Rapid Heating of a Strongly Coupled Plasma near the Solid-Liquid Phase Transition

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Between 10^4 and 10^6 $^9Be^+$ ions were trapped in a Penning trap and laser cooled to $\sim$1 mK, where they formed a crystalline plasma. We measured the ion temperature as a function of time after turning off the laser cooling and observed a rapid temperature increase as the plasma underwent the solid-liquid phase transition at $T \simeq 10$ mK ($\Gamma \sim 170$). We present evidence that this rapid heating is due to a sudden release of energy from weakly cooled degrees of freedom involving the cyclotron motion of trapped impurity ions. This equilibration of cyclotron motion with motion parallel to the magnetic field is more than 10 orders of magnitude faster than that predicted by currently available theory, which is valid only in the absence of correlations ($\Gamma \ll 1$).

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Strongly coupled Coulomb systems encompass diverse many body systems which exist under a wide range of physical conditions. Examples include colloidal suspensions, complex (dusty) plasmas, laser-cooled trapped ions, and dense astrophysical matter [1]. At sufficiently high density or low temperature these systems undergo a liquid-solid phase transition which has been the subject of considerable interest. A particularly simple strongly coupled Coulomb system is the strongly coupled one-component plasma (OCP). An OCP consists of a single species of point charges embedded in a uniform, neutralizing background charge [2,3]. The thermodynamic state of an OCP is determined by a single coupling parameter $\Gamma = q^2/(4\pi\epsilon_0 a_{\mathrm{WS}} k_B T)$, where ϵ_0, k_B, q, and T are, respectively, the vacuum permittivity, Boltzmann's constant, and the ion charge and temperature. a_{WS} is the Wigner-Seitz radius, given by the expression for the plasma density $n_0 = 3/(4\pi a_{\mathrm{WS}}^3)$. Strongly coupled OCPs ($\Gamma > 1$) are believed to exist in dense astrophysical objects such as in the outer crust of a neutron star, but can also exist in less dense objects if the temperature is correspondingly low. Laser-cooled trapped ions form a rigorous but convenient low-density, low-temperature realization of a strongly coupled OCP.

Even though extensive theoretical investigations have shown that a strongly coupled OCP undergoes a first-order solid-liquid phase transition at $\Gamma \simeq 172$–174 [2,4], there has been no experimental confirmation of this result. An abrupt change in ion fluorescence has been observed as ion plasmas in rf traps were laser cooled to low temperature [5,6]. However, rather than a thermodynamic phase transition, this change in the ion fluorescence is due to a sudden large change in the ion temperature resulting from the competition between laser cooling and heating by the rf fields [6,7]. Because the Penning trap uses only static fields for confinement, we are able to change the ion energy in a controlled manner and slowly change the ion temperature. Here we use residual-gas collisions to slowly increase the temperature of a $^9Be^+$ ion crystal and look for evidence (e.g., a latent heat) of the predicted thermodynamic phase transition. We observe an unexpected rapid heating of the $^9Be^+$ ions in the region of the predicted solid-liquid phase transition and show that this rapid heating is due to a very temperature-sensitive coupling between the cold $^9Be^+$ ions and the warmer cyclotron motion of heavier ions that surround the $^9Be^+$ ions. The observed heating indicates that the equilibration of cyclotron motion with motion parallel to the magnetic field is significantly enhanced in a strongly coupled plasma.

We trap between 10^4 and 10^6 $^9Be^+$ ions in a Penning trap. The $\boldsymbol{E} \times \boldsymbol{B}$ fields cause the trapped ion plasma to rotate about the magnetic-field axis, and in thermal equilibrium, this rotation is rigid. The rotation frequency ω_r determines the plasma density and shape, and is precisely controlled by a rotating electric field [3,8]. In addition to $^9Be^+$ ions, heavier singly charged ions [$m = 10$ (BeH^+), 26, 34 amu] are created over many days by collisions between $^9Be^+$ and the room-temperature residual gas at $\sim 4 \times 10^{-9}$ Pa. The plasma rotation causes ions of different masses to centrifugally separate, and the heavy-mass impurity ions occupy a region at larger radii (see Fig. 1). The gap between the $^9Be^+$ ions and heavier ions is on the order of the interparticle spacing. The fact that the rotating electric field can gain phase-locked control of the plasma rotation frequency indicates that the impurity ions have crystallized.

Figure 1 shows a sketch of the setup [9]. The 4.5 T magnetic field of a superconducting solenoid with a room-temperature bore produced a $^9Be^+$ cyclotron frequency of $\Omega_c = 2\pi \times 7.6$ MHz. With $V_{\mathrm{trap}} = 500$ V, the $^9Be^+$ axial and magnetron frequencies were, respectively, $\omega_z = 2\pi \times 565$ kHz and $\omega_m = 2\pi \times 21$ kHz. The data presented here were taken on spherical plasmas obtained with $\omega_r = 2\pi \times 64$ kHz, corresponding to $n_0 = 2 \times 10^8$ cm^{-3} and $a_{\mathrm{WS}} \sim 10$ μm. The plasma is cooled by Doppler laser cooling to $T \sim 1$ mK ($\Gamma \sim 1500$) which is

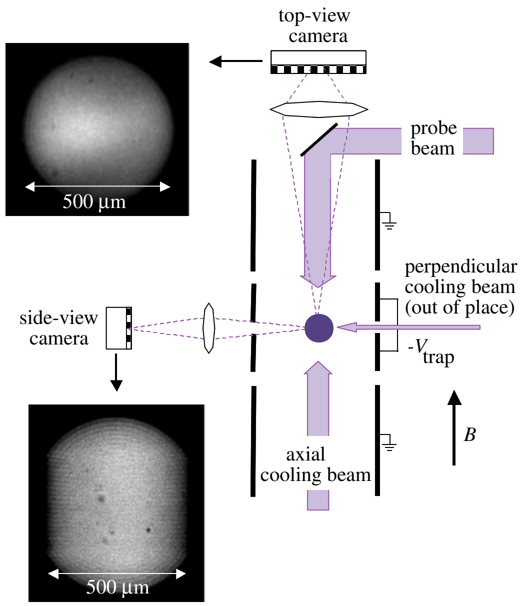

FIG. 1 (color online). Schematic diagram of setup. Figure is not to scale. The trap diameter is 4 cm. Top- and side-view images of a plasma with 26 000 ions are shown. Individual crystalline planes are visible in the side-view image. The vertical edges of the plasma visible in the side-view image are due to the presence of nonfluorescing impurity ions heavier than $^9Be^+$.

well below the liquid-solid phase transition. Cooling laser beams are sent through the trap parallel and perpendicular to the magnetic-field axis. The resulting resonance fluorescence is imaged by side- and top-view cameras. A probe beam is introduced along the magnetic-field axis to measure the temperature associated with motion along this axis. The temperature is measured by Doppler laser spectroscopy on a transition that depopulates the cooling cycle [9].

We measured the temperature as a function of the time t_{delay} after turning off the cooling laser beams. Figure 2 shows temperature curves obtained with different plasmas, all with the same density $n_0 = 2 \times 10^8$ cm^{-3}, over a period of many months. In all cases, the temperature increased slowly ($\sim$0.1 K/s) until $T \simeq 10$ mK ($\Gamma \sim 170$), the temperature of the solid-liquid phase transition. At 10 mK, a sudden increase to temperatures of a few kelvin takes place. The onset of this rapid heating occurs at different values of t_{delay}, depending on the magnitude of the slow heating rate in the solid phase, but always occurs at the same temperature $T \simeq 10$ mK. A measurement of the temperature of the $^9Be^+$ motion perpendicular to the magnetic-field axis showed similar behavior.

We considered several external sources of energy for the rapid heating, including work done by the rotating electric field to maintain a constant rotation frequency, electric field noise from the trap electrodes, and residual-gas collisions. We rule out energy input from the rotating electric field by temperature curves recorded with and without the rotating electric field, which show the same amount of rapid heating. Electric field noise from the trap electrodes appears unlikely, as we observed no change in the rapid heating with the application of small amplitude potentials oscillating near the $^9Be^+$ motional frequencies.

Measurements also show that heating due to residual-gas collisions cannot directly account for the rapid heating. Based on temperature measurements recorded at different residual-gas pressures (see Fig. 3), we established in Ref. [9] that the $\sim$0.1 K/s heating rate measured in the solid phase is due to collisions between trapped ions and room-temperature residual-gas molecules. Figure 4 shows a temperature curve (the ''liquid plasma'' curve) recorded under typical experimental conditions except the parallel laser-cooling beam was blocked. This resulted in an initial parallel temperature at $t_{delay} = 0$ of $\sim$80 mK corresponding to a plasma in the liquid phase. No rapid heating of this plasma is observed. Instead, the same $\sim$0.1 K/s heating rate measured in the solid phase is also observed here. This indicates that the direct heating of the ions due to residual-gas collisions is not any greater in the liquid phase than the solid phase [10].

Even though residual-gas collisions cannot directly explain the rapid heating, Fig. 3 shows that residual-gas collisions have an effect on the magnitude of the heating step. This suggests that residual-gas collisions excite one or more degrees of freedom in the plasma to temperatures above the axial temperature measured in the solid phase. Also, we observed that stronger perpendicular laser cooling can suppress the rapid heating, indicating that the excited motion takes place in a direction perpendicular to the magnetic-field axis. For practical reasons, the data

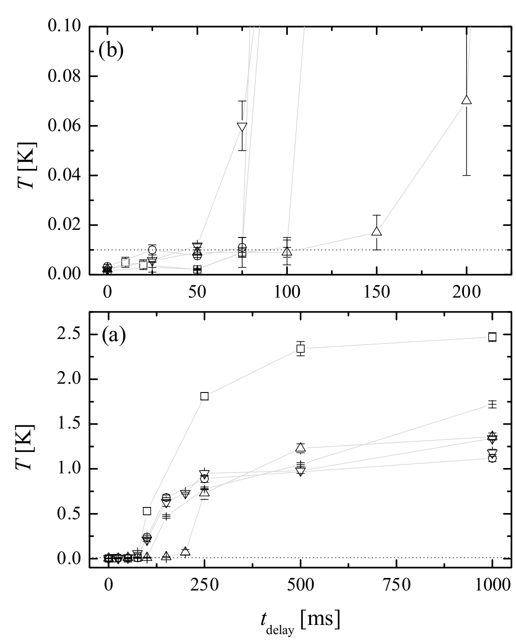

FIG. 2. (a) Temperature curves recorded with different plasmas on different days spanning a period of many months. The horizontal dotted line indicates $T = 10$ mK. (b) is a close-up of (a).

presented in Figs. 2 and 3 were obtained on plasmas containing at least 5% heavy-mass impurity ions. Temperature curves recorded on clean plasmas containing essentially no impurity ions show identical heating rates in the liquid and solid phases with no rapid heating near the anticipated solid-liquid phase transition (see Fig. 4). The rapid heating observed with "dirty" plasmas is therefore likely due to an excited impurity-ion motion.

The impurity-ion temperature T_i is determined by a balance between the heating rate h due to residual-gas collisions ($h \sim 0.1$ K/s) and the sympathetic cooling rate r according to the equation $\frac{dT_i}{dt} = -r(T_i - T_{\mathrm{Be}^+}) + h$. For the case of a crystalline plasma, we estimated the sympathetic cooling rate r of an impurity ion located next to a $^9\mathrm{Be}^+$ ion at the interface of the $^9\mathrm{Be}^+$ and impurity ions. We find a sympathetic cooling rate of the impurity-ion cyclotron motion of $r_\perp \sim \gamma\omega_p^4/\Omega_{c,i}^4$. Here γ is the damping rate of the $^9\mathrm{Be}^+$ motion by laser cooling, ω_p is the plasma frequency, and $\Omega_{c,i}$ is the cyclotron frequency of the impurity ion under consideration. In comparison, the sympathetic cooling rate of the impurity-ion parallel motion is approximately $r_\parallel \sim \gamma$. With $^9\mathrm{Be}^+$ temperatures $\lesssim 1$ mK and with the cooling laser parameters used in this work, we calculate $\gamma \lesssim 2 \times 10^3\ \mathrm{s}^{-1}$. For a 10 amu impurity ion, $\omega_p^4/\Omega_{c,i}^4 \sim 5 \times 10^{-4}$. This results in a weak sympathetic cooling rate $r_\perp \lesssim 1\ \mathrm{s}^{-1}$ for the impurity-ion cyclotron motion in a crystalline plasma.

Molecular dynamics simulations of two-species ion plasmas verify that laser cooling of the $^9\mathrm{Be}^+$ ions efficiently cools the parallel motion ($T_{\parallel,i}$), but not the cyclotron motion ($T_{\perp,i}$), of the impurity ions. For realistic experimental parameters, simulations of 60 ions (50% $^9\mathrm{Be}^+$, 50% $^9\mathrm{BeH}^+$) show sympathetic cooling rates that are zero within error: $r_\perp < 1 \pm 1\ \mathrm{s}^{-1}$. An even smaller rate is expected for larger clouds where the fraction of impurity ions in close contact with $^9\mathrm{Be}^+$ is smaller. Taking $r_\perp = 0.1\ \mathrm{s}^{-1}$ with $h \simeq 0.1$ K/s leads to $T_{\perp,i} \simeq 1$ K, which is the correct order of magnitude to account for the observed heating. Even though $T_{\perp,i}$ is much greater than the temperature of the phase transition, the impurity ions are crystallized because their parallel temperature $T_{\parallel,i}$ is efficiently cooled below the temperature of the phase transition and, for low temperatures and large magnetic fields, the ion correlations are determined by $T_\parallel$ and not $T_\perp$ [11].

We showed experimentally that additional excitation of the impurity-ion cyclotron motion increases the rapid heating. The cyclotron motion of mass-10 ions was excited by an rf field. Figure 5 shows the temperature at $t_{\mathrm{delay}} = 1$ s as a function of the rf frequency, and a full temperature curve recorded with the rf drive tuned near resonance. The energy added to the impurity-ion cyclotron motion is not coupled with the $^9\mathrm{Be}^+$ parallel motion until $T_{\parallel,\mathrm{Be}^+} \sim 10$ mK, the temperature of the solid-liquid phase transition.

The rapid heating can therefore be explained by a warm (several kelvin) impurity-ion cyclotron temperature resulting from residual-gas collisions and weak sympathetic cooling. After the cooling lasers are turned off, the $^9\mathrm{Be}^+$ ions are slowly heated by residual-gas collisions. At about 10 mK, the $^9\mathrm{Be}^+$ ions start coupling with the impurity-ion cyclotron motion. This interaction apparently increases rapidly with temperature, with the result that the impurity-ion cyclotron energy is rapidly shared with the $^9\mathrm{Be}^+$ ions. The "liquid plasma" and "freeze-pulse" temperature curves of Fig. 4 are consistent with this picture. Both these measurements used perpendicular laser cooling

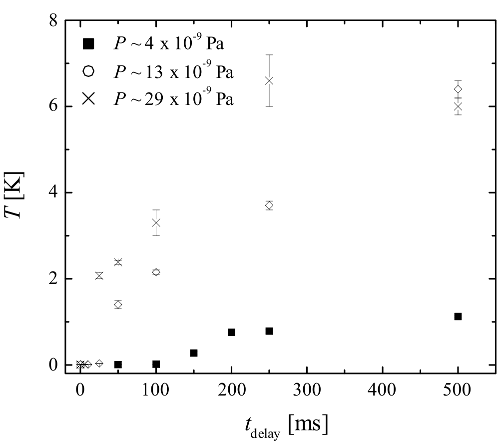

FIG. 3. Temperature curves for a 410 000 ion plasma recorded at three different residual-gas pressures. For the three increasing pressures, the rapid heating started at $t_{\mathrm{delay}} \simeq 100$, 10, and 5 ms, respectively. The corresponding amounts of heating observed immediately thereafter were roughly 0.8 K in 100 ms, 1.5 K in 40 ms, and 2 K in 20 ms.

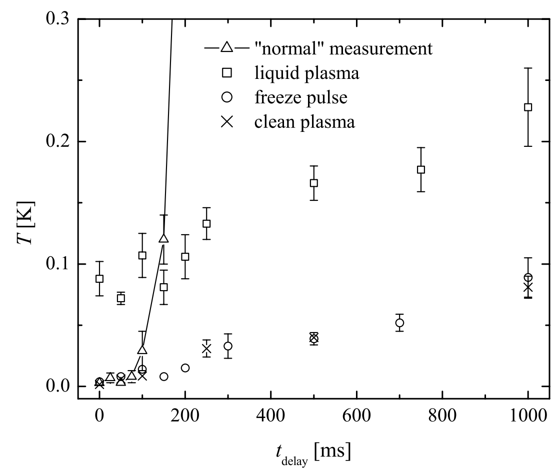

FIG. 4. Temperature curves recorded using different initial conditions. The "normal" curve (△) was obtained using both parallel and perpendicular laser cooling. Only perpendicular laser cooling was applied in case of the "liquid" curve (□). The freeze-pulse method was used to obtain the curve indicated with circles. These three curves were recorded on 56 000 ion plasmas with ~35% impurity ions. The curve shown with × was recorded on a 23 000 ion plasma containing no impurity ions.

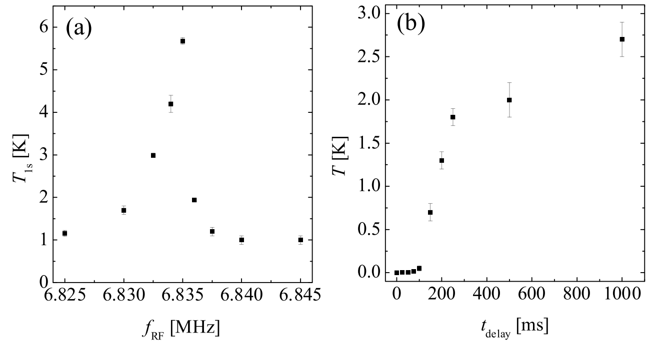

FIG. 5. (a) The temperature at $t_{\mathrm{delay}} = 1$ s as a function of the frequency of an rf field exciting the mass-10 cyclotron motion. (b) A temperature curve recorded with the rf drive tuned near resonance. (a) and (b) were recorded on different plasmas.

to generate a liquid plasma where a strong $r_\perp$ prevented collisions from elevating $T_{\perp,i}$. In the "freeze-pulse" measurement a 100 ms parallel laser-cooling pulse is applied immediately before turning off the cooling lasers ($t_{\mathrm{delay}} = 0$). In this case the plasma is a solid at the start of the heating measurement, but spends less than 100 ms in the solid phase where $r_\perp$ is weak. No additional heating is observed at the solid-liquid phase transition.

The heating step is an example of energy equipartition between cyclotron and parallel degrees of freedom in a plasma with a strong magnetic field. While there is as yet no detailed theory of this equipartition in a strongly correlated plasma, for a weakly correlated plasma it has been shown that close binary collisions produce energy equipartition of the cyclotron and parallel motions. This equipartition rate becomes exponentially small with increasing b/r_c, where $b = q^2/(4\pi\epsilon_0 k_B T_\parallel)$ is the distance of the closest approach and $r_c = (\Omega_c)^{-1}\sqrt{k_B T_\parallel/m}$ is the cyclotron radius, both based on $T_\parallel$ rather than $T_\perp$ [12,13]. For our experimental range of temperatures, the weakly correlated theory predicts an equipartition rate that exponentially increases with increasing $T_\parallel$. However, the predicted equipartition rate is orders of magnitude too small to explain the observed heating step. For example, at $T_\parallel \simeq 50$ mK we observe an equipartition rate of ~ 0.1 K/s which is ~ 13 orders of magnitude faster than that predicted by the theory for uncorrelated plasmas.

On the other hand, the probability of close collisions may be significantly enhanced in a strongly correlated OCP, as surrounding charges screen the Coulomb repulsion of the colliding pair. This phenomenon has been closely studied in dense plasmas, where it has been shown to produce an exponential enhancement (of order $\sim e^\Gamma$) of the nuclear reaction rate [14]. Recent theory [15] shows that the same enhancement can apply to the energy equipartition rate in a magnetized, pure ion plasma in certain parameter regimes: the release of cyclotron energy in a close collision between ions is analogous to the release of nuclear energy in a close collision between nuclei. The experimental work described here lies in a parameter range outside the regime of the simple theory of Ref. [15]. However, simulations [15] in roughly the experimental parameter regime show equipartition rate enhancements of up to 10^{10}, which is the right order of magnitude to explain the observed rapid heating.

More work is required before a careful comparison of theory and experiment can be made. In particular, further measurements of the cyclotron-parallel equipartition over a wide range of densities and magnetic fields are important for determining in detail its dependence on Γ and b/r_c. Nevertheless, this result, along with future work, appears to provide a method to advance our understanding of nuclear reactions in dense stellar plasmas. Finally, with the ability to avoid the rapid heating by using pure, single-species plasmas or short parallel laser-cooling pulses to freeze the plasma, it may be possible to observe the latent heat associated with the solid-liquid phase transition.

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