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Cooperation and competition between two symmetry breakings in a coupled ratchet

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HIGHLIGHTS

- The directed transport in a coupled ratchet with two symmetry breakings is discussed.
- Competition induces current reversal, and cooperation promotes directed transport.
- White noise induces reversed motion when the roles of symmetry breakings are close.

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ABSTRACT

We investigate the collective mechanism of coupled Brownian motors in a flashing ratchet in the presence of coupling symmetry breaking and space symmetry breaking. The dependences of directed current on various parameters are extensively studied in terms of numerical simulations and theoretical analysis. Reversed motion can be achieved by modulating multiple parameters including the spatial asymmetry coefficient, the coupling asymmetry coefficient, the coupling free length and the coupling strength. The dynamical mechanism of these transport properties can be reasonably explained by the effective potential theory and the cooperation or competition between two symmetry breakings. Moreover, adjusting the Gaussian white noise intensity, which can induce weak reversed motion under certain condition, can optimize and manipulate the directed transport of the ratchet system.

1. Introduction

The directed transport of non-equilibrium Brownian particles has been an important topic from physical, biological to social systems [1–6]. The breaking of detailed balance as well as the breaking of symmetries such as the symmetry breaking of periodic potential (space symmetry breaking), the symmetry breaking induced by nonequilibrium perturbations (perturbation symmetry breaking), and the breaking induced by mutual coupling between elements of the system (coupling symmetry breaking), is the precondition of directed motion in the nonequilibrium system [7–15]. The reversed motion and the separation of the coupled Brownian motors are the research hotspots of particle transport, which can be achieved in a variety of ways [16–32], such as the competition between the ratchet effect and the load [33], the value of the

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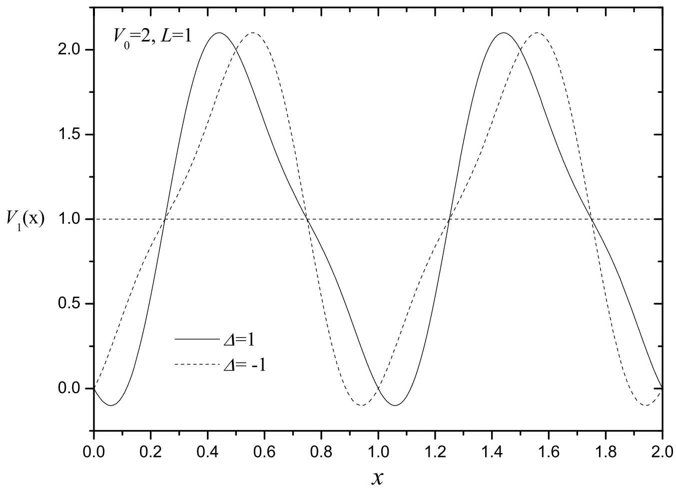

Fig. 1. The asymmetric periodic potential $V_1(x)$ for different space asymmetric coefficient Δ with -1 and 1.

coupling strength and the coupling free length with the periodic potential under the modulations of two time-correlated multiplicative noises [34], the intensity and frequency of rocking force acting on the coupling Brownian motors in an asymmetric periodic potential [35], the intensity of noise and frequency of rocking force in rocking ratchet with bistable potential [36], the ratio of barriers of two potentials (interaction bistable potential and track ratchet potential) in rocking ratchet [37], the feedback time in coupled Brownian ratchets [38], the influence of symmetric, white Lévy noise that mimics the action of external random forcing [39].

The symmetry breaking has always been considered as the precondition of directed transport of ratchet systems in previous studies, but the reversed motion induced by symmetry breakings is rarely involved [40]. In fact, there may be several possibilities of symmetry breakings in ratchet systems, such as that occurring in the transport of molecular motors (e.g., myosin, kinesin, dynein etc.) walking on tracks (e.g., microtubule or microfilament etc.) which are periodic and polarized in cells. Most of these different molecular motors possess the common dimer structure in which each motor is composed of two interacting monomers and each monomer experiences the asynchronous cyclic ATP hydrolyzing process [41–44]. In ratchet systems both the coupling symmetry breaking and the space symmetry breaking simultaneously exist. The question how these symmetry breakings compete and cooperate with each other is worthy of consideration and discussion.

The transport of coupled Brownian motors moving in an asymmetric periodic potential is investigated in the presence of the symmetry breaking between two single particles. We mainly analyze the influence of various parameters on the current. It is found in this paper that the asymmetry of coupled Brownian motors and the asymmetry of the potential are two origins of inducing a net current and the competition between the two symmetry breakings could induce the reversal transport of coupled Brownian motors. The competition is a necessary but not a sufficient condition for current reversals. In the case of strong coupling we give reasonable explanations for these transport behaviors in terms of the effective-potential theory, and the theoretical calculation agrees well with numerical simulation.

2. The coupled ratchet model

We consider the overdamped Brownian motion of two elastically interacting particles in a flashing periodic potential. The dimensionless Langevin equation of the Brownian motion under the action of noise can be written as

$$\dot{x}_i = -\frac{\partial V_i(x_i)}{\partial x_i} Z(t) - \frac{\partial U_0}{\partial x_i} + \xi_i(t), \quad i = 1, 2 \tag{1}$$

where x_i is the position of ith particle, $V_i(x)$ is the periodic potential acting on ith particle. $V_1(x)$ shown in Fig. 1 is chosen as

$$V_1(x) = \frac{V_0}{2}[1 - \cos(\frac{2\pi}{L}x) - \frac{\Delta}{4}\sin(\frac{4\pi}{L}x)]. \tag{2}$$

In contrast to the usually adopted identical periodic potential acting on two particles, we consider the non-identical case, i.e., $V_2(x) = \alpha V_1(x)$, where α is the asymmetry coefficient with $0 < \alpha < 1$, which represents the asymmetric effect of the periodic potential on Brownian motors. Δ is the space asymmetry coefficient of the periodic potential $V_1(x)$ which is symmetric for $\Delta = 0$. L is the period of the potential and V_0 the height of the potential barrier. U_0 (x_1, x_2) denotes the interaction potential between the two particles, which is set to possess the simple harmonic form $U_0 = k(x_1 - x_2 - a)^2/2$,