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Anomalous and KPZ spin dynamics in integrable spin chains from a hard rods gas

We introduce a multi-species generalization of the hard-rod gas in which each species has a distinct effective length, and the repulsive scattering shift is set by the minimal size of the colliding rods. This model has similar quasiparticle and scattering data to the XXZ model. We show that fixing only the functional decay of the bare velocities with rod length is sufficient for the model to reproduce the XXZ spin-transport phase diagram: spin diffusion with anomalous fluctuations in the anisotropic regime and superdiffusion at the isotropic point. We show that the statistics of the charge transfer is entirely different from that of particle trajectories. For long rods, the latter is Gaussian in the diffusive regime and KPZ at the isotropic point. This provides the first direct signature of KPZ physics in the microscopic motion of integrable quasiparticles. On the other hand, the statistic of charge transfer is anomalous in the anisotropic regime, while instead it becomes Gaussian at late times at the isotropic point, resolving the paradox between the presence of KPZ fluctuations and Gaussian statistics. Our results establish classical hard-rod dynamics as a minimal, yet quantitatively faithful, framework for anomalous spin and charge transport in integrable systems, and offer new insight into the origin of KPZ fluctuations in isotropic integrable models.