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Editorial

Topical issue on "Ultracold plasmas and cold Rydberg atoms"

Following the international workshop "Ultracold PARYS" on "Ultracold Plasma and Rydberg Systems" (14–16 March 2005, at Gif-sur-Yvette, France, `http://www.lac.u-psud.fr/LAC/PARYS/PARYS4.htm`), the participants proposed a focussed collection of regular articles in a scientific publication, to increase the visibility of this novel research subject. Containing nine original articles, this topical issue explores the frontier between ultra-cold Rydberg gases and plasmas. This covers the fields of cold Rydberg atoms and ultracold plasmas (experiment and theory), including the ionization processes in cold Rydberg gases; Rydberg atoms or ions in an atomic Bose-Einstein condensate; and back and forth evolution from a Rydberg gas to a plasma. This issue also examines the long-range interaction between Rydberg atoms and its application to quantum information and Rydberg photoassociation, as well as quantum hopping in Rydberg lattices, the manipulation of Rydberg species (atoms or molecules) in external fields, etc. The impact of ultracold plasmas in plasma physics is considered, especially with strongly coupled plasmas and crystallization.

Advances in cooling and trapping of neutral atoms have paved the way towards a new class of experiments with ultracold ($T \ll 1$ K) atomic or molecular systems. Along these lines, the exploration of ultracold Rydberg gases and ultracold plasmas reveals interesting and unexpected behaviour. A new type of plasma is produced by threshold photoionization of cold trapped atoms, and is characterized by an ultra-low temperature and an intermediate density (electron temperature < 100 K, ion temperature < 1 K, density $\approx 10^{10}$ cm^{-3}). The electron temperature can be controlled by varying the frequency of the ionizing laser, whereas the initial temperature of the ions matches that of the original cold atoms. By tuning the excitation laser just below the ionization threshold, cold trapped atoms can be excited into Rydberg states of high principal quantum number. This leads to the formation of a closely related system, referred to as a cold Rydberg gas. Under conditions of sufficiently high density, ionization can occur spontaneously in a cold Rydberg gas, leading to plasma formation. Rydberg gases and ultracold plasmas attract strong theoretical interest as they represent intriguing systems to study using both semiclassical and quantum dynamics of strongly interacting many-body systems. The theories developed to describe these systems have important similarities with the models of star cluster formation.

In a dilute gas, Rydberg atoms can interact at very large distances ($\sim\mu$m), and collective effects become apparent. Resonant energy transfer induced by dipole interactions appears analogous to the migration of an exciton in an amorphous solid. Förster resonances, which play an important role in energy transport in biological systems, can be studied under well-controlled conditions in a cold Rydberg gas. Complex quantum systems can be studied and controlled by tuning the interaction (density and principal quantum number n of the Rydberg states), including entanglement. Several computational schemes have been suggested, using a regime of "dipole blockade" to drive the atomic system into single excited collective atomic state or to implement two-bit quantum gates. Cold Rydberg gases are ideal systems for experimental study of phenomena that for regular atoms would be in the domain of nanophysics.

The field of research described here is in its infancy. Some of the important next steps will include developments in the measurement of plasma temperature, the production of molecular cold-Rydberg systems, and the creation of plasmas of two-valence-electron atoms (such as alkaline earth atoms). In the latter case, the corresponding one-electron ions will be readily detectable in imaging studies and can be laser cooled. The detailed characterization of ionization processes (occurring through Rydberg-Rydberg collisions, electron-Rydberg collisions, or photoionization by black body radiation) and the role of super-elastic collisions in a cold atomic or molecular Rydberg sample is required for understanding the frontier with ultra-cold plasmas. Recombination processes from a strongly coupled plasma into a Rydberg gas and vice versa are of direct relevance to the formation, detection and possible destruction of cold anti-hydrogen which is currently produced at CERN from a merged ensemble of trapped positrons and antiprotons. Ions in a cold Rydberg ensemble offer opportunities to control quantum effects such as quantum hopping on a Rydberg lattice, which would have similarities with plasmon hopping in a metallic nanostructure. Laser induced photo-association can be used to form ultra long-range Rydberg molecular states consisting of two weakly bound Rydberg atoms or a ground state atom bound to a Rydberg atom ("trilobite molecules"). A challenge is to reach the plasma correlated regime where the Coulomb energy dominates the kinetic energy, leading to crystallization of the system, as has been observed for trapped ions.

Several novel directions of research have begun to be investigated. The role of Rydberg atoms or ions in a Bose-Einstein condensate (BEC) represents another new and exciting area of research. An ionic defect within the condensate produces a localized modification of the macroscopic condensate wavefunction. In an applied field, the huge electric dipole moments of Rydberg atoms/molecules permits their manipulation with time-dependent electric field gradients. The development of a Stark decelerator for Rydberg species (atoms or molecules) from a supersonic beam can provide a new tool to prepare cold samples of a large variety of atoms and molecules. Ultracold plasmas could provide a very bright source of electron bunches, acting as a time-resolved probe for solid-liquid phase transitions of surfaces heated by ultrafast lasers and for observing transient structures in femtosecond chemistry. In addition, well-localized samples of Rydberg atoms serve as sensitive micro-probes for thermal or THz radiation.

The above list of possible studies in the field of "ultracold plasmas and cold Rydberg atoms" is not exhaustive. This introduction reports a few elements extracted from in-depth analysis carried out by the European and International communities of physicists. This is a field where, we are confident, demonstrations of novel and fascinating phenomena are expected in the near future.

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