RESEARCH HIGHLIGHTS

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PHYSICS

Observing second sound in ultracold Fermi gases

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Water flowing down a pipe experiences viscous drag that causes it to lose energy and slow down. A superfluid, such as liquid helium (^{3}He and ^{4}He) or electrons in a superconductor, can flow without friction when in contact with a wall. This fascinating phenomenon, or superfluidity, was discovered by Kapitza [1], Allen and Misener [2] in 1937. The formation of a superfluid is related to the formation of a Bose–Einstein condensate (BEC). ^{4}He is a boson as its total spin is zero, an integer. Condensation in fermionic ^{3}He liquid occurs through composite bosons of paired atoms in a process similar to electron pairing in a superconductor.

To explain the peculiar properties of superfluid helium, Landau considered a superfluid to be comprised of two parts: a 'pure' superfluid component with zero entropy and viscosity, and a normal component that behaves like ordinary fluid. An interesting manifestation of this two-fluid model is the existence of two types of oscillations, the 'first and second sounds' as named by Landau. The 'first sound' is a wave that propagates at constant entropy per particle, just like sounds in ordinary fluids. It propagates with pressure and density oscillations. 'Second sound', unlike what its name suggests, is not audible as it propagates at nearly constant pressure (isobaric oscillation). Here, entropy density takes the role of pressure/density in normal sound waves.

Historically, the observation of the second sound in superfluid helium, and the measurement of its speed, played a crucial role in understanding the nature of superfluid helium. The speed of the second sound can be used to determine the superfluid fraction, i.e. the ratio of the superfluid density to the total fluid density [3,4].

In the past decades, the field of ultracold atomic gases has developed into a fertile ground for studying superfluid physics, as the inter-particle interactions between two atoms can be tuned using the so-called Fano–Feshbach resonances. Systematic studies on Fermi gases can be preformed in the limit of strong interactions, whose properties are difficult to predict but important to the understanding of strongly correlated quantum systems of many particles, such as high-temperature superconductors, quark–gluon plasmas and neutron stars.

Quantitative determination of the superfluid fraction in strongly interacting Fermi gases has been an elusive goal of scientists for many years, as the methods that allow the determination of the superfluid fraction in liquid helium cannot be directly applied to ultracold gases. For example, to excite the second sound in liquid helium, a local heat pulse can be created by passing a current through a heating wire submersed in the liquid. The heat pulse can then be detected at the other end of the liquid using a temperature sensitive sensor as illustrated in Fig. 1(a). Such methods cannot be implemented with ultracold atomic gas ensembles that typically contain only about hundreds of thousand atoms at μK (1 millionth of a kelvin) temperatures. Further adding to the difficulties, the propagation of the second sound in liquid helium usually

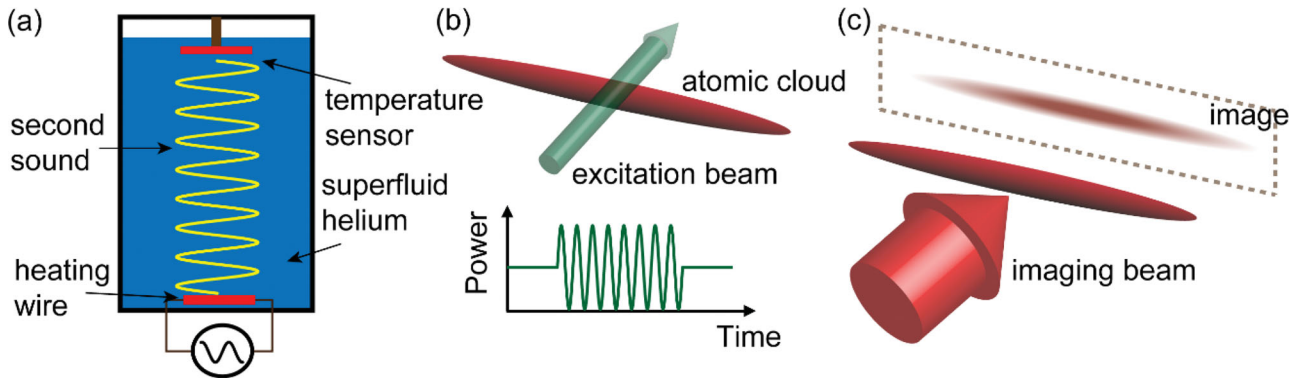

Figure 1. (a) Excitation and detection of the second sound in superfluid helium; (b) local heating through the power modulation of an excitation laser beam; (c) the detection of the second sound in a strongly interacting Fermi gas with direct absorption imaging.

involves no density variation/oscillation. This means that the second sound could not be detected easily with the absorption imaging technique typically used for probing cold atoms, assuming that the strongly interacting Fermi gases behave very much like strongly interacting bosonic liquid helium (^{4}He).

Recently, the group of Professor Rudolf Grimm from the University of Innsbruck (Austria), in collaboration with a theoretical team from the Trento University (Italy) led by Professors Sandro Stringari and Lev Pitaevskii, successfully measured the speed of second sound in a resonantly interacting Fermi gas using a simple and elegant method. Their results were published in [5]. To observe the second sound, the authors created a local heat pulse at the center of an elongated trapped gas by creating a short burst of modulation to the power of a light beam intercepting this gas (see Fig. 1b). They then measured the speed of the second sound by observing the movement of a thermal-induced density dip along the elongated gas (Fig. 1c). Taking advantage of the inhomogeneous density distributions of the superfluid atoms in the trap, they ingeniously determined the temperature dependence of the superfluid fraction without needing to vary the temperature of the samples.

The observation of the second sound in the strongly interacting Fermi gases opens up a new horizon for studying the superfluid properties with tunable interactions. Knowing the speed of second sound can provide a lot of valuable information, allowing physicists working on many-body theories to falsify their models and theories. It demonstrates the importance of using experimentally measured quantities, such as the equation of state employed here, to calibrate and to supplement theoretical investigations. Significant new advances will follow in the understanding of superfluidity of many strongly interacting particles, where faithful theoretical modeling and calculations are impossible at the microscopic level.

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PHYSICS

Successful Mn ions spin polarization in magnetic semiconductor at room temperature in a Co_2FeAl/(Ga,Mn)As bilayer

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Among the family of magnetic semiconductors (Ga,Mn)As is a promising material to manipulate spins in semiconductors and to realize the functionalities of storage, logic and communication on one chip. Some important spintronic functionalities based on (Ga,Mn)As have already been realized, including control of the Curie temperature (T_c) and magnetization using an electric field, spin injection into nonmagnetic semiconductors, tunneling magneto-resistance, electric current-induced magnetization reversal. However, these device operations were demonstrated far below room temperature. For practical applications, increasing T_c beyond room temperature is essential.

Professor Jianhua Zhao's research team at the Institute of Semiconductors, Chinese Academy of Sciences, has been exploring various routes to increase the T_c of (Ga,Mn)As films since 2003. In 2011, by combining a top-down nano-patterning technique with high Mn doping and low-temperature annealing, Professor Zhao and her collaborators successfully increased the T_c of (Ga,Mn)As to 200 K [1], the highest T_c of (Ga,Mn)As ever achieved. They then successfully synthesized all zinc-blende GaAs/(Ga,Mn)As core-shell nanowires with ferromagnetic ordering using the bottom-up approach of molecular-beam epitaxy [2,3].

Despite the T_c breakthrough to 200 K, this is still too low at well below room temperature. Professor Zhao's team and her collaborators in China and UK explored another method to further increase the T_c of (Ga,Mn)As. They investigated the magnetic proximity in bilayers consisting of (Ga,Mn)As and a half-metal, Heusler alloy Co_2FeAl. This alloy is a potentially suitable spintronic material with the desirable characteristics of high spin polarization, low Gilbert damping constant and high T_c. Unlike the typical antiferromagnetic interfacial interaction found in most ferromagnetic/magnetic semiconductor bilayers, a ferromagnetic interfacial interaction was observed in the Co_2FeAl/(Ga,Mn)As bilayer using magnetic hysteresis and X-ray magnetic circular dichroism measurements. The Mn ions in a 1.36-nm-thick (Ga,Mn)As layer remained spin polarized up to 400 K because of the magnetic proximity effect. The minor loops of the