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ON THE 100th ANNIVERSARY OF THE BIRTH OF N G BASOV

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Methods of quantum logic in ion frequency standards, quantum computers, and modern spectroscopy

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Contents

Abstract. Today, precise laser control of the quantum states of single ions cooled to low temperatures in traps ensures significant progress in the development of such physical areas as optical and microwave frequency standards, quantum computing, and accurate measurements of transition frequencies to confirm fundamental physical theories. Pioneering ideas about the possibility of using lasers in the development of frequency standards, expressed in the 1960s by the Nobel laureate N G Basov, have enjoyed rapid development: the relative accuracy of frequency standards has reached the 18th decimal place, and the experimentally demonstrated coherence time of narrow optical transitions amounts to tens of seconds. The paper presents a selective review, as well as the results of research at the Lebedev Physical Institute, in the area of using elements of quantum logic in the action of coherent laser pulses on single ions. Also discussed is the use of quantum logic methods in optical clocks based on the Al^+ ion and the multiply charged Al^+ ion, and also in quantum computers based on Ca^+ and Yb^+ ions.

Keywords: quantum logic, trapped ion, Rabi frequency, frequency standard, quantum computer, laser spectroscopy

1. Introduction

The 21st century in physics is marked by the beginning of the so-called ‘second quantum revolution,’ which is underlain by a wide range of possibilities for making and controlling single quantum systems (quantum technologies). In contrast to the ‘first quantum revolution,’ which led to the emergence of maser-laser radiation sources, LED lighting, semiconductor microelectronics, solar panels, and low-dimensional quantum systems, where large ensembles of particles are involved everywhere, recent years have seen the increasing ability to control single systems which exhibit quantum properties. These include single atoms [1] and ions (as well as their ordered arrays with individual addressing) [2], photons [3], ‘artificial atoms’ (color centers in diamonds, quantum dots, single impurity centers in semiconductors, etc.) [4], selected modes in resonators of various types, Josephson structures [5], and much more. Since the quantum nature is inherent in virtually all physical objects, the main task of researchers is to search for two-level (and sometimes multilevel [6]) quantum systems with a sufficiently high coherence, the possibility of individual addressing using external fields, and efficient readout of states. In the case of photons, polarization states are often used as an analogue of a two-level system, and the states are controlled using linear and nonlinear optical transformations. Such areas as quantum computing [7], quantum sensorics [8], and quantum cryptography [9] have already been established and are developing. Significant progress, including that in applied and commercial problems, has been achieved in the distribution of cipher keys via optical fibers and open channels using single photons [10]. Frequency standards have been made on single ions, which have already reached the frequency reproduction uncertainty at the level of 18 decimal places [11], and the feasibility of using them in global satellite navigation systems is being considered. The pathway of quantum computers is successfully developing, and to date the superiority of such systems over classical supercomputers for solving some specific problems has already been demonstrated [12]. It is not yet clear whether the second quantum revolution will be able to influence the scientific and technological structure of society as much as the first one did, but expectations from the introduction of new types of sensors, means of communication, and computing are very high.

All these achievements undoubtedly rely on the pioneering work of Nikolai Gennadievich Basov, the anniversary of whose 100th birthday we are celebrating this year. The fundamental principles of maser-laser radiation underlie all

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types of lasers operating today [13]. The emergence of semiconductor lasers, whose operation, for example, underlies the entire information and telecommunication system of the Internet, is also inextricably linked with the name of Basov, and his Nobel lecture was dedicated to them [14]. The idea of using lasers and masers as precise standards of frequency and time [15] has led today to the development of global satellite navigation systems used throughout the world. The ideas of laser thermonuclear fusion and the pioneering work on their implementation were also formulated and carried out with Basov playing a key role [16]. Such examples could be continued and expanded almost ad infinitum, but in this paper we would like to focus on laser control of individual quantum objects — trapped ions — present some results, and describe prospects for the development of this line of research.

2. Laser excitation of single ions

The interaction of a two-level system (or its analogue) with an external field can be conveniently described using Bloch equations [17]. In this case, a unit vector representing the state of the system will describe trajectories along the Bloch sphere of unit radius, which can be reduced to rotations along the three axes x, y, z. Accordingly, any impact on the system can be described as a combination of rotation operations around the corresponding axes R_x, R_y, R_z. The use of highly stable electromagnetic field generators makes it possible in most cases to consider the field a monochromatic wave $E = E_0 \exp(-\mathrm{i}\omega t)$, which simplifies the description of the interaction. The advent of laser sources made it possible to transfer to the optical range those methods that were previously well studied and tested in the microwave range, for example, the well-known Rabi and Ramsey excitation methods. Due to the rich structure of levels in atomic systems and the presence of transitions with very different characteristics (spectrally broad and spectrally narrow, cyclic, two-photon, Λ-type, and many others), a wide range of possibilities for controlling atomic systems and their analysis has appeared. Until the end of the 20th century, the main subjects of study for laser spectroscopy were large ensembles of atoms: atomic cells, atomic beams, and solids. Working with single quantum systems remained the most difficult task due to the imperfection of methods for confining such systems, ensuring effective interaction with the field and readout of states.

Pioneering work on the demonstration of the interaction of single atoms with single photons was carried out by Herbert Walther in 1984 [18]. Using a bulk superconducting microwave resonator and a beam of rubidium atoms in Rydberg states, his group was able to demonstrate the operation of the so-called 'micromaser,' which actually marked the beginning of research into methods for controlling single quantum systems. In 2012, David Wineland and Serge Haroche received the Nobel Prize for 'ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems' [19]. Unfortunately, Herbert Walther did not live to see this event, which actually marked the transition to the second quantum revolution. Therefore, the maximum monochromatic source of electromagnetic radiation (for example, a laser) and a single atom confinement system with the possibility of efficient excitation and readout become the key tools in this area. In this section, we will focus our attention on the interaction of laser radiation with ions trapped in a Paul trap.

While in the 1970s lasers were a separate subject of research, today many types of lasers have become very effective tools, including in problems concerning precision spectroscopy. The narrow spectrum of laser radiation, limited by the Shawlow–Townes limit [20], is well suited for excitation of resonant optical transitions in atoms and ions. The outstanding scientist V S Letokhov, developing the ideas of his teacher N G Basov, already in the 1980s described in his work the enormous range of possibilities that open up with laser control of atomic ensembles [21]. Vivid examples are laser isotope separation and laser cooling of atoms [22]. In this case, it is sufficient to ensure the spectral width of the radiation and its frequency stability at a level of 1 MHz, which is easily achieved using long laser cavities and simple frequency stabilization systems with a stable reference.

However, when addressing spectrally narrow transitions (magnetic dipole, electric quadrupole, etc.) used in frequency standards and quantum computers, laser sources with much more stringent spectrum requirements are called for. A characteristic limitation on the spectral width of the optical carrier is 1 Hz, which is achieved by using special methods of frequency stabilization with external ultrastable resonators [23]. Laser systems with a spectral width of about 1 Hz are de facto already a routine tool in many laboratories, and the record carrier spectral width today is tens of mHz, which is achieved by means of stabilization by cryogenic ultrastable silicon resonators [24]. This made it possible to demonstrate the record coherence time of the optical transition in the strontium atom, which was 37 s in experiment [25].

In addition to the requirements for an optical carrier in a number of problems, for example, in quantum computing, also significant is the level of spectral noise away from the carrier (detuning range of 100 kHz–5 MHz) [26]. For instance, for semiconductor lasers in the Littrow scheme stabilized by external cavities, the power fraction in the noise pedestal can range up to 5% [27] and have an undesirable effect on the excitation of vibrational modes and, as a result, lead to a decrease in the quality of operations. The solution to this problem requires special systems for filtering laser radiation (again, additional external high-Q resonators [28]) or the use of lasers with an initially low Shawlow–Townes limit (for example, Ti:Sapphire lasers or some types of fiber lasers). By and large, it can be said that the task of making a spectrally pure source of laser radiation tuned to a certain optical frequency remains relevant, despite the impressive progress in this area achieved in recent decades.

In turn, single ions captured in the Paul trap are one of the most convenient and interesting research subjects from the point of view of physics. Despite the fact that the very principle of confining ions in a linear or three-dimensional alternating quadrupole potential formed by a system of electrodes was formulated by Paul more than 50 years ago [29], significant progress in the field of spectroscopy of trapped single ions began after the advent of deep laser cooling methods, which were first demonstrated by Dehmelt and Wineland [30]. As a result, a single ion is trapped in the minimum of the so-called pseudopotential, and the strength of the confining field at the location of the ion is equal to zero, which opens up many possibilities for precision laser spectroscopy. When using linear traps, it is possible to capture a chain of ions, which, upon laser cooling to the level of millikelvins, will line up in ordered structures, so-called ion crystals (Fig. 1) [31]. In this case, the distance between the ions is several micrometers and is determined by the Coulomb

Figure 1. Photograph of a crystal of 22 ytterbium ions trapped in a linear quadrupole Paul trap.

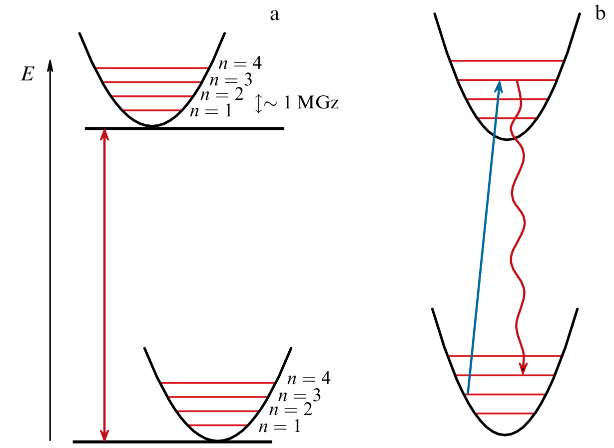

Figure 2. (a) Illustration of the splitting of electronic levels into vibrational sublevels in the RF field of a Paul ion trap. (b) Transfer of the system into a state with a higher vibrational number upon absorption of blue-detuned radiation.

repulsion of particles and the shape of the confining longitudinal potential, which provides the possibility of individual addressing (focusing of laser radiation) and optical readout (recording of luminescence), since the resolution of broad-aperture lenses is usually about 1 μm.

A remarkable property of such systems is the possibility of using normal vibrational modes for the exchange of quantum information [32, 33]. As illustrated in Fig. 2a, each electronic level of the ion is split into many vibrational sublevels, the distance between which is determined by the frequencies of the vibrational modes in the confining potential (usually from 100 kHz to 1 MHz). Accordingly, the quantum state of the two-level system $\Psi = \alpha|0\rangle + \beta|1\rangle$ in the external (harmonic) potential turns into $\Psi' = (\alpha|0\rangle + \beta|1\rangle)|k\rangle$, where k corresponds to the number of the vibrational mode. In a chain of particles, vibrational modes (both axial and radial) are common, which underlies the exchange of quantum information among particles in the chain. The narrowness of the laser radiation spectrum opens up the possibility of effecting transitions with individual addressing of vibrational sublevels, thereby adding or taking away a vibrational quantum from the chain. For example, an ion from the state $|0\rangle|0\rangle$ can be transferred to the state $|1\rangle|1\rangle$ using a π-pulse with the corresponding blue detuning, which will add one vibrational quantum to the system (Fig. 2b). This technique was first proposed by Dehmelt and Wineland for cooling ions to the ground vibrational state in a Paul trap [34, 35].

It is significant that the strong Coulomb interaction of trapped ions also makes it possible to carry out so-called sympathetic cooling, which is widely used in a number of experiments [36]. There are many ion systems where direct laser cooling techniques are either inapplicable or extremely complicated due to the inconvenient wavelengths of the cooling lasers. In this case, such ions can be captured in a trap (sparring ion) with a characteristic depth of 1 eV, which corresponds to a temperature of thousands of kelvins. Ions with transitions convenient for laser cooling can be used as a 'cooler', for example, Be^+, Sr^+, Ba^+, and others, depending on the required charge-to-mass ratio e/m (sympathetic cooling is most efficient for close e/m for the cooling and sparring ion). The use of this method makes it possible to highly efficiently reach both the Doppler limit (a few mK) and the ground vibrational state of the sparring ion. This method is used to cool, for example, aluminum ions in optical clocks [37], ytterbium ions in quantum computers [38], and multiply charged ions [39], and the possibility of cooling an exotic antihydrogen ion is being considered [40].

Therefore, laser-optical control of the states of ions in Paul traps opens up wide possibilities for working with single quantum systems both in precision metrology problems regarding optical clocks and quantum computers, and in a broad range of fundamental areas.

3. Optical clocks

One of the most important lines in the development of time and frequency metrology, which underlies such key areas as global satellite navigation systems and telecommunications, is the creation of optical clocks. The unique properties of single ions captured in a Paul trap, such as (1) the wide variety of research subjects (virtually any ion can be trapped), (2) the presence of spectrally narrow 'clock' transitions that are weakly sensitive to constant electric fields and blackbody radiation, (3) the absence of the contribution of the first-order Doppler effect, and (4) the absence of external perturbing fields in the trap (the ion is at zero quadrupole potential; there is no magnetic field), make them one of the best frequency references. Other advantages are the compactness of the trap, the simplicity of the loading system, a deep confining potential, and a long ion lifetime, amounting to weeks and months, depending on the vacuum level [41]. Probably, the only drawback is the relatively scant statistics on counts in the fluorescence signal of a single ion (compared to optical clocks based on ensembles of neutral atoms) and, accordingly, a decrease in the stability of the system frequency at intervals of 1–100 s by about an order of magnitude compared to clocks based on optical lattices, where $10^4 - 10^5$ atoms are interrogated simultaneously. It is pertinent to note that, in a number of cases, ensembles of charged ions are also used, mainly in radio-frequency standards. Specifically, using a cloud of mercury ions in a radio-frequency trap, a clock operating at a frequency of 40 GHz (the frequency of the hyperfine transition of the ground state) was made [42], and a radio-frequency standard based on ytterbium ions is being developed [43]. In the case of optical standards, the possibility of moving from single ions to ensembles of 5–10 particles is under investigation [44]. This should improve the count statistics, but there are stringent requirements for the immunity of the clock transition to electric fields [45].

A clock based on a single ion in a trap (transition ${}^1S_0 \leftrightarrow {}^3P_0$ in Tl^+) was first proposed by Hans Dehmelt in 1973 [46]. At the same time, the first fully functional optical clock based on a single ion was demonstrated in the USA using the Hg^+ ion [47]. Today, a number of optical standards are successfully operating using Sr^+ (674 nm) [48], Hg^+ (282 nm) [49], Yb^+ (467 nm) [50], Ca^+ (729 nm) [51], Al^+ (267 nm) [37], and some other single ions. The characteristic relative frequency instability for an averaging time of 1 s is usually about 10^{-15} (which is determined by a clock laser) and in record cases decreases to 10^{-18} for an averaging time of 10^6 s. Such characteristics open up a wide range of possibilities for handling both practical problems (the formation of time scales) and high-sensitivity fundamental tests.

To illustrate this point, it is necessary to mention the first laboratory studies of the gravitational red shift, which were carried out using two Al^+ standards separated by 10 cm in height (the measured relative frequency shift was 10^{-17}) [52]. Of no less interest are laboratory experiments to study the possible drift of the fine structure constant α using optical clocks. The first work in this direction began in the 2000s [53], which made it possible to impose a limit on the drift at the level $|d\alpha/dt|/\alpha < 10^{-15}$ yr^{-1}. And in 2021, using a single ytterbium ion captured in a Paul trap, it was possible to strengthen the indicated limitation by three orders of magnitude, which today is $|d\alpha/dt|/\alpha < 1.0(1.1)10^{-18}$ yr^{-1} [54]. This was achieved by a long comparison of the frequencies of two different transitions in the same ion — the quadrupole transition at a wavelength of 436 nm and the octupole at a wavelength of 467 nm — which have different responsivities to a change in α. To date, this is the most stringent restriction on the drift of the fine structure constant in the modern era.

Separately, we would like to describe some aspects of the operation of an optical clock on the Al^+ ion, where elements of quantum computing technology were used for the first time [55]. The aluminum ion has a clock transition at a wavelength of 267 nm (natural linewidth: 8 mHz), which is very attractive for use in optical clocks due to the small contribution of systematic frequency shifts, primarily because of blackbody radiation [56]. In this case, the cooling transition at a wavelength of 167 nm is actually inaccessible to modern lasers, since it lies in the ultraviolet range. And while the problem of ion cooling is relatively easy to solve using the sympathetic cooling method, the question of reading out the ion state after excitation of the clock transition remains open. The now traditional method of quantum jumps, which is widely used in frequency standards and quantum computers [57], requires excitation of a strong (with a width of more than 10 MHz) cyclic transition in the ion and detection of luminescence at the transition wavelength. If the ion is in the ground state, the system will show a strong luminescence signal, and if the ion was excited to the metastable state, there will be no luminescence. However, in the case of the aluminum ion, again, employing the method described necessitates a 167-nm laser, which is not available.

To solve this problem, David Wineland was the first to implement the quantum logic method, described in detail in Ref. [55]. This method involves adding a vibrational quantum to the system (initially in the ground state $|\downarrow\rangle_S|\downarrow\rangle_L|0\rangle$) upon excitation of the clock transition in a logical ion. The Al^+ ion (L) was used as the logical ion; the Be^+ ion (S) was the sympathetic ion. The parameters of the clock laser excitation pulses for the spectroscopic and logical ions were selected in such a way that the wave function of the system evolved as follows: $|\downarrow\rangle_S|\downarrow\rangle_L|0\rangle \to |\downarrow\rangle_S(\alpha|\downarrow\rangle_L + \beta|\uparrow\rangle_L)|0\rangle \to |\downarrow\rangle_S|\downarrow\rangle_L(\alpha|0\rangle + \beta|1\rangle) \to (\alpha|\downarrow\rangle_S + \beta|\uparrow\rangle_S)|\downarrow\rangle_L|0\rangle$. This is achieved by addressing the red vibrational side frequencies, as shown in Fig. 3. One can see that, as a result of the procedure, the amplitude coefficients that determine the probability of excitation of the clock transition in the logical ion (α, β) were first 'written' into the excitation amplitude of the vibrational quanta common to the two ions, and then into the excitation amplitude of the spectroscopic ion. The latter can be easily read using the quantum jump method. This made it possible to make one of the best optical clocks with frequency reproduction instability at the level of the 17th decimal place [58].

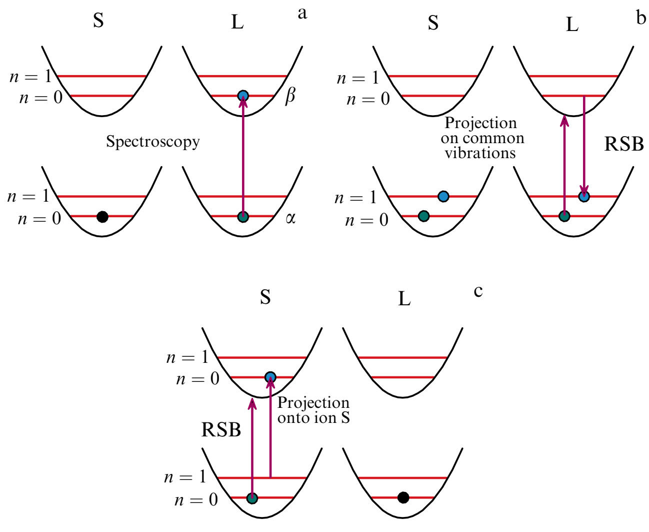

Figure 3. Schematic of the spectroscopic method by means of quantum logic. (a) Spectroscopy of the 'clock' transition in the logical ion (L) is performed; (b) π-pulse is applied at the 'clock' transition in the L ion with detuning to the red side by the vibration frequency (RSB). As a result, the electronic state of the ion L is projected onto the common vibrational state of the ion pair; (c) π-pulse is applied at the 'clock' transition in the S ion with detuning to the red side by the vibration frequency (RSB). As a result, the common vibrational state is projected onto the electronic state S.

The presented method turned out to be extremely effective: D Wineland was awarded the Nobel Prize in 2012 for his work in this area. One of the most striking examples of its use today is the study of the clock transition in the multiply charged Ar^{13+} ion [59]. A heavy multiply charged ion was trapped together with a sympathetic Be^+ ion, and the transition spectroscopy was performed at a wavelength of 441 nm. This was the first work on precision laser spectroscopy of a single multiply charged ion: the relative instability of optical clocks on the Ar^{13+} ion was demonstrated at the level of several units of the 17th decimal place, thereby opening up completely new prospects for the use of multiply charged ions in optical clocks [60]. The quantum information exchange method can also be used to detect single events of spontaneous photon emission, for example, to measure the frequency of the 1S–2S transition in the He^+ ion [61].

One of the important areas in the development of optical frequency standards, which, in fact, has become technological, is the reduction in their size and the transition to transportable systems and, in the future, to space-based systems. A number of projects are underway to develop transportable clocks based on Yb^+ [41, 62], Ca^+ [63] and Al^+ [64] single ions. Since 2018, a transportable standard based on a single ytterbium ion has been under development at LPI [41]. It was shown that the developed setup with dimensions of 1 m^3 and a weight of 300 kg provided instability of frequency reproduction of better than 5×10^{-16} with transfer to the radio frequency range (1 GHz) using a femtosecond optical frequency synthesizer (FOFS). Today, work is underway to improve the mass-dimensional characteristics: under development are a new compact highly stable laser system and a compact Paul trap, and work is underway to improve the characteristics of the FOFS. The system being developed is important to the progress of relativistic geodesy [65], as well as for potential tasks connected to the GLONASS system [66].

4. Quantum computers on a trapped-ion platform

To date, ions trapped in a Paul trap are among the best systems for implementing quantum operations. The combination of a long coherence time ranging up to an hour [67] (for qubits encoded in a hyperfine structure), complete isolation from external fields, simple optical access, and natural Coulomb interaction among the ions ensures that virtually all DiVincenzo criteria formulated for the implementation of a quantum computer are met [68]. The main disadvantage of the ion platform is limited scalability, since the number of ions that can be captured in a linear chain is limited to about 50 [69].

A pioneering proposal on the possibility of using ions for quantum manipulations was formulated by Cirac and Zoller in 1995 [32], and the first two-qubit operations based on this protocol were implemented somewhat later in the USA [70] and Austria [71] in 1998 and 2003, respectively. During the past two decades, this line of research has developed rapidly. Today, the IonQ company [72] is demonstrating the operation of a programmable 11-qubit ion quantum computer, on which a number of key quantum algorithms have been implemented, the reliability of a two-qubit operation on average being equal to about 97.5%. Recently, Honeywell (now spun off into Quantinuum) and IonQ independently announced the making of 20-qubit systems, but the data are yet to be published in peer-reviewed journals. Using Yb^+ ions captured in planar Paul traps, Quantinuum demonstrated for the first time the complete entanglement of two logical qubits using an error correction algorithm (two logical qubits were encoded in 20 physical ones) [73]. It was shown that the correction algorithm made it possible to increase the operation reliability up to 99.6%, with the reliability of physical qubit entanglement below 99.0%. Ion-based computers currently have the highest quantum volume, equal to 4096 (according to announcements by Quantinuum), an indicator characterizing both the number of qubits and the depth of computational operations [74]. Therefore, the ionic platform is considered to be one of the most promising for the implementation of full-fledged programmable quantum computers.

It is noteworthy that the elementary manipulations required for the implementation of ion-based quantum computers (capture, addressing, rotation of the Bloch vector over the Bloch sphere, readout) are similar to those used in optical clocks and, accordingly, are well elaborated. One of the significant differences is the need to perform two-qubit operations on quantum computers, resembling the quantum logic method described in the previous section. The two-qubit operation is the 'heart' of any quantum computer, and for its implementation it is required to entangle two particles in the chain. The method proposed by Cirac and Zoller [32] involves the use of quantized vibrational modes in a chain of ions for their entanglement and, accordingly, the exchange of quantum information. Today, in most experiments, the Cirac–Zoller method has been replaced by the Mélmer–Sórensen method [33], which turns out to be less demanding on the cooling depth of the ion chain. Despite the similarity of some technical and scientific aspects between optical clocks and quantum computers, the latter are much more difficult to implement, since they require simultaneous individual manipulation of dozens of single particles.

Work in the field of quantum computing on single ions commenced at LPI several years ago, and several generations of ion traps have already been made, with which experiments are carried out [75, 76]. An optical qubit based on a quadrupole transition in the ytterbium ion was proposed and studied for the first time [77], the readout reliability was studied [78], and a new method for measuring the ion temperature was developed [79]. At the end of 2021, operations were performed on four qubits, and, in this case, again, for the first time, multilevel systems in the ytterbium ion, so-called qudits, were used [6]. It was shown that two qudits with a Hilbert space dimension of 4 and the possibility of their entanglement are completely equivalent to four qubits. The reliability of the entanglement of two ions in the Paul trap, demonstrated in experiments by the Mélmer–Sórensen method, has so far been about 80%, which is limited by the noise of the laser system as well as by the imperfect fabrication of the trap.

Work at LPI is actively developing, experiments on 16 qubits are already planned for 2022, work is underway to improve the quality of operations, new quantum algorithms are being developed, and the integration of a quantum computer with a cloud platform is underway (Fig. 4). The

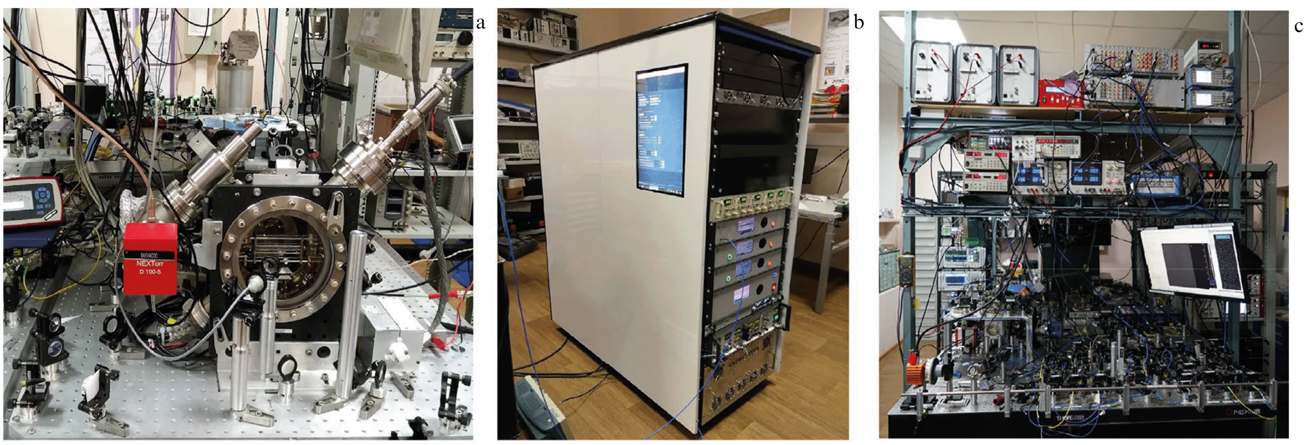

Figure 4. History of the development of research on trapped ions at LPI. (a) First ion trap for magnesium and ytterbium ions. (b) Transportable optical clock based on a single $^{171}Yb^+$ ion. (c) Russia's first 4-qubit quantum computer based on cold $^{171}Yb^+$ ions.

work is being carried out within the framework of the Quantum Technologies Roadmap in cooperation with the Russian Quantum Center and a number of other leading organizations that are part of the National Quantum Laboratory. These studies can significantly reduce the gap with the world level and make this area one of the leaders and locomotives of Russia's scientific development.

5. Conclusions

Unlike many other Nobel Prizes, not only has the scientific heritage of Nikolai Gennadievich Basov not reduced in relevance, but, surprisingly, it has enjoyed rapid development both in fundamental and practical areas. Coming to mind is the work of the Austrian scientist Christian Doppler, who at the beginning of the 19th century discovered the dependence of the speed of sound on the direction of propagation in a moving medium. It is estimated that 24 Nobel Prizes have since been awarded for advances in medicine, technology, and the natural sciences that would not have been possible without the use of the Doppler effect. It would be interesting to calculate how many Nobel Prizes are inextricably linked with the work of N G Basov: we think more than a dozen as well. In the 21st century alone, 9 prizes in physics were awarded for work directly related to laser research, a direct legacy of N G Basov. And the year of 2022 was marked by the awarding of the Quantum Optics Prize to Alain Aspect, Anton Zeilinger, and John Clauser (the first two colleagues lectured at the Lebedev Physical Institute a few years ago) "For experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." Moreover, entangled photons are obtained as a result of the nonlinear transformation of laser pulses in crystals — the parametric conversion of light — which is a direct result of Basov's ideas.

It is important to note another, often forgotten, aspect of Basov's scientific career: he wrote his doctoral thesis, which formed the basis of the Nobel Prize, at the age of 35. And this despite the fact that he was a 'late' student who served on the front during the Great Patriotic War (World War II). Of course, the topic of this work — laser control of ions in traps — is only a small part of N G Basov' legacy, but, as we have tried to show, is topical and enjoys multifaceted development at his native institute — the P N Lebedev Physical Institute of the Russian Academy of Sciences.

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