Photovoltaic Effect of Atomtronics Induced by an Artificial Gauge Field

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(Received 10 December 2018; revised manuscript received 18 March 2019; published 4 June 2019)

We investigate the photovoltaic effect of atomtronics induced by an artificial gauge field in four optical potentials. Under an effective magnetic flux, the atom occupation probability would be polarized in a double-dot system, which gives rise to an atomic current. The relation between the atomic current and magnetic flux behaves like the current-phase property in a Josephson junction. A neutral particle photovoltaic cell is well defined by the atomic opened system that has an effective voltage and two different poles corresponding to two internal states of atomtronics. The atom flow is controllable by tuning the direction of incident light and other parameters. The detection of the atomic current intensity is available through an optical emission spectrum in experiments.

DOI: 10.1103/PhysRevLett.122.223202

Photovoltaic transistors of electrons are widely studied in semiconductors [1–8]. To enhance the efficiency of such transistors, there is a tendency to have electronic components that are manufactured smaller and smaller in size. When the size of a device becomes very tiny, electrons would be hardly detectable, and their heat effect would become serious. In contrast, atoms are very active in light and have a much larger volume compared to electrons; therefore atoms appear more advantageous in designing future devices [9]. Atomic transistors have been widely studied recently by creating nonequilibrium states of atomic gas [10–14]. However, there are at least two basic conditions that are necessary for a photovoltaic atomic transistor. One is the coupling between momentum of atoms and applied light, the other is an opened system of atoms.

Momentum can be transmitted from an electromagnetic field to atoms through spin-orbit coupling [15–22]. The effect of spin-orbit coupling in an atomic system has been improved recently using artificial gauge field and interesting phenomenons are exploited such as effective magnetic flux in synthetic dimensions of atoms [23–25], quantum spin Hall effect [26–28], chiral conductors [29–31], superradiance induced particle flow [32], and the Kondo effect [33,34]. In the above phenomenons, the dynamical exhibition of atoms performs like that of charged particles in electromagnetic fields [35–41]. This feature is important for exploration of atomtronic devices.

In this Letter, we combine the artificial gauge field and local optical potentials to propose a model of photovoltaic cell for neutral atoms. Similar to electrons in semiconductor quantum dots, cold atoms can be trapped in particular optical wells [42–44]. Quite recently, the opened system of cold atoms has been realized in experiments based on optical wells [45,46], where nonequilibrium atom flow has been observed under different chemical potentials. In order to create a net current, we need at least two atomic quantum dots to guarantee that the phase of an atom wave function is coherently amplified when the atom moves from one dot to the other dot under optical driving. Gradient of the phase (scalar) through displacement represents the artificial gauge field. Therefore, the coherence of atom-light interaction is the key mechanism of the artificial gauge field in cold atoms.

The basic setup is shown in Fig. 1. In the four optical wells, two of them are the atomic quantum dots with narrow potentials and play the role of photovoltaic system. The other two work as conductors that connect to the photovoltaic system on the two sides, respectively. We use Fermion atoms and each dot is assumed to allow only one atom occupation due to Pauli's exclusion principle. The two wells localized on the other two sides are very wide to form the source and drain with large number of atoms. Atoms can tunnel through the barrier between neighboring optical wells. A synthetic dimension is formed due to optical transition between internal atom states and atom tunneling between two neighboring quantum dots. We consider the rare earth atom ^{173}Yb, which has a ground state $g = {}^1S_0$ and a metastable state $e = {}^3P_0$, supporting an optical clock transition with a coherent lifetime of 20 s. A clock laser at wavelength $\lambda_C = 578$ nm is acting on the atomic quantum dots. The angle between the direction of

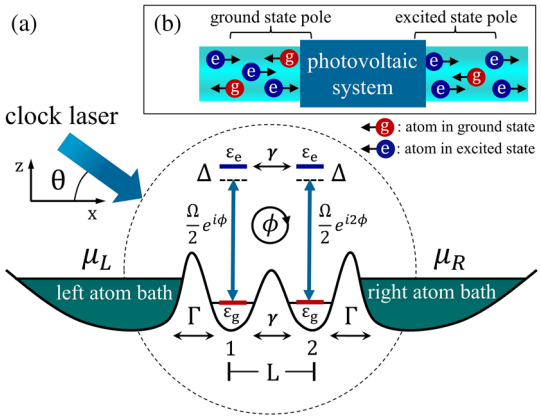

FIG. 1. (a) Atom baths are located on the two sides of the atomic quantum dots with the same chemical potentials μ. x axis is parallel to the array of four optical wells. A clock laser is acting the two dots with angle θ from the x axis. In this case, the clock laser gives momentum $\Delta k = (2\pi\cos\theta/\lambda_C)$ to each atom. Due to the spin-orbit coupling effect, a net artificial magnetic flux $\phi = \Delta k L$ occurs in area rounded by a closed trajectory in the synthetic two dimension. (b) A schematic picture of the photovoltaic cell in figure (a) is shown here. It has two "electrodes" related to the ground state and excited state atoms. Each arrow shows direction of atom motion.

incident clock laser and the line along the optical well array is θ.

Coherent process happens in the two quantum dots system, and the phase change of optical transition in the left dot is assumed to be ϕ, relatively, in the right dot it is 2ϕ [23]. The phase difference $\phi = 2\pi L\cos\theta/\lambda_C$ comes from the momentum change $\Delta k = 2\pi\cos\theta/\lambda_C$ of an atom during a clock field transition and the distance L of atom movement. L denotes the distance between the two quantum dots and k is the wave number of an atom. The net phase ϕ can be seen as a artificial magnetic flux in the closed trajectory of an atom transition in the synthetic dimension.

The whole Hamiltonian of the photovoltaic transistor can be written as $H = H_S + H_B + H_I$. The first term is the Hamiltonian of the two atomic quantum dots driven by the clock laser with frequency ω_c,

$$H_S = \sum_{j=1,2;s=g,e} \varepsilon_s a^\dagger_{j,s} a_{j,s} + \hbar\gamma\left(\sum_{s=g,e} a^\dagger_{1,s} a_{2,s} + \text{H.c.}\right) + \frac{\hbar\Omega}{2}\sum_{j=1,2}(e^{i\omega_c t} e^{ij\phi} a^\dagger_{j,g} a_{j,e} + \text{H.c.}), \quad (1)$$

where, $a_{j,s}$ ($a^\dagger_{j,s}$) is the annihilation (creation) operator of atoms in the jth quantum dot. The atomtronics are characterized by two internal states with the ground level ε_g and an excited level ε_e. Atom tunneling between the two dots occurs with the transition rate γ.$\hbar$ is the Planck constant. The clock light is driving atoms with Rabi frequency Ω. Relative phase change along with the atom transition is described by the term $j\phi$ at position j. Frequency of the clock field is very large comparing with the Rabi frequency; therefore we take the rotating wave approximation for the clock field transitions.

The atom baths are described by the Hamiltonian of free atomic gas

$$H_B = \sum_{\alpha=L,R;s=g,e;k} \varepsilon_k b^\dagger_{\alpha,s,k} b_{\alpha,s,k}. \quad (2)$$

Here, $b_{\alpha,s,k}$ ($b^\dagger_{\alpha,s,k}$) is the annihilation (creation) operator of the atoms with energy ε_k in the baths $\alpha = L, R$. The couplings between the system and the two baths are written as

$$H_I = \hbar g \sum_{s=g,e;k} (b^\dagger_{L,k,s} a_{1,s} + b^\dagger_{R,k,s} a_{2,s} + \text{H.c.}). \quad (3)$$

Atoms are hopping into or out of each atom bath with tunneling amplitude g.

Using Markovian approximation to the couplings between the system and the baths, we obtain following master equation for the opened system [47–50],

$$\frac{\partial}{\partial t}\rho = -\frac{i}{\hbar}[H_S^{\text{eff}}, \rho] + \mathcal{L}_L\rho + \mathcal{L}_R\rho. \quad (4)$$

The first term on the right side of Eq. (4) represents the evolution of the double-dot system with the effective Hamiltonian $H_S^{\text{eff}} = \sum_{j=1,2}\Delta a^\dagger_{j,e} a_{j,e} + (\hbar\Omega/2)\sum_{j=1,2}(e^{ij\phi} a^\dagger_{j,g} a_{j,e} + \text{H.c.}) + \hbar\gamma\sum_{s=g,e}(a^\dagger_{1,s} a_{2,s} + \text{H.c.})$, where $\Delta = \varepsilon_e - \varepsilon_g - \hbar\omega_c$ describes the detuning between the clock field frequency and atom transition levels. The rest terms of Eq. (4) can be written as $\mathcal{L}_\alpha\rho = (\Gamma/2)\sum_{s=g,e}[f_\alpha(\varepsilon_s)(2a^\dagger_{j,s}\rho a_{j,s} - \{a_{j,s}a^\dagger_{j,s},\rho\}) + (1 - f_\alpha(\varepsilon_s))(2a_{j,s}\rho a^\dagger_{j,s} - \{a^\dagger_{j,s}a_{j,s},\rho\})]$ with the anticommutation relation $\{O,\rho\}$ for any operator O. $j = 1$ ($j = 2$) when $\alpha = L$ ($\alpha = R$).

The Liouville superoperators $\mathcal{L}_L$ and $\mathcal{L}_R$, when acting on the density matrix ρ, represent coupling between the double-dot system and two atomic baths with coupling strength Γ, where $\Gamma = 2\pi|g|^2 D(\varepsilon)$ and $D(\varepsilon)$ is density of states of atoms at energy ε in the baths. Throughout this Letter, chemical potentials of the source μ_L and the drain μ_R, which are reflected by the Fermi-Dirac distribution functions $f_\alpha(\varepsilon_s) = [1/e^{(\varepsilon_s-\mu_\alpha)/k_BT} + 1]$, are assumed to be the same, i.e., $\mu_L = \mu_R = \mu$. Here, μ indicates the equal quantity of these chemical potentials. k_B is the Boltzmann constant and T represents the temperature of the two atom baths.

Due to the spin-orbit coupling in atomtronics, momentum gain of atoms depends on the internal states of atoms. As a result, it would be known later that the ground state atoms and excited state atoms move in opposite directions. Using the relation of particle number change and input output current $[d(\langle n_{1g}\rangle + \langle n_{1e}\rangle + \langle n_{2g}\rangle + \langle n_{2e}\rangle)/dt] = I_{Lg} + I_{Le} - I_{Rg} - I_{\text{Re}}$ [50–52], we can reach the ground

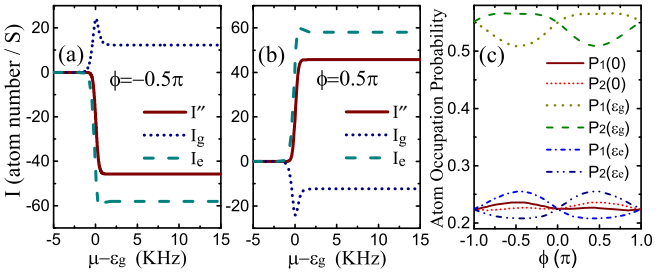

FIG. 2. (a) and (b) The net atomic current I, the ground state current I_g, and the excited state current I_e vs the chemical potential μ of the baths. (c) Occupation probabilities of an atom in the first quantum dot $P_1(0), P_1(\varepsilon_g), P_1(\varepsilon_e)$, and in the second quantum dot $P_2(0), P_2(\varepsilon_g), P_2(\varepsilon_e)$.

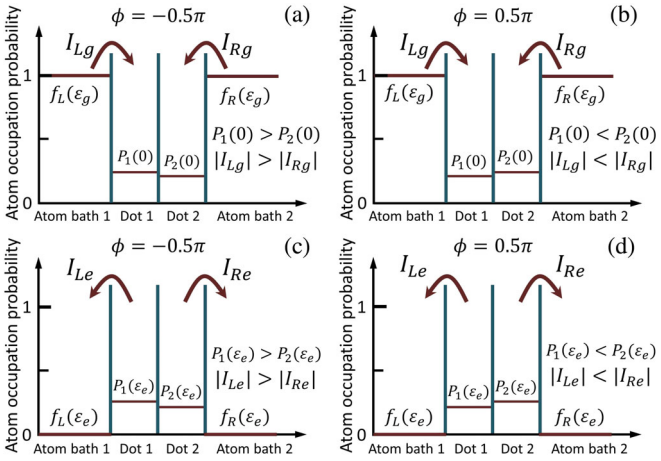

FIG. 3. (Color on line) The probability distributions of empty dots $[P_1(0),\ P_2(0)]$ and excited atom occupations $[P_1(\varepsilon_e),\ P_2(\varepsilon_e)]$ in optical potentials at particular phases $\phi = -0.5\pi$ and $\phi = 0.5\pi$ are illustrated here. Corresponding directions of atomic current are shown using arrows.

state atom current $I_g = (I_{Lg} + I_{Rg})/2$ and the excited state atom current $I_e = (I_{Le} + I_{\mathrm{Re}})/2$, where $I_{\alpha s} = \Gamma(f_\alpha(\varepsilon_s)\langle a_{js}^\dagger \rho a_{js}\rangle - (1 - f_\alpha(\varepsilon_s))\langle \rho a_{js}^\dagger a_{js}\rangle)$ with $j = 1$ $(j = 2)$ when $\alpha = L$ $(\alpha = R)$. In the formula $\langle n_{1g}\rangle + \langle n_{1e}\rangle + \langle n_{2g}\rangle + \langle n_{2e}\rangle$, the bra and ket represent the average value that is calculated through the density matrix ρ of the system [53]. The net atomic current can be obtained through $I = I_g + I_e$. For basic parameters, we take $\Omega = 2\pi \times 600$ Hz, $\gamma = 2\pi \times 500$ Hz, $\Gamma = 2\pi \times 400$ Hz, $\Delta/\hbar = 0.5\Omega$, and $k_B T/\hbar = 0.1\Gamma$, which are based on the recent experiment in Ref. [23].

Energy levels of the model are shown in Fig. 1(a). Only the ground states of the atomic quantum dots are considered and corresponding energies are set to be zero. Therefore, the energy in the quantum dots is represented by the ground energy ε_g of atoms. If the chemical potential μ is lower than the ground energy of the double dot, $\mu < \varepsilon_g$, the two quantum dots would always be empty and atomic current would be zero as shown in Figs. 2(a) and 2(b). When $\mu > \varepsilon_e$, then each dot would be occupied by an atom instantaneously; at the same time, no atom can get into or out of the double-dot system due to an atom blocking effect. In this case, stationary atom flow also cannot occur.

Net atom current can be seen when the chemical potential μ satisfies the relation $\varepsilon_g < \mu < \varepsilon_e$ (see Fig. 1). It indicates that our system has the feature of a common electric cell with an effective voltage $\varepsilon_e - \varepsilon_g$ and that the current can be observed as soon as the potential μ of a conductor is located between ε_g and ε_e. This is the opposite of the case of the particle transport through quantum dots directly driven by bias voltage, where energy levels of the quantum dots must be located between the chemical potentials of their source and drain [47,52]. Since all chemical potentials of the source and drain are the same in our model, atom flow due to a clock field transition is in fact a superfluid. Indeed, spin-orbit coupling can induce a superfluid in Fermion atoms [54,55]. However, our system is an effective cell that has two poles (similar to electrodes) on the left and right sides, respectively. In this cell, the ground and excited states of atoms can be seen as two kinds of charges.

The atom occupation probabilities for the ground state, the excited state and empty dot are defined as $P_j(0) = \langle \rho a_{js} a_{js}^\dagger\rangle$, $P_j(\varepsilon_g) = \langle \rho a_{jg}^\dagger a_{jg}\rangle$, and $P_j(\varepsilon_e) = \langle \rho a_{je}^\dagger a_{je}\rangle$ $(j = 1,\ 2)$, respectively. They satisfy $P_j(0) + P_j(\varepsilon_g) + P_j(\varepsilon_e) = 1$. When chemical potential μ is much higher than the ground state level ε_g as shown in Figs. 2(a) and 2(b), the Fermion distribution functions are close to 1 at the ground state level ε_g. In a good approximation, we could write $f_L(\varepsilon_g) = 1$ and $f_R(\varepsilon_g) = 1$. Then the current I_g is simplified to be

$$I_g = \frac{\Gamma}{2}[P_1(0) - P_2(0)]. \tag{5}$$

From Figs. 2(c) and 3 we know that, for the magnetic flux $-\pi < \phi < 0$, the quantum dot occupation probabilities satisfy $P_1(0) > P_2(0)$. It leads to $|I_{Lg}| > |I_{Rg}|$ and furthermore $I_g > 0$. For the magnetic flux $0 < \phi < \pi$, the quantum dot occupation probabilities satisfy $P_1(0) < P_2(0)$, which gives the opposite result $|I_{Lg}| < |I_{Rg}|$ and so we have $I_g < 0$.

The Fermion distribution functions of atom baths at the excited level ε_e are nearly equal to 0. Therefore, in the same way as above, we could take $f_L(\varepsilon_e) = 0$ and $f_R(\varepsilon_e) = 0$. It allows one to simplify the current formula I_e as

$$I_e = -\frac{\Gamma}{2}[P_1(\varepsilon_e) - P_2(\varepsilon_e)]. \tag{6}$$

Combining Eqs. (5) and (6) with the numerical results in Fig. 2(c), one can estimate that the ground state current and the excited state current are nonzero and always have opposite directions. The current amplitude is proportional

to the polarization (or probability difference) of atom occupations in the two quantum dots. It reveals that the input and output flows of atoms from the two baths are directly decided by the double-dot system. Different probabilities of the atom occupations in the two quantum dots are related to the phase difference of the atom wave function in this system. Then the phase difference of atom wave function between the two quantum dots can be represented by the magnetic flux. Therefore, the atomic currents are created due to the artificial magnetic field. When the magnetic flux is the integer times of π, the polarization of atom distribution probabilities would disappear due to the periodic property of the atom wave functions, and the current should be zero $I = 0$ [see Fig. 4(a)].

It is interesting that, at low Rabi frequency, the relation between atomic current I and phase difference ϕ almost satisfies the sine function as illustrated in Fig. 4(a). In a good approximation, we can write it as $I = I_0 \sin\phi$ with a particular constant current I_0. It is similar to the behavior of superconductor current in Josephson junction. The Josephson effect in the cold atom was also predicted previously in a Fermi superfluid [56] and in momentum space [57]. Because a higher Rabi frequency makes the system more sensitive to the artificial magnetic flux, the maximum point of the current in Fig. 4(a) moves towards the center at a high Rabi frequency.

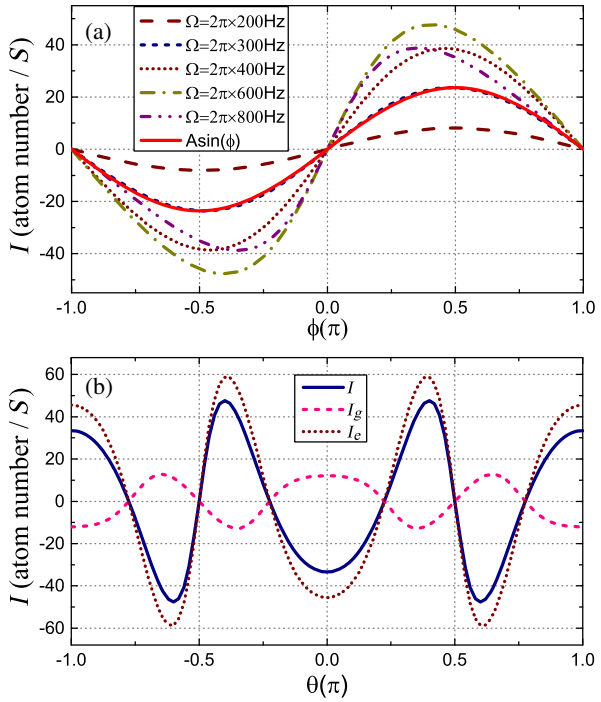

FIG. 4. (a) Atomic current as a function of the artificial magnetic flux ϕ at different Rabi frequencies. $A\sin\phi$ is a sine function with amplitude A (here, $A = 23.6$). (b) Atomic net current I, ground state current I_g, and excited state current I_e as a function of the laser direction $|\theta|$.

For particular lasers with stationary wavelength, the artificial magnetic flux ϕ only depends on the input angle θ of clock laser through the relation $\phi \propto \cos\theta$. Therefore, one can set an experiment as illustrated in Fig. 1 to control the atom current by changing the direction of incident clock laser. Amplitude and direction of current change along the variation of the angle θ with the periodicity 2π as revealed in Fig. 4(b). The current lines are a mirror symmetry for the incident clock field moves clockwise and anticlockwise.

Figure 5(a) further certifies that the applied clock laser creates atomic current since Ω presents the atom-light coupling strength. Red-blue detuning determines the direction of atom flow due to the fact that energy loss and gain depend on the sign of Δ [see Fig. 5(b)]. The strong coupling between two quantum dots is propitious to coherent interaction of the system. Therefore, Fig. 5(c) illustrates that increase of the tunneling rate γ enhances an atomic current. A proper large dot-bath coupling Γ is needed for the occurrence of net current as illustrated in Fig. 5(d), which emphasizes that an opened system is necessary for the photovoltaic transistor.

Since atoms in the ground state and the excited state move in opposite directions, atom currents should be detectable at the two sides of the system through absorption and emission optical band in experiment [58,59]. Optical clock transition has a longer coherent time comparing with the two-photon Raman transition [37] in which heat effect is unavoidable and the lifetime would be limited. The lifetime of the optical clock transitions in alkaline-earth atoms or lanthanide atoms reach from 10 to 10^3 s [60–65], even at a finite temperature.

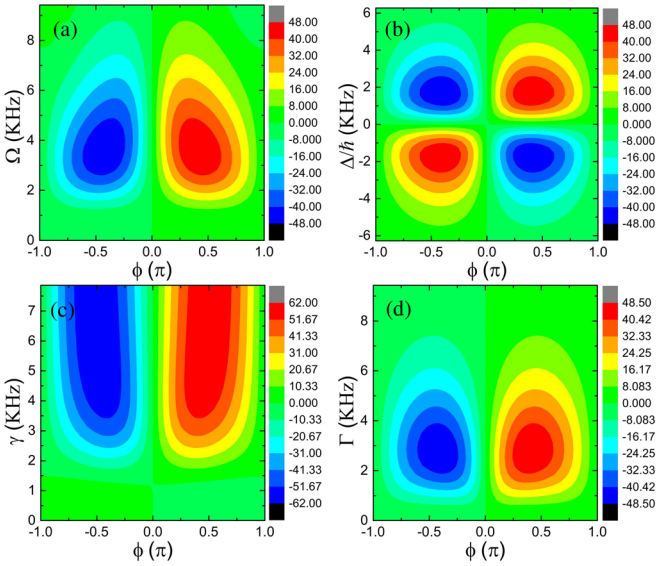

FIG. 5. Different colors plot the quantity of atomic net current I vs (a) Rabi frequency Ω, (b) laser detuning Δ, (c) tunneling rate γ, and (d) coupling strength Γ to the environment, along with the phase ϕ of magnetic flux.

In summary, the occupation probability of single two-level atoms can be polarized in a double-dot system under the spin-orbit coupling effect of an artificial gauge field, which leads to neutral atomic current. The atomic current can be controlled by changing the direction of applied clock field or other parameters. The double-dot opened system is submicrometer sized, which is favorable to its scalability in space and should give rise to much stronger atomic current comparing the above results. Our present Letter is helpful for understanding problems of nonequilibrium neutral atoms under artificial gauge fields. As the first photovoltaic cell for neutral particles, our system may open a new area of technology for neutral particle information processing and energy transformation, such as neutral atomtronic cell, atom-light sensor, and single atom transistor.

This work was supported by the National Key R and D Program of China under Grants No. 2016YFA0301500, NSFC under Grants No. 11434015, No. 61835013, No. 61227902, and No. 61775242, the Strategic Priority Research Program of the Chinese Academy of Sciences under Grants No. XDB01020300 and No. XDB21030300, the NSF of Beijing under Grant No. 1173011, the Scientific Research Project of Beijing Municipal Education Commission (BMEC) under Grant No. KM201711232019, and the Qin Xin Talents Cultivation Program of Beijing Information Science and Technology University (BISTU) under Grant No. QXTCP C201711.

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