Electrons in concert: A simple probe for collective motion in ultracold plasmas

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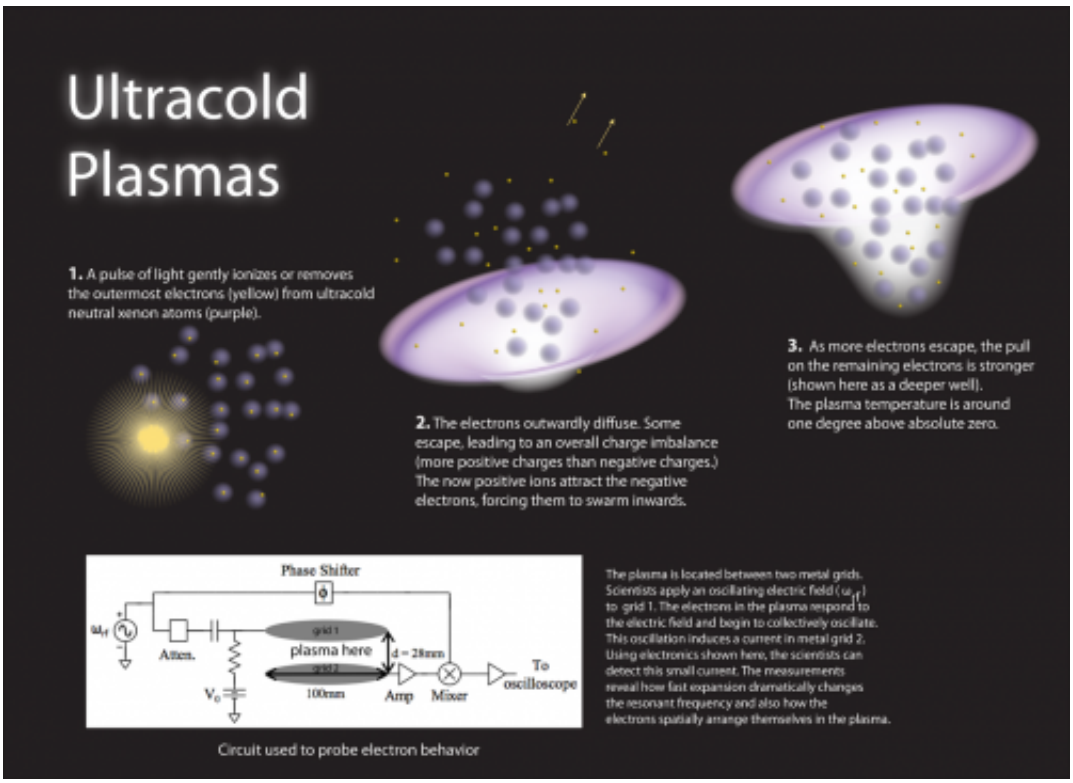

Image credit: E. Edwards; circuit diagram courtesy of authors.

(PhysOrg.com) -- Collective, or coordinated behavior is routine in liquids, where waves can occur as atoms act together. In a milliliter (mL) of liquid water, 10^{22} molecules bob around, colliding. When a breeze passes by, waves can form across the surface. These waves are not present in the same volume of air, where only 10^{19} gas molecules

randomly move about.

Do such waves occur in plasmas, the most prevalent state of matter in the universe? Like gases, they are made of particles bumping around in a shapeless glob. However, plasma densities can range from 10^{26} atom/mL all the way down to much less than 1 atom/mL. Wave-like features that occur even at such miniscule densities are one key feature of plasmas.

Unlike in liquids, these "waves" happen in plasmas because the particles are charged, thus exerting strong forces on each other, even at large distances. But not all seas of charged particles are plasmas. What makes a plasma a plasma is the organized behavior of the charged particles.

Plasmas are found inside the sun, gas-giant planets like Jupiter, the aurora borealis, and those compact fluorescent lights we see everywhere. These plasmas are all hot with the sun's plasma reaching a temperature of 10^7 Kelvin. Plasmas can also exist at the other extreme in temperature, near absolute zero. Recently, JQI researchers devised a way to directly probe the collective motion of electrons found in these ultracold plasmas (UCPs).*

In this experiment, researchers create ultracold plasmas using laser-cooled atoms found in magneto-optical traps (MOTs). Xenon atoms are cooled to around ten millionths of a degree above absolute zero. The ultracold cloud of neutral atoms is then "delicately" blasted with an energetic laser pulse. The pulse of light strips electrons from the neutral atoms, leaving behind positively charged ions. The energy of the pulse is chosen to ensure a gentle ionizing process, thus preserving the cloud's cold temperature.

The liberated electrons begin to migrate away from the ions. Some get away, but it is their freedom from the cloud that sabotages the escape of remaining electrons. The ions are heavy and cold, and thus move slowly.

Because more electrons than ions have left the cloud, there is an overall electrical charge imbalance. The positive ions left behind begin to exert an attractive force on the outwardly diffusing negative electrons. These electrons cannot escape and swarm back around the ions, forming a UCP with a density that ranges between 10^5 and 10^{10} atoms/mL.

Although plasmas are commonplace in nature, studying them can be challenging. Like other ultracold atomic physics experiments that are analogs for condensed matter systems, UCPs can be a platform for investigating plasma physics. While not all plasmas exhibit the same universal properties, UCPs share characteristics with other important plasmas.

The physics of UCPs, for example, overlaps with that of laser-created plasmas, such as those generated in fusion-reaction research at the National Ignition Facility. This facility, located at Lawrence Livermore National Laboratory, is home to the most powerful laser system in the world. During laser fusion experiments, plasmas form with densities and temperatures comparable or exceeding those of sun plasma. Scientists also expect that UCPs share dynamics with astrophysical systems like globular star clusters.

Ultracold plasmas are isolated in a vacuum and relatively simple to create. Yet they are small and fragile, lasting only hundreds of microseconds. Scientists typically measure their properties indirectly, by looking at electrons that depart the plasma. JQI researcher Kevin Twedt and Fellow Steven Rolston have recently devised a simple way to directly probe the electrons in these plasmas.*

An important collective behavior of the plasma comes in the form of electron oscillations that occur at a specific resonant frequency. These ultracold plasmas as a whole are mostly neutral (ion charge cancels electron charge), but the countless electrons within this matter conduct

electricity. In other words, plasmas respond to electric fields. The electrons will move in concert when subjected to an electric field that oscillates at particular frequencies.

In this experiment, the xenon plasma is situated (in free space) between two metal grids. The scientists apply an oscillating radiofrequency field to one of the grids. If there were no plasma, then the oscillating field would produce no change in the signal measured at the other grid. When the plasma is present, the oscillating field excites the collective electron motion, which is like creating a wave. This electron motion induces a small current in the opposing grid. The tiny current can be extracted using sensitive electronics. In this way the researchers can probe the collective behavior of the plasma while it is expanding and changing. The measurements reveal how fast expansion dramatically changes the resonant frequency and also how the electrons spatially arrange themselves in the plasma.

Research in UCPs has also led to other applications outside of plasma physics. Scientists at the National Institute of Standards and Technology (NIST) create a beam of charged particles by ionizing neutral atoms held in a MOT. This beam, in turn, could be used to improve nanofabrication and imaging of biological systems.

UCPs also offer a way to study Rydberg atoms. These atoms have an outer electron that is so excited it is nearly removed entirely from the atom. Within the plasma, electrons and ions can recombine to form Rydberg atoms. Alternatively, scientists can purposely create Rydberg atoms by tuning the photoionization laser just below the threshold necessary for making a plasma. The electrons are barely attached to their parent atoms. These systems will spontaneously decay into a plasma as the atoms lose their tenuously held outer electrons.

Kevin Twedt explains, “Understanding the back and forth between

Rydberg atoms and an UCP may help researchers trying to use Rydberg atoms in quantum information and for the study of quantum many-body physics. These processes also highlight the fascinating aspects of a system literally on the border between atomic physics, with electrons and ions just barely bound together as Rydberg atoms, and plasma physics, with electrons and ions just barely separated in an ultracold plasma."

More information: *"Electronic detection of collective modes of an ultracold plasma," K. A. Twedt and S. L. Rolston, Forthcoming in Physical Review Letters.

More Reading:

"Ultracold neutral plasmas," Thomas C. Killian and Steven L. Rolston, *Physics Today* 63, 46 (2010)

"Trend: Ultracold neutral plasmas," Steven L. Rolston, *Physics* 1, 2 (2008)

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