Expansion and Equilibration of Ultracold Neutral Plasmas

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Access Ultracold Temperatures with Laser Cooled Strontium

d~1mm, N~10^8, n~10^{10}\text{cm}^{-3}, T \sim 1 \text{ mK}
Creation of an Ultracold Neutral Plasma through Photoionization

Photoionization 412 nm

$^1P_1$

$^1S_0$

Cooling 461 nm

Ground State

Ionization Potential

Rydberg Levels

Ground State

$^1S_0$

$^1P_1$
Initial electron kinetic energy, $E_e$, equals excess photon energy (1-1000 K)

- Ions created with mK energies
- Ultracold neutral plasma!
Ultracold Neutral Plasma Interest

Classical plasma physics
- Expansion
- Collective modes
- Recombination
- Ion-electron-atom collisions

Strongly coupled Coulomb systems
- Two-component plasmas
- Equilibration and correlations
- Thermal transport

High energy density and warm dense matter physics
- Laser-produced plasmas
- Similar dynamics

Applications
- Bright charged-particle beams

Surprises?
Neutral Plasmas

The diagram illustrates the relationship between temperature (in Kelvin) and number density (charged particles per cubic meter) for various plasma environments. It shows a range from interstellar space at low temperatures and densities, to auroras, flames, and neon signs at higher temperatures and densities, and finally to the solar corona and solar core at the highest temperatures and densities.

Key features include:
- Magnetic fusion reactor
- Inertial confinement fusion
- Solids, liquids, and gases, too cool and dense for classical plasmas to exist.

The diagram highlights the diversity of plasma states found in nature and technology, from the vastness of interstellar space to the intense conditions of the solar core.
Neutral Plasmas

Strongly-Coupled Plasmas

\[ \Gamma = \frac{e^2}{4\pi\varepsilon_0 a} / k_B T > 1 \]
At $t=0$: Just after photoionization, the plasma is neutral everywhere and the potential is flat.
At $t_1 \sim 10\text{ns}$: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.
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Model for Plasma Creation

At $\tau_2 \sim 1-10\mu$s:
- Ultracold plasma
- Neutral in center

$\lambda_D \sim 10\mu m < \sigma \sim 1\text{mm}$
At $t_2 > 10\mu s$: Ions cloud expands.
Coulomb well depth increases.
At $t_2 > 10\mu s$: Ions cloud expands. Coulomb well depth decreases.
At $t > 10\mu s$: Electrons can escape
At $t_2 > 10\mu s$: Electrons can escape, or be dragged out by residual electric fields.
Absorption Imaging

422 nm laser

plasma

false-color camera image

Simien et al., PRL 2004
Image of Plasma Expansion

A 0.8 μs

B 20.9 μs

C 50.9 μs
Expansion of Other Plasmas

Inertial confinement fusion experiments

Short pulse irradiation of solid targets
Expansion of the Plasma

Expansion is driven by the pressure of the electron gas

electrons

ions
Exact Solution to the Vlasov Equations

\[ \vec{u}_i (r, t) \approx \hat{r} \frac{r k_B T_e (0)}{m_i \sigma_i^2 (t)} t \]

\[ \vec{u}(\vec{r}) = \langle \vec{v}_{a} (\vec{r}) \rangle \]

\( t \) is time since photoionization

This is not a heating of the ions.

Heating is an increase in \( \langle (\vec{v}_i - \vec{u}_i)^2 \rangle \).
Terminal Velocity

with T. Pohl

- Expansion reaches terminal velocity when all electron energy has been transferred to radial ion motion.

- Electrons cool adiabatically.

\[ v_{i,\text{final}} = \sqrt{\frac{k_B T_e(0)}{m_i}} \]
Theory predicts a self-similar Gaussian expansion for a neutral plasma

\[ n(r, t) = \frac{N}{(2\pi)^{3/2} \sigma^3(t)} \exp \left[ -\frac{r^2}{2\sigma^2(t)} \right] \]
Self-Similar Gaussian Expansion

cross-section

Laha et al., PRL 2007
Limits of the Validity of the Exact Solution for the Expansion with T. Pohl

collisionless, exact solution

\[ \Gamma_e (K) \]

\[ 10^0 \]

\[ 10^1 \]

ion expansion energy

initial electron energy

colder and denser electrons
Plasma Ion Absorption Spectrum

Vary frequency of imaging laser beam
Doppler Broadening

spectral linewidth measures the ion velocity and temperature

\[ \sigma_D \propto \sqrt{\langle v_z^2 \rangle} \]

typical velocity along laser direction

cold hot
Rapid Heating of the Ions

Disorder-induced heating

Ion Kinetic Energy (K)

Time After Photoionization (ns)

Potential energy

Position

hot

cold
Rapid Heating of the Ions

Ion Kinetic Energy (K)

\[ k_B T_{\text{Coulomb}} = \frac{e^2}{4\pi\varepsilon_0 a} \]

\[ \tau \approx \sqrt{\frac{\varepsilon_0 m_i}{n e^2}} = \omega_{pi}^{-1} \]

Time After Photoionization (ns)

Position

Potential energy
Disorder-induced heating

Strongly Coupled?

\[ \Gamma_{\text{ion}} \approx 2.5 \]

\[ \Gamma = \frac{e^2}{4\pi \varepsilon_0 \varepsilon a} / k_B T > 1 \]
Disorder-Induced Heating = Strong Coupling

- Ion Temperature (K)
- Disorder
- Induced Heating = Strong Coupling
- Ion Kinetic Energy (K)
- Time
- Position
- Potential Energy
- Time
- Hot
- Cold
Strongly Coupled Plasmas

Jupiter interior

\[ \Gamma = \frac{e^2}{4\pi \varepsilon_0 a} / k_B T > 1 \]

Wigner crystals of trapped ions (NIST, Boulder)

Ions in an Ultracold Neutral Plasmas

Dusty plasma crystals (Taiwan)
Kinetic Energy Oscillations: Heavily Damped Ion Plasma Oscillation

\[ \omega_{pi} = \sqrt{\frac{ne^2}{m_i \varepsilon_0}} \]

- Electrostatic
- Kinetic
- Potential energy
- Position
- Time

Ion Kinetic Energy (K)

Time After Photoionization (ns)
Equilibration and Oscillations in Other Systems

- Inertial confinement fusion experiments
- Fast pulse irradiation of solid targets
- Fast pulse ionization of clusters
We are interested in the long-time ion dynamics:

- Global Equilibrium, heat transport
- Ion adiabatic cooling
- Stronger ion Coulomb coupling

\[ k_B T_i \approx \frac{e^2}{4\pi\varepsilon_0 a} \]

Higher density means higher equilibrium temperature.

Pohl, Pattard, and Rost, PRL 92, 155003 (2004)
Fluorescence Imaging Separates Expansion from Thermal Motion

422 nm laser

plasma

imaging optics

1 mm
Ion Temperature at Later Times

Expected from electron-ion thermalization and adiabatic cooling

Observed temperature, excess heating

Adiabatic cooling

Disorder-induced heating

Expected from electron-ion thermalization and adiabatic cooling
Anomalous Heating Rate

Heating rate:
Weak or no density dependence
Linear with $T_e$
Conclusions

- Ultracold neutral plasmas
  - New regime
  - Great experimental control and diagnostics
  - Strong coupling - ion equilibration, screening, kinetic energy oscillations
  - Dynamics of the expansion, recombination, electron oscillations

- Future plans
  - Spatially resolve collective modes, shock waves
  - Strongly coupled electrons and ions
  - Thermal transport in strongly coupled systems
  - Magnetic confinement, laser-cooling ions
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