the atom occupations. It is leads to polarization of the double-trap system. The ground and a Metastable states of Fermion alkaline-earth(-like) atoms with long lifetime clock transitions can be used in our model (See Fig. 1(b)). At least two traps are necessary to built the cell, since polarization of atom population as an effective bias voltage of the battery have to be constructed in the two traps.

A. Hamiltonian

Optical potentials for the two traps and atomic reservoir are insensitive to the internal state of atoms [22]. For neutral atoms, the main inter atom interaction comes from their collisions. Each trap is set to be narrow enough and either one or no atom occupies the trap in

*Electronic address: wlu@iphy.ac.cn
Planck’s constant is taken to be $\hbar$ in a trap, respectively, where $\epsilon$ represents kinetic energy of the atom for mode 1 and mode 2, $\phi$ is the atomic mass, and $k$ denotes the area of lower energy. It reveals that energy of the two-level energy transformation, in this process, excitation of the excited state levels of alkaline-earth(-like) atoms. (c) Conceptual structure of closed circuit which consists of the neutral atom photovoltaic cell with its effective voltage $U$, a resistance $R$ and a switch $S$.

**FIG. 1:** (Color on line) (a) Schematic illustration of the asymmetric field photovoltaic cell. Atoms in the left and right leads have the same chemical potentials $\mu$. $E_1$ and $E_2$ represent two lights with different amplitudes, different frequencies or different phases, driving atoms in trap 1 and trap 2, respectively. Blue color indicates the area of higher energy and red color denotes the area of lower energy. (b) The ground and excited state levels of alkaline-earth(-like) atoms. (c) Conceptual structure of closed circuit which consists of the neutral atom photovoltaic cell with its effective voltage $U$, a resistance $R$ and a switch $S$.

The collisional blockade regime of strong repulsion [33]. In this blockade regime, the double-trap system could be described by the single-particle Hamiltonian [24, 25]

$$H_{\text{trap}} = \sum_{\alpha,s} \varepsilon_s a_{\alpha s}^\dagger a_{\alpha s}. \quad (1)$$

Here, $\varepsilon_s$ represent energy of a single atom which is the same in trap $\alpha = 1$ and trap $\alpha = 2$, $s = g, e$ denote the ground and excited states an individual atom. $a_{\alpha s}$ ($a_{\alpha s}^\dagger$) would annihilate (create) an atom in state $s$.

In coherent atom-light interaction, pseudospin degree of freedom in a single atom can be coupled to its momentum, it is call spin-orbit coupling [29–31]. Therefore, when a two-level atom is driven from the ground state $g$ to its excited state $e$, correspondingly its momentum change from $k$ to $k + \Delta k$, namely, $|g, k\rangle \rightarrow |e, k + \Delta k\rangle$ [24–28]. The momentum increase $\Delta k$ is related to synthetic magnetic flux per plaquette $\phi$ and the potential scale $\lambda_M$ (magic wavelength) as $\Delta k = 2\phi/\lambda_M$ [21, 22, 20]. In photovoltaic effect, energy transfer is more important than momentum transfer. From the point of view of energy transformation, in this process, excitation of the internal state of an atom is accompanied by its kinetic energy change. It reveals that energy of the two-level atom should be written in the form, $\varepsilon_g = \epsilon_g + u_g$ and $\varepsilon_e = \epsilon_e + u_e$, where $\epsilon_g$ and $\epsilon_e$ denote internal (electronic) level of the atom, $u_g = k^2/2m$ and $u_e = (k + \Delta k)^2/2m$ represent kinetic energy of the atom for mode 1 and mode 2 in a trap, respectively, where $m$ is the atomic mass (Planck’s constant is taken to be $\hbar = 1$ throughout this work). In this way, light energy would be transformed and stored into atomic gas in the form of internal electronic levels and the energy of atom modes.

Inter-trap coupling Hamiltonian is given by the following expression [26]

$$H_{\text{trap}} = \Lambda \sum_s (a_{1s}^\dagger a_{2s} + \text{H.c.}). \quad (2)$$

Atoms coherently transfer to the neighboring trap through the central barrier with the rate $\Lambda$ for any states.

As reservoirs, left lead is connected to the left trap and right lead is connected to the right trap. The two leads consist of non-interacting Fermion atomic gas bounded in large optical wells with the same chemical potentials $\mu$. It means there is no chemical potential difference between the two leads. Hamiltonian of the reservoirs can be described by the energy of free atomic gas,

$$H_{\text{lead}} = \sum_{\alpha,s,p} \varepsilon_{sp} b_{\alpha sp}^\dagger b_{\alpha sp}. \quad (3)$$

Analogous to the energy configuration of atoms in the two traps, energy of the atomic gas in the two leads could be described in the two parts $\varepsilon_{sp} = \epsilon_s + u_p$ with $s = g, e$ for internal states. What difference is atom modes in the leads characterized by the energy $u_p = p^2/2m$ with continuously spectrum of momentum $p$. Operator $b_{\alpha sp}^\dagger b_{\alpha sp}$ represents occupation number in lead $\alpha = 1$ (or 2) with annihilation operator $b_{\alpha sp}$ and creation operator $b_{\alpha sp}^\dagger$. Due to the extension of atom wave function beyond the potential barriers, exchange of atom number occurs between the double-trap system and its reservoirs. Hamiltonian of the exchange interaction could be written as,

$$H_{\text{exch}} = \sum_{\alpha,s,p} V_p (b_{\alpha sp}^\dagger a_{\alpha s} + \text{H.c.}), \quad (4)$$

where, the tunneling amplitude $V_p$ is considered to be insensitive to the atom states $s$ and the same for the left and right leads.

Until now the whole configuration mentioned above is symmetrically designed for the perpendicular line through the system’s midpoint. Asymmetry comes from the optical beams which are driving atoms in the double-trap. In detail, two optical beams, $E_1$ and $E_2$ are applied, where $E_1$ is acting on the trap 1 and $E_2$ is acting on the trap 2 as shown in Fig. 1. The optical beams are expected to import energy into atoms, therefore, they should be running waves in the forms of $E_1 = E_{10}\cos(\omega_1 t + r_1 \cdot k_1 + \phi_{10})$ and $E_2 = E_{20}\cos(\omega_2 t + r_2 \cdot k_2 + \phi_{20})$, respectively. In the electric dipole approximation, two-level atoms interacting with the monochromatic fields can be written as [22, 22]

$$H_{\text{drive}} = \sum_{\alpha} \frac{\Omega_{\alpha}^2}{2} (a_{\alpha e}^\dagger a_{\alpha g} e^{-i(\omega_{\alpha} t + \phi_{\alpha})} + \text{H.c.}), \quad (5)$$

where the Rabi frequency $\Omega_{\alpha} = |\omega_{\alpha}| E_{\alpha 0}/\hbar$ is proportional to the beam amplitude $E_{\alpha 0}$ and the absolute value of
dipole matrix element \( \varphi_{ge} = |\varphi_{ge}| e^{i\Theta} \) (\( i \) is imaginary part of complex number). The phase \( \varphi_{a} \) in the Hamiltonian should include the beam phase \( r_{a} \cdot k_{a} + \phi_{a0} \) and the phase \( \Theta \) of the dipole matrix element.

**B. Equation of motion**

Total density matrix \( \rho_{tot} \) of the whole configuration satisfies the quantum Liouville’s equation \( \frac{\partial \rho_{tot}}{\partial t} = -i[H, \rho_{tot}] \), where \( H = H_{trap} + H_{cold} \), and the Hamiltonian in interaction picture is \( \tilde{H} = e^{i\tilde{H}} \rho_{tot} e^{-i\tilde{H}} \) and \( \tilde{H} \) is Hamiltonian in interaction picture. Using the unitary operator \( e^{i\tilde{H}t} \), the equation of motion can be written into interaction picture,

\[
\frac{\partial \rho_{tot}}{\partial t} = -i[\tilde{H}, \rho_{tot}],
\]

where the free evolution Hamiltonian consists of two parts \( H_{0} = H_{trap} + H_{cold} \), the density matrix in interaction picture is \( \rho_{tot} = e^{i\tilde{H}t} \rho_{tot} e^{-i\tilde{H}t} \).

Atomic gas in lead 1 and lead 2 can be seen as large reservoirs of atoms in equilibrium state with a great number of states. For the density matrix \( \rho_{tot} \) of the whole configuration, the Hamiltonian in interaction picture is \( H = H_{trap} + H_{drive} + H_{exch} \). In detail, each term can be written as

\[
\tilde{H}_{trap} = \Lambda \sum_{s} a_{1s}^{\dagger} a_{2s} + H.c.,
\]

\[
\tilde{H}_{drive} = \sum_{\alpha} \frac{\Omega_{\alpha}}{2} \alpha_{eg}^{\dagger} \alpha_{eg} e^{i(\Delta_{\alpha} \epsilon_s - \varphi_{a})} + H.c.,
\]

\[
\tilde{H}_{exch} = \sum_{\alpha,\epsilon} V_{\alpha \epsilon} a_{\alpha s}^{\dagger} a_{\alpha s} e^{i(\epsilon_{\epsilon} - u_{\epsilon s})t} + H.c.,
\]

where \( \Delta_{\alpha} = \epsilon_{\epsilon} - \epsilon_{g} - \omega_{\alpha} \) denotes the atom-light detunings in trap \( \alpha = 1 \) and trap \( \alpha = 2 \). One can substitute the integration of Eq. (1) into itself and reach

\[
\frac{\partial \rho_{tot}(t)}{\partial t} = -i[\tilde{H}_{trap}(t) + \tilde{H}_{drive}(t), \rho_{tot}(t)] + \frac{\partial}{\partial t} \left[ \tilde{H}_{exch}(t), \rho_{tot}(t) \right] dt'.
\]

Atomic gas in lead 1 and lead 2 can be seen as large reservoirs of atoms in equilibrium state with a great number of microstates. Actually, the total density matrix could be written as \( \rho_{tot}(t) = \rho(t) \rho_{12} \), where \( \rho \) is density matrix of the double-trap system, and \( \rho_{12} \) is time independent density matrices of the two leads, respectively. As a density matrix of the sub-system, \( \rho \) satisfies the following equation in interaction picture,

\[
\frac{\partial \rho(t)}{\partial t} = -i[\tilde{H}_{trap}(t) + \tilde{H}_{drive}(t), \rho(t)] + \frac{\partial}{\partial t} \left[ \tilde{H}_{exch}(t), \rho(t) \right] dt'.
\]

In the leads, the terms \( Tr[\rho_{tot}^{\dagger} b_{sp}^{\dagger} b_{sp} \rho_{tot}] = f_{a}(\epsilon_{sp}) \) in Eq. (11) is actually the mean occupation number of a single particle state, namely, the Fermi-Dirac distribution function, \( f_{a}(\epsilon_{sp}) = \frac{1}{e^{(\epsilon_{sp} - \mu)/k_{B}T} + 1} \), where \( k_{B} \) is the Boltzmann constant and \( T \) is the temperature of the leads.

In the end, using Born-Markov approximation for the time integration in Eq. (11) and transforming the equation back to Schrödinger picture with the unitary operator \( e^{-i\tilde{H}t} \), we can obtain equation of motion of the system 22, 23.

\[
\frac{\partial \rho}{\partial t} = -i[H_{cell}, \rho] + \sum_{a=1,2} \mathcal{L}_{a} \rho.
\]
represents the left current in lead 1, $I_2$ denotes the right current in lead 2. Actually, the left and right current consist of the ground state current $I_{eg}$ and excited state current $I_{e}$, namely $I_1 = I_{eg} + I_e$ and $I_2 = I_{eg} + I_e$.

Furthermore, substituting Eq. (12) into the continuity equation (13), expressions of ground state atomic current and excited state atomic current at lead 1 and lead 2 can be achieved separately, which gives rise to

$$I_{eg} = q \Gamma [f_1(u_{eg})P_{10} - (1 - f_1(u_{eg}))P_{1g}], \quad (14)$$

$$I_e = q \Gamma [f_1(u_e)P_{10} - (1 - f_1(u_e))P_{1e}], \quad (15)$$

$$I_{2g} = -q \Gamma [f_2(u_{2g})P_{20} - (1 - f_2(u_{2g}))P_{2g}], \quad (16)$$

and

$$I_{2e} = -q \Gamma [f_2(u_{2e})P_{20} - (1 - f_2(u_{2e}))P_{2e}]. \quad (17)$$

The continuity equation (13) reveals $I_1 = I_2$ in stationary state circuit. Then, we have the averaged total current $I = (I_1 + I_2)/2$ in the form,

$$I = \Gamma \sum \alpha, \beta (-1)^{\alpha - 1}[f_\alpha(u_{\alpha})P_{\alpha 0} - (1 - f_\alpha(u_{\alpha}))P_{\alpha s}] \quad (18)$$

which represent the net current through the cell. Here, $q = 1$ is considered for a neutral atom.

### III. RESULTS

When energy scales satisfy the relation $\mu - u_g, u_e - \mu \gg k_B T$, the Fermi-Dirac distribution functions tend to their extreme values $f_1(u_{eg}) = f_2(u_{eg}) \approx 1$, $f_1(u_e) = f_2(u_e) \approx 0$. Based on the low temperature limit and the representation of atom state probabilities, one can have the total net current $I$ as follows

$$I = \frac{\Gamma}{2} [(P_{2e} - P_{1e}) + (P_{10} - P_{20})], \quad (19)$$

It would be demonstrated numerically in the following that the probabilities of empty traps always satisfy the conditions $P_{10} \approx P_{20}$ and $|P_{10} - P_{20}| \ll |P_{2e} - P_{1e}|$, then Eq. (19) can be written in a simple form,

$$I = \frac{\Gamma}{2} (P_{2e} - P_{1e}). \quad (20)$$

In this equation, $P_{2e} - P_{1e}$ represent the effective charge collection $Q$ in the cell and $2/\Gamma$ is characteristic time $\tau$ for atom transfer through the double-trap system. Therefore, the current can be written as $I = Q/\tau$ similar to the concept of electronic current.

Next, let us pay attention to more detail properties of the photovoltaic cell. In Eq. (12), amplitudes $E_{\alpha 0}$, frequencies $\omega_{\alpha}$, phases $\varphi_{\alpha}$ of the two applied fields ($\alpha = 1, 2$) are reflected in the system Hamiltonian $H_{cell}$ in the forms of Rabi frequencies $\Omega_{\alpha}$, atom-light detunings $\Delta_{\alpha}$, and phases $\varphi_{\alpha}$, respectively. Next, affects on the atoms from these parameter differences would be discussed in the following. In the Hilbert space of the nine basis states mentioned above, density matrix of the system can be achieved solving Eq. (12) in stationary condition $\partial \rho / \partial t = 0$, considering the relation $Tr(\rho) = 1$ of normalization. The basic parameters are $\Gamma = 2\pi \times 400 Hz$, $\Lambda = 2\pi \times 800 Hz$, $k_B T = \Gamma/10$, $\varepsilon_g = 0$ and $\mu - u_g, u_e - \mu \gg k_B T$. Based on these conditions, numerical results are given in the following sections.

#### A. Different amplitudes $E_{10} \neq E_{20}$

The most simple case is that a single resonant light is used to trap 2 and there is no light in trap 1, $\Omega_1 = 0$. As illustrated in Fig. 2 (a), along with increase of the light strength in trap 2, probability of excited atom $P_{2e}$ in trap 2 would remarkably increase, which is much larger than the corresponding probability $P_{1e}$ in trap 1. The fact induces polarization of the two traps, $P_{2e} \gg P_{1e}$ which determine the charge collection $Q$ in this battery. Therefore, the photovoltaic cell works under single light beams actually.

Due to trap-lead exchange tunneling and external light driving, the system gives nonzero probabilities of empty traps $P_{10}$ and $P_{20}$. Although they are appeared to be not important for determination of the current $I$ because...
of $P_{10} \approx P_{20}$, in fact they are very significant for keeping steady current in the system. As plotted in Fig. 2 (a) and (b), probabilities of empty traps $P_{10}$ and $P_{20}$ really give rise to the ground state atom current. Therefore, the states of empty traps play the role of 'hole' states in semiconductors. The ground state atoms play the role of electrons in filled valence band, excited state atoms play the role of electrons in conduction band in semiconductor quantum dot based electronic solar cells 

The more general case is both two lights are applied to the atoms, contributing nonzero amplitudes $E_{10}$ and $E_{20}$. Currents in this situation ($\Omega_1 \neq \Omega_2$) are plotted in Fig. 2 (c) and (d) under the resonant and non-resonant couplings. When $\Omega_1 = \Omega_2$, current would always be zero. It is known from Fig. 2 (d) that relative phase $\phi_2 - \phi_1$ between light $E_1$ and $E_2$ does not obviously affect the current behavior. The fact reveals an important feature of this system, the cell works even under short coherent light.

When frequencies $\omega_1$ and $\omega_2$ of the two lights are different, which is reflected in the detuning difference $\Delta_2 - \Delta_1$, probability $P_{1e}$ of an excited atom in trap 1 is higher or lower than that $P_{2e}$ in trap 2 as demonstrated in Fig. 3 (a). It is the double-trap polarization in atomic state distribution. The atom distribution probabilities directly determine current of atoms at different state and directions (See Fig. 3 (b)). double-trap polarization $P_{2e} - P_{1e}$ (or $P_{2g} - P_{1g}$) is disappeared when detunings satisfy $|\Delta_1| = |\Delta_2|$. The fact is also reflected in the total current in which current would reduced to be zero at two points as shown in Fig. 3 (c).

For the change of relative phase $\phi_2 - \phi_1$ between light $E_1$ and $E_2$, current fluctuate around a positive value as illustrated in Fig. 3(e). It reveals nonzero mean current can be preserved even under random phase difference of the two light.

C. Different phases $\phi_1 \neq \phi_2$

Now, the two fields $E_1$ and $E_2$ have the same amplitudes and frequencies, but they have different phases.

FIG. 3: (Color on line) (a) Trap states probabilities as a function of atom-light detuning difference $\Delta_2 - \Delta_1$. (b) The ground and excited state currents versus the detuning difference $\Delta_2 - \Delta_1$. (c) Total current as a function of the detuning difference $\Delta_2 - \Delta_1$. The common parameters used in above figures are: $\Omega_1 = \Omega_2 = 2\pi \times 600Hz$ and $\varphi_1 = \varphi_2 = 0$. (d) Total current as a function of phase difference $\varphi_2 - \varphi_1$ under different Rabi frequencies $\Omega_1$ and $\Omega_2$ with the parameter $\Delta_1 = \Delta_2 = 0Hz$. (e) Total current change for the phase difference $\varphi_2 - \varphi_1$ under different detunings $\Delta_1$ and $\Delta_2$ with $\Omega_1 = \Omega_2 = 2\pi \times 600Hz$.

FIG. 4: (Color on line) (a) Current as a function of phase difference $\varphi_2 - \varphi_1$ under several values of detunings. (b), (c) and (d) Trap states probabilities plotted under the change of relative phase in the case of resonant and off-resonant couplings. The common parameters used here are $\Omega_1 = \Omega_2 = 2\pi \times 600Hz$. B. Different frequencies $\omega_1 \neq \omega_2$
Interference of these two fields reflected in the double-trap system with current fluctuation as shown in Fig. 4 (a). The current behavior is directly related to the trap states distribution, especially the double-trap polarization of excited atom distribution $P_{2e} - P_{1e}$ (See Fig. 3 (b)). It is different from the case of amplitude and frequency asymmetry, current should be disappeared if the two fields $E_1$ and $E_2$ are incoherent with random phases, since the current versus their relative phase fluctuates near the zero current.

Fig. 4 (a) displays two interesting features. For one, current is in opposite direction for red detuning $\Delta_\alpha > 0$ and blue detuning $\Delta_\alpha < 0$. For the other, current disappears when lights resonantly interact with atoms $\Delta_\alpha = 0$. It may be interpreted in the theory of wave beat. It is well known that superposition of two waves with near frequencies leads to wave beat effect. When $\Delta_\alpha \neq 0$, atom-light coupling could create wave beat of atom waves \[ \alpha_0 \] and blue detuning $\Delta_\alpha$ (See Fig. 4 (b)). It is different from the case of amplitude and frequency differences, demand of external fields. Finally, net atom current require $\Delta \neq 0$, which is in fact the propagation of atomic beat wave.

IV. FEASIBILITY

Optical traps with both narrow and wide scales have been implemented in experiments for atom controlling and manipulation [42-44]. Bounding and controlling a few atoms in tight optical traps are also achievable using ultra thin laser beams with high Fidelity [33,45]. First choice of neutral atoms are alkaline-earth (like) metals, such as $^{87}$Sr, $^{171}$Yb, $^{174}$Yb and $^{40}$Ca, because they have long lived excited states due to the clock transition $^1S_0(g) \rightarrow ^3P_0(e)$. Since energy would be stored in the excited state of atoms, coherent lifetime of atoms is very important. Lifetime of the clock states in these alkaline-earth (like) atoms, reported to be from a few seconds to a few tens seconds [51]. The time scales including lifetime of atoms, instability of optical potentials and atom collision induced incoherence are limited, they can be avoided as soon as the time scale is longer than the time for operation of light gate and probes. Furthermore, it is demonstrated above that for the photovoltaic cell of amplitude difference and frequency difference, demand of the light coherence is very low.

V. CONCLUSIONS

In conclusions, we show that two different light beams driving atoms in a double-trap opened system create charging of neutral atoms, converting light energy into the atomic energy through both resonant and off-resonant atom-light couplings. The photovoltaic cell mainly have four characteristics. Firstly, energy transferred from external light would be stored both in internal states of atoms and atom modes states. Secondly, effective charge collection at unit time represent current of atoms. Thirdly, currents due to amplitude differences and frequency differences are several times to ten times larger than that created by the phase differences of the external fields. Finally, The cell can works any long time in principle, since the steady current in the system is insensitive to phase change of external lights. Although this mechanism is demonstrated based on alkaline-earth (like) atoms, it should applied to other particles charged or uncharged. Our model may have potential applications on energy transformation and storage, especially on the development of neutral particle circuit.

Acknowledgments

This work was supported by the Scientific Research Project of Beijing Municipal Education Commission (BMEC) under Grant No.KM202011230217, supported by the Research Foundation of Beijing Information Science and Technology University under Grant No. 1925029, also supported by the National Key R and D Program of China under grants No.2016YFA0301500, NSFC under grants No.61835013, Strategic Priority Research Program of the Chinese Academy of Sciences under grants Nos.XDB01020300, XDB21030300.

[1] H. Katori, M. Takamoto, V. G. Pal’chikov, and V. D. Ovsiannikov, Phys. Rev. Lett. 91 (2003) 173005.
[2] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, Rev. Mod. Phys. 87 (2015) 637.
[3] M. Schioppo, R. C. Brown, W. F. McGrew, N. Hinkley, R. J. Fasano, K. Beloy, T. H. Yoon, G. Milani, D. Nicolodi, J. A. Sherman, N. B. Phillips, C. W. Oates, and A. D. Ludlow, Nature Photonics 11 (2017) 48.
[4] A. Cronin, Nature Physics 2 (2006) 661.
[5] P. Hamilton, M. Jaffe, J. M. Brown, L. Maisenbacher, B. Estey, and H. Muller, Phys. Rev. Lett. 114 (2015) 100405.
[6] M. Gebbe, J.-N. Siem, M. Gersemann, H. Müntinga, S. Herrmann, C. Lämmerzahl, H. Ahlers, N. Gaaloul, C. Schubert, K. Hammerer, S. Abend, and E. M. Rasel, Nature Commun. 12 (2021) 2544.
[7] C. J. Kennedy, G. A. Siviloglou, H. Miyake, W. C. Burton, and W. Ketterle, Phys. Rev. Lett. 111 (2013) 225301.
[8] G. Salerno, H. M. Price, M. Lebrat, S. Häusler, T. Esslinger, L. Corman, J.-P. Brantut, and N. Goldman, Phys. Rev. X 9 (2019) 041001.
[9] M. Fuechsle, J. A. Miwa, S. Mahapatra, H. Ryu, S. Lee, O. Warschkow, L. C. L. Hollenberg, G. Klimeck, and M.
Y. Simmons, Nature Nanotech. 7 (2016) 242.

[10] S. C. Caliga, C. J. E. Straatsma, A. A. Zozulya, and D. Z. Anderson, New J. Phys. 18 (2016) 015012.

[11] R. Folman, P. Krüger, D. Casettari, B. Hessmo, T. Maier, and J. Schmiedmayer, Phys. Rev. Lett. 84 (2000) 4749.

[12] M. F. Riedel, P. Böhi, Y. Li, T. W. Hänsch, A. Sinatra, and P. Treutlein, Nature 464 (2010) 1170.

[13] S. Bernon, H. Hattermann, D. Bothner, M. Knufinke, P. Weiss, F. Jessen, D. Cano, M. Kemmler, R. Kleiner, D. Koelle, and J. Fortágh, Nature Commun. 4 (2013) 2380.

[14] A. S. Sørensen and K. Mølmer, Phys. Rev. Lett. 91 (2003) 097905.

[15] T. Calarco, U. Dorner, P. S. Julienne, C. J. Williams, and P. Zoller, Phys. Rev. A 88 (2013) 043641.

[16] M. Frittelli, F. Levi, D. Calonico, J. Catani, M. Inguscio, L. Franchi, C. Clivati, M. L. Wall, A. P. Koller, S. Li, X. Zhang, N. R. Cooper, J. Ye, P. Zoller, and M. D. Lukin, Phys. Rev. Lett. 112 (2014) 235603.

[17] A. V. Gorshkov, A. M. Rey, A. J. Daley, M. M. Boyd, J. Ye, P. Zoller, and M. D. Lukin, Phys. Rev. Lett. 112 (2014) 235603.

[18] S. C. Caliga, C. J. E. Straatsma, A. A. Zozulya, and D. Z. Anderson, New J. Phys. 18 (2016) 015012.

[19] A. A. Zozulya and D. Z. Anderson, Phys. Rev. A 88 (2013) 043641.

[20] A. Reiserer and G. Rempe, Rev. Mod. Phys. 87 (2015) 042306.

[21] M. Saffman, T. G. Walker, and K. Mølmer, Rev. Mod. Phys. 82 (2010) 2313.

[22] S. Safaei, B. Grémaud, R. Dumke, L.-C. Kwek, L. Amico, and C. Miniatura, Phys. Rev. A 97 (2018) 042306.

[23] B. T. Seaman, M. Krämer, D. Z. Anderson, and M. J. Holland, Phys. Rev. A 75 (2007) 023615.

[24] A. J. Daley, M. M. Boyd, J. Ye, and P. Zoller, Phys. Rev. A 75 (2007) 023615.

[25] A. V. Akimov, M. Gullans, A. S. Zibrov, V. Vuletić, M. D. Lukin, Science 340 (2013) 1202.

[26] A. Luque and A. Martí, Phys. Rev. Lett. 78, 5014 (1997).

[27] A. Al-Ahmadi, Quantum Dots - A Variety of New Applications, IntechOpen, 2012.

[28] J. Villavicencio and A. Hernández-Maldonado, Phys. Rev. A 101 (2020) 042109.

[29] J. Twamley, D. W. Utami, H. S. Goan, G. Milburn, New J. Phys. 8, 63 (2006).

[30] P. Y. Yu and M. Cardona, Fundamentals of Semiconductors, Third edition, Springer, 2001.

[31] A. Reiserer and G. Rempe, Rev. Mod. Phys. 87 (2015) 1379.

[32] J. Villavicencio and A. Hernández-Maldonado, Phys. Rev. A 101 (2020) 042109.

[33] J. Twamley, D. W. Utami, H. S. Goan, G. Milburn, New J. Phys. 8, 63 (2006).

[34] A. Luque and A. Martí, Phys. Rev. Lett. 78, 5014 (1997).

[35] A. Al-Ahmadi, Quantum Dots - A Variety of New Applications, IntechOpen, 2012.