White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	

Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Cryogenic Non-neutral Plasmas: Strong Magnetization, Strong Coupling, Quantum Crystals
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

When classical neutral plasmas are cooled to cryogenic temperatures, they rapidly recombine. However, non-neutral plasmas that consist of species with the same sign of charge cannot recombine, and are therefore able to access novel states of matter: strongly coupled, strongly magnetized, and quantum liquid and quantum crystal regimes, governed by the Coulomb interaction between like-sign charges. The equilibrium and dynamical properties of these states pose a fundamental challenge to plasma physics and are of importance to a range of disciplines beyond plasma physics, including atomic physics, astrophysics, condensed matter physics, and antimatter physics (in particular, the effort to create and trap neutral antihydrogen).

Strong Coupling. Single-species cryogenic plasmas are an experimental realization of the One Component Plasma (OCP), a venerable theoretical model of condensed matter whose properties have direct application to a number of other physical systems including degenerate matter found in the crust of white dwarf stars [1,2]. Equilibrium properties of the classical OCP depend on a single dimensionless parameter Γ , the coupling parameter. The Γ value in a white dwarf may range up to several hundred, and non-neutral plasmas with such Γ values can also be created and studied, allowing the examination of ultra high energy density matter using a cryogenic non-neutral plasma. Properties of these extreme materials

such as crystal shear strength[3], ion thermal conductivity[4,5], and even the Salpeter enhancement of nuclear reaction rates in a strongly-coupled plasma[6], can all be experimentally studied without having to replicate the extreme conditions of actual high energy density matter.

Strong Magnetization The behavior of plasmas in strong magnetic fields is of fundamental importance to a number of areas, including ICF plasma physics and plasma astrophysics. When the timescale for a two-body collision becomes longer than the cyclotron period, the plasma enters the novel regime of strong magnetization[7]. For laboratory magnetic fields (other than ultra-strong pulsed fields) this regime requires cryogenic conditions, but in astrophysical objects such as magnetars even high energy density plasmas could be strongly magnetized. Cyclotron energy then becomes an internal degree of freedom of guiding centers, bound up by a novel many-particle adiabatic invariant[8].
Many plasma properties are strongly modified in this regime, including collisional processes such as collisional slowing [9] , energy equipartition[10], electron-ion (or positron-antiproton) three-body recombination[11], as well as transport properties such as cross-field thermal conduction, diffusion, and viscosity [4,12,13]. For example, the energy equipartition rate between parallel and perpendicular degrees of freedom becomes exponentially suppressed in the strongly-magnetized regime[8,10], as cyclotron motion becomes decoupled from the other degrees of freedom. The plasma can be described as a collection of N interacting guiding centers and the statistical mechanics of such an N-body system has many interesting properties; for example, Boltzmann collisions now involve ExB drift dynamics. The collision operator in the strongly magnetized regime is an ongoing research project in the Dubin/Driscoll/O'Neil group.

When ions are introduced into a strongly magnetized electron plasma, recombination proceeds via the formation of novel guiding center atoms in which the electron ExB drifts around the ion[14].Such guiding center atoms are thought to play an important role in the antihydrogen formation experiments currently underway at CERN.

Quantum Liquids and Crystals At sufficiently low temperatures, the quantum nature of cryogenic plasmas cannot be ignored. When $\hbar\omega_p \geq k_B T$, the phonons of a plasma crystal become quantized and the fluid phase must also be described quantum mechanically. While quantum degeneracy effects are inaccessible in current experiments, the behavior of the OCP in the nondegenerate quantum regime has never been tested experimentally and is of current theoretical interest. For instance, a decrease in the required melting temperature of a plasma crystal due to zero-point energy has been predicted but never observed[15]. In addition, by entangling the quantized phonon degrees of freedom in an ionic plasma crystal with the ion spins via laser manipulation, novel many-particle entangled states can be created [16], of importance to the burgeoning fields of quantum simulation and quantum computation.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

This area has historically benefitted from close collaboration between theory and experiment in small university-based research groups, and we urge the DOE to consider ways to advance this successful paradigm for physics research. The experiments involve table-top Penning-trap plasma confinement devices, along with state of the art laser systems used to laser cool and manipulate ion plasmas. Electron and positron plasmas have also accessed the cryogenic regime using cooling through cyclotron radiation in a cold-bore Penning trap[10,17] . Such experiments are excellent venues for graduate student education, since a single student can run the experiment.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Work in the area of cryogenic non-neutral plasmas involves fundamental research on basic physical properties of systems in novel regimes. As such, its ultimate impact on society is unknowable. We believe that some of the theory and experimental work will eventually be required study in physics courses. In the near term, understanding of the properties of cryogenic strongly magnetized plasma has been important in the effort to create and trap cold antihydrogen. The work on quantum simulation and quantum computation could play a pivotal role in advancing computational capabilities. The recent measurement of the Salpeter enhancement to fusion cross sections should have some impact on current controversies in the astrophysics community [18].

References (Maximum 1 page)

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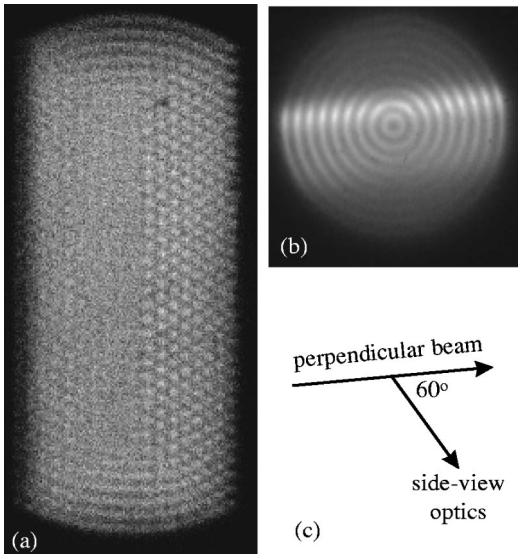
Figures (maximum 1 page)



Side view(a) and Top view (b) images of a crystallized ion plasma. From Ref. [19]