Active Matter Ratchets with an External Drift

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(Dated: May 11, 2014)

When active matter particles such as swimming bacteria are placed in an asymmetric array of
funnels, it has been shown that a ratchet effect can occur even in the absence of an external drive.
Here we examine active ratchets for two dimensional arrays of funnels or L-shapes where there is also
an externally applied dc drive or drift. We show that for certain conditions, the ratchet effect can be
strongly enhanced, and that it is possible to have conditions under which run-and-tumble particles
with one run length move in the opposite direction from particles with a different run length. For the
arrays of L-shapes, we find that the application of a drift force can enhance a transverse rectification
in the direction perpendicular to the drift. When particle-particle steric interactions are included,
we find that the ratchet effects can be either enhanced or suppressed depending on barrier geometry,
particle run length, and particle density.

PACS numbers: 82.70.Dd,83.80.Hj

I. INTRODUCTION

When Brownian particles are placed in an asymmetric potential substrate in the presence of an external ac drive,
itis possible to realize a so-called “rocking ratchet” effect in which the particles undergo net dc motion. Ratchet
effects can also be realized using other forms of external driving such as by flashing the substrate on and off
to create what is called a flashing ratchet. Ratchets have been studied and experimentally realized for a variety
of systems including colloidal particles on asymmetric substrates, vortices in type-II superconductors
interacting with nanostructured pinning sites, and granular media on vibrated asymmetric substrates. It is
also possible to realize ratchet effects on symmetric substrates provided that the external driving has some form
of asymmetry. More recently, what has been termed “active ratchets” have been realized in systems where
there is no external ac driving or flashing but where the particles are self-driven. Active matter systems contain
self motile particles and include biological systems such as swimming bacteria, moving cells, and flocks of
bacteria or fish, as well as non-biological systems such as artificial swimmers and self motile colloidal
particles. In an experiment by Galjada et al., when run-and-tumble swimming E. coli were placed in a microfabricated
array of V-shaped funnels, the bacteria concentrated on the side of the container towards which the funnel
openings were pointing, indicating the existence of a ratchet effect. When non-swimming bacteria that undergo only
weak Brownian motion were placed in the same funnel array, the ratchet effect was absent. Active ratchet effects
have also been observed in funnel geometries for swimming animals as well as artificial swimmers. Subsequent
numerical studies showed that this ratchet behavior can be captured using a model of point particles that
undergo run and tumble dynamics along with a barrier interaction rule stating that when the particles interact
with a barrier they run along the barrier rather than reflecting off of it. As the run length of the particles
is increased, the ratchet effect also increases, while in the limit of Brownian motion the ratchet transport is
lost. Other studies showed explicitly that the rectification is caused by the breaking of detailed balance that
occurs when the particles interact with the barriers, and that the particles must spend a long enough time run-
ning along the barrier for rectification to occur. For other types of barrier interactions such as reflection or
scattering, the rectification is lost. In these simulations it was also shown that the particles accumulate in
funnel tips and along boundaries, a phenomenon that is also observed in experiments. Active ratchets have
been studied for other types of swimming organisms such as crawling cells. In these systems, when collective
effects are included, a ratchet reversal can occur where for a certain range of parameters the particles
ratchet along the easy direction of the funnel, while for other parameters the ratchet motion occurs against
the easy flow direction. It was recently proposed that active ratchet effects can arise on symmetrical substrates
for certain models.

One of the most promising applications for active ratchets is sorting, where different species or particles
with different run-and-tumble swimming lengths could be sorted due to the different speed or direction of motion
through a ratchet geometry of one type of particle compared to another. Variants on this type of ratchet effect
have been harnessed to create active matter powered gears, where asymmetric gears immersed in an assembly
of active matter particles exhibit rotation in a preferred direction. There are also proposals to use asymmet-
ric barriers to capture active matter particles. Another method for sorting rectified Brownian particles is to apply
a dc drift to the particles that forces them to move through a lattice of asymmetric obstacles. In this geom-
etry, particles with different diffusion coefficients follow different trajectories through the array, such that the particle motion perpendicular to the drift force varies as a function of the diffusion coefficient. This and related methods have been used to continuously sort particles such as DNA strands of different lengths using asymmetric post arrays. There have also been several other studies on how to sort particles with different diffusive constants in periodic arrays when there is an additional dc drift applied.

In this work we examine active ratchet systems in which the particles interact with an array of asymmetric barriers in the presence of an additional dc drift force. We consider run-and-tumble particles interacting with two barrier geometries. For an array of V shapes or funnels, in the absence of a drive the particles exhibit an active ratchet effect and move in the easy flow direction; however, when a dc drive is applied against the ratchet effect, we find a ratchet reversal, indicating that it should be possible to set the dc drive such that particles with different run lengths move in opposite directions through the funnels. The velocity-force curves contain nonlinear features that vary as the run length changes. For example, for a fixed dc drive applied against the easy flow direction, increasing the run length initially increases the flow of particles in the reversed ratchet direction as the trapping of particles at the funnel tips is reduced; however, at long run lengths the reversed motion in the direction of the dc drive is suppressed when the forward ratchet effect begins to dominate. We show that the ratchet effect can be controlled by applying a dc drive perpendicular to the the ratchet direction. Inclusion of steric interactions between particles reduces the ratchet effect, and the magnitude of the reduction increases as the size or density of the particles increases. For an array of even L-shaped barriers, application of a dc drive can increase the rectification transverse to the applied drive by almost an order of magnitude compared to the drive-free case. For this geometry, when steric interactions between the particles are included, the transverse ratchet effect is enhanced for some run lengths and particle densities and suppressed for others.

II. SIMULATION AND SYSTEM

We consider a two-dimensional system of size \( L \times L \) containing \( N \) active matter particles obeying the same rules for run-and-tumble self-propelled motion and barrier interactions as previously used to study ratchets without a drift. Steric particle-particle interactions are neglected in some sets of simulations and included in others. We employ periodic boundary conditions in the \( x \) and \( y \)-directions for samples containing a periodic array of V-shaped barriers as in Fig. 1(a) or a periodic array of even L-shaped barriers as in Fig. 1(b). For the V-shaped barriers, there are \( N_B = 24 \) barriers with side length \( l_s = 5.0 \), the V has an angle of \( 45^\circ \), and the barrier

![FIG. 1: (a) Sample geometry for the V shaped barrier array. In the absence of an external drive, run-and-tumble particles ratchet in the positive y-direction. The arrows indicate the two different directions in which the driving current can be applied (\( d_x = 0, d_y = -1 \) and \( d_x = 1, d_y = 0 \)). (b) Sample geometry for the even L-shaped barrier array. In this case, the dc drive is applied in the negative y-direction The arrow indicates the direction in which the driving current is applied (\( d_x = 0, d_y = -1 \)).](image-url)

lattice constant is approximately \( a = 20 \). For the even L-shaped barriers, there are \( N_B = 30 \) barriers with sides of equal length \( l_s = 4.9 \). In each case the system size is \( L = 99 \) and there are \( N = 980 \) particles. The dynamics of particle \( i \) are obtained by integrating the following overdamped equation of motion:

\[
\eta_i \frac{d\mathbf{R}_i}{dt} = \mathbf{F}_i^m + \mathbf{F}_i^s + \mathbf{F}_i^{dc}.
\]

Here the damping constant is \( \eta = 1.0 \) and \( \mathbf{F}_i^m \) is the motor force. The run-and-tumble dynamics is modeled by having the particles move with a constant force \( \mathbf{F}_i^m \) in a randomly chosen direction for a fixed run time \( \tau_r \); after this time, a new running direction is randomly chosen to represent the tumbling process. The tumbling occurs instantaneously. In the absence of interactions with barriers or other particles, a single particle would move a distance \( R_l = F^m \tau_r \) during a single run time. The term \( \mathbf{F}_i^s \) represents the particle-barrier interaction force. The barrier exerts a short-range repulsion on the particle, modeled by a stiff finite range spring. As a result, when a particle strikes a barrier it moves along the barrier at a speed given by the component of its motor force that is parallel to the barrier, until it either reaches the end of the barrier or undergoes a tumbling event, when it has the opportunity to move away from the barrier or continue following the barrier at a new speed. A particle moving along a barrier can become trapped at corners where two barriers meet. The barrier thickness is equal to the particle radius \( R_p \). The steric interaction between particles, \( \mathbf{F}_i^s \), when included, is modeled with a repulsive short-range harmonic force given by \( \mathbf{F}_i^s = \sum_{j \neq i}^N k (R_{ij}^{eff} - |\mathbf{r}_{ij}|) \hat{\mathbf{r}}_{ij} \), where the spring constant \( k = 200 \), \( \mathbf{r}_{ij} = \mathbf{R}_i - \mathbf{R}_j \), \( R_{ij}^{eff} = |\mathbf{r}_{ij}| \) and \( R_{ij}^{s} = r_i + r_j \), where \( \mathbf{R}_{i(j)} \) is the location of particle \( i(j) \) and \( \hat{\mathbf{r}}_{i(j)} \) is the radius of par-
The system exhibits only a positive ratchet effect. The dc force \( F_{dc} \) of barriers illustrated in Fig. 1(a). In the absence of any external drive, this system shows a rectification effect similar to that observed for a single row of V-shaped barriers. In Fig. 2 we plot \( \langle V_y \rangle \) versus run length \( R_l \) for a dc drive applied in the negative \( y \)-direction \((d_x = 0, d_y = -1)\), against the easy flow direction of the funnels. For each \( R_l \) we wait a sufficiently long time before measuring \( \langle V_y \rangle \) to avoid any transient effects. Shown in Fig. 2 are the results for \( F_{dc} = 0, 0.5, 1.0, 2.0, 3.0, 5.0 \), and 10. For \( F_{dc} = 0 \), \( \langle V_y \rangle \) is initially zero for \( R_l = 0 \) and monotonically increases with increasing \( R_l \), consistent with previous results. At finite \( F_{dc} \) and small \( R_l \), \( \langle V_y \rangle \) is initially negative and rapidly becomes more negative as \( R_l \) increases until reaching a maximally negative value between \( R_l = 1 \) and 10, after which it increases with increasing \( R_l \). For \( F_{dc} = 0.5, 1.0 \), and 2, \( \langle V_y \rangle \) crosses from negative to positive \( y \)-direction flow with increasing \( R_l \) when the positive \( y \)-direction ratchet effect becomes large enough to overcome the drift force in the negative \( y \)-direction. This result implies that in a mixed system of particles with short and long running lengths, there is a range of \( F_{dc} \) over which the particles with short running lengths would move in the negative \( y \) direction while the particles with long running lengths would move in the positive \( y \)-direction. The initial decrease in \( \langle V_y \rangle \) with increasing \( R_l \) at smaller values of \( R_l \) occurs because for small \( R_l \) the positive ratchet effect is weak, and many particles become trapped in the funnel tips due to the negative \( y \) drift force. For very small \( R_l \), most or all of the particles are trapped, giving \( \langle V_y \rangle \approx 0 \) as shown in Fig. 2. As \( R_l \) increases, some particles can escape from the funnel tip traps but are then entrained by the drift force to move in the negative \( y \)-direction, giving an increasingly negative value of \( \langle V_y \rangle \) as more particles become mobile. In this regime, increasing the run length can increase the motion in direction of the drift force; however, for larger \( R_l \), the positive ratchet effect begins to dominate the behavior and for large enough \( R_l \) the net flow is in the positive \( y \)-direction.

In Fig. 3 we plot \( \langle V_y \rangle \) versus \( F_{dc} \) for \( R_l = 0.5, 1.0, 2.0, 3.0, 5.0, \) and 10. At small \( F_{dc} \), the ratchet effect produces a positive \( \langle V_y \rangle \). For increasing \( F_{dc} \), \( \langle V_y \rangle \) crosses zero and becomes negative before reaching a maximally negative value. As \( F_{dc} \) increases further, particles begin to be trapped in the tips of the funnels, and at large enough \( F_{dc} \), all the particles are trapped and \( \langle V_y \rangle = 0 \). As \( R_l \) increases, a larger \( F_{dc} \) must be applied for complete trapping to occur. These results show that the system produces highly nonlinear velocity force curves.

In Fig. 4 we plot \( \langle V_y \rangle \) vs \( R_l \) for the same system but with \( F_{dc} \) applied in the positive \( x \)-direction \((d_x = 1, d_y = 0)\), perpendicular to the ratchet flow direction. Here we show \( F_{dc} = 0, 0.5, 1.0, 1.25, 1.5, 2.0, 3.0, \) and 4.0. Due to the barrier shapes, the drift force can alter the motion of the particles in the ratchet or \( y \)-direction even
though the drift is applied perpendicular to this direction. As the particles drift in the positive $x$ direction, they encounter the outer left surface of a V barrier and follow the barrier wall downward in the negative $y$ direction before becoming free of the barrier, encountering another barrier, and again moving in the negative $y$ direction. As $F_{dc}$ increases, the magnitude of $\langle V_y \rangle$ rapidly decreases, and Fig. 4 shows that for $F_{dc} \geq 1.5$, $\langle V_y \rangle$ is negative at small $R_l$ but becomes positive for larger $R_l$ when the ratchet effect becomes strong enough to dominate the particle motion. This indicates that with the correct choice of perpendicular dc drive, particles with different run lengths could be sorted, with one species of particles moving in the positive $y$ direction and the other species moving in the negative $y$ direction. For $R_l = 0$, $\langle V_y \rangle$ is zero since the particles no longer undergo diffusion and end up drifting only in the empty horizontal spaces separating adjacent rows of barriers.

We next consider the effects of steric repulsion on the ratchet effect in the absence of an external drive. In Fig. 5 we plot $\langle V_y \rangle$ versus the particle radius $R_p$ for $R_l = 70, 40, 30, 20, 10, \text{ and } 5$. In each case, inclusion of steric interactions causes a drop in the rectification effect due to trapping and clustering. Each funnel can now trap only a limited number of particles, since particles that would be trapped at the funnel tip in the noninteracting case instead fill up the funnel, reducing the trapping effectiveness for particles moving in the negative $y$ direction. For example, in Fig. 6(a) we illustrate a subsection of a system with $F_{dc} = 0$, $R_l = 40$, and $R_p = 1.15$, where at most three particles can fit inside each V shaped barrier due to the finite size of the particles. We also observe a clustering of the particles that reduces their overall mobility. A similar dynamic clustering effect for repulsively interacting active particles has been studied as a function of particle density in simulations\cite{39} and observed in experiments with active colloids\cite{12}. In Fig. 6(b) we show a sample with $R_p = 0.2$, where a larger number of particles can be trapped in the V barriers. This reduces the net downward motion of the particles since particles traveling in the positive $y$-direction are not trapped by the barriers. As $R_p$ increases, fewer particles can be trapped in each funnel, and the net downward motion of the particles increases. We also find that as the particle radius increases, there is a decrease in the extent to which the particles are guided along the sides of the barriers and pushed in the negative $y$ direction, reducing the
rectification. If two particles are moving along a barrier wall in opposite directions, the particles can block each others’ flow. In the system without steric interactions, the particles could instead pass through each other. As the particle radius increases, the number of particles that can be guided by a given barrier is reduced since fewer particles can fit on the barrier at the same time. An increase in the particle density produces a higher number of particle-particle collisions throughout the system, even in the regions away from the barriers, reducing the effective run length of the particles. When a drift is applied, an increase in the particle radius also monotonically decreases the ratchet effect.

IV. L SHAPED BARRIERS

We next consider the even L shaped barriers illustrated in Fig. 1(b). In this geometry, for $F_{dc} = 0$ and increasing $R_l$ the particles exhibit a ratchet effect in the positive $y$ and $x$ directions. We apply a dc drive in the negative $y$-direction, $d_x = 0$ and $d_y = -1$, and measure the transport in the perpendicular or $x$-direction. In Fig. 7(a) we plot $(V_x)$ vs $R_l$ for systems with $F_{dc} = 0, 0.5, 1, 2, 5, 10,$ and 20. At $F_{dc} = 0$, $(V_x)$ increases with increasing $R_l$ due to the ratchet effect. For increasing $F_{dc}$, $(V_x)$ monotonically increases, indicating that a transverse ratchet effect occurs. This is illustrated more clearly in Fig. 7(b) where we plot $(V_x)$ versus $F_{dc}$ for $R_l = 0.1, 0.5, 1.0, 2.0, 5, 10, 20, 30,$ and 50. The effectiveness of the $x$ direction rectification increases the most rapidly with increasing $F_{dc}$ for the smallest value of $R_l$: at $R_l = 1$ the ratio of the velocities for $F_{dc} = 0$ and $F_{dc} = 20.0$ is nearly 40, while at $R_l = 5$ it is 4.5. This result indicates that a significant increase in the transverse ratchet effect can be achieved in active ratchet systems by applying a drift current. For a system of noninteracting particles with a finite drift force, when $R_l = 0$ there is no transverse ratchet effect since the particles either pile up on the barriers or flow in the regions between the barriers, as illustrated in Fig. 8(a) for $R_l = 0.01$ and $F_{dc} = 5.0$. The mechanism by which the dc drift enhances the $x$-direction ratchet effect is illustrated in Fig. 8(b) for $R_l = 30$ and $F_{dc} = 1.0$, where we highlight the trajectories of a single particle. When the particle encounters the top of a barrier, it can move either along the outer (left) or inner
FIG. 9: \( \langle V_x \rangle \) vs the particle radius \( R_p \) for the L-shaped barrier system from Fig. 7 with sterically interacting particles and \( R_l = 2.0 \) at \( F_{dc} = 0.1, 0.25, 0.5, 1, 2, 3, 5, \) and 10, from bottom to top. For small \( F_{dc} \), the steric interactions reduce the ratchet effect, while for larger \( F_{dc} \) there is a nonmonotonic response with a peak in \( \langle V_x \rangle \) at \( R_p \approx 0.8 \).

(right) upper wall of the barrier. If the particle moves to the inner side of the barrier, it becomes stuck in the corner of the barrier until it undergoes a tumbling event that allows it to move away from the positive \( x \)-direction. Several instances of this trap-and-escape motion appear in Fig. 8(b). If the particle moves to the outer side of the barrier, it enters the region between barriers and is pushed in the negative \( y \)-direction by the dc drive until it encounters another barrier, at which point it can become trapped at the barrier corner before escaping and moving in the positive \( x \)-direction. This produces a net flux in the positive \( x \)-direction over time, as shown in Fig. 8(b). As \( F_{dc} \) is further increased, the particles that move along the outside walls of the barriers into the barrier-free regions travel more rapidly in the negative \( y \)-direction and more quickly encounter additional barriers, increasing the effectiveness of the transverse ratchet effect. In Fig. 8(c), the particle trajectories for \( R_l = 3.0 \) and \( F_{dc} = 7.0 \) clearly show a tilt toward the positive \( x \)-direction. We also observe a particle trajectory shadow on the underside of each barrier.

A. Steric Interactions

We next consider the effects of including steric particle-particle interactions for the L-shaped barrier system from Fig. 7. In Fig. 9 we plot \( \langle V_x \rangle \) versus the particle radius \( R_p \) for \( R_l = 2.0 \) and \( F_{dc} = 0.1, 0.25, 0.5, 1, 2, 3, 5, \) and 10. For small or zero \( R_l \), the addition of steric interactions reduces the transverse ratchet effect as also found above for the V-shaped barriers. At higher values of \( R_l \), however, the steric interactions can increase the ratchet effect when \( F_{dc} \geq 0.5 \), with a maximum in \( \langle V_x \rangle \) occurring at \( R_p \approx 0.8 \). In all cases, for \( R_p > 0.9 \) the rectification effect decreases since fewer particles can fit on the barrier walls to experience guided motion. The initial increase in \( \langle V_x \rangle \) at small \( R_p \) for the larger values of \( F_{dc} \) occurs due to the filling of the barriers by the particles, as illustrated for small \( R_l \) for the non-interacting particles in Fig. 8(a). When there are steric interactions, the number of particles that can be trapped by each barrier is reduced. In addition, the trapped particles are more likely to move in the positive \( x \)-direction since the corner of the barrier becomes blocked by the earliest-arriving particles; thus, interacting particles that are trapped by a barrier tend to be pushed to the right in the positive \( x \)-direction. Additionally, as particles arrive at the barrier from above, they fall onto the particles that are already trapped at the barrier and tend to create a sandpile-like sloped structure with the slope oriented in the positive \( x \)-direction. In Fig. 10(a) we plot the particles and their trajectories at \( F_{dc} = 5.0 \) and \( R_l = 2.0 \) for a system without steric interactions, where a pileup of particles on the barriers occurs. We show the same system with finite steric interactions and \( R_p = 0.7 \) in Fig. 10(b), where we find that fewer particles are trapped on the barriers due to the repulsive particle-particle interactions. In this case, particles arriving from above the barrier that interact with the barrier tend to be deflected in the positive \( x \)-direction, producing an enhanced rectification.

In general, inclusion of steric interactions enhances the rectification for shorter \( R_l \), while at longer run lengths, the steric interactions decrease the ratchet effect. This is more clearly seen in Fig. 11 where we plot \( \langle V_x \rangle \) versus \( R_l \) at \( F_{dc} = 5.0 \) for \( R_p = 0.3, 0.5, \) and 0.9 as well as for a system without steric interactions with \( R_p = 0.3 \). Here for \( R_l < 5.0 \) the rectification is enhanced by the steric interactions while for \( R_p > 5.0 \), \( \langle V_x \rangle \) is higher for the noninteracting particles. At finite \( F_{dc} \) and low \( R_l \),
sterically interacting particles from Fig. 9 at $F_{dc} = 5.0$ for $R_p = 0.5$, and $R_p = 0.9$ with steric interactions (solid lines from bottom left to top left). The dashed line is a system with $R_p = 0.3$ and no steric interactions. Here the particle-particle interactions enhance the rectification at the lower values of $R_l$ and suppresses the rectification at higher values of $R_l$.

the non-interacting particles accumulate in the barriers, reducing the ratchet effect, while the addition of steric interactions reduces the number of particles that can interact with each barrier. At larger $R_l$ for the noninteracting case, the particles do not accumulate in the barriers but there is no limit to the number of particles that can interact with the barriers, while when steric interactions are present, the number of opportunities for particles to interact with the barriers is limited.

We can also examine the effects of the steric interactions by holding $R_p$ and $L$ fixed and varying $N$ to change the particle density, $\rho = N/L^2$. For the noninteracting case, $\langle V_x \rangle$ is independent of $\rho$. In Fig. 12(a) we plot $\langle V_x \rangle$ versus $\rho$ for a system with $R_p = 0.5$, $F_{dc} = 1.0$ and $R_l = 1.0$. The result for the noninteracting particles is a flat line. At low densities where there are almost no particle-particle collisions, the value of $\langle V_x \rangle$ for the interacting and noninteracting systems are almost identical. As $\rho$ increases, $\langle V_x \rangle$ increases for the interacting particle system until reaching a plateau. For values of $\rho$ higher than shown in the figure, $\langle V_x \rangle$ eventually decreases again as the overall system mobility decreases and the system crystallizes. Figure 12(b) shows the same system with $R_l = 60$. At low densities we again find that $\langle V_x \rangle$ for the interacting and noninteracting systems are almost the same; however, as $\rho$ increases, $\langle V_x \rangle$ for the interacting system decreases. In Fig. 12(c) we show a system with $R_l = 1.0$ and $F_{dc} = 10$, where $\langle V_x \rangle$ for the interacting system increases with increasing $\rho$, while Fig. 12(d) shows that for $R_l = 60$ and $F_{dc} = 10$, $\langle V_x \rangle$ for the interacting system decreases with increasing $\rho$. These results show that steric interactions in combination with a dc drive and short but finite run lengths increase the transverse ratchet effect, while for long run lengths the steric interactions decrease the ratchet effect. This indicates that it should be possible to use the L-shaped barriers to sort particles based on both run length and particle radius.

V. SUMMARY

We have investigated self-driven particles undergoing run-and-tumble dynamics in the presence of arrays of V- and L-shaped barriers. For the V-shaped barriers in the absence of a drive, we find a spontaneous ratchet effect where the particles have a net motion in the easy flow direction of the barriers. The efficiency of this ratchet effect increases with increasing run length, as found in earlier studies of single rows of barriers and in experiments. When we apply a dc drift force in the direction opposite to this ratchet effect, we obtain nonlinear velocity-dc force response curves. We also observe regimes in which particles with different run lengths move in opposite directions. The introduction of steric particle-particle interactions monotonically reduces the ratchet effect. For the even L-shaped barriers, which have both arms the same length, we measure the particle velocity in the di-
rection perpendicular to the dc drive and find a transverse ratchet effect that can be substantially enhanced by the dc drive. The inclusion of steric interactions can also increase the magnitude of the transverse ratchet effect. When the particle radii become too large, this increase is suppressed since fewer particles can interact with each barrier. The increase in the transverse ratchet effect occurs for systems with small but finite run lengths and intermediate particle densities or radii. When the run lengths are long, the addition of steric interactions generally reduces the ratchet effect. Our results show that under a dc drift, active ratchet effects can be substantially enhanced, and provide another approach for controlling the sorting of active matter. We also find that steric interactions can in some cases produce an increase in the ratchet effectiveness.

Acknowledgments

This work was carried out under the auspices of the NNSS of the U.S. DoE at LANL under Contract No. DE-AC52-06NA25396.

1 P. Reimann, Phys. Rep. 361, 57 (2002).
2 R.D. Astumian and P. Hänggi, Phys. Today 55(11), 33 (2002).
3 P. Hänggi and F. Marchesoni, Rev. Mod. Phys. 81, 387 (2009).
4 J. Rousselet, L. Salome, A. Ajdari, and J. Prost, Nature 370, 446 (1994).
5 K. Xiao, Y. Roichman, and D.G. Grier, Phys. Rev. E 84, 011131 (2011).
6 C.S. Lee, B. Jankó, I. Derényi, and A.L. Barabási, Nature (London) 400, 337 (1999).
7 C.C. de Souza Silva, J. Van de Vondel, B.Y. Zhu, M. Morelle, and V.V. Moshchalkov, Phys. Rev. B 73, 014507 (2006); W. Gillijns, A.V. Silhanek, V.V. Moshchalkov, C.J. Olson Reichhardt, and C. Reichhardt, Phys. Rev. Lett. 99, 247002 (2007); Q. Lu, C.J. Olson Reichhardt, and C. Reichhardt, Phys. Rev. B 75, 054502 (2007); L. Dinis, D. Perez de Lara, E.M. Gonzalez, J.V. Anguita, J.M.R. Parrondo, and J.L. Vicent, New J. Phys. 11, 073046 (2009).
8 B.L.T. Plourde, IEEE Trans. Appl. Supercond. 19, 3698 (2009).
9 Z. Farkas, P. Tegzes, A. Vukics, and T. Vicsek, Phys. Rev. E 60, 7022 (1999); J.F. Wambach, C. Reichhardt, and C.J. Olson, Phys. Rev. E 65, 031308 (2002); Z. Farkas, F. Szalai, D.E. Wolf, and T. Vicsek, Phys. Rev. E 65, 022301 (2002).
10 S.-H. Lee and D.G. Grier, Phys. Rev. E 71, 060102 (2005).
11 A. Libal, C. Reichhardt, B. Jankó, and C.J. Olson Reichhardt, Phys. Rev. Lett. 96, 188301 (2006).
12 C. Reichhardt, C.J. Olson, and M.B. Hastings, Phys. Rev. Lett. 89, 024101 (2002); C. Reichhardt and C. J. Olson Reichhardt, Phys. Rev. E 68, 046102 (2003).
13 R. Guantes and S. Miret-Artés, Phys. Rev. E 67, 046212 (2003).
14 P. Tienro, T.H. Johansen, and T.M. Fischer, Phys. Rev. Lett. 99, 038303 (2007).
15 D. Speer, R. Eichhorn, and P. Reimann, Phys. Rev. Lett. 102, 124101 (2009).
16 B ten Hagen, S. van Teefelwn, and H. Löwen, J. Phys: Condens. Matter 23, 194119 (2011).
17 P. Romanczuk, M. Bür, W. Ebeling, B. Lindner, and L. Schimansky-Geier, Eur. Phys. J. Special Topics 202, 1 (2012).
18 S. Ramaswamy, Ann. Rev. Condens. Matter Phys. 1, 323 (2010).
19 M.C. Marchetti, J.F. Joanny, S. Ramaswamy, T.B. Liver-
40. G. Lambert, D. Liao, and R.H. Austin, Phys. Rev. Lett. 104, 168102 (2010).
41. L. Angelani, A. Costanzo, R. Di Leonardo, EPL 96, 68002 (2011).
42. J.A. Drocco, C.J. Olson Reichhardt, and C. Reichhardt, Phys. Rev. E 87, 052702 (2013).
43. M.B. Wan, and Y.S. Jho, Soft Matter 9, 3255 (2013).
44. A. Pototsky, A. M. Hahn, and H. Stark, Phys. Rev. E 87, 042124 (2013).
45. M. Mijalkov and G. Volpe, Soft Matter 9, 6376 (2013).
46. L. Angelani, R. Di Leonardo, and G. Ruocco, Phys. Rev. Lett. 102, 048104 (2009).
47. R. Di Leonardo, L. Angelani, D. Dell’Arciprete, G. Ruocco, V. Iebba, S. Schippa, M. P. Conte, F. Mecarini, F. De Angelis, and E. Di Fabrizio, Proc. Natl. Acad. Sci. (USA) 107, 9541 (2010); A. Sokolov, M.M. Apodaca, B.A. Grzybowski, and I.S. Aranson, Proc. Natl. Acad. Sci. (USA) 107, 969 (2010).
48. A. Kaiser, H.H. Wensink, and H. Löwen, Phys. Rev. Lett. 108, 268307 (2012); A. Kaiser, K. Popowa, H.H. Wensink, and H. Löwen, arXiv:1307.0030.
49. T.A.J. Duke and R.H. Austin, Phys. Rev. Lett. 80, 1552 (1998).
50. D. Ertas, Phys. Rev. Lett. 80, 1548 (1998).
51. C.F. Chou, O. Bakajin, S.W.P. Turner, T.A.J. Duke, S.S. Chan, E.C. Cox, H.G. Craighead, and R.H. Austin, Proc. Natl. Acad. Sci. (USA) 96, 13762 (1999).
52. L.R. Huang, P. Silberzan, J.O. Tegenfeldt, E.C. Cox, J.C. Sturm, R.H. Austin, and H.G. Craighead, Phys. Rev. Lett. 89, 178301 (2002).
53. L.R. Huang, E.C. Cox, R.H. Austin, and J.C. Sturm, Science 304, 987 (2004).
54. K. Loutherback, J. Puchalla, R.H. Austin, and J.C. Sturm, Phys. Rev. Lett. 102, 045301 (2009).
55. Z. Li and G. Drazer, Phys. Rev. Lett. 98, 050602 (2007).
56. R. Eichhorn, J. Regtmeier, D. Anselmetti, and P. Reimann, Soft Matter 6, 1858 (2010).
57. D. Reguera, A. Luque, P. S. Burada, G. Schmid, J. M. Rubi, and P. Hänggi, Phys. Rev. Lett. 108, 020604 (2012).
58. L. Bogunovic, M. Fliedner, R. Eichhorn, S. Wegener, J. Regtmeier, D. Anselmetti, and P. Reimann, Phys. Rev. Lett. 109, 100603 (2012).
59. S. Henkes, Y. Fily, and M.C. Marchetti, Phys. Rev. E 84, 040301 (2011); F.D.C. Farrell, M.C. Marchetti, D. Marenduzzo, and J. Tailleur, Phys. Rev. Lett. 108, 248101 (2012).