Single-ion oscillator with radiative cooling

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1. INTRODUCTION

As is well known, physical experiments designed to study the properties and structure of the elementary or atomic particles are concerned, as a rule, not with one individual particle, but rather ensembles of particles of the same kind. This approach is predicted basically on two conditions. First, studying an individual particle requires that it be culled out from an ensemble and confined to a limited region of space during a period of time sufficient to obtain the necessary information. Frequently, the given problem cannot be solved because of either (1) the short lifetime of a particle or (2) the inability to control with sufficient accuracy the time and/or birthplace of a particle, or (3) the disappearance of a particle in the course of interaction with the device that is intended to confine it. Second, even if one succeeds in the experiment to isolate and trap a particle, a study of its properties may be precluded by the insufficient sensitivity of instruments.

In view of the considerable difficulties of both fundamental and technical nature which are encountered in an effort to confine and study an isolated particle, considerable interest centers on those rare cases where the problem is successfully solved. In fact, to date only two examples of this kind are known. One of these is the continuous confinement of a single electron in an electromagnetic Penning trap,[1,2] which is essential for attaining the highest accuracy in the measurement of the electron magnetic moment.[3] We note that in these experiments the duration of continuous confinement of an isolated electron is several weeks.

The second example of the successful solution of the problem of confinement of an isolated particle is the recent confinement of Ba II[4] and Mg II[5] ions in electromagnetic traps. In the case of the Ba II ion the continuous confinement lasts tens of hours.[4] However, strictly speaking, confinement of an isolated ion was not the goal of these experiments.[4,5] The central problem of the work was development of a technique for cooling an isolated ion by laser radiation. Having successfully solved this problem, the authors reported on the attainment of 10^{-2} K[4] as the temperature of confined Ba II ion and the cooling of Mg II ion down to 5×10^{-2} K.[5] Altogether, the number of confined particles, one ion,[4,5] and the temperature of the confined ion, ~10^{-2} K, suggest there is a unique new device in experimental physics, a cold single-ion oscillator.

Generally speaking, the importance of the prolonged confinement of a particle with low translational temperature does not require any special elaboration, since the very occurrence of such a process is a stimulus to new precision experiments both in atomic and nuclear physics and in related fields. However, the potential application of the confined cold ion concept to superhigh-resolution spectroscopy warrants special attention.

The point is that the accuracy of current spectroscopic studies carried out by means of superhigh-resolution laser spectroscopy is limited, to a large degree, by the finite number of particles under investigation and their insufficiently low temperature. Because of the large number of particles in the volume under investigation, the observed spectral resonances always involve

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particle interaction; thus, their widths and positions fail to correspond to the energy diagram of an individual particle. The insufficiently low translational temperature of particles attained cryogenically is, in turn, dependent on different mechanisms of optical resonance broadening, among which the strongest are the quadratic Doppler effect and transit-time broadening.

Inasmuch as the only way to eliminate all effects which mask the true energy structure may be spectroscopy of an individual cold particle, the proposed cold single-ion oscillator is an ideal tool both for exact optical investigations and as the basis for an optical frequency standard.

This review article considers investigations involving confined cold ions. As indicated by the state-of-the-art in this field, we shall consider below methods for ion confinement, advantages of the radiative cooling method, and evaluate certain experiments with confined ions.

2. ION CONFINEMENT

The natural method of limiting the motion of ions in space is to contain them by nonuniform electric fields. At the same time the apparently simplest method involving containment in a nonuniform electrostatic field theoretically cannot be accomplished due to the absence of absolute potential minima or maxima in a static electric field.[6] In order to remove this limitation several schemes of ion confinement have been developed which use more complex types of electromagnetic fields. On the whole, all such schemes can be classified as belonging to one of two types. In one scheme, a combination of a nonuniform electrostatic field and a fixed magnetic field is used,[7,8] and, in the other, a nonuniform hf electric field.[8,9] Among the possible configurations of trapping electric fields, practical development in both cases was achieved using quadrupole fields produced by means of hyperbolic electrodes.[8]

a. The Penning trap

The hyperbolic electrodes of an electromagnetic Penning trap are maintained at the constant potential difference $U = U_0$ (Fig. 1), and they form an electrostatic field in the shape of an axial quadrupole which

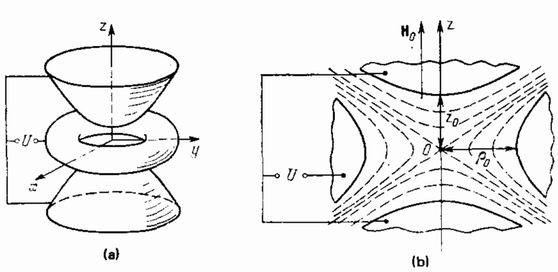

FIG. 1. (a) Electrode configuration in a quadrupole ion trap (electrode surfaces facing the trap center are hyperboloids of revolution); (b) Cross section of a quadrupole ion trap along the Oz symmetry axis, and equipotential surfaces for the potential in Eq. (2.1) (in the case of a Penning trap $U = U_0 =$ const, and in the case of a rf trap, $U = U_0 \cos\Omega t$; magnetic field H_0 is produced only in a Penning trap).

corresponds to the potential

$$\Phi(\mathbf{r}) = A(\rho^2 - 2z^2), \tag{2.1}$$

where

$$A = A_0 = \frac{U_0}{\rho_0^2 + 2z_0^2}, \tag{2.2}$$

ρ and z are cylindrical coordinates of the point $\mathbf{r}$, and ρ_0 and z_0 define the minimum distance to the electrodes. In addition to this, a constant uniform magnetic field H_0 is directed along the symmetry axis Oz.

The motion of an ion in the total electromagnetic field of a Penning trap is highly complex. In the zero approximation, which corresponds to small oscillations of an ion near the symmetry center O, it may be described as a superposition of three motions[8,10]: axial oscillation along the z axis at a frequency

$$\omega_a = \sqrt{\frac{4eA_0}{M}}, \tag{2.3}$$

cyclotron motion along the magnetic field H_0 at a frequency

$$\omega_c = \frac{eH_0}{Mc} \tag{2.4}$$

and drift (magnetron) circular motion along the z axis in the xy plane at a frequency

$$\omega_m = \frac{2cA_0}{H_0}, \tag{2.5}$$

where e is the charge and M the mass of the ion. The frequencies of the three fundamental motions satisfy the explicit relationship $\omega_c\omega_m = \omega_a^2/2$ and, at the typical parameters of a Penning trap, are quite different. Thus, at typical values of $U_0 \sim 10$ V and $H_0 \sim 10^4$ Oe the axial, cyclotron and magnetron frequencies are in the following ranges, respectively: $\omega_a \sim 100$ kHz, $\omega_c \sim 1000$ kHz and $\omega_m \sim 10$ kHz.

b. Rf quadrupole trap

In the case of an rf quadrupole trap with the same configuration (Fig. 1), the hf voltage applied to the electrodes is $U = U_0 \cos\Omega t$. The ion motion in the corresponding nonuniform rf electric field in the simplest approximation may be expressed as a sum of the slow motion $\bar{\mathbf{r}}(t)$, in a certain effective potential field, and rapid oscillations at a frequency of the applied field Ω and having a small amplitude ζ near the position of a local equilibrium $\bar{\mathbf{r}}(t)$:

$$\mathbf{r}(t) = \bar{\mathbf{r}}(t) + \zeta(\bar{\mathbf{r}}) \cos\Omega t. \tag{2.6}$$

The small signal amplitude in Eq. (2.6) is defined by the electric field amplitude of the trap $\mathbf{E}(\bar{\mathbf{r}})$:

$$\zeta(\bar{\mathbf{r}}) = \frac{e\mathbf{E}(\bar{\mathbf{r}})}{M\Omega^2}, \tag{2.7}$$

and the average motion of the center of mass of an ion occurs in the effective potential with an ellipsoidal shape[8,9,11]

$$\Phi_{eff}(\bar{\mathbf{r}}) = \frac{eA_0^2}{M\Omega^2}(\bar{\rho}^2 + 4\bar{z}^2), \tag{2.8}$$

where A_0 is determined from Eq. (2.2), and $\bar{\rho}$ and $\bar{z}$ are the cylindrical coordinates of vector $\bar{\mathbf{r}}$.

In the potential of Eq. (2.8) an ion undergoes oscillations at a frequency $\omega_z = \overline{\omega}$ along the z axis and at a frequency $\omega_\rho = \overline{\omega}/2$ in the xy plane, where

$$\overline{\omega} = \frac{2\sqrt{2}eA_0}{M\Omega}. \tag{2.9}$$

At $U_0 \sim 100$ V, which is typical for the applied field, and frequency $\Omega \sim 10$ MHz, the frequency of axial ion oscillations is of the order of $\overline{\omega} \sim 1$ MHz.

A more rigorous analysis of the ion motion in the rf field of a quadrupole trap leads to three Mathieu equations.[11] The latter show that ion oscillations in the effective potential of Eq. (2.8) are stable at a sufficiently large stability parameter $\Omega/\overline{\omega} \gg 1$. Strict analysis also shows that the ion oscillation spectrum consists of an infinite set of discrete frequencies. In particular, the axial oscillation spectrum contains components at all frequencies $n\Omega \pm \omega_z$, where $n = 0, \pm 1, \ldots$

The limitation of ion motion by the potential well of a trap constitutes basically only the necessary condition for ion confinement. In order that an ion actually be held in a trap for a long time, its average energy must be considerably smaller than the depth of the potential well. In addition, since at any non-zero pressure the remaining particles present in a trap may transfer their thermal energies to an ion through collisions, the sufficient condition for long-term confinement of an ion is that the thermal energy $k_B T$ be small in comparison with the value of the potential barrier of the trap.

The above condition is one of the fundamental criteria for selecting the magnitude of the field applied to the electrodes. These criteria are, however, not stringent since the potential barrier required for thermal energies is exceeded a hundredfold at relatively small electrode voltages (~10–100 V).

We shall now proceed to consider the essence of a radiative method of ion cooling which permits the cooling of ions stored in an electromagnetic trap down to temperatures considerably below room temperature.

3. PRINCIPLE OF RADIATIVE ION COOLING

The idea of radiative cooling of atomic particles was expressed independently by Hansch and Schawlow,[12] for free atoms, and by Wineland and Dehmelt[13] and Dehmelt,[14] for ions bound in electromagnetic traps. The possibility of particle cooling by means of hf fields was considered earlier in a more general form by Kastler[15] and Zel'dovich.[16] In the case of ions stored in an electromagnetic trap, the nature of the method of radiative cooling permits a simple classical or quantum explanation. The classical consideration of the motion of the center of ion mass corresponds in the most natural way to the case of weak coupling between the ion and the trap, when the frequency of vibrations ω_v of the center of ion mass is low compared to the natural width 2γ of the ion optical transition which is in resonance with the optical wave. The opposite case of strong coupling ($\omega_v \gg \gamma$) can be explained naturally from the quantum-mechanical viewpoint.

We shall limit our discussion to the nonrelativistic analysis of motion of an ion which is adequate for all practical cases, and assume that an optical wave with a frequency ω, which is smaller than the frequency of the ion transition ω_0, is incident on a captured ion undergoing harmonic motion near the trap center [Fig. 2(a)]. For the sake of simplicity, we shall assume the resonant ion transition to be between two nondegenerate levels, of which we shall assume the lower one to be the ground level and the upper decaying only to the ground level with the probability 2γ.

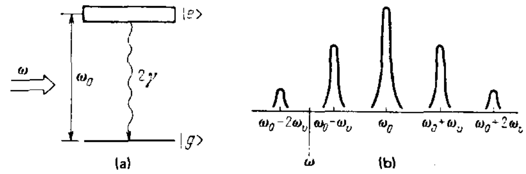

FIG. 2. Interaction of an ion with the cooling laser radiation (a) and the absorption spectrum of an ion confined in an electromagnetic trap (b).

As a result of the harmonic oscillations of the center of ion mass at a frequency ω_v, the resonance absorption (emission) spectrum of an ion splits into components with frequencies $\omega_n = \omega_0 \pm n\omega_v$ $(n = 0, 1, \ldots)$ [Fig. 2(b)]. Each of these spectral lines correspond to the ion optical transition with a concommitant change in the ion vibration frequency. When the frequency of the optical wave ω coincides with one of the low-frequency lines from the absorption spectrum, for example the absorption line of frequency $\omega_0 - \omega_v$ [Fig. 2(b)], ion excitation is accompanied by the absorption of energy $\hbar(\omega_0 - \omega_v)$. Since the ion returns to the ground state as a result of spontaneous decay with the emission of a photon with energy $\hbar\omega_0$, as a result of this the energy lost in the process is $\hbar\omega_v$. This energy is removed from the energy of motion of the ion center of mass which leads to the slowing down of ion vibrations.

The qualitative considerations above may be confirmed by a simple calculation based on conservation laws.

We shall assume for the sake of definiteness that coupling between an ion and a trap is sufficiently weak ($\omega_v \ll \gamma$), and the motion of the center of mass may be considered in the classical sense. In that case, the laws of conservation of energy and momentum for the elementary processes of absorption and emission of a photon can be used to express the absorbing (E_+) and emitting (E_-) energies as follows:

$$E_\pm = \hbar\omega_\pm = \hbar\omega_0 + \hbar\mathbf{k}\mathbf{v} \pm R, \tag{3.1}$$

where $\mathbf{k}$ is the wave vector of an optical wave, $\mathbf{v}$ is the ion velocity, $R = \hbar^2\omega_0^2/2Mc^2$ is the recoil energy. Since the ion absorbs photons propagating along a given direction and emits, on the average, isotropically in all directions, on the average the ion absorbs the following energy

$$\bar{E}_+ = \hbar\omega_0 + \hbar kv + R, \tag{3.2}$$

where v is the component of the velocity along the vector $\mathbf{k}$, and the ion emits the following energy

$$\bar{E}_- = \hbar\omega_0 - R. \tag{3.3}$$

Thus, the energy which an ion acquires on the average in the process of absorption and subsequent emission of a photon is

$$\overline{\Delta E} = \bar{E}_+ - \bar{E}_- = \hbar k v + 2R. \tag{3.4}$$

Now, considering that the excitation of an ion requires that the Doppler shift be compensated

$$\omega - \omega_0 = kv, \tag{3.5}$$

we find that the increase in the translational energy of an ion is

$$\overline{\Delta E} = \hbar(\omega - \omega_0) + 2R \approx \hbar(\omega - \omega_0). \tag{3.6}$$

Thus, when $\omega < \omega_0$, the energy change is $\overline{\Delta E} < 0$ and the ion is actually cooled by the light. In particular, when the frequency of the wave coincides with the first satellite absorption line of frequency $\omega = \omega_0 - \omega_v$, the change in the ion energy is in good agreement with the qualitative expressions, and equals $\overline{\Delta E} = -\omega_v$.

The foregoing analysis assumes that the ion is, in fact, a free particle; this was used to characterize its state in terms of the instantaneous velocity **v**. In the other limiting case $\omega_v \gg \gamma$, i.e., in the case of strong coupling between an ion and a trap its condition can no longer be considered as isolated from the condition of the trap. In this case, the appropriate basis states are those of the coupled system "ion-electromagnetic trap" (Fig. 3). The latter are characterized by the quantum internal state of the ion: $|i\rangle = |g\rangle$ for the ground state and $|i\rangle = |e\rangle$ for the excited state, and the quantum state of the center of mass of the bound ion, $|tr\rangle = |v\rangle$.

In the simplest case of the harmonic potential, the $|v\rangle$ state corresponds to the wave function of an oscillator with energy $E_v = \hbar\omega_v(v + \frac{1}{2})$. Due to coupling between the inner state and the ion center of mass state, absorption or emission of a photon in an inner ion transition is, generally speaking, always accompanied by a change in the vibrational state of the ion. For $\omega = \omega_0 - n\omega_v$, as can be seen from the energy level diagram for the "ion-trap" system (Fig. 3), the light wave most probably undergoes the transition $|g, v+n\rangle \to |e, v\rangle$. In the case of spontaneous decay, the vibrational state of the ion does not change on the average ($|e, v\rangle \to |g, v\rangle$). In this connection, at $\omega = \omega_0 - n\omega_v$, on the average in each photon absorption-emission event an ion loses translational energy $\overline{\Delta E} = n\hbar\omega_0$ and is cooled.

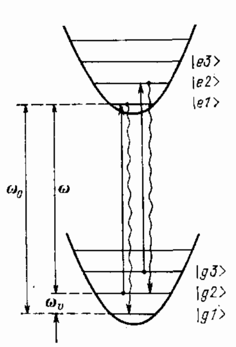

FIG. 3. Energy states of an ion in an electromagnetic trap, and transitions responsible for the ion cooling.

Until now, in our discussion of the mechanism of radiative cooling of ions we have left out of consideration the stochasticity of the processes of absorption and emission of photons by confined ions. It is understood, however, than an allowance for fluctuations in the momentum transferred to an ion during photon scattering is theoretically necessary since the scattered photons are responsible for the diffusion heating of ions. When fluctuations are taken into account the question of the limiting attainable energy of the cold ions becomes important, as well as an associated question concerning the optimal radiation parameters at which deep cooling is achieved. The answers to these questions are substantially different depending on the relations between ion vibrational frequency ω_v and line halfwidth γ.

In the case of weak coupling between a trap and an ion (also for a free atom or ion), the steady-state distribution of ion momenta is Maxwellian and the cold ion state may be characterized by the translational temperature.[1)] The latter, as shown in detailed calculations,[17-21] depends only on the frequency difference $\omega - \omega_0$ and, at $\omega = \omega_0 - \gamma$, it attains the minimum value

$$T_{\min} \approx \frac{\hbar\gamma}{k_B}, \tag{3.7}$$

which is fully defined by the halfwidth of the absorption line γ. At typical values of $\gamma \sim 1$–10 MHz, the minimum possible temperature is of the order of $T_{\min} \sim 10^{-4}$–10^{-3} K.

In the case of strong ion-trap coupling ($\omega_v \gg \gamma$), one may speak only of a distribution function over the levels of a composite quantum system, "ion-trap;" moreover, the shape of the latter depends on the ratio between the amplitude of ion vibrations in a trap, a, and radiation wavelength λ.[19,22,23] In particular, in the important case of small oscillation amplitude ($a \ll \lambda$), the deepest cooling is attained at a frequency $\omega = \omega_0 - \omega_v$. In this case, the distribution over the levels of the composite system is Planckian with the mean energy[19,22,23]

$$E_{\min} \approx \hbar\gamma\left(\frac{\gamma}{\omega_v}\right) \tag{3.8}$$

and temperature

$$T_{\min} \approx \frac{\hbar\omega_v}{2k_B}\ln\frac{\omega_v}{\gamma}. \tag{3.9}$$

4. BASIC EXPERIMENTS

The most comprehensive investigations of radiative ion cooling were carried out at the U.S. National Bureau of Standards[5,24,25] and Heidelberg University.[4,26-28] The first group used a Penning trap, the other an rf quadrupole trap.

a. Cooling of Mg II ions

The Penning trap experiments were concerned with the storage of Mg II ions. The characteristic dimen-

[1)] We note that applying the concept of temperature to an individual ion is consistent with the principles of statistical mechanics, since the ion is in equilibrium with the thermostat whose role is played by the resonant optical field.

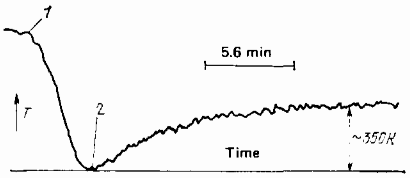

FIG. 4. Dependence of ion temperature in a Penning trap on time.[24] Digits 1 and 2 correspond to "on" and "off" positions of a laser at frequency $\omega=\omega_0-2$ GHz; ω_0 is the central frequency of ion transition with wavelength $\lambda=280$ nm.

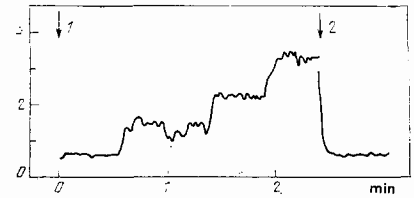

FIG. 5. Fluorescence intensity (in rel. units) of a central point in an rf trap as function of time. Arrow 1 indicates application of trapping potential; arrow 2 indicates removal of cooling radiation. Each new ion is created every 0.5–1 min and the fluorescence signal increases stepwise.[4]

sions of the trap were: $\rho_0 = 1.64z_0 = 0.63$ cm. The typical parameters of the electromagnetic field, $U_0 = 7$ V and $H_0 = 10^4$ Oe, produced the following frequencies: $\omega_a = 200$ kHz, $\omega_c = 700$ kHz and $\omega_m = 30$ kHz. The ion storage time, at the residual gas pressure in the trap of $p \lesssim 10^{-10}$ Torr, was one day. To obtain ions inside the trap a beam of Mg atoms was ionized by a beam of electrons, the two beams intersecting at the trap center. The Mg II ions were cooled by cw laser radiation with the wavelength $\lambda = 280$ nm which was shifted into the low-frequency region from one of the Zeeman lines of the first resonance transition $3s^2S_{1/2} - 3p^2P_{3/2}$.

Two methods were used in these experiments to measure the temperature of cooled ions. A rough estimation of the temperature was carried out by recording the current induced in the trap electrodes by the moving ions which, for a constant number of ions, is proportional to the ion temperature. A more accurate measurement of temperature was carried out by measuring the Doppler broadening of the absorption line of the resonance ion transition.

The results of measurements of the ion temperature have established the high effectiveness of the radiative ion cooling (Fig. 4). Thus, in one of the first experiments,[24] the switching on of a laser with the frequency difference $\omega_0 - \omega = 2$ GHz, which is far from optimal, decreased the ion temperature from 700 K to <40 K. We note that the initial high ion temperature in Fig. 4 was the result of heating of the ions by the same laser radiation, but at a frequency $\omega > \omega_0$. The minimum temperature of an individual ion attained in the Penning trap experiments, as indicated by measurements of the Doppler linewidth of the resonance optical transition, was 5×10^{-2} K.[5]

b. Cooling of Ba II ions

In the experiments with the cooling of ions and involving an rf trap, a single Ba II ion was stored at the temperature ~10^{-2} K. The parameters of the rf trap were: $\rho_0 = \sqrt{2}z_0$, $z_0 = 0.25$ mm. The applied trapping potential was $U_0 = 200$ V, and the frequency $\Omega = 20$ MHz. Corresponding to these values the axial oscillations frequency was $\omega_z = \bar{\omega} = 2$ MHz. Ions were injected into the trap by ionization of the Ba atoms by electron impact.

The resonance transition $6^2S_{1/2} - 6^2P_{1/2}$, with the wavelength $\lambda_0 = 493.4$ nm, was used for the radiative cooling of the Ba II ions. Since the upper level of this transition decays not only to the ground level $6^2S_{1/2}$, but also to the metastable level $5^2D_{3/2}$ (wavelength of the $6^2P_{1/2} - 5^2D_{3/2}$ transition being $\lambda_1 = 649.9$ nm), two lasers had to be used. The principal laser was used to cool ions at the $5^2D_{3/2} - 6^2P_{1/2}$ transition and the auxiliary laser, was used for the excitation of ions at the $5^2D_{3/2} - 6^2P_{1/2}$ transition, preventing, in this manner, the loss of resonance between the ions and the principal radiation.

In these experiments, a spatial distribution of resonance fluorescence intensity was observed in the central portion of the trap. For this reason the trap interior was scanned with a photo lens; at its output, fluorescence could be observed visually and, also, recorded by a photoelectric cell or on photosensitive paper. This method of recording made it possible, first of all, to establish reliably any required number of ions in the trap. With the application of the trapping potential and with the laser beams "on," arrival of each new ion in the trap was accompanied by a discrete increase in the fluorescence intensity. The accumulation of three cold ions in an rf trap is shown in Fig. 5, as an example.

The ion temperature was calculated from the spatial distribution of fluorescence intensity which was recorded on photo sensitive paper (Fig. 6). Based on these

FIG. 6. Photograph of resonance fluorescence from an ion (at center) with temperature $T < 2.5$ K. Light halo is due to scattering of laser radiation by trap electrodes.[4]

measurements, Neuhauser and coauthors concluded that the temperature attained in the storage of a single ion was 10–30 mK.[4]

5. SPECTROSCOPIC INVESTIGATIONS OF TRAPPED IONS

As we mentioned in the introduction, trapped cold ions constitute ideal objects for precision spectroscopic investigations. However, since the laser method of ion cooling is still undergoing experimental verification, spectroscopic studies make use of trapped ions at room temperature. Among the recent works of this nature three deserve attention. Two of these have dealt with the measurement of the frequency of transition between the fine structure components of the Ba II ground state, and examined the possibility of using trapped Ba II ions as a frequency standard in the microwave region,[29,30] while the third conducted a precision measurement of the lifetime of the $5D_{3/2}$ metastable level of a Ba II ion.[31] The storage of Ba II ions in all cases was carried out in an rf quadrupole trap.

To measure the extent of the hyperfine splitting of the $F=1$ and $F=2$ levels of the $6S_{1/2}$ ground state of a Ba II ion, double radio-optical excitation of ions was used. Klystron radiation with the frequency of 8037 MHz, controlled by a secondary rubidium frequency standard, was used to excite ions at the $F=1$ and $F=2$ levels, while a dye laser was used to excite ions to the short-lived $6P_{1/2}$ state. The latter decays into both the ground state and the $5D_{3/2}$ metastable state. By recording the fluorescence intensity at the $6P_{1/2}-5D_{3/2}$ transition as a function of klystron frequency, hyperfine splitting in ^{137}Ba II was measured with a relative accuracy of 10^{-10}.[30] The absolute number of ions used in these experiments was approximately 10^6.

Another interesting test involving trapped Ba II ions was measurement of the lifetime of the $5D_{3/2}$ state. This state may decay into the ground state $6S_{1/2}$ only by an electric quadrupole transition with a lifetime which is theoretically estimated to be several tens of seconds. To measure the latter, conditions were adjusted for an ion trapping time of 30 min.[31] The measurement was derived from dependence of the fluorescence intensity of the $6P_{1/2}$ state on time, with a pulsed dye laser providing excitation of the ions in the $6S_{1/2}-6P_{1/2}$ transition. The laser radiation consisted of a train of nanosecond pulses with a 100 ms separation. Subsequent to analysis and elimination of a possible measurement error associated, in particular, with the residual gas pressure in a trap, and the quenching of the metastable state as a result of coexistence of the $6P_{1/2}$ state in the electric field of the trap, the lifetime of the $5D_{3/2}$ state was determined to be 17.5 ± 4 s.

The aforementioned investigations are directly applicable to development of microwave frequency standards based on trapped ions. Considerable progress toward this goal has been made in recent years.[32-35] In particular, accounts were published on the development of a frequency standard based on ^{199}Hg II ions, with a stability close to that of a cesium frequency standard.[34]

6. CONCLUSIONS

On the whole, the first successful experiments with laser cooling of trapped ions have provided a realistic basis for future progress in precise spectroscopic investigations. In view of this, the literature contains a consensus of opinion that the most important applications of trapped cold ions may be in the areas of high-resolution laser spectroscopy and microwave and optical frequency standards.[36-42] The theoretical analyses support this viewpoint and predict that a resonance with a width determined strictly by natural broadening should exist at the center of the absorption line for a cold ion held in the potential well of a trap.[38-40] Because transit-time broadening and displacement as a result of the quadratic Doppler effect are suppressed for the cold ion, frequency stability is predicted for standards based on trapped cold ions which is several orders better than that of existing frequency standards. In particular, it is anticipated that a ^{205}Tl II cold single-ion oscillator, with the transition wavelength $\lambda = 2022$ Å, is capable of a frequency instability of the order of 10^{-15},[41] and a ^{201}Hg II cold ion may be used for both microwave and optical standards, with a frequency instability of the order of 10^{-16}.[42]

In conclusion, we note that in addition to cooling off trapped ions, cooling and trapping of neutral atoms by laser methods are also under investigation (see review of Ref. 43). The solution of this problem is, however, more complex. The fact is that while ions can be trapped in an electromagnetic field before they are cooled with a laser, only the opposite order is possible for atoms, i.e., radiative pre-cooling of thermal atoms and subsequent trapping of cold atoms in laser beams.[44] In view of this, only the first experiments are being conducted in this direction in which principal attention is focused on studying the radiative retardation of atom beams by opposed laser radiation.[45,46]

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