From laser cooled atoms to an ultracold neutral plasma

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The work presented here resides at the interface of atomic and plasma physics: we demonstrate the creation of an ultracold neutral plasma by photoionization of laser cooled atoms. Using plasma oscillations, we show that under classical plasma conditions of weakly interacting particles, the expansion of the plasma is well described by a hydrodynamic model. At high density and low temperatures, when the thermal energy of the particles is less than their Coulomb interaction energy, the discrepancies between the model and the observations may be attributed to strong coupling effects.

In practice, we photoionize atoms that were laser cooled to about $10\,\mu$K, via a two-photon transition. Because of the small electron-ion mass ratio, the resulting electrons have an initial kinetic energy, E_e, approximately equal to the difference between the photon energy and the ionization potential. In our studies we vary E_e/k_B between 100 mK and 1000 K, and the initial kinetic energy of the ion ranges between $10\,\mu$K and 4 mK. We detect charged particles as well as neutral atoms, which allows us to determine the number of atoms photoionized and also the density of the sample. Typically, we ionize 10-15% of the atoms which yields initial plasma densities between 10^5 and $10^9\,\mathrm{cm}^{-3}$.

Fig. 1a shows the electron signals from an ultracold neutral plasma created by photoionization at time $t = 0$. Some electrons leave the sample and arrive at the detector at about $1\,\mu$s, producing a first peak in the signal. The resulting excess positive charge in the plasma creates a Coulomb potential well in which the remaining electrons are trapped. Up to 99% of the electrons can be trapped. As the plasma expands, the depth of the Coulomb well decreases, allowing the remaining electrons to leave the trap. This explains the broad peak at $\approx 25\,\mu$s. We find a threshold behaviour, that quantifies the competition between the kinetic energy of the electrons and the Coulomb attraction between electrons and ions.

In the ultracold plasma the density is nonuniform and it changes in time. A probe of the density is thus necessary for many future experiments, such as the determination of the three-body recombination rate at low temperature, and the observation of strong coupling effects in this two-component system. Plasma oscillations, in which electrons oscillate around their equilibrium positions and ions are essentially stationary, are a valuable diagnostic of ionized gases. The frequency of these oscillations only depends on the electron density. We excite this collective mode in the ultracold plasma [2] by applying a radio frequency (rf) electric field. An additional peak appears in the electron signal (Fig. 1a), which we relate to resonant excitation of electrons in regions of the appropriate density. We observe a response at frequencies from 1 to 250 MHz, which corresponds to resonant densities n_r between $1 \times 10^4\,\mathrm{cm}^{-3}$ and $8 \times 10^8\,\mathrm{cm}^{-3}$. Using plasma oscillations we map the density evolution of our ultracold system: as the plasma

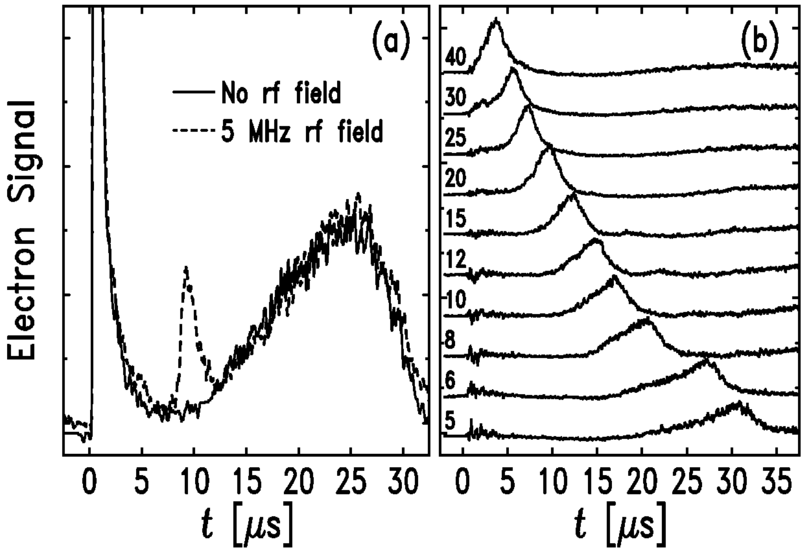

Figure 1: Electron signals from ultracold plasmas. Photoionization occurs at time $t = 0$. (a) 3×10^4 atoms are photoionized and $E_e/k_B = 540\,\mathrm{K}$. Signals with and without rf field are shown. (b) 8×10^4 atoms are photoionized and $E_e/k_B = 26\,\mathrm{K}$. For each trace, the rf frequency in MHz is indicated, and the nonresonant response has been subtracted. The signals have been offset for clarity. The resonant response arrives later for lower frequency, reflecting expansion of the plasma.

expands, the resonant response peak arrives at later times for lower rf frequency (Fig. 1b). For conditions of $E_e \geq 70$ the expansion of the ionized sample occurs at a rate determined by the initial kinetic energy of the electrons and is described by a hydrodynamic model. For lower E_e, when correlations between the particles may become important, electrons and ions expand more rapidly.

The ultracold plasma can also be obtained during a phase transition from a dense gas of highly excited, cold Rydberg atoms. This may be analog to the Mott insulator-conductor transition, and we present preliminary results of such studies [3].

[1] T. C. Killian, S. Kulin, S. D. Bergeson, L. A. Orozco, C. Orzel, and S. L. Rolston, Phys. Rev. Lett. **83** 4776 (1999).

[2] S. Kulin, T.C. Killian, S.D. Bergeson, and S. L. Rolston, submitted

[3] S. Kulin, T. C. Killian, S. D. Bergeson, L. A. Orozco, C. Orzel, and S. L. Rolston, in *Non-Neutral Plasma Physics III*, edited by J. J. Bollinger, R. L. Spencer, and R. C. Davidson (American Institute of Physics, New York, 1999) p. 367.