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Generalised hydrodynamics of optical soliton gases: measurement of correlations

Generalised Hydrodynamics (GHD) has proven successful to describe thermodynamics and hydrodynamics of integrable systems (See see Castro-Alvaredo, O. et al. Phys. Rev. X 6, 041065 (2016)). These systems present infinitely many constants of motion in involution and thus do not relax to a classical Gibbs Ensemble, but to a Generalised Gibbs Ensemble (GGE), taking into account all these constraints. GHD predicts the existence of ballistic two-point space-time correlations for the infinitely many conserved quantities of integrable systems. In particular, the mass $N = \int$
$lvert\psi(x,t)$
$rvert^2\,\mathrm{d}x$ in the focusing (attractive) Nonlinear Schrödinger Equation (fNLS) is conserved and its connected correlation at large scale takes the form:

\begin{equation}
t \,C(x, t) = t \, \langle\lvert\psi(x, t)\rvert^2\, \lvert\psi(0,0)\rvert^2\rangle_c = \int \,\textrm{d} \Re\eta\,\textrm{d}\Im\eta\, \delta(x/t - v^{\textrm{eff}}(\eta))\,\rho(\eta) \left(4\Im(\eta)^{\textrm{dr}}\right)^2
\end{equation}

where η refers to the complex eigenvalue of the Inverse Scattering Transform (or Bethe Ansatz) in fNLS, ρ is the density of state, v^{eff} the effective velocity of solitons, dr the dressing operator (see Koch, R. et al. Phys. A : Math. Theor. 55, 134001 (2022)). Solitons, as quasi-particles, propagate without changing their shape nor spectral parameters and with an effective velocity due to elastic collisions, giving these ballistic properties.

We present here our experimental results in a recirculating optical fibre loop (see Kraych A.E. et al. Phys. Rev. Lett. 122, 054101 (2019)) allowing measurements of these hydrodynamic correlations and of the density of state. The setup enables the propagation of arbitrary initial condition without much losses. At each roundtrip, the signal propagates inside \SI{5}{km} of standard optical fibre where losses are compensated globally by Raman amplification. We then extract 10% of this light to reconstruct the full field space-time dynamics through a heterodyne measurement system. Computing the intensity correlations naturally follows the reconstruction. We show that $C(x,t)$ does follow a polynomial law in $1/t$ with a coefficient that can be computed numerically from the previous formula.

With the same system, we explore other proofs that soliton gases relax to a GGE. In particular, it was predicted in [Bonnemain, T., Doyon, B. & El, G., J. Phys. A: Math. Theor.55 (2022)] that, because of the collisions, the gas undergoes an asymptotic change of metric: the solitons inside the gas perceives a different space than if they propagated freely. We show preliminary measurements of a soliton gas' asymptotic length.

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