Dynamics of the decay of dark solitons in superfluid Fermi gases

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Dark solitons in superfluid Bose gases have been observed to decay into vortices through the snake instability mechanism, unless they are strongly confined. Recent experiments in superfluid Fermi gases have also interpreted soliton decay via this mechanism. We show, however, using both numerical simulations and a perturbative analysis based on a low-energy effective field theory, that there is a significant change in the dynamics of the soliton decay across the BEC-BCS crossover of superfluid Fermi gases. We demonstrate that this transition is driven by a change in the nature of the fluctuations that characterize the unstable soliton mode.

Introduction

Solitons are solitary matter waves which retain their shape while propagating at a constant velocity. They emerge in a wide variety of physical systems, including superfluid quantum gases, where solitons often manifest themselves as localized dips in the background density, called *dark* solitons. In superfluid Bose gases, dark solitons have been observed to decay into vortices through the so-called snake instability mechanism [1], which is characterized by the onset of snake-like oscillations of the soliton's depletion plane. Recent studies in superfluid Fermi gases have also interpreted the soliton decay through this mechanism [2]. However, up until now, no studies have investigated the evolution of the decay process across the whole BEC-BCS interaction domain of a superfluid Fermi gas.

In recent work [3], we have investigated the dynamics of the soliton instability in the entire BEC-BCS crossover domain by means of a low-energy effective field theory [4], which has already been successfully applied to describe the properties and dynamics of stable, one-dimensional, solitons.

Methodology

Based on microscopic principles for the ultracold Fermi gas, we can derive an effective action functional for the superfluid order parameter Ψ, which represents the bosonic field of Cooper pairs that form the superfluid Fermi gas. To investigate the dynamics of the soliton instability, we use the non-linear equation of motion associated to this action functional to perform numerical simulations of the decay of a stationary dark soliton in a two-dimensional Fermi superfluid. Additionally, we also perform a linear stability analysis of the soliton by perturbing the stable, one-dimensional soliton solution and linearizing the equation of motion with respect to the perturbation field.

Main results

The numerical simulations of the soliton instability reveal that the dynamics of the soliton decay change significantly across the BEC-BCS interaction domain. In the BEC-regime, we observe how the decay is preceded by distinct snaking deformations of the soliton plane, which is a well-known phenomenon from superfluid Bose gases. In the BCS-regime, on the other hand, the soliton core simply dissolves into the resulting vortices, without the occurrence of a snaking pattern. The perturbative stability analysis demonstrates that this transition in the instability dynamics is related to a change in the nature of the fluctuations that contribute to the unstable mode. On the BEC-side of the interaction domain, the characteristic snaking deformations in the density are induced by fluctuations of the amplitude of the order parameter. On the BCS-side, on the other hand, the unstable mode is characterized solely by fluctuations of the phase of the order parameter, which disintegrate the soliton core through the formation of local Josephson currents without changing the soliton's position. The difference between these mechanisms should be experimentally observable, providing an incentive to consider both past and future studies from a new perspective.

References

[1] S. Donadello and S. Serafini and M. Tylutki and L. P. Pitaevskii and F. Dalfovo and G. Lamporesi and G. Ferrari, "Observation of Solitonic Vortices in Bose-Einstein Condensates", in *Phys. Rev. Lett.*, vol. 113, 065302 (2014).

[2] M. J. H. Ku and B. Mukherjee and T. Yefsah and M. W. Zwierlein, "Cascade of Solitonic Excitations in a Superfluid Fermi gas: From Planar Solitons to Vortex Rings and Lines", in *Phys. Rev. Lett.*, vol. 116, 045304 (2016).

[3] W. Van Alphen and H. Takeuchi and J. Tempere, "Crossover between snake instability and Josephson instability of dark solitons in superfluid Fermi gases", *arXiv:1901.10751* (2019).

[4] S. N. Klimin and J. Tempere and G. Lombardi and J. T. Devreese, "Finite temperature effective field theory and two-band superfluidity in Fermi gases", in *Eur. Phys. J. B*, vol. 88, 122 (2015).