Keep-Left Behavior Induced by Asymmetrically Profiled Walls

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(Received 4 September 2015; published 7 January 2016)

We show, computationally and analytically, that asymmetrically shaped walls can organize the flow of pedestrians driven in opposite directions through a corridor. Precisely, a two-lane ordered state emerges in which people always walk on the left-hand side (or right-hand side), controlled by the system's parameters. This effect depends on features of the channel geometry, such as the asymmetry of the profile and the channel width, as well as on the density and the drift velocity of pedestrians, and the intensity of noise. We investigate in detail the influence of these parameters on the flow and discover a crossover between ordered and disordered states. Our results show that an ordered state only appears within a limited range of drift velocities. Moreover, increasing noise may suppress such flow organization, but the flow is always sustained. This is in contrast with the "freezing by heating" phenomenon according to which pedestrians tend to clog in smooth channels for strong noise [Phys. Rev. Lett. 84, 1240 (2000)]. Therefore, the ratchetlike effect proposed here acts on the system not only to induce a "keep-left" behavior but also to prevent the freezing by heating clogging phenomenon. Besides pedestrian flow, this new phenomenon has other potential applications in microfluidics systems.

Subject Areas: Computational Physics,
Interdisciplinary Physics

I. INTRODUCTION

Counterflowing streams of particles appear in many situations in science and technology [1–11], such as pedestrian dynamics, granular matter, and oppositely charged colloidal particles on an electric field. The classical paradigm is a channel through which one species moves in one direction and another in the opposite direction. The particles could be driven by gravity when there is a density difference, by chemical gradients or by their own propulsion as in the case of pedestrians. As it happens, for instance, in the London tube during rush hour, motion can come to a standstill in narrow corridors because of mutual hindrance at high densities. Since Boycott's elucidating experiments on blood sedimentation [12], it is known that such gridlock situations can be efficiently overcome by organizing the system into only two main streams. In the London tube, signs saying "keep left" are intended to impose such flow segregation. Here, we show that it is possible to indirectly induce a "keep-left" behavior by giving the walls an asymmetric zigzag shape. Coming

either from the left or right, objects colliding with the wall will then encounter different inclinations and thus lose more or less (of the horizontal component of their) velocity.

Ratchets, like those in a bicycle hub, have been used not only in gears but also in many other physical systems. For instance, the so-called Feynman-Smoluchowski ratchet, also known as the "Brownian ratchet," is a thought experiment of a purported perpetual motion machine, based on the idea of extracting work from a heat bath without a temperature gradient [13,14]. This experimental setup was proposed a century ago by Smoluchowski as an example of Maxwell's demon, although it was shown by Feynman decades later to actually fail. In any case, today it is still one of the most ingenious devices to supposedly defy the second law of thermodynamics. More recent ratchet-based experiments have been designed in many other areas, such as the superconductivity vortex [15], silicon wafer [16], optics [17], granular material [18–20], controlling transport on the nanoscale [21], and particle transport in fluid flow [22]. The main purpose to use a ratchet is to store energy in the system to then induce coherent motion. In fact, what is now known as the ratchet effect is the phenomenon where directed transport emerges in a spatially periodic system [14].

In the present work, we show that corridors with asymmetrically profiled walls can induce organization in the flow of pedestrians. Precisely, the key element of our approach is to use walls having the geometry of a ratchet,
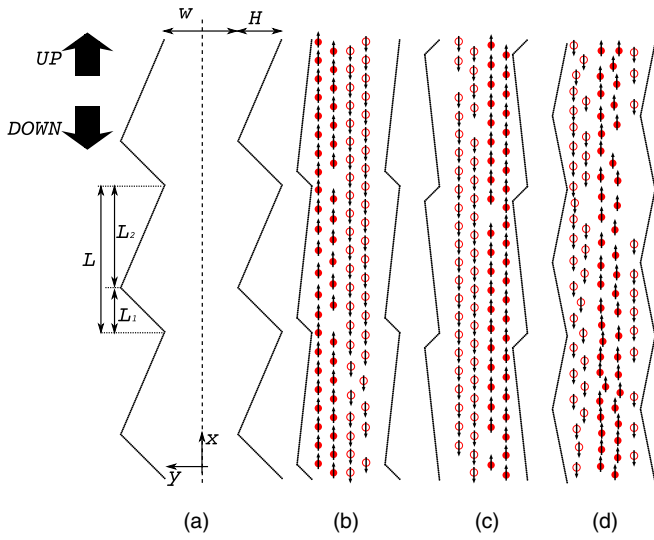
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FIG. 1. Channel geometry and final configurations of pedestrians for different asymmetry parameters. (a) Channel, of depth H and width W, through which a preferred flow orientation of particles is induced. The meaning of geometric parameters is indicated. (b–d) Typical configurations in the steady state, where the particles are keeping left in asymmetric wall channels but are mixed in symmetric ones. Upward movers (downward movers) are represented by full (hollow) particles. The velocity of each particle is indicated by arrows. The asymmetry parameter $b = L/2 - L_1$ takes the values $b = 8$ in (b), $b = -8$ in (c), and $b = 0$ in (d), for $H = 2$, $v_d = 6$, and $\rho = 0.6$. The length unit is written in terms of particle diameter. Noise was not included in these simulations.

i.e., a zigzag structure such as the one shown in Fig. 1(a). We consider that all pedestrians (modeled here as self-driven particles) in the channel are identical except that half of them are downward movers, i.e., driven by a force downward, while the other half are upward movers, i.e., driven by a force upward. These forces try to impose a constant drift velocity. A repulsive potential acts between particles and with the walls, while a stochastic force introduces disorder. The flow orientation along the walls strongly depends on the system's parameters. Moreover, as we will see later, increasing the strength of the disorder may suppress organization. We will present simulations showing the existence of a crossover between organized and disorganized flow, as well as analytical calculations in order to support our findings.

II. METHODS

Let us now consider N spherical particles of mass m and radius r. The equation of motion for each particle i is assumed to be given by

$$m\frac{d\boldsymbol{v}_i}{dt} = -m\frac{\boldsymbol{v}_i - v_d\boldsymbol{e}_i}{\tau} + \sum_{j\neq i}\boldsymbol{f}_{ij} + \boldsymbol{f}_{iW} + \boldsymbol{\xi}_i, \quad (1)$$

where v_d is the drift velocity, $\boldsymbol{e}_i = \hat{\boldsymbol{x}}$ for $i = 1, ..., \frac{N}{2}$, and $\boldsymbol{e}_i = -\hat{\boldsymbol{x}}$ for $i = \frac{N}{2} + 1, ..., N$, and $\hat{\boldsymbol{x}}$ is the unit vector in the channel direction (x direction), as shown in Fig. 1(a). In this Langevin-like equation, the first term on the right-hand side corresponds to a Stokesian drag force which tends to impose a speed v_d on particle i within a characteristic time τ. The particles interact with each other through the repulsive forces $\boldsymbol{f}_{ij}$ and with the walls through $\boldsymbol{f}_{iW}$. $\boldsymbol{\xi}_i$ corresponds to an uncorrelated, normally distributed stochastic force with zero mean and finite variance θ for each component. Notice that the intensity of noise, in the case of a pedestrian, may be related to the desire of the person to veer other people in a crowd.

The force between particles is assumed to be given by [7,8]

$$\boldsymbol{f}_{ij} = [Ae^{-r'_{ij}/B} - kr'_{ij}u(-r'_{ij})]\boldsymbol{n}_{ij} - gr'_{ij}u(-r'_{ij})\Delta v^t_{ij}\boldsymbol{t}_{ij}, \quad (2)$$

where $r'_{ij} = r_{ij} - 2r$ is the perpendicular distance between the surfaces of particles i and j, $r_{ij} = \|\boldsymbol{r}_i - \boldsymbol{r}_j\|$ is the distance between the centers of these particles, $\boldsymbol{n}_{ij} = (n^1_{ij}, n^2_{ij}) = (\boldsymbol{r}_i - \boldsymbol{r}_j)/r_{ij}$ is the unit vector connecting these centers, and $\boldsymbol{t}_{ij} = (-n^2_{ij}, n^1_{ij})$ is the unit vector in the tangential direction. The Heaviside function $u(x) = 1$ if $x \geq 0$ and $u(x) = 0$ otherwise, so that, when particles are in contact ($r_{ij} < 2r$), there are two forces added to this interaction, one elastic and repulsive acting radially and the other dissipative acting in the tangential direction. These two contact forces are typically found in granular materials [23–25]. For distances $r_{ij} > 2r$, $u(x) = 0$, and the particles only interact weakly. Furthermore, when the distance between particles is above a cutoff λ_P, the forces are completely neglected. Finally, Δv^t_{ij} is the tangential component of the relative velocity, and A, B, k, and g are constants that allow for a wide range of options; e.g., setting $g = 0$ restricts the interaction to radial forces, while setting both $A = 0$ and $g = 0$ allows only elastic repulsion, etc. This generality in fact also encompasses the human interaction between pedestrians [7,8].

The interaction of a given particle with the walls is implemented by considering that one puts a pointlike "wall particle" at the position on the wall which is closest to the particle. The interaction of particle i with the wall is then given by the force

$$\boldsymbol{f}_{iW} = [A_w e^{-r'_{iW}/B_w} - kr'_{iW}u(-r'_{iW})]\boldsymbol{n}_{iW} - gr'_{iW}u(-r'_{iW})\Delta v^t_{iW}\boldsymbol{t}_{iW}, \quad (3)$$

which is the same expression for the force between particles in Eq. (2), but now $r'_{iW} = r_{iW} - r$ is the perpendicular distance between the surface of particle i and the wall, and r_{iW} is the distance between the center of particle i and the wall. Again, a cutoff, given by λ_W, limits the range of this interaction.

We employ molecular dynamics to simulate the collective particle flow in the channel, using a Verlet-like method to numerically integrate the equations of motion [26,27]. We use a time step $\Delta t = 10^{-3}$ and impose periodic boundary conditions in the channel direction.

The formalism adopted here is similar to that used in Refs. [7,8], where it was shown that pedestrian counterflow in smooth channels ($H = 0$) can split up in several lanes, as long as noise is sufficiently small. However, that system is intricate as it can clog when temperature increases, a fascinating anomaly called "freezing by heating," as observed in Ref. [8]. Clogging due to flow of particles was also studied in Ref. [28], but again, channels, into which particles flow, were assumed to be smooth. We are now interested in setting up a counterflow system where a two-lane flow of pedestrians is established, in which particles keep left, or right, controlled by geometrical parameters, as depicted in Figs. 1(b) and 1(c). Moreover, we want this system to be more resilient to noise, as compared to the results found for a smooth corridor with $H = 0$, so that the "freezing by heating" phenomenon is avoided. To achieve this, we propose channel walls built as a zigzag pattern [see Fig. 1(a)]. Each unit cell of that zigzag pattern has a length L and consists of two pieces, of lengths L_1 and L_2, so that $L_1 + L_2 = L$, and the asymmetry of this wall ratchet can be quantified by $b = L/2 - L_1$. The depth of the zigzag geometry is quantified by H, and length units are written in terms of particle diameter.

III. RESULTS AND DISCUSSION

To measure how well the pedestrians keep left, we introduce a lane-ordering parameter Φ defined as

$$\Phi = \frac{1}{N} \sum_{i=1}^{N} \frac{v_{i,x} \cdot y_i}{|v_{i,x} \cdot y_i|}, \qquad (4)$$

where y_i and $v_{i,x}$ are the y component of the position and the x component of the velocity of particle i, respectively. Since $y = 0$ is the central line of the channel [dashed line in Fig. 1(a)], the argument of the sum is positive when most particles keep left, and when they mostly keep right, then the order parameter is negative. In the limiting cases of $\Phi = \pm 1$, the two types of particles flow completely separated from each other in only two lanes, displaying what we call here ordered states. Once the system achieves one of those configurations, and noise is small enough, no pedestrian enters in a "collision route" with any other, and the system is stable. It is important to note that, at the stationary regime in which collisions are not observed anymore (in the absence of noise), the displacement speed of pedestrians is the same for symmetric and asymmetric channels.

In order to achieve these two maximally organized states, we vary some geometrical parameters, namely, the depth H

and the asymmetry parameter b of the zigzag walls. We also vary other parameters, namely, the drift velocity v_d of the pedestrians, the particle density $\rho = N/A_c$ (where A_c is the total area of the channel, including the space in the zigzag part), and the noise level θ. All other parameters, given in Ref. [29], are kept fixed throughout our simulations. Initially, nonoverlapping particles start moving within the channel with random velocities and positions. Then, the system evolves during 3×10^8 time steps, so the influence of transient states is eliminated. The final configurations, such as those depicted in Figs. 1(b)–1(d), for different values of b, clearly show the ratchet effect on the particle flow. When the walls are asymmetric, such as those shown Fig. 1(b) (for $b = 8$) and in Fig. 1(c) (for $b = -8$), yielding $\Phi = 1$ and $\Phi = -1$, respectively, particles flow completely segregated in a two-lane pattern. However, in the symmetric case of $b = 0$, as shown in Fig. 1(d), particles flow through multiple lanes in the same way as they do in the case of smooth channels, yielding $\Phi \approx 0$. To investigate this ratchet effect, we compute the average order parameter $\langle \Phi \rangle$, taken over up to several thousands of realizations for each set of parameters.

In Fig. 2, we show, for different drift velocities in systems without noise, how the degree of asymmetry b changes the lanes and induces preferential sides of the particle flows in the channel. Interestingly, the larger v_d, the more abrupt the change between the ordered states, $\Phi = \pm 1$, as b changes. For large positive values of b, we find $\langle \Phi \rangle = 1$; i.e., everybody is keeping left perfectly. For large negative values of b, we find $\langle \Phi \rangle = -1$, corresponding to everybody keeping right. Finally, there is a mixed state for b close to zero, where no preferred side is observed.
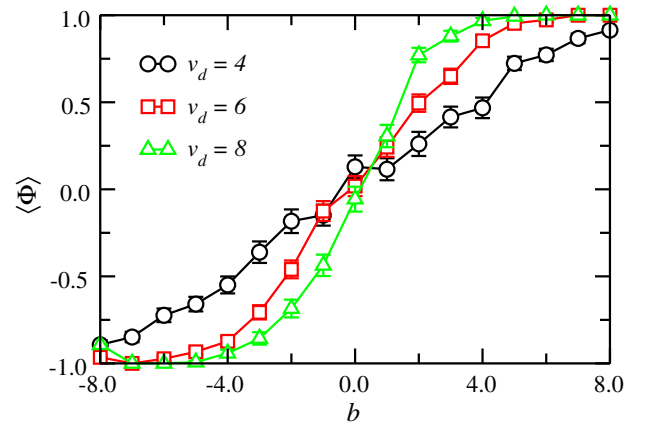

FIG. 2. Average order parameter $\langle \Phi \rangle$ as a function of the asymmetry parameter b, for three different values of the drift velocity. We see that order is only induced for $|b| > 0$. The slower v_d, the higher $|b|$ should be in order to achieve a two-lane pattern. The remaining parameters, including the lack of noise, are the same as in Fig. 1.
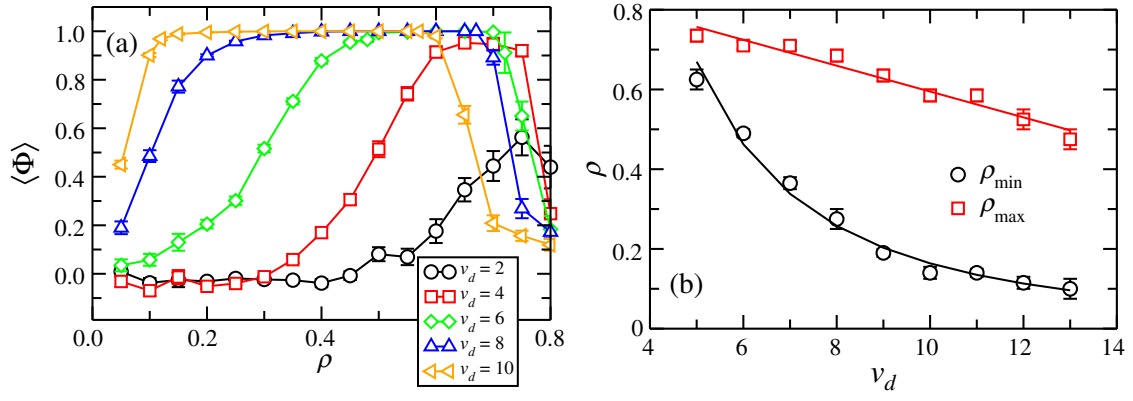
FIG. 3. Dependence of density on drift velocity for ordered states. In panel (a), the average order parameter $\langle \Phi \rangle$ is shown as a function of the density for $\theta = 0$, $b = 8$, $H = 2$, and several values of the drift velocity v_d. In panel (b), we show the maximum (red squares) and minimum (black circles) densities for which $\langle \Phi \rangle = 1$, as functions of the drift velocity. A power-law fit for the minimum density yields $\rho_{\min} = 17.6 v_d^{-2.03}$, whereas a linear fit for the maximum density gives $\rho_{\max} = 0.919 - 0.032 v_d$. The equations extracted from the fits meet at two points, namely, $v_d \approx 4.67$ and $v_d \approx 28.09$.

The density also has a strong influence on the ordering of the system, as can be seen in Fig. 3(a). We observe that, for a fixed channel geometry, complete order is obtained for intermediate densities. Three states can be clearly distinguished. For low densities, pedestrians interact only weakly with the walls, and ordering is highly dependent on the drift velocity. For larger densities and sufficiently large v_d, pedestrians do feel the walls enforcing strong ordering, and the flow yields a value of $\langle \Phi \rangle = 1$. By increasing the density further, the two-lane state is suppressed by too many collisions, making $\langle \Phi \rangle$ approach zero.

In Fig. 3(a), we also observe that the region of density giving perfect ordering depends on the drift velocity v_d. For instance, for $v_d = 10$, two-lane flow is obtained for $0.14 \leq \rho \leq 0.58$. The effect of the drift velocity v_d on the size of this region can be investigated by estimating the minimum ($\rho_{\min}$) and maximum densities ($\rho_{\max}$) at which perfect ordering is observed, for different values of v_d. As shown in Fig. 3(b), these densities can be properly described in terms of the power-law relation, $\rho_{\min} = 17.6 v_d^{-2.03}$, and the "weak" linear relation, $\rho_{\max} = 0.919 - 0.032 v_d$. An approximate analytical treatment (see Sec. II of Ref. [30]) predicts $\rho_{\min} \sim v_d^{-2}$ and no dependence of $\rho_{\max}$ on v_d, both in excellent agreement with the numerical results.

In our analytical treatment, we consider first a very dilute system where collisions are very rare, and therefore, downward movers and upward movers should be uniformly distributed along the width, while no particles visit the serrated sectors of the channel. Indeed, it is observed in our numerical results that $\Phi \approx 0$ for $\rho \approx 0$. However, as the density increases, between-particle collisions become more frequent. In this case, particles move towards the serrated sectors, where they collide elastically either with the steeper wall or with the wall whose slope is smaller, depending on the direction of their drift velocity. As shown

in Ref. [30], y momentum after collision is a sinusoidal function of 2 times the angle of the wall the particles collide with. Then, for small H, collisions with the steeper wall result in larger y momenta (pushing particles away to the other side of the channel) than those from collisions with the less steep wall (keeping particles close to this side of the channel). The aftermath of such a ratchet effect is that particles are led to move along the wall with which they have the smaller y momentum after collision.

The fits obtained from the numerical results in Fig. 3 suggest that complete segregation of pedestrian flow can only be achieved for $4.67 \lesssim v_d \lesssim 28.09$, where the two limits correspond to the values at which the equations obtained from the fits to the data of $\rho_{\min}$ and $\rho_{\max}$ against v_d meet. This result shows that, although the range of intermediate densities for which $\langle \Phi \rangle = 1$ initially increases with v_d, for $v_d \gtrsim 4.67$, it eventually starts to decrease and finally comes to a collapse at $v_d \approx 28.09$.
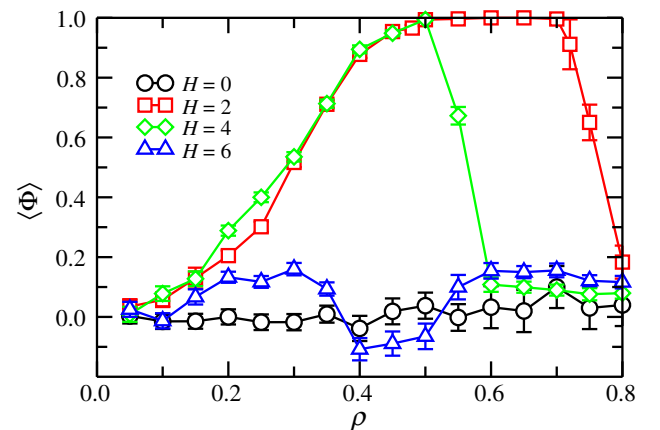

FIG. 4. Average order parameter as a function of the particle density, for $\theta = 0$, $b = 8$, $v_d = 6$, and various values of the depth H of the serrated region.

We now consider the effect of changing the parameter H, which, as shown in Fig. 1(a), represents the depth of the serrated region. Figure 4 shows the behavior of the order parameter as a function of the particle density for several values of H, with $\theta = 0$, $b = 8$, and $v_d = 6$. The case $H = 0$, which corresponds to a smooth channel, leads to $\langle \Phi \rangle = 0$ regardless of ρ. For $H = 2$ (a case also depicted in Fig. 3), complete order, $\langle \Phi \rangle = 1$, can be observed for a certain range of densities. This range becomes narrower as the depth increases from $H = 2$ to $H = 4$. At $H = 6$, a fully organized two-lane state is no longer stable for any density.

The results in Fig. 3 are obtained for a small value of H, namely, $H = 2$, for which the ordered region is always characterized by $\langle \Phi \rangle = 1$. As shown in Fig. 4, by varying H we observe four phases. For the case of smooth channels, $H = 0$, no order is reached and $\langle \Phi \rangle \approx 0$. For small H, namely, $2 \leq H < 6$, $\langle \Phi \rangle = 1$ is obtained for a certain range of densities, whereas at $H = 6$, the average order parameter $\langle \Phi \rangle$ is approximately zero for all densities. When H becomes larger than W, the corridor becomes more a sequence of rooms, and then an inversion of the flux directions occurs, as shown analytically and numerically in Fig. S2 and Sec. II of Ref. [30], respectively.

In order to investigate the effect of noise, we choose a set of parameters which, for the case of $\theta = 0$, leads the system spontaneously to an ordered state with $\langle \Phi \rangle = 1$ as shown in Fig. 5. For weak noise, i.e., for $\theta \lesssim 1$, an ordered state appears as expected. However, as θ approaches unity, order is destroyed and $\langle \Phi \rangle$ abruptly decreases, being approximately 0.17 at $\theta = 2$. As noise increases further, $\langle \Phi \rangle$ converges systematically to zero. The transition between the two ordered states, i.e., from $\langle \Phi \rangle = -1$ to $\langle \Phi \rangle = 1$, as the asymmetry parameter b changes from -8 to 8, becomes more gradual for $\theta \gtrsim 1$. The role of the noise is therefore to drive the system to a completely random configuration,

where no lanes are formed (see Fig. S1 of Ref. [30]). Notice that $\Phi \approx 0$ can be obtained both from multiple lanes [as shown in Fig. 1(d)] or from random configurations, the difference between these two states being characterized by the intensity of noise. The system that once presented a two-lane or a multilane pattern, depending on b, for small θ, can no longer support such lane structures as θ increases. Remarkably, and differently from what was found in Ref. [8] for smooth channels, we do not observe any "freezing by heating effect." Thus, the ratchet effect acts on the system not only to keep particles on one side but also to avoid clogging, as shown in Fig. S1 of Ref. [30].

We also investigate the effect of "stubborn" pedestrians on the flow. This is performed by first considering a set of parameters for which we know that the flow naturally evolves to a stationary regime, where all pedestrians keep left. Then, we choose a fraction c of the pedestrians to be "stubborn keep-right." These pedestrians always insist to walk on the right-hand side of the channel. Half of these stubborn pedestrians are upward movers, and the other half are downward movers. The order parameter is computed as in Eq. (4), but now the summation only runs over regular (nonstubborn) pedestrians. According to these new results (see Sec. III and Figs. S4 and S5 of Ref. [30]), the presence of stubborn pedestrians can either completely destroy the keep-left traffic or can impose no effect at all. It all depends on the level of stubbornness, i.e., the willpower of a stubborn pedestrian to walk on the right-hand side.

IV. CONCLUSIONS

Our computational and analytical results therefore show that asymmetric zigzag walls induce pedestrians to keep on one side. For small fluctuations, this flow pattern is stable since few collisions between pedestrians are observed. For high fluctuations, however, this configuration is no longer stable. Although a two-lane pattern is no longer supported for strong noises, pedestrians can still flow rather than clog, in contrast to what is often observed in smooth channels. The tendency to keep left also depends on a certain range of asymmetry, wall depth, drift velocity, and density. We have found, for the case without noise, that this state can only be achieved for drift velocities in the range $4.67 \lesssim v_d \lesssim 28.09$ and for ratchet depths of the wall in the range $2 \leq H < 6$, where $\langle \Phi \rangle = 1$, or $H > 6$, where $\langle \Phi \rangle = -1$. $H = 6$ is a crossover between $\langle \Phi \rangle = 1$ and $\langle \Phi \rangle = -1$. We propose that our zigzag wall design might be used in pedestrian corridors as well as in microfluidic applications. Finally, it is worth mentioning that, for some conditions, the flow of pedestrians may exhibit hysteresis behavior. For instance, increasing and decreasing the number of pedestrians with time, instead of starting with a random configuration as we do here, may carry some "memory" of the state of the system and hence produce different $\Phi \times \rho$ curves, when ρ is increased or decreased. Besides, noise can play a role. For instance, after a system has reached a steady state with
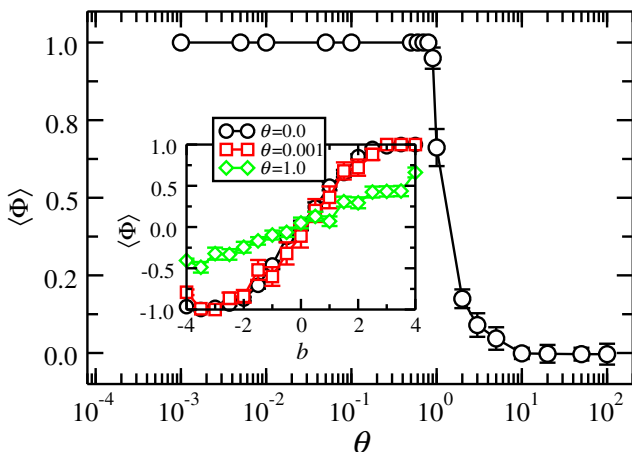

FIG. 5. Average order parameter as a function of θ, for $\rho = 0.6$, $b = 8$, $v_d = 6$, and $H = 2$. The inset shows the crossover from $\langle \Phi \rangle = -1$ to $\langle \Phi \rangle = 1$ as b changes from -8 to 8, for different values of θ.

$\Phi = 1$ and $b = 8$, changing b continuously with time to -8 may eventually allow the system to be reorganized with $\Phi = -1$, if noise is large enough. These possibilities to find hysteresis in pedestrian dynamics will be explored in future work.

Previous work [8] has shown that partial counterflow organization can be disturbed by thermal noise, leading to clogging. Here, we have demonstrated the novel concept that by changing the geometry of the channel, not only are clogging effects avoided but also full ordering of counterflow is achieved. In particular, we have shown that the asymmetric shape of the walls allows imposing a favorite direction, caused by the different angles with which objects collide against the wall coming either from the left or from the right. This has clear implications for the design of highly efficient separation devices with potential application to a range of situations spanning several length scales, from pedestrian flow, to granular matter, and to microfluidics, where, for instance, lane formation is observed for oppositely charged colloidal particles in the presence of an electric field [10,11]. In summary, from an entirely microdynamical perspective, our work unveils that exquisite ordered states, like the two-lane formation observed here, can emerge as a consequence of a very fine trade-off between local geometrical details of the system and the effective interactions among its many elementary constituents.

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[29] The following are the constants used in this work. The particle mass is given by $m = 80$, and other geometrical parameters are given by $L = 20$ and $W = 8$, in units of particle diameter. The parameters of the interaction potentials are given as follows: $A = 2 \times 10^3$, $B = 0.16$, $A_W = 10^4$, $B_W = 0.04$, $k = 1.2 \times 10^3$, $g = 2.4 \times 10^3$, $\tau = 0.5$, $\lambda_P = 4$, and $\lambda_W = 2$.

[30] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevX.6.011003 for an analytical heuristic treatment in the absence of noise and for details on the molecular dynamics algorithm.