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Andrei Sakharov's research work and modern physics

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Contents

Abstract. We follow the work carried out by Andrei Sakharov in both research and engineering, from the first domestic thermonuclear charges to fundamental physics. We emphasize the current status of the research fields recognized to have originated in Sakharov's work: controlled fusion, magnetic cumulation and magnetic explosion generators, induced gravity, cosmological 'Sakharov' (baryonic acoustic) oscillations, and baryon asymmetry of the Universe. Another subject that unexpectedly gained momentum in the 21st century is the model of a pulsating universe, which was among Sakharov's ideas. Other subjects that were dear to him, such as quantum cosmology and the anthropic principle, are also currently at the forefront of science.

Keywords: Andrei Sakharov, atomic bomb, hydrogen bomb, controlled fusion, magnetic cumulation, magnetic explosion generators, induced gravity, Sakharov oscillations, baryon asymmetry of the Universe

1. Introduction. Prediction of the Internet

Fundamental physics was always an object of admiration for Sakharov during his entire life. "I felt I was a messenger of the gods" [1, Pt. I, Ch. 5], is how he referred to his first talk on quantum field theory at the seminar in the Theory Depart-

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Andrei Sakharov
(21.05.1921–14.12.1989)

ment, Lebedev Physics Institute (FIAN) in 1945. Although that work was done, in his own words, "on the sidelines" [2] of defense-related and societal problems that he was constantly occupied with, some of the subjects later turned out to become sources of whole new research areas.

Previous publications on Sakharov's scholarly studies include the papers by Altshuler and Golfand in *Sakharov's 1981 Almanac* [3], the annotated collections of studies published in 1982 [4] and 1995 [5], and papers published in *Physics–Uspekhi* [6–8] in 1991, 1996, and 2012 and in a dedicated issue of the journal *Priroda* in 1990 [9]. The main point that we address here is the legacy of Sakharov's scientific and engineering ideas in modern physics and technology.

Before systematically setting forth, we note a prediction made by Sakharov, which is quite remarkable in its exactness. In 1974, he wrote a paper, "The World in Fifty Years," where he in fact addressed precisely our current time. The most important innovation of our time, affecting each and every person on Earth, is the Internet, linking everyone to everyone and offering the opportunity of gleaning practically any information instantaneously. This is what Sakharov wrote about it almost 50 years ago and 15 years prior to the appearance of the World Wide Web concept itself:

Strong and controversial feelings overtake anyone who ponders the future of the world in 50 years, the future in which our grandchildren and great-grandchildren are going to live. These feelings are despondency and horror in the face of the tangle of tragic perils and unfathomable future difficulties awaiting mankind, but at the same time, trust in the vigor of reason and humaneness harbored in the souls of billions of people, which is the sole factor that can overcome the impending chaos. This also is the admiration and most vivid curiosity fueled by multifaceted and unstoppable progress in modern science and technology. ⟨...⟩

I am deeply convinced, however, that enormous material promises imminent in scientific and technological progress, despite all of their utmost importance and necessity, still do not decide the fate of humanity in and of themselves. Progress in science and technology does not produce happiness unless it is complemented by very profound changes in the social, ethical, and cultural life of mankind. The psyche of the people, the internal impetus of their activities, are most difficult to predict, but they ultimately decide between the destruction or prosperity of our civilization. ⟨...⟩

One of the early stages of that progress is represented by the creation of means for worldwide telephone and video-telephone communication. In the long run, maybe even later than 50 years from now, I presume a worldwide information system (WIS) will be established that will provide access for anyone at any instant to the content of any book that has ever been published, no matter where, the content of any article, the answer to any query. The WIS must include individual miniature transceivers to make queries, control stations to operate the information streams, and communication channels including thousands of communication satellites, cable, and laser communication lines. Even a partial construction of the WIS would deeply affect the life of every person, their leisure, intellectual, and artistic growth. Unlike TV, which is the main source of information for many of our contemporaries, the WIS will offer anyone maximum freedom in choosing information and will require individual actions. ⟨...⟩

But the truly historic role of the WIS will be the downfall of all barriers for information exchange between people and countries. Total accessibility of information, especially if extended to pieces of art, is fraught with the danger of their depreciation. But I believe that this contradiction will eventually be overcome. Art and its perception are typically so personal that the value of face-to-face interaction with an object of art and an artist will remain. The value of books and of private selections of books will also be retained, just because they embody the result of a personal choice of the individuum, and also due to their fairness and conventionalism in the better sense of that word. Interaction with arts and books will always be a celebration. ⟨...⟩

I tend not to attach absolute value to the technological and material side of progress. I am convinced that the grand purpose of human institutions, and of progress in particular, is not only to protect every person born from too much suffering and an untimely death but also to preserve all that is humane in humankind. And, at any rate, progress saving people from hunger and disease cannot be in conflict with cherishing the maxim of active pursuit of good causes, which is the most humane part of man [10].

2. Fundamental research 'prior to the bomb': 1945–1947

In 1942, during his wartime relocation to Ashgabad, Sakharov graduated from university, turned down an offer to enter postgraduate studies, and was dispatched to an ammunition plant in Ulyanovsk. There, he proposed several inventions that were important for the production line (as we briefly discuss in the next section), and also married K A Vikhireva. At the end of 1944, Igor Tamm invited him to enter postgraduate studies at FIAN.

M S Rabinovich, who was Sakharov's friend at the time of postgraduate studies at FIAN, writes in his recollections "How we started" ([11, p. 549]):

I became a postgraduate student at the Theory Department. There were five of us: Andrei Sakharov, Zhabaga Takibaev, Shura Taksar, Petya Kunin, and myself. My advisor was E L Feinberg, and Andrei's advisor, I E Tamm....

We made good progress, especially Andrei. He was ahead of schedule, so to say. A year and a half after he started, he was prepared to defend his thesis. But he had not passed all the necessary exams. Well, he passed the language and physics exams, and only philosophy remained. He studied with Kunin, and they went to the exam together. As far as I remember, Petya got a three, and Andrei a two. That is where they failed: the question was whether they had read Chernyshevsky, something about esthetics in nature. Petya, understandably, said he had read it, but Andrei, with his outstanding honesty, said he hadn't, but only looked it up in a Dictionary of Philosophy. So he got a two, and this postponed his defense for a year. He could not complete his postgraduate studies ahead of time.

I remember the Andrei of those days: he made a very strong impression by his ability to solve physical problems and agility in proposing ideas. He was very fond of various paradoxes and loved solving them, invented his own problems, and formulated nontrivial answers to them.

Sakharov's thesis was titled, "Theory of nuclear transitions of the $0 \rightarrow 0$ type." It is published in full in [5, pp. 427–471]. R G Dalitz (1925–2006), who in 1950 wrote a thesis, "Zero — zero transitions in nuclei," refers there to Sakharov's 1948 paper, "Interaction of an electron and a positron with pair production" [12], which, even before its publication,

became the backbone of Sakharov's thesis. The thesis itself was read by Dalitz only in 1990, a copy he received from FIAN; he wrote extensive commentaries on it (see [6, pp. 121–136] and [5, pp. 485–499]). I have an unforgettable experience associated with Dalitz: the sancta sanatorium of Oxford University is the department, closed to the public, of old science manuscripts from the Bodleian Old Library, founded in the 14th century, which Dalitz arranged for my wife and me to visit when we came for the first time to England in 1996.

The following is an excerpt from a statement by A B Migdal, who was an official reviewer at Sakharov's defense on November 3, 1947: *Especially interesting is the part of the thesis dealing with the problem of the interaction between the components of the pair. This problem, which used to be considered extraordinarily difficult, is solved by the author with outstanding elegance by passing to the moving reference frame in which the problem reduces to an elementary problem on Coulomb interaction of two nonrelativistic particles* [5, p. 478].

And this is from the report of the other official reviewer, I Ya Pomeranchuk: *In defining the probability of electron–positron pair production, Sakharov noted the possibility of taking the Coulomb interaction between the electron and the positron into account in the case where this interaction is strong, i.e., when relative velocities of the electron and positron are small. The result obtained in the thesis, taking the interaction of the electron and positron into account, applies to any processes leading to production of electron–positron pairs, and not only to the case of pair production in $0 \rightarrow 0$ transitions addressed in the thesis* (ibid, p. 480).

The last remark by Pomeranchuk was remarkably vindicated in 2020. In [13], Sakharov's recipe to account for the interaction of components of a pair produced with small relative velocities was applied to the pair production process in strong electromagnetic fields at ultra-peripheral collisions of relativistic nuclei.

The thesis also covered Sakharov's first paper, "Generation of the hard component of cosmic rays" [14], written in 1946. His advisor, Tamm, at the same defense session on November 3, 1947, noted: *This work shows the outstanding mastering of mathematical analysis by Sakharov. It involves a very complicated question of the generation of a meson in the collision of two protons. This is the so-called third-order process. It is extremely difficult to evaluate mathematically. Sakharov was able to find a smart method and rearrange the different elements of this complicated process such that he could pursue the calculation of these complicated matters to the end and obtain an entirely closed solution* ([5], p. 482). The original title of the paper, "Generation of mesons," was altered by the editors of *JETP*. Sakharov recalls: *Tamm explained the alteration to me this way: 'Even Beria knows what mesons are.' I do not think that an intervention by Beria himself was meant seriously; he was only mentioned as an extreme example, but the reaction of 'vigilant' persons of a somewhat lower rank, sufficiently dangerous for both the author and the editor, could surely be well apprehended* [1, Pt. I, Ch. 5].

In 1948, Sakharov wrote three more papers. The first of them was "Temperature of excitation in gas-discharge plasma" [15].

I I Sobelman refers to it this way: *An important step was to clarify the specific features of energy exchange between electrons and atoms and molecules in the case where the energy loss by an electron in the collision is much less than its energy and can have either sign (losing and acquiring energy). Sakharov showed that this exchange has the nature of a*

Fokker–Planck process.... At the time, Sakharov's short paper played a very important principal role [5, p. 23].

L A Vainshtein notes: *In this paper, Sakharov, having apparently discovered it for himself, discusses corollaries of deviations from thermodynamic equilibrium in the moderate- and low-density plasma that he studies. Obviously, he (or anyone else at FIAN) could not then be aware of Edlen's work (Sweden, 1942) in which the limit case of low densities (the so-called coronal limit) was formulated. In his subsequent work, Sakharov used this limit case as a standard toolbox. These ideas (evidently duly developed) are relevant to this day* (ibid, p. 24).

The second paper was a classified report, "Passive mesons" [16], which we discuss in Section 4.3 in what follows.

Sakharov's third 1948 paper, "The effect of scattering on the synchrotron beam intensity" [17], is another unpublished FIAN report. A N Lebedev recalls: *The first electron synchrotrons in this country were being put into operation in those days at FIAN. The aim was not to develop a general theory of beam scattering in accelerators but to find specific estimates for the installation then under construction.... The key problem was the clear physical separation of the cases of large and small screening parameters, and also a simple and elegant derivation of an analytic expression for the losses, suitable for direct evaluation for the specific installation. Although Sakharov was later occupied by totally different problems, he appears to not have lost interest in accelerators, and much later he even proposed a beautiful and radical idea of a single-use 'explosive' accelerator, which, hopefully, will be worked out in detail from the technological and economic standpoints* [5, p. 111]. More details on 'explosive' single-use accelerators are given in Section 5 in what follows.

According to Sakharov,

...The thesis had been prepared, and I was deliberating on my further research work. The existence of some anomaly contradicting a theoretical formula for the optical spectrum of the hydrogen atom was discussed in the literature. Specifically, there were indications (not very precise due to the extreme smallness of the effect; at the edge of the sensitivity of optical measurement methods for atomic levels) that two levels of the hydrogen atom that were to be exactly coincident according to theory in fact lay slightly one above the other. It occurred to me that this could be a manifestation of what is now called radiation corrections, the effect of the interaction of the electron with quantum mechanical oscillations of the electromagnetic field, or more precisely, the difference between such effects for an electron bound in an atom and a free electron.... The energy of this interaction turned out to be infinite in calculations!... This was the greatest challenge of the theory, which determined the entire progress in the physics of quantum fields over many decades. I assumed that the difference between the effects for a bound and a free electron had to be considered. Because the binding effect shows up, as I rightly assumed, only at not very high frequencies of zero-point oscillations, the hope was that the difference effect would be finite.

Of course, I realized that the significance of that idea reaches far beyond the particular problem of the anomaly in the hydrogen atom and should, in particular, extend to scattering processes. I was very excited. I then addressed Tamm with all these ideas (in the summer or fall of 1947). Unfortunately, he did not encourage me, acting rather to the contrary. First, he said, these ideas are by no means new: they have been expressed several times in one form or another. This was indeed so, but that alone would not deter me, because I was already intrigued by the problem strongly enough to care little

about things like priority; I was interested in the crux of the matter. Second, Tamm continued, the idea appears to not go through, to not yield a finite result. He then referred to the recently published paper by American theorist Dankoff.... Dankoff had actually made a mistake, but, naturally, neither Tamm nor myself could detect it immediately and pin down the details. Had our intuition not failed us, we should have kept expressing doubts about Dankoff's paper as many times as it would take to discover the error, or, even better, temporarily ignored the apparent contradiction and sought simpler doable problems where the result could be confronted with experiment. As is well known, just that was the course of action of many more perspicacious and daring people that have succeeded. But not us. This way, I missed my chance to do the most important work of that time (and the most important, far ahead of a distant second, in my life)....

When recalling that summer of 1947, I feel that never before or after did I come so close to big science, to its forefront. Today, understandably, I am somewhat disappointed that I personally was not up to the task (no objective circumstances are to blame here). But on the other hand I cannot help feeling admiration for the steady progress of science; if I had not come into close contact with it, I would not be able to feel this so acutely [1, Pt. I , Ch. 5].

The subject discussed here is Lamb's shift of energy levels of the hydrogen atom. A year after the events just described, in 1948, western theoreticians managed to calculate this subtle effect of quantum electrodynamics, achieving a fantastic level of coincidence between theory and experiment. These classical results were rightly awarded Nobel prizes. The calculations became feasible when a systematic strategy was found for eliminating (subtracting) infinities due to the infinite number of degrees of freedom of quantized fields (in this case, Maxwell's electromagnetic field). Sakharov hit upon a critically important way to subtract these infinities and was therefore close to an explanation of Lamb's shift. But he did not drive it home.

This was what happened to a young researcher. Four years later, in 1951, when already at the Facility, Sakharov, together with Tamm, trusting their intuition and expressing doubts as many times as it would take, did not let themselves be persuaded by prominent Moscow colleagues regarding the fundamental unfeasibility of Sakharov's idea of magnetic confinement of plasma (for the peaceful use of nuclear energy in installations for controlled thermonuclear fusion). Quoting Sakharov:

We could already envisage major prospects and did not want to give up without a fight. This was, superficially, nearly a reenactment of the situation described in Einstein's well-known parable of how inventions come about. First, all experts claim that this is impossible, and adduce solid arguments. Then comes someone who is too ignorant to know all of that, and it is this person who makes the invention. This is not to be taken too literally, however: the 'ignorant' must be up to the level of contemporary scientific knowledge and have a number of qualities in addition, otherwise it would not go through; the best case scenario is that he knows about the difficulties, but has the intuition to not be daunted by them at the stage when he is still unable to vindicate himself logically [1, Pt. I, Ch. 9].

3. Hydrogen bombs: 1948–1967

How gifted Sakharov was in terms of engineering and design was already apparent during the war years, when he was working at the Ulyanovsk ammunition plant in 1942–1944 and made several inventions there. The first was a device for controlling the quality of the hardening of armor-piercing cores. Sakharov described the outline of the device in his "Recollections": the tested core slides down a titled copper tube between magnetizing and demagnetizing coils; at the end of the tube is located an instrument that measures the magnetic moment of the core. The instrument is gauged such that the full hardening leaves the indicator at zero. Deviations of the indicator are proportional to the degree of failure in hardening.

Sakharov writes:

The device was approved by a committee for use in the production line and was actually used for many years.... In 1945, I received a Certificate of Authorship for this invention. Several years later I accidentally saw the description of my device in a textbook, Ammunition Production, *written by the former chief engineer N N Malov* [1, Pt. I, Ch. 4].

Next, Sakharov invented a method to control the thickness of the brass coating on TT bullets (for machine guns), a method that did not require etching, which would degrade the bullets; this was followed by an express method for determining the grade of steel, and so on.

Sakharov recalls:

My principal occupation in 1944 was related to working out a device for controlling armor-piercing cores of a 14.5-mm bore for the presence of longitudinal cracks. The bullets whose cores had cracks were torn apart in the tight bore of antitank rifles. This was a very dangerous defect, which required total control (ibid).

The device worked out by Sakharov jointly with the engineer A N Protopopov with support from the shop foreman F P Balashov replaced the hellish toil of the visual control of the cores, which did not necessarily ensure the desired results. *The device was accepted for use.... It worked until the end of 1945 or until mid-1946, then it broke down and they could not repair it. This is a typical story of the use of new technologies, with underlying management problems. In that case, I am consoled by the fact that the production of armor-piercing ammunition must have practically stopped in 1946* (Sakharov, ibid).

But in 1948, Sakharov was drawn into the production of entirely different 'ammunition.' Many facts have been declassified during the decades that passed since then, as regards both the design of nuclear charges and the history of their creation.

3.1 'Sloika'

After the American atomic bombing of Hiroshima and Nagasaki in Japan on August 6 and 9, 1945, extraordinary measures were taken in the USSR to spur the work on the Atomic Project.

On August 20, 1945, the State Defense Committee (SDC) issued a decree (SDC-9887, exceptionally controlled information) stipulating the formation of a "Special Subcommittee of SDC," chaired by L P Beria, to "supervise all work on the use of the atomic energy of uranium." Associated with the Special Subcommittee was the newly created First Chief Directorate responsible for managing all the work on the Atomic Project, under B L Vannikov.

On November 30, the SDC Special Subcommittee passed a motion on choosing the location (southern shore of lake Kyzyl-Tash, Chelyabinsk Oblast) for the Mayak facility (Plant 817) for the production of nuclear weapon components.

On April 9, 1946, a decree was passed on organizing Design Engineering Department 11 (DED-11, later known as Arzamas-16, the Facility, the Russian Federal Nuclear Center/National Research Institute for Experimental Physics (RFNC/NRIEP) in the town of Sarov, southern part of Gorkii Oblast, subordinated to Laboratory No. 2 of the USSR Academy of Sciences (LIPAN, later the Kurchatov Institute for Atomic Energy). P M Zernov was appointed the head of DED-11 and Yu B Khariton, the chief engineering officer.

The physical scheme of the first Soviet atomic bomb (RDS-1), with a power of 22 kt of TNT equivalent, tested on August 29, 1949, was a copy of the Fat Man bomb dropped by the USA on Nagasaki (although the construction of RDS-1 involved many elements that were different from Fat Man's). The key role there was played by the data provided in 1945 and later to Soviet intelligence by Klaus Fuchs and other participants in the Manhattan atomic project, who imperiled their lives for the sake of restoring nuclear balance between the former anti-Hitler allies.

Also in 1945, intelligence information was received in the USSR about research underway in the USA into weapons more powerful than the atomic bomb — thermonuclear, or hydrogen, weapons. These American investigations were focused on the scheme of the so-called classical Super. In 1946, Ya B Zeldovich jointly with his colleagues (S P Dyakov and A S Kompaneets) from the Institute for Chemical Physics of the USSR Academy of Sciences was given the task to work out a hydrogen bomb design corresponding to the intelligence information. This design was called The Tube (RDS-6t, which is 'Super' in the USA). In the USA, this design was realized to be a dead end within a few years, and was abandoned in 1950. In the USSR, Zeldovich's group also faced major problems in their attempts to implement The Tube design.

By a Decree of the Council of Ministers of the USSR of June 10, 1948, support teams were formed in a number of research institutions, including FIAN, to help improve The Tube project under the supervision of Khariton and Zeldovich. At FIAN, this was Tamm's Special Task group comprising S Z Belenkii, V L Ginzburg, Yu A Romanov, Sakharov, and E S Fradkin; by the decree, V A Fock, who worked in Leningrad, was also made part of that group.

From Sakharov's recollections,

For two months I diligently studied reports of Zeldovich's group, and was also expanding my very sparse knowledge in gasdynamics and astrophysics (this latter because the physics of stars and of thermonuclear explosions have much in common). Gasdynamics was the subject we all had studied along the lines of the appropriate volume of the famous multiple-volume course by Landau and Lifshitz. I was constantly deliberating on these subjects. Once, having read in Landau and Lifshitz about the so-called self-similar (automodel) solutions of gasdynamic equations (i.e., solutions of partial differential equations that reduce to solutions of ordinary differential equations), I went to a bathhouse (there was no bathing facility in our flat). Lining up for a ticket, I realized that (by virtue of the similarity argument) the hydrodynamic picture of an explosion in a cold ideal gas at the instantaneous point-like release of energy can be described by functions of one variable. True, it turned out later on that that solution had previously been found by Sedov (later, a full member of the Academy) and even before that, by Taylor. But, following the pattern, I soon invented several more self-similar solutions that were useful for a qualitative and
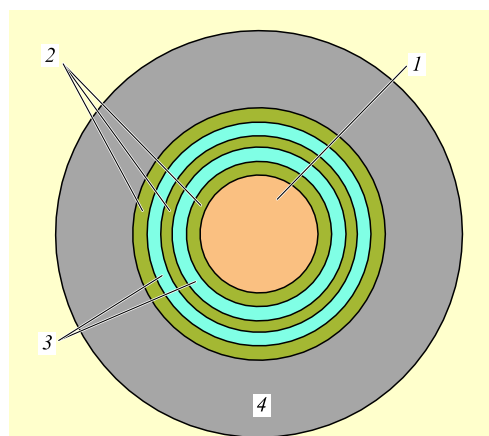

Figure 1. Diagram of a thermonuclear charge based on the Sloika principle: *1*—core of the atomic bomb (uranium-235 or plutonium), *2*—uranium-238, *3*—thermonuclear fuel (lithium deuteride), *4*—layer of explosives.

semiquantitative description of the processes that were of interest to me.

Two months later, my studies took a sharp turn: I proposed an alternative project of a thermonuclear charge, totally different from those considered by Zeldovich's group as regards the physical processes occurring at the explosion and even as regards the main source of energy release. I call this proposal the first idea in what follows.

Before long, my proposal was substantially augmented by Ginzburg, who put forward the second idea [1, Pt. I, Ch. 6].

In brief, the First Idea consisted of a proposal to place thermonuclear fuel (heavy water) and uranium-238 in alternating layers (hence the name, 'Sloika,' referring to layers). The Second Idea was to use not heavy water but the solid deuteride of lithium-6 as the thermonuclear fuel.[1] The design of the Sloika is outlined in Fig. 1, which is based on numerous declassified descriptions. Numerical parameters (size, etc.) of the elements shown in the figure remain classified, in accordance with the Treaty on the Non-Proliferation of Nuclear Weapons, and will remain undisclosed forever.

As can be seen, Sloika is a standard atomic bomb augmented with layers of deuteride of lithium-6 and uranium-238. Initiation of the explosives induces a convergent shock wave, which reaches the central core and initiates the atomic bomb explosion. As a result, the layers of lithium-6 deuteride must be compressed and heated to the threshold of the thermonuclear fusion reaction, i.e., the condition for the hydrogen bomb explosion. However, if thermonuclear fuel alone is placed between the explosive and the central atomic core, the thermonuclear fusion threshold cannot be attained.

Sakharov's idea to alternate layers of light elements and heavy uranium-238 was key to initiating the thermonuclear reaction due to the approximately ten-fold ionization compression of light layers by heavy ones. This compression is caused by the difference between the atomic numbers (and

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[1] In his first report in 1948, Sakharov considered a planar system of uranium-238 layers and heavy water, whereas the idea of a spherical construction with an atomic initiator at the center occurred in discussions with Khariton and Zeldovich during Sakharov's first visit to the Facility in the summer of 1949, when he was introduced to the construction of the RDS-1 atomic bomb and to its weight and dimensional characteristics, which were determined by the size of the bomb hatch of the launch aircraft. (Private communication of A K Chernyshev, as told by Khariton.)

hence, the number of electrons) of heavy and light elements and occurs in the case of full ionization of the atoms of these elements under the action of a shock wave; in thermodynamic equilibrium of the electron gas of heavy and light layers, the density of matter in them is inversely proportional to the atomic number. This effect of increasing the density of thermonuclear fuel in the explosion was termed Sakharization by Sakharov's colleagues.

Sakharization occurs when any heavy element is used in Sloika, e.g., lead. Sakharov chose uranium-238 because, under irradiation with high-energy secondary neutrons, its nuclei undergo fission, with a release of atomic energy, similarly to how this occurs in the case of nuclear fission of uranium-235 or plutonium in an atomic bomb.

The primary fusion reactions of deuterium in light layers are

$$D + D = p + T + 4 \text{ MeV}, \tag{3.1}$$

$$D + D = n + {}^3\text{He} + 3.3 \text{ MeV}. \tag{3.2}$$
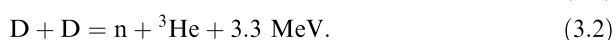
The nuclei of tritium (T) and helium (^{3}He) formed in these reactions, in turn, enter secondary thermonuclear reactions

$$T + D = n + {}^4\text{He} + 17.6 \text{ MeV}, \tag{3.3}$$

$${}^3\text{He} + D = p + {}^4\text{He} + 18.34 \text{ MeV}, \tag{3.4}$$
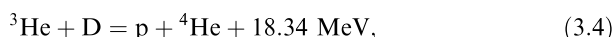
which occur with a much greater energy release. As noted above, the secondary neutrons of reactions (3.2) and (3.3) initiate fission of uranium-238, which is energetically advantageous.

It is of fundamental importance that the cross section of the secondary DT fusion reaction (3.3) is greater than the cross section of DD reactions (3.1) and (3.2) by a factor greater than 100. Industrial production of tritium is a very costly process, and, in addition, thermonuclear charges containing tritium do not allow long-term storage. It is therefore of utmost importance that tritium is produced on the spot in the course of the explosion, in accordance with reaction (3.1).

Here, a step forward was made due to Ginzburg's Second Idea, which was the proposal to replace heavy water or heavy liquid ethane (originally proposed by Sakharov) with solid deuteride of lithium-6 as the thermonuclear fuel. Then, due to the large flux of secondary neutrons and the large cross section of the reaction

$${}^6\text{Li} + n = {}^4\text{He} + T + 4.6 \text{ MeV}, \tag{3.5}$$

this reaction becomes an essential exothermic additional source of tritium. Subsequently, lithium-6 deuteride, being a source of such energetically beneficial tritium, has become the main thermonuclear fuel in all hydrogen bombs. Its industrial production was rapidly launched at Facility 817 (Mayak).

The physical principles underlying Sloika are discussed in more detail by Ritus [18–20].

Sloika is not a full-fledged hydrogen bomb: thermonuclear fusion makes up only 15 to 20% of its energy release, the remaining part being due to the fission reaction of heavy elements in the central core and in uranium-238 layers.

Sakharov used to say that "an idea not implemented is not yet an idea." It was a long way from the smart ideas and proposals outlined above and shown in Fig. 1 to the workable construction of RDS-6s. Making that trek took five years of hard dedicated work, including working out fundamentally

new computation methods. Diverse computations were performed at the Institute for Physical Problems (L D Landau, N N Meiman, I M Khalatnikov), the Department of Applied Mathematics, the Steklov Mathematical Institute (A N Tikhonov, A A Samarskii), and other research institutions, including the FIAN Special Task Group (Ginzburg, Belenkii, Fradkin), who stayed in Moscow after Tamm, Sakharov, and Romanov left for the Facility in the spring of 1950.

Here is an episode of this work relating to Sakharov, as told by Zeldovich, shortly before his death, to I M Dremin (private communication), and also described by A I Pavlovskii in his recollections [11, p. 495].

It was about a year before the test of Sloika, when Sakharov was already working at the Facility. Doubts arose regarding the validity of one of the constants that was essential for the computations. Because the schedule set up by the government was very tight, it was decided to determine the correct value of the constant within one month. The task was assigned to two theoretical teams (Zeldovich's and Sakharov's) and two experimental teams, that of Pavlovskii at the Facility and a Moscow group. Each team worked unaware that the same work was being done in parallel by three others. Zeldovich alone knew that all four teams were involved. His theoretical team checked numerical computations for a month, but still could not come to any definitive result. As the month passed, Zeldovich came to Sakharov and asked him about his result. Sakharov replied that he personally had done some estimates and got a handle on the desired number. Several days later, I V Kurchatov, Zeldovich, Sakharov, Pavlovskii, V A Davidenko, and Yu A Zysin gathered in Khariton's office. Ahead of time, Zeldovich wrote the numbers obtained by Sakharov and by the Moscow experimental team on a blackboard and covered them with his hands. He then asked Pavlovskii, who was entering the office, to write down the result of his group, and then removed his hands from the board. The difference between the numbers written on the blackboard was no more than 20%. It remains a mystery how Sakharov could guess the correct result. And this is not a unique case of this sort. *My brain is a computer that is 10 times more efficient than the brain of an ordinary person. Sakharov's brain is in a class of its own, it's just made differently*, as Zeldovich is quoted to have said.

Sloika (RDS-6s) was tested on August 12, 1953; its power was 400 kt of TNT, which was 18 times greater than the power of the first Soviet atomic bomb.

We now return to Moscow — to FIAN — in 1948.

Sakharov:

In the autumn, following Zeldovich's advice, I phoned Kurchatov asking him to facilitate my moving flats, from our 14-square-meter room, one of many along a corridor. Kurchatov promised to help. Soon we were indeed moving into a huge — by our standards — three-room flat in the outskirts of Moscow (with a view of a park, even if quite littered; still, a hare once strayed around: not only the kids, but I as well was quite happy about that). Zeldovich joked about my new flat that this was the first use of thermonuclear energy for peaceful purposes.

Rabinovich continues [11, pp. 551–552]: *The Theory Department at FIAN was increasingly involved in the atomic problem. I was not part of that work and remained an outside observer. But Andrei Sakharov was engulfed by it. He stopped mentioning anything about his work, but spoke a lot about mundane problems. Once he told me: 'This is how it goes. I am*

frequently invited to the Kremlin, to take part in meetings. They typically last till 4 AM, then all the participants go to their cars, but I have no car, and nobody knows that I have no car, I haven't told anyone. From the Kremlin, I have to travel all the way to Oktyabrskoe Pole, which is about 12 kilometers away, or maybe even 15.' Unless he could catch a taxi, he would walk all the way home.[2]

Another conversation that I remember. Andrei: 'You know, I got an offer to take a new, important position. Should I accept it?' I replied with handwaving theoretical constructs: 'You should keep doing science, do you think you need those high positions?' He then said, 'There are various people who are making the offer. And there are those who you cannot refuse, whatever they offer.' He mentioned no names, but I could roughly figure it out. 'I am now entering the very high echelons,' he added, 'and I have no idea what will become of my life.'

L V Parijskaya (a mathematician and software engineer, staff member at the Theory Department of FIAN in 1943–1974, who worked with Sakharov in the Special Task Group):

Sakharov was increasingly more frequently needed here and there. A gasping secretary would run in: 'Sakharov to the director!' or 'Sakharov to the phone! Quick, quick!'

A nondescript person would appear, reporting: 'The car for Sakharov.' He would stay in the doorway, shuffling his feet, but did not dare hurry up. Sakharov, as he always did, showed no haste in methodically pushing papers into his old bag, then politely said goodbye to us, and departed.

I had the feeling that some powerful whirlpool was engulfing Sakharov, and all of our Department along with him.... Superficially, he remained the same as he used to be. As before, wearing a bleached olive-drab costume, which he brought along from a munition factory. He still had that childish trusting smile, but he was smiling much less. And overall he looked preoccupied. Or, should I say, detached. He would stand at a window and freeze, in long silence. We did not bother him then. Then, he would blink emphatically, rub his face with the palm of his hand from the temple down, as if shaking off something. A gesture totally foreign to his self-composed, calm nature.... It sometimes seemed to me that he was tired to death and he must be forced to leave for some quiet place to have 10 to 15 hours of deep sleep.

But then he would come to himself, take heed of what was being said around him, take a piece of chalk with either his left or right hand, and start writing down formulas in his childish handwriting. Our bosses then listened to him with full attention, without interrupting him, as just a short while ago his comrade students were listening attentively.

Sakharov worked more and more frenetically. My frequent impression was that he was exhausted to death: either he kept working through the nights or did not sleep well. Once he showed up late. I immediately came up to him to discuss work. But his glance was so devastated that I only asked, 'What's with you?' He was silent for a while and then suddenly squeezed his head with his hands and whispered 'You must understand, it is terrifying. This is horrible, horrible. What am I doing?' and then he added in a very low voice, 'You know, I am having an internal meltdown. There is nothing I can do....'

So here was my reply: 'You go home right away to sleep. Get going.' He pondered the idea, agreed, and departed. The next

day he came up to me and said triumphantly, 'You know, I slept for 13 hours nonstop'... [21, 11].

Sakharov himself:

"I could not help realizing what kind of horrible, inhumane matters we were dealing with. But the war had just ended — another inhumane matter. I was not a soldier in that war, but felt I was a warrior in this next one, waged in science and technology. (Kurchatov sometimes said: 'We are warriors,' and this was not a shallow-souled phrase for him.) We gradually became aware of and hit upon notions such as strategic balance, mutual thermonuclear deterrence, and so on. I still think that these global ideas did indeed contain some (hopefully, even if not fully satisfactory) intellectual apology for the creation of thermonuclear weapons and our personal participation in it. But at the time, we likely perceived all this at the emotional level" [1, Pt. I, Ch. 6].

3.2 Third Idea

In October 1953, after the successful test of Sloika, Sakharov, then 32, was elected full member of the USSR Academy of Sciences, and at the same time V A Malyshev, then the minister in charge of the nuclear industry, asked him to write a memorandum describing his vision of the further steps in developing thermonuclear weapons. In the memorandum, drawn up right at the ministry, Sakharov carelessly, as he writes in his recollections, announced further improvements to the Sloika design and specified the parameters (weight and size) of future thermonuclear charges.

Sakharov:

In two weeks, I was invited to a meeting of the Presidium of the Central Committee of the Communist Party (which in 1952 was renamed the Politbureau of the Central Committee, and in 1966 the original name was restored). As a result of the meeting of the Presidium — of the part I attended and of the other part, where different people, rocket engineers, were invited — two resolutions were produced, which were soon passed by the Council of Ministers and the Central Committee of the Communist Party. One of them stipulated that in 1954–1955 our ministry had to design and test the device that I had announced so carelessly.

The other resolution stipulated that the people dealing with rockets work out an intercontinental ballistic missile to carry that charge. An essential point was that the weight of the charge, which determined the entire scale of the rocket, was taken as in my memorandum. This dictated all of the design and management work on a huge scale for years ahead. Just that rocket launched the first artificial satellite in 1957 and the spaceship with Yuri Gagarin aboard in 1961. The charge that was to be carried and for which all this was done had 'evaporated' long before that, however, and was superseded by something entirely different... [1, Pt. I, Ch. 13].

Upgrading Sloika (i.e., increasing its released power while staying within reasonable size) proved impossible, and in the spring of 1954 the theoreticians at the Facility, in defiance of the government decree, started off with the design of a thermonuclear charge of potentially unlimited power based on the Third Idea. "Formally, our actions — which we did not advertise — were a flagrant usurpation" — Sakharov, [1, Pt. I, Ch. 12].

By the Third Idea, Sakharov was referring to radiation implosion, which amounted to dropping the idea of hydrodynamic compression of thermonuclear fuel by an atomic bomb explosion, compressing it instead by the pressure of X-ray radiation induced by the explosion of an atomic-bomb

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[2] According to a Decree of the USSR Council of Ministers of June 5, 1948, motorized transport was allotted to atomic personnel at their request at any time. But Sakharov had told no one about this problem.

primer. Sakharov writes that that idea came about as a result of a collective brainstorm of theoreticians at the Facility. In the USA, Teller proposed it three years earlier (and whipped it into shape jointly with Ulam), but there was no intelligence information on this matter, and researchers in the USSR arrived at this idea independently.

At Robert Oppenheimer's congressional hearings in April–May 1954, Hans Bethe said: *There was a very brilliant discovery made by Dr. Teller. It was one of the discoveries for which you cannot plan, one of the discoveries like the discovery of the relativity theory, although I don't want to compare the two in importance. But something which is a stroke of genius, which does not occur in the normal development of ideas. But somebody has to suddenly have an inspiration. It was such an inspiration which Dr. Teller had which put the program on a sound basis* (see [22], where a reference to the original source is given).

The twists of the story that was developing in the USSR at the Facility are vividly described in a paper by Khariton, V B Adamskii, and Yu N Smirnov, "On the creation of the Soviet hydrogen thermonuclear bomb" in book [23]:

So, once Zeldovich, rushing into the office of young theoreticians G M Gandelman and V B Adamskii, located across the corridor from his own office, joyfully exclaimed: 'We should not do it that way, we will rather release radiation from a spherical charge!' No later than a couple of days, the computing office, headed by Tikhonov, which was working for Sakharov's team, was given the task of computing whether radiation is released from an atomic charge and how it depends on the materials used.

The crux of the matter, on which the feasibility hinged, was whether the internal surface of the shroud would absorb most of the energy released in the form of radiation, thus leaving too little energy for efficient compression of the charge. Using simple and elegant estimates, Sakharov showed that, although the losses to absorption by the shroud walls are not small, they do not make the compression of the main charge impossible. An equally big question was that of the specific mechanism of utilizing the radiation energy for efficient compression of the thermonuclear charge. Important proposals to solve this problem were made by Yu A Trutnev. All these ideas had to survive thorough and numerous collective discussions.

I also quote the testimony of Ritus, who took part in those events: *The third idea started shaping up in the design of the RDS-37 hydrogen bomb made of a Sloika and an atomic bomb compressing it with its radiation and placed under the same shroud* (see Document No. 120 in [24]).

The RDS-37 device was tested on November 22, 1955. The energy release was 1.7 Mt TNT (ibid, Documents No. 184 and No. 188). *Tritium was not used in RDS-37, it was generated in the reactions* $D + D \rightarrow p + T + 4$ MeV *and* $^{6}Li + n \rightarrow {}^{4}He + T + 4.6$ MeV *mainly due to the use of lithium-6 deuteride, proposed by Ginzburg. This thermonuclear fuel then found its use as the principal fuel in all hydrogen bombs, along with plutonium, which initiated its radiation compression and heating* [20].

The hydrogen bomb based on the Third Idea is said to be a two-stage construction, where the X-ray radiation of the first-stage explosion (the atomic bomb) compresses the second stage (the thermonuclear fuel), reducing its volume by a factor of 10 to 20, which then allows achieving 'star-like' conditions for igniting thermonuclear fusion. This could hardly have been imagined by P N Lebedev, who in 1899 was the first to measure the tiny pressure of light. But D A Frank-Kame-

netsky, an expert in stellar astrophysics and a participant in that brainstorm at the Facility, was already well aware of that.

As with Sloika, the path from a stroke of genius to a successful test was rough.

Sakharov recalls:

The decisions regarding the timeline of the tests only increased the rate of work on the third idea, which already was very aggressive. I have already written about the close collaboration with engineers. Here, a good deal happened to be my responsibility. Proactively, before computations were completed and final clarity was reached, I was writing down technical briefs, explaining the points that were especially important in my view to the engineers, providing 'permission' to reasonably relax the technological conditions whose original formulation was too stringent; all in all, I put quite a lot on my plate, taking it under my responsibility, relying not only on computations but also on intuition. I was a frequent visitor in the engineering sector, and established close and straightforward working relations with engineers, fully appreciating their hard and painstaking work that required a special type of knowledge and skills.

But, of course, all the theoreticians, including myself, were most deeply involved in calculations. While still at an early stage of the work, I was able to find some approximate descriptions of the essential processes unfolding in the framework of the 'third idea' (mathematically, these were self-similar solutions of partial differential equations; they were given a closed mathematical form by Kolya Dmitriev; I can still remember quite vividly that at first Zeldovich did not appreciate that I was right, and only became a believer after Kolya's work; that was a rare occasion for Zeldovich: he is a very edgy person).

For calculations associated with the devices based on the 'third idea,' it did not suffice to analyze individual processes under simplifying assumptions; rather, new methods of complex numerical computations, suitable for computers, were needed. Such methods were worked out by the mathematicians at the Facility and by special mathematical teams in Moscow. An especially prominent role was played by the team headed by the corresponding member of the Academy, I M Gelfand [3] [1, Pt. I, Ch. 13].

3.3 Tsar Bomb

A feature of the Third Idea was that it allowed constructing theoretically arbitrarily powerful thermonuclear charges. It would only take sufficiently many Sloikas or simply slabs of lithium-6 deuteride to be placed under a common shroud with an atomic bomb.

In 1961, Sakharov and his colleagues (Adamskii, Yu N Babaev, Smirnov, and Trutnev) constructed a hydrogen bomb with the power of 100 Mt TNT. This power was subsequently halved because 100 Mt could 'smash out the windows at home,' as Nikita Khrushchev, speaking at the 22nd CPSU Congress, referred to the test due in a few days. The largest ever hydrogen bomb, AN-602, with the power of 50 Mt TNT was exploded on October 30, 1961 at Novaya Zemlya. The bomb is known as the Tsar Bomb, Kuzkina Mat, or Ivan. The shock wave passed around Earth three times.

The power of 50 Mt TNT does not mean much to the layperson. It can be usefully compared with some 'visible'

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[3] I M Gelfand (1913–2009), one of the most prominent mathematicians of the 20th century.

Figure 2. Museum in Sarov: Sloika (1953), RDS-2 (1951), RDS-1 (1949).

parameters of a thermonuclear explosion that was 360 times less powerful, the 140 kt exploded in the Chagan project, the first Soviet industrial thermonuclear explosion, which occurred on January 15, 1965 in Kazakhstan: outwardly, the device was a case 86 cm in diameter and 3 meters in depth; it was planted in the floodplain of the Chagan River, in a borehole 178 m beneath the surface; the explosion resulted in ejecting 10.3 mln tonnes of the ground to a height of 950 m, producing a crater 430 m in diameter and 100 m in depth.

I conclude the 'weaponry' part of Sakharov's scientific work with some of his observations that explain why he became a prominent public figure.

In the second half of the 1960s, the range of problems to the discussions of which I was related to one degree or another extended even greater. In those years, I acquainted myself with some economic and technological studies related to the production of active substances, nuclear ammunition, and their delivery vehicles; I had several occasions to visit classified institutions ('postboxes') and one or two information exchange meetings on military strategic matters. Of necessity, I had to learn more and see much. Fortunately, despite my security clearings, an even greater scope of information escaped me.

But what I did see was more than enough to keenly feel the horror and the reality of a large-scale thermonuclear war, madness on a global scale, and the danger imminent to all of us on this planet. In the printed reports, at the meetings on operational performance analysis, including the strategic thermonuclear attack of a suspected opponent, on maps and charts the unthinkable was transpiring into the subject of detailed analysis and calculations, was becoming mundane; even as it still was imaginary, it was discussed as something possible [1, Pt. II, Ch. 1].

A few days after Sakharov's return from exile, in late December of 1986, journalists Yuri Rost and Oleg Moroz asked him, among other things, the standard question of whether he was filled with remorse as the creator of the most dreadful means of destruction and mass murder in history. Sakharov replied with a definitive 'no,' because the weapons that he had created, due to the balance of terror, served to stave off a third world war over the course of many decades. But then he made a very precise addition related to ethics and, arguably, self-scrutiny: *But if this ultimate calamity — thermonuclear war — does happen and I still have enough time to think about anything, then my evaluation of my personal role might tragically change"* (see Moroz's "Return from exile (the history of one interview)" [25, p. 320]).

One more of Sakharov's observations:

As of today, thermonuclear weapons have never been used against people, in war. My most passionate dream, which lies deeper in my soul than anything else, is that this never happens, that thermonuclear weapons deter war but never be used [1, Pt. I, Ch. 6].

4. Controlled thermonuclear fusion

4.1 Magnetic thermonuclear reactor (tokamak)
Sakharov's recollections:

My first years at the Facility (1950–1951) also relate to my joint work with Tamm on the problem of controlled thermonuclear reaction. Problems of this sort started appearing on my horizon, as I have mentioned, back in 1949, but without any reasonable ideas shaping up. In the summer of 1950, at the Facility, we received a letter forwarded from Beria's office. It was a proposal written by a young sailor serving with the Pacific Fleet, named Oleg Lavrentiev. In the introductory part, the author noted the importance of controlled thermonuclear reactions for the power industry of the future [1, Pt. I, Ch. 9].

Sakharov wrote up a positive assessment of Lavrentiev's proposal ("The author raised a problem of tremendous value"), adding that a strategy of achieving electrostatic thermal isolation of hot plasma proposed by Lavrentiev was not feasible. Sakharov later recalled that the idea of magnetic confinement of plasma occurred to him in the process of writing that assessment:

In early August of 1950, Tamm returned from Moscow, I believe he was granted a short-term vacation. He found my ideas quite interesting, and all the subsequent development of the idea of magnetic thermoisolation was our joint venture.... We compiled a report with proposals and, more importantly, told Kurchatov about our ideas.

Early in 1951, a team of experts arrived at the Facility to assess our proposals. The team included L A Artsimovich and M A Leontovich, who later supervised work on the magnetic thermonuclear reactor (MTR). Artsimovich was the head of the team. Tamm and I gave a series of talks in which, in addition to the problems mentioned above, we touched upon other issues, such as the first estimates of the efficiency of the system if 'all goes well'; we discussed systems with both pure deuterium and a mixture of deuterium and tritium (which is apparently more realistic), near-wall effects, and many other things.... The main attention of the discussions was focused on so-called plasma instabilities.... The theories of turbulent plasma diffusion in a magnetic field that were available at the time suggested very large values of the heat removal factor (albeit less than in the absence of a magnetic field). If those theories were valid and applicable to the MTR, then the MTR would be rendered practically unfeasible or, at least, extremely complex and cumbersome to implement and, in addition, economically useless. But we did not know about that in the summer of 1950. And when Artsimovich did tell us about those theories, both he and we had already developed some vision of promising prospects and would not retreat without a fight....

The whole point in the history of designing the MTR was that instabilities are indeed extremely dangerous and come in very many different types, which no one knew at the time....

Based on the report of the expert team, a decree of the Council of Ministers was passed, according to which work on the MTR problem was assigned to LIPAN. Artsimovich was

made executive director, and Leontovich the head of theoretical work... (ibid).

The MTR design proposed by Sakharov and Tamm with toroidal and poloidal magnetic fields was later called the tokamak (from the Russian for "toroidal chamber with magnetic coils"). Sakharov's paper "Theory of a magnetic thermonuclear reactor" [26] and the corresponding paper by Tamm, summarizing their classified reports of 1951 as well as LIPAN theoretical and experimental reports of 1951–1956, were declassified in the famous talk given by Kurchatov at the Atomic Energy Research Establishment in Harwell on April 25, 1956 [27]. They were published in the Proceedings of the First Geneva Conference on peaceful uses of atomic energy, 1958. Sakharov: "Kurchatov's talk (especially the part of it relating to the MTR) made an enormous impression on the audience, and then on the public across the world" [1, Pt. I, Ch. 9].

To give a brief account of subsequent developments, the T-10 tokamaks at the Institute for Atomic Energy and PLT at the Princeton Plasma Physics Laboratory were launched in 1957. But the temperature of deuterium–tritium plasma attained there, in the range from one to several keV, was still insufficient for efficient ignition of thermonuclear reactions. More tokamaks were launched in the 1980s: TFTR in the USA, JET in Europe, JT-60 in Japan, and two large tokamaks with superconducting coils: Torus-Supra in France and T-15 in the USSR.

The best performance was shown by the JET reactor (where a plasma temperature up to 30 keV was achieved) and the successor of the PLT, the experimental TFTR (Tokamak Fusion Test Reactor) of the Princeton Plasma Physics Laboratory, which in 1995 achieved a world record plasma temperature of 510 million K, which is 25 times higher than at the center of the Sun. These temperatures greatly exceeded those needed to ignite a thermonuclear reaction. But the working capacity of a thermonuclear reactor is determined by the value of the crucial parameter Q, the fusion energy gain factor — the ratio of the obtained energy of thermonuclear fusion to the energy spent on heating the plasma. Formally, self-sustained plasma combustion requires $Q \geqslant 1$. In reality, taking losses into account, plasma combustion can be maintained without external heating at $Q \geqslant 5$. And a commercially sensible reactor requires $Q \geqslant 20$. In 1997, the world record power of controlled thermonuclear fusion, 16 MW, was attained at JET, with $Q \approx 0.7$. Obtaining the required values of Q has so far been impossible, despite a number of innovative ideas. Among these, we note tokamaks with an altered (compared to Sakharov's) configuration of the confining magnetic field, such as stellarators and spherical tokamaks.

In 1985, Mikhail Gorbachev and Ronald Reagan agreed on the realization of a joint project of a large thermonuclear reactor, ITER (International Thermonuclear Experimental Reactor). In practical terms, the international program of ITER was adopted only in 2005, with the participation of 35 countries: Russia, the USA, China, Japan, India, South Korea, and all the EU countries. The construction, whose cost was initially estimated as 5 billion euros, was planned to be completed in 2016. The schedule was then modified several times, along with increases in the costs. The current estimate is 19 billion euros, with the first plasma to be obtained in 2025. This must be the world largest tokamak, larger than each of the approximately 100 reactors for controlled thermonuclear fusion constructed in various countries since 1950.

In many respects, ITER follows the model of a tokamak proposed by Sakharov in 1950–1951, but also incorporates essential differences. The target power of the reactor is 500 MW at the energy expenditure of about 50 MW, which means $Q \approx 10$. ITER is not regarded as a commercial reactor; it is being constructed to study the possibility of building economically acceptable tokamaks. Currently, the feasibility is being discussed of building a commercial successor to ITER in Europe, the DEMO reactor.

A number of experts are critical of the ITER project in view of its huge cost and rather shaky prospects of being successful, noting that the redirection of the contributions of participant countries to the ITER budget has made a number of other, less costly, projects impossible, despite their significance for studying the thermonuclear ignition of plasma (see, e.g., [28, 29]). Reports by the National Academy of Sciences, USA (2019, [30]) and of the American Physical Society (2020, [31]) emphasize that, although it is impossible for the USA to leave the ITER project, alternative avenues of investigation must be pursued, such as compact experimental installations for thermonuclear fusion (Fusion Pilot Plants) with superstrong magnetic fields. For example, the volume of the vacuum chamber in the Ignitor installation developed at MIT is 10 m^3 (850 m^3 in ITER), while the confining magnetic field strengths (of the order of 13 T) are equal in these reactors, but the expected power of the Ignitor (100 MW) is only one fifth the target power of ITER (see [32] on the Ignitor program).

4.2 Laser thermonuclear fusion

Inertial thermonuclear fusion, or ICF for inertial confinement fusion, is the name given to a broader range of developments, part of which is laser thermonuclear fusion (LTF). It rests on the idea that compression of deuterium-tritium microtargets to the threshold temperature of the thermonuclear reaction can be achieved not only with the help of a laser but also, for example, by electron or ion beams. But featuring most frequently in this context are lasers. The required compression occurs due to the recoil of the ejected vapors imparted to the spherical shell of the target heated by a laser beam. Each such target is in fact a microscopic hydrogen bomb.

Sakharov recalls:

In 1960–1961, I once again came up with a proposal pertaining to the controlled thermonuclear reaction. At that time, information came that Maiman had built the first ruby laser. I gave a talk at the Facility, where I justified the possibility of laser-assisted excitation of the thermonuclear reaction in small balls containing thermonuclear fuel and compressed via the hydrodynamic effect under instantaneous heating of their surfaces with a laser beam. In the talk, I estimated the required parameters of these devices. The estimates were subsequently refined in a number of numerical computations done on a computer by my colleagues (especially by N A Popov). As possible applications of this principle, I named the power industry and thermonuclear pulsed jet engines of spacecraft of the future. My talk became known not only to the staff at the Facility but also to experts in lasers from other institutions [1, Pt. I, Ch. 9].

Popov remarked:

Sakharov himself did not make much of this beautiful idea. For him, it was too trivial and too remote from any practical realization that he would waste his time writing anything about it. Later, the idea of inertia confinement of thermonuclear

plasma in LTF was proposed and realized in experimental installations independently from Sakharov, who in due time did not bother to record it, let alone publicize it (this was virtually impossible due to the information security procedures applicable at the time). This reminds us once more of the indisputable truth that science has a common logic of its development, independent of who personally implements that development [33].

LTF as a way to inertially confine thermonuclear plasma is arguably the most promising direction within the general approach of gasdynamic thermonuclear fusion (GDTF, see review [34]), an alternative to magnetic confinement of plasma. As noted already, in the early 1960s, Sakharov suggested igniting the thermonuclear reaction in isotopes of hydrogen with the help of symmetric irradiation by powerful lasers of a hollow sphere filled with deuterium-tritium gas.

At the same time, the idea of LTF was proposed at FIAN, where lasers with the maximum attainable energy were being constructed. At a meeting of the Presidium of the USSR Academy of Sciences in 1961, N G Basov advocated the concept of LTF. An important stage in the development of the physics of powerful lasers was represented by the joint work of researchers from NRIEP (Facility, the town of Sarov) and FIAN on lasers pumped by the radiation of a strong photodissociation wave produced in an inert gas by explosion of chemical agents. This work resulted in attaining the then record high energy value (more than 1 MJ) in a single-pulse laser. But the duration of this pulse was such that its power was certainly below the threshold needed for the ignition of thermonuclear fuel. At the same time, Department 13 was organized at NRIEP, which currently is the NRIEP Institute for Laser Physics Studies. The very first meeting devoted to the possibility of using lasers in NRIEP experiments was chaired by Khariton on March 13, 1963. But none of this was directly related to LTF, and full-fledged studies of the feasibility of LTF started at NRIEP only in 1972.

"The first published study on the use of a laser for igniting thermonuclear fuel was Basov and Krokhin's paper (*JETP* **46** 171 (1964); *Zh. Eksp. Teor. Fiz.* **46** 171 (1964)). Somewhat later, a paper by American scientists was published (Nuckolls J et al. *Nature* **239** 139 (1972)). The first successful experiments on spherical targets were performed at the Kalmar installation (FIAN) (Basov et al. *JETP Lett.* **26** 581 (1977); *Pis'ma Zh. Eksp. Teor. Fiz.* **26** 581 (1977)). These studies laid the foundation for creating laser installations for studying the physics of inertial thermonuclear fusion. At RFNC–NRIEP, work on the construction of single-pulse lasers and their use for studying various aspects of LTF were started in 1972 on the initiative of Khariton, S B Kormer, and G A Kirillov. To study the main questions related to the fulfillment of the LTF tasks, a complex of powerful laser installations was created at NRIEP: Iskra-4, Iskra-5, Luch, and Femto" [35].

Calculations justifying the LTF concept were provided in work done at FIAN, the Keldysh Institute for Applied Mathematics, RFNC–NRIEP, and RFNC–NRITP (Russian Federal Nuclear Center–National Research Institute for Technical Physics). FIAN is among the leaders in physics and technology of producing targets for LTF studies. For over 30 years, targets of different types have been used in experiments on plasma compression and heating at the Russian installations Delfin and Kalmar (FIAN), Feniks (Institute for General Physics, Russian Academy of Sciences), Mishen, and Angara-5 (TRINITI), Iskra-4, and Iskra-5

(NRIEP), and others, and also at research centers in Great Britain, Germany, Italy, the USA, India, and China.

In the USA, LTF studies were pioneered by researchers from the Livermore National Laboratory and at the installations Shiva on Nd-glass (1977) and Nova (1984), which were superseded in the early 2000s by the giant national project NIF (National Ignition Facility) with a laser pulse energy of about 1.8 MJ at a pulse duration of the order of several nanoseconds. In that case, the peak power of the pulse is about 500 TW, which is hopefully close to the thermonuclear fusion threshold. It is expected that, in the nearest future, this level of high power of laser radiation will be attained by the French installation LMJ (Laser Mégajoule). Each of these installations costs several billion dollars. We note that studies in the domain of LTF are actively underway with Nd-lasers on a smaller scale, with an energy of several ten kJ, such as Omega (University of Rochester, USA) and Gekko-12 (University of Osaka, Japan).

The increase in the degree of laser compression is a major problem to be addressed in improving LTF installations. At RFNC/NRIEP, in addition to the iodine laser Iskra-5, the Luch installation was constructed on Nd glass. Currently, an Nd-glass installation is being constructed whose power will exceed that of NIF [35].

Besides LTF, also actively being developed are GDTF areas, such as heavy-ion inertial thermonuclear fusion and magnetic compression MAGO/MTF (magnetic compression/magnetized target fusion). By its physical scheme, the MAGO system occupies an intermediate position between stationary systems with magnetic confinement (tokamaks, stellarators, etc.) and pulsed systems with inertial confinement.

4.3 Muon catalysis
In Sakharov's classified report of 1948, 'Passive mesons' [16] (named so for the lack of the term 'mu meson' at the time, with 'passive' referring to those not taking part in the nuclear reaction, unlike the 'active' pi mesons), the main idea of muon catalysis of nuclear fusion reactions was already pronounced: because the mu-meson mass is 200 times greater than the electron mass, the size of the ground-state orbit of a Dμ-mesoatom is 200 times less than the size of that orbit in the deuterium atom, and the possibility of two deuterium nuclei coming so close to each other increases the probability of their tunneling through the Coulomb barrier by many orders of magnitude, resulting in their fusion and release of thermonuclear energy.

In a subsequent nonclassified paper of 1957, "On the reactions induced by mu mesons in hydrogen" [36] (jointly with Zeldovich), the mu meson is already called so, and this paper gives the first ever reference to the "Passive mesons" report, which was obtained at the Facility from FIAN on Zeldovich's request. The report was declassified only after Sakharov's death and published in [5].

S S Gershtein and L I Ponomarev, in their paper "Forty years later: comments on a report by ADS" [5, pp. 49–57]), noted:

The publication of the legendary report by Sakharov, where he proposed the idea of the practical use of muon catalysis, and for the first time introduced the term itself, meson-catalyzed nuclear reactions, just for that reason is of considerable historic interest. This report was written in the spring of 1948, even before Sakharov started working on thermonuclear fusion issues. Moreover, in his recollections, Sakharov expresses the

conjecture that at a certain moment of time the report was one of the reasons he was included in the group of FIAN researchers headed by Tamm and invited to work on thermonuclear weapons. In accordance with the practice at the time, this report was classified....

The negatively charged mu meson entering a liquid or gaseous medium of deuterium forms mesomolecular ions $DD\mu$, where one of the main mu-catalysis reactions of nuclear synthesis occurs, accompanied by an energy release:

$$DD\mu \to {}^3He + n + \mu. \qquad (4.1)$$
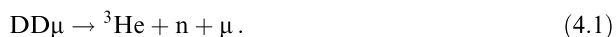
The released mu meson catalyzes the next fusion reaction, etc. For the total useful energy of nuclear fusion to be greater than the energy needed to produce one mu meson, the mu meson must have enough time to generate about 300 fusion reactions (4.1). As it turned out later, the main difficulty in realizing that scenario consists of the so-called sticking effect, when a mu meson is captured by helium-3 formed in reaction (3.1) and thus drops out of the process:

$$DD\mu \to {}^3He\mu + n. \qquad (4.2)$$

Sakharov:

In calculating the yield of the catalyzed reaction per μ-meson, the following factors must be taken into account: the μ-meson is an unstable particle; it decays in a very short time, two millionths of a second. The formation of a molecular ion and the subsequent nuclear reaction occur not instantaneously but in a finite time. "Catalyst poisoning" occurs, using a term from conventional chemistry; in this case, this is the formation of a meso-ion with a helium nucleus. Obviously, if we expect a noticeable yield of the nuclear reaction, the time of formation of the molecular ion and the time of the nuclear reaction must be much less than the μ-meson lifetime, and catalyst poisoning must occur rather infrequently.

All these factors have been carefully evaluated. Among those who were conducting these investigation in the USSR are S Gershtein and L Ponomarev and their colleagues. The main conclusions are as follows:

1. In pure deuterium, there are no grounds to expect a reaction yield that would allow recovering the energy spent on the production of μ-mesons.

2. In a mixture of deuterium and tritium, the situation is more encouraging ([1, Pt. I, Ch. 5], 1982).

In the subsequent years, mu-catalysis reactions were primarily investigated in D/T and triple H/D/T mixtures (see, e.g., [37, 38] and the references therein). The possibility of combined two-stage energy production was also considered with the use of mu-catalysis when the neutrons released in nuclear fusion reactions are used for breeding [39].

In a number of experiments, more than 100 fusion reactions per muon could be obtained (yielding 2 GeV of energy in total), but this does not compensate energy expenditure on the production of one muon (5 to 8 GeV). To become commercially viable, muon catalysis must yield an order of magnitude greater fusion reaction energy per muon. The main challenge that this development faces is a relatively high probability of a muon sticking to helium in a process of type (4.2) (in Sakharov's terminology, "Catalyst poisoning").

We thus observe a massive effort exerted worldwide in both classical magnetic confinement of plasma and gasdynamic compression, including LTF, and muon catalysis. It is to be hoped that controlled thermonuclear fusion will soon finally become a reality, and humankind will acquire an inexhaustible source of energy. "Sakharov mobilized us for the solution to the great atomic problem of the 20th century: the production of inexhaustible energy by burning ocean water" (one of Kurchatov's deputies writes this around New Year's Eve, late on December 31, 1950, in book [40]).

5. Magnetic cumulation and magnetic explosion generators

In 1951–1952, Sakharov proposed two designs of the MK-1 and MK-2 magnetic cumulation installations to obtain superstrong pulsed magnetic fields and currents with the use of the energy of an explosion. Initially, magnetic cumulation installations were built to solve the main problems dealt with at the Facility. In 1950, Tamm and Sakharov wrote to the authorities about the possible use of magnetic cumulation for defense purposes. After that, in accordance with a Decree of the Council of Ministers of the USSR, magnetic cumulation studies were made part of the defense procurement.

Pavlovskii recalls:

The idea of magnetic cumulation was conceived and the MK-1 and MK-2 generators were invented as part of the search for a resolution to the problem of pulsed controlled thermonuclear fusion and the task, which was relevant at the time, of transferring small masses (100 g) of active substance into the overcritical state (a low-power nuclear explosion) [5, p. 83].

Because the magnetic flux is conserved, fast deformation of the contour (reducing its area under the action of an explosive shock wave) results in an increase in the magnetic field and its full energy (ignoring the losses) in inverse proportion to the area of the contour.

MK-1 is a cylinder-shaped construction with a coaxial arrangement of a thick outer layer of explosives and, inside it, a cylinder with coils that create a magnetic field inside the cylinder. Detonation of the explosives compresses the cylinder, increasing the magnetic field. Sakharov: "Already in the first MK-1 test in May of 1952, a magnetic field of 1.5 million Gauss was obtained, which was a record high at the time" [1, Pt. I, Ch. 9].

MK-2 (also known as the "explosive magnetic generator," EMG) is a more sophisticated system, with explosives placed inside the cylinder along its axis, and the coils located outside, as is the produced magnetic field. The explosive is detonated from the butt end of the cylinder, which means that the explosion does not occur in a single instant; rather, its initiation propagates along the cylinder, as does the induced cone that short-circuits the coils carrying the current, leading to a pulsed increase in current and in the magnetic field that it produces.

Sakharov:

In 1964, the use of MK-2 to feed the primary coils allowed obtaining a field of 25 mln Gauss; the pressure produced by it is 25 mln kg per square centimeter.... The MK-2 system is a pulsed source of high current, with high power (in moderate-size installations, it is possible to transfer the energy of 1 kg of detonated explosives into magnetic field energy, with the current reaching 100 to 200 mln ampere). It can be used to solve many technological problems. In my paper (see [42]), I describe an electric cannon that can shoot an aluminum ring at the speed of 100 km/s (ibid).

All of that was classified. The first two publications on the subject were "Magnetic cumulation" (1965, co-authored) [41] and "Magnetic explosion generator" [42]. The first experimental team performing these experiments was headed by

E A Feoktistova, and later the work was supervised by Pavlovskii. Presently, RFNC–NRIEP investigations of magnetic cumulation are supervised by V D Selemir, and those on EMG, by S G Garanin.

From Sakharov's recollections:

I remember well my first visit to the experimental pad in May of 1952. Explosions were performed on a testing ground surrounded by fresh birch and aspen trees, which were just acquiring their first gentle foliage. Many trees had their bark damaged by the debris; something similar must have been observed in woods near the front line. I went down to the bunker that protected the personnel and the data recording equipment and met there Robert Lyudaev, Yura Pleshchev, and Zhenya Zharinov, who were sitting on their haunches next to a hot plate with a kettle placed on it. But they did not offer me any tea: the kettle was used to melt the explosives, which they then poured into the prepared casting mould. I was moved by such an attitude towards the substance, a small amount of which would suffice to tear one's hand off or indeed do something worse. But they knew what they were doing, and in fact that was a safe procedure. Robert readily acquainted me with an improvement that they (apparently, Lyudaev himself, but I am not sure) had made to the design of MK-1. Along the generatrix of the metallic cylinder, a skew cut was made. The cut allowed the magnetic field to be passed along the cylinder. Without it, the pulsed primary magnetic field created by the coils on the outer surface of the cylinder would take too long to penetrate into the bulk of the cylinder through its highly conducting walls. Under the explosion, the cut was closed seamlessly. This simple invention was quite instrumental to the success of the experiments" (ibid).

In his comments on papers [41, 42], Pavlovskii mentions the disruption of the cumulation process due to the growth of symmetry violations under compression, as a result of which, as noted by Sakharov, *it was practically possible to have variations in the radius by not more than a factor of 10*. This problem was overcome by creating cascade generators: *Every time the loss of stability threatens the inner surface of the shell that compresses the magnetic flux, it transfers the job of compression to the next shell. Implementing this principle in the design of a cascade allowed reliably obtaining fields of* $1.6 \cdot 10^7$ G (Pavlovskii [5, p. 85]).

Subsequently, the MK-1 installations allowed reaching a record high value of the magnetic field, about 28 MG. The magnetic fields obtained at NRIEP with the magnetic cumulation generators remain unsurpassed. For more details about this area, we refer the reader to a relatively recent review [43], where the main focus is on cascade generators of superstrong magnetic fields in the 10 MG and 20 MG ranges and options are described for their use in solid state physics (optical, magnetic, transport properties of matter), in superstrong magnetic fields, and the physics of extremal states of matter (isentropic compression by magnetic field pressure in the megabar range), etc.

In the same issue of *Physics–Uspekhi* in 2011, the development of the MK-2 explosive magnetic generator is reviewed [44]. Two types of EMGs are described: the spiral (SEMG) and disk (DEMG); the latter is a monopoly of NRIEP: "attempts to create DEMG that were repeatedly undertaken abroad have not been successful" [44]. At NRIEP, a peak current of 265 MA under load and a magnetic energy of 205 MJ under load were achieved at a DEMG with an explosive charge up to 1 m in diameter, with a characteristic current build-up time under load equal to 12 µs.

The SEMG design is closer to that of MK-2 proposed by Sakharov. Two types of EMGs are also used in combination, with an SEMG serving to initially load a DEMG. In constructing EMGs, the main problem is to reduce the energy accumulation time. At characteristic times of the order of several ten microseconds, the use of EMGs is impossible in experiments on heating plasma to the temperature of the thermonuclear fusion threshold. An important area of application of SEMGs is their use in MAGO (Magnetic Compression) installations for controlled thermonuclear fusion, with the reduction in the formation time of the current pulse in the SEMG being critically important. To decrease that time, innovative circuit breakers of different types were worked out in NRIEP. In a number of experiments, an energy accumulation time shorter than 1 µs was achieved. To reach the thermonuclear fusion threshold, a current pulse up to 100 MA is needed with a characteristic time of the order of 0.1 µs. Attempts to create EMGs with such parameters are underway both in Russia and elsewhere.

One of Sakharov's favorite ideas was to use an EMG as a one-off accelerator of elementary particles, possibly with the use of an underground nuclear explosion. Sakharov then admits that expendability is a major drawback of the idea because *the standard wisdom of experimentalists dictates multiple preliminary tests and somewhat varying the conditions of the experiment before anything reasonable can come out. The whole experimental design sometimes changes as the experiment is already underway. But I believed that one-off systems with record-high characteristics can also yield very valuable scientific information. I do not rule out the possibility that pulsed magnetic cumulation accelerators will be in demand one day* [1, Pt. I, Ch. 9].

But if we come down (or maybe rise up) to our erring earth, then magnetic cumulation is used quite widely.

Pavlovskii notes:

Magnetic cumulation of energy, irrespective of the implementation of grandiose projects of accelerating elementary particles, turned out to be useful in various areas of research. Currently, there is no other way to generate superstrong magnetic fields. The large volumes in which they are produced allow combining superstrong magnetic fields, high pressure, and extremely low temperatures. The 10-MG range of magnetic fields is desirable in investigations of magnetooptical effects, equations of state of isentropically compressed substances at megabar pressure, and properties of solid hydrogen compressed to high densities; it is used in direct measurements of the critical field of high-temperature ceramic superconductors and in a number of other studies [5, p. 86].

Laser guns and electromagnetic microwave guns are among other potential military applications of generators with explosive compression of the magnetic field. In that sphere, as in experiments on the pulsed ignition of thermonuclear fusion, the competitors of EMGs are reusable capacitor banks (CBs); just these are used on US aircraft carriers. However, the weight, size, and cost of powerful CBs are much greater than those of EMGs, and in mass production, single-use EMGs might even be advantageous compared with CBs.

6. Gravity and space–time as quantum effects

In the now classical two-page paper of 1967, "Vacuum quantum fluctuations in curved space and the theory of gravitation" [45], Sakharov showed that the Einstein–

Hilbert action of general relativity,

$$S(g_{\mu\nu}) = -\frac{c^4}{16\pi G_N} \int d^4x \sqrt{-g}\, R\,, \qquad (6.1)$$

does not necessarily have to be postulated but can be induced as a response of the quantum vacuum of matter fields to the curvature of space–time. In (6.1), $g_{\mu\nu}(x)$ is the metric of a 4-dimensional curved space–time with coordinates x^μ ($\mu = 0, 1, 2, 3$); $g = \det g_{\mu\nu}$; R is the scalar curvature; c is the speed of light; and G_N is Newton's gravitational constant. Specifically, in [45], the first terms were written of the covariant expansion of the vacuum one-loop diagram in derivatives of the metric tensor for a quantum scalar field propagating in the background of a space with the metric $g_{\mu\nu}$. The second term in this expansion has the form of the right-hand side of (6.1), which allows expressing Newton's constant through the ultraviolet (UV) cutoff parameter Λ:

$$\frac{1}{G_N} \sim \int_0^\Lambda k\, dk \sim \Lambda^2\,. \qquad (6.2)$$

In 1975, Sakharov published a much more extensive paper, "Spectral density of eigenvalues of the wave equation and polarization of the vacuum" [46], where he justified the heuristic argument of the 1967 paper with greater mathematical rigor. *It turns out that I have come to the conclusion that was advocated many years ago by Vladimir Fock and then by Julian Schwinger. But my derivation and the strategy of the construction and the methods were entirely different. Sadly, I could not send my work to Fock, who had just passed away* [1, Pt. II, Ch. 19].

Interestingly, by February 2021, according to the NASA/ADS (Astrophysics Data System) site https://ui.adsabs.harvard.edu, the 1967 paper [45], together with its English versions, has been cited 787 times, including very recent citations, whereas the 1975 study [46] had only 6 citations. Sakharov's quantum-induced gravity was also given due attention in the famous *Gravitation* by Misner, Thorne, and Wheeler [47]. These papers by Sakharov are discussed in sufficient detail in the 1995 collection of his works [5] by Adler, Kirzhnits, and Terazawa. But this was a quarter century ago.

This idea proposed by Sakharov has been developed in several directions, which, somewhat conventionally, can be divided into two big classes, called induced gravity and emergent gravity (see the 2012 review [48]).

In the first case, Sakharov's approach is adopted, in which the metric $g_{\mu\nu}(x)$ of a curved background space–time is regarded as a classical external field and is fixed *a priori*, whereas the general relativity equations for this metric are not postulated, as was done by Einstein, but are induced by diagrams of quantum fields propagating in space endowed with the given metric.

The term 'emergent gravity,' on the other hand, suggests the emergence of not only the dynamics but also of the notion of space–time itself, as a low-energy collective effect in the framework of an unknown fundamental microscopic theory, similarly to how the hydrodynamics or elastic properties of bodies emerge from the physical properties of atoms and molecules described within the appropriate theories.

We briefly discuss these two classes of ideas, mainly following the most recent work.

6.1 Induced gravity

For the development of this direction, we refer the reader, first, to [49, 50] and the 2002 review [51]. Therein, Sakharov's approach of cutting off the UV divergences by hand at some scale $\sim \Lambda$ is mainly adopted, with the induced cosmological term $\sim \Lambda^4$, the inverse Newton constant $\sim \Lambda^2$, and the terms quadratic in curvature $\sim \ln \Lambda^2$.

But not everyone is happy with introducing the UV cutoff by hand. One of the strategies to eliminate UV divergences is to calculate the sum of one-loop diagrams for a collection of quantum fields of matter (scalar, spinor, and vector) such that the infinities of the induced cosmological constant and Newton's constant cancel each other (see, e.g., [52] (2019), [53] (1998), and the references therein; we note that it is shown in [53, 54] that expressions for the entropy of a black hole have a universal nature and are independent of the specific model if the gravitational field action is assumed to be induced à la Sakharov; see also [55]).

Because quantum infinities are absent in the above models, it follows that the role of a dimensional parameter is played in the quantum effective action not by the cutoff Λ but by the maximal mass M of quantum fields in a given model; this mass then determines the magnitude of the induced cosmological constant ($\sim M^4$) and Newton's constant ($1/G_N \equiv M_{Pl}^2 \sim M^2$). However, it has to be seen whence quantum fields with a Planck mass $M \sim 10^{19}$ GeV would come. Introducing them into the theory by hand is as artificial as introducing the UV-cutoff energy Λ.

Next, the persisting problem is that of a nonphysical giant cosmological term (vacuum energy), which is inevitably induced along with the Einstein–Hilbert action. Obviously, in models with unbroken supersymmetry, the quantum energy of the vacuum is equal to zero, but the induced Planck mass vanishes there as well, and supersymmetry breaking at a mass scale M brings us back to the above questions.

The same questions arise in models of initially scale-invariant field theories, which are free of quartic and quadratic one-loop divergences and where the Einstein–Hilbert action is induced in spontaneous breaking of scaling symmetry (see the references to pioneering 1977–1984 papers by Minkowski, Smolin, Adler, Zee, and Spokoiny, e.g., at the beginning of [56]). Models of a Weyl-invariant theory of gravity must also be mentioned, where the dimensional Newton constant is induced as a result of spontaneous breaking of scale invariance (see [49, 50, 56, 57] and the references in recent paper [58]). We also note the induced Einstein action in quantum chromodynamics [59].

In all these models, the mass scale M of the theory arises just as in the theory of electroweak interactions and the Standard Model, i.e., due to the dynamical emergence of a vacuum expectation value for a scalar field ϕ (the Higgs field): $M = \langle \phi \rangle$. But, in the Standard Model, $\langle \phi \rangle = M_{SM} \approx 10^2$ GeV, whereas obtaining the correct value of Newton's constant requires $\langle \phi \rangle = M_{Pl} = 10^{19}$ GeV. It remains unknown whence comes the gigantic (17 orders of magnitude) ratio of the Planck mass $M_{Pl} = 1/\sqrt{G_N}$ to the characteristic mass of the observable world of elementary particles, the ratio called the mass hierarchy.

Currently, the most promising approach to possibly explaining the giant mass hierarchy observed in nature is offered by the 1999 Randall–Sundrum (RS) model [60] of 5-dimensional anti-de Sitter (AdS) space–time, in which the scale of a 4-dimensional cross section endowed with 'our' metric $g_{\mu\nu}(x^\alpha)$ ($\alpha, \mu, \nu = 0, 1, 2, 3$) depends exponentially on

an extra, 4th spatial coordinate y:

$$g_{AB}^{(5)} = \mathrm{d}y^2 + \exp\left(\frac{2y}{R_{\mathrm{AdS}}}\right) g_{\mu\nu} \, \mathrm{d}x^\mu \, \mathrm{d}x^\nu \,. \qquad (6.3)$$

Here, $A, B = 0, 1, 2, 3, 4$ and R_{AdS} is the radius of curvature of the AdS space.

In the RS model, this 5-dimensional space–time is bounded by two 4-dimensional surfaces, the infrared (IR) and ultraviolet (UV) branes located at two values of the y coordinate: $y = y_{\mathrm{IR}}$ and $y = y_{\mathrm{UV}}$. The fields of massive elementary particles are then confined to the IR brane (this possibility had been discussed much earlier in [61, 62]), whereas the zero-mass fields (the graviton and the photon) are uniformly distributed over the entire slice of the 5-space $y_{\mathrm{UV}} < y < y_{\mathrm{IR}}$. As a result, the above gigantic (10^{17}) ratio of energy scales of gravity and of the world of elementary particles occurs naturally at a moderate thickness of the slice in five dimensions:

$$y_{\mathrm{IR}} - y_{\mathrm{UV}} = R_{\mathrm{AdS}} \, \ln\left(10^{17}\right) = 39 R_{\mathrm{AdS}} \,.$$

The number 39, unlike 10^{17}, is something conceivable for a theorist, and the last 20 years have witnessed numerous attempts, unfortunately not entirely convincing, to derive this number from some first principles.

In view of the significance of the RS model and also of the fact that quantization of fields on an AdS background offers a natural way to cancel UV infinities (by subtracting the one-loop diagrams corresponding to two different asymptotic fields on the AdS horizon), an attempt was undertaken in [63] to combine the RS model with Sakharov's induced gravity approach. The induced vacuum energy and Newton's constant are then determined by the mass parameter of the theory, the AdS curvature R_{AdS}^{-1}.

In [64], in a model of 5-dimensional space (with an extra coordinate of infinite size) whose boundary is given by 'our' 4-dimensional space–time, it was shown that inducing the Einstein–Hilbert action on that boundary by quantum effects leads to a nontrivial modification of Newton's law at short and long distances (of the order of the size of the observed Universe).

Speaking of branes in the context of Sakharov's induced gravity, we cannot escape mentioning a nontrivial result obtained in a relatively recent paper [65], where one-loop quantum-induced gravitational action for the metric

$$g_{\mu\nu}(x) = \frac{\partial X^A}{\partial x^\mu} \frac{\partial X^B}{\partial x^\nu} G_{AB}(X) \qquad (6.4)$$

on a brane $X^A(x^\mu)$ was calculated in the general case of an arbitrary Riemannian bulk space with a metric $G_{AB}(X^C)$ ($A, B, C = 0, 1, 2, \ldots, D, \mu, \nu = 0, 1, 2, \ldots, d, d < D$).

The brane Nambu–Goto action

$$S_{\mathrm{NG}} = \frac{1}{\alpha} \int \sqrt{-\det\left[\frac{\partial X^A}{\partial x^\mu} \frac{\partial X^B}{\partial x^\nu} G_{AB}(X)\right]} \, \mathrm{d}^{d+1}x \qquad (6.5)$$

is rewritten in [65] with the help of (6.4) in the form of a Polyakov action

$$S_{\mathrm{P}} = \frac{1}{2\alpha} \int \left[g^{\mu\nu} \frac{\partial X^A}{\partial x^\mu} \frac{\partial X^B}{\partial x^\nu} G_{AB}(X) - (d-1)\right]$$
$$\times \sqrt{-g^{(d+1)}} \, \mathrm{d}^{d+1}x \,, \qquad (6.6)$$

which is the action of a sigma model with a nontrivial nonlinear coupling of quantum fields $X^A(x)$. Covariant expansion of action (6.6) through the second order in small deviations $\xi^A(x)$ of the brane coordinates from their background values $Y^A(x)$, satisfying the equations of motion ($X^A(x) = Y^A(x) + \xi^A(x)$), and the subsequent Gaussian functional integration over $\xi^A(x)$ give an effective action whose terms proportional to the UV-cutoff energy squared Λ^2 contain not only the familiar Einstein–Hilbert action $R^{(d+1)}[g_{\mu\nu}(x)]$ but also a term quadratic in the external curvature of the background brane $Y^A(x)$ and a term linear in the components of the Riemann tensor $R_{ABCD}(Y(x))$ of the bulk space, projected onto the brane $Y^A(x)$ and on the directions perpendicular to the brane. (In [65], a 4-dimensional brane, $d = 3$, was considered, but this is easy to generalize to an arbitrary d.)

As regards a note by Sakharov made in [45] on the physical similarity between induced gravity and Casimir forces (which is also the subject of Kirzhnitz's comment in [5, p. 190]), we note paper [66].

We also note a relatively recent work [67], where induced gravity 'à la Sakharov' was calculated for scalar and spinor quantum one-loop diagrams on the background of a Riemann–Cartan space with curvature and torsion. The UV infinities are then eliminated in the same way as in Sakharov's study [45] by introducing a cutoff energy Λ. The paper was a contribution to a commemoration volume for Jacob Bekenstein, whose work laid the foundation for studies of profound relations between gravity and thermodynamics.

6.2 Emergent gravity

In the introduction to [67], in reviews [48, 68–70], and in papers [71–79] and the references therein, a sufficiently comprehensive review of different approaches (in the frameworks of stochastic gravity [75], holographic duality [70], and analogue gravity [48, 78, 79]) to gravity and space–time as low-energy manifestations of some more fundamental theories is given, including references to Sakharov's 1967 paper (see also recent papers [80, 81] and references therein). All these interesting approaches are impossible to discuss here.

We also note earlier work in the framework of the so-called 'pregeometry,' where the metric of 'our' space–time is expressed by a formula like (6.4) in terms of scalar ([61, 82], with more details to be found in the comments in [5, p. 191–193]) or scalar and spinor ([83] and the most recent study [84]) fields X^A for a flat metric G_{AB} in (6.4)–(6.6).

Nonetheless the most systematic development of the idea of induced gravity is arguably realized in string theory ($d = 1$ in Eqns (6.4)–(6.6)), which is renormalizable and hence allows a meaningful one-loop approximation. Sakharov notes: "String theory is, on a new stage, a realization of my old idea of induced gravity! I cannot help being proud of that" ([85], p. 14, 15). In this case, the role of the metric of 'our' space–time (with 4 or more dimensions, with 10 dimensions in superstring theory, $D = 9$, the six extra dimensions being compactified) is played not by the brane metric $g_{\mu\nu}(x)$ but by the target-space metric $G_{AB}(X)$, which comprises all of the coupling constants of the two-dimensional quantum theory (6.6) of $D + 1$ quantum fields $X^A(x)$.

The quantum effective action of string theory [86] (see also [87] and references therein) contains the Einstein–Hilbert

term

$$\int R^{(D+1)}[G_{AB}] \sqrt{-G^{(D+1)}} \, \mathrm{d}^{D+1} X,$$

which is what allowed Sakharov to speak of the legacy of his induced gravity in string theory: Newton's constant G_N is determined in this case by a dimensional parameter of action (6.6), the string tension $1/\alpha$, with $\sqrt{\alpha}$ taken equal to the Planck length $\alpha = \sqrt{G_N} = 10^{-33}$ cm. Expansion of the effective action in powers of the target-space curvature is expansion in powers of α.

String theory deals with scales of the order of the Planck length, and the major problem in that theory is how to relate its predictions to the observable world of elementary particles, whose scale, as we have noted, differs by 17 orders of magnitude.

7. Sakharov oscillations

Sakharov wrote:

My first work on cosmology was done in 1963–1964, under the title 'Initial stage of the expansion of the Universe and the occurrence of an inhomogeneous distribution of matter' ([88] — B.A.). *Rigorous and comprehensive investigations of gravitational instability as applied to Friedmann cosmic models had been done by E M Lifshitz in 1946. As a specific outcome of his theory, Lifshitz intended to explain the formation of galaxies and their clusters.... The theory of gravitational instability shows how small initial inhomogeneities of density grow. However, finding these initial inhomogeneities required additional physical ideas or assumptions. This is one of the major problems in big cosmology. In my work published in 1965, I was just trying to address this problem"* [1, Pt. I, Ch. 18].

In that study, Sakharov for the first time proposed the hypothesis (which is now universally accepted) that initial inhomogeneities form due to quantum fluctuations that occur in the first instants of the existence of the Universe and which are unavoidable in view of the uncertainty relation. Sakharov based his argument on the model of a 'cold' Universe and considered quantum fluctuations of cold baryonic matter at densities of the order of 10^{98} baryons per cubic centimeter (which corresponds to the linear size of a baryon equal to the Planck length 10^{-33} cm). The Compton wavelength of a baryon is of the order of 10^{-13} cm, and it is hardly possible to imagine a baryon whose linear size is 20 orders of magnitude less; nor is this necessary. We here have a case where good mathematics is more sagacious than our imagination.

And mathematics proves so good in this case that the main conclusion of Sakharov's paper regarding an oscillatory dependence of the amplitude of the forming inhomogeneities on their wavelength remains valid even though he chose a wrong 'cold' model of the origin of the Universe. The fact is that the cosmic microwave background, which is compelling evidence in favor of the 'hot' model, was discovered in the same year of 1965, but after the appearance of [88]. Because of this error in choosing the model of the initial state of the Universe, Sakharov is somewhat skeptical when evaluating his paper [88] in his recollections. Today, though, there are no grounds for this skepticism. So what has happened over the last 55 years?

Sakharov discussed the evolution of small acoustic fluctuations of the density of baryonic matter in the background of an expanding Universe with the equation of state of baryonic matter varying with the unfolding expansion: from the radiation-dominated stage ($P = \rho/3$, where P is the pressure and ρ is the energy density) to the stage of heavy matter domination ($P = 0$). In the 'cold' model considered in [88], this change in the equation of state occurs in the first instants after the Big Bang; in the 'hot' model that is currently of interest and which has been confirmed by a wealth of observations, this change in the equation of state is associated with a universe 70,000 years of age, when the energy densities of the cosmic microwave background and of heavy matter equalized, i.e., when the energy of a microwave background photon (currently 2.7 K) was equal to the rest energy of a baryon (1 GeV = 10^{13} K) times the coefficient of baryon asymmetry of the Universe (approximately 10^{-9}; see Eqn (8.1) in Section 8).

It is quite remarkable that, despite Sakharov's error in selecting the model of the Universe, the main result in [88] turned out to be rather universal. A periodic dependence of the amplitude of inhomogeneities on their wavelength, with a varying maximum value, is also inherent in both the hot model and inflation theory. This means that this is not about oscillations in space-time, as for ordinary waves, but about baryonic acoustic oscillations (BAOs) in the Fourier-transformed space, in the space of momenta. This is nontrivial. *I treated the quantum case of instability using an exact self-similar solution for the wave function of a harmonic oscillator with variable parameters*; *major difficulties were associated with taking the effects of pressure into account, but I was able to overcome them* (as to how, I refer the interested reader to my paper; I remember the day when I found the solution, 22 April 1964) (Sakharov, ibid.).

In the model of a hot Universe, a periodic dependence of the density of inhomogeneities on the wavelength and its effect on the anisotropy of the background radiation temperature were predicted by Zeldovich and Syunyaev [89] and Peebles [90], both papers appearing in 1970. Grishchuk, the author of review paper [91] written on the occasion of the 90th anniversary of Sakharov's birth, rightly notes: "Zeldovich realized the importance of this discovery, and it was he who proposed calling this effect Sakharov oscillations." The universality of Sakharov's result is clarified in [91], where it is shown that the fluctuation amplitude oscillates as its wavelength varies, not only for the cold baryonic matter considered by Sakharov, but also in other cases, including quantum fluctuations of the gravitational field. It is also shown in [91] that a necessary condition for the occurrence of BAOs is that initial fluctuations are described not by traveling waves but by standing acoustic waves, which inevitably occur if the initial fluctuations have a quantum nature, as was assumed by Sakharov (a heuristic argument in [91] goes as follows: a quantum fluctuation is similar to quantum production of a particle–antiparticle pair from a vacuum with zero total momentum, which in quantum mechanics is described by a standing wave).

For the inflationary model of the Big Bang, the calculation of the evolution of primordial quantum fluctuations was first done in 1981 by Mukhanov and Chibisov [92] (see also review [93]). These authors, like the authors of [89, 90], implied the possibility of detecting BAOs in observing this fine structure of the temperature of cosmic microwave radiation coming from different celestial points. Background radiation arrives to us unchanged (other than being cooled by a factor of 1000 due to the expansion of the Universe) from the instant of recombination, when the temperature and age
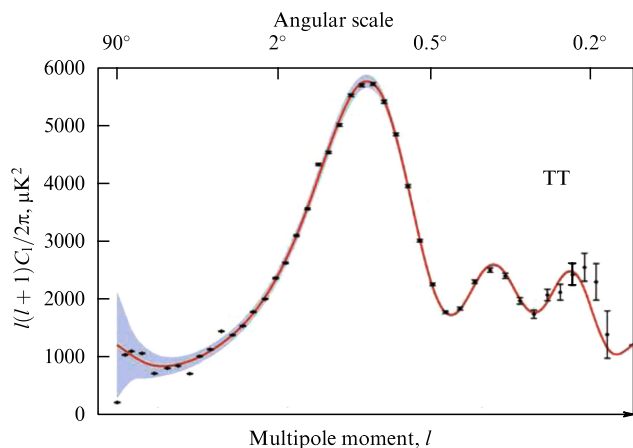
Figure 3. Sakharov oscillations [97].

of the Universe were 3000 K and 370,000 years. According to calculations, the main peak of acoustic oscillations must be located at the wavelength equal to the size of the 'acoustic horizon' at a instant of recombination; today, this size occupies about 0.7 degrees in the sky (Fig. 3). But when the theoretical predictions in [89, 90, 92] were made, the possibility of measuring the background radiation temperature at small angular scales, down to several millionths of a degree, was far beyond feasible.

The first peak of acoustic oscillations of the background radiation temperature was detected in 1996. Subsequent observations of the background radiation anisotropy (1997–2010) with the use of radio telescopes mounted on balloons and satellites revealed other peaks of acoustic oscillations. These experiments have in particular confirmed the flat model of the observed Universe, which is evidence in favor of the inflationary (exponentially expanding) stage in the first moments after the Big Bang. Inflation, in turn, inevitably requires a dynamical mechanism responsible for the baryon asymmetry of the Universe, as was described by Sakharov in another 1967 paper; we defer this discussion until Section 8.

Primordial quantum fluctuations and their peculiar evolution with the expansion of the Universe are not only imprinted on the fine spectrum of the background radiation but also have determined the large-scale structure of the Universe, i.e., the features of the observed distribution of galaxies, galactic clusters, and superclusters — which, as we have already noted, was the original problem posed by Sakharov in [88]. Here, too, there are abundant opportunities to compare theory with experiment (see, e.g., [94–96]).

If Sakharov had only seen the power spectrum of angular harmonics of the background radiation! (see Fig. 3 — B.A.) *Zeldovich could not see it either, but many of those who directly participated in developing the theory did live to see it. The observation of the very fact of acoustic oscillations was only the beginning. It turned out that they were much more helpful than anything else in measuring a number of parameters of our Universe, including its age and geometry. This is just as if a map of the early Universe were provided with a ruler with graduations in megaparsecs* [97].

As regards the 'cosmological ruler' and acoustic oscillations, see, e.g., [98, 99]. Review paper [100], devoted to background gravitons (assuming they can be observed one day) is essentially based on Sakharov's 1965 paper [88]. As regards modeling Sakharov oscillations in laboratory experiments, see [101].

It suffices to query a search engine for 'Sakharov oscillations' to see how relevant that 'erroneous' paper by Sakharov is today. Still, some caution has to be exercised in making conclusions, including about the value of that paper by Sakharov, because considerable uncertainty remains in interpreting astrophysical data on temperature fluctuations of the background radiation.

8. Baryon asymmetry of the Universe

Another of Sakharov's papers that has become classical, "Violation of *CP*-invariance, *C*-asymmetry, and baryon asymmetry of the Universe" ([102], 1967), was already based on the model of a hot Universe, which, as we have noted, received compelling evidence in 1965 with the discovery of the microwave background radiation uniformly filling the Universe. The density of background radiation photons is $n_\gamma = 410$ cm^{-3}, whereas the mean density of baryons making up most of the mass of observable stars and galaxies is $n_B = 2.4 \times 10^{-7}$ cm^{-3}. The numerical value of the ratio of these densities, called the baryon asymmetry of the Universe (BAU),

$$(\text{BAU}) = \frac{n_B}{n_\gamma} = 6.1 \times 10^{-10}, \qquad (8.1)$$

is one of the main mysteries in cosmology, along with the mysterious absence of antimatter (antigalaxies and antistars) in the Universe.

At the stages when the photon energy (the temperature T of the Universe) exceeded the baryon–antibaryon pair production energy ($T > 1$ GeV; the age of the Universe $t < 10^{-6}$ s), the densities of photons, baryons, and antibaryons must have been practically the same in thermodynamic equilibrium. Why then did the baryonic 'garbage' remain in the Universe in the amount of one part in 10^{-9} (one ten-millionth of a percent) in the course of cooling to below temperatures of 1 GeV, after annihilation of baryons and antibaryons?

The assumption that this small excess of baryons over antibaryons was fixed in nature as the initial condition in ultrarelativistic hot plasma seems unnatural. In inflationary models of the early Universe, moreover, an asymmetric initial state is impossible in principle, because exponential expansion smooths out all primordial inhomogeneities and results in a universal initial state with a nonvanishing positive energy density. Quantum production of hot matter in the decay of that state (reheating) is guaranteed to yield equal amounts of matter and antimatter. Therefore, a dynamical mechanism is needed for the formation of the baryon asymmetry from the primordial symmetric state of matter.

Such a mechanism of baryon asymmetry generation was proposed by Sakharov in [102]. It relies on three conditions: (1) baryon number nonconservation; (2) *C*- and *CP*-symmetry breaking; (3) the absence of thermal equilibrium at the stage of asymmetry generation.

The weak violation of charge (*C*) and combined (*CP*) parities in scattering and decay reactions of elementary particles had already been established experimentally by that time (1967). Violation of thermodynamic equilibrium in a rapidly expanding Universe is apparently unavoidable; we see in what follows, however, that this condition was the most difficult to realize. Revolutionary input was given by Sakharov's first condition, the assumption about the possibility of decay (with a lifetime of 10^{50} years) of the main building

block of the cosmos, the proton. It did not receive a warm welcome: "The author's hypothesis regarding violation of baryon charge conservation appeared too contrived at the time, and this determined the skeptical attitude toward the paper overall"[4] (Sakharov in his commentaries in [4]; see [5, p. 246]). The mechanism of BAU generation was also considered in 1970 by Kuzmin [103], but that paper, too, remained largely unnoticed.

The tide turned in the late 1970s with the appearance of the grand unification theory (GUT) of strong, weak, and electromagnetic interactions [104]. In the GUT, the baryon number is not conserved in reactions involving heavy quark–lepton bosons (with a mass of the order of 10^{15} GeV). Due to the huge mass of these bosons, the proton half-life is too long ($> 10^{30}$ years) to be in conflict with the reality of our existence. What happens in about 10^{30} years should rather be left beyond our deliberations; as noted by one wise person, "Over that period of time, our concepts will change, and we will be saved." However, baryon asymmetry is not a fantasy but an observable paradox that requires an explanation to be given here and now.

In [102], in the follow-up 1969 paper, "Antiquarks in the Universe" [105], and in the 1979 paper, "Baryon asymmetry of the Universe" [106], written after the advent of the GUT, Sakharov considered a mechanism of baryon asymmetry generation at Planck ($\sim 10^{19}$ GeV) and near-Planck GUT ($10^{15} - 10^{16}$ GeV) energy/temperature scales. Resorting to such high temperatures is dictated by Sakharov's third condition: the need for violation of thermodynamic equilibrium. This means that the characteristic time determining the Universe's expansion rate (the inverse Hubble constant H^{-1}) should not be much larger than the characteristic time τ of nuclear or other reactions proceeding with baryon symmetry violation. And because this applies to the ultra-relativistic radiation-dominated stage of the evolution of the Universe, with the scale factor $a(t) \sim t^{1/2}$, $H^{-1} = 2t$, it follows that the characteristic time of reactions of strongly interacting particles is [105]

$$\tau \sim \frac{1}{T} \sim t^{1/2} \qquad (8.2)$$

(where $T \sim 1/a$ is the temperature of the Universe, and t is the age of the Universe).

At conventional low temperatures, the characteristic time of nuclear reactions is equal to the time that it takes light to cross a baryon: $\tau_0 = 10^{-23}$ s. According to astrophysical observations extrapolated backward in time, the Universe had the temperature $T_0 = 1$ GeV (the rest energy of a baryon) at the instant $t = t_0 = H_0^{-1}/2 = 10^{-6}$ s. It follows that $\tau_0 \ll H_0^{-1}$, i.e., thermal equilibrium of nuclear reactions is safely ensured at that instant, and the generation of baryon asymmetry is impossible. With the above values of τ_0 and H_0^{-1} and the dependence $\tau(t) \sim t^{1/2}$ in (8.2) and $H(t)^{-1} \sim t$, we find that the equality $\tau(t) = H^{-1}(t)$ ensuring violation of thermodynamic equilibrium is attained at $t = 10^{-40}$ s, when the temperature of the Universe is $T = 10^{17}$ GeV. That is why Sakharov considered such an early Universe with such high temperatures, assuming that the small baryon asymmetry occurring at that stage is 'hardened' [105] and, after annihilation of the major part of the baryon and antibaryon mass at $T = 1$ GeV, manifests itself in the residual baryon matter that we observe in the Universe.

[4] See, e.g., Zeldovich and Novikov's book *Relativistic cosmology*.

However, the problem lies in the fact that the above superhigh temperatures are not attained in modern models of the early Universe (including the inflationary model, supported by a wealth of independent astrophysical data). On the other hand, if we wish to generate baryon asymmetry at lower temperatures at later instants in the evolution of the Universe, i.e., at much longer times H^{-1}, then we should rather have a theory in which baryon-charge-violating reactions occur much more slowly than nuclear reactions.

In a 1988 review talk [107], Sakharov also discussed other mechanisms of baryon asymmetry generation, different from the high-energy GUT: quantum tunneling between different degenerate vacua of the theory of gauge fields [108], super-symmetric versions of the GUT [109], and electroweak interaction [110]. Recently, the third of these directions, generation of baryon asymmetry in electroweak interactions, has undergone the most rapid development (see also [111] and reviews [112–114]).

Generally speaking, already the familiar Standard Model involves processes with baryon number violation, which occur via the formation of so-called sphalerons (spatially localized states of the Higgs and W-boson fields). In high-temperature quark-gluon plasma, these processes occur constantly, but turn out to be in thermal equilibrium, because their rate is much higher than that of expansion of the Universe H. This means that Sakharov's third condition is not satisfied: no matter how many extra baryons are produced, that very number disappear in reverse processes.

The situation changes when the Universe is cooled to the temperature of spontaneous breaking of the electroweak symmetry $SU(2)_L \times U(1)_Y$, of the order of $T = 100$ GeV [115, 116]. This temperature of the Universe is attained at times $H^{-1} = 10^{-10}$ s (see (8.2)), which correspond to the energy scale of the order of 10^{-4} eV. The question is, what reactions with baryon symmetry breaking have such a negligible energy scale in a plasma with a temperature of 100 GeV? It turns out that, with characteristic times of the order of 10^{-10} s, a first-order phase transition occurs: the formation of bubbles of the new broken electroweak phase. Baryon asymmetry is generated on moving walls of these bubbles, and expansion of the Universe 'locks' this result by suppressing the reverse process. But this entails a number of problems, including those that require going beyond the Standard Model.

The conviction that the Standard Model is only some low-energy approximation to an exact theory is currently practically universal. Modifications of the Standard Model are also required by nonzero neutrino masses detected experimentally (neutrino oscillations), by the need for an artificial fine tuning of Higgs scalar masses, by the mystery of dark matter, and so on, just as, going beyond the Standard Model is required by the need to explain the baryon asymmetry of the Universe.

An important, and possibly decisive, advance was brought about by the idea to relate violation of the baryon symmetry of the Universe (baryogenesis) to violation of its lepton symmetry (leptogenesis) (see [117] and reviews [118, 119]). In processes described by the electroweak theory, the difference between the baryon and lepton charges $B - L$ is conserved. Therefore, if (going beyond the Standard Model) it is possible to generate the lepton asymmetry of the Universe (LAU), then baryon asymmetry would inevitably be generated in a hot quark–gluon plasma in thermal equilibrium, in electroweak processes involving sphalerons. In these theories,

based on the introduction of a massive singlet neutrino and the see-saw mechanism to explain the observed masses of light neutrinos, it is possible to have all three of Sakharov's conditions satisfied; the only problem that would then remain is to ensure the right number in (8.1).

A beautiful development of the idea of leptogenesis being the cause of baryogenesis is the νMSM (neutrino minimal Standard Model) theory, where the sole generalization of the Standard Model amounts to the introduction of three additional heavy sterile (singlet) neutrinos, one for each of the active neutrinos ν_e, ν_μ, ν_τ. Lepton asymmetry occurs in this theory due to mutual transformations (oscillations) of the new heavy neutrinos [120, 121] (see reviews [122, 123]). In turn, as we have already mentioned, BAU occurs from LAU in electroweak processes involving sphalerons.

As regards the generation of lepton asymmetry, the key question regarding the satisfaction of Sakharov's third condition — violation of thermal equilibrium due to expansion of the Universe — can be solved by choosing extremely small Yukawa couplings between new neutrinos and the old active ones. As a result, the characteristic time of reactions with lepton symmetry breaking increases to values comparable to H^{-1} (where H is the Hubble constant).

The small values of the coupling constants for the new heavy neutrinos, which are necessary for obtaining LAU (and then BAU) can solve another great problem in cosmology: the dark matter mystery. It is known that active neutrinos interact weakly with matter. But if the Yukawa coupling constants of the new neutrinos are taken to be sufficiently small, then these new neutrinos become promising candidates for the role of dark matter of the Universe. In addition, these heavy neutrinos, if their masses are chosen appropriately, can explain neutrino oscillations. It is remarkable in this approach that it can, in principle, be checked in experiments that are feasible at the Large Hadron Collider. Without a doubt, various and diverse astrophysical data on baryon asymmetry, dark matter, properties of the background radiation, neutrinos in the Universe, etc. impose stringent constraints on the choice of parameters of leptogenesis, νMSM, and other theories.

The number of papers on the origin of the baryon asymmetry of the Universe is huge. Among the most recent ones, we name papers on leptogenesis [124], 'gravitational leptogenesis,' avoiding the satisfaction of Sakharov's third condition [125], baryogenesis in the process of inflation [126], the idea, traced back to Hawking and Zeldovich, of accretion of antibaryons by primordial black holes as the cause of BAU [127], and the references in these papers.

We also mention reviews [128, 129]: *In the course of 50 years after the appearance of Sakharov's paper, the subject of baryogenesis was demonstrating remarkable connections with all attempts to extend the Standard Model, including Grand Unification, dynamical electroweak symmetry breaking, low-energy supersymmetry, and neutrino masses* (from the conclusion in [129]).

9. Pulsating ('multisheeted') Universe

The study of 'multisheeted' (oscillating, pulsating) models of the Universe is the subject of Sakharov's 1970, 1980, and 1982 papers [130–132]; he also returned to this subject in [106, 107]. Two model types are considered, each evading the 'what was before' question (before the Big Bang, before the inflation epoch, etc.). One type involves an infinite repetition of past

cycles of cosmological expansion and contraction, and the second, the initial singular point of 'tame arrow reversal' [131]. The hypothesis of *CPT*-symmetry of the Universe is among the cornerstones of Sakharov's views of the structure of the Universe in general. The singular point of time arrow reversal is *T*-symmetric and is a minimum-entropy point from which time flows (entropy increases) forward in either direction, and the question of what was before that is meaningless. Accordingly, the Universe oscillates in both directions in time.

In the framework of the oscillating Universe models, the observed huge value of entropy of the Universe was attained by accumulating it from cycle to cycle; it is thus assumed that our cycle was preceded by a number of others with smaller maximal sizes of the Universe. Also discussed in these studies is the remote future of the Universe, when all protons have decayed, and expansion is superseded by contraction at the maximal size of the Universe due to a small negative cosmological constant, which is introduced by hand.

Admittedly, unlike Sakharov's oscillations and the baryon asymmetry of the Universe, this set of Sakharov's cosmological papers did not win broad recognition. A possible reason was apparently that they did not solve two principal difficulties of oscillating models, which were well known to Sakharov himself. The first one: "A drawback of the model is the high degree of inhomogeneities occurring in a contracting space" (Sakharov, commentaries on [130] in [4], see [5, p. 276]). The second difficulty: the absence of a clear-cut theoretical description of the bounce — a smooth transition from the contraction of the Universe to its expansion at its minimal size.

Nevertheless, the pattern of an oscillating ('multisheeted,' in Sakharov's wording) Universe, with repeated cycles of cosmological expansion and contraction, underwent an interesting development in recent decades, mainly in the 21st century. The motivation came from problems with the inflation theory, such as the existence of the initial cosmological singularity and the impossibility of answering the question "what was before, prior to the inflation." Nontrivial strategies are being proposed to overcome the two difficulties of oscillating models named above.

A universal problem of all the models of an oscillating Universe is the increase in Belinsky–Khalatnikov–Lifshitz (BKL) inhomogenities at the contraction stage. For example, according to BKL, the anisotropy energy density increases with a decrease in the scale of the Universe $a(t)$ as $\sim a^{-6}$. Suppressing this anisotropy and maintaining the isotropy and homogeneity of the Universe under contraction are not easy problems for models of the oscillating Universe. One of the solutions is to introduce a scalar (ekpyrotic) field with nonconventional dynamics, leveling off the Universe in the course of its contraction [133–136].

As regards a smooth (nonsingular) bounce at the minimal size of the Universe $a = a_{\min}$, its realization requires introducing nonconventional forms of matter violating the energy condition $P + \rho > 0$ (for a bounce to be realized in closed Universe models, a weaker condition $P < -\rho/3$ is required). A number of models have been proposed whose dynamics ensure the bounce condition based on both the introduction of a special scalar field (Galileon) and modifications of the general relativity equations at a high curvature of space-time (see [137–142]).

Among the proposed models, there are those with the vacuum-like equation of state $P = -\rho$ at high densities, when

contraction (so-called antiinflation) followed by a bounce followed by expansion (inflation) occur in the model of a closed Universe in the range of its minimal sizes in accordance with the hyperbolic cosine law. The notion of a vacuum-like state of matter at the final stage of collapse was first introduced by Gliner [143]. According to the pioneering work by Kirzhnits [115], restoration of a 'spontaneously' broken symmetry (in particular, gauge symmetry of electroweak interactions) must occur in superdense matter at a sufficiently high temperature. But the transition of a closed system under contraction into a low-entropy state of a 'false vacuum' contradicts the second law of thermodynamics. In an attempt to overcome this difficulty, we have considered some toy theories of matter (with a nonlinear dependence of the Lagrangian on the kinetic energy, i.e., on gradients of the fields, in the spirit of the Born–Infeld electrodynamics), in which the vacuum-like state occurring at high fields has not only energy but also entropy [144].

The general problem with all models of an oscillating Universe, still defying a final solution, is the instabilities (ghost, gradient, etc.) [145]. In a number of recent papers [146–149], it has been possible to obtain stable solutions with a bounce in the framework of a rather fastidious 'extended Horndeski theory' of a scalar field, with the general relativity equations modified as well. Obviously, a standard question then persists: what happens to these solutions if the equations are taken to include the energy–momentum tensor of ordinary matter whose energy increases under contraction up to the threat of the development of a singularity? A smooth bounce can be guaranteed only by a theory in which the dynamics of ordinary matter at high densities become nonconventional and violate the energy condition. That such modifications of standard theories are necessary was noted in [133], and an attempt to modify electrodynamics equations, as we have already mentioned, was undertaken in [144], where two types of theory were considered: with asymptotic freedom and with asymptotic confinement in large fields. But the problem of ghost and gradient instabilities persists in these models.

Despite the difficulties, enthusiasm of the proponents of oscillating models is not waning—among other reasons, because these models arguably allow obtaining the nontrivial properties of the observable Universe that are so successfully explained by inflation theory [150].

10. Quantum cosmology. The anthropic principle

In Sakharov's 1984 paper, "Cosmological transitions with changes in the signature of the metric" [151], the Universe is regarded as a quantum object allowing quantum tunneling between states with different topologies and different numbers of spatial coordinates and time directions (signatures). This is quite close to the idea of the Mega-Universe (Multiverse in modern terms) and, consequently, to the anthropic principle.

Sakharov:

In the 1950–1970s, several authors independently proposed the hypothesis that, along with the observable Universe, there exist infinitely many 'other' universes, many of which have essentially different characteristics and properties compared with 'our' Universe; our Universe and universes similar to it are characterized by parameter values that allow the emergence of structures (atoms, molecules, stars, planetary systems, and so on), facilitating the development of life and intelligence. This hypothesis eliminates many questions, such as why the world is made just that way and not some other way — eliminates them with the help of the assumption that there are worlds constructed differently, but they are observationally inaccessible, at least at present. Some authors consider the anthropological principle unproductive and even not part of the scientific method. I cannot agree with that" [151].

The term 'anthropic principle' was first proposed in 1973 by the English physicist Brandon Carter [152]. But the idea itself had been voiced several times previously. Regarding the anthropic principle, we refer the reader to [153, 154] or to popular paper [155], whose authors, among other things, note: "Reliance on the anthropic principle in conjunction with repudiation of searches for a specific explanation is in a sense in contradiction to the spirit of science." But, as Sakharov insists in [151], the idea of a Mega-Universe endows the anthropic principle with scientific flavor. This idea has become an inalienable part of modern physics due to the theory of chaotic inflation [156], and also due to the so-called string theory landscape [157, 158]. The landscape is made up of a huge number of potentially equivalent ground states of these theories, each of which can correspond to its own set of values of the fundamental constants (the number of noncompactified dimensions, the value of the Λ-term, the fine structure constant, the mass of the electron, proton, neutron, etc.).

In accordance with the Mega-Universe concept we, homo sapiens, appeared where conditions were suitable for our appearance. Sakharov embraced the following approach: "In the spirit of the anthropological principle, we assume that the observable Universe is selected by the entirety of values of the parameters conducive to the development of life and intelligence" [151].

A remark on the subject of the "anthropic principle and the three dimensions of space" is in order. It has been known since Ehrenfest (1917, [159]) that Keplerian orbits, just like the orbits of electrons in atoms, are stable only in a 3-dimensional space. There are other specifically dynamical factors (scale invariance of Maxwell's action, validity of the Huygens principle) that select the number $n = 3$ of spatial dimensions. Could it be that theoreticians will show one day that the $(3 + 1)$-dimensional space–time is also dynamically preferred in the inflationary scenario of the expansion of the Universe, and that inflation is impossible (unstable) for $n > 3$? It is desirable to at least explain the three dimensions of our world dynamically, without resorting to the anthropic principle.

In [151], Sakharov discussed the possibility of the transition to Euclidean space at a final stage of collapse, and also the possibility of the creation of the Universe 'from nothing' in quantum tunneling from four Euclidean dimensions (signature zero) to our Universe with signature one. These ideas, expressed by Sakharov in 1984, gained popularity later (see, e.g., review paper [160]).

The indeterminacy and weak predictive power of higher-dimensional superstring theories and the M-theory manifest themselves not only in zillions of possibilities of choosing the ground state but also in an essential arbitrariness in choosing the action of the theory. In [151], Sakharov put forward an interesting idea regarding the choice of the gravitational action in a higher-dimensional theory in a scale-invariant form. The standard Einstein–Hilbert Lagrangian in four dimensions, just like the entire series in the curvature of 'our' space–time, is to be reconstructed at the next stage,

that of compactification of the extra dimensions. In string theory and in supersymmetric theories with 'flat potentials,' in scale-free models of the Kaluza–Klein type, the spectrum of fields of the 4-dimensional effective theory includes massless scalar modes (the dilaton, the compactification scale), which enter multiplicatively into the expression for Newton's constant, the fine structure constant, etc. This leads to the known difficulty of the 'fifth force' (violation of the equivalence principle) and 'floating,' cosmologically varying constants, which is robustly ruled out by observations. The hopes here are pinned to the low-energy quantum radiation correction, as a result of which the original flat potential might acquire a minimum that fixes the vacuum expectation value of scalar zero modes [161, Chs 13 and 14]. Sakharov's idea on the initial conformally invariant theory of gravity in higher dimensions offers an entirely different solution to the 'floating' constant problem. In such a theory, the dependence of the compactification radius on macroscopic coordinates in four dimensions can always be gauged away by a scaling transformation. As a result, gravity in the 4-dimensional space is described by the standard Einstein theory, whereas dimensionless gauge field coupling constants remain numbers independent of the compactification scale. In [162], as an illustration of this series of Sakharov's ideas, the results of a calculation of gauge and Newton's constants are given for a compactification model in a theory with the original conformally invariant, supersymmetrizable, so-called 'geometric' action given by a 'chain' product of Weyl tensors (see review [163]).

11. In lieu of a conclusion

In the epilogue of the book of his recollections, Sakharov writes:

The miracle of science. Although I am not optimistic about the chances that a comprehensive theory will be constructed soon (or constructed at all), I see gigantic, fantastic achievements in the course of just my life, and I expect that this stream will not wane but, on the contrary, will gain strength in both width and depth [85, p. 160].

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