AFRL-AFOSR-VA-TR-2017-0030

Collisional Thermalization in Strongly Coupled Ultracold Neutral Plasmas

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02/07/2017
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTB1

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
25-01-2017

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
05-2011 to 01-2017

4. TITLE AND SUBTITLE
Collisional Thermalization in Strongly Coupled Ultracold Neutral Plasmas

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0267

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Thomas C Killian

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Rice University
6100 Main St.
Houston, TX 77005

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph Street
Suite 325, Room 3112
Arlington VA, 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A: Distribution approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project studies collisional phenomena such as thermalization and diffusion in strongly coupled plasmas. In strongly coupled plasmas, the Coulomb interaction energy per particle exceeds the thermal energy. This occurs in high-energy-density plasmas such as inertial confinement fusion experiments and in nature in the interiors of gas giant planets and the crusts of neutron stars. Classical plasma theory breaks down in strongly coupled systems because of the non-perturbative nature of particle interactions. Improving our understanding of this regime is an important fundamental challenge and it is necessary for modelling plasmas in this regime. We perform our experiments in ultracold neutral plasmas, which are formed by photoionizing laser cooled atoms. These are the coldest neutral plasmas every created, and they allow us to study physics of strongly coupled plasmas in a controlled, well-diagnosed environment.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Progress Report for “Collisional Thermalization in Strongly Coupled Ultracold Neutral Plasmas”
AFOSR grant FA9550-12-1-0267

1/25/17

Abstract

This project studies collisional phenomena such as thermalization and diffusion in strongly coupled plasmas. In strongly coupled plasmas, the Coulomb interaction energy per particle exceeds the thermal energy. This occurs in high-energy-density plasmas such as inertial confinement fusion experiments and in nature in the interiors of gas giant planets and the crusts of neutron stars. Classical plasma theory breaks down in strongly coupled systems because of the non-perturbative nature of particle interactions. Improving our understanding of this regime is an important fundamental challenge and it is necessary for modelling plasmas in this regime.

Using ions in ultracold plasmas, which are strongly coupled at extremely low density because of their low temperature, we developed a pump-probe, laser-induced-fluorescence technique for probing collisional processes. This allowed us to make the first direct measurements of collision rates and self-diffusion in a strongly coupled plasma. Our results are in good agreement with state-of-the-art molecular dynamics computer simulations and provide a valuable check on these methods.

During the last year, we published our results on self-diffusion in Physical Review X. We also published a combined numerical and experimental study of equilibration of ultracold plasmas after their creation, which demonstrated the underlying universal scaling of plasma dynamics with Coulomb Coupling parameter Γ and screening parameter κ. This paper appeared in Physical Review E and received the “Editors’ Suggestion” distinction. We also completed numerical modeling of laser cooling a neutral plasma and construction of the needed experimental apparatus.

Personnel

Thomas C. Killian – PI, 0.5 month summer salary funded by AFOSR grant FA9550-12-1-0267
Trevor Strickler –research scientist, full time, funded by AFOSR grant FA9550-12-1-0267 and Rice funds
Thomas Langin – graduate student, started 5/13, funded by a National Defense Science and Engineering Fellowship

Overview

This project studies collisional phenomena such as thermalization and diffusion in strongly coupled plasmas. In strongly coupled plasmas, the Coulomb interaction energy per particle exceeds the thermal energy. This occurs in high-energy-density plasmas such as inertial confinement fusion experiments and in nature in the interiors of gas giant planets and the crusts of neutron stars. Classical plasma theory breaks down in strongly coupled systems because of the non-perturbative nature of particle interactions. Improving our understanding of this regime is an important fundamental challenge and it is necessary for modelling plasmas in this regime. Measurements of collision rates, diffusion, and other collisional processes in these systems are also needed as inputs for hydrodynamic models, such as for optimizing plasma conditions in fusion experiments.

We probe this physics using ions in ultracold plasmas, which are strongly coupled at extremely low density because of their low temperature. This slows the plasma dynamics to the microsecond timescale, which is much more accessible than the femtosecond timescales of solid-density plasmas. Ultracold plasmas also offer precise control of initial conditions and powerful diagnostics adopted from ultracold atomic physics experiments. Because of this unique collection of characteristics, ions in ultracold plasmas provide the first opportunity to perform many important measurements of collisional phenomena in the strongly coupled regime and allow us to make quantitative comparison with kinetic theories and molecular dynamics simulations attacking these problems from the theoretical side.

The experimental program funded through this grant has been extremely successful. We achieved our main goals of using a newly developed pump-probe technique to measure collision rates in a strongly coupled plasma. Improvements in the technique allowed us to measure the self-diffusion rate and observe two new effects that reflect the strongly coupled nature of the plasma – non-Markovian dynamics at short times and coupling of single-particle motion to collective modes. Our results are in good agreement with state-of-the-art molecular dynamics computer simulations and provide a valuable check on these methods. Collaboration with theorists at Los Alamos and the Max Planck Institute for Complex Systems in Dresden has added significantly to the project. This work appeared in *Physical Review X*.

We published a combined numerical and experimental study of equilibration of ultracold plasmas after their creation, which demonstrated the underlying universal scaling of plasma dynamics with Coulomb Coupling parameter Γ and screening parameter κ. This paper appeared in Physical Review E and received the "Editors' Suggestion" distinction.

We have also completed and published several experimental and theoretical studies increasing the range of Coulomb coupling accessible in ultracold plasmas, which is important for future experiments and to connect results to classic plasma theory.

During the last year, we have focused on revamping the experimental apparatus for laser-cooling ions in the plasma. This involved switching to a new method of photoionizing the ultracold atoms to create plasmas with larger numbers of atoms. We also had to install several laser systems for driving the laser-cooling transitions in the ions and for repumping atoms out of dark states.

Collision Rates in a Strongly Coupled Plasma

In the first year of this grant, we published the first measurement of collision rates in a strongly coupled plasma ("Velocity Relaxation in a Strongly Coupled Plasma," G. Bannasch, J. Castro, P. McQuillen, T. Pohl and T. C. Killian, Phys. Rev. Lett. **109**, 185008 (2012)). This took advantage of a new optical pump-probe method developed in our group to perturb and study the velocity distribution of a population of tagged ions in the plasma (Fig. 1). Collaboration with the theory group of Thomas Pohl at the Max Plank Institute for Complex Systems in Dresden provided complimentary numerical simulations and allowed us to make comparison with the best existing theory. Our measurements (Fig. 2) indicate that further theoretical development is required to accurately describe collisions in this regime.

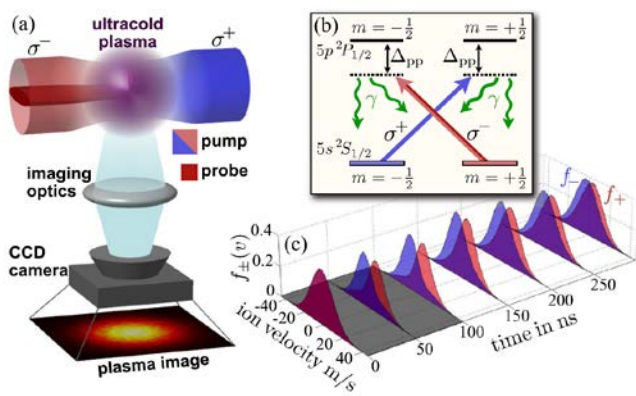

FIG. 1 (color online). (a) Schematics of the experimental approach to probe ion relaxation in an ultracold plasma. Two counter-propagating, circularly polarized lasers, detuned by $\Delta_{pp}/2\pi = -20$ MHz from the $5s^2S_{1/2} - 5p^2P_{1/2}$ transition, optically pump population between the two ground-state magnetic sublevels ($m = \pm 1/2$) of ions in an ultracold strontium plasma. The corresponding level-scheme is shown in (b), also indicating excited-state decay with the spontaneous emission rate γ. The optical pumping produces skewed velocity distributions $f_\pm(v)$ for each of the ground states, which we probe via ion fluorescence induced by a circularly polarized light sheet, applied at a variable time t after optical pumping. A typical, simulated time evolution of the velocity distributions, f_+ (red) and f_- (blue), during the optical pumping stage (gray) and subsequent relaxation is shown in (c).

Figure 1. Pump-probe method for tagging ions and studying collisions in an ultracold neutral plasma. From Bannasch *et al*., PRL **109**, 185008 (2012).

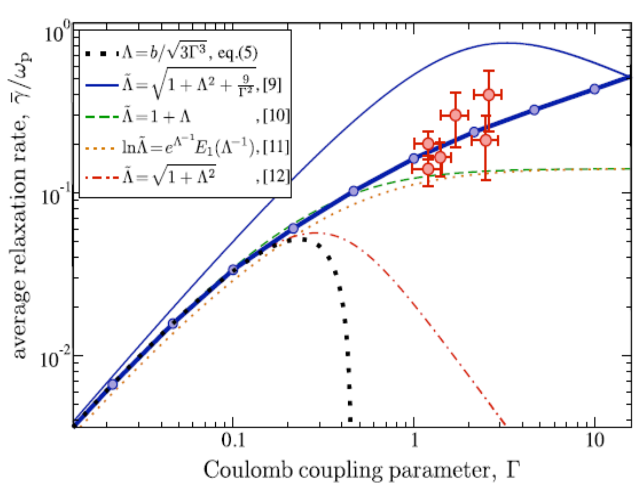

FIG. 5 (color online). Average relaxation rate as a function of coupling strength Γ. The large circles show the experimental results for different combinations of plasma density and temperature, within a range of $6 \times 10^8\ \mathrm{cm}^{-3} \lesssim \rho \lesssim 5 \times 10^9\ \mathrm{cm}^{-3}$, and $1\ \mathrm{K} \lesssim T \lesssim 3.3\ \mathrm{K}$. Using dimensionless quantities ($\bar{\gamma}/\omega_p$ and Γ), the data collapses onto a universal curve, which verifies the expected Coulomb scaling and provides experimental evidence that, in the strongly coupled regime, the velocity dependence of the relaxation rate is negligible [see Fig. 3(b)] within our measurement accuracy. The thick solid line is obtained from MD simulations for a wider range of Coulomb coupling parameters. In the weak-coupling limit it approaches the LS form, Eq. (6), shown by the thick dotted line. The other lines show different proposed extensions [9–12] into the strongly coupled regime, obtained by replacing Λ by $\tilde{\Lambda}$ in Eq. (6) according to the expressions given in the figure. The function $E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt$ denotes the exponential integral.

Figure 2. Measured and calculated collisions rates in a strongly coupled plasma. From Bannasch *et al*., PRL **109**, 185008 (2012).

Self-Diffusion Constant in a Three-Dimensional, Strongly Coupled Coulomb System

After making several important improvements in the capabilities of our diagnostic, such as improving the temporal resolution and signal-to-noise ratio of the measurement, we made first measurement of the self-diffusion constant of a strongly coupled plasma in three dimensions. (Diffusion has been measured in strongly coupled dusty plasmas, but these systems are two-dimensional, which substantially changes the dynamics and limits the applicability to other plasmas.) We use a Green-Kubo relation to extract the diffusion constant from our measurements of the relaxation towards equilibrium of the velocity of the tagged ions in the plasma (Fig. 1). This analysis has been developed with the help of Jerome Daligault, a physicist from Los Alamos National Laboratory who is an expert on the statistical mechanics and numerical simulation of liquids and strongly coupled Coulomb systems. Our measurements have provided the first experimental tests of theoretical models he has developed which are used as inputs for models of high-energy-density plasmas (Fig. 3). This publication appeared in *Physical Review X* (Strickler et al., *Phys. Rev. X* 6, 021021 (2016)).

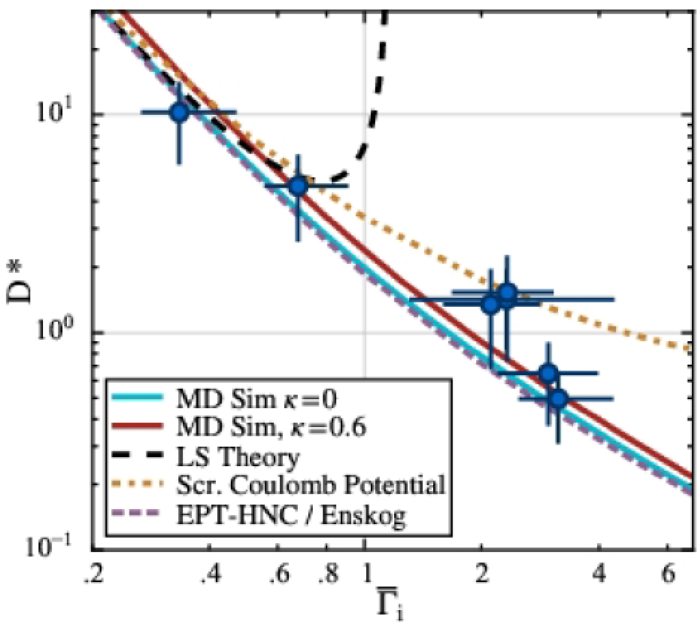

Figure 3. Self-diffusion constant (D*) plotted versus the Coulomb Coupling Constant, Γ, which is the ratio of Coulomb interaction energy to thermal energy. Systems are strongly coupled when $\Gamma>1$. Classic plasma transport theory (dotted black line) breaks down in the strongly coupled regime. Collisional equilibration and transport in strongly coupled plasmas is difficult to describe theoretically because of the breakdown of conventional plasma models centered on Debye screening and hydrodynamic treatments. It is an important problem because of its relevance for modelling plasmas created from intense-laser interaction with matter and plasmas in dense astrophysical environments. Using techniques to tag populations of ions in a strongly coupled plasma, we are able to measure their velocity evolution (Fig. 1). This measurement can be used to extract the diffusion coefficient $D=D^*a^2_{ws}\omega_p$ (a_{ws} is the inter-particle spacing and ω_p is the ion plasma oscillation frequency), which can be compared with molecular dynamics simulations beyond the regime of validity of classic plasma theory. To our knowledge, the only other experimental measurements of diffusion in a strongly coupled system are in dusty plasmas, which have distinct features such as low-dimensionality and damping by background gas collisions that complicate comparison with other strongly coupled systems. Our measurements (data symbols) agree with numerical calculations (solid lines) from J. Daligault, PRL 108, 225004 (2012).

New Emergent Phenomena in Strongly Coupled Coulomb Systems: Non-Markovian Dynamics and Coupling of Single-Particle Motion to Collective Modes

We also observed two additional emergent phenomena that have been predicted but never observed experimentally for strongly coupled Coulomb systems: non-Markovian dynamics at short times and coupling of single particle motion to collective modes.

The traditional statistical description of gases relies on the molecular chaos approximation, which assumes that particle motion between collisions is uncorrelated. This works well for weakly coupled systems and leads to exponential decay towards equilibrium of thermodynamic quantities. The approximation breaks down, however, in strongly coupled systems in which correlations of particle positions and velocities lead to a memory time in the dynamics, which is an example of non-Markovian behavior. In general, dynamics are non-Markovian when the evolution of system variables at the current time is a function of variables at past times, not just at the current one. Non-Markovian theories are well-developed from the description of liquids and Brownian motion. There are many published predictions and discussions of memory-time effects in strongly-coupled Coulomb systems, but to our knowledge there have been no experimental measurements because the effects are confined to very short times. Ultracold plasmas slow the plasma timescales significantly, and with recent experimental improvements reducing the temporal resolution of our measurements to on the order of 10 ns, we have now been able to observe non-exponential relaxation of the velocity of tagged ions towards equilibrium, an example of non-Markovian behavior (Fig. 4). In addition to demonstrating this new phenomenon arising from strong coupling, we should be able to quantitatively relate the timescale of the shoulder in the relaxation curve at early times to the underlying physics of collisions in the plasma. We described these observations in Strickler et al., *Phys. Rev. X* 6, 021021 (2016).

At later times in the evolution of the velocity of tagged ions toward equilibrium, the average velocity shows a revival or oscillation (Fig. 4) at a time given by the inverse of the ion plasma oscillation frequency in the plasma, which is the fundamental timescale for collective density oscillations in the plasmas. This shows that single particle motion, which is what the pump-probe technique measures, couples to collective modes in the system. Such coupling is a signature of strong interactions and the emergence of liquid-like behavior. It is often discussed as a possible contributor to thermalization processes in strongly coupled plasmas, but to our knowledge there has never been such a clear experimental observation of the effect.

Pursuit of Stronger and Weaker Coulomb Coupling

An important goal of the work is to extend the range of accessible Coulomb coupling to more strongly coupled systems (Γ>5) and more weakly coupled systems (Γ<1). The current methods for creating an ultracold plasma leads to a very small range of coupling (2<Γ<4), independent of initial conditions.

More weakly coupled systems are desirable in order to extend the range of measurements and connect to classic plasma theory. We investigated several techniques and had best success with shaping the initial density distribution of the plasma with intensity masks on the photo-ionizing laser beams. This excited large amplitude density waves that rapidly damp and convert their energy into ion thermal energy. With this technique, we have been able to reach Γ=0.3 (Fig. 3). This is a valuable new technique for the field. Initial work on the technique and the behavior of the density waves is described in "Ion Holes in the Hydrodynamic Regime in Ultracold Neutral Plasmas," P. McQuillen, J. Castro, T. Strickler, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas 20, 043516 (2013).

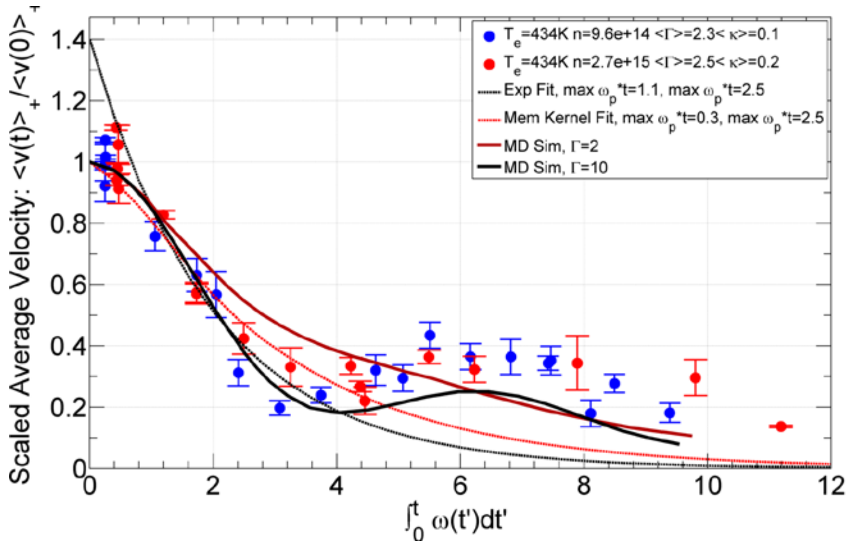

Figure 4. Non-Markovian relaxation at short times and coupling of single-particle motion to collective modes. The plot shows the evolution of the average velocity of a tagged population of ions in an ultracold neutral plasma using the pump-probe diagnostic shown in Fig. 1. The time axis has been rescaled by the ion plasma oscillation frequency, a natural unit of time in the plasma. Data cover 10 μs of evolution. Different color symbols represent two different plasma densities. The shoulder, or rollover, at very early times is a signature of non-Markovian dynamics. It is described with a modified Langevin equation with a memory kernel (red dashed line), and it clearly deviates from an exponential fit (dashed black line) to data with scaled time of 0.5-3. Later data with scaled time of 3-10 shows a revival of the average particle velocity reflecting coupling of the single particle motion to collective density-oscillation modes in the system, which oscillate at the ion plasma oscillation frequency. The oscillation can only be reproduced with full molecular dynamics simulations, shown in the solid red and black lines for two different values of the Coulomb coupling parameter Γ.

More strongly coupled plasmas would allow us to observe additional effects of liquid-like behavior, such as modification of the collective mode structure and more prominent non-Markovian dynamics. A long term goal is to observe the phase transition to a Wigner crystal, which has never been observed for a neutral plasma and is predicted to occur near Γ=200. In pursuit of stronger coupling, we collaborated with Thomas Pohl at the Max Planck Institute in Dresden to propose and analyze a new scheme to produce ultracold neutral plasmas deep in the strongly coupled regime. The method exploits the interaction blockade between cold atoms excited to high-lying Rydberg states and therefore does not require substantial extensions of current ultracold plasma experiments. Extensive simulations reveal a universal behavior of the resulting Coulomb coupling parameter, providing a direct connection between the physics of strongly correlated Rydberg gases and ultracold plasmas. The approach is shown to reduce currently accessible temperatures by more than an order of magnitude, which promises to open a new regime for ultracold plasma research. This work was published in “Strongly Coupled Plasmas via Rydberg-Blockade of Cold Atoms," G. Bannasch, T. C. Killian, and T. Pohl, Phys. Rev. Lett. 110, 253003 (2013). Using our current apparatus, we have performed some preliminary experiments on creating plasmas with this method. This was published in “Imaging the Evolution of an Ultracold Strontium Rydberg Gas,” P. McQuillen, X. Zhang, T. Strickler, F. B. Dunning, and T. C. Killian, Phys. Rev. A 87, 013407 (2013).). Our conclusion from the experiments is that in order to create the conditions for stronger coupling, we need a small modification of our setup in order to create plasmas via 5sns $^3S_1$ Rydberg states, which have repulsive interactions. With the laser system we use now, we can access 5sns $^1S_0$ and 5sns $^1D_2$ Rydberg states, which have attractive interactions that frustrate the Rydberg blockade effect.

Towards Laser Cooling an Ultracold Neutral Plasma

For the last year, we have focused on modelling laser-cooling of an ultracold neutral plasma and constructing the necessary experimental apparatus. Laser cooling is one of the most promising schemes for achieving more strongly coupled plasmas and it has been a long-term goal of multiple experimental groups since the inception of the field. With our new understanding of collisional phenomena in these systems and improved modelling capabilities, the completion of this quest is within reach.

In order to gain a quantitative understanding of the effectiveness of laser cooling ions in the plasma, we developed a simulation of one-dimensional laser cooling in a three-dimensional plasma. The plasma dynamics are described with a full molecular dynamics simulation of a Yukawa one-component plasma. We couple this to a quantum-jump, or quantum-trajectories-method simulation of the laser-ion interaction that includes all the important electronic states of the ions. The strategy is to scatter photons on the principal $^2S_{1/2}$-$^2P_{3/2}$ transition at 408 nm. Repump lasers are required at 1033 nm and 1092 nm to clear out metastable D states that are populated by decay of the $^2P_{3/2}$ state. Figure 5 describes typical expected results, including effects of plasma expansion and electron-ion collisions. There are many factors to take into account, but based on our results, we conservatively set our goal at increasing the Coulomb Coupling factor to Γ=10.

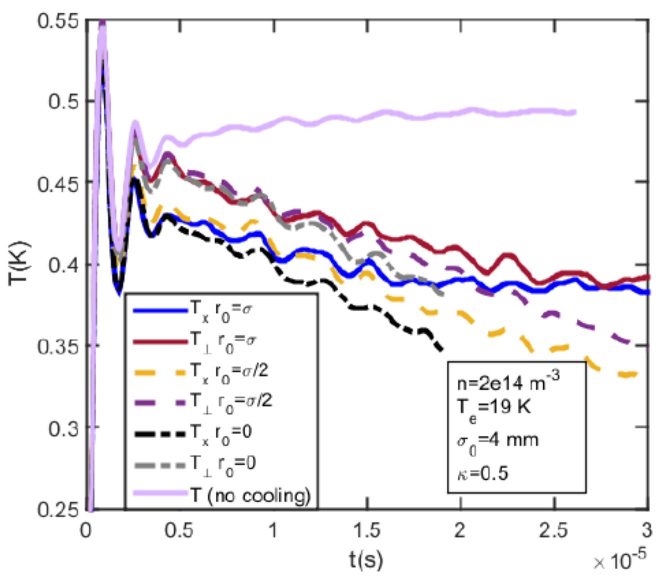

Figure 5. Results of a numerical model of laser cooling showing that the ion temperature can be decreased by a factor of two in 30 μs.

We have installed the required lasers from Toptica and built the systems for controlling the laser frequencies and delivering the light to the ions.

We have also installed a new imaging camera. Our older version of the main diagnostic camera for imaging the plasma - an intensified CCD camera - suffered an extensive failure of the intensifier unit. The camera was 15 years old, and the manufacturer was unable to repair it. We bought a new camera of a similar type, which costs $50k. This expensive camera is needed because it is the only technology that combines single-photon sensitivity with sub-microsecond timing resolution.

Summary of Results

(1) First measurement of the collision rate in a strongly-coupled plasma; collaboration with a theoretical group at the Max Plank Institute for Complex Systems in Dresden to provide complimentary numerical simulations (Bannasch et al., PRL **109**, 185008 (2012))

(2) Theoretical investigation of the potential to use the Rydberg blockade to create a more strongly coupled plasma (G. Bannasch, et al., Phys. Rev. Lett. **110**, 253003 (2013))
(3) Preliminary experimental studies investigating creation of more strongly coupled plasmas from a blockaded Rydberg gas (P. McQuillen, et al., Phys. Rev. A **87**, 013407 (2013))
(4) Development of techniques to imprint large-amplitude density modulations on the ultracold plasma (P. McQuillen, et al., Phys. Plasmas **20**, 043516 (2013)).
(5) Demonstration of universal behavior in the equilibration of an ultracold neutral plasma after plasma creation (Langin , et al., Phys. Rev. E **93**, 023201 (2016), *Editors' Suggestion*).
(6) First measurement of the self-diffusion constant in a three-dimensional Coulomb system; collaboration with a theoretical group from Los Alamos to facilitate comparison with the best existing theory (Strickler et al., Phys. Rev. X **6**, 021021 (2016)).
(7) First experimental observation of non-Markovian dynamics and coupling of single particle motion to collective modes in a strongly coupled Coulomb system (Strickler et al., Phys. Rev. X **6**, 021021 (2016))
(8) Numerical modelling of laser cooling an ultracold neutral plasma.
(9) Construction of the laser systems for laser cooling ions in the plasma.

Publications

"Velocity Relaxation in a Strongly Coupled Plasma," G. Bannasch, J. Castro, P. McQuillen, T. Pohl and T. C. Killian, Phys. Rev. Lett. **109**, 185008 (2012).

"Strongly Coupled Plasmas via Rydberg-Blockade of Cold Atoms," G. Bannasch, T. C. Killian, and T. Pohl, Phys. Rev. Lett. **110**, 253003 (2013)

"Imaging the Evolution of an Ultracold Strontium Rydberg Gas," P. McQuillen, X. Zhang, T. Strickler, F. B. Dunning, and T. C. Killian, Phys. Rev. A **87**, 013407 (2013).

"Ion Holes in the Hydrodynamic Regime in Ultracold Neutral Plasmas," P. McQuillen, J. Castro, T. Strickler, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas **20**, 043516 (2013).

"Ion Temperature Evolution in an Ultracold Neutral Plasma ," P. McQuillen, T. Strickler, T. Langin, and T. C. Killian, Phys. Plasmas **22**, 033513 (2015).

"Emergence of Kinetic Behavior in Streaming Ultracold Neutral Plasmas," P. McQuillen, J. Castro, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas **22**, 043514 (2015).

"Demonstrating Universal Scaling for Dynamics of Yukawa One-component Plasmas after an Interaction Quench," T. Langin, T. Strickler, N. Maksimovic, P. McQuillen,T. Pohl, D. Vrinceanu, and T. C. Killian, Phys. Rev. E **93**, 023201 (2016), *Editors' Suggestion*.

"Experimental Measurement of Self-Diffusion in a Strongly Coupled Plasma," T. Strickler, T. Langin, P. McQuillen, J. Daligault, and T. C. Killian, Phys. Rev. X **6**, 021021 (2016).

Invited Presentations

The PI has given 15 invited talks on the work funded by this grant, including presentations at three international conferences: the 11th International Workshop on Non-Neutral Plasmas, Takamatsu, Japan (12/14), the 16th International Symposium on Laser Aided Plasma Diagnostics, Madison, WI (9/13), and the 14th International Conference on the Physics of Non-ideal Plasmas, Rostock, Germany, (9/12). The topic has also been a popular one for colloquia in physics departments at universities in the US and abroad.

The most recent international workshop in Takamatsu, Japan, featured two sessions on ultracold neutral plasmas including five PIs funded by the AFOSR program.

``Studying Collisions and Transport in Strongly Coupled Systems with Ultracold Plasmas," Atomic Physics Seminar, Yale University, New Haven, CT (12/16).

``From Ultracold Plasmas to White Dwarf Stars," Physics Department Colloquium, Union College, Schenectady, NY (11/16).

``Studying Collisions and Transport in Strongly Coupled Systems with Ultracold Plasmas," Department of Physics Colloquium, Stony Brook University, Stony Brook, NY (11/16).

“From Ultracold Plasmas to White Dwarf Stars," Keynote address at the Joint Spring 2016 Meeting of the Texas Sections of APS, AAPT, and Zone 13 of the SPS, Lamar University, Beaumont, TX (4/16).

“Studying Strongly Coupled Systems with Ultracold Plasmas," Department of Physics and Astronomy Colloquium, University of South Alabama, Mobile, AL (11/15).

“Collective Modes and Correlations in Strongly Coupled Ultracold Plasmas," Department of Physics and Astronomy Colloquium, Purdue University, West Lafayette, IN (4/15).

Collective Modes and Collisions in Strongly Coupled Ultracold Plasmas," Department of Physics Seminar, Tsinghua University, Beijing, China (12/14).

Collective Modes and Collisions in Strongly Coupled Ultracold Plasmas," Institute of Quantum Electronics Seminar, Peking University, Beijing, China (12/14).

Collective Modes and Collisions in Strongly Coupled Ultracold Plasmas," Department of Physics Seminar, Osaka University, Osaka, Japan (12/14).

Collision Rates, Diffusion, and Non-Markovian Dynamics in Strongly Coupled Ultracold Neutral Plasmas," 11th International Workshop on Non-Neutral Plasmas, Takamatsu, Japan (12/14).

Collective Modes and Correlations in Strongly Coupled Ultracold Plasmas," Department of Physics Colloquium, Texas Southern University, Houston, TX (5/14).

Collective Modes and Correlations in Strongly Coupled Ultracold Plasmas," Department of Physics Colloquium, Boston College, Chestnut Hill, MA (3/1).

Studying Ion Equilibration in Ultracold Neutral Plasmas with Spatially Resolved LIF Spectroscopy," 16th International Symposium on Laser Aided Plasma Diagnostics, Madison, WI (9/13).

Collective Modes and Correlations in Ultracold Neutral Plasmas," Department of Physics Colloquium, West Virginia University, Morgantown, WV (11/12).

Beyond Landau-Spitzer: Collisions in Strongly Coupled Ultracold Plasmas," 14th International Conference on the Physics of Non-ideal Plasmas, Rostock, Germany, (9/12).

AFOSR Deliverables Submission Survey

Response ID:7543 Data

1.

Report Type

Final Report

Primary Contact Email
Contact email if there is a problem with the report.

jason.marshall.3@us.af.mil

Primary Contact Phone Number
Contact phone number if there is a problem with the report

703-696-7721

Organization / Institution name

Rice University

Grant/Contract Title
The full title of the funded effort.

Collisional Thermalization in Strongly Coupled Ultracold Neutral Plasmas

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0267

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Thomas Killian

Program Officer
The AFOSR Program Officer currently assigned to the award

Jason Marshall

Reporting Period Start Date

05/01/2012

Reporting Period End Date

01/26/2017

Abstract

During the last year, we published our results on self-diffusion in Physical Review X. We also published a combined numerical and experimental study of equilibration of ultracold plasmas after their creation, which demonstrated the underlying universal scaling of plasma dynamics with Coulomb Coupling parameter ᄀᄀ and screening parameter ᆸᄉ. This paper appeared in Physical Review E and received the "Editors' Suggestion" distinction. We also completed numerical modeling of laser cooling a neutral plasma and construction of the needed experimental apparatus.

Distribution Statement
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2017AFOSRPlasmareportFinalJan2017+.pdf

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Archival Publications (published) during reporting period:

"Velocity Relaxation in a Strongly Coupled Plasma," G. Bannasch, J. Castro, P. McQuillen, T. Pohl and T. C. Killian, Phys. Rev. Lett. 109, 185008 (2012).

"Strongly Coupled Plasmas via Rydberg-Blockade of Cold Atoms," G. Bannasch, T. C. Killian, and T. Pohl, Phys. Rev. Lett. 110, 253003 (2013)

"Imaging the Evolution of an Ultracold Strontium Rydberg Gas," P. McQuillen, X. Zhang, T. Strickler, F. B. Dunning, and T. C. Killian, Phys. Rev. A 87, 013407 (2013).

"Ion Holes in the Hydrodynamic Regime in Ultracold Neutral Plasmas," P. McQuillen, J. Castro, T. Strickler, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas 20, 043516 (2013).

"Ion Temperature Evolution in an Ultracold Neutral Plasma ," P. McQuillen, T. Strickler, T. Langin, and T. C. Killian, Phys. Plasmas 22, 033513 (2015).

"Emergence of Kinetic Behavior in Streaming Ultracold Neutral Plasmas," P. McQuillen, J. Castro, S. J. Bradshaw, and T. C. Killian, Phys. Plasmas 22, 043514 (2015).

"Demonstrating Universal Scaling for Dynamics of Yukawa One-component Plasmas after an Interaction Quench," T. Langin, T. Strickler, N. Maksimovic, P. McQuillen,T. Pohl, D. Vrinceanu, and T. C. Killian, Phys. Rev. E 93, 023201 (2016), Editors' Suggestion.

"Experimental Measurement of Self-Diffusion in a Strongly Coupled Plasma," T. Strickler, T. Langin, P. McQuillen, J. Daligault, and T. C. Killian, Phys. Rev. X 6, 021021 (2016).

New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

N/A

Change in AFOSR Program Officer, if any:

During the course of the grant, Jason Marshall became the program officer.

Extensions granted or milestones slipped, if any:

N/A

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Jan 26, 2017 12:17:23 Success: Email Sent to: jason.marshall.3@us.af.mil