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Ultracold atoms and atomic optics

V I Balykin

1. Introduction

As a quantum mechanical system, the atom is characterized by two sets of degrees of freedom: internal (electron configurations and spin) and external (momentum and center-of-mass position), which can change in the interaction with laser radiation. The physics of ultracold atoms and atom optics made their appearance due to successful investigations into the action of laser radiation on precisely the external degrees of freedom of the atom — its momentum and center-of-mass position. In an elementary 'photon absorption–emission' cycle, the reradiated photon can be spontaneous or induced. The 'stimulated absorption–spontaneous emission' process is inherently dissipative and it is precisely this cycle that underlies the laser cooling of atoms. Numerous laser cooling techniques enable forming atomic ensembles in the range from room temperature to several nanokelvins. Laser cooling and the subsequent evaporative cooling allow obtaining both ultralow temperatures and ultrahigh atomic densities, which in turn permits realizing quantum Bose and Fermi gases. The 'stimulated absorption–stimulated emission' photon process is coherent and forms the foundation of atom optics — a new type of optics of material particles (along with electron and neutron optics), which evolved from the development of the methods of laser cooling and atom localization and which is concerned with the formation, control, and application of the ensembles and beams of neutral atoms.

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2. Laser cooling of atoms

It is common knowledge that one of the main properties of laser radiation is its extremely high effective temperature, which exceeds the solar temperature by many orders of magnitude, even for low-power lasers. This unique property of laser radiation sharply distinguishes it from the light emitted by conventional thermal sources. Owing to this property, laser radiation has gained wide acceptance in thermal material processing. Also considered is its application for the initiation of thermonuclear reactions.

Not immediately evident is the idea of cooling substances by laser light. On the face of it, this seems to be hardly compatible. Nevertheless, not only has it been proved in the past 20 years that lasers can cool atoms moving freely in a low-pressure gas or in an atomic beam, but a new area of research has also emerged — the physics of ultracold atoms. The minimal temperatures attainable presently are as low as several nanokelvins.

The laser cooling of an ensemble of atoms occurs in the resonance or quasiresonance energy and momentum exchange between the atoms and laser radiation. The energy of the atomic ensemble then decreases and the radiation energy increases. Three laser cooling mechanisms are known, which are referred to as Doppler, sub-Doppler, and subrecoil mechanisms.

2.1 Doppler cooling

In the interaction of an immobile atom with monochromatic laser radiation of frequency ν_L, the atom absorbs a resonance photon ($\hbar\nu_L = \hbar\nu_0$, where ν_0 is the optical transition frequency) and experiences a transition from the ground state to an excited one. The photon absorption changes the atomic velocity by the value of the recoil velocity $v_{ret} = \hbar k/M$, where $\hbar$ is the Planck constant, $k = 2\pi/\lambda$ is the wave vector, λ is the radiation wavelength, and M is the atomic mass. The atom can return from the excited state to the initial one with the stimulated or spontaneous emission of a photon. In the stimulated emission, the photon has the same energy and propagation direction as the absorbed photon, resulting in the reverse change of the atomic velocity by v_{ret}. In

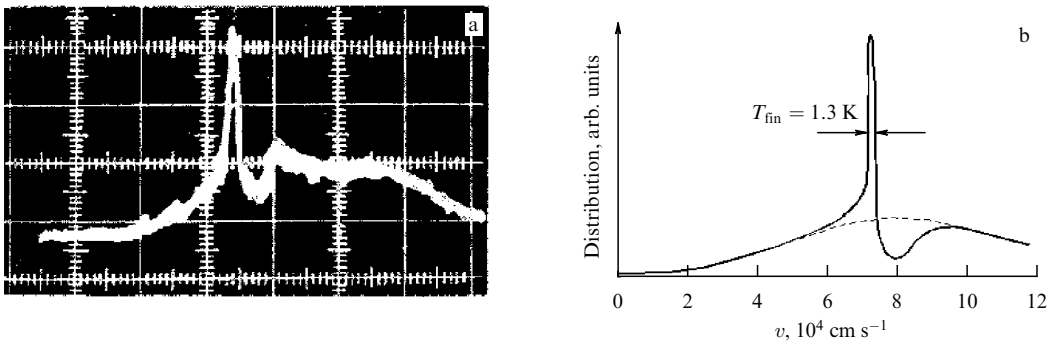

Figure 1. First experiment on the laser cooling of neutral atoms. (a) Experimental profile of the velocity distribution of an atomic sodium beam after its laser irradiation. The cooled atoms form a narrow velocity group with the temperature 1.5 K. (b) Calculated dependence.

the spontaneous emission, the photon has an arbitrary propagation direction, and therefore the average contribution of such photons to the variation of atomic velocity and momentum is equal to zero. On average, the photon momentum is therefore transferred to the atom in the stimulated absorption followed by the spontaneous emission of a photon. As a result, when an atom interacts with light of the resonance frequency, it experiences light pressure in the direction of the laser beam propagation.

The resonance between the frequency of laser light and the atomic absorption frequency is extremely narrow owing to the small width of atomic absorption lines. Consequently, if the frequency of laser light is changed by the width of an absorption line, the atom does not undergo excitation and the force of light pressure sharply decreases in magnitude. In the case of a moving atom, the resonance between monochromatic laser radiation and the atom shifts due to the Doppler shift, and the light pressure experienced by the atom is highest at the resonance velocity $v_{\text{res}} = (\nu_{\text{L}} - \nu_0)/\lambda$. For $\nu_{\text{L}} > \nu_0$, the resonance emerges when the atom is moving in the propagation direction of the laser beam; for $\nu_{\text{L}} < \nu_0$, the resonance emerges when the atom is moving in the opposite direction to the beam. Therefore, the force of light pressure of monochromatic radiation is a selective function of the atomic velocity, and the atom experiences the force of light pressure when the direction and magnitude of its velocity satisfy the resonance condition.

Under a multiple repetition of the photon absorption–emission cycle, the atomic momentum changes by $\Delta p = N\hbar k$, where N is the number of cycles. When the direction of atomic motion is opposite to the direction of the laser beam, the atom decelerates. For instance, for a sodium atom, which has the velocity about 10^5 cm s^{-1} at room temperature and the recoil velocity $v_{\text{ret}} = 3$ cm s^{-1}, the velocity of the atom is reduced to virtually zero after approximately 10^4 'absorption–spontaneous emission' cycles.

When an atom decelerates under the action of laser radiation, a Doppler shift emerges between the atomic absorption frequency and the laser radiation frequency, with the consequential decrease in the efficiency of reradiation of laser photons by the atom and, accordingly, of the atomic deceleration efficiency. The Doppler shift is eliminated by changing the laser radiation frequency or the atom transition frequency (for instance, in a magnetic field) in the course of deceleration of the atom. When permanent resonance is maintained between the atom transition frequency and the radiation frequency, deceleration of all atoms with the velocity equal to the velocity projection occurs in the direction of the laser beam. The application of three pairs of mutually perpendicular counter-propagating laser beams allows decreasing all velocity components of the atoms, i.e., realizing three-dimensional cooling of the atomic gas. This kind of laser cooling is known as the *Doppler cooling*.

The idea of laser cooling of neutral atoms was first introduced by Hänsch and Schawlow in 1975 [1]. The first experiments on the laser cooling of atoms were carried out at the Institute of Spectroscopy, RAS (ISAN) [2] (Fig. 1) using a sodium atomic beam. A collimated beam of sodium atoms was irradiated by a counter laser beam with a frequency lying within the Doppler profile of the absorption line. Because the laser radiation spectrum was much narrower than the Doppler width, efficient deceleration was experienced only by the atomic fraction that was at resonance with the radiation field. The velocities of the remaining atoms were only slightly changed. The deceleration of atoms continued until they went out of resonance with the radiation due to the emergence of a Doppler shift. The decelerated atoms formed a narrow velocity cluster. Because the temperature in an ensemble of atoms is defined by their velocity spread, knowing the velocity distribution allows determining the temperature of the atomic ensemble. In the first experiments with sodium atoms (see Fig. 1), the temperature was decreased from 1000 K to 1.5 K [2]. In the subsequent experiment on transverse cooling of an atomic beam at the ISAN, a temperature of 35 mK was attained.

The photon absorption and emission by an atom are inherently random in time and direction, resulting in a random variation of atomic momentum and an increase in its rms value and in the heating of an atomic ensemble. The lowest atomic temperature in the Doppler cooling is determined by the equilibrium between laser cooling and the heating due to momentum diffusion under spontaneous atomic transitions. The lowest atomic temperature in the Doppler laser cooling is $k_{\text{B}} T_{\text{Doppler}} \approx \hbar\Gamma$, where Γ is the width of the excited atomic level. The Doppler temperature is typically about 100 μK. This is the so-called *Doppler limit* for laser cooling of atoms; its magnitude was first determined by Minogin and Letokhov [3].

One of the most important consequences of the first experiments on laser cooling of atoms was the possibility of their localization under different configurations of electric, magnetic, and laser fields [4]. The localization of atoms opened the way to different methods of laser cooling, whose

application allowed a further decrease in the atomic temperature.

2.2 Sub-Doppler cooling

For a long time, the Doppler limit of atomic temperature was regarded as the fundamental limit decreasing the temperature below which was impossible in principle. In 1988, in experiments with Na atoms localized in a magnetooptical trap (MOT), W Phillips's group of the National Institute of Standards and Technology (NIST), USA, unexpectedly recorded an atomic temperature substantially lower than the Doppler temperature limit [5]. It was not long before an explanation for the cooling to temperatures below the Doppler limit was provided.

As noted in the Introduction, atomic particles are characterized by internal (electron configuration, spin) as well as external (momentum and center-of-mass position) degrees of freedom. A strong correlation between the dynamics of the internal and external degrees of freedom underlies the laser cooling to below-Doppler-limit temperatures. In the Doppler laser cooling, an atom is assumed to be a nondegenerate two-level quantum system, and the laser field is assumed to be spatially uniform and unpolarized. When the states of the atom are multilevel and degenerate in Zeeman sublevels while the laser beams make up a nonuniform field distribution with polarization varying periodically in space, the atom finds itself in a periodic potential depending on the magnetic sublevel. When moving in this potential field, the atom periodically rises and descends between the potential peaks and valleys, converting its potential energy into kinetic energy and vice versa. If the frequency of the laser field is taken to be lower than the atomic transition frequency, then the atom is more likely to absorb a laser photon at the peak of the potential and, on emitting a spontaneous photon, transit to another magnetic sublevel, at which the potential energy of the atom is minimum. The difference in potential energy is carried away by the spontaneously emitted photon, with the consequential decrease in the kinetic energy of the atom and cooling in the atomic ensemble. This mechanism of laser cooling was called the *sub-Doppler cooling*. The lowest atomic temperature for sub-Doppler cooling is determined by the photon recoil energy and is about 1 μK for alkali atoms.

2.3 Subrecoil cooling

In the majority of laser cooling systems, the 'stimulated absorption–spontaneous photon emission' cycle never terminates. Because the momentum $\hbar k$ transferred to an atom by a spontaneously emitted photon is random in time and direction, it seems that there is no way to decrease the spread of atomic momentum δp below the photon momentum $\hbar k$. But this fundamental limitation on the atomic temperature has also been overcome. The main idea of subrecoil laser cooling is to make a small domain around the zero atomic velocity in the momentum space where the probability of photon absorption and the rate of spontaneous photon reradiation tend to zero. If this strategy is implemented successfully, the atom in the laser field 'wanders' in the momentum space when executing the 'stimulated absorption–spontaneous photon emission' cycles and may acquire a velocity close to $v = 0$, whereby it no longer absorbs photons and is protected from the detrimental influence of light. By selecting special configurations of the laser field defined by the type of atoms and their interaction conditions, it is possible to make a small domain where the photon absorption probability and the spontaneous photon reradiation rate tend to zero.

There are two methods of laser cooling below the single-photon recoil level: *Raman* cooling and cooling based on *velocity-selective coherent population trapping* (VSCPT).

In *Raman* cooling, a two-photon transition between two hyperfine structure components of the ground state of an atom is used. The atom is irradiated by two laser pulses. When the frequencies of the pulses differ by the hyperfine splitting of the atomic ground state and are far away from the domain of single-photon resonances, the atom goes over from one state of the hyperfine structure to another due to a two-photon Raman event. Raman transitions are insensitive to the Doppler shift in the configuration of unidirectional laser beams. In the configuration of oppositely directed laser beams, the Doppler shifts add up and the atomic resonance with the field depends on the atomic velocity. The width of the resonance is extremely narrow and is typically determined only by the atom–field interaction time. This, in turn, signifies that it is possible to selectively excite very narrow velocity groups of atoms. When the frequency difference is offset to the red side of the spectrum relative to the frequency of the two-photon resonance, an atom traveling with a positive velocity is at resonance with the field due to the Doppler shift and acquires a momentum such that its velocity decreases. By using a sequence of varied-frequency pulse pairs with varying directions of the laser beams, it is possible to increase the density of atoms with nearly zero velocities. The temperature thus reached is about 100 nK, which corresponds to 1/10 of the recoil energy. Raman cooling was first observed at Stanford University, USA (S Chu) [6].

In another method of subrecoil atom cooling, the effect of velocity-selective coherent atomic population trapping is used. The heart of the method is as follows: in the course of interaction with laser radiation, atoms are transferred to a state that is a superposition of sublevels of the ground atomic state, wherein atoms no longer interact with the radiation. The interaction vanishes owing to the destructive interference of the amplitudes of absorption in the atomic transition from sublevels of the ground state to the excited state. The absorption suppression is velocity selective, and the absorption becomes zero for those atoms that reach zero velocity as a result of random walk in the momentum space [7].

With advances in laser cooling techniques and the subsequent confinement of atoms in traps, it became possible to reach subrecoil atomic temperatures by using only one cooling technique, the Doppler one. The cooling proceeds in two stages. Doppler cooling is accomplished at the first stage with the use of *allowed* atomic transitions; at the second stage, Doppler cooling with a *forbidden* transition is used.

Therefore, the use of combinations of different laser techniques for cooling and trapping neutral atoms presently enables lowering the temperature of atomic ensembles from about 1000 K to 10 nK, i.e., by eleven orders of magnitude. Figure 2 shows the main physical mechanisms of laser cooling of neutral atoms. The initial atomic ensemble is an atomic gas or an atomic beam at near-room temperature. Doppler cooling permits decreasing the atomic temperature to about 1 mK (cold atoms). The localization of atoms in different electromagnetic traps and their further cooling by laser sub-Doppler techniques to temperatures about 1 μK (ultracold

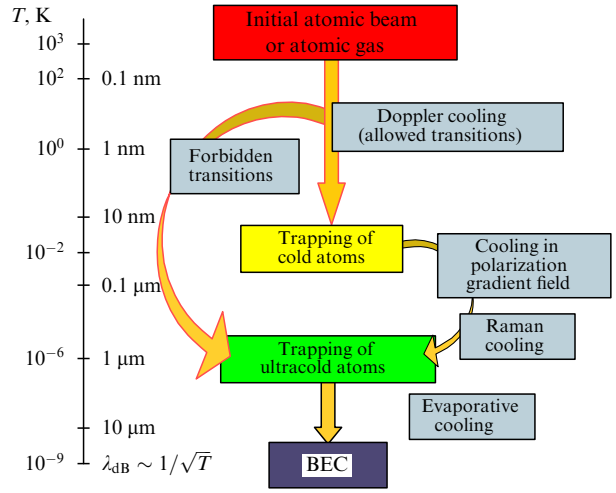

Figure 2. Principal physical mechanisms of laser cooling of neutral atoms.

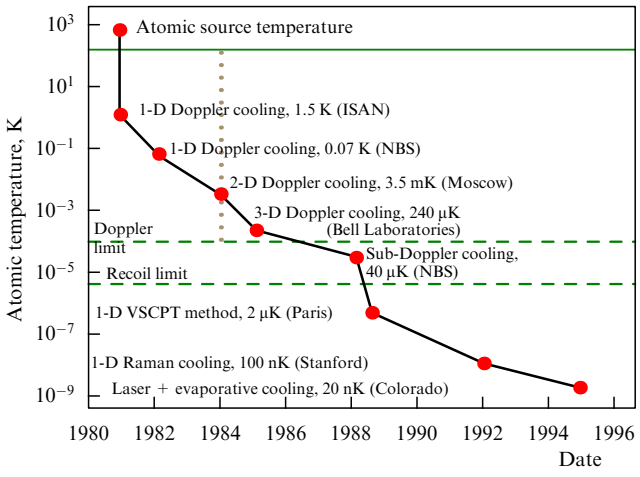

Figure 3. Progress in the laser cooling of atoms (the key experiments), which traces back to the work carried out at the Institute of Spectroscopy, RAS, in 1981. (NBS: National Bureau of Standards, USA).

atoms) are made possible at these temperatures. Evaporative cooling allows additionally decreasing the temperature of the atomic ensemble to about 100 nK with a simultaneous increase in the atomic phase density, which permits realizing the Bose–Einstein condensation (BEC) of the atoms. Ultracold atoms can also be obtained from cold atoms in the Doppler cooling using forbidden transitions.

Figure 3 is representative of the progress in the laser cooling of atoms (the key experiments), which traces back to the work carried out at the ISAN in 1981.

In 1997, S Chu, W Phillips, and C Cohen-Tannoudji were awarded a Nobel Prize in physics for development of methods to cool and trap atoms with laser light.

2.4 Localization of atoms

One of the fundamental physical problems, apart from the cooling of atoms, is their confinement in a bounded spatial domain — in a trap. The laser cooling of atoms allowed the localization of atoms under different configurations of electric, magnetic, and laser fields. Three approaches to atom localization were developed, which rely on the use of magnetic fields, laser fields, and a combination of laser, magnetic, and gravitational fields [4].

In a *magnetic trap* (first realized in [8]), atoms are confined by a nonuniform stationary magnetic field. In this field, an atom with a permanent magnetic moment experiences a force directed to the minimum of the magnetic field for the required orientation of the atomic moment; the atoms are localized at the field minimum. One of the versions of a magnetic trap is a spherical quadrupole magnetic trap, in which two oppositely directed circular currents induce a static magnetic field in the form of a spherical quadrupole. The magnetic field increases from the trap center toward its edge and therefore forms a potential well for atoms with a negative projection of the magnetic moment on the field direction. For an atomic magnetic moment approximately equal to the Bohr magneton and a moderate magnetic field at the trap edges (about 100 G), this trap is capable of confining atoms with the temperature about 10 mK.

Localization in optical fields is based on the action of the dipole radiation force. The simplest optical trap for cool atoms consists of only one focused laser beam. The dipole force of light pressure, which acts on an atom in a laser beam, forms a three-dimensional potential well near the focus of the laser beam for a negative laser frequency detuning relative to the frequency of the atomic transition. The properties of this optical trap, which is referred to as the dipole trap, depend on the magnitude of this frequency offset and the laser radiation intensity. The depth of this potential well may be 0.1–1 mK and the atom lifetime in the dipole trap may range from several tens of milliseconds to approximately 10 min [9], depending on these parameters.

The simultaneous use of static magnetic fields and laser beams makes the *magnetooptical trapping* of atoms possible. The force of light pressure on an atom in this trap is equal to the sum of two forces: the friction force and the harmonic restoring force, which permits the atoms to be cooled and localized. In a magnetooptical trap, the temperature of the atomic cloud ranges between 1 mK and 10 μK, the atom density is $10^8 - 10^{12}$ cm^{-3}, and the trap depth is 1 K, which is far greater than in purely magnetic and laser traps. Such a trap was first implemented by Raab et al. [10]. This trap permits localizing isotopes of lithium, sodium, potassium, rubidium, cesium, and francium and atomic isotopes of alkaline-earth elements, calcium, strontium, and rare-gas isotopes.

One more method that has been developed for trapping cool atoms relies on the combined use of electromagnetic and gravitational forces. The conceptually simplest *gravitational–optical atom cavity trap* may consist of only one horizontally arranged concave laser mirror for atoms [11, 12]. In this geometry, the function of the second spatially distributed mirror is fulfilled by the gravitational field.

2.5 Evaporative cooling

Evaporation — the conversion of matter from the liquid state to the gaseous state — is a well-known physical phenomenon. In the course of evaporation, particles with energies exceeding the binding energy escape from the particle ensemble, and this depletion of the ensemble in high-energy particles leads to its cooling. Evaporative cooling is a universal process inherent in the microworld (evaporation of a neutron from a nucleus) as well as in the macroworld (evaporation of stars from stellar clusters).

The evaporative cooling of neutral atoms preliminarily localized in electromagnetic traps permitted obtaining low temperatures, down to 10 nK [13]. The procedure for obtaining these low temperatures has several stages. First, atomic ensembles are preliminarily cooled by laser cooling to temperatures at which their localization in electromagnetic traps is possible. The next step is evaporative cooling. The main prerequisites for the evaporative cooling are a sufficiently long atomic lifetime in the trap and a sufficiently high atom density for the onset of efficient cooling. The atomic lifetime in the trap is limited by inelastic atomic collisions ('bad' collisions). On the other hand, elastic ('good') atomic collisions are needed to thermalize the atomic ensemble. Realizing atomic evaporative cooling requires the thermalization time to be shorter than the atomic lifetime in the trap.

A significant disadvantage of evaporative cooling is the loss of a large fraction of atoms, up to 0.1%. But the evaporative cooling transforms ensembles with a large number of atoms to high-density low-temperature ensembles, i.e., to ensembles with a high phase density. It is the attainment of a high phase density in the evaporative cooling of atoms that has allowed implementing Bose–Einstein condensation of atoms [14, 15] and quantum Fermi gases [16, 17].

3. Atom optics

Atom optics, along with electron, ion, and neutron optics, is the optics of material particles concerned with the formation of ensembles and beams of neutral atoms, controlling them, and applying them to basic research and practical uses [18–22]. Atom optics came into being as a physical discipline in its own right in the mid-1990s as a result of investigations into the action of the forces of light pressure on the translational motion of atoms.

The advancement of atom optics is intimately related to the development of the techniques of laser cooling and localization of neutral atoms. The laser cooling of atoms and their localization allow forming atomic ensembles and beams with prescribed parameters and decreasing the atomic temperature to only one millionth of a degree above absolute zero. At these temperatures, the atomic de Broglie wavelength is comparable to the wavelength of light and the wave properties of atoms make themselves evident.

The potential of atom optics is substantially greater than for other types of material particle optics (electron and neutron optics) due to the existence of the internal atomic structure. The wavelengths and the types of interactions relevant to the different types of optics are indicated in Table 1.

Table 1.

Type of optics	Wavelength range, m	Interaction types
Photon optics	$10^{-5}-10^{-11}$	Light with matter
Charged-particle optics	$10^{-10}-10^{-11}$ (electrons) $10^{-13}-10^{-14}$ (ions)	Electrons and ions with electric and magnetic fields
Neutron optics	$10^{-7}-10^{-10}$	Neutrons with nuclei
Atom optics	$10^{-5}-10^{-11}$	Atoms with laser, electric, and magnetic fields

For a temperature close to absolute zero, when the de Broglie wavelength is comparable to the interatomic distance, the behavior of an atomic ensemble is markedly affected by an internal quantum characteristic of an atom, its spin. The striking difference between the behavior of fermions and bosons is observed at very low temperatures: Bose–Einstein condensation is observed for Bose particles. The first atomic condensates were obtained by several groups of American physicists with the use of laser and evaporative cooling of atoms in 1995 [14, 15]. A magnetic trap that confines BEC atoms is an analog of an optical resonator for photons in an optical laser. The atoms that can 'emanate' from a magnetic trap in a specific direction (like photons through the semitransparent mirror of an optical laser resonator) make up a coherent directional beam, which is similar to a laser beam. This device was given the title 'atom laser' [23, 24]. The keen interest in atom lasers is due to the prospect of applying coherent atomic beams in high-precision measuring instruments and high technologies in the fabrication of atomic and molecular nanostructures.

We consider only two of the numerous fields of research in atom optics: atomic interferometry and atomic nanolithography.

3.1 Sources in atom optics

In light optics, an ideal source for both basic research and applied problems is the laser: its radiation has a long coherence length, is highly collimated, and provides a high-intensity photon flux in the beam. In atom optics, there are two main source types: thermal atomic beams and the beams from cool and localized atomic ensembles. Both source types find application, but just the development of laser techniques for the cooling of atoms and their confinement has allowed creating atomic sources with a high phase density. One of the decisive prerequisites for the successful development and application of atomic interferometry and atomic nanolithography is the use of atomic sources with a high phase density.

3.2 Atomic interferometry

Since the early 20th century, studies of the wave behavior of light, including the capacity of waves for interference, have been an important area of physics. During the past century, light interferometers have come to be the most precise measuring devices, finding use in both basic research and numerous applications.

De Broglie's and Schrödinger's initial idea that moving particles are waves has led to the advent of electron and neutron interferometers, and in the last decade of the 20th century, in connection with the development of the methods of laser cooling and confinement of atoms, to the advent of atomic interferometry [25, 26]. Atom interferometers offer several advantages over their electron and neutron counterparts. First, the parameters of atomic particles (mass, magnetic moment, polarizability) occupy a wide range of values; accordingly, the force of interaction of atoms with an external field may vary by many orders of magnitude, depending on the type of atoms selected. Second, both internal and external degrees of freedom of an atom can be efficiently controlled by laser radiation because the light scattering cross section for an atom is about 10^{-9} cm^2, while that for the electron is only 10^{-25} cm^2. Third, the frequency and wavelength of laser radiation are presently measured with a very high precision, 10^{-15} and 10^{-11}, which predetermines a

higher accuracy of measurements with atom interferometers than with the electron and neutron ones. Lastly, atom sources are relatively simple and inexpensive compared to electron and neutron sources.

The implementation of an atom interferometer involves the creation of the following elements: an atom source, a coherent splitter of atomic de Broglie waves, mirrors for the recombination of the waves, and an interference pattern detector.

The simplest *atomic source* is an atomic beam formed by two collimating slits. A disadvantage of this source is its low phase density, and the important advantage of using a thermal beam in interferometry — its initially high atom flux — is therefore lost. A source prepared by laser cooling and subsequent trapping of atoms in electromagnetic traps is preferable.

The next step in the making of an atom interferometer is the coherent *splitting* of an atomic wave. One splitting technique relies (by analogy with that in optics) on the effect of diffraction of atoms. To realize diffraction, material nanogratings and light gratings are used. A disadvantage of the former is that a significant fraction of the incident atomic beam is blocked. Light gratings, which are a standing wave, i.e., are phase gratings, transmit all of the atoms and therefore turn out to be higher in efficiency for atom interferometers.

Another technique for the coherent splitting of an atomic wave is based on the possibility of coherent superposition of two atomic states in momentum space. This coherent superposition is produced by irradiating atoms with resonance laser radiation. In this case, a coherent superposition of internal degrees of freedom of the atom — its ground and excited states — occurs. These internal states also differ by their translational momentum, equal to the photon momentum. If the initial momentum state of the atomic ensemble is well localized, the components of the atomic wave function become spatially separated with time.

Observing an interference pattern requires arranging a *recombination* of two atomic waves. In an atom interferometer, as in an optical one, the recombination is effected involving *atom mirrors*. The reflection of atoms from a surface light wave was the first demonstration of the atom mirror [27]. This wave, when spatially modulated, can also serve as a coherent splitter of an atomic beam. The role of an atom mirror can also be played by a laser beam. In this case, an atom undergoes a transition to an excited state on absorbing a laser photon, which in turn leads to its deflection by the angle determined by the momentum of the absorbed photon.

Recombination of atomic beams can be realized (like their splitting) by using the effect of atom diffraction from material nanogratings or standing light waves. The first experiments were carried out using precisely diffraction for both the splitting and the recombination of atomic beams [25, 26].

Interference fringes in an atom interferometer can be observed as the oscillations of the atomic beam intensity directly in space with the help of a *coordinate-sensitive detector*. Another way of observing interference involves transfer of information from the wave function phase to the populations of internal atomic states. This is achieved in the recombination of wave-function components by laser pulses. The subsequent application of an *internal-state-selective detector* of atoms enables detecting oscillation of the atomic beam intensity at the interferometer output as a function of the phase difference.

The scheme of an atom interferometer based on laser pulses is most common today. It is pertinent to note that so 'simple' a control over the atom had never been possible until the development of methods for laser cooling and the trapping of atoms, which allowed producing slow atomic beams and beams with a narrow velocity distribution. The first circumstance permits the atom of a beam to be appreciably deflected even on transferring the momentum of a single photon to the atom, and the second circumstance permits separating the beams in space.

The major significance of atomic interferometry for basic research and numerous applications lies in the fact that it is possible to measure phase shifts induced by extremely low potentials. For instance, a beam of sodium atoms acquires a phase shift of about 1 rad for the potential of 6×10^{-12} eV and the interaction length of 10 cm. The measurement of a 10^{-3} rad phase shift corresponds to the measurement of potential with the relative precision $\approx 10^{-14}$. When cold atoms are used, the precision of measurements additionally increases by a factor of 1000. With atom interferometers, it has been possible to carry out superhigh-accuracy measurements of rotation (gyroscopes), Earth's gravitational field, atomic polarizability, the fine structure constant, and atom–surface interactions. The precision of these measurements greatly exceeds that of previous methods [26].

Phase shifts in an atom interferometer are subdivided into four types: (i) dynamic, (ii) topological, (iii) gravitational, and (iv) inertial (the last two are caused by gravitational and inertial forces). In a potential field, where the energy of an atom depends on its coordinate, the atom experiences a force, which determines its dynamics. From the dynamics, it is possible to decide about the magnitude and character of the field; in other words, the atom plays the role of a test body. An alternative possibility for extracting information about the field is provided by interference measurements, in which the phase increase of the atomic wave function is determined by the nature and magnitude of the potential. In such fields, the phase shift is termed dynamic.

Atomic interferometry allows investigating physical fields that are independent of spatial coordinates, when the field gradient and, accordingly, the force experienced by an atom in the field are equal to zero. Such a field is not detectable by classical methods involving particle trajectory measurements. It can nevertheless be discovered and investigated by atomic interferometry techniques, because the phase of the wave function changes in the motion of the atom in the field. The phase shift in such fields is referred to as *topological*. The best-known examples of the topological phase shift are the Berry phase and the phases in the Aharonov–Bohm and Aharonov–Cashier effects.

Among the most impressive applications of atomic interferometry is decoherence research [28]. Quantum systems can be in the state of coherent superposition of many states. Interactions with the environment are responsible for the coherence breakdown of the states. This effect is known as 'decoherence.' Research into decoherence and the ways to suppress, correct, and control it is central to the area of quantum informatics, the development of quantum computers, and nanotechnology [29–31]. A quantum computer can be perceived as a complicated interference device that performs operations on superposition (and coherent) states. The coupling to the environment, arising due to decoherence, its rate and the capability of controlling it underlie the success of operation of the quantum computer.

Because the operation of an atom interferometer is based on the coherence of atomic ensembles in use and its constituent elements (source, splitter, mirrors), it is sensitive to the processes that disrupt coherence. Numerous experiments have been carried out to investigate the loss of coherence due to coupling to the environment (spontaneous photon reradiation in the transit of an atom through the interferometer), during the procedure of acquiring the information as to which interferometer arm the atom is flying through, etc. [25, 26].

An atom interferometer opens outstanding possibilities of verifying fundamental physical laws. *Verification of the charge neutrality* of the atom (the charge equality of the electron and the proton, the neutrality of the neutron) is of significance for the fundamental particle theory. The experimental neutrality test for a macroscopic amount of substance sets a limit on the accuracy of the electron and proton charge equality: $(q_p + q_e)/e < 10^{-21}$. It has been theoretically shown that atomic interferometry is able to improve the measurement accuracy to 10^{-22}.

The *Newton constant G* in the law of universal gravitation $V(r) = Gm_1m_2/r$ is among the fundamental constants measured with the lowest accuracy. Its relative accuracy is 1.4×10^{-4}. Atomic interferometry is a relatively new method of determining this constant, but even in the first measurements performed by atomic interferometry [26], it was possible to achieve an accuracy of 3×10^{-3}. Experiments to measure G with an accuracy of 10^{-4} are planned for the future.

The effort of the physical scientific community to *unify the description of all known types of interaction* (strong, electromagnetic, weak, and gravitational) leads to the model of the interaction of two masses that differs from the Newtonian law of universal gravitation. In all experiments aimed at the verification of the law of universal gravitation, macroscopic test and probe masses have been used up to now. At present, experiments intended to verify the law of universal gravitation with the help of atomic interferometry are being lively discussed, which opens the door to the use of microscopic probe masses to verify the law of universal gravitation in the microworld.

One of the most accurate measurements performed with atomic interferometry was the measurement of the ratio $\hbar/m$ of two physical constants, Planck's constant and mass. The significance of this measurement stems from the fact that the mass enters quantum mechanical equations precisely in the form of this ratio. Until recently, the most exact value of $\hbar/m$ resulted from neutron diffraction by crystalline silicon. The precision of diffraction measurements is 8×10^{-7}. Experiments with the use of atom interferometers [26] yielded an accuracy of 14×10^{-9}, whence follows an accuracy of 7×10^{-9} for the fine structure constant.

The efforts of numerous research laboratories have led to the development of a variety of high-precision instruments based on an atom interferometer, which are intended for acceleration (accelerometer), gravitational field (gravitometers and gradiometers), and rotation (gyroscopes) measurements.

3.3 Atomic clock

A fundamental limitation on the accuracy of measurement of frequency and time in atomic clocks is the *measurement time* of the frequency of the atomic transition. In the primary cesium frequency standard, it is defined by the time of atomic transit through the probing field. The methods of laser cooling and atom optics have made a new type of atomic clock possible, called the *atomic fountain*. In this case, the duration of the measurement is larger by two orders of magnitude in comparison with that in the frequency standard involving a thermal atomic beam. In an atomic fountain, atoms are first cooled by laser radiation and are next captured by an atomic magnetooptical trap, in which they experience further cooling. The resultant cloud of ultracold atoms serves as the source of slow atoms in the fountain: with the help of a laser pulse, the cloud of cold atoms is thrown vertically up and the atoms, describing ballistic trajectories, cross the probing field in their upward motion. Owing to free-fall acceleration, the atomic velocity gradually subsides to zero and the atoms fall again, passing through the probing field for the second time. Therefore, the atoms experience a double passage through the probing field, in which the readout of atomic transition oscillations takes place. The long interaction time allows realizing a relative accuracy of 4×10^{-14} with atomic fountains.

3.4 Atomic nanolithography

Nanolithography is used to fabricate material structures ranging in size from a single atom to about 100 nm. These structures are of interest for both basic science and applications. The incentive to develop nanolithography is the 'race' for a high transistor density in a chip, described by Moor's law. According to this empirical law, in new microchip models, which make their appearance 1.5–2 years after the previous ones, the density of elements doubles. To date, lithography techniques involving ultraviolet radiation, electron and ion beams, X-ray radiation, scanning probes, and self-organization have been well developed. Each of these techniques has advantages and disadvantages: optical lithography is diffraction-limited; charged particle beam lithography encounters problems associated with mass production of structures and the significance of Coulomb repulsion; scanning probes, which manipulate single atoms, exhibit poor efficiency; self-organization fabrication still calls for a better understanding of physical processes. Meanwhile, an extensive quest is underway for alternative ways of making nanostructures, and the nanolithography based on atom optics holds much promise as a fabrication technique.

The title 'atomic nanolithography' is used in reference to a family of techniques for the making of nanostructures in which laser light is used as atomic microlenses. Diversified configurations of laser fields have been proposed for the atomic microlenses: traveling [32] and standing [33] waves, as well as spatially localized laser fields [34]. The most significant results have been obtained with microlenses produced by standing laser waves quasiresonant with atomic transitions. An atom in the nonuniform laser field of a standing wave experiences a dipole force. The beam of atoms passes through the standing wave whose frequency is shifted to the blue side of the spectrum relative to the atomic resonance, and is drawn in the nodes of the standing wave under the action of the dipole force (Fig. 4). One period of the standing wave is an atomic lens and has the spatial size $\lambda/2$.

The size of the focused atomic spot and hence the size of the nanostructure on the surface depend on several physical factors. The atomic beam has a finite divergence and, as a consequence, a spherical aberration of the atomic lens emerges. Its effect is suppressed by using laser cooling. The small transverse size of the atomic lens also brings diffraction

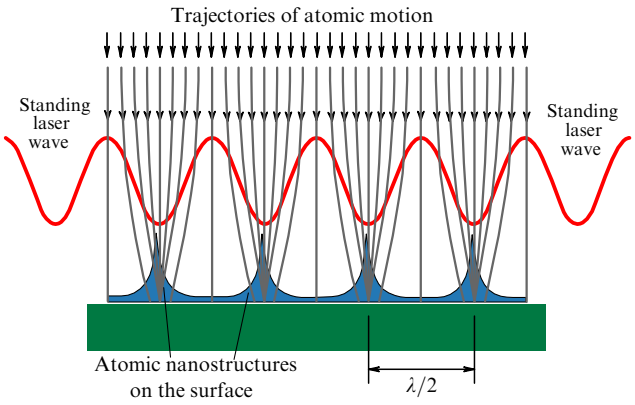

Figure 4. Atomic lens formed by a standing light wave.

aberrations into effect. For the atomic velocity about 200 m s^{-1}, the de Broglie wavelength is equal to about 0.01 nm; this wavelength corresponds to the diffraction limit $\sim \lambda/40$. The atoms experience the transverse velocity and spatial broadening owing to the spontaneous reradiation of laser photons. The broadening of atomic nanostructures is due to chromatic aberration and physical and chemical processes on the surface.

A standing light wave is ideally suited to the fabrication of one- and two-dimensional periodic structures — line and point arrays. The use of two orthogonally related interfering standing laser waves allows the formation of a two-dimensional array of 'photon microlenses' and the fabrication of two-dimensional nanostructures on a surface. By varying the wavelength, it is possible to change the grating period $\lambda/2$. By changing the polarization in the standing wave, it is possible to obtain the period equal to $\lambda/8$. Using the interference of three laser beams intersecting at 120° or five laser beams intersecting at 72° allows producing more complex quasiperiodic structures. To date, experiments on the focusing of atoms have been carried out on Na, Rb, Cs, Cr, Fe, Ni, Co, and Yb atoms. The prospect of experiments on aluminum, gallium, and indium atoms, which are of microelectronic interest, has also been considered. Figure 5 shows chromium nanostructures in the form of lines and spots [33]. The nanoline width at half maximum is 50 nm and the height is 28 nm. The smallest size of the nanostructures produced using the atomic microlenses of a standing wave is about 15 nm.

It follows from general physical considerations that in the construction of atom optics elements, an atomic lens in particular, preference should be given to spatially localized atom–field interaction potentials. Two types of localized fields are used for this purpose: the light field resulting from light diffraction by structures smaller than the light wavelength (Bethe holes) [34] and the light field localized in partially open waveguides. The diameter of a Bethe hole is smaller than the incident radiation wavelength. The field diffracted by the hole consists of a traveling wave field and a near-field component. The near-field component is used for making an atomic lens. The size of the minimal atomic spot in the focus of this lens, which may be equal to 0.1 of the optical wavelength, is determined by spherical and chromatic aberrations, atomic diffraction, interatomic interaction, and spontaneous radiation.

Another example of a localized laser field used for making an atomic lens is the field in a two-dimensional waveguide in which the interplane distance is of the order of or shorter than the wavelength of light; in the waveguide surfaces, there are two small coaxial holes whose radius is much smaller than the wavelength of light [34]. The radiation is barely transmitted through these small holes, but in the vicinity of each of them, the field is strongly modified inside and outside the waveguide. The character of modification depends on the polarization of the input radiation. The field distribution with an intensity minimum between the holes is referred to as a 'photon hole' and the distribution with an intensity maximum is termed a 'photon dot.' The photon dot and the photon hole can be used for focusing atomic beams.

Despite the numerous proposals concerning the focusing of atomic beams and the equally numerous experimental realizations of atomic lenses, this problem remains unsolved as regards construction of the images of nanoobjects of an arbitrary shape. The main complication is in the formation of the atom–electromagnetic field interaction potential that would approximate a 'perfect lens' for the atoms.

First implemented at the Institute of Spectroscopy, RAS, was an approach to nanostructure fabrication by the

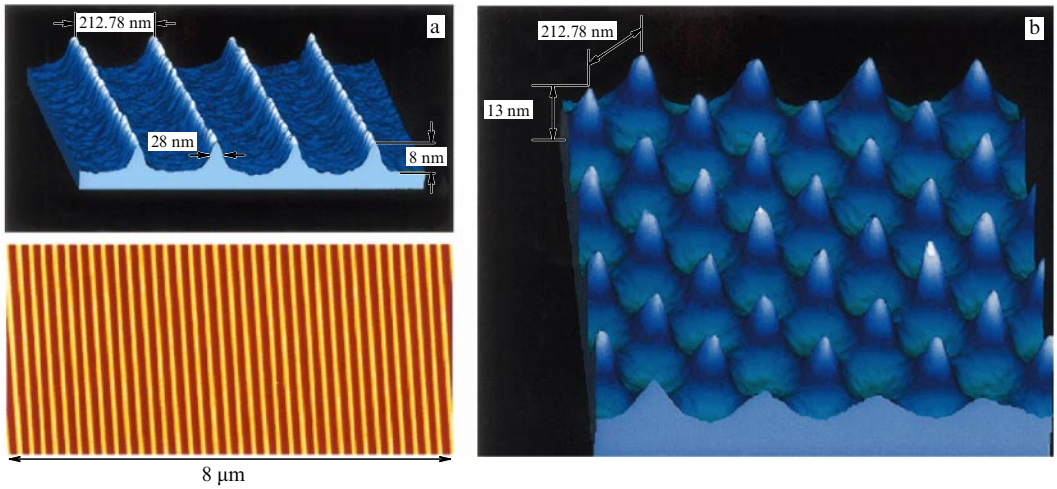

Figure 5. Chromium nanostructure images produced by focusing with (a) one-dimensional and (b) two-dimensional photon lens systems. The period of chromium lines and spots is $\lambda/2 = 213$ nm [33].

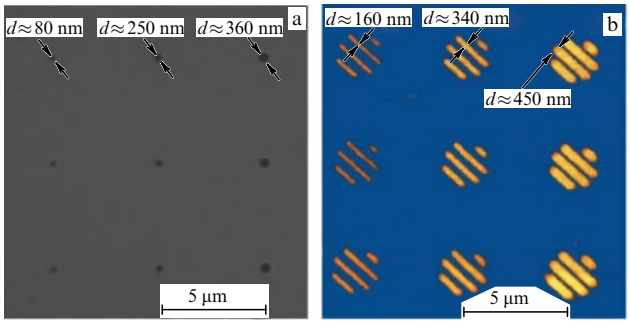

Figure 6. Production of nanostructures with the aid of an atom pinhole camera. The picture demonstrates the effect of nanohole diameter on the resolution of the atom pinhole camera. (a) Electron image of the membrane with nanoholes (atomic nanolenses) of various diameters: $d = 80$, 250, and 360 nm. (b) Images of nanostructures made of In atoms on the surface of silicon with the use of the nanoholes of the membrane shown in Fig. 6a [35, 36].

methods of atom optics, which is based on the analogy with a pinhole camera known in light optics [35, 36]. The atom pinhole camera comprises an atomic beam, a mask, a membrane with holes, and a substrate on which nanostructures are produced. The atoms transmitted through the mask, much as in optics, form a 'luminous object' with a geometry determined by the mask. The parameters of the atom pinhole camera are selected so as to maximize the resolution. The ratio between the mask–nanohole distance L and the nanohole–substrate distance l defines the 'demagnification' of the atom pinhole camera $N = L/l$. For $L = 10$ cm and $l = 10$ μm, the 'demagnification' is 10^4.

Masks in the atom pinhole camera are typically 10 μm in size, and the resultant nanostructures are therefore $N = 10^4$ times smaller, i.e., of the order of 10 nm. In this way, the objects of the *microworld* are transformed into *nanoworld* objects, and the atom pinhole camera can be considered a realization of Feynman's famous device: "...a scalable manufacturing system could be made which will manufacture a smaller scale replica of itself" [37].

In an atom pinhole camera, not only a single nanohole but also a nanohole array can be used (Fig. 6). Such a parallel pinhole camera has the capacity to simultaneously fabricate a large number of identical nanostructures of arbitrary atoms or molecules, with the minimal element size being equal to several nanometers. A simultaneous fabrication of 1 million identical nanostructures was demonstrated with an atom pinhole camera [35, 36].

4. Conclusions

Laser cooling as a method of achieving ultralow temperatures and atom optics as a new type of material particle optics have led to rapid progress in the area of modern physical technologies. Ultracold atomic ensembles, including quantum-degenerate Bose and Fermi gases, have become readily available to physical laboratories. Achievements in high-resolution optical spectroscopy have furnished tools for the coherent control over external and internal degrees of freedom of atomic matter. Atom optics, whose development has covered a relatively short period, has found practical uses in many areas, including atomic interferometry, quantum frequency and time standards, and atomic nanolithography. During the 20-year period of their development, atom interferometers have traveled the way from mere demonstration of their feasibility to the verification of basic physical laws and the making of the most precise quantum clock, accelerometers, gravitometers, and gradiometers. It is not unlikely that atom interferometers will find use in the detection of gravitation waves on Earth and in space. Another avenue of development showing great promise is an atom chip — an atom microtrap based on magnetic and light fields. This integrated micromanipulator of atomic waves is a candidate for quantum information technology. At present, atomic nanolithography is considered an alternative technique for nanolithography of the future. Further research in the areas of ultracold atoms and atom optics will allow a deeper understanding of quantum physics and will broaden the field of ultracold substance application in different technologies.

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