Strongly Coupled Nonneutral Ion Plasma

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Radiation pressure from a laser has been used to cool and compress small nonneutral plasmas of $^9Be^+$ ions confined by static electric and magnetic fields. A second laser has been used as a probe to measure ion densities of 2×10^7 cm^{-3} and ion temperatures below 100 mK. A Coulomb coupling constant, Γ, as large as 10 has been measured indicating that the plasma is strongly coupled. In the future, values of Γ large enough to observe a liquid-solid phase transition should be accessible.

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This Letter reports measurements of the density and temperature of a small nonneutral plasma composed of $^9Be^+$ ions. The thermodynamic state of such a classical Coulomb system is determined by the coupling constant Γ (defined below) which is a measure of the ratio of the Coulomb energy to kinetic energy per particle.[1] For values of Γ on the order of 1 or larger, correlation effects become important and the plasma is called strongly coupled. Recently, values of Γ on the order of 2 have been estimated for a pure electron plasma cooled to near the 4 K temperature of its surroundings.[2] By use of electrodynamic storage, very large values of Γ have been obtained with highly charged aluminum particles several microns in size.[3] Classical, two-dimensional, strongly coupled plasmas have been realized with the system of electrons on the surface of liquid helium. In this system, values of Γ as large as 200 are experimentally accessible, and a liquid-solid phase transition has been observed[4] at $\Gamma \cong 137$. To the authors' knowledge, the experiments reported in this paper give the largest values of Γ reported in a steady-state, magnetically confined, three-dimensional plasma.

The experimental arrangement used here[5,6] is similar to that used in other nonneutral-plasma studies.[7–12] It is different in that the spatial extent of the plasmas could be nondestructively mapped and in that it was possible to control the shape, density, internal temperature, and angular momentum (add or subtract) of the plasmas with radiation pressure from lasers. A uniform magnetic field $\vec{B} = B_0\hat{z}$ ($B_0 \cong 0.8$ T) provided confinement of the $^9Be^+$ ions perpendicular to the magnetic field. Static electric fields produced by three electrodes were used to provide confinement of the ions along the magnetic field. The only qualitative difference between this confinement geometry and that of Refs. 7–12 is that the electric potential produced by the electrodes varied continuously over the confinement region and had the form $\phi_T(r,z) = m\omega_z^2(2z^2 - r^2)/4q$, where ω_z is the single-particle "axial" or z oscillation frequency, q is the ion charge, m is the ion mass, and (r,z) are cylindrical coordinates. This system has usually been called a Penning trap.[13,14] A pressure below about 10^{-8} Pa was maintained in the confinement region. Radiation pressure from a laser was used to cool and compress the ion plasma.[15,16] This was accomplished with a focused, frequency-doubled dye laser beam tuned to the low-frequency side of the $2s\,^2S_{1/2}(M_I = -\frac{3}{2}, M_J = -\frac{1}{2}) \rightarrow 2p\,^2P_{3/2}(-\frac{3}{2}, -\frac{3}{2})$ transition in $^9Be^+$ ($\lambda = 313$ nm) and directed at the ion plasma perpendicular to the magnetic field. The beam had a waist of about 60 μm and a power of about 10 μW. The ions were optically pumped into the $2s\,^2S_{1/2}(-\frac{3}{2}, -\frac{1}{2})$ ground state and detected by observing the ion fluorescence scattering induced by this cooling laser beam. The plasma radius was decreased by directing the cooling laser beam to the side of the plasma which receded from the laser beam because of the $\vec{E}\times\vec{B}$ rotation.[15–17] On the average, each photon-scattering event decreased the canonical angular momentum [in the gauge where $\vec{A}(\vec{r}) = \frac{1}{2}\vec{B}\times\vec{r}$] of the system by dh/λ, where d is the distance between the laser beam and the trap axis and h/λ is the photon momentum. Since the scattering rate was large ($\cong 10^6$ scattered photons per second per ion) this effect could dominate other external torques on the ions such as collisions of the ions with the background gas. In practice, relatively high-density, stable plasmas were maintained for many hours.

The ions were expected to be in near thermal equilibrium with each other. The equilibrium state of a nonneutral plasma confined by static electric fields and a uniform magnetic field has been discussed by O'Neil and co-workers.[11,12] The ion distribution function is

$$f(r,z,\vec{v}) = n_0(m/2\pi k_B T)^{3/2} \exp\{-[\tfrac{1}{2}m(\vec{v}-\omega r\hat{\theta})^2 + q\phi(r,z) + \tfrac{1}{2}m\omega(\Omega-\omega)r^2]/k_B T\}, \quad (1)$$

where n_0 is the ion density at the center of the trap, $\Omega = qB_0/mc$ is the cyclotron frequency, ω is determined by the total canonical angular momentum of the system, and $\phi = \phi_I + \phi_T$ is the sum of the potential due to the ions (including the potential due to the induced charges on the trap electrodes) and the applied trap potential. The distribution function is a Maxwellian velocity distribution superimposed on a rigid rotation of frequency ω. This rotation is due to the $\vec{E}\times\vec{B}$ force on the ions and is often called the magnetron rotation. $\phi(r,z)$ and the spatial shape of the plasma are determined from Poisson's equation (Eq. 3, Ref. 11), $\nabla^2\phi = -4\pi q n_0 e^{\psi}$, where $\psi = -[q\phi + \frac{1}{2}m\omega(\Omega-\omega)r^2]/k_B T$. In the limit $T \rightarrow 0$, this is satisfied when the plasma is a uniformly charged figure of revolution with $\phi_I(r,z) = -2\pi q n_0(\alpha r^2 + \beta z^2)/3$, where $n_0 = m\omega \times(\Omega-\omega)/2\pi q^2$, $\beta = 3\omega_z^2/2\omega(\Omega-\omega)$, and $2\alpha+\beta = 3$. In the limit that the ratio of the plasma dimensions to the trap dimensions approaches zero (about 10^{-2} here) the plasma becomes a uniformly charged spheroid.

In a frame of reference rotating about the trap axis with frequency ω, the ion plasma behaves like a neutral one-component plasma.[10] That is, the positively charged ions behave as if they are moving in a uniform, negatively charged background. The properties of a one-component plasma are expressed in terms of the Coulomb coupling constant[1]

$$\Gamma \equiv q^2/ak_B T, \quad (2)$$

where a is defined by $4\pi n_0 a^3/3 = 1$, and T is the temperature of the ions from the distribution of Eq. (1). Theoretical calculations[1] predict that at $\Gamma \cong 2$, the pair-correlation function should begin to show oscillations characteristic of a liquid, and at much larger values[18,19] of Γ ($\Gamma \cong 170$), crystallization may take place. (For the small plasmas of this experiment, surface effects may be important; however, this is not expected to greatly alter the theoretical prediction.)

Values of Γ in this experiment were determined by separately measuring the density, n_0, and temperature, T, of the ions. A second laser beam (beam waist $\cong 60\ \mu$m) was used to probe the plasma. When the probe laser frequency was swept through the $2s\,^2S_{1/2}(-\frac{3}{2},-\frac{1}{2}) \rightarrow 2p\,^2P_{3/2}(-\frac{3}{2},+\frac{1}{2})$ transition, some of the ion population was removed from the optically pumped ground state, resulting in a decrease in the resonance fluorescence induced by the cooling laser as shown in Fig. 1. The size of this depopulation signal depended on the local density of the plasma at the intersection of the probe beam and the plasma. With the probe beam perpendicular to the magnetic field, spatial maps of the plasmas were taken by moving the probe beam across the plasma in both the radial and

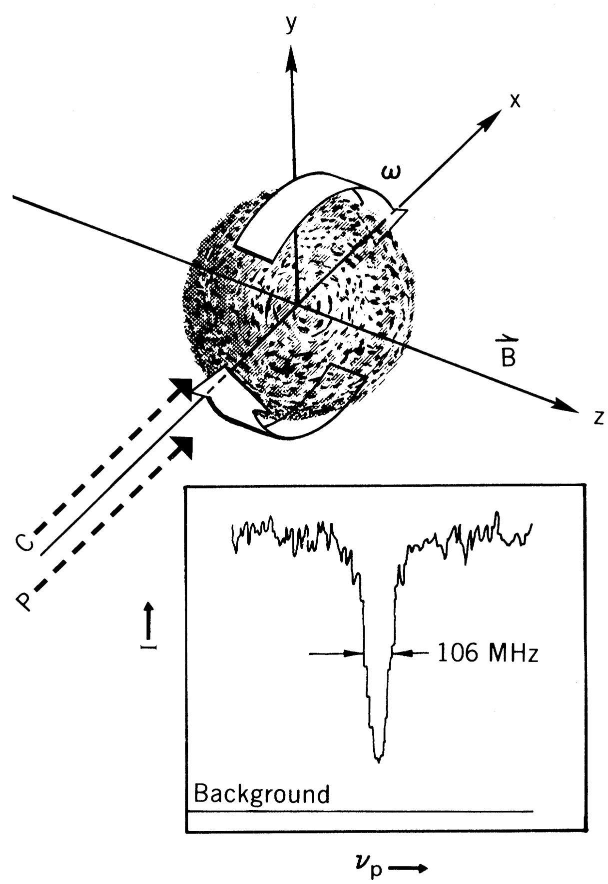

FIG. 1. Sketch of the plasma with the cooling (C) and probe (P) laser beams. The cooling beam was directed at the side of the plasma which receded from this beam. For much of the data, the probe beam was directed approximately parallel to the cooling beam. The rotation frequency, ω, was measured by translating the probe beam in the y direction (radially). Spatial maps of the plasma were obtained by translating the probe beam in both the y (radial and z (axial) directions. The inset shows the depopulation signal obtained when the frequency (ν_p) of the probe laser was slowly swept through the $2s\,^2S_{1/2}(-\frac{3}{2},-\frac{1}{2}) \rightarrow 2p\,^2P_{3/2}(-\frac{3}{2},+\frac{1}{2})$ transition. I is the $^9Be^+$ fluorescence intensity from the cooling laser.

TABLE I. Summary of measurements on four nonneutral plasmas taken at three values of ω_z. All data were taken at a magnetic field of $B_0 = 0.819$ T. The coupling Γ and the Debye length λ_D were calculated with use of the axial temperature T_z. N is the number of ions and r_c is the rms radius of the cyclotron orbit.

$\omega_z/2\pi$ (kHz)	$10^{-7} n_0$ (cm^{-3})	a (μm)	N	T_c (mK)	T_z (mK)	Γ	λ_D (μm)	r_c (μm)
243	2.1(6)	23(2)	142(51)	45(12)	144(34)	5.1(1.3)	6(1)	1.1(1)
243	2.0(5)	23(2)	172(62)	56(13)	151(36)	4.9(1.2)	6(1)	1.2(1)
198	2.0(5)	23(2)	126(45)	10(12)	75(30)	9.7(3.9)	4(1)	0.5(3)
175	1.8(5)	24(2)	95(34)	19(12)	82(30)	8.6(3.2)	5(1)	0.7(2)

axial directions. The spatial maps were consistent with a uniform-density, spheroidal plasma (typical dimensions 100 to 300 μm) with a sharp drop in density (in less than a few Debye lengths) at the plasma edge. The rotation frequency ω was determined by measuring the change in the Doppler shift of the depopulation transition as the probe beam was moved radially across the plasma (see Fig. 1). n_0 was then determined from $n_0 = m\omega(\Omega - \omega)/2\pi q^2$ with use of the measured value of ω. (Ω was determined by auxiliary measurements.[5]) T was determined from the width of the depopulation signals. The 19.4-MHz natural width and the plasma rotation convoluted with the Gaussian spatial intensity profile of the probe beam contributed to the width of the depopulation signals. In addition there was a saturation broadening of the depopulation signals when the signal size approached the total fluorescence count rate. These broadening mechanisms were calculated and the Doppler broadening due to the nonzero temperature of the ions was extracted. With the probe laser beam perpendicular to the magnetic field, the temperature, T_c, of the cyclotron motion was measured.

The cooling laser beam, directed perpendicular to the magnetic field, only indirectly cooled the axial motion of the ions by collisional coupling of the axial motion with the cooled cyclotron motion. The axial motion was directly heated by the recoil of the scattered photons[17]; therefore, the axial temperature, T_z, was possibly higher than T_c. T_z was measured by passing the probe beam along a diagonal between the three electrodes. In this case, the depopulation signals contained a contribution due to the Doppler broadening by the axial (z) motion of the ions. Table I summarizes the measurements on four separate plasmas in this experiment. Γ was calculated by use of T_z, because it was the larger of the two temperatures. In future experiments, by directing the cooling beam along the diagonal and cooling the axial motion directly, an axial temperature equal to the cyclotron temperature should be obtained.

The theoretical cooling limit[17] depends on the linewidth, $\Delta\nu$, of the cooling transition and predicts a temperature equal to $h\Delta\nu/2k_B$, where h is Planck's constant. For $^9Be^+$, $\Delta\nu = 19.4$ MHz which gives a limiting temperature of 0.5 mK. At a magnetic field of 10 T, the density, limited by the Brillouin density,[14,20] could be as high as $n_0 = 3 \times 10^{10}/cm^3$ for $^9Be^+$ ions. Therefore, values of Γ as large as 15 000 are perhaps accessible and crystallization in a nonneutral ion plasma might be obtained. We note that fairly direct measurements of the pair-correlation function could be made by observing interferences in the low-angle laser scattering from the ions, similar to x-ray crystallographic techniques. Ion diffusion (or lack thereof) could be measured by spatially separating the cooling and probe beams (along z) and pulsing the probe beam, similar to that described by Stern, Hill, and Rynn.[21] Classical mechanics has been assumed to give an adequate description in the preceding discussions. At temperatures below $\hbar\Omega/k_B$, the discreteness of the Landau (quantized cyclotron) levels becomes important. At slightly lower temperatures, $T \lesssim \hbar\omega_p/k_B$, where $\omega_p = [2\omega(\Omega - \omega)]^{1/2}$ is the plasma frequency of the ions, the collective motion of the ions should be treated quantum mechanically.[10] Both of these interesting regions may be accessible with $^9Be^+$ or perhaps other ions which have a much smaller radiative linewidth $\Delta\nu$ where even lower temperatures could be expected.

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