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A time-asymmetric delta-kicked model for the quantum ratchet effect

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HIGHLIGHTS

- A time-asymmetric delta-kicked model is investigated.
- A flashing potential periodically acts on a particle at unequal time intervals.
- Ratchet currents emerge when quantum resonances are excited.
- Currents in our model may be stronger than currents in the previous model.

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ABSTRACT

We investigate a time-asymmetric delta-kicked model for the quantum ratchet effect, in which a flashing potential acts on a particle at unequal time intervals. Ratchet currents emerge when quantum resonances are excited. The currents in time-asymmetric models may be stronger than those found in the previous time-symmetric model. Our work expands upon the quantum delta-kicked model and may contribute to experimental investigation of the quantum transport of cold atoms.

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1. Introduction

The ratchet effect is an intriguing phenomenon in which directed transport emerges in a system without a net force. This traces back to the idea of extracting useful work from thermal fluctuations [1]. The ratchet effect can potentially be used in technologies and devices such as rectifiers, electron pumps, molecular switches, particle separation devices, and microscopic and mesoscopic transport devices [2]. Feynman's gedanken experiment [3] showed that it is impossible to achieve the ratchet effect in equilibrium systems, by virtue of the second law of thermodynamics. Hence, equilibrium must be broken by an additional perturbation to induce the ratchet effect. Furthermore, symmetries of the system have to be broken because they would also prohibit directed currents [4–7]. A ratchet system with thermal noise is also referred to as a Brownian motor [8], which can be considered a version of the molecular motor in biology [9]. There are also other kinds of ratchet systems without noise, such as the chaotic dynamical ratchet with dissipation and the purely Hamiltonian ratchet [10–17].

The ratchet effect has also been investigated in the quantum regime. Early research on quantum Brownian motion in an adiabatically rocked ratchet system predicted that current reversal could be induced by quantum tunneling [18]. Using the method of quantum trajectories, Carlo et al. [19] studied a quantum chaotic dissipative ratchet appearing for particles in a pulsed asymmetric potential in a dissipative environment.

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The emergence of the optical lattice has made it possible to study the dynamics of systems of quantum particles in periodic potentials without noise. Some important physical phenomena can be investigated experimentally, such as dynamic localization [20,21], decoherence [22], quantum resonance [23], and chaos-assisted tunneling [24,25]. The optical lattice also provides novel settings to achieve the ratchet effect. For example, the quantum delta-kicked (QDK) potential, which is switched on and off periodically, can be easily realized in an experiment with an optical lattice. The quantum ratchet effect based on the QDK model is investigated in Refs. [26,27], where a bichromatic asymmetric optical lattice was used to periodically act on a particle with a symmetric state. In those studies it was surprisingly found that a current can emerge when quantum resonances occur at specific values of the effective Planck constant. There has been further work on the quantum ratchet effect based on the QDK model [28–31].

In this paper, we investigate a time-asymmetric QDK model for the quantum ratchet effect. A flashing potential periodically acts on a ratchet particle at unequal time intervals instead of the uniform interval in the previous model. A ratchet particle with homogeneous initial zero-momentum state can directly move when quantum resonances are excited. We study the influence of parameter values on the transport properties of this system. Wang and Gong have studied a similar model, the "on-resonance double kicked rotor model" (ORDKRM) [32]. For two particular quantum resonances, the quantum ratchet effect in the ORDKRM was studied as function of several parameters. In our time-asymmetric QDK model, the flashing potential is different from that in Ref. [32]. The quantum ratchet effect in our model is also studied for quantum resonances in which $\tilde{\hbar}$ takes values different from the 2π and π in Ref. [32]. Our work expands upon the QDK model, and may contribute to experimental investigation of the quantum transport of cold atoms.

2. Previous QDK model

In the previous QDK model [26,27], a one-dimensional particle obeys the Schrödinger equation:

$$\mathrm{i}\tilde{\hbar}\frac{\partial\psi}{\partial t} = -\frac{\tilde{\hbar}^2}{2}\frac{\partial^2\psi}{\partial x^2} + v(x)\sum_{n=0}^{\infty}\delta(t-n)\psi, \tag{1}$$

where $v(x)$ denotes the sawtooth-shaped ratchet potential. Mathematically, $v(x) = v_0[\sin(x) + \alpha\sin(2x)]$, where the parameter α determines the spatial asymmetry of the potential. This potential can be realized experimentally by combining a standing-wave potential of $\lambda/2$ spatial periodicity with a lattice potential of $\lambda/4$ periodicity, as was done in Refs. [33,34]. The ratchet potential is switched on and off periodically in the time domain, and every period is assumed to be a delta function. The integer n signifies that the potential kicks the particle at discrete instants separated by the same time interval. In Eq. (1), $\tilde{\hbar}$ is the effective Planck constant and is equal to $8\omega_R T$, where T is the kicking period and $\omega_R(=\hbar k_L^2/2m)$ is the recoil frequency of the applied laser field, with k_L being the photon wave number and $1/(2k_L)$ the lattice period of the standing laser wave. Both the temporal period of kicks and the spatial period of the lattice are set to unity.

Because of the temporal periodicity of the system, the evolution of the state of the particle over a single period can be described as

$$|\psi(t)\rangle = \hat{U}(t,t-1)|\psi(t-1)\rangle, \tag{2}$$

where $\hat{U}(t,t-1) = \exp(-\mathrm{i}\tilde{\hbar}\hat{k}^2/2)\exp(-\mathrm{i}Pv(\hat{x}))$ with $P = v_0/\tilde{\hbar}$. Here $\hat{k} = -\mathrm{i}\frac{\partial}{\partial x}$ is the wave number operator and $\hat{x}$ is the position operator. Because of the periodicity, $\hat{x}$ can be considered an angle operator and $\hat{k}$ a scaled angular-momentum operator. Obviously, $\hat{U}(t,t-1)$ comprises two parts, the kinetic factor $\exp(-\mathrm{i}\tilde{\hbar}\hat{k}^2/2)$ and the potential factor $\exp(-\mathrm{i}Pv(\hat{x}))$. When solving Eq. (2), we first calculate the evolution of the wave function in position space where the potential factor acts, and then with a fast Fourier transform (FFT) we obtain the wave function in wave number space and calculate the effect of the kinetic factor. Finally, by transforming the wave function back into position space, one evolution period is completed. Here the initial state of the particle is assumed to be homogeneous with zero momentum, which is a good approximation when a Bose–Einstein condensate is used for loading in optical lattices, in which a wave packet extends over many lattice sites [29,35,36]. The time dependence of the expectation value of the wave number $\langle k\rangle$ of the ratchet particle can be obtained numerically.

When the kicking period (or frequency) is commensurate with the recoil period (or frequency) of the applied laser field, a quantum resonance occurs. Mathematically speaking, when the effective Planck constant $\tilde{\hbar}(=8\omega_R T)$ takes a value of $4\pi r/s$, where r and s are mutually prime integers, a quantum resonance occurs. Such resonances can cause $\langle k\rangle$ to linearly increase, causing the ratchet effect to emerge. Relevant detail can be found in Refs. [26,27]. Fig. 1(a) is based on Ref. [27] and gives an example of $\langle k\rangle$ after 200 kicks as a function of $\tilde{\hbar}$ for the configuration $P = 0.5,\ \alpha = 0.3$. The four distinct peaks indicate that ratchet currents emerge when $\tilde{\hbar}$ is a half-integer multiple of π. The evolution of the state of the ratchet particle is identical for $\tilde{\hbar}$ and $\tilde{\hbar} + 4\pi$ [26], and thus the range of $\tilde{\hbar}$ is set to $[0, 4\pi]$ in Fig. 1(a).

3. Time-asymmetric QDK model

It has been traditionally viewed as a necessary condition for the ratchet effect that the spatiotemporal symmetry of a system be broken. In the previous QDK model, the temporal symmetry of the system is preserved, which means that the

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