This paper published in Intense Position Beams, edited by E.H. Ottewitte and W. Kells (World Scientific, Singapore, 1988), p. 63.

Ion Trapping Techniques: Laser Cooling and Sympathetic Cooling*

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ABSTRACT

Radiation pressure from lasers has been used to cool and compress $^9Be^+$ ions stored in a combination of static electric and magnetic fields (Penning trap) to temperatures less than 10 mK and densities greater than 10^7 cm^{-3} in a magnetic field of 1.4 T. A technique called sympathetic cooling can be used to transfer this cooling and compression to other ion species. An example of $^{198}Hg^+$ ions sympathetically cooled by laser cooled $^9Be^+$ ions is given. The possibility of making an ultracold positron source via sympathetic cooling is also discussed.

Ion traps have been used in low energy atomic physics experiments for a period of roughly 30 years.[1,2] During the past 10 years, however, the technique of laser cooling and compression has greatly increased the potential use of stored ions in a number of applications. One example is time and frequency standards. With the technique of laser cooling and compression, ion temperatures less than 10 mK, densities a factor of 10 less than the Brillouin limit (defined below), and essentially indefinite confinement times have been obtained.[3,4] Unfortunately, elementary charged particles (electrons, positrons, protons, etc.) can not be directly laser

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cooled. In addition the number of atomic ion species that can be directly cooled by a laser is limited. Sympathetic cooling,[5,6] where one charged species is cooled by the Coulomb interaction with a second, directly cooled species, provides a means of transferring the desirable properties of a laser cooled ion species to a species, such as positrons, which can not be laser cooled directly.

The idea of sympathetic cooling is general and can, in principle, be used with any type of trap. In this paper, though, the idea of sympathetic cooling is examined only in the case of two different charged species in a Penning-type trap. The Penning trap[7] uses a uniform magnetic field $\vec{B} = B\hat{z}$ to confine ions in a direction perpendicular to the z axis. The ions are prevented from leaving the trap along the z axis by an electrostatic potential, φ_T, typically provided by three electrodes. In the general discussion that follows, unless explicitly stated, it is only assumed that the trap potential, φ_T, is symmetric about the z axis (i.e. $\varphi_T = \varphi_T(r,z)$ where r,z are cylindrical coordinates). This includes the Penning trap typically used in atomic physics experiments where the electrodes have hyperbolic shapes which give rise to a quadratic trap potential.[1,2] It also includes the traps of the University of California at San Diego (UCSD) group which use cylindrical tubes as the trap electrodes.[8-10]

In the next section, the technique of laser cooling and compression is described and some results of measurements on laser cooled $^9Be^+$ ions are summarized. The idea of sympathetic cooling is then described in more detail and the results of an experiment where Hg^+ ions were sympathetically cooled by laser cooled Be^+ ions are given. We conclude with a discussion of the possibilities of sympathetically cooling positrons and speculate at some possible applications of very cold positrons.

LASER COOLING AND COMPRESSION

The technique of laser cooling[11-13] utilizes the resonant scattering of laser light by atomic particles. By directing a laser beam at the ion plasma we can decrease the thermal velocity of an ion in a direction opposite to the laser beam. The laser is tuned to the red, or low frequency side of the atomic "cooling transition" (typically an electric dipole transition). Some of the ions moving in a direction opposite to the laser beam propagation will be Doppler shifted into resonance and absorb photons at a relatively high rate. Ions moving with the laser beam will be Doppler shifted away from the resonance and the absorption rate will correspondingly decrease. When an ion absorbs a photon its velocity is changed by an amount

$$\Delta\vec{v} = \hbar\vec{k}/m \qquad (1)$$

due to momentum conservation. Here $\Delta\vec{v}$ is the change in the ion's velocity, $\vec{k}$ is the photon wave vector where $|\vec{k}| = 2\pi/\lambda, \lambda$ is the wavelength of the cooling radiation, m is the mass of the ion, and $2\pi\hbar$ is Planck's constant. The ion spontaneously re-emits the photon in a symmetric way. In particular, averaged over many scattering events, the reemission does not change the momentum of the ion. The net effect is that for each photon scattering event, the ion's average velocity is changed by an amount shown in Eq. 1. To cool an atom from 300 K to mK temperatures takes typically 10^4 scattering events. The theoretical cooling limit, due to photon recoil effects[11-13] is given by a temperature equal to $\hbar\gamma/(2k_B)$ where γ is the radiative linewidth of the atomic transition in angular frequency units and k_B is Boltzmann's constant. For a linewidth $\gamma = 2\pi\cdot 19.4$ MHz, which is the radiative linewidth of the $2s^2S_{\frac{1}{2}} \rightarrow 2p^2P_{3/2}$ transition in $^9Be^+$ (λ = 313 nm) used for cooling, the theoretical minimum temperature is 0.5 mK.

Laser scattering can also be used to change the angular momentum and compress the ion "cloud" or plasma. For simplicity, in the discussion of this paper it is assumed that particles with charge $q>0$ are trapped. In thermal equilibrium the plasma in a Penning trap undergoes a uniform rotation at an angular frequency $-\omega$.[14-16] The minus sign indicates that for positively charged particles, the rotation is in the $-\hat{\theta}$ direction. The z component of the canonical angular momentum for an individual particle is

$$l_z = mv_\theta r + \frac{qBr^2}{2c}. \tag{2}$$

The two terms in Eq. 2 are the plasma mechanical angular momentum and the field angular momentum. The total z component of the angular momentum of the plasma is[16]

$$L_z = m(\Omega/2 - \omega)N < r^2 >. \tag{3}$$

Here N is the total number of ions, $\Omega = qB/(mc)$ is the cyclotron frequency and $\langle r^2 \rangle$ is the mean squared radius of the plasma. For all of the work described in this paper, $\omega \ll \Omega$ and

$$L_z \cong \frac{m\Omega N}{2} \langle r^2 \rangle \ > 0 \ . \tag{4}$$

Suppose the cooling laser beam is directed at the side of the plasma which is receding from the laser beam due to the plasma rotation. Because the rotation of the positive ions is in the $-\hat{\theta}$ direction, the torque of the laser on the ions will also be negative. Consequently angular momentum is removed from the plasma and according to Eq. 4 the radius of the plasma must decrease. As the radius decreases, the density of the plasma increases. In principle, the plasma compression continues until $\omega = \Omega/2$ where the maximum density, known as the Brillouin density occurs. The Brillouin density, n_B, is given by

$$n_B = \frac{m\Omega^2}{8\pi q^2} \ . \tag{5}$$

In practice, the plasma is compressed until the torque due to the cooling laser is balanced by an external torque. Collisions with background gas particles and axial asymmetries of the trap are possible sources of external torques. The group at UCSD has observed that the axial asymmetry of their cylindrical traps plays an important role in the electron confinement time.[10)] With the use of the plasma compression, it is possible to stop the normal processes which lead to an increase in the plasma radius and obtain a steady state plasma indefinitely. In our laboratory we routinely maintain a steady state plasma of laser cooled $^9Be^+$ ions for a period of a day.

We have used an optical double resonance technique[3,4,16)] to measure the shape, density, and temperature of clouds of a few hundred to a few ten thousand laser cooled $^9Be^+$ ions stored in a Penning trap. Densities of 10^7 - 10^8 ions/cm^3 at a magnetic field of 1.4 T were obtained on both the large and small clouds. The Brillouin density for $^9Be^+$ ions in this magnetic field is 6 x 10^8 ions/cm^3. We believe that axial asymmetries of the trap were responsible for limiting the ion densities to about an order of magnitude less than the Brillouin density.[3,4,16)] Ion temperatures less than 100 mK were routinely obtained. On smaller clouds consisting of a few hundred ions, ion temperatures less than 10 mK were measured.

SYMPATHETIC COOLING

The idea of sympathetic cooling is to use the Coulomb interaction to transfer the long term confinement, high densities, and low temperatures of a laser cooled ion species (for example, $^9Be^+$) to a charged species (for example, positrons) which can not be directly laser cooled and compressed. O'Neil has investigated the equilibrium distribution of a nonneutral multispecies ion plasma for the case where the plasma is assumed to have infinite extent along the z axis.[17] For simplicity consider a two species ion plasma consisting of ion species with like charge q but different masses $m_2 > m_1$. Thermal equilibrium requires that both ion species undergo a uniform rotation at the same frequency, ω.[17] The uniform rotation tends to produce a centrifugal separation of the two ion species. In particular, the heavier ion species tends to reside outside the lighter species.

For the case of an infinitely long two species plasma, the lighter species forms a column of plasma centered on the z axis with outer radius b_1. The heavier species forms a cylindrical shell outside the lighter species with inner radius a_2 and outer radius b_2. In the limit of zero temperature, the edges of the plasma become sharp and the separation between the two species is complete with $b_1 < a_2 < b_2$. The separation $d = a_2 - b_1$ between the two species depends on b_1 and the density ratio n_2/n_1 of the two species and is given by the expression

$$d = b_1\{(n_2/n_1)^{-\frac{1}{2}} - 1\}. \quad (6)$$

The density ratio depends on the rotation frequency according to

$$n_2/n_1 = 1 - \frac{(m_2 - m_1)\omega^2}{2\pi q^2 n_1} \quad , \quad (7)$$

$$n_1 = \frac{m_1 \omega(\Omega_1 - \omega)}{2\pi q^2} .$$

For a finite length plasma, the situation is similar. The heavier species tends to form a "doughnut" around the lighter species (see Fig. 1(c)). The gap, d(z), between the two species now depends on the z coordinate. Zero temperature calculations of plasma shapes for a two component nonneutral plasma in a harmonic Penning trap [18] show that in general $d(0) \le d(z)$ and $d(0)$ depends in a complicated way on b_1, b_2, n_2/n_1, and the voltage applied to the trap. Eq. 6 provides a lower estimate for $d(0)$. For a large range of the input parameters, this actually turns out to be a good estimate of $d(0)$.

For finite temperatures, the edge of the plasma is not perfectly sharp, but falls to zero over a distance characterized by the Debye length, $\lambda_D \equiv [k_B T/(4\pi n q^2)]^{\frac{1}{2}}$.[15] Here n is the density of the particular ion species and T is the temperature. One expects the thermal coupling between the two different ion species to be strong if the gap $d(0)$ is small compared to either of the species' Debye lengths. If $d(0)$ is large compared to the Debye lengths, the thermal coupling may be weak. The exact strength of the thermal coupling is a difficult theoretical problem to estimate.

We experimentally tested the idea of sympathetic cooling by loading $^{198}Hg^+$ in the same trap with laser cooled $^9Be^+$ ions.[6] Without the Hg^+, Be^+ rotation frequencies up to 200 kHz were observed. A dramatic change in the rotation frequency and shape of the Be^+ cloud occurred when Hg^+ ions were introduced into the trap (see Fig. 1). With Hg^+ and Be^+ in the trap, the largest observed rotation frequency was 21 kHz. Clearly the Hg^+ ions applied a substantial torque to the Be^+ ions. The source of this torque is not clearly understood. The Hg^+ ions remained in the trap for at least several hours unless the cooling was interrupted. If the cooling laser was blocked the Hg^+ ions were lost in several minutes demonstrating that the long term confinement of the Hg^+ was dependent on the torque applied to the Hg^+ ions by the cooling laser via the coupling to the Be^+ ions. Measured Hg^+ temperatures ranged from 0.4 to 1.8 K and Be^+ temperatures ranged from less than 0.05 to 0.2 K. The difference in the temperatures may result from the thermal coupling between the Be^+ and Hg^+ ions being weak. Because we were only able to measure the plasma boundaries from a perspective along a direction perpendicular to the z axis (see Fig. 1), we were unable to experimentally verify the existence of a gap between the two ion species. Future experiments are planned which should enable us to study the two species nonneutral plasma in more detail. In particular, by viewing the plasma in a direction along the z axis, a measure of the plasma boundaries in the $z = 0$ plane can be obtained. This should enable us to experimentally check the presence of a gap between the two ion species. In summary, the effectiveness of sympathetic cooling and compression was demonstrated. Long confinement times, high densities, and low temperatures were achieved on the trapped Hg^+ ions.

ULTRACOLD POSITRON SOURCE

Cooling and compression of positrons by sympathetic cooling with laser cooled $^9Be^+$ ions appears to be experimentally possible. The gap between the species in this case where $m_2/m_1 >> 1$ can be quite small. For $\omega < \Omega_2 << \Omega_1$, Eq. 7 can be rewritten $n_2/n_1 \cong 1 - \omega/\Omega_2$. For a rotation frequency of $\omega \cong 0.01\Omega_2(Be^+)$ (the condition achieved in the Be^+, Hg^+ experiment), $n_2/n_1 \cong 0.99$. According to Eq. 6 this means the gap between the positrons and Be^+ ions can be quite small and the thermal coupling high. It also follows that the density of the positrons will be approximately limited to the density of the Be^+ ions. In particular, positron densities will be limited to values much less than the Brillouin density for positrons. The principal advantages of sympathetic cooling and compression of positrons, then, are long term confinement and low temperatures. Positron temperatures less than 10 mK appear possible. Two potential applications of such a source of ultracold positrons are as follows.

In a magnetic field $B \geq 6$ T, positron densities greater than 10^{10} cm^{-3} are potentially achievable by sympathetic cooling with Be^+

ions. A positron plasma with densities $n \geq 10^{10}$ cm^{-3} and temperatures $T < 10$ mK is an interesting object to study. In addition to being strongly coupled, the cyclotron and plasma frequencies are quantized,[14] making a quantum mechanical description of the plasma dynamics necessary. Another application of ultracold positrons may be in antihydrogen production. A recent proposal[19] for making antihydrogen uses the three body recombination

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+.$$

The rate of this three body process has a $T^{-9/2}$ temperature dependence. Production of antihydrogen would therefore be greatly enhanced by using ultracold positrons.

We gratefully acknowledge the support of the U.S. Office of Naval Research and of the U.S. Air Force Office of Scientific Research. We thank Carl Weimer and Jerome Helffrich for carefully reading the manuscript.

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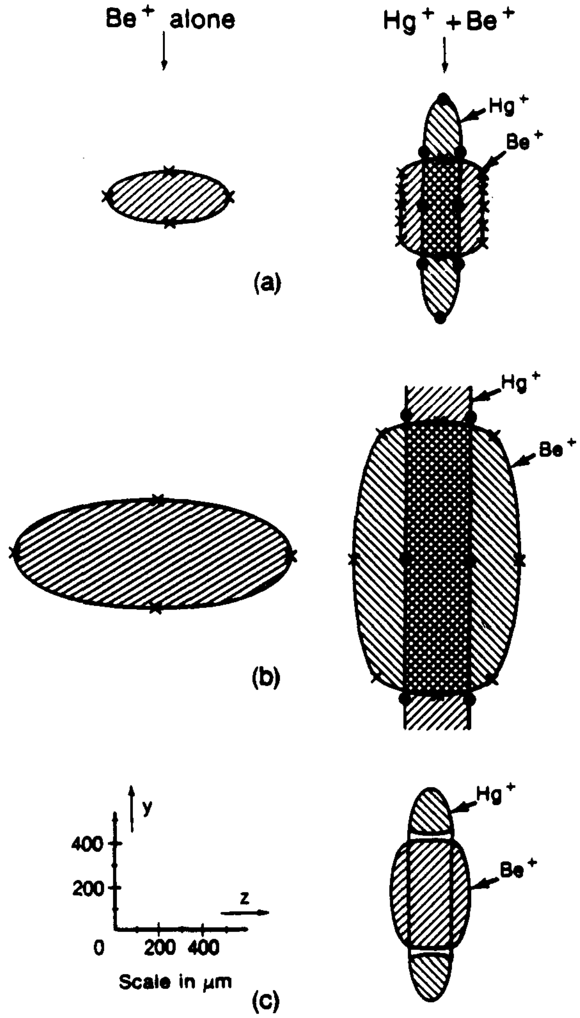

Fig. 1. (a) Measured Be^+- and Hg^+-ion-cloud shapes. The magnetic field is along the z axis. The Be^+ cloud, which contained about 800 ions, is shown with and without the Hg^+ present. The measured rotation frequencies were 41 kHz without Hg^+ [corresponding to a density, $n(Be^+)=3.9 \times 10^7$ cm^{-3}] and 20 kHz with Hg^+ present [$n(Be^+)=1.9 \times 10^7$ cm^{-3}, $n(Hg^+)=1.6 \times 10^7$ cm^{-3}]. The solid lines drawn through the data points conform to the theoretically predicted and separately confirmed spheroidal shape for Be^+ alone but are drawn without consideration of theoretical shapes for Be^+ and Hg^+ together. The edges of the clouds were measured with an uncertainty of about 25 μm. (b) Measured cloud shapes for a Be^+ cloud which contained about 12 000 ions and a Hg^+ cloud which was larger in radial extent than the aperture through the ring electrode (diameter ≅ 2100 μm). The measured rotation frequencies were 73 kHz without Hg^+ [$n(Be^+)=7.0 \times 10^7$ cm^{-3}] and 18 kHz with Hg^+ [$n(Be^+)=1.8 \times 10^7$ cm^{-3}, $n(Hg^+)=1.5 \times 10^7$ cm^{-3}]. (c) Theoretically predicted shapes for cold Be^+ and Hg^+ clouds under conditions similar to those in (a). The scale in (c) also applies to (a) and (b).