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Transport reversals of chiral active particles induced by a perpendicular constant force

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HIGHLIGHTS

- Perpendicular constant force can induce the rectification of chiral active particles.
- The transport direction can be reversed under appropriate conditions.
- Active particles with different chiralities can be effectively separated.

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ABSTRACT

Transport of chiral active particles in a symmetric periodic potential is investigated in the presence of a constant force. It is found that due to chirality of active particles the transversal constant force can break the symmetry of the system and induce a longitudinal net current. There exists an optimal constant force at which the rectification is maximal. Remarkably, longitudinal current reversals can occur by suitably tailoring the transversal constant force. Therefore, particles with different chiralities move to different directions and can be effectively separated.

1. Introduction

The study of active particles has attracted wide attention and shown lots of interesting new physics [1–9]. Active particles ranging from bacteria [10–15] to artificial microswimmers [16–19] can perform active Brownian motion by extracting energy from an external source. Artificial microswimmers are driven by self-phoretic forces, which may be produced from self-diffusiophoresis by catalyzing a chemical reaction [20–22] or self-thermophoresis by inhomogeneous light absorption [23,24]. Under certain conditions, active particles could exhibit peculiar collective behaviors [25–30] and spontaneous rectification transport [31–35].

Compared with simple active particles, chiral active particles perform circular motion in two dimensions and helicoidal motion in three dimensions due to the self-propulsion force being not aligning with the propulsion direction [36]. For an active particle with a specific chirality, the particle is asymmetric and shows completely different behaviors with non-chiral particle in the presence of asymmetric conditions. For example, a transversal driving force could induce the longitudinal movement of chiral particles [36] and be applied to separate chiral particles [37]. The rectification transport of chiral

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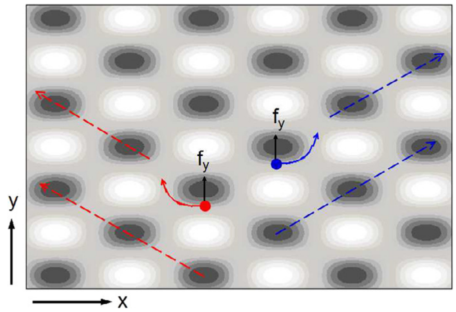

Fig. 1. Sketch of the two-dimensional periodic potential $U(\vec{r})$. The red and blue balls demote clockwise and counterclockwise particles, respectively. The particles are driven by a constant force f_y pointing to the $+y$ direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

particles could also occur autonomously in transversal asymmetric channels [38,39]. In addition, chiral particles could be captured and sorted by chiral flowers [40] or rotary obstacles [41]. Recently, Nourhani and coworkers [42,43] investigated the transport of chiral self-propellers in a soft periodic two-dimensional potential, and utilized the potential asymmetry to separate and guide these particles. Based on the work [43], we extend this study to the symmetric potential with a transversal constant force. It is found that the transversal constant force can be used to control longitudinal current and reverse the current direction. Our simulation results suggest that one can utilize the method in this paper to separate active particles with different chiralities.

2. Model

We consider chiral active particles moving in a two-dimensional periodic symmetric potential as shown in Fig. 1. In the absence of any external force, a chiral particle moves along circle trajectory and the radius of the circle $R = v_0/\Omega$ [31]. v_0 is the self-propulsion speed, and Ω is angular velocity which determines the chirality of particles. We define particles as the counterclockwise particles for positive Ω and the clockwise particles for negative Ω. In the presence of a constant force, the chiral particle may move along an ellipse trajectory in a confined structure. In Fig. 1, the transversal constant force f_y pointing to the $+y$ direction produces the asymmetry of the present system. The counterclockwise (blue) particle is more likely to escape from the potential in the upper right corner. Thus one may predict that active particles with different chiralities move along the corresponding trajectories, i.e., the red and blue balls move along red and blue lines in Fig. 1, respectively. When the potential is a superposition of two standing waves $U(\vec{r}) = U_0 \sum_{i=1}^{2} \cos(\vec{k}_i \cdot \vec{r})$ with U_0 being the strength of the potential, active particles with different chiralities may exhibit different transport behaviors. Here we only consider unit wave vector $\vec{k}_i$ and the position $\vec{r} = (x, y)$. In the overdamped limit, the dynamics of chiral active particles can be described by the following Langevin equations,

$$\frac{dx}{dt} = v_0 \cos\theta + \mu F_x + \sqrt{2D_0}\xi_x(t), \tag{1}$$

$$\frac{dy}{dt} = v_0 \sin\theta + \mu(F_y + f_y) + \sqrt{2D_0}\xi_y(t), \tag{2}$$

$$\frac{d\theta}{dt} = \Omega + \sqrt{2D_\theta}\xi_\theta(t), \tag{3}$$

where $F_x = -\partial U/\partial x$, $F_y = -\partial U/\partial y$, and μ is the mobility. The angle θ denotes the direction of v_0 with respect to the x axis. D_0 and D_θ represent the translational diffusion and rotational diffusion, respectively. $\xi_x(t)$, $\xi_y(t)$, and $\xi_\theta(t)$ model white Gaussian noise with zero mean and obey $\langle \xi_i(t)\xi_j(t')\rangle = \delta_{ij}\delta(t-t')$, $i, j = x, y$, and $\langle \xi_\theta(t)\xi_\theta(t')\rangle = \delta(t-t')$.

For convenience, we introduce the dimensionless variables and choose the characteristic length scale 1, energy scale U_0, and time scale $\tau = 1/\mu U_0$. Therefore, Eqs. (1), (2), and (3) can be rewritten in dimensionless form,

$$\frac{d\tilde{x}}{d\tilde{t}} = \tilde{v}_0 \cos\theta + \tilde{F}_{\tilde{x}} + \sqrt{2\tilde{D}_0}\tilde{\xi}_{\tilde{x}}(\tilde{t}), \tag{4}$$

$$\frac{d\tilde{y}}{d\tilde{t}} = \tilde{v}_0 \sin\theta + \tilde{F}_{\tilde{y}} + \tilde{f}_{\tilde{y}} + \sqrt{2\tilde{D}_0}\tilde{\xi}_{\tilde{y}}(\tilde{t}), \tag{5}$$

$$\frac{d\theta}{d\tilde{t}} = \tilde{\Omega} + \sqrt{2\tilde{D}_\theta}\tilde{\xi}_\theta(\tilde{t}), \tag{6}$$

where $\tilde{x} = x$, $\tilde{y} = y$, and $\tilde{t} = t/\tau$. The rescaled parameters are $\tilde{v}_0 = v_0/\mu U_0$, $\tilde{\Omega} = \Omega/\mu U_0$, $\tilde{D}_0 = D_0/\mu U_0$, $\tilde{D}_\theta = D_\theta/\mu U_0$, $\tilde{f}_{\tilde{y}} = f_y/U_0$, and $\tilde{U} = \sum_{i=1}^{2} \cos(\vec{k}_i \cdot \tilde{r})$. In the following, we will use only the dimensionless variables and omit the hat for all