A biased intruder in a dense quiescent medium: Looking beyond the force-velocity relation

Carlos Mejia Monasterio

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Abstract

I will survey our recent results obtained in collaboration with O. Bénichou and G. Oshanin on dynamics of a biased particle (biased intruder, BI) in a very dense molecular crowding environment modelled as a lattice gas of unbiased, randomly moving hard-core particles. Going beyond the usual analysis of the force-velocity relation (FVR), we will focus on the behaviour of the higher moments of the BI vector displacement $\mathbf{R}_n$ at time $n$ (the FVR is just the first moment). We will prove that in infinite two-dimensional systems the probability distribution $P(\mathbf{R}_n)$ converges to a Gaussian as $n \to \infty$, despite the fact that the BI drives the system into a non-equilibrium steady state with a non-homogeneous spatial distribution of the lattice gas particles. We will show that in two-dimensions $P(\mathbf{R}_n)$ broadens along the direction of the bias (weakly) super-diffusively: here the interplay between the bias, vacancy-controlled transport and the back-flow effects of the medium on the BI entails an accelerated growth of the variance, $\sigma_x^2 \sim \alpha_1 n \ln(n)$. In the perpendicular to the bias direction the variance $\sigma_y^2 \sim \alpha_2 n$. We determine $\alpha_1$ and $\alpha_2$ exactly for arbitrary bias, in the lowest order in the density of vacancies. Note that for small pulling forces $F$ the coefficient $\alpha_1 \sim F^2$ which signifies that such a behaviour emerges beyond the linear-response approximation. Further on, capitalising on our exact results, we will present analytical arguments showing that such an anomalous, field-induced broadening of fluctuations is dramatically enhanced in confined, quasi-1D geometries – infinite 2D stripes and 3D capillaries, which have applications in micro-fluidics. We predict that for such confined, dense molecular crowding environments the variance follows a strongly super-diffusive behaviour $\sigma_x^2 \sim n^{3/2}$. Monte Carlo simulations confirm our analytical results.