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Laser-cooled ions in hybrid optical/electrical traps for studying collision physics in strongly-coupled plasmas

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This document is the final report on Project FA9550-17-1-0302, “Laser-cooled ions in hybrid optical/electrical traps for studying collision physics in strongly-coupled plasmas.” The primary motivation for this work is to understand collision physics in the strongly-coupled neutral plasma regime. Research supported by this grant resulted in 7 peer-reviewed publications, 8 invited talks, and 17 contributed conference presentations at national meetings from 2017 to 2022. Highlights include building a hybrid ion/MOT trap at BYU, creating and characterizing the first dual-ionspecies ultracold neutral plasma, measuring temperature relaxation in a dual-species plasma, and organizing two DPP mini-conferences on topics related to this research.

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Final report: Laser-cooled ions in hybrid optical/electrical traps for studying collision physics in strongly-coupled plasmas

Abstract

This document is the final report on Project FA9550-17-1-0302, "Laser-cooled ions in hybrid optical/electrical traps for studying collision physics in strongly-coupled plasmas." The primary motivation for this work is to understand collision physics in the strongly-coupled neutral plasma regime. Research supported by this grant resulted in 7 peer-reviewed publications, 8 invited talks, and 17 contributed conference presentations at national meetings from 2017 to 2022. Highlights include building a hybrid ion/MOT trap at BYU, creating and characterizing the first dual-ion-species ultracold neutral plasma, measuring temperature relaxation in a dual-species plasma, and organizing two DPP mini-conferences on topics related to this research.

1 Publications

1.1 Peer-reviewed publications

The following peer-reviewed publications acknowledge financial support from this grant.

1. R. Tucker Sprenkle, S. D. Bergeson, Luciano G. Silvestri, and Michael S. Murillo, "Ultracold neutral plasma expansion in a strong uniform magnetic field," Phys. Rev. E 105, 045201 (2022), DOI: 10.1103/PhysRevE.105.045201

2. R. Tucker Sprenkle, L. G. Silvestri, S. D. Bergeson, and M. S. Murillo, "Temperature relaxation in strongly-coupled binary ionic mixtures," Nature Communications 13, 15 (2022), DOI: 10.1038/s41467-021-27696-5

3. Liam G. Stanton, Scott D. Bergeson, and Michael S. Murillo, "Transport in non-ideal multi-species plasmas," Physics of Plasmas 28, 050401 (2021), DOI: 10.1063/5.0048227

4. Luciano G. Silvestri, R. Tucker Sprenkle, Scott D. Bergeson, and Michael S. Murillo, "Relaxation of strongly coupled binary ionic mixtures in the coupled mode regime," Physics of Plasmas 28, 062302 (2021), DOI: 10.1063/5.0048030

5. Scott D. Bergeson, et al. (9 authors), "Exploring the crossover between high-energy-density plasma and ultracold neutral plasma physics," Physics of Plasmas 26, 100501 (2019), DOI: 10.1063/1.5119144

6. Tucker Sprenkle, Adam Dodson, Quinton McKnight, Ross Spencer, Scott Bergeson, Abdourahmane Diaw, and Michael S. Murillo, "Ion friction at small values of the Coulomb logarithm," Phys. Rev. E 99, 053206 (2019), DOI: 10.1103/PhysRevE.99.053206

7. Q. McKnight, A. Dodson, T. Sprenkle, T. Bennett, and S. D. Bergeson, "Comment on 'Laser cooling of Yb-173 for isotope separation and precision hyperfine spectroscopy," Phys. Rev. A 97, 016501 (2018), DOI: 10.1103/PhysRevA.97.016501

1.2 Invited talks

The following invited talks acknowledged financial support from this grant.

1. “Ionic thermalization in a mixed dual species ultracold neutral plasma,” R. Sprenkle, L. Silvestri, M. Murillo, S. D. Bergeson, DPP Mini-conference on transport in non-ideal multi-species plasmas, APS DPP, November 2020.
2. “Ion friction in strongly-coupled plasmas,” High Energy Density Science Seminar, LLNL, Livermore, CA, June 2019,
3. “Inertial confinement at 1 K: an example from ultracold neutral plasmas,” LLE HED Science Seminar, Laboratory for Laser Energetics, University of Rochester, Rochester, NY, July 2019.
4. “Ultracold neutral plasmas as high-energy-density plasma simulators,” APS Division of Plasma Physics Miniconference on the Crossover Between High-Energy-Density Plasmas and Ultracold Neutral Plasmas, Portland, OR, November 2018
5. “High energy density plasma simulations using ultracold neutral plasmas,” Wisconsin Atomic Physics Seminar, Madison, Wisconsin, April 2018
6. “Dense plasma physics on the tabletop at 1 Kelvin,” Utah State University, Department of Physics colloquium, November 2017
7. “Some thoughts on energy relaxation in an ultracold neutral plasma – expanding and trapped dual-species plasmas,” University of British Columbia Chemical, Plasma and AMO Physics Seminar, Vancouver, BC, Canada, July 2017
8. “Can you measure a Coulomb logarithm in an ion trap?” NIST Ion Storage Group Seminar, Boulder, CO, July 2017

1.3 Contributed conference presentations

The following contributed conference presentations acknowledged financial support from this grant.

1. Scott D. Bergeson and Chanhyun Pak, “Plasma oscillations in an expanding magnetized ultracold neutral plasma,” APS DPP, October 2022
2. Scott D. Bergeson and Chanhyun Pak, “Ion thermometry in ultracold neutral plasmas,” APS DAMOP, May 2022
3. Scott D. Bergeson, Robert T Sprenkle, Luciano G. Silvestri, Michael S. Murillo, “Temperature relaxation in strongly coupled binary ionic mixtures,” APS DAMOP, June 2021
4. Robert T. Sprenkle and Scott D. Bergeson, “Ultracold neutral plasma expansion in a strong uniform magnetic field,” APS DAMOP, June 2021
5. Scott D. Bergeson and Robert T. Sprenkle, “Ultracold neutral plasma expansion in a strong uniform magnetic field, “APS DPP, Pittsburgh, PA, November 2021
6. Tucker Sprenkle, Ross Spencer, Scott Bergeson, “Thermalization in strongly coupled dual species plasma expansions,” APS DAMOP, Portland, OR, June 2020

7. Robert Sprenkle, Luciano Silvestri, Michael Murillo, Scott Bergeson, “Ionic thermalization in a mixed dual species ultracold neutral plasma,” APS DPP, November 2020

8. Luciano Silvestri, Tucker Sprenkle, Scott Bergeson, Michael Murillo, “Approach to equilibrium in ultracold binary plasma mixtures,” APS DPP, November 2020

9. Tyler Bennett, Sarah Hill, Robert Sprenkle, and Scott Bergeson,“A dual-species hybrid MOT/Paul trap,” APS DAMOP, Milwaukee, WI, May 2019

10. Robert Sprenkle and Scott Bergeson, “Ion friction at small values of the Coulomb logarithm,” APS DAMOP, Milwaukee, WI, May 2019

11. T. Sprenkle, R. Spencer, and S. D. Bergeson, “Ion friction in dual species ultracold plasma expansion,” APS DAMOP, Fort Lauderdale, FL, June 2018

12. R. T. Sprenkle and S. D. Bergeson, “Energy relaxation in a Ca/Yb dual-species ultracold neutral plasma,” APS DPP, Portland, OR, November 2018

13. T. Bennett, S. Hill, R. T. Sprenkle, and S. D. Bergeson, “A dual-species hybrid MOT/Paul trap,” APS DPP, Portland, OR, November 2018

14. Tucker Sprenkle, Adam Dodson, Quin McKnight, and Scott Bergeson, “ Equilibration rates in a dual-species ultracold neutral Ca/Yb plasma,” APS DPP, Milwaukee, WI, October 2017

15. Tucker Sprenkle, Adam Dodson, and Scott Bergeson, “Temperature measurements in a Yb/Ca dual-species ultracold neutral plasma,” APS DAMOP, Sacramento, CA, June 2017

16. Quinton McKnight, Michaela Kleinert, and Scott Bergeson, “Frequency-comb based spectroscopy of the Yb I 399 nm transition,” APS DAMOP, Sacramento, CA, June 2017

17. Adam Dodson, Quinton McKnight, Tucker Sprenkle, and Scott Bergeson, “Ultracold neutral plasma heating due to resonance excitation,” APS DAMOP, Sacramento, CA, June 2017

2 Participants

The following students worked on projects supported by this grant. Note that in many cases, the grant investment was leveraged at BYU. The BYU College of Physical and Mathematical Sciences offers supplementary financial support for students working on externally-funded research projects.

2.1 Graduate students (3)

Three graduate students worked on research supported by this grant. Chanhyun Pak is a current M.S. candidate in the BYU Department of Physics and Astronomy. He anticipates graduating in April of 2023. Tucker Sprenkle received his Ph.D. in 2021 and accepted a position at Honeywell Quantum Solutions in Boulder, CO. Sarah Hill was a M.S. candidate in our department. However, she has left the program and is working in the optics industry in Pennsylvania.

2.2 Undergraduate students (9)

The following students co-authored publications or presentations of projects supported by this grant: Adam Dodson, Quinton McKnight, Tyler Bennett, and Sarah Hill. The following students are currently working in my lab, continuing work on projects initiated with the support of this grant: Matthew Schlitters, Virginia Billings, Michael Peterson. Two others worked for a period of time and have moved on to other research groups: Mason Christiansen and Joseph Buck.

3 Other Partners or Collaborators

Although not funded directly by this grant, the following collaborators contributed to this research. Ross Spencer, BYU Faculty, served on Tucker Sprenkle's graduate committee and provided theoretical support for his work. Michael Murillo, MSU faculty member, provided theoretical and computational support. Luciano Silvestri, MSU Post-doc, provided theoretical and computational support.

4 Technical report

4.1 Accomplishments

4.1.1 Hybrid MOT/ion trap

The original proposal outlined a research program based on combining an ultracold neutral plasma with a trapped non-neutral plasma to probe time scales longer than are possible using the expanding ultracold neutral plasma platform. The hybrid magneto-optical trap and RF ion trap, sometimes called a MOTion trap in the literature, has been demonstrated by other research groups. We built such a trap and made initial meaurements of the ion temperature and lifetime. However, three issues quickly became apparent. 1. The ion measurements were severely constrained by the secular motion of the trapped ions. Collision characteristics were dominated by the driven collective motion of the ions and not the more interesting relaxation dynamics. 2. The allowable trapped ion densities were 100 times lower than in our ultracold neutral plasma work. Consequently, the time scales for relaxation were extended. The previously-mentioned driven ion motion became even more significant relative to the quiescent processes of interest. 3. The background pressures in the beam, required for MOT loading, severely limited the lifetime of ions in the ion trap. We therefore threw our remaining effort and time into our dual-species ultracold neutral plasma work. This was justified on the basis that the primary focus of the project was to study collision physics in strongly coupled plasmas, a focus that aligned well with the dual-species plasma work. This change resulted in 7 publications, including a high-profile publication in Nature Communications, as described in the next section.

Publications:

1. Tyler Bennett, Sarah Hill, Robert Sprenkle, and Scott Bergeson,"A dual-species hybrid MOT/Paul trap," APS DAMOP, Milwaukee, WI, May 2019

2. T. Bennett, S. Hill, R. T. Sprenkle, and S. D. Bergeson, "A dual-species hybrid MOT/Paul trap," APS DPP, Portland, OR, November 2018

4.1.2 Dual-species ultracold neutral plasmas

Our work in creating and characterizing a dual-species ultracold neutral plasma was designed to understand the approach to equilibrium in strongly-coupled plasmas. During this funding cycle we built the first dual (ion) species ultracold neutral plasma using low mass Ca atoms (40 a.m.u.) and high mass Yb atoms (174 a.m.u.). The 4:1 mass ratio mimicked the helium to hydrogen mass ratio in some high-energy-density fusion-class plasmas. Working with Michael Murillo (Michigan State University) and Liam Stanton (San Jose State University) we organized two DPP mini-conferences on topics related to this research.

We measured the temperature relaxation rate and found excellent agreement with MD simulations. We also compared to three popular plasma theories, all of which disagreed with the experimental and simulation results. Careful study indicates that the disagreement results from coupled modes in the ion systems. These results have implications for HEDP simulations, which typically use average atom approximations and are unable to extend to coupled mode calculations.

We observe spatial separation of the ions as the plasma expands. This result may explain thermal and spatial decoupling of ion species in HEDP experiments.

Publications (conference presentations listed previously):

1. R. Tucker Sprenkle, S. D. Bergeson, Luciano G. Silvestri, and Michael S. Murillo, "Ultracold neutral plasma expansion in a strong uniform magnetic field," Phys. Rev. E 105, 045201 (2022), DOI: 10.1103/PhysRevE.105.045201

2. R. Tucker Sprenkle, L. G. Silvestri, S. D. Bergeson, and M. S. Murillo, "Temperature relaxation in strongly-coupled binary ionic mixtures," Nature Communications 13, 15 (2022), DOI: 10.1038/s41467-021-27696-5

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5. Scott D. Bergeson, et al. (9 authors), "Exploring the crossover between high-energy-density plasma and ultracold neutral plasma physics," Physics of Plasmas 26, 100501 (2019), DOI: 10.1063/1.5119144

6. Tucker Sprenkle, Adam Dodson, Quinton McKnight, Ross Spencer, Scott Bergeson, Abdourahmane Diaw, and Michael S. Murillo, "Ion friction at small values of the Coulomb logarithm," Phys. Rev. E 99, 053206 (2019), DOI: 10.1103/PhysRevE.99.053206

4.1.3 Magnetized plasmas

Towards the end of this funding cycle we initiated experiments in magnetized ultracold neutral plasmas. There is no analytical theory for a spherically-symmetric plasma expanding in a uniform magnetic field. We proved that a diffusion treatment, the most common approach used to describe cross-field transport, is completely inappropriate for ultracold neutral plasmas, contrary to a 2008 publication claiming otherwise. We measured the unexpected result that the density profile in the expanding ultracold neutral plasma is Gaussian and self-similar across the entire regime from unmagnetized to highly magnetized. Work in this area is ongoing. The current focus is to determine the conditions under which the parallel and perpendicular expansion deviates from the adiabatic expansion model.

Publications and presentations:

1. R. Tucker Sprenkle, S. D. Bergeson, Luciano G. Silvestri, and Michael S. Murillo, "Ultracold neutral plasma expansion in a strong uniform magnetic field," Phys. Rev. E 105, 045201 (2022), DOI: 10.1103/PhysRevE.105.045201

2. Scott D. Bergeson and Chanhyun Pak, "Plasma oscillations in an expanding magnetized ultracold neutral plasma," APS DPP, October 2022

3. Scott D. Bergeson and Chanhyun Pak, "Ion thermometry in ultracold neutral plasmas," APS DAMOP, May 2022

4.1.4 Spectroscopy

Our primary tool in diagnosing our plasmas is laser spectroscopy. To help train the students and contribute to the scientific literature, we have measured the transition frequencies for several transitions important to our work.

Publications and presentations:

1. Chanhyun Pak, Matthew J. Schlitters, and Scott D. Bergeson, "Improved ionization potential of calcium using frequency-comb based Rydberg spectroscopy," Submitted to Phys. Rev. A, July 27, 2022, Currently under review.

2. Q. McKnight, A. Dodson, T. Sprenkle, T. Bennett, and S. D. Bergeson, "Comment on 'Laser cooling of Yb-173 for isotope separation and precision hyperfine spectroscopy," Phys. Rev. A 97, 016501 (2018), DOI: 10.1103/PhysRevA.97.016501

3. Quinton McKnight, Michaela Kleinert, and Scott Bergeson, "Frequency-comb based spectroscopy of the Yb I 399 nm transition," APS DAMOP, Sacramento, CA, June 2017

4.2 Impacts

This research helped inform collision dynamics in strongly-coupled plasmas. The importance of coupled modes in plasmas where the mass ratio is in the 1 to 10 range was demonstrated. Popular plasma relaxation theories neglect these modes and do not reproduce the experimental or simulation results.

We organized two DPP mini-conferences on topics related to this grant.

1. Miniconference on the Crossover Between High-Energy-Density Plasmas and Ultracold Neutral Plasmas, APS DPP, November 2018.

2. Mini-Conference on Transport in Non-Ideal, Multi-Species Plasmas, APS DPP, November 2020.

These mini-conferences brought together experimental, computational, and theoretical scientists working in these subfields of plasma physics. The first resulted in a massive review article. The second in a special issue of Physics of Plasmas.

As reported in the "Personnel" section, two women worked on research supported by this grant: Virginia Billings and Sarah Hill. Both worked as undergraduate students and Sarah continued her work during her first year as a masters student.

5 Changes

The original proposal outlined a research program based on combining an ultracold neutral plasma with a trapped non-neutral plasma to probe time scales longer than are possible using the expanding ultracold neutral plasma platform. The hybrid magneto-optical trap and RF ion trap, sometimes called a MOTion trap in the literature, has been demonstrated by other research groups. We built such a trap and made initial meaurements of the ion temperature and lifetime. However, three issues quickly became apparent. 1. The ion measurements were severely constrained by the secular motion of the trapped ions. Collision characteristics were dominated by the driven collective motion of the ions and not the more interesting relaxation dynamics. 2. The allowable trapped ion densities were 100 times lower than in our ultracold neutral plasma work. Consequently, the time scales for relaxation were extended. The previously-mentioned driven ion motion became even more significant relative to the quiescent processes of interest. 3. The background pressures in the beam, required for MOT loading, severely limited the lifetime of ions in the ion trap. We therefore threw our remaining effort and time into our dual-species ultracold neutral plasma work. This was justified on the basis that the primary focus of the project was to study collision physics in strongly coupled plasmas, a focus that aligned well with the dual-species plasma work. This resulted in 7 publications, including a high-profile publication in Nature Communications.