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Theory of Magnetized Ultracold Neutral Plasmas

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Final Report

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14. ABSTRACT

The success of this project can be measured by a number of metrics. It completed the proposed work plan, which included advancing the theoretical description of transport properties of strongly coupled magnetized plasmas, testing that description using molecular dynamics simulations, and using both approaches to suggest interesting physics problems that future magnetized ultracold neutral plasma experiments might explore. The theoretical work led to our \mean force kinetic theory' which has been communicated in references 1, 2, 4, 6, 8 and 10 (here, the numbers correspond to the citation list in section 2). This theory was tested using molecular dynamics simulations, and the results of these tests were communicated in references 2, 3, and 9. Both the theory and simulation results suggested interesting physical effects that future magnetized ultracold plasma experiment may explore. One example is that ultracold plasmas are uniquely situated to explore fundamentally new regimes of plasma transport due to their ability to access both strong magnetization and strong coupling.

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Final Project Report

Theory of Magnetized Ultracold Neutral Plasmas

1 Overview

The success of this project can be measured by a number of metrics. It completed the proposed work plan, which included advancing the theoretical description of transport properties of strongly coupled magnetized plasmas, testing that description using molecular dynamics simulations, and using both approaches to suggest interesting physics problems that future magnetized ultracold neutral plasma experiments might explore. The theoretical work led to our "mean force kinetic theory" which has been communicated in references 1, 2, 4, 6, 8 and 10 (here, the numbers correspond to the citation list in section 2). This theory was tested using molecular dynamics simulations, and the results of these tests were communicated in references 2, 3, and 9. Both the theory and simulation results suggested interesting physical effects that future magnetized ultracold plasma experiment may explore. One example is that ultracold plasmas are uniquely situated to explore fundamentally new regimes of plasma transport due to their ability to access both strong magnetization and strong coupling. Our work in reference 3 was the first to propose the parameters at which these fundamental transitions occur, and it tested them using molecular dynamics simulations of diffusion and temperature anisotropy relaxation. A second example is that strong magnetic fields can significantly reduce electron heating in ultracold plasma experiments by confining the heating to the single dimension aligned along the magnetic field (reference 5). This was predicted to lead to a temperature anisotropy, suggesting a new means of measuring the energy relaxation rate in magnetized ultracold plasmas.

In addition to completing the proposed work plan, our exploration also uncovered an unanticipated new fundamental physics result. Considering the average motion of a test charge moving through a plasma, the friction force acting on that test charge is commonly thought to always act anitparallel to its velocity vector. Our new result showed that if the plasma is strongly magnetized in the sense that the gyrofrequency significantly exceeds the plasma frequency, the friction force also has a second component that is perpendicular to the velocity vector in the plane formed by the velocity and magnetic field vectors. This result, communicated in reference 7, also showed that the transverse force significantly influences the trajectory of the test charge. It is a finding that has broad implications for transport properties in strongly magnetized plasmas, and we have planned a range of followup work to investigate this further. Ultracold plasmas are an excellent candidate experiment to test this prediction.

One of the ultimate goals of this project was to use the theoretical investigations to show that interesting physics effects can be accessed by magnetized ultracold plasmas, and to motivate experimentalists in this field to include applied magnetic fields in their experiments. The work has led to a number of interesting proposals, including the self-consistent generation of electron temperature anisotropy, definition of the fundamental coupling-magnetization phase-space defining regimes of plasma transport, and the discovery of the transverse friction force. The goal of motivating experimentalists to create magnetized ultracold plasmas has promising signs of progress, as the group of Prof. Jacob Roberts at Colorado State University has recently demonstrated a successful set of experiments at conditions of moderate electron coupling strength ($\Gamma_e \approx 0.1$) and very strong magnetization ($\beta_e > 20$). These are ideal conditions to test the physical effects proposed from our work, and we see this as a promising sign for the future growth of this field.

2 Published Work

The results of this project were disseminated in the following peer-reviewed publications:

1. S. D. Baalrud, and J. Daligault, "Effective Potential Kinetic Theory for Strongly Coupled Plasmas," AIP Conference Proceedings **1789**, 130001 (2016).
2. S. D. Baalrud and J. Daligault, "Temperature Anisotropy Relaxation of the One-Component Plasma," Contributions to Plasma Physics **57**, 238 (2017).
3. S. D. Baalrud, and J. Daligault, "Transport Regimes Spanning Magnetization-Coupling Phase-Space," Physical Review E **96**, 043202 (2017).
4. N. R. Shaffer, S. K. Tiwari, and S. D. Baalrud, "Pair Correlation Functions of Strongly Coupled Two-Temperature Plasma," Physics of Plasmas **24**, 092703 (2017).
5. S. K. Tiwari, and S. D. Baalrud, "Reduction of Electron Heating by Magnetizing Ultracold Neutral Plasma," Physics of Plasmas **25**, 013511 (2018).
6. S. D. Baalrud and J. Daligault, "Mean Force Kinetic Theory: A Convergent Kinetic Equation for Weakly and Strongly Coupled Plasmas," Physics of Plasmas **26**, 082106 (2019).
7. T. Lafleur and S. D. Baalrud, "Transverse Force Induced by a Magnetized Wake," Plasma Physics and Controlled Fusion **61**, 125004 (2019).
8. S. D. Bergeson, S. D. Baalrud, C. L. Ellison, E. Grant, F. R. Graziani, T. C. Killian, M. S. Murillo, J. Roberts and L. G. Stanton, "Exploring the Crossover Between High-Energy-Density Plasma and Ultracold Neutral Plasma Physics," Physics of Plasmas **26**, 100501 (2019).

Two manuscripts are currently in the late stages of preparation, and will be submitted within a few weeks (July 2020):

9. K. R. Vidal, J. Daligault, and S. D. Baalrud, "Size Effects in Molecular Dynamics Simulations of the Unmagnetized and Magnetized One-Component Plasma," in preparation.
10. L. Jose, and S. D. Baalrud, "A Generalized Boltzmann Kinetic Theory for Strongly Magnetized Plasmas," in preparation.

3 Results

The following sections summarize the main results of this project, categorized in terms of the three categories of goals: analytic theory, molecular dynamics simulations (for validation), and exploring implications for ultracold plasma experiments.

3.1 Theory

3.1.1 Mean force kinetic theory

One of the main results of this project was first derivation of a kinetic theory for a strongly coupled plasma based upon a single expansion parameter. Traditional plasma theories are based on expansion parameters that order either in the strength or range of interactions. However, these ultimately fail to provide a self-consistent theory because they apply only in the short or long range limits, respectively. As a result, the kinetic equations diverge in one or the other limits. These divergences are resolved via ad hoc assumptions related to the plasma being weakly coupled. Since we are interested in strongly coupled plasmas, these do not apply, and the basic starting points of the traditional theories are not appropriate.

The new theory proposes a new expansion parameter. Instead of ordering in the strength or range of interactions, this expansion parameter orders the difference between higher and lower order correlations, referenced to their equilibrium values. The reference to equilibrium values ensures that the theory remains consistent with equilibrium statistical mechanics (a limit that is not obeyed by the traditional theories) and, as a consequence, does not encounter divergences. The result of this expansion parameter is a self-consistent derivation of the effective potential theory (EPT) collision operator that has formed the basis of our theoretical developments to date. Previously, this collision operator was obtained from a postulate that interactions occur via the potential of mean force (rather than the bare Coulomb potential). The results of this postulate were shown to agree very well with MD simulations and ultracold neutral plasma experiments, extending plasma theory well into the strong coupling regime. The new theory places this on a rigorous footing by deriving the collision operator in a self-consistent way (i.e., by deriving the previous postulate of mean force interactions). It also extends the previous theory by providing the non-ideal aspects of the equation of state properties. Since the theory preserves the exact limit of local thermodynamic equilibrium, it retains the exact statistical expressions for excess pressure and internal energy (which are not included in traditional kinetic theories). We consider this to be a significant advance toward our goal of understanding transport in magnetized ultracold neutral plasmas.

These results were published in reference 6 cited above, and connections with ultracold neutral plasma experiments are described in the review paper of reference 8.

3.1.2 Landau form of the Effective Potential Theory

The Effective Potential Theory (EPT) that we have developed is a modification of the Boltzmann collision operator. A disadvantage of the Boltzmann collision operator is that it is difficult to solve in a direct kinetic simulation. Currently there is no direct kinetic simulation technique available for strongly coupled plasmas because of the absence of a tractable kinetic equation (particle simulations, such as MD, are confined to very small physical dimensions). In this work, we derived an approximate version of the EPT collision operator cast in the form of the Landau collision operator (or, equivalently, as a Fokker-Planck collision operator). Such a collision operator is computationally much less expensive to solve, but questions remain on the comparative accuracy between this and the Boltzmann equation because the former is derived from an approximation of the later. In this paper, we showed that the lowest-order expression for the friction force density and energy exchange density between shifted Maxwellian distributions are identical from each formalism. This is encouraging because it suggest that one may be able to base a kinetic code on this simplified equation without sacrificing much in terms of accuracy. This has motivated a more thorough study of the transport properties implied by this approximate expression, where heat flux and energy weighted heat flux terms are included in a comprehensive Chapman-Enskog type solution including a magnetic field.

These results were published in reference 1 cited above.

3.1.3 Friction in a strongly magnetized plasma

In our development of a kinetic theory for strongly magnetized plasmas, we discovered an unanticipated result that we consider significant. Applying a linear response approach, we computed the friction force on a single particle moving through a strongly magnetized plasma. In this context, strong magnetization refers to a plasma in which the electron gyrofrequency significantly exceeds the electron plasma frequency. Usually friction is thought to be a force that acts in opposition to the motion of a body (or particle in this case), so that it is aligned antiparallel to the velocity vector. We found that a novel effect arises if the plasma is strongly magnetized: a second component of the friction force arises that is directed perpendicular to both the velocity vector and Lorentz force vectors. We dubbed this the "transverse friction force". The physical origin of this force can be understood within the linear response theory by considering the electrostatic wake potential that is excited in the plasma by the motion of the charge (see figure 1). Usually this wake is symmetric about the velocity vector, and the friction force computed from the induced electric field associated with this wake acts antiparallel to the velocity vector. However, if the background plasma is strongly magnetized, the action of the Lorentz force on the background plasma causes the wake to rotate such that the center of induced charge no longer lies along the velocity vector. This rotation is the origin of the transverse component of the force.

This work is a significant milestone because it identifies a novel effect that collisions in the presence of strong magnetization causes a coupling between parallel and perpendicular dynamics that is not a part of traditional plasma kinetic theory. That is because the collision operator in traditional plasma kinetic theories are based on an assumption that the gyrofrequency is much smaller than the plasma frequency, in which case gyromotion does not influence dynamics at the spatial scale of interactions. This work shows qualitatively new physics arises at strong magnetization, and may explain the apparent coupling between parallel and perpendicular diffusion coefficients that we observed in MD simulations in our previous work on this project (see below), which is not yet explained.

These results were published in reference 7 cited above.

3.1.4 Kinetic theory of strongly magnetized plasmas (Louis Jose)

Graduate student Louis Jose developed a new kinetic theory to treat Coulomb collisions in strongly magnetized plasmas. Coulomb collisions in plasmas are typically modeled using the Boltzmann collision operator, or its variants, which apply to weakly magnetized plasmas in which the typical gyroradius of particles signicantly exceeds the Debye length. Conversely, O'Neil has developed a kinetic theory to treat plasmas that are so strongly magnetized that the typical gyroradius of particles is much smaller than the distance of closest approach in a binary collision. In this work, we develop a generalized collision operator that applies across the full range of magnetization strength. To demonstrate novel physics associated with strong magnetization, it was used to compute the friction force on a massive test charge. In addition to the traditional stopping power component, this is found to exhibit a transverse component that is perpendicular to both the velocity and Lorentz force vectors in the strongly magnetized regime, as was predicted recently using linear response theory (described in the previous section). Good agreement is found between the collision theory and linear response theory in the regime in which both apply (see figure 2) but the new collision theory also applies to stronger magnetization strength regimes in which the linear response theory breaks down.

The significance of this result is that provides a generalized theory to treat any regime of magnetization, and it also provides a framework that be solved using known methods (the Chapman-

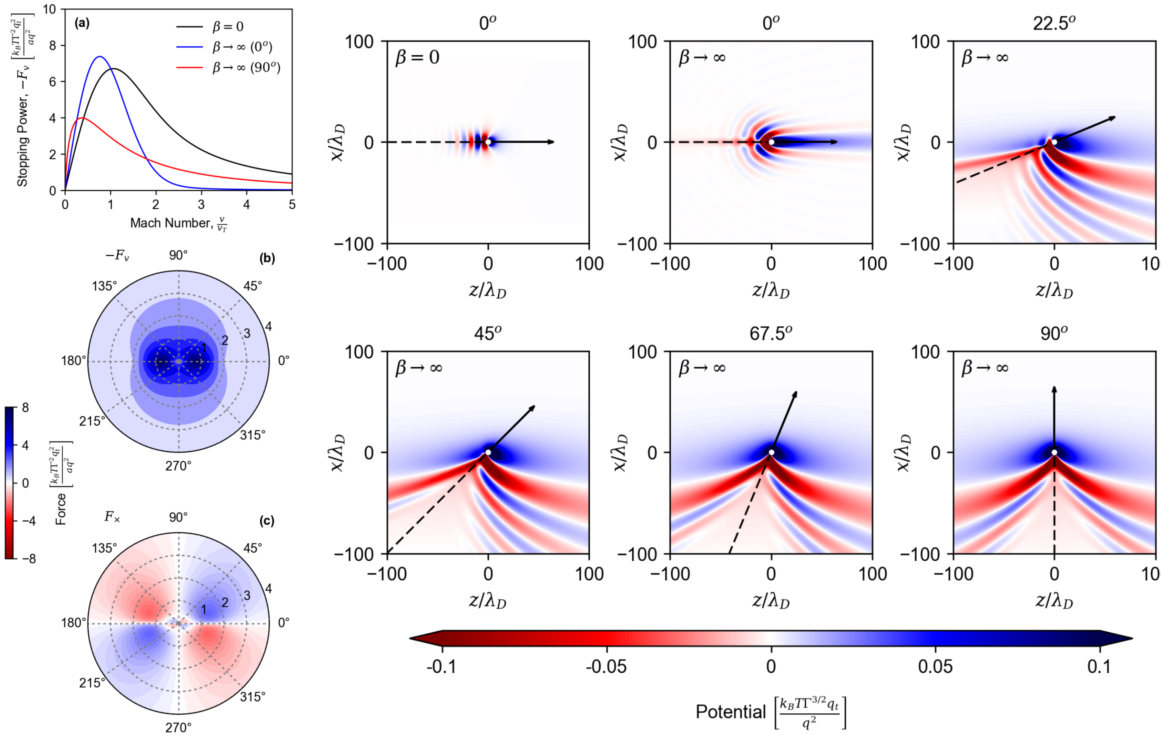

Figure 1: (left) a) Stopping power ($-F_v$) of a test charge in an unmagnetized plasma (black line) compared with the strong field limit when the velocity of the charge is oriented parallel (blue line) or perpendicular (red line) to the magnetic field. The bottom panels show polar plots of the two force components computed in the strong field limit: (b) stopping power ($-F_v$) and (c) transverse force $F_\times$. Here, the coupling strength is taken to be $\Gamma = 10^{-3}$. (right) Wake potential surrounding a test charge moving at a supersonic velocity ($M = 2$) at the indicated angle with respect to the magnetic field. The magnetic field is zero in the top left panel, while it is computed from the strong field limit in the others.

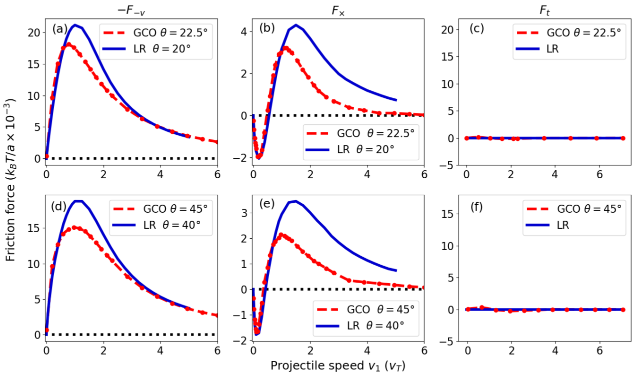

Figure 2: Comparison of the linear response theory predictions and the generalized collision operator predictions for the three components of the friction force acting on a test charge in a plasma. Here, $\Gamma = 0.1$ and $\beta = 10$.

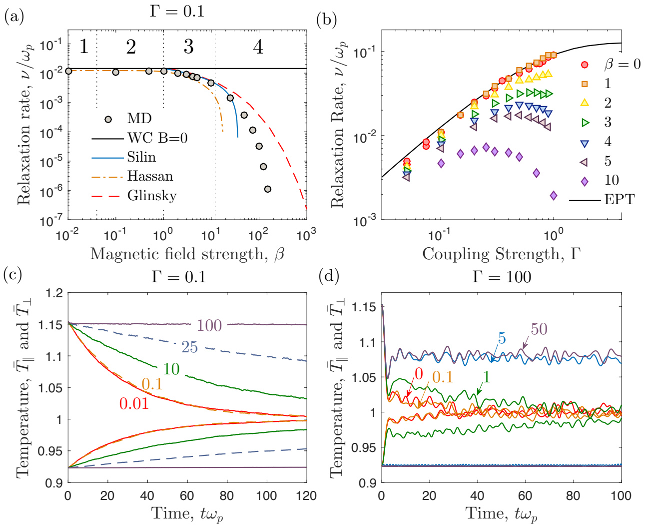

Figure 3: (a) Temperature anisotropy relaxation rate versus magnetization strength at $\Gamma = 0.1$ from the standard theories (lines) and MD (circles). (b) Temperature anisotropy relaxation rate versus coupling strength from MD simulations (data points) and the EPT theory (line). (c) and (d) Parallel and perpendicular temperature time profiles from MD for $\Gamma = 0.1$ and 100 at fixed values of β indicated on the figure.

Enskog method) to derive magnetohydrodynamics equations. Evaluating this theory has been a significant computational challenge that has required several significant numerical developments. The first was the development of a code to simulate the collision of two charged particles orbiting in a strong magnetic field. The particular challenge that we ran into is that, under some conditions of magnetic field strength, the particles could get extremely close to one another. This led to errors because a fixed time step was being used. To overcome this, Mr. Jose wrote a code using an adaptive time stepping algorithm. The result has been verified and is now being used routinely. The second main computational challenge is that the evaluation of the friction force, or transport rates, requires evaluating a 5-dimensional integral. Louis developed a Monte Carlo integrator, coupled with his trajectory calculator, to perform this integral.

These results are being finalized for publication, see reference 10 above.

3.2 MD simulation tests

3.2.1 Temperature Anisotropy Relaxation of the OCP

The relaxation rate of a Maxwellian velocity distribution function that has an initially anisotropic temperature ($T_\| \neq T_\perp$) is an important physical process in space and laboratory plasmas. It is also a canonical example of an energy transport process that can be used to test theory. It is one that is especially relevant to ultracold neutral plasmas, as experiments are currently being conducted to measure this rate, and a temperature anisotropy is expected for form naturally in a magnetized ultracold plasma (see below). Here, this rate is evaluated using molecular dynamics simulations of the one-component plasma. Results are compared with the predictions of four kinetic theories; two treating the weakly coupled regime (1) the Landau equation, and (2) the Lenard-Balescu equation, and two that attempt to extend the theory into the strongly coupled regime (3) the effective potential theory and (4) the generalized Lenard-Balescu theory. The role of dynamic screening

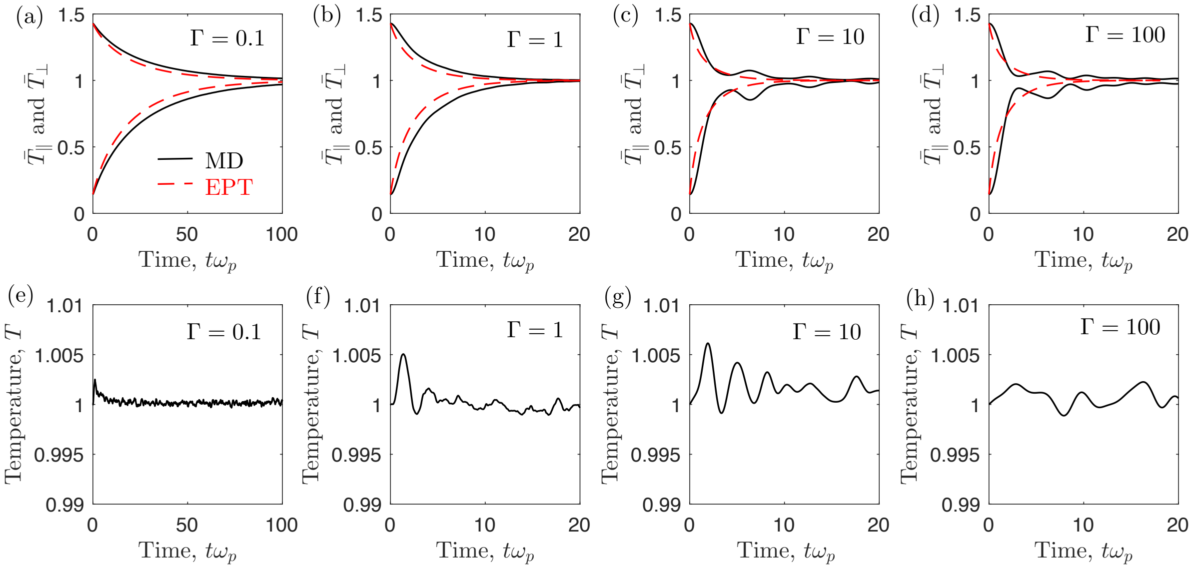

Figure 4: Time dependent temperature profiles with a highly anisotropic initial condition of $T_\perp/T_\parallel = 10$ ($A = 9$). Panels (a)–(d) show the parallel ($\bar{T}_\parallel = T_\parallel/T$) and perpendicular ($\bar{T}_\perp = T_\perp/T$) temperatures from MD simulations (black solid lines) and predictions from EPT (red dashed lines). Panels (e)–(h) show the total kinetic temperature as a function of time in terms of its initial value ($T(t)/T_o$).

is studied, and is found to have a negligible influence on this transport rate. Oscillations and a delayed relaxation onset in the temperature profiles are observed at strong coupling, which are not described by the kinetic theories.

The main results of this work include:

1. Development of EPT theory for temperature anisotropy relaxation.
2. Validation of the EPT using MD simulations: see fig 4.
3. First test of several other theories using MD (Landau, Lenard-Balescu and Ichimaru).
4. Observation and quantification of how the standard exponential relaxation breaks down, and is influence by oscillations in time due to correlation effects at strong coupling; see fig. 4.

These results were published in reference 2 cited above.

3.2.2 Pair Correlation in Two-Temperature Plasmas

Transport theory for ultracold plasmas must account for the fact that electrons are much hotter than ions. Doing so is complicated in the moderate-to-strongly correlated regime because one cannot rely on equilibrium statistical thermodynamics to provide inputs to the theories, such as a local field correction or effective interaction potential (potential of mean force). Such inputs are provided by a thermodynamic property called the pair distribution function (or pair correlation function), which is often modeled using the hypernetted chain approximation in combination with the Ornstein-Zernike equation. Extending these to non-equilibrium (two temperature) plasmas is a formidable task. A few independent attempts have been made, but their accuracy had never been tested.

In this work, we used molecular dynamics simulations to test the three leading proposed theories. We found that the model proposed by Seuferling, Vogel and Toepffer [Phys. Rev. A **40**, 323 (1989)] consistently provided the most accurate predictions over conditions relevant to ultracold neutral plasmas. This model was found to be quite accurate over the range of conditions of interest, with an accuracy comparable to the traditional HNC-OZ theory at equilibrium conditions. Having this validation significantly advances our project because we now have a working model that provides the input to the effective potential theory that we are using to model transport properties. We also developed an accurate approximation of the model for ultracold plasma conditions, where the electron coupling is weak to moderate. In this regime, we found that a piece of the multispecies Ornstein-Zernike equations could be decoupled in the electron-ion interaction. This simplification allows one to accurately model the electron-electron and electron-ion pair correlation functions based on knowledge of the ion-ion pair correlation function; a significant computational advantage.

These results were published in reference 4 cited above.

3.2.3 Diffusion in strongly magnetized plasmas (Keith Vidal)

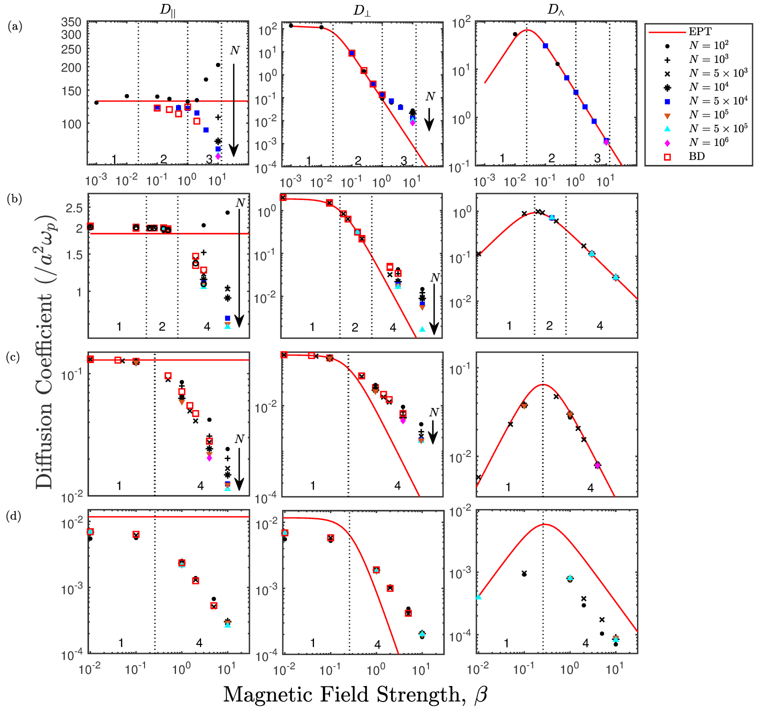

Figure 5: MD simulation results for diffusion coefficients in the unmagnetized regime (Regime I), weakly magnetized regime (Regime II), and the strongly magnetized regime (Regime III).

Graduate student Keith Vidal has completed his study of the computational requirements for MD simulations of magnetized strongly coupled plasmas. Molecular dynamics simulations are often used to compute transport coefficients in plasmas with moderate or strong Coulomb coupling and either weak or no magnetization. This work investigates the computational requirements necessary to extend this method to regimes of weak Coulomb coupling, as well as strong magnetization, with an emphasis on the number of particles required to compute self-diffusion coefficients. In comparison to expectations from the strongly coupled unmagnetized regime, far fewer particles are required if the plasma is both weakly coupled and either unmagnetized or weakly magnetized because the

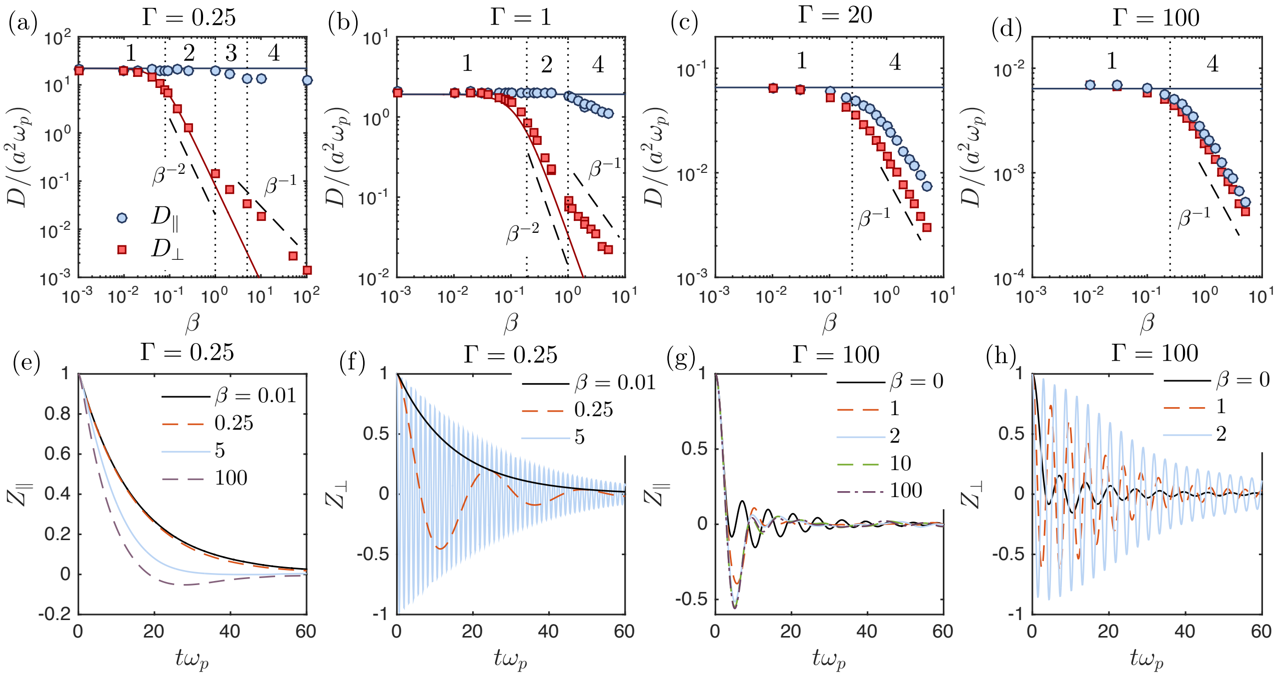

Figure 6: (a)-(d) $D_\parallel$ (circles) and $D_\perp$ (squares) obtained from MD simulations. Solid lines in (a) and (b) show predictions of the EPT theory, and in (c) and (d) show D_o obtained from MD at $B = 0$. The vertical dashed lines indicate the boundaries from Fig. 7. Panels (e)-(h) show the velocity autocorrelation functions at $\Gamma = 0.25$ (e,f) and $\Gamma = 100$ (g,h).

particle-particle particle-mesh (P3M) method accurately accounts for weak long-range interactions across periodically replicated cells. In contrast, far more particles are required if the plasma is strongly magnetized in the sense that the gyrofrequency is greater than the plasma frequency. This is because strong magnetization creates a long-range correlation parallel to the magnetic field that increases in range with increasing magnetic field strength. These results suggest that compared to previous expectations it is less computationally expensive to simulate plasmas that are weakly coupled and weakly magnetized, but more computationally expensive to simulate plasmas that are strongly magnetized (see figure 5).

These results are being finalized for publication, see reference 9 above.

3.3 Exploring implications for experiments

3.3.1 Transport Regimes of Magnetized Plasmas

The manner in which transport properties vary over the entire parameter-space of coupling and magnetization strength was explored for the first time. Four regimes are identified based on the relative size of the gyroradius compared to other fundamental length scales: the collision mean free path, Debye length, distance of closest approach and interparticle spacing. Molecular dynamics simulations of self-diffusion and temperature anisotropy relaxation spanning the parameter space are found to agree well with the predicted boundaries. Comparison with existing theories reveals regimes where they succeed, where they fail, and where no theory has yet been developed.

Some exciting discoveries are described in this manuscript, including:

1. The first identification of the fundamental regimes of plasma transport spanning the coupling-

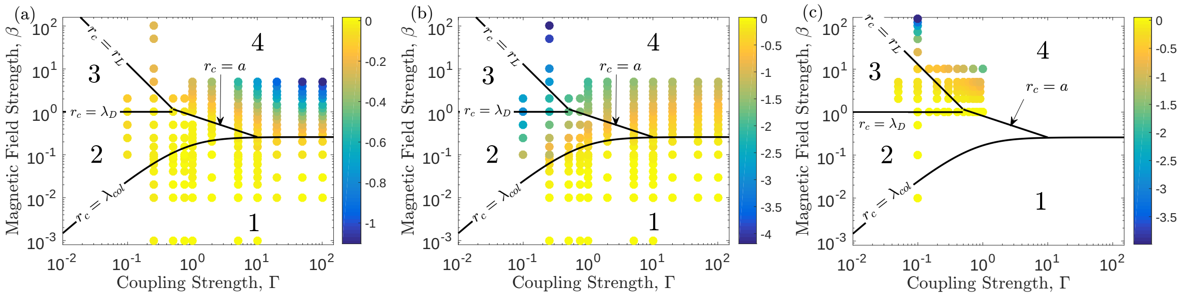

Figure 7: Four transport regimes in the magnetic field strength (β) versus coupling strength (Γ) phase space: the color of circles indicates the value of (a) $\log_{10}(D_{\parallel}/D_o)$, (b) $\log_{10}(D_{\perp}/D_o)$, and (c) $\log_{10}(\nu/\nu_o)$ obtained from MD simulations.

magnetization phase-space. These are indicated in Fig. 7: 1) unmagnetized, 2) magnetized (Braginskii), 3) strongly mangetized, 4) extremely magnetized. Especially interesting is that the standard regimes from weakly coupled plasma theory (2 and 3) completely vanish at strong coupling.

2. Validation of the proposed transport regimes using MD simulations of self-diffusion and temperature anisotropy relaxation of the OCP. This can be seen in figures 7-3 where transitions in transport properties occur at the predicted boundaries.

3. The first test of the standard Branginskii transport theory using MD simulations (Fig. 6), as well as many others for the temperature anisotropy relaxation 3.

4. Development and validation of the EPT theory in the magnetized regime for diffusion and temperature anisotropy relaxation. This was the primary milestone for year 1.

5. Discovery that strong magnetization can onset strong Coulomb coupling effects due to reducing the number of degrees of freedom of particle motion. This can be seen via correlation features in the velocity autocorrelation functions in Fig. 6.

6. Discovery of Bohm scaling B^{-1} of the perpendicular diffusion coefficient in region 3; see Fig. 6. This is a result that is not predicted by any theory that we are aware of, and could potentially have major consequences for understanding strongly magnetized plasmas.

These results were published in reference 3 cited above.

3.3.2 Reducing Electron Heating in Ultracold Plasmas with a Magnetic Field

This work showed two significant results: (1) An applied magnetic field can dramatically suppress electron disorder induced heating in the direction perpendicular to the magnetic field, and (2) an applied magnetic field can suppress electron heating due to three-body recombination by a factor of 3. These conclusions are based on a series of molecular dynamics simulations. The suppression of electron heating occurs because the strong magnetization effectively confines electron motion to one dimension. Heating is observed to occur only in the direction of the magnetic field. This leads to a spontaneously generated and highly anisotropic electron velocity distribution function (anisotropic temperature). Eventually the distribution function collisionally relaxes (equipartitions), and heating occurs perpendicular to the field as well. However, the temperature anisotropy relaxation rate is dramatically reduced if the field is high enough, and may be essentially eliminated over the timescales at which experiments are performed.

These results have interesting implications for possible experiments. They suggest that a modest applied magnetic field of 0.1 T could strongly magnetize electrons at current experimental conditions over the timescales of electron dynamics (several to hundreds of electron plasma periods). Experiments such as Prof. Robert's at Colorado State University are designed to focus on such electron processes. Furthermore, a field strength of 0.5 T, or so, could extend the suppression of electron heating (and the temperature anisotropy) to timescales characteristic of ion dynamics (μs timescales). This is interesting because it has the potential to increase the overall electron coupling strength by a factor of 3. It also causes a dramatically slower expansion of the plasma (particularly in the direction perpendicular to the magnetic field), which may be used in combination with ion cooling to substantially increase the ion coupling strength. The spontaneous formation of a temperature anisotropy is also potentially interesting because observing it's relaxation may provide a direct measure of electron energy transport. Furthermore, the anisotropic electron distribution may have an interesting influence on ion transport via anisotropic screening.

These results were published in reference 5 cited above.

4 Interactions and Collaborations with Experimental Groups

We continue to interact with experimental groups in the ultracold plasma field. One significant activity was participation in the workshop on the "Cross Over of High Energy Density and Ultracold Neutral Plasmas" at the 2018 APS Division of Plasma Physics meeting. PI Baalrud presented at this meeting, and is participating in a manuscript co-authored by the group participants was published in Physics of Plasmas (reference 8).

Prof. Jacob Roberts of Colorado State University visited the University of Iowa in March of 2018 to give a colloquium and to discuss potential collaborations. This has continued to be a fruitful interaction. We are currently exploring two avenues with them. The first is on the "Barkas" effect, where it is predicted theoretically that the opposite sign of electron and ion charge may influence electron-ion transport rates if the plasma is moderate to strongly coupled (our work on this topic was supported by an NSF grant). This work was completed by Nathaniel Shaffer, who graduated in December of 2018, and Prof. Roberts served on his thesis committee. The second avenue we are exploring (more directly based on our AFOSR project) is the possibility of measuring the electron-ion collision rate if electrons are magnetized. We are currently working on the theory of this process (as described above), and they are beginning experiments with an applied magnetic field. We are discussing these future experiments so that we can evaluate our theory for a transport process that is as close as possible to the process that they will measure.

In addition, Prof. Baalrud visited Rice University to give a plasma seminar and to discuss results and potential collaborations with Prof. Thomas Killian in late March 2018. This also led to interesting interactions. Their group is currently measuring temperature anisotropy relaxation rates. We discussed the application of our recent theory to their measurements, as well as how similar measurements in the presence of an external magnetic field might be interesting. We also discussed the possible combination of their recent ion cooling technique, along with magnetization, to potentially reach much higher ion coupling strengths. This seems promising, and we expect to continue these conversations.

5 Contribution to career advancement of participants

This Young Investigator Award has supported the PI (Scott Baalrud), two graduate students (Keith Vidal and Louis Jose) and one postdoc (Dr. Sanat Tiwari until Nov. 2017). It has contributed significantly to career advancement. Both graduate students are making steady progress toward their PhD theses. In 2017, Dr. Sanat Tiwari obtained a faculty position as an Assistant Professor at the Indian Institute of Technology, Jammu. The PI was awarded the "2018 Hershkowitz Early Career Award" by the journal Plasma Sources Science and Technology. In the previous year, he was awarded tenure and promotion to Associate Professor in 2018, as well as the "Dean's Scholar Award" in the College of Liberal Arts and Sciences at U. Iowa, and the university-wide "Early Career Scholar of the Year Award" for 2017.

6 Presentations

The following provides a list of presentations that communicated the results of the research supported under this grant:

Colloquia and seminars (by PI Baalrud):

1. *Is This Even a Plasma? The Physics of Strongly Coupled Plasmas*
   Colloquium, Physics Department, University of Wisconsin, Madison, WI (7 February 2020).
2. *Mean Force Kinetic Theory: a Convergent Kinetic Theory for Weakly and Strongly Coupled Plasmas*
   Plasma Physics Seminar, University of Iowa, Iowa City, IA (11 March 2019).
3. *Is This Even a Plasma? The Physics of Strongly Coupled Plasmas*
   Seminar, Physics Department, Rice University, Houston, TX (26 March 2018).
4. *Transport Properties of Dense Plasmas*
   Seminar, High Energy Density Science Center, Lawrence Livermore National Laboratory, Livermore, CA (11 January 2018).
5. *Is This Even a Plasma? The Physics of Strongly Coupled Plasmas*
   Colloquium, Physics Department, Grinnell College, Grinnell, IA (3 October 2017).
6. *Is This Even a Plasma? The Physics of Strongly Coupled Plasmas*
   Colloquium, Physics and Astronomy Department, University of Iowa, Iowa City, IA (13 November 2017).
7. *Is This Even a Plasma? The Physics of Strongly Coupled Plasmas*
   Colloquium, Physics Department, Auburn University, Auburn, AL (22 September 2017).
8. *Intriguing Transport Properties of Magnetized Ultracold Neutral Plasmas*
   Plasma Physics Seminar, University of Iowa, Iowa City, IA (20 Febrary 2017).

Invited conference presentations (by PI Baalrud):

1. *Mean Force Kinetic Theory*
   Sixty-First Annual Meeting of the American Physical Society Division of Plasma Physics, Fort Lauderdale, FL (October 2019).

2. *Transport Regimes of the Magnetized One-Component Plasma*
   Twelfth International Workshop on Non-neutral Plasmas, Lawrence University, Appleton, WI (July 2017).

Contributed Conference Presentations:

1. L. Jose and S. D. Baalrud
   Collisional Relaxation of Temperature Anisotropy in a One-Component Plasma
   Sixty-First Annual Meeting of the American Physical Society Division of Plasma Physics, Ft. Lauderdale, FL (October 2019).

2. K. Vidal, S. D. Baalrud, and J. Daligault
   Diffusion of Strongly Magnetized One-Component Plasma
   Sixty-First Annual Meeting of the American Physical Society Division of Plasma Physics, Ft. Lauderdale, FL (October 2019).

3. S. D. Baalrud and T. Lafleur
   Transverse Force Induced by a Magnetized Wake
   Sixty-First Annual Meeting of the American Physical Society Division of Plasma Physics, Ft. Lauderdale, FL (October 2019).

4. S. D. Baalrud, J. Daligault, C. Starrett, and D. Saumon
   Theory for Ion Transport in Ultracold and High Energy Density Plasmas
   Sixtieth Annual Meeting of the American Physical Society Division of Plasma Physics, Portland, OR (November 2018).

5. S. D. Baalrud
   Effective Potential Theory for Magnetized Plasmas
   Sixtieth Annual Meeting of the American Physical Society Division of Plasma Physics, Portland, OR (November 2018).

6. K. R. Vidal, S. D. Baalrud, and J. Daligault
   Molecular Dynamics Simulations of Diffusion in the Strongly Magnetized One-Component Plasma
   Sixtieth Annual Meeting of the American Physical Society Division of Plasma Physics, Portland, OR (November 2018).

7. S. D. Baalrud, J. Daligault, C. Starrett and D. Saumon
   Theory for Ionic Transport Properties of High Energy Density Plasmas
   LaserNetUS, Lincoln, NE (August 2018).

8. S. D. Baalrud and J. Daligault
   Collisional Transport in Strongly Magnetized Plasmas
   International Sherwood Fusion Theory Conference, Auburn, AL (April 2018).

9. S. D. Baalrud, S. Tiwari and J. Daligault
   Transport Regimes Spanning Magnetization-Coupling Phase Space
   Fifty-Ninth Annual Meeting of the American Physical Society Division of Plasma Physics, Milwaukee, WI (October 2017).

10. K. Vidal and S. D. Baalrud
    Diffusion of Magnetized Binary Ionic Mixtures at Ultracold Plasma Conditions
    Fifty-Ninth Annual Meeting of the American Physical Society Division of Plasma Physics, Milwaukee, WI (October 2017).

11. N. R. Shaffer, S. K. Tiwari and S. D. Baalrud
    Radial Distribution Functions of Strongly Coupled Two-Temperature Plasmas
    Fifty-Ninth Annual Meeting of the American Physical Society Division of Plasma Physics, Milwaukee, WI (October 2017).

12. S. K. Tiwari, N. R. Shaffer, and S. D. Baalrud
    Structural and Dynamical Properties of Recombining Ultracold Neutral Plasmas
    Fifty-Ninth Annual Meeting of the American Physical Society Division of Plasma Physics, Milwaukee, WI (October 2017).

13. N. R. Shaffer, S. K. Tiwari, and S. D. Baalrud
    Radial Distribution Functions of Strongly Coupled Two-Temperature Plasmas
    Twelfth International Workshop on Non-neutral Plasmas, Lawrence University, Appleton, WI (July 2017).

14. S. K. Tiwari, and S. D. Baalrud
    Reduction of Electron Heating in a Magnetized Ultracold Plasma
    Twelfth International Workshop on Non-neutral Plasmas, Lawrence University, Appleton, WI (July 2017).

15. S. Baalrud and J. Daligault
    Transport Theory for Plasma that are Strongly Magnetized and Strongly Coupled
    Fifty-Eighth Annual Meeting of the American Physical Society Division of Plasma Physics, San Jose, CA (November 2016).