Dynamics of vortices in spatially modulated superfluids

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Superfluids may exhibit spatial density modulations either because of an external potential or because the system is in a supersolid state. This is a topic of current interest, for instance, in the field of cold atoms. We have investigated bosonic systems, studying how the dynamics of a single vortex and of a vortex dipole is modified with respect to their behavior in a uniform superfluid.

We consider ^{87}Rb bosons at $T = 0$ K in a flat geometry under the influence of an external periodic potential, using Gross-Pitaevskii theory [1]. A single vortex excitation has an energy that depends on the position of its core. This energy is lowest where the density is minimal; hence, the equilibrium positions of a vortex coincide with the maxima of the external potential.

In a uniform superfluid, a vortex dipole, namely a pair of vortices with opposite chirality, is a stable excitation that moves with constant velocity. This is no longer true in a modulated superfluid. For a two-dimensional modulation, where the equilibrium positions of the vortices are isolated points, the vortices move mainly by jumping between equilibrium sites and approach each other until they annihilate within a short time. Since our theory includes neither thermal nor stochastic effects, these jumps are manifestations of vortex tunneling between equilibrium sites. This dynamics is very similar to that of a vortex dipole in a supersolid.

In the case of a one-dimensional modulation, where parallel density ridges are present, the equilibrium positions of a vortex are localized in the channels between ridges. The dynamics of the dipole depends on the positions of the two vortices. If they are in the same channel, the vortices approach each other until they annihilate within a short time. If they are in distinct channels, the dipole undergoes translation, with a velocity that depends on the intensity of the external potential and can even change sign with respect to the uniform-superfluid case. Superimposed on this translation, an oscillatory transverse motion is also present. This transverse motion is one-sided, in the sense that the vortex cores never cross the equilibrium positions nearest to their starting positions.

In the presence of a circular trap, an off-center single vortex undergoes uniform circular motion around the trap center. Also in this case, the vortex dynamics is quite different when a one-dimensional modulation is present: the motion is a superposition of translation along a channel and oscillation. This oscillatory motion can be either longitudinal, i.e., along the ridge, or transverse to it, depending on the geometry and on the initial state. In all cases, the transverse oscillatory motion is one-sided.

In conclusion, a vortex dipole can be a short-lived excitation in a spatially modulated superfluid, and a peculiar one-sided oscillatory motion can occur both for a single vortex and for a dipole.

References

[1] F. Ancilotto and L. Reatto, “Controlling quantum vortex dynamics and vortex-antivortex annihilation in Bose-Einstein condensates with optical lattices”, *Phys. Rev. A* **110**, 013302 (2024).