White Paper for *Frontiers of Plasma Science Panel*

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• Statistical mechanics of plasmas	P

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Title:	**Ultracold Neutral Plasmas at the Plasma Physics Frontier**
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I. DESCRIBE THE RESEARCH FRONTIER AND IMPORTANCE OF THE SCIENTIFIC CHALLENGE

Neutral plasmas typically require temperatures in excess of 1000 K to sustain thermal ionization. However, recent work has dropped this threshold dramatically, introducing a new domain of plasma physics. Ultracold neutral plasmas (UCNPs) form with ion temperatures on the order of 1 K and tunable electron temperatures from 1-1000 K [1]. Pulsed laser excitation creates these unusual plasmas by photoionizing laser-cooled atomic gases, or in some cases, atoms or molecules cooled in supersonic atomic or molecular beams [2, 3]. Around a dozen experimental teams, using lasers and tabletop vacuum systems, have established a set of well-characterized quasi-equilibrium ultracold atomic and molecular plasmas. A similar number of theoretical groups are using computer clusters and large-scale computational facilities to develop increasingly complete particle and continuum models for UCNP dynamics.

UCNPs offer a powerful platform for studying important topics at the frontiers of fundamental plasma physics. Among important emerging utiliities, UCNPs: • Provide a unique window on collisions and transport in strongly coupled plasmas [4, 5]; • Offer controlled conditions for continuum lowering measurements [6–8]: • Facilitate equilibration and shock formation studies in colliding plasmas [9]; • Support the study of collisions and transport under highly magnetized conditions [10]; • Directly test the predictions of theoretical simulation models across a large range of time and length scales [11]; and • Serve as new sources for bright electron and ion beams with improved resolution for imaging and nanomachining [12].

The adjustment of experimental parameters can tune an ultracold plasma system over a range of Coulomb coupling from weak to strong. Strong coupling represents a frontier of particular importance to many fields beyond plasma physics, including atomic, condensed matter, and nuclear/particle physics. This condition gives rise to extremely non-ideal states of charged-particle systems, defined by structural and dynamical order, and it fundamentally changes transport properties [12–16]. These effects play an important but incompletely understood role in shaping in astrophysical, warm dense matter, and ICF plasmas.

As millimeter-scale laboratory systems, UCNPs provide a highly accessible medium for studying the physics of strongly coupled plasmas, especially involving transport and collisional phenomena and dynamics far from local-thermal equilibrium. The low density of UCNPs slows dynamical timescales, facilitating a mapping of time-resolved density and velocity distributions and coupling microwave and RF fields to collective modes. UCNPs typically possess few if any complications owing to the electronic structure of ionic components, as found in high-density strongly coupled plasmas, such as a competition between ionization states, isolating the effects of strong coupling. UCNPs differ significantly from other low-temperature strongly coupled plasmas such as non-neutral ion or electron plasmas or dusty plasmas. They represent perhaps the purest realization of an ideal Yukawa one-component plasma, a paradigm widely used in statistical physics to explore the transition from very long to very short interactions [17].

The realization of strong coupling in a laboratory ultracold plasma presents profound challenges for plasma theory. Coulomb collisions in plasmas are traditionally described in terms of the Coulomb logarithm (CL), which is defined by the ratio of the impact parameter of closest approach to the Debye screening length. In terms of the usual Coulomb coupling parameter Γ the CL is roughly $\ln(1/3\Gamma)$. It is therefore clear that a collision model that employs the CL catastrophically breaks down when $\Gamma \sim \frac{1}{3}$. Such plasmas respond very sensitively to changes in collisional conditions without the usual complexities of very strong coupling. In the regime from $\Gamma = 1/3$ to 10, details of the trajectories that determine the minimum impact parameter critically depend on the shape of the screening cloud, which deviates from its usual Debye-Hückel form, and is likely affected by dynamical screening effects. UCNPs very readily probe this regime of plasma physics [18, 19]. Everything we learn from collision processes in such plasmas will impact our understanding of plasma kinetic theory beyond the usual Fokker-Planck approach and provide validation for collision models in plasma modelling codes.

The number of particles in an UCNP experiment strain the scale limits of molecular dynamics (MD) simulations. Reduced fidelity models (e.g., hybrid hydro-kinetic) more readily handle the length and time scales, but fail to capture important aspects of the collisional and strong coupling physics. Therefore, experimental progress in UCNP research drives the development of MD algorithms to realistically simulate all the observed physics, including moderate coupling, collision dynamics on electron and ion time scales, (heterogeneous) hydrodynamic expansion, and possibly the added effects of magnetic fields. Because experiments can readily contol initial conditions, they can produce a range of plasmas that challenges the computational state-of-the-art. Moreover, recent progress in experiment and theory has led to the introduction of new computational models that include the physics of moderate coupling but more easily reach the scales required, such as multiscale models that employ MD coupled to a macroscale model. The scale of UCNP is ideal for validating such models, which would have a wider utility in the plasma community.

II. DESCRIBE THE APPROACH TO ADVANCING THE FRONTIER AND INDICATE IF NEW RESEARCH TOOLS OR CAPABILITIES ARE REQUIRED.

Advances in the field are driven by innovation in experiment and theory that occurs in small-scale research groups, adapting cost effective improvements in laser technology, and rapidly increasing computational power.

- **Stronger Coupling:** Present research in ultracold plasma physics seeks to create plasmas with greater Coulomb coupling reaching deeper into the liquid regime, even to the solid-liquid phase transition. Schemes under consideration include laser cooling to reduce the translational energy of UCNP ions [20], and the use of Rydberg interactions to create states of pre-correlation [21, 22]. This will increase ion-ion correlation by an order of magnitude. Novel excitation geometries promise to harness hydrodynamic effects to cool and compress evolving plasmas to similar effect.

- **Multispecies Plasmas:** Experiments have succeeded in creating a second neutral plasma or Rydberg gas within an established ultracold plasma [9]. Related approaches will engineer the microstructure of atomic and molecular plasma volumes. Extending this work to multi-speices UCNPs where both species can be individually imaged will enable one plasma to probe or alter another, and open new avenues for equilibration studies.

- **Magnetization:** Low UCNP temperatures permit magnetizations such that the Larmor radius of ions (electrons) is comparable to (much smaller than) the Coulomb collision parameter at relatively low magnetic fields of $\sim$0.1T.
- **Plasma Kinetic Theory:** Most of plasma kinetic theory is based on perturbative expansions of the BBGKY hierarchy, including the binary scattering expansion of Boltzmann/Fokker-Planck and the correlation expansion of Vlasov/Lenard-Baslescu models [23]. When the collective and collision dynamics become inseparable, kinetic models must incorporate elements from each of these branches of kinetic theory. Ultracold neutral plasma physics operate in such a regime, demanding a coordinated effort between theory and experiment.
- **Computational Plasma Modelling:** Experiments at LCLS/SLAC, NIF, Omega, and other intense laser sources readily produce matter that is both in a highly non-equilibrium state and not physically modelled by the usual assumptions of ideal plasma theory. New computational models are needed to include non-ideal plasma physics over time and length scales important to each platform. By scaling, UCNP can access similar regimes at densities where time is "slowed" enough to allow for precise time measurements. Coordinated efforts will develop computational tools needed broadly in the plasma physics community.

The capacity to produce more complex and more strongly coupled plasmas and make the theoretical advances itemized above will open new avenues of research at the ultracold plasma physics frontier, some of which are listed below. Advances in our understanding of strongly coupled systems will also help develop new tools for the analysis of more complicated correlated plasmas in general.

- **Equations of State for Strongly Coupled Plasmas:** Insights gained from imaging and spectroscopic studies of ultracold plasmas in states of stronger coupling will enable the development of predictive analytical models rooted in fundamental statistical mechanical and computational understanding [24].
- **Collisions and Transport:** Resolved temporal and spatial structures in liquid-like strongly coupled multi-species ultracold plasmas will lead to a comprehensive understanding of transport properties in the context of a hierarchy of many-body interactions, including for example caging [25].
- **Dynamics of Plasma Microstructures Under Strongly Coupled Conditions:** Multistep excitation strategies will create novel shock structures for studies of energy transport and relaxation offering new insights on plasma accelerators and sources of energetic radiation [26].
- **Collisions and transport in magnetized plasmas:** Electron density and temperature control will create UCNPs in a strongly or weakly magnetized regime, collision-dominated or collisionless regime, and a strongly-coupled or weakly-coupled regime. This allows exploration of e.g. unlike-charge electron-ion collisions over a wide range of parameter space in an isolated, classical, low-temperature plasma [27].

III. DESCRIBE THE IMPACT OF THIS RESEARCH ON PLASMA SCIENCE AND RELATED DISCIPLINES AND ANY POTENTIAL FOR SOCIETAL BENEFIT.

Because of the scale of UCNP science, graduate students and post-docs engage in all the experimental and theoretical aspects of a project. Thus, they gain an unusually broad and useful scientific and technical training experience that spans the field from laser-cooling to strong-coupling plasma physics. Such a learning environment causes them to become versatile scientists with a profound command of important background knowledge in physics.

The development of bright, ultracold plasma electron and ion beam sources will stimulate important practical advances that offer societal benefits such as imaging as well as medical diagnosis and therapy. Similarly, ultracold plasmas may figure in strategies for fabricating and machining complex materials, and could serve as simulators for condensed matter systems in which strong coupling is an issue. Many further applications will develop as a result of insights gained from fundamental advances in plasma kinetic theory, as well as a deeper understanding of the evolution of plasma properties through the regimes from weak to moderate to strong coupling, of magnetized plasmas in novel regimes, as well as continuum lowering, shocks, collisions and transport processes. This research will provide important insights that aid in the understanding of large-scale problems less accessible to direct measurement, such as multi-species equilibration in astrophysical contexts. They will help to validate computational plasma models in general, and advance knowledge in the statistical mechanics of strongly coupled plasmas.

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