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The robustness in dynamics of out of equilibrium bidirectional transport systems with constrained entrances

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Macroscopic and microscopic long-distance bidirectional transfer depends on connections between entrances and exits of various transport mediums. Persuaded by the associations, we introduce a small system module of Totally Asymmetric Simple Exclusion Process including oppositely directed species of particles moving on two parallel channels with constrained entrances. The dynamical rules which characterize the system obey symmetry between the two species and are identical for both the channels. The model displays a rich steady-state behavior, including symmetry breaking phenomenon. The phase diagram is analyzed theoretically within the mean-field approximation and substantiated with Monte Carlo simulations. Relevant mean-field calculations are also presented. We further compared the phase segregation with those observed in previous works, and it is examined that the structure of phase separation in proposed model is distinguished from earlier ones. Interestingly, for phases with broken symmetry, symmetry with respect to channels has been observed as the distinct particles behave differently while the similar type of particles exhibits the same conduct in the system. For symmetric phases, significant properties including currents and densities in the channels are identical for both types of particles. The effect of symmetry breaking occurrence on the Monte Carlo simulation results has also been examined based on particle density histograms. Finally, phase properties of the system having strong size dependency have been explored based on simulations findings.

1. Introduction

Many biological and physical transport systems exhibit bidirectional flow when either driven by some external field or are self-driven. At the microscopic level, intracellular transport of cargo vesicles such as lipid droplets, endosome, and viruses is often accomplished bidirectionally by sets of oppositely directed motor proteins along one-dimensional cytoskeleton filaments such as microtubules (MTs) [1]. For example, the majority of kinesin motors proceeds to the MT-plus end (away from the cell nucleus) whereas dynein motors walk to the MT-minus end (toward the nucleus) while carrying cargo [2,3]. Additionally, experiments suggest that molecular motors traveling in opposite direction on the same microtubule can also cross each other and continue with their motion along the same filament [1]. The bidirectional movement along with pass through is also evident in other transport systems, including traffic flow and pedestrian motion. All these dynamical processes, directed by steady energy supply, are steadily out of equilibrium systems.

Driven lattice gas (DLG) models are particular kinds of discrete models which are extensively used to study such diffusive systems. In DLG, particles interact with their nearest neighbors and move forward in a preferred direction. The totally asymmetric simple exclusion process (TASEP) is a particular illustrative of DLG and is treated as the simplest stochastic model for studying driven diffusive systems, in which particles hop along the lattice under the hard-core exclusion principle with a pre-assigned set of conditions. Despite its simplicity, TASEP is competent enough to efficiently explain some complex non-equilibrium phenomena originating in single and multiple species system, including boundary-induced phase transitions [4,5], phase segregation [6], spontaneous symmetry breaking (SSB) [7–9] and localized shocks [10], etc.

Spontaneous symmetry breaking is a captivating phenomenon observed in many physical systems under the symmetrical conditions of the involved dynamical processes [11,12]. The 'bridge model', being the first model that displays SSB in bidirectional transport systems, [7,13], under the symmetrical conditions of the dynamical rules for two distinct types of particles in the single

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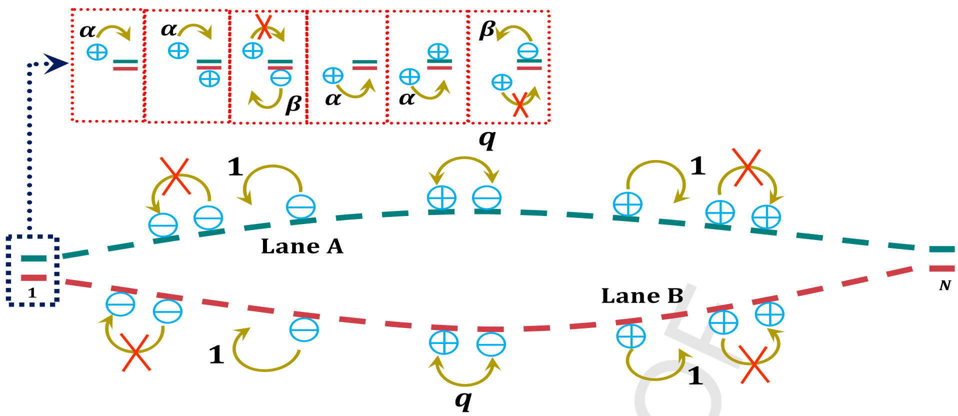

Fig. 1. (Color online.) Schematic representation of the model. Allowed transitions are shown by arrows. Crossed arrows indicate impermissible transitions. (+)-particles progress from left to right on both the lanes, while, (−)-particles transverse in the reverse direction. The dynamics of N-th site are similar to that on 1-st site, except that the entering particle is negative while the exiting particle is positive.

channel reported phases with the broken symmetry of particles. However, the structure of this phenomenon is still not well understood as the alteration to the symmetry-broken state remained an issue of discussion [14–16]. It is noteworthy to mention here that the SSB phenomenon has not been observed in the equivalent single species model.

In addition, MTs are polymers with primary subunits as protofilaments [2], on which motors progress collectively. The motor attachment rate enhances in presence of similar types of motors [17]. Several investigations and experiments have revealed that protofilaments displays a twist and, in addition, a small preferred curvature due to their internal arrangement [18]. The natural structural bend in protofilaments contributes to the helical nature of MTs resulting in connections between the entrance and exit of the various filaments [19]. Further, the point of traffic obstruction delaying or disrupting free directional transfer also results in constrained entrances. These outcomes developed curiosity in investigating the role of constrained entrances mainly, in bidirectional transport systems seeing the exit of particles as an open system only. Owing to these observations, later the study of SSB was extended to two-channel TASEPs with two distinct types of particles moving in opposite directions along different channels with constrained entrances [8]. Four apparent steady-state phases, in which two displays SSB phenomenon has been noted.

Motivated by the indispensable role of multiple species and constrained entrances in the occurrence of SSB phenomenon, the present study analyzes more realistic two-channel transport system with bidirectional movement on each trail. Understanding the complexity involved in the system, it is interesting to examine the evolving steady-state dynamics under the impact of constrained entrances. Our motive is to study the structural changes in the phase diagram, both qualitative as well as quantitative, in comparison to those observed in previous works [7] and [8]. Besides, the above observations excite the need to answer some substantial queries like: (a) How bidirectional flow on each channel induces the robust complex dynamical processes of the system in steady-state including phase separation? (b) Does symmetry breaking appear in the system? (c) If yes, does the phases with broken symmetry appears channel wise or particle wise or both?

In this direction, we organized the discussion as follows. In the next section, we briefly describe the model and present theoretical analysis using a mean-field approximation. The third section discusses the results of Monte Carlo simulations and the conclusion is given in the last section.

2. Bidirectional two-channel model and mean-field approximation

We consider a structure of two parallel one-dimensional lattice channels of equal length L, each with fixed N sites, denoted by lane A and lane B (Fig. 1). The system consists of two types of particle species, positive (+) and negative (−), distributed under the hard-core exclusion principle on both the channels. Provoked by the collective transport on curved MTs in biological transport and relevant congestions in traffic flow, as discussed, it is assumed that the channels interact at boundaries only and entry of a particle is influenced by the type of neighboring particle on another channel. Each lattice site can be either empty or can be occupied by either positive or negative particle. The (+)-particles progress from left to right along both the channels, while (−)-particles transverse in the reverse direction, illustrating the bidirectional lane flow. The two types of particles, if encountered, may cross each other with rate a q. Both the lanes follow similar dynamical processes for the displacement of both types of progressing particles.

The positive (negative) particles enter from the left (right) end and exit from the right (left) end of the channel. In the bulk, a particle hops forward with a rate unity to the next site provided the target site is empty. At the empty entrance site, for both particles in either lane, a particle is injected with rate α provided the exit site of another lane is either empty or is occupied by the particle of similar type only. The particles exit both lanes with the same rate β, that does not depend on the configuration of the corresponding site on another lane. At each time step a lattice site (i, k); $i = 1, 2, 3, ..., N$, $k = A, B$, is chosen and random sequential update rules are adopted.

Following mean-field approach, we introduce p_k^i and m_k^i as average densities at the i-th site of the k-th channel for positive and negative particles, respectively and ignores particle spatial correlations to obtain

$$\begin{aligned} J_k^+ &= p_k^i(1 - p_k^{i+1} - (1-q)m_k^{i+1}), \\ J_k^- &= m_k^{i+1}(1 - m_k^i - (1-q)p_k^i), \end{aligned} \tag{1}$$

for $i = 1, 2, 3, ..., N-1$, where, $J_k^{\pm}$ are the position independent steady state bulk currents of the positive and negative particles, respectively, in k-th channel. In addition to the bulk currents, eight other equations for the currents at the boundaries are given by