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Localized visible Ba^+ mono-ion oscillator

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An individual barium ion, continuously observed by laser fluorescence, has been isolated in a Paul rf quadrupole trap at room temperature. By optical sideband cooling its microscopically measured image has been reduced in thickness to $\sim 2\ \mu$m in the object plane, the diffraction limit. Estimated ion temperatures reached are $T_i \simeq 10$ to <36 mK. With cooling, the ion could be held indefinitely, without cooling ~ 30 s. In the future the technique seems capable of attaining kinetic temperatures $\sim 10^{-8}$ K, much lower than realized so far by other means, with corresponding far-reaching implications.

The localization of an individual atomic particle in empty space is one of the most fundamental problems of physics and one of enduring interest.[1] The scarcity of experimental work bearing on it is therefore surprising. Because of the importance of permanent localization in high-resolution spectroscopy, with its applications to atomic clocks, it is by no means of merely academic interest. The present work as well as our previously published preparatory studies,[2,3] grew out of proposals to use a refrigerated Tl^+ mono-ion oscillator[4,5] in a high-resolution ($10^{14}\ \Delta\nu_0 < \nu_0$) spectroscopic experiment, and, in the spirit of Mach,[6] to observe *visually* an individual Ba^+ ion[7] in a very small Paul rf quadrupole trap.

Using the previously described[2,3] apparatus but with improved observation optics, see Fig. 1, and laser stability, we have been able literally to see an individual Ba^+ ion, highly refrigerated by sideband cooling,[2,3,5,8-10] sit at the bottom of the parabolic well for hours, confirming our previous brief report.[2] The individual ion was identified via step increases in the resonance fluorescence when the trap was slowly filled by electron-impact ionization of Ba atoms traversing the trap in a very weak atomic beam, see Fig. 2. The very small visual one-ion image of thickness $t_i \simeq 2\ \mu$m (in the object plane) as observed through the microscope, see Fig. 3, was markedly different from those for 2 or more ions. The latter resembled the previously described many-ion clouds[2] homogenized by fast ion-ion collisions but with $t_i \simeq 5$ and $9\ \mu$m for 2 and 3 ions.[11] Part of this size is simply due to electrostatic repulsion. Two ions find stable equilibrium in the $z=0$ plane, and their distance is then 4.3 μm. The rest is due to diffraction and increased ion temperature presumably resulting from weak transfer of energy from the forced ion motion at Ω into the secular ω_w motion via ion-ion collisions.[2] This heating obviously disappears for only a single ion in the well. The long lifetime in the trap measured in the absence of side-band cooling for a single ion, $\tau_F \simeq 30$ s, in contrast to the quick loss of many-ion clouds in $\tau_F < 1$ s, confirms this model. Since for 10 μm clouds about $2z_0/\lambda\!\!\!^{-}_0 \simeq 100$ sideband components form $100\omega_w$-wide Doppler bands around the laser frequencies ω, ω_a the down-tuning values $\omega_0 - \omega \lesssim 2\pi\times 500$ MHz and $\omega_{a0} - \omega_a \lesssim 2\pi\times 1000$ MHz were chosen large enough that the Doppler bands did not contain the resonance frequencies ω_0, ω_{a0}. This minimized critical dependence of the resulting weak side band cooling on the precise setting of the occasionally jerky laser frequencies and promised fluorescence signals roughly proportional to the ion number for the even isotopes. As a qualitative analysis of an equivalent[12] spin $\frac{1}{2}$ magnetic resonance system showed that saturation destroys side-band cooling the ω, ω_a laser powers were adjusted to $\lesssim 0.3$ mW and $\lesssim 0.6$ mW resulting in estimated scattering rates $\sim 10^7$ Hz and $\sim 3\times 10^6$ Hz for the down-tuning values given above.

We now attempt to adapt our previous discussion of a *one-dimensional* motion side-band cooling model[2] to the *three-dimensional* motion of the experiment. We note that the practical potential will be slightly ellipsoidal with $|\omega_{wy*} - \omega_{wx*}|/\omega_{wx*} \simeq 0.01$, $2\omega_{wx*} \simeq \omega_{wz}$. Here ω_{wx*}, ω_{wy*}, ω_{wz} are the oscillation frequencies associated with the x^*, y^*, z principal axes. Also for the z motion the cooling vanishes for the direction of the laser beams $z' \perp z$ while the reemission heating remains finite. For uniform cooling it seems desirable therefore to choose the unit vector $\hat{k}'$ parallel $\hat{i}^* + \hat{j}^* + \hat{k}$. It now suffices to focus on the motion along one of the principal axes, for example z, because of symmetry. The ion, here as in Ref. 2, is modeled as a Thomson atom, i.e., an electron bound in a spherically symmetric parabolic po-

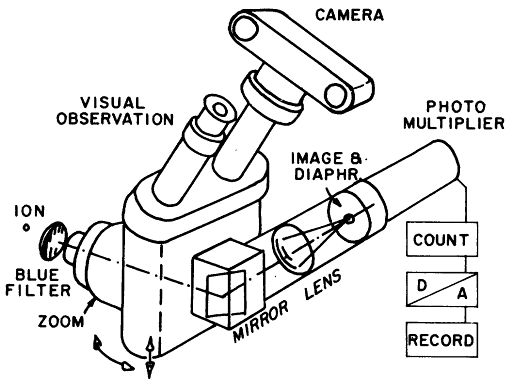

FIG. 1. Observation optics employing binocular microscope. The optics allowed simultaneous visual, photographic, and photoelectric observation of the stored ions. For a single ion the photon counting rate was $\sim 10^4$/s.

tential, in an approximation. We assume in a further approximation an unpolarized light beam and that the photons are reemitted *only* parallel or antiparallel to the principal axes $s = x^*,\ y^*,\ z$ in equal numbers on the average. Realizing that now the power in the $\omega \pm \omega_{wz}$ excitation sidebands is only $(\hat{k}' \cdot \hat{k})^2 = \frac{1}{3}$ of that for the case $z' \parallel z$, we obtain the cooling power[13,14] *for the z motion* and with $\omega_w \equiv \omega_{wz}$

$$p_c \simeq \hbar\omega_w S[vg_+ - (v+1)g_- - g_\omega]/3v_L \ .$$

Here $S < \Delta\omega_0/(1+e)g_\omega$ is a measure of the energy density of the laser field expressed as a hypothetical scattering rate at $\omega = \omega_0$ evaluated for a stationary ion as if the ω_0 resonance would not saturate. The P_c formula differs only unimportantly from the expression for the one-dimensional model of Ref. 2. The three terms in the square bracket respectively arise from absorption cooling, absorption heating, and net reemission heating. Implicit here is also the assumption of $\Delta\omega_0$ not too small compared with ω_{ws}, thus that the principal excitation occurs at ω. Due to the z motion the reemission spectrum along the $\pm z$ axis then consists of the carrier at ω and two weak sidebands at $\omega + \omega_w$, $\omega - \omega_w$ of fractional intensity[15] v/v_L and $(v+1)/v_L$. This entails the familiar retention of the additional average energy $\hbar\omega_w/v_L$ per photon emitted along the $\pm z$ axis or per every *third* photon scattered. The minimal average oscillation quantum number

$$\langle v\rangle_{\min} \simeq (g_\omega + g_-)/(g_+ - g_-)$$

follows by setting $P_c = 0$. In the limit

$$\omega_{ws} \ll \Delta\omega_0 \ll \omega_0 - \omega, \quad 1 \ll v_s$$

applicable to the current stage of the experiment we find for the characteristic cooling time valid for the x^*, y^*, z motions

$$\tau_c \simeq \tfrac{3}{2}(\lambda_0/\lambda_C)(1/Sg_\omega)(\omega_0 - \omega/\omega_0) \ .$$

Optimum cooling occurs for $S \simeq \Delta\omega_0/(1+e)g_\omega$. The expression for the optimum cooling time is

$$\tau_c^\dagger \simeq (6/\Delta\omega_0)(\omega_0 - \omega/\omega_0)(\lambda_0/\lambda_C) \ .$$

In the absence of any external heating independent of the laser field intensity we have

$$\langle v\rangle_{\min} \simeq (\omega_0 - \omega)/2\omega_w \ , \quad \langle W\rangle_{\min} = kT_{i\,\min} \simeq \hbar(\omega_0 - \omega)/2 \ ,$$

and

$$\langle z^2\rangle_{\min} \simeq (\omega_0 - \omega/2\omega_w)(\lambda\!\!\!^-_w \lambda\!\!\!^-_C) \propto 1/\omega_w^2 \ .$$

The formulas for τ_c, $\tau_c^\dagger$, $\langle v\rangle_{\min}$, $T_{i\,\min}$, and $\langle z^2\rangle_{\min}$ may be shown to be approximately valid far into the Doppler regime. Neither τ_c nor $\langle W\rangle_{\min}$ depend on ω_w, the cooling is symmetric in x^*, y^*, z. With our parameters we find numerically $v_L \simeq 600$, $\langle v\rangle_{\min} \simeq 155$, $T_{i\min} \simeq 10$ mK, $\tau_c^\dagger \simeq 3$ ms, and $\langle z^2\rangle_{\min}^{1/2} \simeq 0.09$ μm. Very likely these values have been reached in the experiments. Strictly on the basis of the empirical data we may argue as follows: *neglecting diffraction* we compare the one-ion and three-ion images in Fig. 3 using the fact that the image-rim brightness must be identical and assuming brightness distributions[11] $\propto \exp(-p^2/\Delta_p^2 - q^2/\Delta_q^2)$. The coordinates (p, q) lie in the object plane, p along its intersection with the xz plane. Then, with $\Delta \equiv \Delta_p$ and $\langle x^2\rangle = 4\langle z^2\rangle$, $\Delta^2 = 2\langle p^2\rangle = \frac{2}{3}\langle x^2\rangle + \frac{4}{3}\langle z^2\rangle = 4\langle z^2\rangle = \frac{1}{2}\Delta_q^2$ holds. With the reasonable and uncritical assumption $2\Delta = t_i(3) = 9$ μm for the three-ion image we easily show $2\Delta = 0.94$ μm for the $1/e$

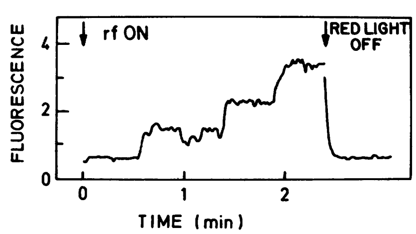

FIG. 2. Ba^+ fluorescence power (arbitrary units) vs time. With both electron and Ba beams on in ultrahigh vacuum the trapping rf potential at Ω was switched on at zero time. We ascribe the three steps visible to the consecutive capturing of 3 barium ions, presumably isotopes 138 or 136, in the trap. We attribute the drop in the fluorescence by $\sim\frac{1}{2}$ unit in the $\sim$15 s time interval starting at $\sim$1 min to collisional heating to such a degree that the image of the ion cloud expanded beyond the opening of the limiting diaphragm (Fig. 1), the presumable cause being the temporary capture of a second non-cooled energetic odd Ba^+ isotope. When the auxiliary red laser was switched off after about 2.5 min the (blue) fluorescence signal fell to its base value. The zero-point drift measured after $\sim$4 min was <0.2 units. Note the small background scattering of $<\frac{1}{2}$ units.

FIG. 3. Micro-photographic images of 1, 2, and 3 trapped Ba^+ ions. The large photograph shows the ~2-μm-thick image (white arrow) of a single ion inside the rf quadrupole trap as viewed through the gap between the ring and the left cap electrodes (trap structure illuminated by scattered laser light). A sketch of the whole trap structure seen from the same angle is inserted. The three small photographs, going from top to bottom, show, 10-fold enlarged, the central trap region, containing 1, 2, and 3 ions. The trap parameters were $\Omega = 2\pi \times 43.7$ MHz, $\omega_{wz} = 2\pi \times 1.61$ MHz, electron beam off, and Ba beam on. An exposure of 10 min and Kodak 103*a-F* film were used throughout.

width of the one-ion image with $t_i(1) = 2$ μm reflecting its ~30-fold peak brightness. Taking this distribution now as the convolution of two Gaussians of equal $1/e$ width $2\Delta' = \sqrt{2}\Delta = 0.66$ μm, one for the quasithermal one-ion motion, the other as a gross underestimate of the diffraction contribution (2 μm diameter of the first minimum Airy disc circle), we get the high estimates $\frac{1}{2}\Delta' = \langle z^2\rangle^{1/2} = 0.17$ μm and $T_i = 36$ mK. As a test of the sensitivity of T_i to changes in t_i we assume $t_i(1) = 3$ μm. Now $2\Delta' = 1.13$ μm follows which, one one hand happens to describe the diffraction distribution fairly well and, on the other would correspond to $T_i = 104$ mK. Conversely, the observed value $t_i(1) = 2$ μm is compatible with $T_i \lesssim 10$ mK, as the corresponding $2\Delta = 0.94$ μm may be exclusively ascribed to diffraction. It is worth pointing out that effective cooling of *all three* degrees of freedom[16] has been clearly established, as the observation direction x' makes large angles with the x^*y^* plane and the z axis. The principal axis directions x^*, y^* can be determined by microscopic observation of the ion motion associated with the very sharp ω_{wx^*}, ω_{wy^*} resonances of the mono-ion oscillator when excited by rf. By a fortunate accident, they apparently did not deviate too much from the $\hat{k}' \parallel \hat{i}^* + \hat{j}^* + \hat{k}$ condition. Also, the condition for efficient uniform cooling, that a somehow induced momentary motion $\perp z'$ does not persist longer than $\tau_c^\dagger$, namely,

$$|\omega_{wx^*} - \omega_{wy^*}|,\ |\omega_{wx^*} - \omega_{wz}|,\ |\omega_{wy^*} - \omega_{wz}| \gg 1/\tau_c^\dagger ,$$

was found easily fulfilled by $2\omega_{wx^*} \simeq 2\omega_{wy^*} \simeq \omega_{wz}$ and imperfections in the trap electrodes. Approximate spherical symmetrization[4] of the potential by application of a supplementary dc voltage to the electrodes appears desirable in the future. Eventually the technique[17] seems capable of attaining uniform, low temperatures in all three degrees of freedom never obtained so far by other means, e.g., ~10^{-8} K for an atomic transition at $\lambda_0 = 3$ μm with $\Delta\omega_0 \simeq 2\pi \times 300$ Hz, $\omega = \omega_0 - \omega_{wz}$, $\omega_{wx^*} \simeq \omega_{wy^*} \simeq \omega_{wz} \simeq 2\pi \times 1$ kHz, $\lambda_C = 10^{-15}$ cm, $v_L \simeq 6$, and $\langle v\rangle_{min} \simeq 0.03$. Also, the highly refrigerated mono-ion oscillator is likely to turn out an extremely sensitive probe of a variety of interactions too small to be measured before. Sharp two-photon transitions[7,18] to the metastable $5\,^2D_{3/2}$ level have also been observed, but will be discussed in another paper.

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[11]The marked increase in cloud size with ion number demonstrated by us is in sharp contrast to a recent study of hot ion clouds dominated by Ω-rf heating via collisions with the background gas and evaporation cooling [R. D. Knight and M. H. Prior, J. Appl. Phys. 50, 3044 (1979)].

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[13]The Lamb-Dicke level $v = v_L$ marks the boundary between the dominant-carrier or Lamb-Dicke regime and the multiside band or Doppler regime.

[14]Important results of our simple approximate analysis based on the correspondence principle and checked by standard perturbation theory (Ref. 8) appear to be in agreement with a more elaborate treatment published by D. J. Wineland and W. Itano, Phys. Rev. 20, 1521 (1979) after the submission of this work. The authors in their criticism of Ref. 2 seem to have overlooked that the discussion there was restricted to a *one-dimensional ion motion* model. In Ref. 2 due to printers errors a factor $\hbar$ *was* omitted in the expression for the cooling power and g_ω *was* rendered as g_w in the formula for v_{min}. Further, the expression for the laser power should have read $P^* \simeq (w/\lambda_0)^2 \hbar\omega_0 \Delta\omega_0$.

[15]Here, as in Ref. 2, we have made use of very general symmetry arguments applicable to the absorption and emission spectra of the ion moving in the well.

[16]The ≤ 0.1 K temperature reported by R. E. Drullinger and D. S. Wineland, Bull. Am. Phys. Soc. 24, 608 (1979), refers strictly only to the motion parallel to and inside the narrow laser beam. Due to the 26-kHz magnetron motion the perpendicular velocity of the $\sim 10^5$ ions in the 1-mm diameter cloud was about 10^4 cm/s corresponding to $T_\perp \simeq 20$ K, not to mention its $\sim k(250$ K) potential energy in the trap.

[17]To suppress heating of the ion by electric noise fields associated with the thermal motion of the electrons in the trap electrodes it may be necessary to go to liquid helium temperatures and use superconducting materials.

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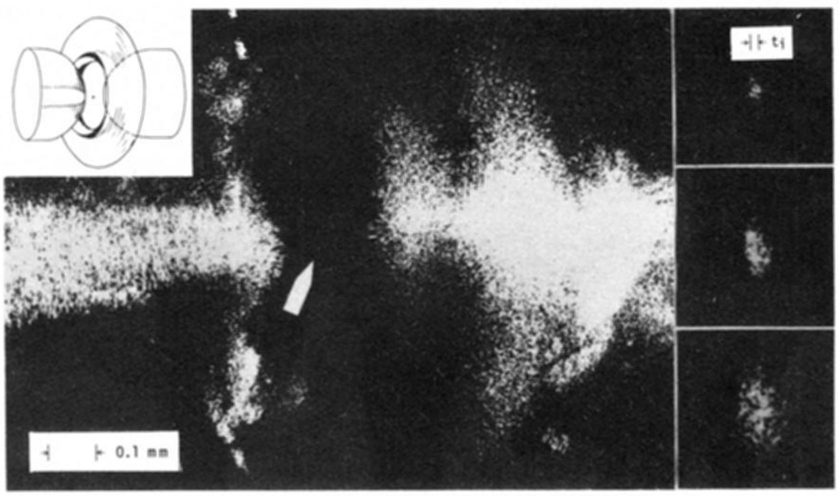

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