Trapped atomic particles in action

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A review of recent papers on research on trapped ions cooled by laser radiation is given. Experiments are described on observing quantum jumps in atoms and on investigating antibunching and sub-Poisson statistics of photons of fluorescence radiation from single atoms. Experiments on phase transitions in a system of cold ions are discussed.

1. Introduction. Atomic particles localized (trapped) in high vacuum in electromagnetic traps and cooled to ultralow temperatures are an exceedingly convenient setting for carrying out some extremely "clean" physical experiments. The range of possible applications of trapped cold particles has been clearly outlined in reviews by Toschek[1] and Balykin *et al.*[2] and in a monograph by Minogin and Letokhov.[3] Among these applications are precise spectroscopic measurements, the development of extremely accurate optical frequency standards, and experiments in fundamental physics, chemical physics, etc. By now the basic fundamental problems standing in the way of the realization of these possibilities have essentially already been solved. First, miniature electromagnetic traps have been developed, and methods have been developed for accumulating and confining small numbers of ions—even individual ions—in them. The next task is to solve the same problem for neutral particles. Second, laser cooling has made it possible to reach an ion temperature $\sim 10^{-3}$ K, so that, in particular, it has become possible to extend the ion confinement time in a trap to tens of minutes or more. Third, the method of resonance fluorescence and the technique of photon counting have been developed into systems which can not only detect the emission of individual atoms but also observe individual atoms in a trap visually or photographically.

The status of this field of research as of mid-1985 is reflected well in some monographs[1–3] (see also the supplementary bibliography in Ref. 1). Numerous recent publications contain reports of new and impressive results achieved with localized ions. In the present brief review we will discuss primarily those studies which not only brilliantly illustrate the possible practical applications of cold ions in traps but also *contain results touching the foundations of physics.* We are thinking primarily of experiments on the observation of quantum jumps in atoms, on the quantum properties of radiation, and on phenomena of phase-transition type which occur in an ensemble of cold ions.

2. Quantum jumps. As early as 1913, Bohr suggested that the absorption or emission of optical radiation by an atom was accompanied by instantaneous transitions of the atom from one state to another.[4] These transitions have been labeled *quantum jumps.* The concept of quantum jumps was subsequently extended to transitions in quantum systems of a radiationless nature (e.g., of a collisional nature). For a long time, however, experimental observation of these jumps was hindered by the circumstance that in order to study the absorption and emission of electromagnetic radiation it was generally necessary to deal with large ensembles of atoms. Only recently has the situation changed in a fundamental way: An individual atom caught in a trap and held there for a sufficiently long time can be used for a series of repeated measurements for a study of the time evolution of the internal state of the atom.

The method for observing quantum jumps is based on a scheme which was originally proposed by Dehmelt in 1975.[5] This scheme can be outlined as follows: We have an individual three-level atom [Fig. 1a) for which the rates of radiative transitions from excited states 1 and 2 to ground state 0 are sharply different: $\gamma_1 \gg \gamma_2$. An intense laser beam at resonance with the 0–1 transition causes a fluorescence on this transition, which signals the "circulation" of an atom between levels 0 and 1. If at some instant the atom goes abruptly into long-lived state 2, the result will be an instantaneous termination of the fluorescence signal. This signal will then be restored, again abruptly, after the atom reverts to its ground state. The time evolution of the fluorescence on the strong transition in a scheme of this sort should take the form of a random telegraph signal in which "bright" and "dark" intervals alternate. The average duration of the dark intervals will be the lifetime of level 2.

This scheme might be thought of as an extremely efficient device for amplifying the signal on the weak transition. The gain here is actually determined by the ratio of the probabilities for radiative transitions on the strong (1–0) and *weak (2–0) transitions and can reach values on the order of* 10^6–10^3. The outlook for the use of such an amplifier in spectroscopy and for developing extremely accurate optical frequency standards was discussed in Refs. 5–9.

Cook and Kimble[9] have carried out a preliminary theoretical analysis of the possibility of directly observing quantum jumps in a three-level system. They worked from the rate equations for an effective system with two states: "on" and "off." In particular, they showed that the distribution of the durations of the bright (+) and dark (−) intervals is

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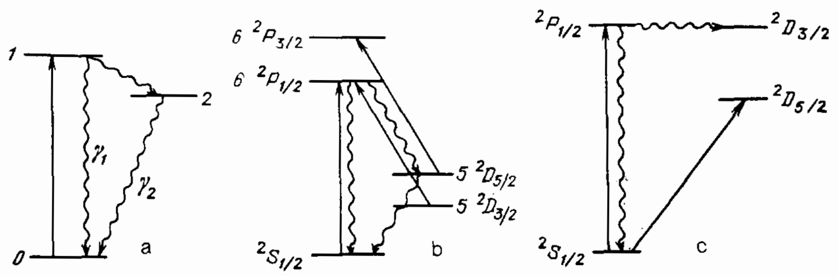

FIG. 1. Energy level schemes of (b) the Ba^+ ion and (c) the Hg^+ ion.

described by the probability density

$$W_\pm(T) = \frac{1}{\tau_\pm} e^{-T/\tau_\pm}, \tag{1}$$

where $\tau_\pm$ are the mean durations of the corresponding intervals. In the model discussed above (Fig. 1a), τ is equal to the lifetime of metastable level 2. In the same approximation, the following expression is found for the autocorrelation function of the intensity of the resonance fluorescence:

$$g^{(2)}(\tau) = 1 + \frac{\tau_-}{\tau_+} \exp\left[-\left(\frac{1}{\tau_-} + \frac{1}{\tau_+}\right)\tau\right]. \tag{2}$$

Note that the conclusions of this paper are based on the initial assumption that quantum jumps exist. A more rigorous quantum-statistical theory of resonance fluorescence of three-level atoms was derived in subsequent papers.[10–14] In particular, that theory includes a proof of the manifestation of quantum jumps.

In 1986 Nagourney *et al.*[15] (University of Washington, Seattle) reported the first experimental observation of quantum jumps. Appearing soon thereafter were papers by Toschek[16,17] (Hamburg University; see also Ref. 18) and by researchers at the US National Bureau of Standards.[19] Those experiments used Ba^+ ions (Refs. 15–18) and Hg^+ ions (Ref. 19) localized in rf traps. The schemes of the low-lying (working) levels of these ions are shown in Fig. 1, b and c.

Let us first look at the results obtained on Ba^+ ions; for the most part we will be following the more comprehensive and detailed papers.[16–18] In these experiments, one, two, or three Ba^+ ions captured in the trap were illuminated simultaneously by the cw beams from two dye lasers. The beam with $\lambda_1 = 493.4$ nm was tuned to a frequency slightly below the resonance with the strong transition $6^2S_{1/2} - 6^2P_{1/2}$ (Fig. 2a) and performed two roles. First, it excited resonance fluorescence, whose emission served as the signal which was detected. Second, it cooled the ions to $\sim 10^{-2}$ K. The beam from a laser with $\lambda_2 = 649.7$ nm was tuned precisely to resonance with the $5^2D_{3/2} - 6^2P_{1/2}$ transition and served to excite an ion in the long-lived $5^2D_{3/2}$ level into the $6^2P_{1/2}$ state. In other words, it returned the ion to the signal transition.

The fluorescence signal was detected by a photomultiplier and a photon-counting system. Figure 3 shows the results of measurements in the case of a single Ba^+ ion. We see that the time evolution of the signal has random interruptions. At certain times the signal instantaneously drops to the noise level; i.e., the fluorescence disappears. A period of darkness sets in and later terminates in an abrupt restoration of the previous signal level. An additional application of the light from a barium lamp to the ion sharply increases the frequency of the interruptions of the fluorescence (cf. Figs. 3a and 3b).

This behavior of the signal can be explained on the basis that at certain instants an ion jumps into the $5^2D_{5/2}$ metastable state, thereby escaping from the signal transition. The fluorescence is restored as the result of a quantum jump (of a radiative or collisional nature) of the ion from the $5^2D_{5/2}$ state, whose radiative lifetime is about 47 s, to the $6^2S_{1/2}$ ground state. Analysis shows that the processes which fill the $5^2D_{5/2}$ level are the following: a two-photon Raman electronic scattering of the laser light, which starts from either the $6^2S_{1/2}$ state or the $5^2D_{3/2}$ state, and a real filling of the $6^2P_{3/2}$ level by the resonant light from the barium lamp, followed by a spontaneous decay to the $5^2D_{5/2}$ level (the $6^2P_{3/2} - 5^2D_{5/2}$ transition is allowed). Despite the relatively low intensity of the light from the lamp, the latter process is predominant by virtue of its resonant nature.

Note that turning on the auxiliary laser beam, at resonance with the allowed $5^2D_{5/2} - 6^2P_{3/2}$ transition, causes the dark intervals to disappear, since this light prevents the ion from "lingering" in the $5^2D_{5/2}$ level. It can thus be asserted that a termination of the fluorescence on the strong transition is reliable evidence of a jump of an ion to the $5^2D_{5/2}$ metastable state.

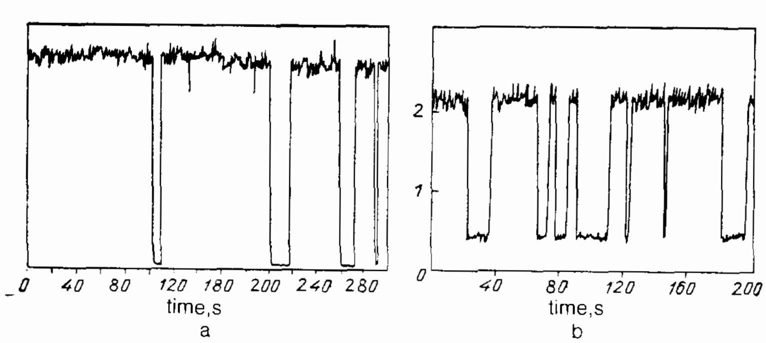

FIG. 2. a—Intensity of the resonance fluorescence of an individual ion (the signal level is 4000 photon counts per second[16]); b—the auxiliary light from a barium lamp is turned on.[17]

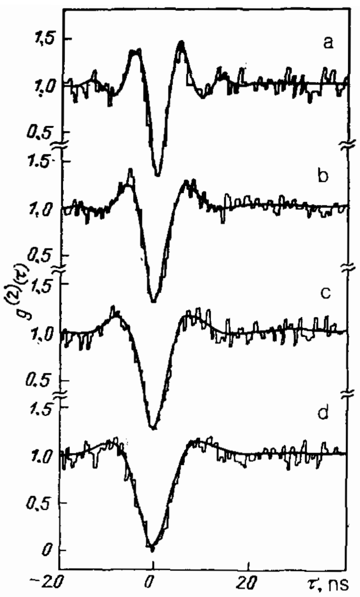

FIG. 3. Intensity correlation function of the resonance fluorescence of an individual Mg^+ ion. The intensity of the exciting light decreases from part a to part d (Ref. 29).

Experiments carried out with two or three Ba^+ ions in the trap made it possible to detect gaps in the fluorescence signal due to the simultaneous attainment of the $5^2D_{5/2}$ level by one, two, or all three ions.[17] The authors point out that the frequency of appearance of these gaps due to the simultaneous "turning off" of two or three ions is substantially higher than the frequency of such gaps which would be characteristic of random coincidences. This circumstance was attributed to collective effects in the interaction of the atoms with the electromagnetic field. Calculations by Lewenstein and Javanainen[20] show that collective effects should indeed arise when the distances between atoms are substantially smaller than the wavelength of the light.

A slightly different approach was taken in the experiments by the group at the National Bureau of Standards.[19] Singly charged mercury ions, Hg^+, were localized in an rf trap and exposed to narrow-band laser light with a wavelength of 194 nm, whose frequency was tuned slightly below the resonance with the strong allowed transition between the $^2S_{1/2}$ ground level and the $^2P_{1/2}$ level (Fig. 2b). As in Refs. 15–18, this light cooled the ions and excited resonance fluorescence. Part of this fluorescence was detected by a photon counting system and served as a signal. An auxiliary laser beam with a wavelength of 281.5 nm was tuned to resonance with the $^2S_{1/2} - {}^2D_{5/2}$ weak transition, which is allowed in the electric quadrupole approximation. Each event in which a photon is absorbed from this beam should lead to the disappearance of the fluorescence signal, since the ion jumps to the $^2D_{5/2}$ metastable state in the process. In this scheme, the observation of gaps in the fluorescence is essentially a method for detecting absorption on the weak transition.

It is clear that in this case the fluorescence signal may also be turned off because of collisional or radiative processes which send the ion from the $^2P_{1/2}$ level to the $^2D_{3/2}$ level. Measurements were accordingly carried out with the probing laser light with $\lambda = 281.5$ nm both on and off. The results showed that turning the probing light on causes a sharp increase in the rate of the jumps, which is evidence of absorption on the weak transition. The presence of two ions in the trap, as in the observations by Toschek's group, was manifested in the appearance of two types of gaps in the fluorescence, due to the turning off of one or two ions, respectively.

A point which deserves attention is that in this scheme the repetition frequency of the dark intervals depends on the precision with which the probing field is tuned to resonance. This circumstance makes it possible to carry out spectral measurements on the weak transition. The effectiveness of this spectroscopic method was demonstrated in Ref. 21, where it was used to determine the structure of the absorption line corresponding to the $^2S_{1/2} - {}^2D_{5/2}$ quadrupole transition of the Hg^+ ion in the case in which the size of the volume in which the ion was localized was smaller than the wavelength, i.e., in the "Lamb-Dicke regime." In particular, satellite bands due to a phase modulation resulting from a residual secular motion of the cold ion in the trap were resolved.

A statistical analysis of the results of the experiments carried out to observe directly quantum jumps in individual ions[15–19] revealed good agreement between expression (1) and the distribution of the durations of the dark and bright intervals. It was also found that the measurements of the intensity autocorrelation function of the fluorescence agree with (2). The method of quantum jumps is thus completely suitable for determining the lifetime of combining levels. This facility is particularly important for long-lived metastable levels, for which other methods are frequently ineffective.

3. Antibunching and sub-Poisson statistics of photons. The photon antibunching effect is that the conditional probability for observing a "second" photon at some short time τ after a "first" is smaller than the unconditional probability for observing a photon (Refs. 22 and 23, for example). The occurrence of antibunching is evidence that the repetition of photons is more ordered than in natural light or even in laser light. Another manifestation of this elevated regularity of the stream of photons is the so-called sub-Poisson distribution of photon counts, whose variance is smaller than that of a Poisson distribution.

The observation of photon antibunching is based on measurements of a second-order correlation function: the intensity correlation function $g^{(2)}(\tau)$ (Ref. 22), which is proportional to the probability for the appearance of a "second" photon at a time τ after the detection of the "first." When antibunching occurs, $g^{(2)}(\tau)$ has a minimum at the point $\tau = 0$. With increasing τ, the correlation function $g^{(2)}(\tau)$ approaches a constant value which corresponds to independent photon-detection events and which is of course the same as the asymptotic value $g^{(2)}(\infty)$ for thermal radiation. Completely coherent light has a correlation function $g^{(2)}(\tau) = g^{(2)}(\infty)$.

A typical example of radiation which exhibits photon antibunching is the fluorescence of an individual atom on an individual transition.[22,24–28] The reason for the antibunching in this case is obvious: Each successive photon can be emitted only after the external agent has restored the atom to its excited state. The length of the delay obviously depends on the excitation rate. The correlation function $g^{(2)}(\tau)$ is proportional to the probability for the atom to be in the excited state under the condition that the atom was initially in the ground state 0; i.e., $g^{(2)}(\tau) \propto \rho^{(00)}{}_{11}(\tau)$. For resonance fluorescence, $\rho^{(00)}{}_{11}(\tau)$ is determined by the solution of the equations for the density matrix of the corresponding two-level system subjected to resonance radiation. The simplest expression for $\rho^{(11)}{}_{00}$ is found in the limit of a strong monochromatic field for which the Rabi frequency $\Omega = |\mathbf{d}_{10}\mathbf{E}|\hbar$ is substantially greater than both the decay rate of the upper level, γ, and the deviation from the resonance frequency, $\delta = \omega - \omega_{10}$: $\Omega \gg \gamma, |\delta|$ (Ref. 22). In this case the expression is

$$g^{(2)}(\tau) \backsim \rho_{11}^{(00)}(\tau) \approx \frac{1}{2}\left[1-\exp\left(-\frac{3\gamma\tau}{4}\right)\cos(\Omega\tau)\right]. \quad (3)$$

We see that in the case $\tau = 0$ the correlation function is $g^{(2)}(0) = 0$, so the fluorescence of an individual atom is characterized by so-called 100% antibunching.[1)] The oscillatory way in which $g^{(2)}(\tau)$ approaches its asymptotic value $g^{(2)}(\infty)$ reflects the optical nutation at the Rabi frequency Ω. If several independent atoms are fluorescing simultaneously, the depth of the minimum of $g^{(2)}(\tau)$ at $\tau = 0$ decreases, and in the limit of very large ensembles the antibunching essentially disappears. The effect may also be "smeared over" by fluctuations in the number of atoms, as it was, for example, in experiments with a low-density atomic beam,[27,28] where a special trigger system had to be used in order to bring out the effect clearly.

The localization of a small fixed number of atoms or, especially, a single atom in a trap creates conditions ideal for a study of antibunching. These possibilities have been realized most fully in some recent experiments by Diedrich and Walther[29] (see also Ref. 30). They studied the photon statistics in the resonance fluorescence of individual Mg^+ ions in an rf trap. The fluorescence was excited by a laser beam with a wavelength of 280 nm which was tuned to resonance with the $3^2S_{1/2} - 3^2P_{3/2}$ transition. The recoil effect cooled magnesium ions, which were confined near the center of the trap.

The intensity correlation function of the fluorescence, $g^{(2)}(\tau)$, was measured by conventional Brown-Twiss apparatus. The light was split into two beams, each of which was detected by a photomultiplier. The delay time τ in one of the beam channels could take on either positive or negative values. Figure 3 shows the results of the measurements in the case in which there is a single ion in the trap. We see that with $\tau = 0$ the correlation function $g^{(2)}(\tau)$ vanishes, providing evidence of "100%" photon antibunching. An increase in the intensity of the laser light leads to a narrowing of the dip in $g^{(2)}(\tau)$, since the time required for the repeated excitation of the atom is shorter in a more intense field. Another noteworthy point is that as $g^{(2)}(\tau)$ approaches its asymptotic value, which is unity and which corresponds to the absence of antibunching, there are oscillations which reflect Rabi nutations. This behavior agrees qualitatively well with relation (3).

Measurements carried out with two or three ions in the trap revealed a corresponding decrease in the depth of the dip in $g^{(2)}(\tau)$. At the same time, the regular oscillations in $g^{(2)}(\tau)$, due to the oscillatory microscopic motion of the ions in the trap, were smoothed over.

It was also established that the fluorescence has sub-Poisson statistics. The so-called Mandel parameter

$$Q = \frac{\sigma^2 - \langle n\rangle}{\langle n\rangle}, \quad (4)$$

which characterizes the deviation of the variance σ^2 of the number of photon counts from the variance for a Poisson distribution, $\langle n\rangle$, turned out to be $-7\cdot 10^{-5}$. This negative value of Q is evidence of sub-Poisson statistics of the photons.

An even larger deviation from Poisson statistics of photons was found in Ref. 31 for the fluorescence of Hg^+ ions on the $^2P_{1/2} \to {}^2D_{3/2}$ transition (with a wavelength $\sim 11\ \mu$m). The measured Mandel parameter Q turned out to be -0.24.

Serious difficulties confront attempts to detect directly the emission of fluorescence on this transition. Aside from the fact that the wavelength is in a not very convenient region, the rate of spontaneous transitions from the $^2P_{1/2}$ level to the $^2D_{3/2}$ level is only $52 \pm 16\ s^{-1}$ (Ref. 32). This circumstance means that at a detection efficiency of $5\cdot 10^{-4}$ for the system used in that study the signal would not have exceeded 0.02–0.03 photon counts per second. The investigators accordingly took a different approach. They used laser light with a wavelength of 194 nm to excite individual Hg^+ ions in an rf trap, and they detected the resonance fluorescence on the $^2P_{1/2} - {}^2S_{1/2}$ transition. The maximum level of the signal from an individual ion was about $5\cdot 10^4$ photon counts per second. The "signal" representing the emission of a photon with a wavelength of 11 μm, on the other hand, was identified as an interruption in the resonance fluorescence. Such an interruption was almost conclusive evidence of a quantum jump from a $^2P_{1/2}$ level to the $^2D_{3/2}$ level. Analysis showed that only 5% of the cases in which the fluorescence was turned off were consequences of quantum jumps to another state.

In the course of the experiments, the numbers of photons of the resonance fluorescence detected in a series of sequential 1-ms intervals were recorded. The number of intervals reached 10^5. Analysis of the data made it possible to establish that the statistics of the photons at the wavelength of 11 μm were of a sub-Poisson nature, as discussed above. In addition, the correlation function $g^{(2)}(\tau)$ was constructed; it clearly reflected photon antibunching. As can be seen from Fig. 4, the experimental results agree quantitatively well with calculations based on a solution of the equations for the density matrix. Note that with two ions in the trap the calculations were carried out under the assumption that there was

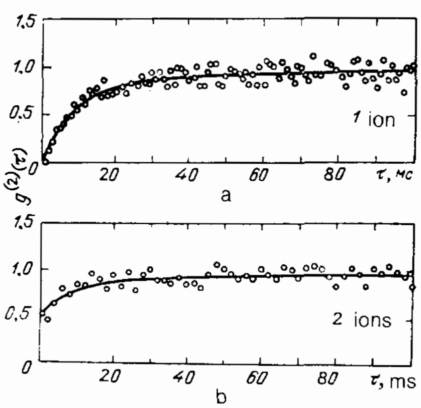

FIG. 4. Correlation function of the light with $\lambda = 11\ \mu$m for Hg^+ ions. The solid line are theoretical.[31]

no correlation between the processes by which these ions emitted photons.

A similar approach to a study of the statistics of photons emitted on the $^2D_{5/2} \rightarrow {}^2S_{1/2}$ transition in Hg^+ ions was taken successfully by Bergquist *et al.*, [19] whose work was discussed in the preceding section of this paper. The primary distinctive feature of Ref. 19 was that the emission of a photon on this transition was detected from the restoration of resonance fluorescence.

4. Phase transitions in a system of cold ions. The behavior of a group of ions caught in a trap depends on the Coulomb coupling constant Γ, which is the ratio of the energy of the Coulomb interaction between neighboring ions to the average kinetic energy of these ions. When Γ becomes much greater than unity as a result of a cooling of the ions, we can expect the formation of a regular lattice: The ions should localize at points at which an equilibrium is reached between the repulsive Coulomb forces and the confining field of the trap.

The formation of ordered structures in a system of trapped charged particles is not in itself a new phenomenon. Back in 1959, photographs were taken of regular lattices of charged particles about 20 μm in diameter, and melting and recrystallization were observed in this system.[33] Experiments with ions, however, have several important advantages, primarily the circumstance that we are dealing in this case with an ensemble of particles with identical masses and charges, which can be controlled well by laser light.

It was observed in 1980 that the size of the images of two Ba^+ ions in an rf trap agrees with the expected equilibrium distance[34] (see also the review[35]). The possibility of observing structural phase transitions was subsequently confirmed in experiments with Be^+ ions which were captured in a Penning trap and cooled by laser light.[36] Clear proof of the existence of phase transitions in a system of trapped ions was found, and a detailed study of these ions was carried out, in 1987 studies by Walther's group (Max Planck Institute for Quantum Optics in Munich[37]; see also Ref. 30) and by a group led by Wineland (the US National Bureau of Standards).[38]

We will look at the results of Ref. 37 first. In these experiments a study was made of the behavior of Mg^+ ions in an rf trap which were cooled by laser light with a linewidth of 1 MHz at resonance with the $3^2S_{1/2} - 3^2P_{1/2}$ transition (wavelength of $\lambda = 280$ nm, natural linewidth of 43 MHz). The number of ions varied from 2 to 50. As usual, the signal was the resonance fluorescence of the ions.

Excitation spectra at various values of the rf potential U_0 were recorded by scanning the frequency of the laser light over the red wing of the absorption line. The following features were found in the behavior of these spectra: At a high voltage U_0 (~ 560 V) the spectrum had a significant width, and its peak was shifted in the red direction from resonance. As U_0 was reduced (in particular, at $U_0 = 460$ and 360 V) the excitation spectrum became sharply narrower and acquired a structure characteristic of an individual cooled ion.

These results were interpreted in the following way: An intense rf field causes a substantial heating of the group of ions, so this group is in a cloudlike ("gaseous") state. The random motion of the ions in the cloud leads to an effective broadening of the spectrum by virtue of the Doppler effect. A lowering of the potential U_0 is accompanied by a corre-

FIG. 5. Crystalline structure formed by seven ions (exposure time of 40 s).[29]

sponding reduction of the heating, so the laser cooling brings the ions to a lower temperature, with the result that Γ increases sharply. The group of ions goes into a "crystalline" state in this case, in which the motions of the ions are correlated. This circumstance in turn gives the spectrum a sharp "single-atom" nature.

This interpretation was verified by the direct observation of the ion structures. For these measurements, a highly sensitive system, equipped with a video camera, was used to visualize the fluorescence of the individual ions. It was established that the appearance of a single-atom spectrum of a group of ions was indeed associated with the formation of an ordered lattice of ions. Figure 5 illustrates the situation with a photograph of the crystalline structure formed by seven ions. The ions are in a plane perpendicular to the axis of the trap. There is some asymmetry, which is a consequence of the asymmetry of the trap field.

A smooth variation of the frequency or power of the laser light, as well as a smooth variation of the rf voltage, made it possible to observe transitions from the "gaseous" (or "liquid") state to the crystalline state and vice versa. These transitions occurred extremely rapidly, i.e., in a time which was at the very most shorter than the interval between the video frames, which was 0.04 s. In all cases a hysteresis characteristic of phase transitions was observed. For example, jumps from the cloudlike state to the crystalline state always occurred at rf voltages higher than those at which the transitions went in the opposite direction. Figure 6 illustrates the results with a hysteresis loop found by gradually varying the laser power at fixed values of the tuning down from the resonant frequency and of the rf voltage. The deviation from the resonance frequency was chosen such that the crystalline state corresponded to a lower rate of photon counts.

In Ref. 38, experiments were carried out with groups of Hg^+ ions cooled by laser light to a temperature below 8 mK; this situation corresponded to a parameter value $\Gamma \approx 500$. Crystal lattices in the form of rings and linear configurations were photographed. Wineland *et al.* termed these structures "pseudomolecules." The distances between ions were of the order of a few microns—far greater than the distances between atoms in ordinary molecules. The configurations which were observed agreed with those which calculations

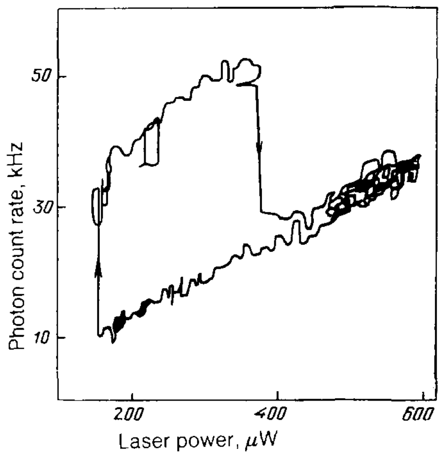

FIG. 6. Observation of phase transitions as the rate of laser cooling is varied. The lower rate of photon counts corresponds to the crystalline state.[29]

predicted would minimize the potential energy of the ions for the particular geometry of the confining field.[39] A good agreement with the calculations was also found in terms of the frequency of the vibrations of the ions in a pseudomolecule made up of two Hg^+ ions. This frequency was found for measurements of the satellite bands reflecting the Doppler shift of the absorption line caused by the motion of the ions.

The experiments on phase transitions in a system of trapped ions stimulated a theoretical effort to explain the nature of these transitions.[35,40,41] Hoffnagle *et al.*, [40] for example, analyzed the results of the experiments by Walther *et al.* in terms of transitions from order to chaos. The molecular dynamics method has also been used to model the motion of ions in an rf trap. In particular, working from calculations of the excitation spectra and jumps in them, the investigators succeeded in reproducing hysteresis loops and in predicting the values of the parameters at which a transition would occur from a cloud to a crystal.

Some interesting results were obtained with a Penning trap which made it possible to accumulate a large number of ions: from hundreds to several thousand. A simulation of the behavior of the ions in this case showed that structures consisting of spheroidal shells should form in a Penning trap.[39] The ions would drift freely along the surfaces of these shells but not between them. This picture is reminiscent of the behavior of smectic liquid crystals, as was pointed out by Dubin and O'Neil.[39]

The predicted shell structure was observed in experiments with clouds of Be^+ ions in a Penning trap.[42] A probing light beam was used along with the two laser beams used for cooling in those experiments. Each beam induced a fluorescence of the ions and made it possible to see individual sections of the shells which formed. Depending on the number of ions accumulated, the structures which formed contained from 1 to 16 shells. In the latter case the number of ions reached 15 000. The number of shells corresponded completely to the theoretical predictions, but their shape was cylindrical, not spheroidal.

By carrying out some manipulations with the probing laser beam, the investigators managed to follow the motion of individual ions. It was found that the ions diffuse a distance of more than 100 μm over 0.1 s within "their own" shell, while a transition between neighboring shells requires several seconds.

5. Conclusion. The papers which we have discussed in this review give a fairly comprehensive picture of the extensive opportunities which are being opened up to researchers by the use of ions localized in electromagnetic traps and cooled by laser beams. We should emphasize, however, that the importance of the results which have been obtained goes far beyond the realm of demonstrations. For example, experiments with individual ions have actually made possible the first study of the time evolution of the internal state of atoms. The experiments showed that the evolution of a quantum system with several internal-motion states as it interacts with continuous exciting light is characterized by a random sequence of quantum jumps. This conclusion essentially touches the foundations of quantum mechanics.[18]

We should point out that this new possibility of carrying out repeated experiments with individual atoms has stimulated the formulation of new problems in the theory of the interaction of atoms with electromagnetic radiation (see, for example, Refs. 9–14 and 43–47).

Experiments with "collectives" of cold ions are also important. "Crystallization" and "melting" processes which can be well controlled make possible a more profound study of the physics of phase transitions in systems with a finite and adjustable number of identical particles. The sharp narrowing of the spectra upon the transition of an ensemble of cold ions into a crystalline state raises the hope that such "crystals" could be utilized in extremely accurate optical frequency standards.[30]

We do not have room here to discuss a long list of studies involving spectroscopic applications,[21,32,48,49] optical bistability in individual atoms,[50] the problem of optical frequency standards, etc. In those areas again there are substantial accomplishments and interesting possibilities.

The next few years will undoubtedly bring some striking new results in this rapidly developing field of research. In effect, trapped atomic particles have only just begun to operate.

[1)] The antibunching effect in resonance fluorescence is ignored in expression (2) since the calculation model itself rules out fast processes on the resonant transition.

[1]P. E. Toschek, *Atomic particles in traps, in: Course 3 // Tendences actuelles en physique atomique / New trends in atomic physics. Les Houches, Session XXXVIII, June 28–July 29, 1982.* Eds. G. Grynberg, R. Stora, Elsevier, Amsterdam, 1984, V. 1, pp. 383–450. [Russ. transl., Usp. Fiz. Nauk **158**, 451 (1989)].
[2]V. I. Balykin, V. S. Letokhov, and V. G. Minogin, Usp. Fiz. Nauk **147**, 117 (1985) [Sov. Phys. Usp. **28**, 803 (1985)].
[3]V. G. Minogin and V. S. Letokhov, *Pressure of Laser Radiation on Atoms* (In Russian), Nauka, M., 1986.
[4]N. Bohr, Philos. Mag. **26**, 476 (1913).
[5]H. G. Dehmelt, Bull. Am. Phys. Soc. **20**, 60 (1975).
[6]H. G. Dehmelt, IEEE Trans. Instrum. Meas. **IM-31**, 83 (1982).
[7]H. G. Dehmelt, Laser Spectroscopy V, Springer-Verlag, N.Y., 1981, p. 353.
[8]F. T. Arecchi, A. Schenzle, R. G. De Voe, K. Jungmann, and R. G. Brewer, Phys. Rev. A **33**, 2124 (1986).
[9]R. J. Cook and H. J. Kimble, Phys. Rev. Lett. **54**, 1023 (1985).
[10]J. Javanainen, Phys. Rev. A **33**, 2121 (1986).
[11]A. Schenzle, R. G. DeVoe, and R. G. Brewer, Phys. Rev. A **33**, 2127 (1986).
[12]D. T. Pegg, R. Loudon, and P. L. Knight, Phys. Rev. A **33**, 4085 (1986).
[13]C. Cohen-Tannoudji and J. Dalibard, Europhys. Lett. **1**, 441 (1986).
[14]H. J. Kimble, R. J. Cook, and A. L. Wells, Phys. Rev. A **34**, 3190 (1986).

[15]W. Nagourney, J. Sandberg, and H. G. Dehmelt, Phys. Rev. Lett. **56**, 2727 (1986).
[16]Th. Sauter, R. Blatt, W. Neuhauser, and P. Toschek, Phys. Rev. Lett. **57**, 1696 (1986); Commun. **60**, 287 (1986).
[17]Th. Sauter, R. Blatt, W. W. Neuhauser, and P. E. Toschek, Opt. Commun. **60**, 287 (1986).
[18]P. E. Toschek, Phys. Scripta T **23**, 170 (1988).
[19]J. C. Bergquist, R. G. Hulet, W. M. Itano, and D. J. Wineland, Phys. Rev. **57**, 1699 (1986).
[20]M. Lewenstein and J. Javanainen, Phys. Rev. **59**, 1289 (1987).
[21]J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A **36**, 428 (1987).
[22]D. R. Smirnov and A. S. Troshin, Usp. Fiz. Nauk **153**, 233 (1987) [Sov. Phys. Usp. **30**, 851 (1987)].
[23]D. H. Klyshko, Basic Physics of Quantum Electronics (In Russian), Nauka, M., 1986.
[24]H. J. Carmichael and D. E. Yalls, J. Phys. B **9**, 1199, 143 (1976).
[25]H. J. Kimble and L. Mandel, Phys. Rev. A **13**, 2123 (1976).
[26]D. L. Smirnov and A. S. Troshin, Zh. Eksp. Teor. Fiz. **72**, 2055 (1977) [Sov. Phys. JETP **45**, 1079 (1977)].
[27]H. J. Kimble, M. Dagenais, and L. Mandel, Phys. Rev. Lett. **39**, 691 (1977).
[28]R. Short and L. Mandel, Phys. Rev. Lett. **51**, 384 (1983).
[29]F. Diedrich and H. Walther, Phys. Rev. Lett. **58**, 203 (1987).
[30]F. Diedrich, J. Krause, G. Rempe, M. O. Scully, and H. Walther, Physica B **151**, 247 (1988).
[31]W. M. Itano, J. C. Bergquist, and D. J. Wineland, Phys. Rev. A **38**, 559 (1988).
[32]W. M. Itano, J. C. Bergquist, R. G. Hulet, and D. J. Wineland, Phys. Rev. Lett. **59**, 2732 (1987).
[33]R. F. Wuerker, H. Shelton, and R. V. Langmuir, J. Appl. Phys. **30**, 342 (1959).
[34]W. Neuhauser, M. Hohenstadt, P. E. Toschek, and H. G. Dehmelt, Phys. Rev. A **22**, 1137 (1980).
[35]B. G. Levi, Phys. Today **39**, No. 8, 9 (August 1986).
[36]J. J. Bollinger and D. J. Wineland, Phys. Rev. Lett. **53**, 348 (1984).
[37]F. Diedrich, E. Peik, J. M. Chen, W. Quint, and H. Walther, Phys. Rev. Lett. **59**, 2931 (1987).
[38]D. J. Wineland, J. C. Bergquist, W. M. Itano, J. J. Bollinger, and C. H. Hanney, Phys. Rev. Lett. **59**, 2935 (1987).
[39]D. H. E. Dubin, and T. M. O'Neil, Phys. Rev. Lett. **60**, 511 (1988).
[40]J. Hoffnagle, R. G. De Voe, L. Reyna, and R. G. Brewer, Phys. Rev. Lett. **61**, 255 (1988).
[41]R. Blümel, J. M. Chen, E. Peik, W. Quint, W. Schleich, Y. R. Shen, and H. Walther, Nature **334**, 309 (1988).
[42]S. L. Gilbert, J. J. Bollinger, and D. J. Wineland, Phys. Rev. Lett. **60**, 2022 (1988).
[43]P. Zoller, M. Marte, and D. F. Walls, Phys. Rev. A **35**, 198 (1987).
[44]G. Nienhuis, Phys. Rev. A **35**, 4639 (1987).
[45]M. S. Kim and P. L. Knight, Phys. Rev. A **36**, 5265 (1987).
[46]D. T. Pegg and P. L. Knight, Phys. Rev. A **37**, 4303 (1988).
[47]D. T. Pegg and P. L. Knight, J. Phys. D **21**, S128 (1988).
[48]D. J. Wineland, W. M. Itano, J. C. Bergquist, and R. G. Hullet, Phys. Rev. A **36**, 2758 (1987).
[49]H. Dehmelt and W. Nagourney, Proc. Natl. Acad. Sci. USA **85**, 7426 (1988).
[50]V. M. Savage and H. J. Carmichael, IEEE J. Quantum Electron. **QE-24**, 1495 (1988).

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