Studying Equilibration in Strongly Coupled Plasmas with Pump-Probe LIF

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Ultracold Atoms and Plasmas
Rice University Laboratory for Ultracold Physics
RICE
Laser-Aided Plasma Diagnostics
University of Wisconsin
2013

National Science Foundation
Excellent Science Attractive Energy
Office of Fusion Energy Sciences
U.S. Air Force
Matter Under Extremely Cold Conditions

Absolute Temperature Scale (K):

- 1,000,000 K
- 10,000 K
- 100 K
- 1 K
- 10 mK
- 100 μK
- 1 μK
- 10 nK

High Energy-Density

Ultracold neutral plasma

Laser cooling; quantum world
Outline

- Strontium ultracold plasma intro
- LIF imaging and spectroscopy
- Collisional equilibration in a strongly coupled plasma
Laser Cooled Strontium Atoms

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
  - 10 ns pulse dye laser
- Cooling
  - 461 nm
- Ionization Potential
- Rydberg Levels
- Ground State
- Initial electron kinetic energy, $E_e$, equals excess photon energy (1-1000 K)
- Ions created with mK energies
- Gaussian, mm-sized, density distribution, $n_{peak} = 10^{10} \text{cm}^{-3}$
At $t=0$: Just after photoionization, the plasma is neutral everywhere and the potential is flat.
At $t_1 \sim 10$ns: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.
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At $t_1 \sim 10\text{ns}$: Electrons escape due to their kinetic energy and a charge imbalance builds up until electrons are trapped.
Model for Plasma Creation

At $t_2 \sim 1-10\mu s$: Ultracold plasma neutral in center
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.
Model for Plasma Creation

At $t_2 > 10\mu$s: Electrons can escape
Model for Plasma Creation

At $t_2 > 10 \mu s$: Electrons can escape, or be dragged out by residual electric fields.
Basic Dynamics

\[ \tau_e \approx \frac{1}{\sqrt{\frac{ne^2}{\varepsilon_0 m_e}}} \approx \frac{1}{\omega_{pe}} \]

\[ \tau_i \approx \frac{1}{\sqrt{\frac{ne^2}{\varepsilon_0 m_i}}} \approx \frac{1}{\omega_{pi}} \]

\[ \tau_H \approx \frac{\sigma}{\sqrt{\frac{k_B(T_e + T_i)}{m_i}}} \]

- electron equilibration
- ion equilibration
- plasma expansion

0 \quad \sim 10 \text{ ns} \quad \sim 1 \mu \text{s} \quad \sim 100 \mu \text{s} \quad \text{time after photoionization}
Strongly Coupled or Non-Ideal Plasmas

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

Wigner crystals of trapped ions

Dusty plasma crystals

Intense-laser experiments

Ions in an Ultracold Neutral Plasmas
Ultradense Neutral Plasma Research

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

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

Connections to high-energy-density/warm-dense-matter physics
- Laser-produced plasmas
- Similar dynamics

Applications
- Bright charged-particle beams

Surprises?
Laser-Induced Fluorescence Imaging and Spectroscopy

422 nm LIF laser

plasma

imaging optics

image recorded on an intensified CCD camera
Fluorescence Image of Plasma Expansion
Sculpting the Density Distribution
Creating a Plasma Gap
Hydrodynamic Gap Splitting and Localized Sound Propagation
Spectroscopic Measure of Ion Velocities

Absorption (arbitrary units) vs. Image beam detuning (MHz)

Vary frequency of imaging laser beam
Doppler Broadening: 1-D Velocity Distribution

- spectrum approximately equals the velocity distribution

- spectral linewidth measures the ion velocity and temperature

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

typical velocity along laser direction

[Graphs showing cold and hot velocity distributions]
Disorder-Induced Heating and Ion Strong Coupling

\[ \Gamma_{ion} \approx 2 \]

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

Ion Temperature (K)

Time After Photoionization (ns)

disorder-induced or correlation heating

Gammatime
Kinetic Energy Oscillations in Resolved Regions of the Plasma

\[ \omega_{Pi} = \sqrt{\frac{ne^2}{\varepsilon_0 m_i}} \]
Collision Rates in Dense, Strongly Coupled Systems

Inertial confinement fusion experiments


X-ray scattering, Riley, et al. PRL, 2000

Short pulse irradiation of solid targets

Optical emission, Celliers, Ng et al. PRL, 1992
Landau-Spitzer Collision Rate

- Landau-Spitzer derivation of collision rates: thermalization, equipartition, conductivity, diffusion, etc.
- Dominance of weak, long-range ion-ion interactions.

\[ \gamma_{da} = \gamma_{damping} \propto \frac{n}{v^3} \ln \Lambda \]

\[ n = \propto \omega_{pi} \Gamma^{3/2} \ln \Lambda \]

\[ \ln \Lambda = \ln \left( \frac{b_{\text{max}}}{b_{\text{min}}} \right) \]

\[ b_{\text{max}} = \text{Debye shielding length} \]

\[ \lambda_D = \sqrt{\varepsilon_0 k_B T_i / n e^2} \]

\[ b_{\text{min}} = \text{Landau length} \]

\[ = e^2 / 4\pi\varepsilon_0 k_B T \]
Collision Rate for $\Gamma > 1$

- Spitzer-Landau derivation assumes dominance of weak, long-range interactions.

$$\gamma_{\text{damping}} \propto \omega_{pi} \Gamma^{3/2} \ln \Lambda$$

$$\Gamma = \frac{e^2}{4\pi \epsilon_0 a} / k_B T \quad \Lambda \propto 1 / \Gamma^{3/2}$$

- For $\Gamma \geq 1$, the formula becomes invalid and diverges.
Collision Rate for $\Gamma > 1$

- Spitzer-Landau derivation assumes dominance of weak, long-range interactions.

\[ \Gamma \sim \frac{e^2}{4\pi \varepsilon_0 a} / k_B T \quad \Lambda \sim 1 / \Gamma^{3/2} \]

\[ \ln \Lambda = \ln \left( \frac{b_{\text{max}}}{b_{\text{min}}} \right) \]

- For $\Gamma \sim$, the formula becomes invalid and diverges.
- Strong, short-range collisions dominate; mode coupling, dynamic screening, etc. may contribute too.
- Can be probed with directly in ultracold neutral plasmas.
## Extending Landau-Spitzer into the Strongly Coupled Regime

<table>
<thead>
<tr>
<th>Expression</th>
<th>$b_{\text{max}}$</th>
<th>$b_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln \Lambda = \ln \left( \frac{b_{\text{max}}}{b_{\text{min}}} \right) = \ln \left[ \sqrt{3/\Gamma^3} \right]$</td>
<td>$\lambda_D$</td>
<td>$b_0$</td>
</tr>
<tr>
<td>$\ln \Lambda = \ln \left( \frac{b_{\text{max}}}{b_{\text{min}}} \right) = \ln \left[ \sqrt{(3 + 9\Gamma)/\Gamma^3} \right]$</td>
<td>$\left(\lambda_D^2 + a^2\right)^{1/2}$</td>
<td>$b_0$</td>
</tr>
<tr>
<td>$\ln \Lambda = \max (2, \ln \Lambda')$ [\ln \Lambda' \text{as in Spitzer #1}]</td>
<td>$\lambda_D$</td>
<td>$b_0$</td>
</tr>
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<td>$\ln \Lambda = \frac{1}{2} \ln \left( 1 + \frac{b_{\text{max}}^2}{b_{\text{min}}^2} \right) = \frac{1}{2} \ln \left[ 1 + 3/\Gamma^3 \right]$</td>
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Landau-Spitzer Construction: Tagged Ions in a Thermal Background
Pump-Probe LIF: Tagging Ions in Ultracold Plasmas

(b) $m = -\frac{1}{2}$

$\Delta_{pp}$

$\sigma^+$

$\gamma$

$m = -\frac{1}{2}$

$\Delta_{pp}$

$\sigma^-$

$m = +\frac{1}{2}$

(a) ultracold plasma

$\sigma^-$

$\sigma^+$

pump

probe

$N(t)$

$-1/2$

$+1/2$

$-\Delta_{pp}/k$

$\Delta_{pp}/k$
Tagging Ions in Ultracold Plasmas

(b) $m = -\frac{1}{2}$

$5p^2P_{1/2}$

$\Delta_{pp}$

$m = +\frac{1}{2}$

$5s^2S_{1/2}$

$m = -\frac{1}{2}$

$m = +\frac{1}{2}$

(a)

ultracold plasma

$\sigma^+$

$\sigma^-$

pump

probe

N(t)

V

-1/2

+1/2

probe
Total Velocity Distribution Remains Maxwellian

(b) $m = -\frac{1}{2}$

$5p^2P_{1/2}$

$\Delta_{pp}$

$\gamma$

$\sigma^+$

$m = -\frac{1}{2}$

$m = +\frac{1}{2}$

$5s^2S_{1/2}$

$\Delta_{pp}$

$\gamma$

$\sigma^-$

(N(t))

V

(a) ultracold plasma

$\sigma^-$

$\sigma^+$

pump

probe
Extract Relaxation Rate
Extract Relaxation Rate from Average Velocity of m=1/2 ions

- pump
- no pump

Fit to spectrum determines underlying velocity distribution, $f_+(v)$

$f_+(v)$ determines the average velocity for m=1/2 ions

$$\langle v \rangle_+ = \int dv \, v f_+(v)$$
Extract Collision Rate

\[ \frac{d}{dt} \bar{v}_z(t) = - \int_{0}^{t} M_z(v_z^{(0)}, t') \bar{v}_z(t - t') \, dt' \]

\[ M_z(v_z^{(0)}, t) = \frac{2 \gamma_z(v_z^{(0)})}{\sqrt{2\pi\tau^2}} \exp\left(-\frac{t^2}{2\tau^2}\right) \]

\( \Gamma = 1.2 \)

\( \Gamma = 2.6 \)
Collision Rate

\[ \frac{\gamma_{\text{damping}}}{\omega_{pi}} \propto \Gamma^{3/2} \ln \Lambda \]

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

\[ \ln \Lambda_{LS} = \ln \left( \frac{C \lambda_D}{R_L} \right) = \ln \left( C \sqrt{\frac{1}{3 \Gamma^3}} \right) \]

...with help on analysis and interpretation from Thomas Pohl and Georg Bannasch, MPI for Physics of Complex Systems, Dresden
Proposed Extensions of Landau-Spitzer

\[ \Lambda = \frac{C}{\sqrt{3} \Gamma^3}, \text{LS} \]

\[ \tilde{\Lambda} = \sqrt{1 + \Lambda^2 + \frac{9}{\Gamma^2}}, [9] \]

\[ \tilde{\Lambda} = 1 + \Lambda, [10] \]

\[ \ln \tilde{\Lambda} = e^{\Lambda^{-1}} E_1(\Lambda^{-1}), [11] \]

\[ \tilde{\Lambda} = \sqrt{1 + \Lambda^2}, [12] \]

\[ \gamma_{\text{damping}} / \omega_{\text{pi}} \propto \Gamma^{3/2} \ln \Lambda \]

\[ \ln \Lambda_{\text{LS}} = \ln \left( \frac{C \lambda_D}{R_L} \right) = \ln \left( C \sqrt{\frac{1}{3 \Gamma^3}} \right) \]

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Not Exactly the Same as in Other Strongly Coupled Systems

Inertial confinement fusion experiments

Short pulse irradiation of solid targets

Conclusions

- Ultracold neutral plasmas provide new opportunities to probe the physics of strongly coupled plasmas
- We’ve performed clean measurements of the charged-particle collision rate in the strongly coupled regime
- Future plans
  - More accuracy
  - Non-exponential decay at short time
  - More weakly and strongly coupled systems
  - Other transport properties (diffusion, stopping power)
- Thanks to
  - Jose Castro (Astra Rockets, Costa Rica)
  - Patrick McQuillen
  - Trevor Strickler
  - Dresden: Thomas Pohl, Georg Bannasch