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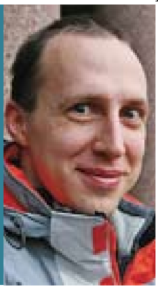
Superfluids, Superconductors and Supersolids:

Macroscopic Manifestations of the Microworld Laws

A superconductor is a state of matter in which electrons flow without resistance. A superfluid is a fluid devoid of viscosity. Superfluidity was first discovered in experiments on helium conducted by Petr Kapitsa in 1937. The lack of viscosity is a phenomenon which is highly counterintuitive from the point of view of the classical physics on which our intuition is based. This phenomenon has a quantum nature, i.e. it is related to the physics of the microworld, where particles are divided into two classes: bosons and fermions. One of the fundamental properties of bosons is that at a sufficiently low temperature, multiple boson particles can occupy the same quantum mechanical state, which results in a large number of them behaving in a coherent manner. Having a large number of particles 'conspire' to behave coherently is a prerequisite for superfluidity. It is precisely this type of collective behavior that makes it difficult for the system to dissipate energy. As a result, once you make such a liquid flow, the flow will essentially persist indefinitely, as opposed to the flow in a cup of tea which eventually stops some time after you stop stirring.



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My most important point is that particles in a superfluid or superconductor behave coherently, according to microworld laws. These systems involve very large numbers of particles. This essentially 'amplifies' the behavior of a single particle which obeys microworld laws, making its behavior manifest in the collective behavior of a liquid. The quantum mechanics aspect then manifests itself in the fact that the abovementioned dissipationless flows are not arbitrary but are subject to quantization. To illustrate this point, if you stir a cup of tea, you create an arbitrary vortex, be it large or small. However, you cannot create an arbitrarily small or an arbitrarily large vortex, and you cannot circulate a quantum fluid arbitrarily. Quantum fluids allow only a discrete number of vortices, and the discreteness is controlled by fundamental constants. Accordingly, superconductivity and superfluidity are *macroscopic* manifestations of microworld laws, i.e. they allow us to observe the laws of the microworld by watching flows in systems consisting of a large number of particles.

Experimental discoveries of new quantum fluids have therefore often had ramifications far beyond the physics of condensed matter. Notable examples are:

1) superconductivity in metals (1911);
2) superfluidity in 4He (1937);
3) superfluidity in 3He (1972);
4) high-Tc d-wave superconductivity in copper oxides (1986);
5) Bose-Einstein condensation of ultracold atomic vapors confined in traps (1995);
6) I should also mention recent experiments on *supersolidity* in 4He, which might add crystalline, poly-crystalline or glassy solids to the list of systems with superfluid properties, along with liquids, vapors and electrons in metals. The term 'supersolid' refers to a solid state of matter in which interior a fraction of particle density can move without friction, resulting in counterintuitive behavior. For example, some of the particles in a rotating supersolid do not rotate, but remain irrotational by slipping through the rotating crystalline lattice.

Because the 'super' state of matter is a macroscopic manifestation of microworld laws, most of these experimental discoveries required novel theoretical ideas for their interpretations. They have subsequently also inspired a number of correspondingly novel notions in other branches of physics. For example, the seminal work of Bardeen, Cooper, and Schrieffer provided a theory of conventional phonon-mediated superconductivity and influenced the appearance of the Nambu-Jona-Lasinio model which describes dynamical symmetry breaking in particle physics. The phase and spin degrees of freedom in neutral superfluids are naturally related to Goldstone bosons. The Higgs effect is a counterpart to the Meissner effect in superconductors, while the Nielsen-Olesen cosmic strings form counterparts to the Abrikosov vortices in superconductors. There are also numerous other examples of deep connections between physical phenomena which take place on macro- and micro-scales. This illustrates rather strikingly how Nature appears to employ similar principles on vastly different energy and length scales, and especially how experimental advances in condensed matter physics indirectly influence and inspire ideas relevant to other branches of physics.

The experimental discovery of Bose-Einstein condensation in atomic gases and recent reports of the possible experimental discovery of supersolidity (more than 40 years after its prediction) may have a special impact on theoretical condensed matter physics. In a sense, it will mark the first time that all the classes of predicted 'aggregate' super states of matter have been proven by experiment. It is therefore crucially important to raise the question of where we can expect further experimental advances in the field of quantum fluids to be made.

One possible candidate for a novel quantum fluid is hydrogen under extreme compression. Wigner, Ashcroft and others have predicted that under sufficient compression hydrogen should become a metal (i.e. the ultrahigh pressure can strip the protons in a hydrogen molecule from their accompanying electrons). Ashcroft also predicted that it might become a liquid metal at extremely low temperatures.

It is currently held that the interiors of Jupiter and Saturn are largely composed of liquid metallic hydrogen, which makes it the most abundant substance in our planetary system. In a terrestrial laboratory, hydrogen was metallized only at high compression and high temperatures [1], but current experiments aim at metallizing hydrogen at extremely low temperatures which is prerequisite for a state to form a quantum fluid.

Could liquid hydrogen be a novel quantum fluid?

To answer this question, we have to examine the quintessential state-defining properties of superfluids and superconductors, i.e. at their reactions to rotation or stirring or to the application of a magnetic field. If we (slowly) rotate a superfluid, a fraction of the system which is superfluid will not follow the rotation. At rotations exceeding a certain critical velocity, a superfluid forms vortices (tiny quantum tornadoes) with quantized circulation. Superconductors do not form vortices in response to rotation, but rather a dissipationless quantum fluid of electrons manifests itself as a property of the superconductor to expel the magnetic field. The reaction of the projected liquid metallic state of hydrogen to the application of a magnetic field was studied in [2,3,4]. Its reaction to a magnetic field was quite unexpected: it can drive the system from states with superconductivity (where charge flows have no resistance) and superfluidity (i.e. dissipationless mass transfer) to exclusively superconducting or exclusively superfluid states. Moreover, these states can be experimentally probed at extreme pressures [5].

As mentioned above, one hallmark of the quantum-ordered states is their non-classical response to rotation (i.e. when the reaction to the rotation or stirring of a solid or a liquid contradicts the behavior expected by classical physics). The rotational responses of all currently known 'super' states of matter (superconductors, superfluids and supersolids) are largely described by two fundamental principles that are more than half-century old, and they fall into two categories according to whether the systems are composed of charged or neutral particles. A superconductor (i.e. a system composed of electrically charged particles) obeys the London law, which relates the angular velocity to a subsequently established magnetic field that depends on fundamental constants alone and does not depend on any details of the microscopic physics of a superconductor. Superfluids obey the Onsager–Feynman quantization of superfluid velocity, i.e. that a superfluid can only react to stirring by creating quantum vortices with quantized circulation. A recent publication [6] states that these laws will be violated in the projected liquid metallic states of hydrogen and deuterium. The predicted rotational response of the quantum state of liquid metallic hydrogen will be highly complex, involving a counterintuitive situation in response to stirring a fraction of the particle density to flow in the direction opposite to that of the stirring. Imagine, if you would, a cup of tea that you stir with a spoon. Classical physics would expect the tea to flow in the same direction as that of the stirring. However, quantum effects cause the opposite to be the case in projected liquid metallic hydrogen: stirring in one direction will make protons flow in the direction *opposite* to that of stirring. Since the reaction to a magnetic field and the rotational response are quintessentially state-defining properties of quantum fluids, the above results suggest a classification of the projected liquid state of metallic hydrogen as a new class of quantum fluids, which can be a projected new state of matter awaiting an experimental discovery.

Experimental discoveries of superfluids and superconductors teach us about more than just the physics of the microworld. In medicine, most of today's MRI scanners are based on superconducting magnets. Many exciting applications for quantum fluids were suggested recently, including precision instruments such as highly accurate navigation, superfluid gyroscopes and accelerometers. It may also be possible to use quantum fluids for radically new computational devices, e.g. quantum computers. Moreover, it has been discussed whether it might be possible to perform quantum computations with quantum vortices, similar to the above-mentioned vortices which form in a quantum fluids in response to rotation.

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