Rotating ultracold quantum gases *

A. Sedrakian and H. Warringa
Institut für Theoretische Physik, J. W. Goethe-Universität Frankfurt am Main, Germany

Rotating condensates of ultracold Bose or Fermi gases form vortex lattices above a critical rotation frequency. Such states were indeed observed in a number of experiments on superfluid bosonic and fermionic vapors confined to magnetic and/or optical traps. The measurements of the $l = 2$ modes are in good agreement with the theoretical predictions based on the coarse grained hydrodynamics. The studies of rotating condensates provide a useful testbed for exploring strongly correlated systems under rotation, due to the high experimental flexibility available in these systems. We anticipated insights from experiments for systems that are difficult or impossible to manipulate and/or observe. One such example are the rotating neutron stars containing strongly interacting condensates of nuclear and quark matter.

In our work [1] we use superfluid hydrodynamics to explore the rotational states and oscillations of *non-uniformly rotating* condensates. We concentrated on a special class of departures from rigid body rotation, which feature a constant condensate circulation in the frame rotating with the surface of the condensate. These states are supported by sufficiently dense mesh of quantum vortices, which guarantee the non-zero circulation in the laboratory frame. We have studied both the equilibrium structure of the condensates and their lowest order non-trivial $l = 2$ modes.

Within this set-up a new state of rotating, harmonically trapped, condensates of atomic clouds was found. The resulting equilibrium configurations are non-axisymmetric, and thus are a manifestation of the spontaneous symmetry breaking (SSB) in superfluid hydrodynamics (see Fig. 1). We have derived the complete set of $l = 2$ harmonic modes. Several experimental tests have been suggested, including the violation of the Feynman formula relating the rotation frequency to the number of quantized vortices, which can shed light on the structure and small amplitude oscillations of non-uniformly rotating clouds of Bose and Fermi condensates.

In Ref. [2] a two-component Fermi gas with attractive s-wave interactions, which forms a superfluid at low temperatures, was studied. When this gas is confined in a rotating trap, fermions can unpair at the edges of the gas and vortices can arise beyond certain critical rotation frequencies. We computed these critical rotation frequencies and constructed the phase diagram in the plane of scattering length and rotation frequency for different total numbers of particles. The calculations are performed in the Hartree-Fock-Bogoliubov approximation. We find that in the phase diagram three phases can be distinguished. For small rotation frequencies the entire gas forms a superfluid. At a certain critical frequency a second order transition occurs to a superfluid phase, which features unpaired fermions that are concentrated at the edges of the gas. At this critical rotation frequency the gas resides at a quantum critical point when the temperature vanishes. For even larger rotation frequencies vortices are formed via a first order transition.

* Work supported by the GSI-GU R&D project and EMMI.

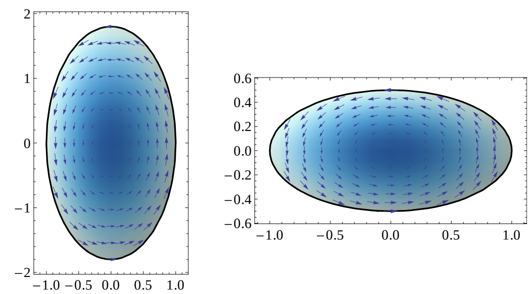

Figure 1: Illustration of the velocity vector field in the x-y plane for two possible solutions with SSB.The color coding reflects the Thomas-Fermi density distribution of the cloud.

The method of Ref. [2] was used in Ref. [3] to analyze numerically the phase diagram of a trapped, rotating, and weakly-interacting two-component Fermi gas including vortices. Detailed predictions were made for the conditions under which superfluidity with and without vortices is formed as a function of rotation frequency, scattering length, temperature, number of atoms and population imbalance. The phase diagram is quantitatively reliable and is in principle directly comparable to a possible future experimental determination. The analysis can be extended to more complicated systems, like Fermi gases with p-wave pairing, Fermi gases with more than two components, and Fermi gases in which the two components have unequal mass. This will be useful for the experimental search for superfluidity in such systems.

References

[1] A. Sedrakian, *Spontaneous symmetry breaking in rotating condensates of ultracold atoms.* Phys. Rev. A **86**, 051602(R) (2012).

[2] H. J. Warringa, A. Sedrakian, *Vortex formation in a rotating two-component Fermi gas.* Phys. Rev. A **84**, 023609 (2011).

[3] H. J. Warringa, *Location of the vortex phase in the phase diagram of a rotating two-component Fermi gas.* Phys. Rev. A **86**, 043615 (2012).