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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

Commemoration of the 90th anniversary of the birth of Andrei Dmitrievich Sakharov

(Scientific session of the Physical Sciences Division, Russian Academy of Sciences, 25 May 2011)

DOI: 10.3367/UFNe.0182.201202f.0181

On 25 May 2011, the scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), devoted to the 90th anniversary of Andrei Dmitrievich Sakharov's birthday, was held at the conference hall of the Lebedev Physical Institute, RAS.

The agenda of the session announced on the website www.gpad.ac.ru of the PSD RAS contains the following reports:

(1) **Mesyats G A** (Lebedev Physical Institute, RAS, Moscow) "Introduction. Greetings";

(2) **Ritus V I** (Lebedev Physical Institute, RAS, Moscow) "A D Sakharov: personality and fate";

(3) **Altshuler B L** (Lebedev Physical Institute, RAS, Moscow) "Scientific and public legacy of A D Sakharov today";

(4) **Ilkaev R I** (Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics', Sarov, Nizhny Novgorod region) "The path of a genius: Sakharov at KB-11";

(5) **Novikov I D** (Astrocosmic Center, Lebedev Physical Institute, RAS, Moscow) "Wormholes and the multielement Universe";

(6) **Azizov E A** (National Research Centre 'Kurchatov Institute', Moscow) "Tokamaks: 60 years later";

(7) **Kardashev N S** (Astrocosmic Center, Lebedev Physical Institute, RAS, Moscow) "Cosmic interferometers";

(8) **Lukash V I** (Lebedev Physical Institute, RAS, Moscow) "From the cosmological model to the Hubble flux formation";

(9) **Grishchuk L P** (Shternberg State Astronomical Institute, Lomonosov Moscow State University, Moscow; School of Physics and Astronomy, Cardiff University, Cardiff, United Kingdom) "Cosmological Sakharov oscillations and quantum mechanics of the early Universe".

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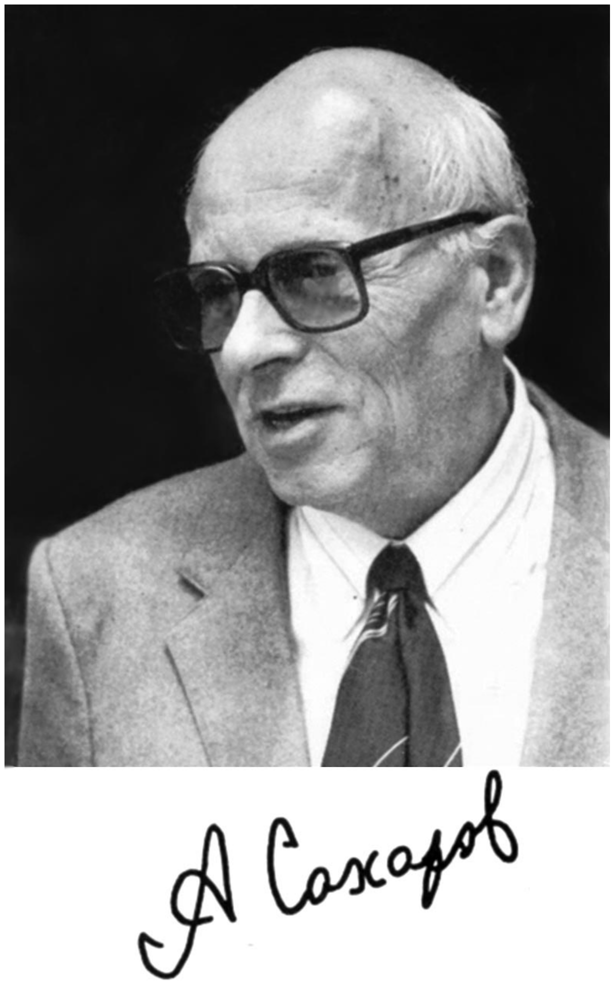

Andrei Dmitrievich Sakharov (21.05.1921—14.12.1989)

Articles based on reports 2–4, 6, 8, and 9 are published below. The content of report 5 is close to papers "Multicomponent Universe and astrophysics of wormholes" by I D Novikov, N S Kardashev, A A Shatskii [*Phys. Usp.* **50** 965 (2007)] and "Dynamic model of a wormhole and the Multiuniverse model" by A A Shatskii, I D Novikov, N S Kardashev [*Phys. Usp.* **51** 457 (2008)]. The content of report 7 is close to the paper "Radioastron — a radio telescope much larger than the Earth: scientific program" by N S Kardashev [*Phys. Usp.* **52** 1127 (2009)].

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

A D Sakharov: personality and fate

V I Ritus

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Contents

Abstract. **A D Sakharov was an amazingly gifted person for whom, with his combined talents as a physicist and inventor, "physical laws and the relation among phenomena were directly visualized and tangible in all their inherent simplicity" (I E Tamm). The author of the key ideas involved in the hydrogen weapons and fusion reactor programs, and well aware of his scientific and public status, Sakharov was, nevertheless, a modest and highly decent man, always trustful of people in discussing their or his problems. Although his greatest satisfaction lay in successfully solving fundamental problems in physics and cosmology, fate and duty made him turn to matters of universal human significance, particularly human rights, to the gruelling struggle to which he devoted many years of his life.**

Andrei Dmitrievich said in one of his interviews in 1988: "...my fate proved to be larger than my personality. I only tried to be at the level of own fate" [1].

This statement is equally modest and exact.

1. "We do not choose our fate"

In the fall of 1961, having received a communication about the successful test of the highest-power 50-megaton hydrogen bomb on Novaya Zemlya island, A D Sakharov came to Moscow to see his ill father. Already in Moscow, he learned about the successful test of another bomb, a 'gadget' that he had worked hard on and called the 'initiative gadget'. One of the parameters of this gadget was record breaking.

When visiting his father at a hospital, he did not know then that only five weeks remained for Dmitrii Ivanovich to live. Sakharov remembered this meeting, which was important in his life, and the words that Dmitrii Ivanovich said to him:

"When you were studying at the university, you once said that you could take great enjoyment in discovering the secrets of nature. We do not choose our fate. However, I am sad that your destiny proved to be different. It seems to me that you could be happier."

"I do not remember," Sakharov wrote, "what I replied to him. It seems that I somehow agreed with his thought that we do not choose our fate. What else could I say to him on that November day in 1961?... Turns of my fate, which could be gratifying or terrifying to him, were still ahead. However, I could not tell him about the successful test, and this would not be a reply to his question. Nor could I tell him that I was puzzled with the task of tests. Papa knew about my peaceful thermonuclear studies and he was proud of them. However, this was not enough for him not to feel the psychological discomfort. Perhaps the only thing that I could tell him was that I was going to seriously get into physics and cosmology. But this also seemed very vague to me at that time" [2].

Note the phrase about the psychological discomfort: the father felt it for both of them.

I would like to relate in my report about the turns of fate which played, in my opinion, a considerable role in the life of Andrei Dmitrievich (AD for brevity). In my opinion, there were six or even seven twists. But first we return to 1945, the joyful year the war ended.

In 1945, Sakharov became a postgraduate of Igor Evgen'evich Tamm and defended his thesis for Candidate of Physicomathematical Sciences in 1947. These were the years of the very rapid development of quantum electrodynamics caused by two fundamental experimental discoveries.

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First, Lamb and Retherford (1947) confirmed by radiospectroscopy methods with a high accuracy the splitting of the $n = 2,\ j = 1/2$ energy level of a hydrogen atom into two sublevels, $2S_{1/2}$ and $2P_{1/2}$. This splitting, only barely noticeable by optical methods away back in 1934, contradicted the relativistic Dirac theory for a hydrogen atom, according to which these levels should coincide.

Second, Kusch and Foley (1947–1948) discovered, also by the radiospectroscopy method, the comparatively small addition, on the order of 10^{-3}, to the electron magnetic moment equal to the Bohr magneton, according to the Dirac theory.

AD hit on an idea that the splitting of the degenerate energy level of the hydrogen atom appears due to the interaction of electrons with quantum fluctuations of the electromagnetic field in a vacuum, more exactly due to the difference between this interaction for an electron bound in the atom and a free electron. Although high-frequency fluctuations of the field introduce an infinite contribution to each of these interactions, this contribution is identical for the bound and free electrons and disappears in the calculation of the difference effect determined by fluctuations of the field at subatomic frequencies.

Unfortunately, Igor Evgen'evich did not support Sakharov's idea, referring to Dancoff's work, which proved to be erroneous. At this time, Bethe (1947) reported the nonrelativistic calculation of the difference between levels $2S_{1/2}$ and $2P_{1/2}$. Twenty years later, he was awarded a Nobel Prize in Physics for his work.

"Thus, I missed an opportunity to do the most important work of that time (and the most important, with a huge gap, in my life)", AD writes [2]. We know now that he believed that the best his work was that on the baryon asymmetry of the Universe. It seems that the huge gap he was talking about is the time gap between the latter paper and the work he thought about and dreamed to have done in the past.

The theoretical explanation of the 'anomalous' addition to the magnetic moment of the electron was given by Schwinger in the same year that it was discovered experimentally. It reduced to taking into consideration of the same interaction of the electron with fluctuations of the electromagnetic field in a vacuum. AD was delighted with Schwinger's work and reported it at Tamm's seminar, "feeling like a messenger of the Gods." Seventeen years later, Schwinger was also awarded a Nobel Prize in Physics for this work.

2. Hydrogen bomb development at KB-11

One should not think that the first turn of Sakharov's fate occurred when he, together with Belen'kii, Ginzburg, and Romanov, entered Tamm's group for verifying the calculations of Zel'dovich's group for the development of a hydrogen bomb.

And this turn did not occur even when Andrei Dmitrievich and Vitaly Lazarevich proposed their 'First' and 'Second' ideas which provided the basis for creating our first hydrogen bomb, RDS-6s.

The first turn of his fate took place in early 1949 when B L Vannikov, Chief of the First Main Directorate of USSR Council of Ministers — the powerful organization supervising the Soviet Atomic project — invited I E Tamm and A D Sakharov to his office. He informed them that Sakharov must be transferred to work under Khariton, which was necessary for the successful development of the project.

Igor Evgen'evich began to tell him that Sakharov is a very talented theoretical physicist who can make many significant contributions to the most important fields of modern science. Vannikov listened very attentively, smiling slightly, until a telephone rang. His face became strained.

"Yes, they are here... . Talking, doubting."

A pause.

"Obey, I will pass this them."

He hung up the receiver and said:

"Lavrenty Pavlovich called. He seriously asks you to accept our proposal."

Once outside, Igor Evgen'evich said:

"It seems that the matter has taken a serious turn."

Nobody wanted to plunge completely into the bosom of secret physics.

In March 1950, Sakharov, Romanov, and somewhat later Tamm came to work permanently at KB-11 (Design Bureau No. 11 of the USSR AS Laboratory No. 2). I joined this group in May 1951 after graduating from the Department of Physics at Moscow State University and a sudden 'detachment' from postgraduate studies. This was an abrupt turn of my destiny as well.

The development of the RDS-6s was well on its way. Less than a year into my participation in the work, the time was right to prepare the main mathematical task for detailed calculations of physical processes and the energy release in the *sloika* (named after a Russian layer cake) requiring the numerical solution of a system of equations in partial derivatives.

Andrei Dmitrievich wrote the plan of the task in my work notebook and asked me to check it and add the required details, which I did for a few days. After AD read the task and made some remarks, I rewrote it with my fountain pen with greenish – blue ink on a large sheet of graph paper which was specially given to me [3].

Now it is known from documents that this task was written on 5 April 1952, was titled "Formulation of the problem on the action of the MZ," and was signed by Sakharov and me (MZ is the acronym of a Russian multilayer charge) [4]. It was first sent to Landau's group, for which this task was the first one sent from Tamm's group, and then was forwarded to Tikhonov's group.

After a few days, Tamm received a top-secret note from Landau containing the following:

"Dear Igor Evgen'evich,

The very instructive note you sent, unfortunately, does not contain the values of velocities of particles of all groups. I ask you promptly to send them to us.

Your L Landau 11/IV 52."

This was obviously my fault. The velocities of neutrons of three groups in the task were simply denoted as v_1, v_2, and v_3.

Both groups fulfilled the task by the end of December 1952 and obtained considerable energy releases of 250 and 220 kilotons, respectively.

The energy release of the *sloika* tested on 12 August 1953 proved to be noticeably higher, 400 kilotons, because the actual cross section of the DT reaction was larger than that assumed in calculations and due to the use of tritium not only in the first layer, as in calculations, but also in the second light layer. This was the spectacular success of Tamm's group. IE and AD became Heroes of Socialist Labor and received very large Stalin Prizes, cottages, and cars.

I do not know why it was me whom AD asked to take part in the formulation of this important task. Possibly he wanted to arouse my interest in a higher level of calculations of the 'gadget' and simultaneously introduce me to the elite of Soviet theoretical physics: Landau, Lifshitz, Khalatnikov, and Meiman, to whom I came in two months to write down the data on the Li^6 burning out.

Later on, E M Lifshitz was a reviewer of my doctoral dissertation, and during the difficult years for AD, when we met at the editorial office of *JETP*, he used to take me away to the garden of the institute and question me in detail about him. G N Flerov also sympathized with AD, but I met him rarely.

Due to my participation, AD was spared the preliminary appraisal of his personality and his offspring, the MZ, by Landau's group. I remember how closely they questioned me about him, trying to assign a 'star number' to him according to Landau's classification. It proved to be that they never saw him and did not read documents written by his hand.

There was another reason to take me on as a co-author, which I understood when visited Tikhonov's group after Landau's group. Sakharov had been in contact with this group already for a few years. And I knew almost all the members of the group. Tikhonov read lectures for our course, Samarskii gave me exams, and Rozhdestvenskii was my classmate. I did not know only V Ya Gol'din, but he met me with such a smile as if we had parted only yesterday, and said: "Vladimir Ivanovich, you wrote the task so clearly, write it always for us." It seems that the tasks written by Sakharov were intended for 'supermen'. I knew that to understand AD was not simple.

3. Main turn of Andrei Sakharov's fate

Rumors about the huge energy release in American thermonuclear tests 'Mike' and 'Bravo' started our scientists thinking about the atomic implosion of the *sloika*. Collective discussions and probably some elements of ideas from the top-secret materials from Fuchs of 1948 [5] led to the 'Third' idea — the implosion of the 'sloika' by radiation from a usual atomic bomb. This idea was realized, together with the two previous ideas, in the RDS-37 hydrogen bomb.

The test of this bomb at the Semipalatinsk proving ground on 22 November 1955 terminated in a banquet where Marshal Nedelin proposed that AD give the first toast. AD said (citation from book [2]):

"'I propose that we drink that our gadgets exploded successfully today over the test site will never be exploded over cities.'

Breathless silence came over the table as if I had said something indecent. All conversations died off. Nedelin sneered, stood up with a glass in his hand, and said:

'Let me tell you a proverb. An old man, in a shirt only, is standing in front of an icon with a lamp and praying: "Direct and strengthen, direct and strengthen." And his old woman is lying by the heater and says from there: "Pray only for strength; I can direct myself." Let us drink to strengthening.

...All men in the room were silent for a few seconds, and then began to talk unnaturally loudly. ... Many years have elapsed, but I am still feeling this crack of the whip."

Yes, this was a stab at Sakharov's pride and his hidden pacifism. And it initiated a new, maybe the main, turn of his fate. He understood, of course, that the use of the awful weapon would entirely depend on the party and the military administration. "But it is one thing to understand and quite another to feel it with all of own's being as the reality of life and death." The conviction that "this is good physics" and that "this work is necessary" gradually gave way to the second plan, conceding to the moral, panhuman position of the preservation of peace.

The success of the test in 1955 earned AD a second medal of the Hero of Socialist Labor. At the same time, AD more and more perceived the danger of nuclear tests: while in 1953 the express mass transplantation of the civilian population from the proving ground was required, in 1955 a girl and a soldier perished and many people away from the proving ground were seriously injured. In 1958, AD published two articles about the radiation danger of nuclear tests with a brief conclusion that each megaton detonation leads in the future to ten thousand victims of oncological diseases.

In the same year, Sakharov attempted in vain to achieve a continuation of the moratorium on atomic detonations imposed in the USSR, and persuaded Kurchatov, but the latter failed to persuade Khrushchev.

During the next moratorium, Sakharov probably decided to increase his authority in the eyes of the administration by the development of an unprecedented high-power gadget. As a result, the moratorium was interrupted in 1961 by the test of this superhigh-power 50-megaton hydrogen bomb, which had a political character rather than a military one. AD was awarded the third star of the Hero of Socialist Labor. This contradictory activity on the development of weapons and a weapon test ban, involving sharp conflicts with colleagues and administration, especially in 1962, was a peculiar zigzag in his fate, but it also had a positive result in 1963: the Partial Treaty Banning Nuclear Weapon Test in the Atmosphere, in Outer Space, and Under Water, signed in Moscow.

It seems that zigzags and contradictions are unavoidable and, therefore, they are forgivable for a man understanding his real scientific and technical contribution to the Soviet Atomic project, which was no less than the contributions of other three-star Heroes: Zel'dovich, Kurchatov, Khariton, and Shchelkin. And they are especially forgivable for a man going much farther already along the path of panhuman significance.

4. Beginning of open public activism

In 1964, AD successfully spoke at the Academy of Sciences against the election of biologist N I Nuzhdin to the Academy, considering him and Lysenko responsible for "the shameful, bad pages in the development of Soviet science." In 1966, he signed a letter of 25 famous people against the rehabilitation of Stalin and got acquainted with R Medvedev and his book about Stalin, which noticeably influenced the evolution of his views. In 1967, AD sent a letter to Brezhnev in defense of four dissidents. In response, the administration relieved him of one of his positions at the secret 'object'.

In June 1968, a long article, "Reflections on progress, peaceful coexistence, and intellectual freedom" by AD was published in foreign papers. He wrote about the dangers of thermonuclear destruction, ecological self-poisoning, the dehumanization of humankind, the necessity of the convergence of the socialist and capitalist systems, the crimes of Stalin, and the absence of democracy in the USSR. This time, AD was completely dropped from work at the 'object'.

On 26 August 1968, AD met A I Solzhenitsyn. This encounter revealed their different views concerning the necessary public transformations.

5. Wife's death and his return to FIAN

On 8 March 1969, Sakharov's wife died, leaving him in despair and grief, followed by long desolation. This was a cruel blow by destiny for AD, who was, in fact, a big child taken care of all his life by his grandmother, mother, and then Klavdiya Alekseevna. In fact, he had no real friends.

E L Feinberg came to AD's home and proposed on behalf of Tamm and theorists from the Theory Department that he return to FIAN. AD agreed at once and wrote an application to D B Skobel'tsyn, the director of FIAN. Igor Evgen'evich, who was gravely ill, also asked M V Keldysh, the President of the Academy of Sciences, to help. After three months, the approval was received and AD became again a Senior Researcher at FIAN.

Between 1967 and 1980, AD published more than 15 scientific papers: on the baryon asymmetry of the Universe, predicting proton decay (in the opinion of AD, it was his best purely theoretical work; this work influenced the formation of scientific opinion in the following decade), on the cosmological models of the Universe, on the relation between gravity and quantum fluctuations of a vacuum, etc.

During these years, his public activity also increased. In early 1970, together with V Turchin and R Medvedev, he wrote the Memorandum on Democratization and Intellectual Freedom. After a few months, he initiated an appeal to release Grigorenko and Zh Medvedev from the hospitals for mental diseases. The letter in defense of Medvedev was also signed by theorists of the Theory Department — Renata Kallosh, Yury Gol'fand, and me. And we were greatly surprised when Medvedev was released after 19 days. This victory inspired AD.

In October 1970, AD went to Kaluga on the trail of *samizdat* activists Pimenov and Vail', where he got acquainted with a human rights activist, Yelena Bonner. In November, he, along with Chalidze and Tverdokhlebov, founded the Committee on Human Rights.

At this time, AD invited me suddenly to his home. The door to the flat was ajar. Seeing my surprise, he said that he had nothing to hide. He told me about a letter in defense of participants of the 'airplane case'. I did not sign this letter. Feeling very awkward with AD, I gave him then three reasons: one must not endanger the lives of other people for personal aims; the participants and details of this case were unknown to me, and I had no reliable immunity against the administration's repression. It seemed to me that AD himself was not deeply convinced. He probably anticipated the appeal of his new acquaintance, Y G Bonner, who was interested in this case. Somehow or other, a collective letter was not written. AD himself wrote a telegram to Brezhnev and a letter to Podgorny, asking them to lighten the sentences on the participants in the airplane case.

6. Lucy is "my second and better life". The Nobel Peace Prize

A radical turn of Sakharov's fate was his marriage to Yelena Georgievna Bonner, who became his adorable friend and whom he needed so much. AD, like people close to her, called her Lucy. She concentrated Sakharov's activities on the advocacy of individuals' human rights. But it seemed to me that he should have restricted himself to and concentrated on writing a series of articles and talking about global questions affecting humankind and our country, which he did very carefully and with profound thought. His actions in the advocacy of individuals and on some particular questions were sometimes, in my opinion, too vulnerable for orthodox criticism and took from him much time, energy, and nerves. Once, during a reception in I E Tamm's family devoted to his memory, I told Yelena Georgievna about this. She exclaimed: "I always talk to him about this!" However, I felt that it was very important for AD to achieve a victory in any, even a small, human rights case. And he achieved it, but what a price he paid!

Despite his ideological disagreement with Sakharov, during the height of Sakharov's human rights activities and the Soviet media campaign against him, Solzhenitsyn nominated Sakharov for the Nobel Peace Prize in 1973, which AD received two years later. This prize was given through Sakharov's wife, who travelled abroad at this time for medical treatment. It is surprising that Zh Medvedev and Zel'dovich expressed their negative attitude to his receiving this prize, the latter expressing it not only orally but also in written form.

At the same time, the new family and FIAN introduced some order into Sakharov's life. He regularly visited Tuesday and even Friday seminars at the institute and briefly resumed writing reports in his diary [6]. I looked over his notes concerning forty-one seminars and present here only two of them, which contain, along with his summaries, his remarks concerning the reports and a note about the seminar with the report by AD himself.

"7 February 1978, Tue. FIAN — Zakharov's report — a phenomenological theory based on chromodynamics and dispersion relations for describing resonances in the region

$$2m_\pi \leqslant \sqrt{t} \leqslant 1.5M_{\mathrm{N}}$$

by using the hypothesis

$$\langle 0|F^a_{ik}F^a_{ik}|0\rangle = \mu_1^4\,,$$

$$\langle 0|\psi^b_\mu\bar{\psi}^b_\mu|0\rangle = \mu_2^3\,.$$

(The finite value of these vacuum expectations, in my opinion, does not follow from chromodynamics invariant with respect to the scale transformation, while the spontaneous break of the scale transformation will give rise to 'scale' goldstones which are not observed in nature.)

25 April 1978, Tue. Volodya Ritus reported at FIAN his work on radiative corrections to the electron Lagrangian function in a strong electromagnetic field (by the proper time method in ε, η variables (the fields in the system where $\mathbf{E}\parallel\mathbf{H}$) there is the term $\Delta m \sim -|\mathbf{E}|$) ($\sim -|\varepsilon|$). I said that a term of this type opens up the possibility of solving the confinement problem (see my note of 20 April to which I did not refer).

Igor Tyutin also reported on phase transitions in a gauge field, considered in 't Hooft's paper."

In reality, my work (I took it to the *JETP* editorial office in two days) was devoted to the electron mass operator in a strong electromagnetic field, which is closely related to the double-loop Lagrangian function of this field, which I considered in 1975 and 1977.

The idea to which AD wanted to refer was written on 22 April, not on 20 April. Here it is:

"22 April 1978, Sat. ...I have an idea, possibly very stupid, that the formation of a 'string' is related to the interaction of the form $|E_i|\varphi_i^2$,

E_i is the electric-like field SU_3,

φ_i is the Higgs type field, i.e., $\langle\varphi_i\rangle \neq 0$.

In the string, the phase transition occurs to $\langle\varphi_i\rangle = 0$."

Further events are curious. On the first of May, AD called me and asked me to come promptly to his home in Shchukino to talk about my work. I begged: "AD, it's May first, I have other plans. Let's postpone it until 3 May." I managed to persuade him, but all the same we also discussed the essence of the matter. This is reflected in AD's diary as:

"1 May 1978, Mon. I had a long telephone talk with Volodya Ritus about his and my ideas. Not everything is clear.

2 May 1978, Tue. All day I was busy trying to obtain the term $\varphi\varphi|\varepsilon|$ by the Fock–Schwinger method. Unsuccessful attempts. The next day (3/V) I had a long talk (for 3 hours) with Volodya and established that his effect is $\alpha_x E_x$, which is of little interest for me."

I do not understand the formula $\alpha_x E_x$. It seems that AD obtained it for his non-Abelian case when I left. My formula for the electron mass shift in the electric field ε was

$$\Delta m = -\frac{1}{2}\,\alpha\beta m\,, \qquad \beta = \frac{\hbar|e\varepsilon|}{m^2c^3} \ll 1\,,$$

α is the fine-structure constant, β is the acceleration in units of $mc^3/\hbar$. It is important here that we are dealing with a uniformly accelerated electric charge — a source of the vector field. For a uniformly accelerated scalar charge (a source of the scalar field), the mass shift is absent, i.e., the shift explicitly depends on the spin of the intrinsic field of the charge.

AD continued to work on his idea, and after a month a new note appears in his diary:

"31 May 1978, Wed. ...The calculation of the $A\varphi^2$ interaction in the limit linear in the field gives zero."

And here is the note about AD's own report at a Friday seminar:

"13 October 1978, Fri. I gave a talk, "Baryon asymmetry of the Universe" at FIAN. Many gusts were present (Zel'dovich, Okun, Komar, and others). Unfortunately, my estimates were not quite right yet. According to Ioshimura, the effect is $\sim q^{-1/2}$. I argued that $q^{+1/2}$, while it should be — independent!!! (I understood this on 21/X!)."

7. Exile to Gorky

Our military invasion of Afghanistan led to the sharpest turn of AD's fate. After his interview for *The New York Times* about the situation in Afghanistan and its remedy, and a TV interview for ABS, AD was detained without trial in Gorky and deprived of all his governmental awards. All of us, including our rulers, should have been grateful to AD for his brave condemnation of this war against the country and its people, who were friendly to us.

Deprived of contacts with foreigners and people needing human rights advocacy, AD could concentrate now on his scientific work. But the question of obtaining permission for Liza Alekseeva and Yelena Georgievna herself to travel abroad arose. AD's decision to obtain this permission by hunger strikes was wrong, in my opinion, and I shared the words of many people close to him that "Personal happiness cannot be bought by the sufferings of a great man." In particular, during my second visit to Gorky, I also asked AD to at least postpone the hunger strike because of rumors in Moscow about the illness of the General Secretary (indeed, Andropov died on this day and Chernenko succeeded him, but the postponed hunger strike solved nothing).

Unfortunately, hunger strikes, forced hospitalizations, and agonizing force-feedings were continued, and, as a result, we had what we had.

Theorists from our Theory Department often visited AD. Unfortunately, these visits were purely informative. Here are AD's notes about two of them that he found the most interesting [7]:

"30 March 1986, Sun. Wrote 10 questions that I want to ask Kallosh and Vasil'ev, but do not know whether I can understand their scholarly answers.

2 April 1986, Wed. Today Kallosh and Vasil'ev were at my place. Renata talked interestingly about a superstring, although I did not understand many things and for this reason to listen to her was very fatiguing.

21 May 1986, Wed. Volodya Fainberg and Arkady Tseitlin came to see me. I had a very interesting talk with Arkady. He rejects the string interpretation in terms of the induced gravitation and uses the interpretation based on the σ model. There is something in this approach: I will think about it. But as a whole, in my opinion, he is wrong. I told them about Weisskopf's opinion. Volodya is also in some doubt."

And here are sad reflections on a holiday.

8. One day in the life of Andrei Dmitrievich

"4 May 1986, Sun. Easter Sunday. In the morning I celebrated Easter, having cracked another Easter egg and boiled cocoa. It is awfully cold in my home. I am sitting in a red knitted sweater put on over another sweater. Went to buy some bread and vegetables (there are no products in the shops, even beets are absent, the shops being quite empty. I bought a bottle of apple juice).

I went quickly over many articles, selecting those that I need to attempt to understand (some of them I have already tried to understand many times). Unfortunately, I should confess that it is already beyond my powers to master the entire superscience at the required level. I have failed to do it for 5 months, having all the required articles. Of course, I do not have some primary articles, but this is not the basic argument. The major cause is that I have missed many things, beginning from 1948. In addition, having returned to FIAN in 1969, I was not working at physics with the required consistency and was distracted by many things. I attended only Tuesday seminars and did not work in the field of modern physics (gauge fields, quantum field theory as a whole, the new cosmology, especially supersymmetry) and could not do it. In fact, only in Gorky has such an opportunity arisen for me; however, many things still distract me (especially in recent years, but earlier as well), but the main thing was that my strength and the freshness of mind were already insufficient. I should say that in my youth, in the 1940s, field theory was also difficult for me, although it was then only in its infancy. And what tens of sharp minds have done with it in these 40 years! Absolute miracles. I felt it especially strongly in the last few months. Of course, I will survive it as a man with a quite stable mentality, happy in my personal life, self-critical enough, and ready to be content with what has been done. But in some respects this is nevertheless a great intellectual tragedy for me!!! I will attempt, however, to do something on the 'roadside', something in my declining strength. Yes, I need a strong will and bravery. I should look the facts in the face and should work. I should not spread myself thin and should accomplish my work.

It is $+5\,^{\circ}$C outside, and $+14\,^{\circ}$C at home. I am going to make supper (0:20 a.m.)."

9. "You could be happier"

On returning from exile to Moscow and being elected to the Congress of People's Deputies, critical, nervous times came again for AD. It was sad to see his lanky figure on a tribune with lifted hands and clenched fists, as if a weighty cross was seen behind him, as if malicious shouts of 'crucify him' were heard.

After his speech on 2 June about the criminal war in Afghanistan, I called him at his home. The telephone line proved to be unexpectedly free and AD himself picked up the phone. I began at once to calm him, expressing my support. He said that he was calm, felt that he was right, and had already long ago become accustomed to such an attitude toward him. Yelena Georgievna asked him who was calling. We talked for some time and I calmed down myself.

Only after AD's death did I learn something new, unexpected, and even contradictory in this modest and unusual man.

It appears that he was a good connoisseur of Pouchkine, seeing him as a kindred spirit who helped him to perceive himself.

It appears that after Stalin's death, he wrote a letter to his wife (knowing that letters from KB-11 were read): "I have the impression of the death of a great man, and I am thinking about his humanity." However, I remember our sober conversations about possible changes in our country and his words about the governmental machine that is too inertial to change anything.

It appears that he designed a 100-megaton thermonuclear torpedo and substantiated its use in a conversation with Admiral Fomin, who called this idea a 'cannibal' project.

Yelena Georgievna sincerely related many new and candid things about her relationship with AD [6–8]. Her revelations only confirm the correctness of Solzhenitsyn's impressions [2, 8, 9].

The three volumes of AD's diaries [6–8] contain a list of almost 2300 names of people mentioned in there. Most of them needed the help of AD and he, together with Yelena Georgievna, did the best he could to help them. But, unfortunately, a considerable part of these people treated him as consumers, weakening his ideological and moral positions, compared to the hard position of Solzhenitsyn.

Was AD happy? Probably yes. But then return and read again what he writes on 4 May 1986. This is written by a Laureate of the Nobel Peace Prize — the highest prize in the direction where his fate turned him. So, was he happy?

References

1. Sakharov A D "Molodezh' Estonii" newspaper, 11 October 1988, interview
2. Sakharov A D *Vospominaniya* (Recollections) Vol. 1 (Moscow: Prava Cheloveka, 1996)
3. Ritus V I *Priroda* (12) 57 (2004)
4. Kiselev G V *Usp. Fiz. Nauk* **178** 947 (2008) [*Phys. Usp.* **51** 911 (2008)]; *Usp. Fiz. Nauk* **178** 1371 (2008)
5. Ryabev L D (Gen. Ed.), Goncharov G A (Exec. Comp.) *Atomnyi Proekt SSSR. Dokumenty i Materialy* (Atomic Project in the USSR. Documents and Materials) Vol. 3 *Vodorodnaya Bomba. 1945–1956* (Hydrogen Bomb. 1945–1956) Book 1 (Moscow: Nauka, 2008)
6. Sakharov A D, Bonner Ye G *Dnevniki* (Diaries) Vol. 1 (Moscow: Vremya, 2006)
7. Sakharov A D, Bonner Ye G *Dnevniki* (Diaries) Vol. 3 (Moscow: Vremya, 2006)
8. Sakharov A D, Bonner Ye G *Dnevniki* (Diaries) Vol. 2 (Moscow: Vremya, 2006)
9. Solzhenitsyn A I *Bodalsya Telenok s Dubom* (The Oak and the Calf) (Moscow: Soglasie, 1996)

CONFERENCES AND SYMPOSIA

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

Andrei Sakharov today: lasting impact on science and society

B L Altshuler

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Contents

Abstract. **The 20-year period of 1948–1968, during which Andrei D Sakharov crucially contributed to the creation of the Soviet nuclear shield, was followed by the same length of time from 1969 to 1989, when he was no less patriotic in his human rights activities and in his efforts to save humankind from self-destruction in a thermonuclear war. When free of these commitments, Sakharov always turned to his favorite pastime, theoretical physics, where, working on the 'roadside' (to use his own words), he obtained a number of results of continuing importance. Some of these are described in this talk, as are Sakharov's actions and approaches, highly nontrivial and still relevant today, to solving the problems of major public concern.**

1. Introduction

"We heard several times how he read Pouchkine by heart, quietly, almost to himself: 'When a noisy day dies for a mortal...'." He said once: "I want to follow Pouchkine.... It is impossible to imitate a genius. But it is possible to follow him in something different, maybe, higher...." (from the recollections of Raisa Orlova and Lev Kopelev [1]). Speaking about Sakharov's legacy today, I have in mind first of all his methods of solving formulated problems and achieving the required result. Of course, 'it is impossible to imitate a genius', but it is possible to learn something from him.

On 23 May 2011, public lectures devoted to the 90th anniversary of A D Sakharov's birth, organized by the Dinastiya Foundation, were held at the Conference Hall of the Lebedev Physical Institute, RAS (FIAN). Youth packed the hall, and this engenders hope.

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During the 20 years from 1948 to 1968, Andrei Dmitrievich was involved in the development of the Soviet nuclear shield, and during the next 20 years, from 1969 to 1989, guided by the same patriotic sense of duty, he was engaged in the protection of human rights and preventing mankind from self-destruction in a thermonuclear war. When free from these commitments, he devoted all efforts to his favorite pastime — theoretical physics. And although his works were performed on the 'roadside' (*Diaries* [2], the note on 4 May 1986), many of them initiated the development of whole scientific fields: the peaceful use of thermonuclear fusion, the explanation of the baryon asymmetry of the Universe and the appearance of primary inhomogeneities of matter at the early evolutionary stage of the Universe, muon catalysis, magnetoimplosive generators for producing ultrastrong pulsed magnetic fields... [3]. His daring idea (for that time, 1967) of induced gravitation received a full-scale development in string theory, and Andrei Dmitrievich always talked about this with great satisfaction. The modern state of some of these scientific fields will be discussed below.

I will also talk about the possibility of applying 'actions à la Sakharov' to solve a number of acute public problems in modern Russia, such as the salvation of domestic science, the creation of an effective system for protecting childhood and family, the development of public control and the participation of citizens of our country in making decisions, including the implementation of the new technologies of Internet democracy, the combination of mobile communications and the Internet, etc.

2. The past that did not pass

But first of all, we will see what made Andrei D Sakharov one of the most significant figures of the 20th century.

Andrei Dmitrievich's public activity was directed at realizing in life and implanting in the mind of society, politicians, and State rulers the idea of connecting closely the two seemingly unrelated spheres of protecting individual human rights, on the one hand, and international security, on the other. It is in fact, his major message to humankind, which was clearly expressed in his Nobel lecture in 1975. In principle, we are dealing with a practical global implementation of Fyodor Dostoevsky's famous saying that "the happiness of the world does not cost a tear of a child," which had never and nowhere before been perceived seriously by politicians, reformers, and revolutionaries of various stripes (many shortsighted pragmatics considered and consider Sakharov a 'naive man'). The successful realization of this approach made Sakharov a man of the World, because it is this connecting that allowed humankind to step away from the edge of the thermonuclear abyss. Clearly recognizing that the possibility of falling into this abyss was more than real.

The danger of mutual assured destruction and the nuclear balance between the USSR and USA were, indeed, the most important irenic factors preventing the eruption of a third world war. But, on the other hand, the gradual accumulation of nuclear arsenals made the achieved 'balance of fright' more and more unstable. Ballistic missiles with thermonuclear warheads aimed at each other, which cannot be called back after their launching, the nuclear suitcase, and the finger of the highest leaders in the USSR and USA on the nuclear button — the decision of each of these two individuals determined whether life on Earth continued or not. We all hung by a single hair: any error in early warning systems signaling about a nuclear missile attack by the enemy could lead to global catastrophe.

It is clear that the only solution was to end the confrontation of the two systems and to reach agreement between each other. But this is clear only now. As a rule, later generations understand old events well. (V L Ginzburg joked: "I would like to be as clever yesterday as my wife is today.") Sakharov was also a child of his epoch, raised in the 1930s and believing that socialism was the future of humankind, whereas capitalism was historically doomed. And he only very gradually understood that, whether you wish it or not, it is necessary to agree because the only alternative to agreement is mutual destruction. Notice that the problem of a reconciliation between the two systems appeared to be absolutely insolvable. Recall that all leading ideologists and leaders in the USSR (Lenin, Trotsky, Stalin, Khrushchev, and others) thought in terms of the world revolution and the inevitable destruction of capitalism–imperialism, all of politics and the potential of the USSR being aimed at realizing these ravings. And here Sakharov writes to the 'top' about some intellectual freedom and convergence (a closed letter to M A Suslov in 1967, found in the early 1990s in the archive of the Central Committee of the Communist Party of the Soviet Union by a historian of physics, G E Gorelik (see [4], pp. 422–427). Sakharov was, of course, well known and respected at the very top of the Soviet power pyramid, and his opinions on the problems of defense and the production of nuclear weapons were taken into account. But his 'humanistic' reflections were simply ignored, and he received no answer at all.

And then miracles began to occur, which only Sakharov could 'produce' and which his physicist colleagues called quite spectacularly as 'the violation of the energy conservation law', 'Sakharov — the talking horse', and so forth.

Having received no answer from the commanders of our country, Andrei Dmitrievich laid out the same ideas in his famous memorandum, *Reflections on Progress, Peaceful Coexistence, and Intellectual Freedom*, which he launched, through his friends in May 1968, as samizdat, understanding that the document would be published abroad. He signed the memorandum with his real name, not hiding from anybody. And this was done by a top-secret academician working at the top-secret Arzamas-16 (Sarov) nuclear center. In early July 1968, the Memorandum was published in the West, and this was a shock to the Kremlin, the Ministry of Medium Machine Building, and Sarov. "Why did you decide to appeal abroad?" asked my father, L V Altshuler, who also still worked in Sarov in 1968 and was long on friendly terms with Sakharov. "I decided to appeal to those who are ready to listen to me," Andrei Dmitrievich answered mathematically accurately (L V Altshuler, *Next to Sakharov*, in books [5, 6]).

And such examples of 'going beyond the scope of given circumstances' are plenty. Special insistence was required to save individuals ("And you want to save a friend, but cannot think out how" — Yuly Kim, poem "19 October"). But, they 'thought it out', and first and foremost Sakharov. And if the regime did not give in, the task was to make the action grow like a snowball, assuming a worldwide character. In essence, this was the method of all human rights movements. Even today, to save a child in modern Russia, we child rights activists are forced to use the same methods of 'global response' because, under conditions of total 'departmentalism' and the absence of a workable legal system, we simply do not have any other methods for convincing officials. Talking about the past, it is necessary to emphasize the special role, the unbelievable energy, and the insistence of Yelena Bonner in the task of saving individuals,[1] as Andrei Dmitrievich writes in his *Recollections* [7].

Indeed, during many years of his human rights activity, Sakharov constantly acted as a patient teacher, carrying forward by his words and deeds the seemingly simple but in reality absolutely nontrivial idea that the tragedy of an individual is a calamity no less than the tragedy of millions. And the famous scientist, human rights activist, and Nobel Peace Prize laureate went to Siberia to see a repressed dissident, stood in the rain in front of the court buildings, and started an indefinite hunger strike for the rights of 'some girl'. I well remember that these 'trifling' Sakharov's actions caused irritation even among some people close to him — they sincerely did not understand him. However, it was by such actions that Sakharov changed the entire system of international security.

All manner of absurdities are being told about Andrei Dmitrievich, both sincerely and 'made-to-order'. One of the most lasting and certainly made-to-order legends is that a quite decent Russian Soviet genius was seduced into anti-Soviet activity by some Yelena Bonner. To refute this stupidity, I recall several episodes from Sakharov's life 'before Yelena Bonner'.

November 1950, Stalin's no-joke epoch, the town of Sarov near Gorky. The work of the KB-11 nuclear center was inspected by an important commission from Moscow. In particular, the commission had conversations with leading scientists, asking a standard question: Do you agree with the politics of the Communist Party? All the reasonable people routinely answered 'yes', but two, Sakharov and L V Altshuler, did not agree with the Party's politics in the field of biology (it was two years after the destruction of genetics and the triumph of Lysenkoism). The recently unclassified KB-11 documents edited by R I Ilkaev and published at the Russian Federal Nuclear Center 'All-Russian Research Institute of Experimental Physics' (RFNC–VNIIEF), contain, notably, the conclusion of this commission: "The heads of laboratories

[1] Yelena Georgievna Bonner died after a grave disease in Boston on 18 June 2011. (*Author's footnote*)

such as Altshuler, Sakharov, and others who do not inspire political trust and come out against the Marxism–Leninism foundations of Soviet science should be dropped from the leadership of research bodies'' (see [6], p. 460). It is clear that if such instructions were had been fulfilled, no bombs would have appeared in the USSR.

22 November 1955. The well-known conflict with Marshal of Artillery M I Nedelin, when, during a banquet after the successful testing of the hydrogen superbomb, Sakharov proposed a pacifistic toast that shocked the participants at the banquet.

1962. A significant conflict with N S Khrushchev caused by Sakharov's demand to put off 'the double test'.

1964. The speech at the General Meeting of the USSR Academy of Sciences against the election of N I Nuzhdin, who was a creature of T D Lysenko and was supported by Khrushchev, to the members of the Academy. I E Tamm, V A Engelgardt, and M A Leontovich also protested against the election of Nuzhdin. But Andrei Dmitrievich addressed the academicians in a hard tone, which was quite unusual for such meetings, and said that Nuzhdin was responsible for ''the shameful backlog of Soviet biology,'' ''for the ostracism of real science and true scientists, for persecutions, mockeries, the deprivation of the possibility to work, dismissals — up to arrests and the deaths of many scientists.'' Nuzhdin was not elected. Khrushchev was mad with rage and decided to dissolve the Academy, excluding all research institutes under it. At that time, the Academy was saved due to the state upheaval on 4 October 1964, after which Khrushchev's place was occupied by L I Brezhnev. This raises the natural question: What will save the Russian Academy of Sciences today?

1966. Sakharov, together with other well-known scientists (P Kapitza, M Leontovich), artists, and writers (M Plisetskaya and others), altogether more that 20 people, addressed the XXIII Communist Party Congress with a letter against attempts to rehabilitate Stalin.

In September 1966, Sakharov sent a telegram to the Supreme Soviet of the Russian Soviet Federative Socialist Republic protesting against the inclusion of article 190-1 (the dissemination of certainly false information and defamation slandering the Soviet state and public system) in the Criminal Code of the USSR, as a pretext for persecuting Soviet citizens for their convictions.

On 5 December 1966, Sakharov participated in a demonstration near Pouchkine's monument (an annual demonstration on Constitution Day for human rights and against anticonstitutional articles in the criminal code. The clear legal foundation for these demonstrations was created by a well-known mathematician Aleksandr Sergeevich Esenin-Volpin, son of the poet Sergey Esenin. We see how everything is intersected in our life).

In February 1967, Sakharov wrote a letter to the General Secretary of the Central Committee of the Communist Party of the Soviet Union in defense of Yury Galanskov, Aleksandr Ginzburg, Vera Lashkova, and Aleksandr Dobrovolsky. As a result, Andrei Dmitrievich was relieved of his duties in Sarov as the head of department. In summer of 1967, Sakharov takes part in the fate of a political prisoner, Yu Daniel.

In the same 1967, Sakharov wrote the above-mentioned letter to M A Suslov, and after a year he acquired a new status: having become known around the world, he was banned from all classified military-related research and returned to FIAN in Moscow.

In spring of 1969, K A Vikhireva, the first wife of A D Sakharov, the mother of his three children, died from cancer. I got acquainted with Andrei Dmitrievich in 1968. In March 1969, I was at Klavdiya Alekseevna's funeral and remember that Andrei Dmitrievich wept bitter tears. He took his wife's death very badly: ''lived as in a bad dream, doing nothing in either science or public affairs.'' But he always cared about his children. And his first wife well knew about all his 'political' actions mentioned above, which occurred long before his acquaintance with Y G Bonner, about two years after Klavdiya Alekseevna's death. Sakharov and Bonner married on 7 April 1972. Talking about this union, it is impossible not to talk about its third participant, Russian poetry, verses, which were for them a way of existence. They happily found each other in this — even notes passed back and forth during Sakharov's hunger strikes were coded with lines of Pouchkine's verses [8].

Yes, Sakharov and Bonner, as other human rights activists and dissidents, became an insolvable problem for the totalitarian system. It is sufficient to write the words 'a furious beast in a skirt' (*zveryuga v yubke* in Russian) into an Internet search engine, and you will find at once the record of the historical meeting of the Political Bureau of the Central Committee of the CPSU on 29 August 1985. M S Gorbachev raised a question at this meeting as to what should be done to force Sakharov to abandon a half-year hungry strike, demanding permission for his wife to travel to the Unites States for medical treatment (during this hunger strike, Sakharov was subjected to painful force-feeding). Andrei Dmitrievich struggled to save his wife, i.e. he behaved like a real man. In discussing this question, the members of the Political Bureau called Sakharov's wife 'a furious beast in a skirt', while Gorbachev added: ''This is what is called Zionism.'' But we should give him his due: he forced through the Political Bureau permission for Bonner's medical treatment in the USA, and after about a year he returned Sakharov and Bonner to Moscow from exile in Gorky. The question arises: Why did Yelena Georgievna attract such attention at the highest political level in the USSR? The same question concerns Andrei Dmitrievich Sakharov. I have no answer, and I think that it is a question for future historians.

And it is quite amazing that all this is relevant today as well. This past has not passed at all. On the 90th birthday of Sakharov, Channel 1 of Central TV showed a 'jubilee' film in which all the mud and slander disseminated about Sakharov and Bonner a quarter of a century ago by the authorities was repeated word for word. Andrei Dmitrievich died 21 years ago, and Yelena Georgievna did not travel to Russia for almost 10 years because of heart disease. Why are their names still unhearable for 'ever yesterday's people', who were inherited by the new Russia from the former USSR? All this is strange and disturbing.

3. Sakharov's scientific ideas today

I wrote a long article, pearing the title of this section, for the recently published jubilee *Sakharov's Collection–2011* [9]. In essence, this is the major theme of the current scientific session of the Physical Sciences Division of the RAS devoted to the 90th anniversary of the birth of A D Sakharov. Therefore, I will only briefly present this topic here, trying to avoid overlapping with other reports.

Peaceful use of nuclear fusion: *tokamaks*. In the report ''The theory of a magnetic thermonuclear reactor'' (MTR) prepared by A D Sakharov and I E Tamm in 1951, they proposed for the first time an idea for the magnetic insulation of deuterium–tritium plasma heated up to a few million degrees ('a magnetic trap', which was later called a tokamak). These Sakharov's and Tamm's works are acknowledged as pioneering. Further investigations were continued under the supervision of L A Artsimovich, and theoretical studies were headed by M A Leontovich. In 1956, the results of Soviet research on the possibility of confining hot plasma in a limited spatial volume by means of a magnetic field were unclassified by the order of N S Khrushchev and reported by I V Kurchatov in Harwell (Great Britain), and then published in the *Proceedings of the First Geneva Conference on the Peaceful Use of Nuclear Power*. It is this publication that became a revelation for researchers all over the world. Hans A Bethe wrote about this in 1976: "At present, the prospects appear to be better than ever before; a few years ago, Russian experimentalists invented a setup called the 'tokamak'.... This setup was comparatively successfully reproduced in the USA" [10].

The realization of the idea of controlled nuclear fusion promises the production of infinite energy. These prospects are so attractive that tokamaks have been under development for already 60 years, with the efforts in their studies increasing. However, a positive energy balance has not been achieved so far. Many ideas were proposed to overcome the encountered problems. Altogether, more than 200 tokamaks have been developed, 35 of them operating today (see http://www.tokamak.infor). The history's largest tokamak [the International Thermonuclear Experimental Reactor (ITER) project] will be constructed at the CEA Cadarache Research Center in the southern France, 60 km from Marseille. The concept of this project was advanced for more than 15 years, and it was finally accepted in July 2010. This is a great and very expensive project, involving about 30 counties, including Russia and the USA.

It should be noted that a number of researchers (for example, Bruno Coppi [Massachusetts Institute of Technology (MIT)], who is also known to have actively helped Sakharov in his difficult years) doubt the efficiency of the ITER project and justifiability of the huge investment in it. Bruno Coppi argues, and reported it at the Third International Sakharov Conference on Physics in 2002, that 'Ignitor' type tokamaks being developed at MIT, in Italy, and at the National Research Centre 'Kurchatov Institute' in Moscow are much more promising and also less expensive.

Surprisingly, despite all the difficulties and high cost of these experimental projects, the enthusiasm of researchers and State leaders has not diminished. The stakes are too high, especially taking into account the rising cost of oil and natural gas. Thus, we see that problems in the field of controlled nuclear fusion formulated by Sakharov 60 years ago remain more than urgent today.

Explanation of the baryon asymmetry of the Universe. This classic article [11], published in 1967, occupies only three journal pages. The essence of the problem is that it was assumed for a long time that the theory of elementary particles is charge-symmetric and, therefore, it was unclear why galaxies and stars consisting of baryons (protons, neutrons, etc.) are observed in the Universe, whereas antigalaxies and antistars consisting of antibaryons (antiprotons, antineutrons) are not observed (see also Refs [12, 13]).

Sakharov formulated three following conditions for the appearance of the baryon asymmetry at the early instants of the hot Universe expansion.

(1) Violation of the combined parity (*CP*-parity) in scattering processes of elementary particles, which was discovered shortly before this by S Okubo (the numerical values of the scattering characteristics of some particles differ by 0.6% from the characteristics of spatially (*P*) reflected scattering of their antiparticles). Sakharov wrote his own verse on a copy of his article, which he gave to E L Feinberg [7]:

Based on S Okubo effect
At a high temperature,
A fur coat made for the Universe,
Fitting its crooked figure.

(2) Symmetry violation during time reversal, i.e. under the dynamic conditions of a strong nonstationarity, which takes place due to the rapid expansion of the Universe immediately after the Big Bang.

(3) Baryon number violation. Sakharov considered in his paper the simplest mechanism of such a violation — proton instability. According to Sakharov's estimates, for the observed baryon asymmetry of the Universe to appear at the initial stage of its existence, it is sufficient to assume the proton is unstable, with a lifetime of about 10^{50} years. This 'crazy' idea suggested by Sakharov in 1967 was established in theoretical physics in 1979, although today other mechanisms of baryon number violation, differing from proton instability, are being considered.

In recent years, models of baryogenesis at the reheating stage — the decay of the vacuum-like state in inflation models (the inflating Universe) — are being widely discussed. It is at this stage that Sakharov's three conditions for the appearance of the observed baryon asymmetry of the Universe 'operate'. At the same stage, the initial quantum inhomogeneities of vacuum produce the primordial density fluctuations of matter from which galaxies and stars were later formed. (See below comments on the relevant paper by Sakharov).

"*The initial stage of an expanding Universe and the appearance of nonuniform distribution of matter*" [14]. This was Sakharov's first paper following his return to 'major science' after a 15-year 'bomb' interruption and performed in 1963–1964. How were spatially inhomogeneous accumulations of matter such as galaxies and galaxy clusters produced, while everything was absolutely uniform at the early evolution stage of the Universe? Sakharov writes in his *Recollections* ([7], Part 1, Ch. 18): "The theory of gravitational instability shows how initially small density inhomogeneities increase. However, to find these inhomogeneities, additional physical considerations or hypotheses are needed. This is one of the major problems of large cosmology. In my paper published in 1965, I tried to study this question."

I will cite comments on this paper published in Sakharov's collection *Scientific Works* ([3], pp. 214, 215]:

"*This work is quite typical for the scientific style of A D Sakharov. As with his subsequent work, it is significantly ahead* (*in time*) *of the development of science in this field. In fact, this paper laid the foundation of a new avenue of inquiry in cosmology — the theory of the origin of the initial perturbation spectrum for the formation of galaxies and their clusters*" (V F Mukhanov).

"*This work by A D Sakharov is remarkable in that he put forward for the first time the assumption about the origin of pregalactic inhomogeneities from quantum fluctuations.... At present, most cosmologists are sure that pregalactic inhomogeneities were produced namely from quantum zero-point oscillations, not of cold baryonic matter, but, for example,* *scalar fields, which are substantial components of modern models of the Grand Unified Theory.... These fields determine the inflation stage*'' (G V Chibisov).

Paper [14] was written just before the discovery of relic radiation in 1965, which proved the validity of the hot Universe model. Much later, while in exile, Sakharov wrote about this paper: ''*I proceeded then, following Zel'dovich and many other authors of that time, from the so-called cold Universe model, according to which the initial temperature of superdense matter was assumed to be zero.... The use of the cold model considerably depreciated my first cosmological work*'' ([7], Part 1, Ch. 18).

However, the situation drastically changed after the discovery of the anisotropy of relic radiation with the help of extraterrestrial radio telescopes in 1992. The difference between the 'relic temperatures' at different points in the expanse of heaven is extremely small, within 0.01% of the mean temperature of 2.725 K of relic radiation. But this became a powerful tool for studying the early evolution stages of the Universe, because the observed small fluctuations of relic radiation are the 'prints' of primordial density fluctuations of the matter and cosmological gravitational waves.

And it is remarkable that baryon acoustic oscillations of relic radiation discovered by astrophysicists in 2001 are similar to the matter oscillations described theoretically by Sakharov in his paper in 1965 (see, for example, book [15]). These inhomogeneities of the relic background were rightly called 'Sakharov oscillations'. It is sufficient to search for this term on the Internet in order to see how Sakharov's ideas are actively being used in modern science.

4. Sakharov's public legacy today

Sakharov's method in science and public activity was in fact the same: he always remained a man of exact sciences, a physicist, a constructor, and a designer. I talked about this in detail in my report at the IV International Sakharov Conference on Physics in 2009 [16]. Here, I will talk about the possible application of his 'method' to solving some modern social problems.

Through his public activity, Andrei Dmitrievich Sakharov gave an example of the powerful influence of civil society on the authorities. Today, Russia is ready to take in this experience. There are two reasons for this:

(i) The 'unwhipped' post-Soviet generation, free of the ineradicable Soviet fixation of passively waiting for decisions from higher comrades;

(ii) the development of social networks on the Internet, which is called Internet democracy.

In 1968, Sakharov wrote in his futurological article ''Future science'': ''Progress in cybernetics will result in deep displacements in ideology and philosophy... will introduce great and unexpected corrections to the prediction of the domestic, social and political structure of future society.''

In his interview for the *Book Review* newspaper in spring of 1989, he said about the youth: ''I believe that moral strength is always preserved in people. I especially believe that youth, which in each generation begins to live as if anew, is capable of taking a high moral position. I do not mean the revival but rather the necessity of the development of moral strength, which is inherent in each generation and can proliferate again and again.''

Today, we see this with our own eyes. In recent years, wide volunteer initiatives have appeared to help children inmates of boarding schools (it is namely this 'moral strength proliferating again and again'); the actions and hunger strikes of the All-Russia movement Accessible Preschool Education for Russian Children against queues for kindergartens; mass movements of car drivers; ecological movements, the best known being To the Defense of the Khimki Forest, etc. are occurring all over our country. The activists of these movements are mainly young people, young parents 30–35 years old, i.e. grown up after the collapse of the Soviet Union. They are united primarily by the Internet. At the same time, it is obvious that we are only at the beginning, and all these initiatives require support, including technological support, for the more efficient use of social networks, and the entanglement of wider population layers interested in the solution to various essential problems for people.

One well-known example of internet lobbying, which was amazing in its effectiveness, is a letter (January 2011) by Sergey Volkov, a teacher at school No. 57 in Moscow, against new educational standards, which was supported by thousands of bloggers and evoked a positive response from V V Putin and A A Fursenko.

And questions arise: Where is the Russian scientific community? Why is there nothing similar to Sergey Volkov's letter in our scientific media? Whereas the problems are acute and well-known to all:

(i) While the leading scientific institutes of our country suffer a miserable existence, huge portions of the budget are being spent to construct a scientific paradise in one separately picked town of Skolkovo: 5.75 billions rubles (appr. $ 190 mln) having been already spent just to build the 5-km highway from Skolkovo to the Moscow belt highway (and after six months this highway became worthless).

(ii) So-called 'efficient managers', who are infinitely far from science, were appointed the directors of a number of the largest institutes in our country (NRC 'Kurchatov Institute', SSC 'Alikhanov Institute of Theoretical and Experimental Physics', Konstantinov Petersburg Nuclear Physics Institute, RAS), and this was done by ignoring completely the opinion of the researchers from these institutes.

(iii) There also exist many problems in the organization of the work of the Russian Academy of Sciences itself.

Clearly, it is possible to get out of the quagmire in this and all other spheres only with the help of an 'external force', an 'external fulcrum', such as well-organized and sufficiently 'high-pressure' scientific and civil societies. [2]

Now I will tell about children and the defense of their rights — the everyday occupation in which I and my friends and colleagues have been involved for the last 15 years. Obviously, children are the future of our country, and we have serious problems with this future (in direct and

[2] The role of such an authoritative publicly active platform could be played by the Russian Association for the Promotion of Science, founded on 28 July 2011 on the initiative of Academician E P Velikhov, the Secretary of the Public Chamber of the Russian Federation. The aims and tasks of the association are discussed in Velikhov's interview presented on the site, Tribune of the Public Chamber (http://top.oprf.ru/interviews/3894.html). The aim is beautiful, but what will happen in practice is not clear now. Maybe this will come to good if foreign scientists working in Russia, some of whom at a meeting with the President of the Russian Federation on 23 May 2011 straightforwardly related stories about Russian bureaucrats preventing the development of native science (http://kremlin.ru/news/11309), join the active core of the association. But we should not rely only on foreigners, even if they are former Russians. Now the question arises: Where are our scientific analogues of Sergey Volkov, the teacher at school No. 57 in Moscow. (*Author's footnote*)

figurative senses). The number of children in Russia is decreasing, thus approaching our country to a 'demographically irreversible' point. In 1998, 22 million pupils were educated in eleven grades in all Russian schools; in the 2010–2011 academic year, this number was 12.8 million, i.e. 9.2 million less in 12 years. The total number of children in Russia in 2003 was 31.18 million (21% of the country's population), while in 2010, this number was 25.981 million (18% of the population). At the same time, the number of preschoolers increased by 1.5 million in the same 7 years. Specialists explain this growth by the introduction of financial incentives to mothers in 2007, but mainly by the fact that the last demographically intact generation born in the 1980s reached child-bearing age in the 2000s. Farther, the inevitable failure and accelerated aging of the population will follow.

One of the major lessons from Andrei D Sakharov is that people should not be sacrificed for achieving 'great goals', the fulfillment of desirable reforms, etc. This lesson was neglected by the architects and leaders of the 'market' reforms in the 1990s (in reality, pseudomarket reforms that annihilated any competition and gave away our country to the power of uncontrollable monopolies). As a result, millions of families with children, budgetary employees, and pensioners were set on the edge of survival, and beyond it. People ceased having children in the 1990s, and they do not do so today because the cost of the necessities of life (food and housing) is so high that they cannot feed their children, and the children have no place to live. Russian poverty has a 'child's face'. I say this with the full knowledge of the facts, being engaged in these problems with my colleagues in the Public Chamber of the Russian Federation and in the Expert Group No. 9 ("The reduction of social inequality and overcoming poverty") to develop the so-called Strategy 2020 (the concept of the social and economic development of our country up to 2020).

There also exist other acute problems concerning childhood. For example, the mass separation of children from parents (more than 100 thousand new orphans appear each year, about 300 orphans per day, and this has gone on for many years), or the fact that 300 thousand children (in 2009) are living permanently in children's institutions, only 30% of them being orphans, while others were abandoned by their parents and leaved in care of the State because of a disability of the child or unfavorable conditions in the family, in particular, due to the absence of money for feeding the child.

The methods of solving all these social and economic problems of childhood and the family, including legislative measures, are well known: they have been proposed many times by specialists, and have even been considered at the highest political level. Nevertheless, all remain 'as always' because the corporative interests of departments and monopolies, which are not interested in these reforms, always win, whereas the pressure from society is negligibly small.

Sakharov could produce pressure leading to the desirable effect, whether it was the pressure required to compress the hydrogen isotope nuclei in the hydrogen bomb or the public pressure which the leaders of the great superpowers were forced to take into account.

Andrei Dmitrievich Sakharov passed away in another country during another epoch. The history does not have the conjunctive, but I am sure that if Sakharov was alive, the history of Russia would be quite different.

5. Conclusions

I was closely acquainted with Andrei Dmitrievich for more than 20 years, and the same period of time has elapsed since his death. Many recollections have been written, but I was pleased most of all when the First September Publishing House suggested recently that I write an article commemorating the 90th birthday of Sakharov for teachers and school kids [17]. There are strong grounds to believe that interest in Sakharov will only increase in the course of time with the appearance of new generations in our world.

In conclusion, I will speak again about science, to which Andrei D Sakharov was infinitely devoted. In August 1989, four months before his death, he completed his recollections with these words:

"Of course, the end of the work on the book creates the feeling of a borderline, a summing-up. 'Why, however, is an obscure sorrow secretly troubling me? (Alexandre S Pouchkine). And at the same time, I am feeling a powerful life flow, which has begun before us and will continue after us.... This is the miracle of science. Although I do not believe in the possibility of the creation of the 'theory of everything' in the near future (or at all?), I have seen gigantic, fantastic achievements during my life alone and I expect that this flow will be not exhausted, but, on the contrary, will widen and branch out..." [18].

References

1. Orlova R, Kopelev L *My Zhili v Moskve. 1956 – 1980* (We Lived in Moscow. 1956 – 1980) (Moscow: Kniga, 1990)
2. Sakharov A, Bonner Y *Dnevniki*: *Roman-Dokument* (Diaries: Documentary Novel) Vol. 3 (Moscow: Vremya, 2006) pp. 187 – 188
3. Sakharov A D *Nauchnye Trudy* (Scientific Works) (Editorial Board: B L Altshuler, L V Keldysh (Chair), D A Kirzhnits, V I Ritus) (Moscow: OTF FIAN – TsentrKom, 1995)
4. Gorelik G E *Andrei Sakharov*: *Nauka i Svoboda* (Andrei Sakharov: Science and Freedom) (Moscow: Vagrius, 2004)
5. Altshuler B L, Bolotovsky B M, Dremin I M, Keldysh L V (Chair), Fainberg V Ya (Editorial Board) *On Mezhdu Nami Zhil... Vospominaniya o Sakharove* (Moscow: OTF FIAN – Praktika, 1996) [Translated into English as *Andrei Sakharov. Facets of Life. Reminiscences of Colleagues* (Gif-sur-Yvette-Sedex France — TheorDep-FIAN–Editions Frontiers, 1991)]
6. Altshuler B L, Fortov V E (Ed.) *Ekstremal'nye Sostoyaniya L'va Al'tshulera* (Extremal States of Lev Altshuler) (Moscow: Fizmatlit, 2011)
7. Sakharov A *Vospominaniya* (Recollections) (New York: Izd. im. Chekhova, 1990); *Vospominaniya* (Recollections) (Eds.-Comp. E Kholmogorova, Yu Shikhanovich) (Moscow: Prava Cheloveka, 1996); *Vospominaniya* (Recollections) (Comp. Y Bonner) (Moscow: Vremya, 2006) [Translated into English as *Memoirs* (New York: Alfred A. Knopf, 1990)]
8. Altshuler B L "Pushkin, stikhi, muzyka v 'Dnevnikakh' Andreya Sakharova" ("Pouchkine, verses, music in 'Diaries' of Andrei Sakharov"), http://berkovich-zametki.com/2007/Starina/Nomer3/Altshuler1.htm
9. Altshuler B "Nauchnye idei A.D. Sakharova segodnya" ("Scientific ideas of A D Sakharov today"), in *Sakharovskii Sbornik — 2011* (Sakharov Collection — 2011) (Comp. A Babenyshev) (Moscow: Izd. Tsentr RGGU, 2011); http://www.pereplet.ru/text/altshuler01jul11.html.
10. Bethe H A "The necessity of fission power" *Sci. Am.* **234** (1) 21 (1976) [Translated into Russian: "Neobkhodimost' yadernoi energii" *Usp. Fiz. Nauk* **120** 455 (1976)]
11. Sakharov A D "Narushenie *CP*-invariantnosti, *C*-asimmetriya i barionnaya asimmetriya Vselennoi" *Pis'ma Zh. Eksp. Teor. Fiz.* **5** 32 (1967) ["Violation of CP-invariance, C-asymmetry, and baryon asymmetry of the Universe" *JETP Lett.* **5** 24 (1967)]

12. Sakharov A D "Barionnaya asimmetriya Vselennoi" *Zh. Eksp. Teor. Fiz.* **76** 1172 (1979) ["Baryonic asymmetry of the Universe" *Sov. Phys. JETP* **49** 594 (1979)]
13. Sakharov A D "Barionnaya asimmetriya Vselennoi" ("Baryon asymmetry of the Universe"), *Conf. Devoted to the 100th Anniversary of the Birth of A A Friedmann, Leningrad, 22–26 June 1988*, A Review Report
14. Sakharov A D "Nachal'naya stadiya rasshireniya Vselennoi i vozniknovenie neodnorodnostei raspredeleniya veshchestva" *Zh. Eksp. Teor. Fiz.* **49** 345 (1965) ["The initial stage of an expanding Universe and the appearance of a nonuniform distribution of matter" *Sov. Phys. JETP* **22** 241 (1965)]
15. Gorbunov D S, Rubakov V A *Vvedenie v Teoriyu Rannei Vselennoi*: *Kosmologicheskie Vozmushcheniya, Inflyatsionnaya Teoriya* (Introduction to the Theory of the Early Universe: Cosmological Perturbations and Inflationary Theory) (Moscow: Krasand, 2010) [Translated into English (Singapore: World Scientific, 2011)]
16. Altshuler B L "Andrei Sakharov as a physicist in all facets of his life", in *Proc. of the IV Intern. Sakharov Conf. on Physics, LPI, 18–23 May 2009*); http://www.sc4.lpi.ru/proceedings/altshuler_mem.pdf
17. Altshuler B L "Ne do ordena. Vspominaya Andreya Sakharova" ("Not up to the order. Remembering Andrei Sakharov") *Klassnoe Rukovodstvo Vospitanie Shkol'nikov* (1) (2011)
18. Sakharov A *Gor'kii, Moskva, Dalee Vezde* (Gorky, Moscow, Farther Everywhere) (New York: Izd. im. Chekhova, 1990); *Vospominaniya* (Recollections) Vol. 2 *Gor'kii, Moskva, Dalee Vezde* (Gorky, Moscow, Farther Everywhere) (Eds-Comp. E Kholmogorova, Yu Shikhanovich) (Moscow: Prava Cheloveka, 1996); "Gor'kii, Moskva, dalee vezde" ("Gorky, Moscow, farther everywhere"), in *Vospominaniya* (Recollections) Vol. 3 (Comp. Y Bonner) (Moscow: Vremya, 2006)

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

Sakharov at KB-11. The path of a genius

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Contents

Abstract. 21 May 2011 would have marked the 90th birthday of Andrei Dmitrievich Sakharov, a towering 20th-century figure in science and human thought, whose ideas, research contributions, and life example exerted enormous influence on the history of the second half of the 20th century and, in particular, on the history of Russia. Whether as a scientist or a private person (including his public activities and exceptional attitude to human personality), he always displayed creativity and a freedom of spirit, thought, and action. Sakharov's life and creative work make him a model scientist and citizen for many and undoubtedly provide a legacy for the development of science and society in the 21st century. In this paper, some of Sakharov's key ideas and achievements relating to his KB-11 period are exemplified, and how they influence present day research and technology, notably as employed for affording national security, is examined.

1. Development of the *sloika*

In spring 1948, A D Sakharov formulated a new principle for producing a pulsed thermonuclear reaction, which became the most important contribution to the development of nuclear weapons in our country. Later on, he wrote about this: "After two months, I made a sharp turn in the work and proposed an alternative project of a thermonuclear charge, which was completely different... in the physical processes proceeding during the explosion and even in the main energy-release source. Below, I call this proposal 'the first idea'" ([1], p. 9).

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A D Sakharov substantiated the physical principles of his proposal in the following way [2]:

"(1) In a *sloika* (Translator's note: named after a Russian layer cake), the local temperature equilibrium of matter and radiation is established. The question about the existence of such a detonation mode does not arise (this mode undoubtedly exists).... The width of the detonation wave zone is not very large.

(2) Thermal reactions produce fast neutrons in D, which can cause the fission of ^{238}U nuclei, resulting in a considerable increase in caloricity.

(3) The weak transparency of uranium to photons provides a moderate width of the shock wave zone moving ahead the burning zone.

(4) ...The temperature in adjacent phases is equalized by the heat conduction of radiation. Therefore, the equality of pressures in adjacent phases implies the equality in the number of particles in the U and D unit volumes; the ionized uranium 'swells', compressing D by its electron pressure...."

Sakharov's radical solution consisted first of all in passing to the ignition and burning of a compressed thermonuclear fuel, initially by a shock wave in the detonation mode and then by a process which was called 'sakharization', the conditions for them being produced by the heterogeneous structure of a system consisting of the thermonuclear material and uranium.

Primarily, A D Sakharov intended to make a large spherical uncompressed *sloika* with an initiating atomic bomb placed at its center. After visiting KB-11 (Design Bureau No. 11)[1] in June 1949, where he became familiar with the design of the RDS-1 device and discussed the problem with Yu B Khariton, Ya B Zel'dovich, and E I Zababakhin, Sakharov proposed the more efficient *sloika* design based on the implosion principle. An atomic detonator was placed at the center of the *sloika* surrounded by the layers of a thermonuclear fuel and uranium. The whole system was

[1] Later, the All-Union Research Institute of Experimental Physics and, after 1992, the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–ARRIEP)

compressed with an explosive placed outside a multilayer system, while the *sloika* was initiated by implosion and explosion of an atomic detonator.

This was an exceptionally fruitful and pragmatic combination of the fundamental physical ideas of the *sloika* and implosion.

The principal features of the *sloika* allowed varying widely the features of its design and materials of its composition. The first such proposal was made almost at once after A D Sakharov's formulation of the main ideas. He wrote about this the following: "Soon my proposal was substantially supplemented by V L Ginzburg, who put forward 'the second idea' ([1], p. 9). On 3 March 1949, V L Ginzburg pointed out in the account, "The use of ^{6}LiD in the 'sloika'", "The advantages of using the deuterium-containing material $^6_3$LiD in the 'sloika' are noted. In this case, the reaction $^6_3\mathrm{Li} + ^1_0\mathrm{n} \rightarrow ^4_2\mathrm{He} + ^3_1\mathrm{H}$ produces tritium $^3_1\mathrm{H} \equiv \mathrm{T}$, which, taking part in reactions $\mathrm{D} + \mathrm{T} \rightarrow ^4_2\mathrm{He} + \mathrm{n}$ and $\mathrm{T} + \mathrm{T} \rightarrow ^4_2\mathrm{He} + 2\mathrm{n}$, yields neutrons producing uranium fission" [3].

These principles were fundamental for all the thermonuclear weapons, and they were first realized in practice in combination with gas-dynamic implosion (RDS-6s) and then with atomic compression (RDS-37), which was implemented by A D Sakharov and researchers under his supervision. All this determined the basic features and properties of thermonuclear modules of several generations of military equipment of our nuclear arsenal for a few decades, up to the present time.

A D Sakharov worked on the *sloika* in I E Tamm's theoretical group organized in summer 1948 to tackle the thermonuclear problem at the Lebedev Physical Institute, Academy of Sciences of the USSR (FIAN) and later, in early 1950, transferred to KB-11. A D Sakharov's attitude toward I E Tamm is characterized by his wonderful words: "I want to express my gratitude to I E Tamm who never spared either time or effort to put me on the right scientific path" [4].

"...We were all very lucky that Igor Evgen'evich happened to be nearby.... Near a blackboard in his office, we received the methodical lesson of theoretical studies. At conferences with authorities, we received the lesson of the businesslike, human, and scientific fidelity to principles. And in any circumstances, he gave us the lesson of good faith and thoughtful industry" [5].

A D Sakharov wholeheartedly adopted this style of scientific work and then cultivated it among his younger colleagues in our institute. This style became the fundamental basis for the efficient scientific search and practical realization of ideas for the development of many nuclear and thermonuclear weapon designs.

A D Sakharov and his colleagues were faced with extremely complicated problems. Here, I will point out only some of them. At the initial stage of the work, neither A D Sakharov nor I E Tamm nor V L Ginzburg knew about the unique quality of tritium as a thermonuclear fuel related to the fact that the rate of the tritium–deuterium (TD) reaction is two orders of magnitude higher than the rate of the deuterium–deuterium (DD) reaction. These data were classified and not available to them until May 1949. The required data on neutron-nuclear processes for TD neutrons and the conversion of neutrons to tritium on the ^{6}Li isotope were also absent. It was clear that hydrodynamic instabilities will develop in a layered system, their scale being rather uncertain. The data on the gas-dynamic implosion of layered systems were absent. To study the burning of nuclear and thermonuclear materials in the *sloika* and the energy release in it, sophisticated mathematical calculations were required to perform, which had no precedent. It was necessary to find out how nuclear tests should be conducted to reach a comprehensive conclusion about the quality of realization of thermonuclear burning.

By the summer 1953, all these issues were resolved. The answers to many of them were obtained within the framework of fundamental physics, and their importance lies in the fact that they laid the groundwork for the development of thermonuclear weapons in our country.

2. Creation of the RDS-6s *sloika*

On 15 July 1953 (less than one month before the test), an account with theoretical calculations substantiating the operation of a model of the RDS-6s hydrogen bomb (referred to as gadget in the confidential materials), signed by I E Tamm, A D Sakharov, and Ya B Zel'dovich, was written.

The account was called "A model of the RDS-6s gadget", although the tested model "does not differ from the military gadget except for the mass of active materials, which is 2–3 times greater in the military gadget." Below, we follow Sakharov's original text [6].

The account contained four main parts:

I. Operation principles and basic properties of the RDS-6s gadget.

II. Studies of the processes taking place during the operation of the RDS-6s gadget.

III. Analysis of the reliability of the RGS-6s gadget.

IV. Tasks and RDS-6s testing methods.

In part I, the basic principles of the physical layout of the RDS-6s gadget, thermonuclear reactions, the problems of tritium regeneration on the ^{6}Li isotope, and the fission of uranium nuclei by thermonuclear neutrons are considered.

The operational process of the gadget consisted of a few stages. The first was the implosion of the gadget by a spherically symmetric converging detonation of an explosive, ending with the operation of a neutron initiator, similar to the initiator in the first atomic bomb, RDS-1.

The second stage began with the initiation of a chain reaction in fission material and represented a nuclear explosion intended to stimulate a thermonuclear reaction.

The third stage began with an increase in temperature in the internal thermonuclear fuel, achieving a level sufficient for thermonuclear burning. This process led to the burning of uranium nuclei and the ignition of the next layer of the thermonuclear fuel. At this stage, the sakharization process became important.

In this part of the account, the expected energy release and its distribution over the main energy releasing layers are presented. These fundamental values were obtained from the 'exact' mathematical computation performed by L D Landau's group.

In the second part of the account with theoretical calculations, the authors pointed out: "At the beginning of the work on RDS-6s, quantitative data on basic processes determining the behavior of a nuclear detonation of the hydrogen gadget were missing, and thus it was impossible to calculate the power of the gadget and the amount of tritium required to make it.

To obtain these data, it was necessary to perform numerous experimental and theoretical studies and to improve considerably the accuracy of nuclear measurements and mathematical calculations."

The authors of the account point out that, to calculate the parameters of the hydrogen gadget, it was necessary to know first of all the cross sections for various elementary processes. "The most comprehensive investigations of the rate of the D + T reaction were performed at the Physical Institute, USSR Academy of Sciences (I M Frank's laboratory).... The results obtained considerably improve and correct data published in the foreign literature. The achieved accuracy is outstanding for such complicated investigations. These studies have shown with a complete confidence that the rate of the D + T thermonuclear reaction is extremely high, which is fundamentally important for the development of RDS-6s" [6].

The authors write about the fission parameters for uranium nuclei bombarded by thermonuclear neutrons: "Neither the fission cross section nor the number of secondary neutrons produced during the fission of ^{238}U irradiated by 14-MeV neutrons are published in the literature. These quantities were repeatedly and carefully measured at the Physical Institute of USSR AS, Institute of Chemical Physics, Laboratory of Measuring Instruments, Hydraulic Engineering Laboratory, and KB-11 and were found to be considerably higher than those for neutrons produced in the chain reaction" [6].

Then, the authors of the account write about the regeneration parameters of tritium: "The data on the interaction of neutrons with ^{6}Li available in the literature were inaccurate and contradictory. The cross section for the reaction of tritium production and neutron scattering was studied at the Ukraine Physical and Technical Institute and the Institute for Physical Problems. It was found that the cross section had a maximum at a neutron energy of about 250 keV, and data from the literature were quantitatively refined" [6].

An important part of experimental nuclear investigations comprised physical measurements with RDS-6s models, in which the numbers of ^{238}U fission events caused by TD neutrons and their 'offsprings' were determined. "The models were fabricated in numerous variations and consisted of layers containing uranium and a light material.... The great part of these complex and time-consuming experiments were performed in 1951–1953 at KB-11, the Hydraulic Engineering Laboratory, and FIAN. A method for calculating the number of fission events during detonation, based on the theoretical processing of these experiments, was developed" [6].

A separate group of model experiments was conducted to study the capture parameters for neutrons in ^{6}Li. Experiments in this area were performed at KB-11 using equipment developed at the Institute for Physical Problems of USSR AS. Some experiments were also conducted at the Hydraulic Engineering Laboratory.

An efficient and symmetric implosion was very important for the success of the project. The authors write in the account [6]: "Compression in RDS-6s proceeds somewhat differently than in gadgets tested earlier. These features of the compression process take place due to the presence of alternating light and heavy layers."

The results of implosion calculations were verified by several experimental methods. "Altogether, more than 300 experiments were performed with models during the development of the design and about 40 experiments with charges of natural size, but representing only a part of a sphere... for the convenience of observation and accommodation of the measuring equipment" [6].

The authors write about the influence of mixing: "Mixing is performed in two stages. In the compression stage, the interfaces of the layers become uneven and rough. In the nuclear detonation stage, all materials are transformed into gas; the interface roughnesses rapidly increase, leading to chaotic, turbulent mixing.

The theory of turbulent mixing was developed by S Z Belen'kii at FIAN by using experimental data obtained at KB-11 and LIPAN.[2] A commission organized at KB-11 considered the possible role of mixing effects and estimated that they can reduce the energy detonation effect by no more than 20–25%....The direct and indirect investigation of the role of mixing effect during nuclear detonation at testing ground No. 2 is becoming very important" [6].

The indirect answer to the influence of mixing was received from the results of RDS-6s tests.

Mathematical calculations were extremely important for understanding processes proceeding in RDS-6s and determining the parameters of the gadget.

"The presence of the layered structure in the system does not allow one to use averaged quantities and requires the knowledge of accurate values of temperature, material density, density of neutrons, etc. in each of the layers.

Methods for 'detailed' calculations of detonation processes were developed in A N Tikhonov's and L D Landau's groups on the orders by KB-11...

The development of these mathematical methods for detailed calculations for KB-11 required serious research and time-consuming calculations. In the course of the search for the optimal variant of RDS-6s and methodical investigations, 12 detailed calculations of hydrogen gadgets were performed (7 calculations at A N Tikhonov's bureau, 3 calculations at L D Landau's bureau, and 2 calculations at K A Semendyaev–I M Gel'fand's bureau). The number of arithmetical operations performed during these computations amounted to many tens of millions.

Note some principal moments. A method of calculations was developed in which small errors unavoidable in such cumbersome calculations are not accumulated and do not produce a considerable error in the final result. This method offers, in particular, possibilities for using electronic computers instead of slow and time-consuming manual calculations" [6].

The main task of the RDS-6s test was to produce a nuclear detonation using a thermonuclear reaction. Along with the measurement of the total energy release, it was necessary to obtain data on the rate of the thermonuclear reaction and its proceeding conditions. It was assumed that "these data will provide the possibility for the reliable design of RDS-6s gadgets of any power and size" [6].

Testing ground measurements included:

(i) the determination of the total energy release in the explosion;

(ii) radiochemistry measurements of the composition of materials produced during the detonation of RDS-6s, including the measurement of activation of special detectors placed in the gadget;

(iii) temporal characteristics of the detonation process;

(iv) investigations of the action of the shock wave and parameters of γ-rays and neutron radiation.

[2] The Laboratory of Measuring Instruments, USSR Academy of Sciences; today — National Research Centre 'Kurchatov Institute'. (*Editor's footnote*)

The RDS-6s test performed on 12 August 1953 completely confirmed the physical and constructive principles of the hydrogen bomb and its calculation methods. The total trotyl equivalent measured by different methods was 400 kt, coinciding within the measurement accuracy with the calculated power. The first thermonuclear module was created, whose significance is difficult to overestimate in light of the further development of thermonuclear weapons.

The outstanding successes of researchers and engineers in the development and testing of improved atomic bombs and the first thermonuclear bomb in the period from 1948 to 1953 had important scientific, technological, and political significance and were highly regarded by the USSR Government.

The main developers were awarded the Stalin Prizes of different classes and the highest decorations of our country. A D Sakharov's contribution was especially recognized. He was awarded the Stalin Prize of the First Class (with remuneration equivalent to a ten-year salary), received the title of a Hero of Socialist Labor, and was elected Full Member of the USSR Academy of Sciences, passing the step of Corresponding Member.

3. Atomic compression

The successful test of the *sloika* solved the formulated practical problem. However, two problems remained unsolved:

(i) the exclusion of large amounts of tritium from the composition of a thermonuclear charge with the power of ~ 1 Mt;

(ii) the development of multimegaton thermonuclear charges within the framework of existing restrictions imposed on the size and mass of the gadget by the carriers.

Initially, A D Sakharov and his colleagues attempted to solve these problems by optimizing the *sloika* under conditions of gas-dynamic implosion. However, they soon understood that it is necessary to achieve a considerably higher compression of the thermonuclear material compared to that obtained by utilizing ordinary explosives for compression.

"Already in the first months of new 1954, we theorists at the object understood that my proposals... promise nothing good... At the same time, we proposed a principally new idea which was conditionally called 'the third idea'. This idea had already been discussed earlier, rather as a wish, but in 1954 these wishes became a real possibility" ([1], pp. 10, 11).

The idea was to replace the hydrodynamic implosion of the *sloika* by its atomic compression. Initially, in January 1954, A D Sakharov and Ya B Zel'dovich considered the conceptual feasibility of compressing the *sloika* by gas-dynamic products of the nuclear explosion.

It was proposed to design the physical layout of the secondary module based on the analogue of the internal part of the RDS-6s charge, i.e. the 'layered' spherical system. It should be noted that it was an extremely complex system from the point of view of real computational capabilities of that time. The main problem was how to provide in such a charge the compression of the secondary module close to the spherically symmetric regime.

After that, the atomic compression acquired its canonical form in which X-rays were considered carriers for energy from the primary charge to the thermonuclear module. To produce the directional energy transfer, A D Sakharov proposed placing the primary and secondary modules inside one shell, which provided good reflection for X-rays. Inside the charge, conditions were established for the efficient transfer of X-rays in the required direction.

A D Sakharov described the development of the atomic compression idea in the following way:

"It seems likely that a few researchers in our theoretical departments came simultaneously to 'the third idea'. I was one of them. It appears to me that I understood the basic physical and mathematical aspects of 'the third idea' already at the early stage. Because of this, and also due to my authority acquired earlier, my role in the adoption and implementation of 'the third idea' was possibly one of the decisive ones. However, undoubtedly the role of Zel'dovich, Trutnev, and some others was also very important, and maybe they understood and foresaw the prospects and difficulties of 'the third idea' no less than I did" ([1], pp. 10, 11).

The third idea appeared as a fundamental scientific answer to the practical requirement of creating a qualitatively new universal thermonuclear weapon. This idea allowed us to exclude large amounts of tritium from thermonuclear charges and create multimegaton thermonuclear charges.

"Yu B Khariton, who trusted theorists and believed in a new line of inquiry, took a great responsibility on himself by sanctioning the reorientation of work at the object.... Kurchatov also knew about the course of events... Formally, our activity was blatant self-government.... Malyshev visited the object....[3] His speech was long and had no effect at all. We all retained at our opinion... Kurchatov decisively took our part" ([1], pp. 10, 11).

The path to practical realization of atomic compression was open, and the task was accomplished by the successful confirmation of this principle in the RDS-37 test on 22 November 1955.

The contribution of A D Sakharov to the development of the atomic compression principle and the RDS-37 gadget was highly regarded. He received the second title of a Hero of Socialist Labor and became, together with Ya B Zel'dovich, Yu B Khariton, and I V Kurchatov, one of the first laureates of the newly founded Lenin Prize, which was given him "for the development of physical principles and theoretical calculations of the RDS-37 gadget" [7].

The principle of atomic compression became the basis for the development of particular prototypes of military equipment for strategic nuclear forces and many complexes of nonstrategic weapons, while the RDS-37 gadget is rightly considered the prototype of the domestic thermonuclear weapons providing nuclear parity and nuclear deterrence guarantees.

4. Creation of a superbomb and development of new types of thermonuclear weapons

Consider briefly the history of the development of the superbomb.

The thermonuclear project appeared from the very beginning as the project of a superbomb, i.e. a bomb with a multimegaton energy release. The initial project based on the detonation of liquid deuterium, Super in the USA and 'Tube' in the USSR, was namely such a project. The initial choice of a *large sloika*, not using implosion, was also such a project.

In 1954, Edward Teller proposed the idea of the possibility of developing a thermonuclear charge providing

[3] V A Malyshev was the Minister of Medium Machine Building of the USSR.

an energy release of up to 10,000 Mt. In 1956, the Pentagon formulated the requirements for 100-Mt warheads, and the Los Alamos Laboratory substantiated the possibility of creating a 1000-Mt thermonuclear charge.

After the creation of RDS-37, the superbomb issue was considered again at a completely different level. In early 1956, A D Sakharov, Ya B Zel'dovich, and V A Davidenko proposed developing a series of superpower hydrogen bombs based on the atomic compression principle providing an energy release of up to 1 billion tons in the trotyl equivalent. This was the urgent proposal in response to the enormous increase in the thermonuclear arsenal in the USA, which achieved ~ 9 billion tons in the trotyl equivalent.

Initially, the 30-Mt superbomb was developing at the NII-1011 (Research Institute No. 1011) [4] (project No. 202). However, this project was cancelled.

After the end of the moratorium in 1961, KB-11 returned to the question of developing the superbomb. Now, it was entrusted with creating a 100-Mt thermonuclear charge (project No. 602). Original solutions and accumulated experience allowed researchers and engineers to realize very rapidly this development, and the charge was successfully tested on 30 October 1961. Beginning in 1961, increases in the megaton-range nuclear arsenal of the USA ceased.

The full-scale test of a 100-Mt charge would result in a considerable radioactive yield determined by the ^{238}U fission products. The danger was aggravated by the fact that the height of the explosion of a dropped aerial bomb was insufficient to exclude the touch of an explosion fire ball with Earth's surface, which would considerably increase the radioactive contamination. A D Sakharov proposed and realized the test of the superbomb at less than full scale. Uranium-238 in the thermonuclear module was replaced by passive, nonfissile, and weakly activated materials. The reduction of the energy release to 50 Mt excluded the touch of the fire ball with Earth's surface. Thus, despite the huge energy release, this test was comparatively ecologically safe.

In 1961–1962, A D Sakharov was in charge of the development and successful tests of a few dozen thermonuclear charges of different types, which became the foundation of our nuclear arsenal until the mid-1970s. Importantly, all these charges were based on the sloika and atomic compression principles. The tests of these charges gave unique experimental material about the features of pulsed thermonuclear burning, which is widely used at present in different tasks related to maintaining the nuclear arsenal of Russia.

For his work on the creation of the superbomb and supervision of the development of thermonuclear charges, A D Sakharov was awarded a third Hero of Socialist Labor title.

At this period, A D Sakharov was the head of the theoretical department responsible for the development of thermonuclear weapons. I D Sofronov, an outstanding mathematician and organizer of mathematical studies at the RFNC–ARRITP, wrote the following about the working style of A D Sakharov as the head:

"Andrei Dmitrievich invited me in early 1961. He explained that the Government was considering the question about a long moratorium.... We should prepare for it... and develop for a short time many new constructions and test them.... Sakharov enumerated the approximate number of calculations of different types and the desired schedule of their fulfillment" [8]. And below he continued:

"Before the emergency work, A D gave the impression of a rather phlegmatic man, who was sitting, as a rule, in his office and was somewhat 'aloof from the world'. However, during the emergency work period, he changed and became the strong-willed and energetic leader who was completely on top of all the work. His voice acquired new strength. Every morning he... invited all the participants of the emergency work and gave them clear instructions. Sakharov gave the impression of a general guiding a battle" [8].

5. Fundamental physical ideas suggested by A D Sakharov during his work at KB-11

In 1950, A D Sakharov formulated the most important idea for the projects of 'continuous' thermonuclear energy production — the idea of magnetic plasma confinement, and outlined the general features of a magnetic thermonuclear reactor (MTR) which became the prototype of tokamaks and the modern project of the International Thermonuclear Experimental Reactor (ITER).

A D Sakharov's studies in 1950 in the field of explosive implosion, on the one hand, and on using a magnetic field for thermal insulation of plasma, on the other hand, undoubtedly initiated his new fundamental idea of magnetic cumulation (MC), i.e. the conversion of the explosion energy to magnetic field energy. A D Sakharov formulated the idea of "compression of a bundle of magnetic lines of force by the moving metal walls of a cylinder" and proposed conceptual schemes of devices for practical realization of this idea ([1], p. 79) to obtain superstrong megagauss-range magnetic fields (MC-1 device) and high-intensity megaampere-range currents (MC-2 device), based on the explosive action on 'current-carrying circuits'.

These proposals were then extensively developed at the RFNC–ARRIEP. At present, magnetic explosion generators (MEG) are used in various fields, from fundamental studies of physical properties of materials under extreme conditions to the investigation of the formation processes and action of electromagnetic pulses. This is a large field in physics in which our Institute has occupied a leading position in the world, while work based on MEG technologies is the direct creative legacy of A D Sakharov.

A D Sakharov was the originator of laser fusion.

"In 1960–1961, I again made a proposal concerning a controlled thermonuclear reaction. At this time, a communication came that Maiman had created the first (ruby) laser in the USA. I gave a talk at our object in which I substantiated the possibility of using a laser to excite a thermonuclear reaction in small spheres containing a thermonuclear fuel and compressed due to hydrodynamic effects during the pulsed heating of the external surface of spheres by the laser beam. I presented estimates of the parameters required for such devices. Later on, these estimates were refined in a series of numerical computer-aided calculations performed by my collaborators.... I specified power engineering as a possible field for application of this principle..." ([1], p. 36).

These ideas were extensively developed at the RFNC–ARRIEP. We have built a number of high-power laser facilities at which we performed and are performing now

[4] Today — the Russian Federal Nuclear Center 'Zababakhin All-Russian Research Institute of Technical Physics' (RFNC–ARRITP). (*Editor's footnote*)

unique experiments with microtargets of different types, including thermonuclear microtargets.

At present, the outlook for studying the properties of materials under extreme conditions is related to the use of high-power megajoule-range laser facilities. Such facilities are being constructed in the USA, France, and China. The absence of such a facility in Russia inhibits achievement of unique fundamental results in this field. In the last year, a crucial decision was announced to build a megajoule laser facility at the RFNC–ARRIEP.

6. Initiatives in nuclear test and nuclear arms limitations

The name A D Sakharov is related to a number of important stages in nuclear arms limitation.

In 1958, he initiated a wide discussion of long-term radiological hazards caused by the action, in particular at the genetic level, of radiocarbon C-14 accumulating in the biosphere after atmospheric nuclear tests. This was an important argument for the atmospheric nuclear test ban.

At a period from 1958 to 1961, the USSR, USA, and Great Britain imposed the three-party nuclear test moratorium.

A D Sakharov played an important role in the 1963 Treaty Banning Nuclear Weapon Test in the Atmosphere, in Outer Space and Under Water, signed in Moscow. He wrote later: "I believe that the Moscow Treaty has historical significance. It has preserved hundreds of thousands and possibly millions of human lives that would inevitably perish during these tests.... But maybe even more important is that this is a step toward reducing the danger of world thermonuclear war. I am proud of my involvement in the Moscow Treaty" [9].

A D Sakharov was one of the initiators of the limitation of the development of antiballistic missile defense (AMD). He wrote in 1967:

"Let me explain briefly my opinion about the essence of the issue....

...Protection from a strike of a small number of enemy and provocateur missiles... on any, preliminarily unknown target... is technically possible; however, one should understand that the solution of even this 'simplified' problem will require very large investments of intellectual and material resources at a great scale comparable to the development of the offensive massive strike system. This includes the construction of a huge network of stations for enemy missile detection and antimissile guidance, of computational stations and communication lines, the development of methods for separating false aims, and the creation of highly maneuverable antimissiles... used at near and distant defense frontiers" [10].

"Although the AMD system in itself is not intended for assault or aggression, it can serve for aggressors as a means providing impunity, thereby increasing the temptation of a preventive war. Therefore, the refusal of the USSR and USA to enter into AMD would be a spectacular demonstration of their readiness to coexist.

The absence of a moratorium treaty will lead to a race of not only defensive but also offensive systems, which would be ramped up to guarantee a defensive breakthrough. Such an outcome is unprofitable for us economically, politically, and strategically... reducing the possibility of a 'general political settlement' " [10].

"...Offensive arms exhibit a so-called 'saturation effect' — if you can annihilate the enemy, further strengthening changes almost nothing. However, AMD has no 'saturation effect', and the outcome of the competition is determined, on the contrary, by the relation of technical and economical potentials.... By signing the moratorium treaty, the USSR and USA thereby abandon the mutually menacing policies and the temptation of striking a preventive blow under protection of the antimissile 'shield' producing the illusion of security....

Such a treaty would encourage peaceful coexistence forces and facilitate further steps in the field of disarmament and the reduction of tension" [10].

The conclusions reached by A D Sakharov became, in fact, the intellectual basis for the position of our country with respect to AMD for many decades, even now.

These conclusions are still mainly correct today, as the USA has abandoned the AMD Treaty and is developing national and regional AMD systems employing space technologies.

Amazingly, many of A D Sakharov's achievements in science are ongoing and developing today. Tens of institutes and laboratories in many countries are involved in studies developing his ideas. I will end this small review with his words appealing to the future:

"It is known... that the USSR, the USA, and other countries are performing extensive work to achieve a thermonuclear reaction with the help of laser ablation (and by means... of some other inertial methods). However, I think that systems based on magnetic thermal insulation are most promising for large-scale power engineering.... I suppose that these will first be breeder systems in which the energy source will ultimately be a fission reaction. As for systems not using uranium and thorium... I assume they will use 'tritium breeding'.... It is quite possible that energy production in the 21st and following centuries will be based on controlled nuclear fusion facilities. My participation in the early studies on a controlled thermonuclear reaction is a source of great satisfaction for me" ([1], p. 36].

References

1. Sakharov A D *Nauchnye Trudy* (Scientific Works) (Editorial Board: L Altshuler, L V Keldysh (Chair), D A Kirzhnits, V I Ritus) (Moscow: OTF FIAN – TsentrKom, 1995)
2. Sakharov A D "Statsionarnaya detonatsionnaya volna v geterogennoi sisteme A-9 + '180' " ("Stationary detonation wave in the A-9 + '180' heterogeneous system"), in Andryushin I A, Ilkaev R I, Chernyshev A K *'Sloika' Sakharova. Put' Geniya* (Sakharov's 'Sloika'. The Path of a Genius) (Sarov: FGUP "RFYaTs–VNIIEF", 2011) p. 144
3. Ginzburg V L "1. Ispol'zovanie ^{6}LiD v 'sloike'. 2. Vliyanie vzaimodeistviya mezhdu yadrami urana v 'sloike' " ("1. The use of ^{6}LiD in the 'sloika'. 2. The influence of interaction between uranium nuclei in the 'sloika' "), in Andryushin I A, Ilkaev R I, Chernyshev A K *'Sloika' Sakharova. Put' Geniya* (Sakharov's 'Sloika'. The Path of a Genius) (Sarov: FGUP "RFYaTs – VNIIEF", 2011) p. 146
4. "Stenogramma zasedaniya Uchenogo Soveta FIAN SSSR im. Lebedeva ot 3 noyabrya 1947 goda" ("Stenography of a meeting of the Scientific Council of LPI on 3 November 1947"), in Sakharov A D *Nauchnye Trudy* (Scientific Works) (Editorial Board: B L Altshuler, L V Keldysh (Chair), D A Kirzhnits, V I Ritus) (Moscow: OTF FIAN – TsentrKom, 1995) p. 481
5. Sakharov A D "Pamyati Igorya Evgen'evicha Tamma" ("To the memory of Igor Evgen'evich Tamm"), in Sakharov A D *Nauchnye Trudy* (Scientific Works) (Editorial Board: B L Altshuler,

L V Keldysh (Chair), D A Kirzhnits, V I Ritus) (Moscow: OTF FIAN – TsentrKom, 1995) p. 420
6. Tamm I E, Sakharov A D, Zel'dovich Ya B "Model' izdeliya RDS-6s" ("RDS-6s gadget model"), in Andryushin I A, Ilkaev R I, Chernyshev A K *'Sloika' Sakharova. Put' Geniya* (Sakharov's 'Sloika'. The Path of a Genius) (Sarov: FGUP "RFYaTs–VNIIEF", 2011) pp. 92 – 95
7. "Postanovlenie SM SSSR No. 1253-634 ot 7 sentyabrya 1956 goda" ("USSR Council of Ministers Resolution, No. 1253–634 of 7 September 1956"), in Andryushin I A, Ilkaev R I, Chernyshev A K *Reshayushchii Shag k Miru. Vodorodnaya Bomba s Atomnym Obzhatiem RDS-37* (A Decisive Step to Peace. The RDS-37 Hydrogen Bomb with Atomic Compression) (Sarov: FGUP "RFYaTs – VNIIEF", 2010) p. 88
8. Sofronov I D "Rabota s A.D. Sakharovym" ("Work with A D Sakharov"), in *Materialy Otkrytogo Zasedaniya NTS VNIIEF, Posvyashchennogo 80-Letiyu so Dnya Rozhdeniya A.D. Sakharova* (Materials of the Open Meeting of the Scientific and Technical Council of the RFNC–VNIIEF Commemorating A D Sakharov's 80th Birthday) (Sarov: RFYaTs – VNIIEF, 2003)
9. Sakharov A *Vospominaniya* (Recollections) (New York: Izd. im. Chekhova, 1990) p. 309
10. Sakharov A D "Pis'mo v TsK KPSS 27 iyulya 1967 goda" ("Letter to the Central Committee of the Communist Party of the Soviet Union of 27 July 1967") (Special Archive of the RFNC–VNIIEF)

CONFERENCES AND SYMPOSIA

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

Tokamaks: from A D Sakharov to the present (the 60-year history of tokamaks)

E A Azizov

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Contents

Abstract. **The paper is prepared on the basis of the report presented at the session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) at the Lebedev Physical Institute, RAS on 25 May 2011, devoted to the 90-year jubilee of Academician Andrei D Sakharov — the initiator of controlled nuclear fusion research in the USSR. The 60-year history of plasma research work in toroidal devices with a longitudinal magnetic field suggested by Andrei D Sakharov and Igor E Tamm in 1950 for the confinement of fusion plasma and known at present as tokamaks is described in brief. The recent (2006) agreement among Russia, the EU, the USA, Japan, China, the Republic of Korea, and India on the joint construction of the international thermonuclear experimental reactor (ITER) in France based on the tokamak concept is discussed. Prospects for using the tokamak as a thermonuclear (14 MeV) neutron source are examined.**

1. Introduction

Prior to the commencement of controlled thermonuclear fusion (CNF) research, the history of humankind presumably had not encountered a vital technical problem which required more than 20 years for its solution. This 'historical' rule is consistent with the well-known statement made by the Indian physicist Homi J Bhabha at the United Nations First International Conference on Peaceful Uses of Atomic Energy held in Geneva in 1955: "I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades."

At the 2nd (1958) Geneva Conference, the English physicist P C Thonemann stated that "it is still impossible to answer the question, 'Can electrical power be generated using the light elements by themselves?' I believe that this question will be answered in the next decade. If the answer is yes, a further ten years will be required to answer the next question, 'Is such a power source economically valuable?' "

At the 1st (1961) IAEA Fusion Energy Conference in Salzburg, M N Rosenbluth (USA) delivered the summing-up report about the achievements in plasma theory and stated: "While it is unfortunately true that theorists have not told the experimentalists how to build a thermonuclear machine, it is also true that we have been looking hard for very many years for a fundamental reason why a plasma fusion reactor should be impossible and we have not found any such reason." Next, he added: "If I may make a statement from the heart, I believe the chances are very good that in twenty years or so mankind will have solved the problem of controlled fusion if only he has not lost in the meantime the far more difficult struggle against uncontrolled fusion."

Today, 60 years after the commencement of controlled thermonuclear fusion research, we may conclude that the complexity of the problem was strongly underestimated in the initial stage of the work, especially so when it is considered that the final objective, namely the demonstration of electric power production by a thermonuclear power plant, is still several decades away.

This paper gives a brief review of the development of the concept of magnetic thermal insulation of plasma, which was proposed by Andrei D Sakharov and Igor E Tamm in 1950

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and which underlies the international thermonuclear experimental reactor (ITER) project presently being implemented jointly by the European Union, India, China, Korea, Russia, the USA, and Japan in France.

2. Conception of magnetic thermal insulation of plasma. Magnetic fusion reactor

In 1950, an undistinguished event occurred, whose description by the well-known theoretical physicist and a future Full Member of the RAS Vitaly Dmitrievich Shafranov would open with the humorous couplet:

Listen, guys, to the story of yours,
It all commenced with a soldier who served.

The case in point is sergeant Oleg Aleksandrovich Lavrent'ev, who served in the Army on Sakhalin and wrote a letter to the Central Committee of the Communist Party of the Soviet Union (Bolsheviks) (CC CPSU) on 22 July 1950 to propose:

(i) the use of lithium-6 deuteride instead of liquefied deuterium and tritium in a hydrogen bomb;

(ii) the development of a system with electrostatic confinement of hot plasma for realizing controlled thermonuclear fusion.

It was not long before this letter found itself under review by Candidate of Physicomathematical Sciences Andrei Dmitrievich Sakharov (from 1953 — Doctor of Physicomathematical Sciences, Full Member of the USSR Academy of Sciences), who was working at that time on the development of a hydrogen bomb in the secret town of Arzamas-16 (Sarov). Sakharov later reminisced about that episode:

"In the summer of 1950, a letter was delivered from Beria's secretariat to our organization with a suggestion by a young sergeant Oleg Lavrent'ev, who was serving in the Army on Sakhalin. In its introductory part, the author wrote about the significance of the problem of controlled thermonuclear reaction for the future power engineering....

"...In my review I wrote that the idea of controllable thermonuclear reaction conceived by the author is extremely important.... As regards Lavrent'ev's concrete scheme I wrote that it seemed to me unrealizable, because it did not preclude the contact of hot plasma with grids... While reading the paper, I conceived the first foggy ideas of magnetic thermal insulation....

"Early in August 1950, Igor Evgen'evich [Tamm] returned from Moscow.... He expressed genuine interest in my reflections — subsequently we developed the idea of magnetic thermal insulation entirely in our collaborative work. I E's contribution was especially valuable in all calculations and estimates, as well as in the treatment of the main physical concepts — magnetic drift, magnetic surfaces, and some others [1]."

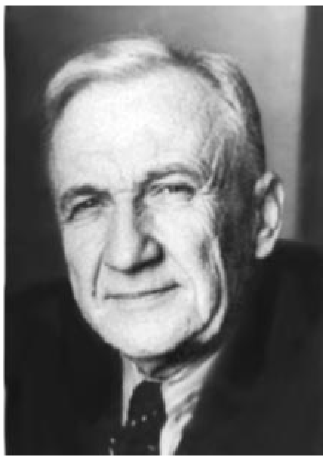
By October 1950, Sakharov and Tamm had completed a preliminary theoretical substantiation of the magnetic thermonuclear reactor (MTR) and made the first estimates of its parameters. In January 1951, I V Kurchatov organized a discussion of the project among the leading physicists involved in the Soviet Atomic project. The meeting supported the continuation of work on the MTR, and in February 1951 I V Kurchatov forwarded to Beria [1] a draft governmental resolution about organization of work on the MTR. On May 5, 1951 the resolution was approved by Stalin. According to the resolution of the USSR Council of Ministers, the task of working on the MTR issue was entrusted to the Laboratory of Measuring Instruments (LIPAN in *Russ. abbr.*, presently the National Research Centre 'Kurchatov Institute'). L A Artsimovich was charged with responsibility for the whole project, and M A Leontovich became supervisor of theoretical research. The originators of the suggestion, A D Sakharov and I E Tamm, were invited as permanent consultants.

In Sakharov's report [2] he came up with the idea of confining hot plasma in a toroidal chamber with a strong longitudinal magnetic field. To compensate for the toroidal drift of charged particles, it was suggested to induce, along with the toroidal magnetic field, a poloidal magnetic field, either by passing electric current along a ring conductor placed inside the plasma or by exciting longitudinal current in the plasma itself with the help of a poloidal coil located outside of the vacuum chamber. To maintain the stability of the major discharge radius, Sakharov proposed the employment of a copper casing.

[1] Lavrentiy Beria headed the Special Committee which was founded first under the USSR State Defense Committee in August 1945 "for supervising all the work on the use of the intraatomic energy of uranium."


O A Lavrent'ev
(07.07.1926 – 10.02.2011)


A D Sakharov
(21.05.1921 – 14.12.1989)


I E Tamm
(08.07.1895 – 12.04.1971)

Initiators of controlled thermonuclear fusion research.

Table 1. Parameters of the 'large model' of an MTR.

Major torus radius	R	12 m
Minor plasma column radius	a	2 m
Toroidal magnetic field	B_t	5 T
Longitudinal plasma current	I	0.2 MA
On-axis deuton density	n_0	3×10^{20} m^{-3}
On-axis plasma temperature	T_0	100 keV
Thermonuclear power	P_{DD}	880 MW
Tritium recovery	N_T	100 g (per day)

Sakharov's calculations, which relied on classical transport coefficients and neglected the curvature of the system, resulted in the parameters of the 'large model' of an MTR, collected in Table 1 [2].

I E Tamm [3, 4] proposed the general methods of solving the kinetic equation for toroidal plasmas in the presence of a stabilizing current and showed that the thermal plasma conductivity in a torus may be substantially higher than in a straight cylinder for equal magnitudes of a longitudinal magnetic field and a current-induced magnetic field. At about the same time, G I Budker [5] called attention to the special features of the behavior of particles with a low relative longitudinal velocity, which should be rapidly lost from the plasma.

Unfortunately, this basic work by I E Tamm and G I Budker was not continued and was soon forgotten. Their findings were rediscovered and further elaborated on more than ten years later by D Pfirsch and A Schlüter (1962) [6], V D Shafranov (1965) [7], and A A Galeev and R Z Sagdeev (1967) [8].

3. 1955–1969 experiments

The first toroidal facility with a strong longitudinal magnetic field, based on the ideas of A D Sakharov and I E Tamm and known as TMF (torus with a magnetic field) (Fig. 1) [9], was constructed under I N Golovin's and N A Yavlinskii's supervision at LIPAN in 1955. This facility had the following parameters: $R = 0.8$ m, $a = 0.13$ m, $B_t = 1.5$ T, and $I = 0.26$ MA. The plasma volume, $V = 0.27$ m^3, was approximately 3500 times smaller than that in the MTR project discussed in Section 2. The porcelain discharge chamber was enclosed in a copper casing with slits; a stainless steel helix was accommodated inside the chamber near the wall to weaken the plasma–porcelain contact. The electron temperature was low ($\leqslant 10$ eV), which was due to the high level of radiative energy losses.

Subsequent facilities of this type received the name tokamak (an acronym comprising the initial syllables of the word combination '*to*roidal'naya *ka*mera *mag*nitnaya', where the letter 'g' was replaced with letter 'k' for euphony) [10].

During 1955–1965, eight facilities of this type (TMF, T-1, T-2, T-3, T-5, TM-1, TM-2, and TM-3) were built at the Kurchatov Institute, i.e. on average nearly every year saw the construction of a new facility. This underlay the relatively rapid progress in the revelation of and recovery from the 'childhood diseases' of tokamaks, like excessive inflow of impurities into the plasma and a high level of 'scattered' magnetic fields from external circuits.

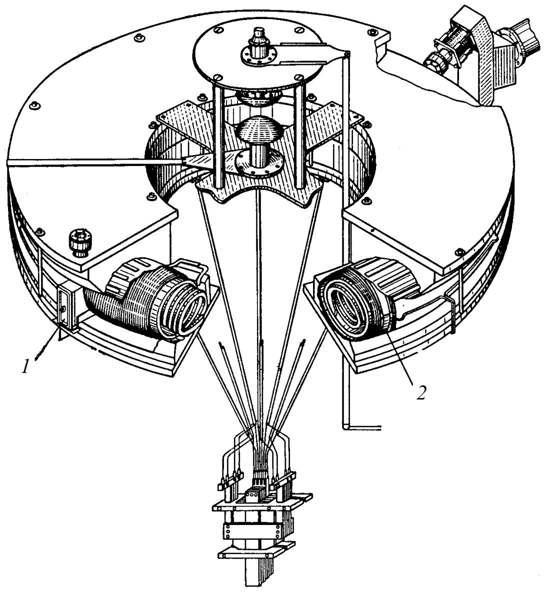


Figure 1. Schematics of the toroidal chamber with coils: *1* — window for photographing, and *2* — longitudinal magnetic field coil.

At the T-1 facility ($R = 0.62$ m, $a = 0.13$ m, $B_t = 1.0$ T, $I = 0.04$ MA) [11], it was shown for the first time that fulfillment of the condition $q_a = 5a^2 B_t / RI > 1$, which is known as the Shafranov–Kruskal criterion, where q_a is the so-called stability margin, is necessary for improving the macroscopic plasma stability. Furthermore, it was shown that the plasma in the facility with a metal chamber without baking also loses 80–90% of the energy due to the radiation of impurity atoms.

The T-2 facility, which was close in parameters to the T-1 facility, had a stainless steel bellows vacuum chamber bakeable to 400–450 °C, with a limiter placed inside the chamber [12, 13]. As a result of chamber baking, the fraction of plasma radiation energy losses lowered to $\approx 30\%$. These experiments revealed the last of the childhood diseases of tokamaks. It turned out that the plasma column shifted inside the chamber by far longer distances than would be expected proceeding from the variation of plasma parameters. It was determined that the shifts were caused by the transverse component of the scattered magnetic field, which penetrated inside the chamber due to the nonideality of the conducting casing. After these experiments, all facilities under construction were equipped with special correcting and controlling coils, which cancelled out the scattered magnetic fields and controlled the position of the plasma column.

Comprehensive investigations of plasma equilibrium inside the conducting casing and a comparison of their results with theoretical ones were performed on the T-5 facility ($R = 0.625$ m, $a = 0.2$ m, $B_t = 1.2$ T, $I = 0.045$ MA) in 1961–1964. In 1965, this facility was transferred to the A F Ioffe Physical-Technical Institute (PTI) (Leningrad), where it received the name FT-1.

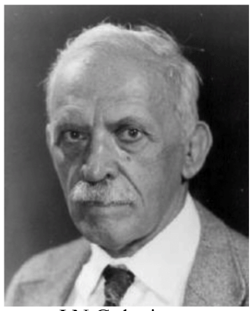
A larger facility, T-3 ($R = 1.0$ m, $a = 0.06$ m, $B_t = 4.0$ T, $I = 0.06$ MA), was built in 1960. Before long it was upgraded and was termed T-3A ($R = 1.0$ m, $a = 0.15$ m, $B_t = 3.8$ T, $I = 0.14$ MA).

In 1962, E P Gorbunov and K A Razumova obtained for the first time a discharge which retained macroscopic stability throughout the current pulse on the TM-2 facility ($R = 0.4$ m,

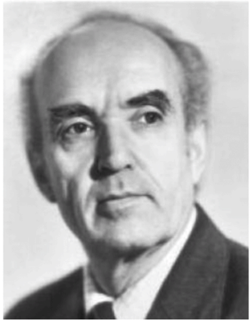

I V Kurchatov

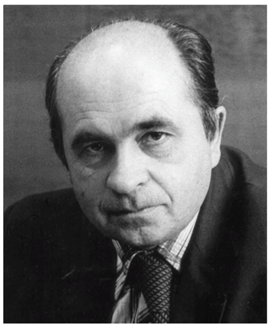

L A Artsimovich


M A Leontovich


I N Golovin


N A Yavlinskii


V D Shafranov


B B Kadomtsev


E P Velikhov

Supervisors of the thermonuclear program at the Kurchatov Institute.

$a = 0.08$ m, $B_t = 2.2$ T, $I = 0.02$ MA) with a rather large stability margin: $q_a \approx 5$. They identified the most dangerous instability in a tokamak — disruption instability [14].

The lowering of radiation energy losses and attainment of stable modes put on the agenda the question about the plasma energy transport lifetime $\tau_E = W/(P_{heat} - P_{rad} - \mathrm{d}W/\mathrm{d}t)$, where W is the store of plasma kinetic energy, P_{heat} is the power of heating, and P_{rad} is the radiation loss power. These investigations were carried out primarily at the TM-2 (TM-3 after the 1966 upgrade) and T-3 (T-3A after the 1967 upgrade) facilities. In these experiments, the sum of electron and ion temperatures $\langle T_e + T_i \rangle$ averaged over the section of the plasma column was determined from diamagnetic signal measurements (K A Razumova on TM-2, S V Mirnov on T-3A) and multichannel interferometric electron density measurements (E P Gorbunov). Proceeding from these data, it was possible to obtain for the first time in the history of tokamaks the similarity law for the plasma energy lifetime, which has come to be known as GMS scaling,[2] or Mirnov scaling [15]. Its more recent version assumes the form $\tau_{MI} = (0.05 - 0.15) f_L a I \kappa^{0.5}$ ($f_L \sim 1$ for the L mode, and $f_L \sim 2$ for the H mode). This scaling law also predicts, correct to $\approx 50\%$, the magnitudes of τ_E in present-day tokamaks. The magnitudes of τ_E obtained in these experiments were also compared with the so-called Bohm time $\tau_B \approx 8a^2(eB/\kappa T_e)$ characteristic of turbulent plasmas. As reported by L A Artsimovich to the Second (1965) IAEA Fusion Energy Conference in Culham [16], the τ_E magnitudes in tokamaks turned out to be three times higher than the Bohm values observed in the majority of experiments at that time. In 1967, V S Strelkov reported to the 2nd Workshop on Plasma Confinement (Princeton, USA) the data on τ_E values in tokamaks, which exceeded τ_B by up to a factor of 10, while measurements on the C stellarator[3] yielded good agreement with the Bohm time [17]. Measurements of the energy spectra of fast neutral atoms at the T-3 facility were indicative of Maxwellian spectrum and yielded values of the ion temperature of several hundred electron-volts for the central regions of the plasma column (M P Petrov).

A year later, the evidences of further experiments on T-3A — magnitudes of τ_E up to 50 times higher than the Bohm time [18] — were presented at the 3rd (1968) IAEA Fusion Energy Conference in Novosibirsk. S V Mirnov, a participant in those experiments, thus described the events that followed [19]: "So important a result called for careful verification. Also there, in Novosibirsk, Director of the Culham Laboratory (England) R S Pease and L A Artsimovich reached the final agreement about the execution of a joint Soviet–English experiment in laser probing at T-3A. In spring of 1969, a group of experimentalists headed by N J Peacock came from Culham Centre for Fusion Energy to T-3A and brought experimental instrumentation. They were joined by D C Robinson, a Culham researcher working on an exchange basis at T-3A, and V V Sannikov from the Soviet side. It was precisely they, Robinson and Sannikov, who managed in July 1969, on transferring the English laser to the giant pulse mode, for the first time 'to force their way through' the plasma noise background and record the scattered laser radiation signal, which paved the way to the success of the experiment" (Fig. 2). The measured radial profiles of the electron temperature showed that the bulk electron temperature at the center of the plasma column amounts to ≈ 1 keV. These results, which were reported to the 2nd International Symposium on Plasma Confinement in Toroidal Systems in Dubna in autumn 1969, were hardly different from the diamagnetic ones [20, 21]. The doubts of the skeptics about

[2] GMS scaling is an abbreviation comprising the first letters of the surnames of all the authors of Ref. [15].

[3] A stellarator is a toroidal currentless magnetic trap, in which the magnetic configuration required for plasma confinement, unlike that in tokamaks, is produced by currents flowing in external conductors.

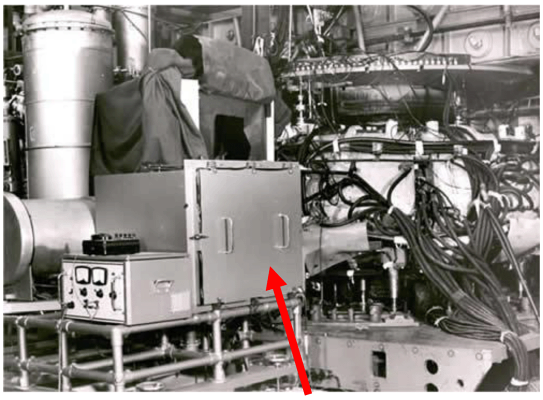


Figure 2. English laboratory equipment (indicated by an arrow) for measuring the electron temperature in T-3A by examining Thomson scattering of laser light.

the correctness of the interpretation of experimental data were thereby dispelled, and the Dubna Symposium proceeded as major triumph of tokamaks.

In parallel with the laser-assisted measurements of the electron temperature, intensity measurements of neutron radiation were made on T-3A in experiments on deuterium. The absolute magnitude of the neutron flux and the character of its temporal variation allowed a conclusion that the physical thermonuclear reaction was obtained for the first time in the T-3A tokamak in 1969 [22].

4. 1970–1990 experiments

After the Dubna Symposium, the world saw the onset of a 'tokamak boom'. While only one tokamak type facility — LT-3 in Canberra (Australia), with rather modest parameters ($R = 0.4$ m, $a = 0.1$ m, $B_t = 1$ T, and $I = 0.033$ MA) — had been constructed outside of the USSR prior to 1969, during the subsequent years tokamaks were built in 29 countries, including the USA, Japan, the majority of European countries, Canada, India, China, South Korea, Iran, Libya, and Egypt. In 1970, the C stellarator at Princeton was transformed to the ST tokamak. In all, over 200 tokamaks have been constructed in the world to date, including 31 in the USSR and Russia, 30 in the USA, 32 in Europe, and 27 in Japan [23].

The T-6 facility ($R = 0.7$ m, $a = 0.25$ m, $B_t = 1.5$ T, $I = 0.27$ MA) was constructed at the Kurchatov Institute in 1970. At this facility, the copper casing was accommodated inside a bellows vacuum chamber made of stainless steel. A gold layer was deposited onto the inner surface of the casing to reduce the impurity particle flux into the plasma. Shortening the gap between the plasma and the conducting casing was shown to improve the magnetohydrodynamic (MHD) plasma stability. Specifically, for $d/a \leqslant 1.2-1.3$ (d is the radius of the casing section), the feasibility of obtaining discharges with no disruption instability was demonstrated for $q_a \approx 1.2-1.3$, though with a shorter plasma energy lifetime. Measurements of the perturbations of the poloidal magnetic field outside the plasma with a high spatial ($\sim 15°$) and temporal (~ 1 μs) resolution revealed for the first time that the disruption instability (major disruption) begins with a buildup of the helical harmonic with $m = 2$, which is replaced with rapidly growing $m = 3$ and $m = 4$ harmonics [24]. The toroidal solenoid in T-6 consisted of 32 coils, which ensured a small ripple of the magnetic field. As it turned out, the plasma current at a low initial gas pressure was carried by runaway electrons with an energy of 10–500 keV, while the bulk plasma temperature remained low: $T_e \sim T_i \approx 10$ eV [25]. Gas preionization or the formation of a local magnetic mirror with an amplitude of about 2% transferred the discharge to the normal state.

In 1971, the T-4 facility ($R = 0.9$ m, $a = 0.16$ m, $B_t = 5$ T, $I = 0.25$ MA), the most powerful at that time, was built at the Kurchatov Institute and replaced the T-3A facility. In T-4, advantage was taken of a carbon limiter for the first time. Due to a higher current, a stronger magnetic field, and the use of a carbon limiter, record values of the electron temperature (≈ 3 keV) and ion temperature (≈ 0.65 keV) were reached at this facility.

In the same 1971, a TUMAN-2 tokamak ($R = 0.40$ m, $a = 0.08$ m, $B_t = 1.2$ T, $I = 0.08$ MA) of circular cross section with a limiter was constructed at the Ioffe PTI (Leningrad). This facility was employed to investigate the heating of plasma through its adiabatic compression by the growing toroidal magnetic field. In 1976, after the reconstruction of this facility, the toroidal magnetic field and the plasma current were raised to 1.5 T and 0.12 MA, respectively. The experiments on adiabatic compression were continued and the facility received the name TUMAN-2A.

In 1972, the first experiments on plasma heating by electron cyclotron resonance (ECR) were carried out at the TM-3 facility ($R = 0.4$ m, $a = 0.08$ m, $B_t = 2.5$ T, and $I = 0.1$ MA) [26].

In the same 1972, a TO-1 facility ($R = 0.6$ m, $a = 0.13$ m, $B_t = 1.5$ T, $I = 0.07$ MA) was put into operation, where use was first made of a feedback system to stabilize the plasma column position relative to the major radius [27]. A TO-2 facility was commissioned in 1976, which was equipped with two toroidal divertors and a system for plasma heating and current generation by Bernstein ion waves.

In 1972, L A Artsimovich and V D Shafranov revealed that the neoclassical ion thermal conductivity in tokamaks with a vertically prolate cross section should be lower than in tokamaks having circular cross section [28]. The influence of cross sectional plasma shape on discharge characteristics was experimentally investigated on the T-8 (1973–1978) and T-9 (1973–1976) tokamaks at the Kurchatov Institute.

At the T-8 facility ($R = 0.28$ m, $a = 0.05$ m, $B_t = 0.9$ T, $I = 0.024$ MA) [29], the plasma shape was set by the combined effect of the conducting casing with the elliptical cross section, the limiter, and the currents in quadrupole coils controlled by the feedback system. The highest plasma ellipticity reached in these experiments was $\kappa_{max} \approx 1.6$. A lengthening of plasma energy confinement time was observed with an increase in the ellipticity, being roughly proportional to κ^2. The feasibility of obtaining stable regimes with $\kappa_{max} \approx 2.0$ in the limiter configuration was demonstrated on the T-9 facility ($R = 0.36$ m, $a = 0.07$ m, $B_t = 1.0$ T, $I = 0.04$ MA) [30]. The T-12 facility, which was constructed on the basis of T-9, was equipped with a double-null poloidal divertor. This facility, as well as its subsequent modifications [T-13, TVD — *T*okamak *V*ytyanutyi s *D*iverterom (Prolate Tokamak with a Divertor)], was employed to investigate the stability of the plasma column with respect to vertical shifts and to develop methods of controlling the column position.

In 1976, the T-6 facility was modernized and renamed to T-11: the number of magnetic coils was lowered to 24 to make possible the tangential injection of fast neutral atomic beams.

A molybdenum liner was mounted on the inner surface of the copper casing. Initially, the system was degassed by baking it at a temperature of 400–450 °C; then the liner was processed with a glow discharge (for the first time in tokamaks) — initially in krypton, and next in helium. After this processing, the effective ion charge Z_{eff} in ohmic discharges in deuterium was approximately unity. Proceeding from the results of studies of thermal plasma insulation in the ohmic heating regimes, a scaling was proposed for the electron thermal conductivity, which is referred to as the Merezhkin–Mukhovatov scaling or the T-11 scaling. In 1976, experiments were performed (for the first time in the USSR) to heat the plasma by neutral particle injection with a power of ≈ 0.6 MW [31]. In 1983, in connection with a start of constructing the T-15 facility, the T-11 facility was transferred to the Branch of the I V Kurchatov Institute of Atomic Energy [presently the Troitsk Institute for Innovation and Fusion Research (TRINITI), Troitsk], where it received the name T-11M on reconstruction. In recent years, lithium technologies aimed at weakening the interaction between the plasma and the chamber walls and the limiter have been pursued at this facility [32].

In 1975, a large tokamak machine, T-10 (Fig. 3), with the following parameters: $R = 1.5$ m, $a = 0.39$ m, $B_{\mathrm{t}} = 4$ T, and $I = 600$ kA, was put into operation at the Kurchatov Institute [33]. The T-10 tokamak was equipped with a gyrotron complex providing a power supply up to 2 MW for ECR plasma heating. With ECR heating, it was first possible to obtain plasma in T-10 with a central electron temperature of ≈ 10 keV, which is only two times less than that expected of a thermonuclear reactor. The feasibility of generating current with the help of ECR was first demonstrated and a study was made of several physical effects in the plasma, which determined its confinement.

In the USA, two new facilities were created almost simultaneously with T-10: the Princeton Large Torus (PLT) [34], having nearly the same size as T-10, and Alcator [35], which was smaller in size but had a stronger longitudinal magnetic field, $B \leqslant 10$ T. In 1978, ion heating by neutral atomic beam injection was implemented in the PLT, and an ion temperature $T_{\mathrm{i}} \approx 5$ keV was obtained.

In 1976, a TUMAN-3 tokamak ($R = 0.55$ m, $a = 0.23$ m, $B_{\mathrm{t}} = 1.0$ T, $I = 0.15$ MA) with the capacity of adiabatic plasma compression and high-frequency heating was commissioned at the PTI.

A TMG facility ($R = 0.4$ m, $a = 0.078$ m, $B_{\mathrm{t}} = 3.2$ T, $I = 0.082$ MA) [36], which was developed on the basis of TM-3, was the first tokamak with a graphite first wall. It was revealed that the optimal temperature of the graphite discharge chamber amounted to ≈ 350 °C, when chemical sputtering was insignificant. Under these conditions, the plasma parameters of the TMG facility turned out to be close to those obtained in tokamaks with a metal discharge chamber.

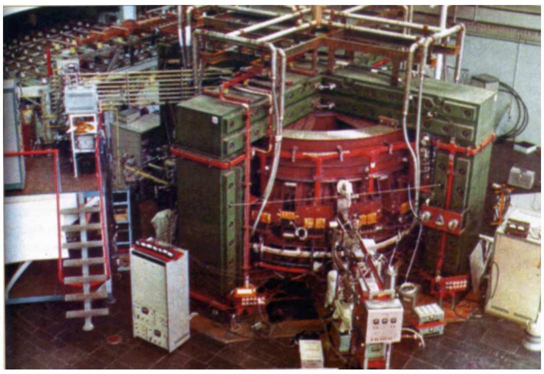


Figure 3. Photo of a T-10 tokamak taken immediately after its assembling (1975).

In 1979, a T-7 facility — the first tokamak with a toroidal magnetic field winding made of NbTi superconductor ($R = 1.2$ m, $a = 0.3$ m, $B_{\mathrm{t}} = 3$ T, $I = 0.3$ MA) — was constructed at the Kurchatov Institute. The T-7 facility was equipped with electron-cyclotron and lower hybrid heating means.

In 1982, researchers participating in the Axially Symmetric Divertor EXperiment (ASDEX) (Max-Planck Institute, Garching, Germany) were able to transfer for the first time the discharge from the divertor mode with a sufficiently high power of additional heating to the so-called high mode (H-mode) with improved energy confinement time due to a transport barrier formation at the plasma boundary [37].

The construction of facilities of progressively larger size was being continued in the USA, Europe, Japan, and the USSR. A Tokamak Fusion Test Reactor (TFTR) in Princeton (USA) and a Joint European Torus (JET) in Culham (UK) were commissioned in 1983. These nuclear fusion machines were equipped with a neutron shield which permitted operating with highly intense deuterium–tritium (DT) reactions. The biggest tokamaks are the JET and the Japanese JT-60 tokamak, whose latest modification, JT-60U, was put into operation in 1991. Both facilities have a vertically elongated plasma column cross section and a single-null divertor (Fig. 4).

In 1986, a DIII-D tokamak ($R = 1.66$ m, $a = 0.67$ m, $B_{\mathrm{t}} = 2.2$ T, $I = 3$ MA), which could operate both with single-null and double-null divertors, was commissioned in San Diego (USA). The facility was equipped with twenty independently powered poloidal coils which made it possible to optimize the shape of the cross section of the column (ellipticity, triangularity, quadraticity) and stabilize the instability localized at the plasma boundary. The total power of additional heating systems amounted to ≈ 30 MW. It has been possible to achieve at this facility the parameter $\beta = 8\pi \langle p \rangle / B_{\mathrm{t}}^2 = 12.5\%$, which is a record high value for ordinary tokamaks. A vast program of physical research in support of the ITER is being pursued at this facility [38], which is presently the largest tokamak in the USA.

The construction of two large facilities with superconducting magnetic coils was completed in 1988: Tore Supra with NbTi coils ($R = 2.25$ m, $a = 0.7$ m, $B_{\mathrm{t}} = 4.5$ T, $I = 2$ MA) in Cadarache (France), and T-15 with Nb_3Sn coils ($R = 2.4$ m, $a = 0.7$ m, $B_{\mathrm{t}} = 3.6$ T, $I = 1$ MA) at the Kurchatov Institute. At these facilities, the round cross section of the plasma column was bounded by limiters (Fig. 5).

In 1989, the H-mode was obtained in the ohmic heating mode at the TUMAN-3 facility. The transition to the H-mode was initiated by applying an electric potential to a peripheral probe. The transfer to the H-mode could also be initiated by a short gas puff, a fast plasma compression in the minor radius, or a pellet injection. The maximum value of τ_{E} in the H-mode turned out to be an order of magnitude greater than in the ordinary ohmic mode [39]. The dependences of τ_{E} on B, I, and n_{e} turned out to be close to those observed at large facilities in the H-mode with additional high-power heating in the absence of instability localized at

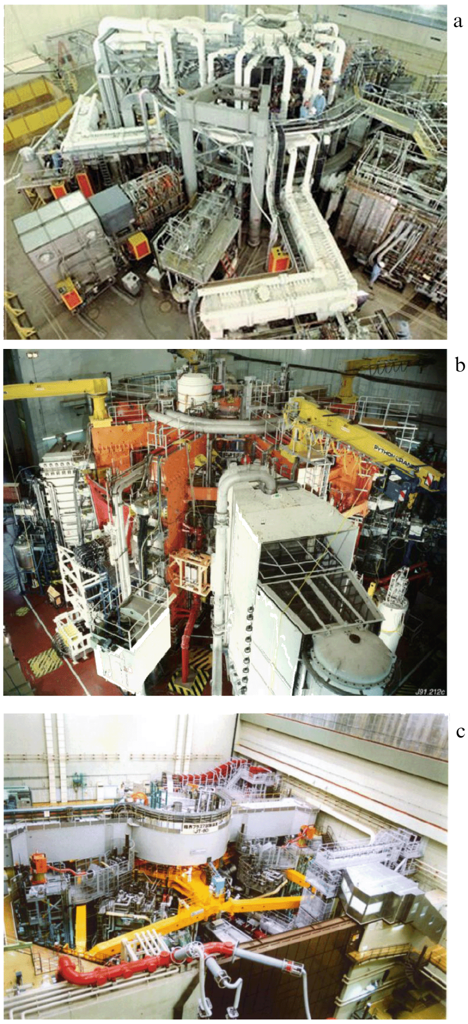


Figure 4. Three largest tokamaks with warm coils: (a) TFTR (1983–2002): $R = 2.4$ m, $a = 0.8$ m, $B_t = 6$ T, $I = 3$ MA, $P_{ICRH} = 11$ MW, $P_{NBI} = 39$ MW; (b) JET (since 1992): $R = 2.96$ m, $a/b = 0.96/2.1$ m, $a = 0.96$ m, $B_t = 4$ T, $I = 6$ MA, $P_{ICRH} = 12$ MW, $P_{NBI} = 24$ MW, $P_{LH} = 7$ MW, and (c) JT-60U (1991–2010): $R = 3.4$ m, $a = 1$ m, $B_t = 4.2$ T, $I = 5$ MA, $P_{ECRH} = 4$ MW, $P_{ICRH} = 10$ MW, $P_{NBI} = (40 + 10)$ MW, $P_{LH} = (8 - 12)$ MW) [22]. ICRH — Ion Cyclotron Resonance Heating; ECRH — Electron Cyclotron Resonance Heating; NBI — Neutral Beam Injection Heating; LH — Lower Hybrid Heating.

the plasma boundary. The authors attributed these results to the formation of transport barriers at the plasma boundary and in the inner zone in the region where $dq/dr \sim 0$.

5. Progress in experimental research on tokamaks over the last 20 years

The most impressive event was the production of significant thermonuclear power in deuterium–tritium plasma experiments in the TFTR (11 MW, 1994) and JET (16 MW, 1997) tokamaks (Fig. 6) [40]. The maximum value of $Q = P_{fus}/P_{aux}$ attained at the JET facility was ≈ 0.65. These results were obtained in the modes with hot ions, $T_i \gg T_e$, which are not typical for the nuclear fusion reactor. In the reactor-like H-mode at the JET facility with $T_i \approx T_e$, a thermonuclear power $P_{fus} = 3-5$ MW was obtained in a long (≈ 5 s) pulse. Similar results were achieved on the JT-60U facility in deuterium discharges: the equivalent value of Q_{eqv} calculated for a DT plasma amounted to $\cong 1.25$ in a short pulse for $T_i \gg T_e$, and to $\cong 0.5$ in the quasistationary mode [41].

Figure 7 exhibits the values of a factor $M = n_i(0)\, T_i(0)\, \tau_E$ as a function of $T_i(0)$, which were obtained in experiments on several tokamaks [42]. The shaded domains of M values in Fig. 7 correspond to the calculated values $Q = 0.1, 1.0$, and ∞ for a DT plasma. When the JET and TFTR data with $T_i \gg T_e$ are excluded in accordance with the aforesaid, and it is considered that the DT reaction ignition mode at $T_i(0) \approx 30$ keV calls for a value of $M \approx 100$, one can see from this figure that the distance (in units of ΔM) from the modes with the best quasistationary discharges at the JET and JT-60U facilities to the mode with DT reaction ignition amounts to 20–30.

Figure 8 depicts the maximal thermonuclear power measured in DT discharges, or the equivalent power calculated from the DD plasma parameters in different tokamaks, P_{fus}^{max}, as a function of the calendar date between 1975 and 1995 [19]. One can see that P_{fus}^{max} rose by a factor of 10^8 over the 20-year period. This was achieved by constructing new, larger facilities and equipping them with higher-power additional heating. On obtaining the record-high power pulses at the JET and JT-60U facilities, no further increase occurred in P_{fus}^{max}. The new superconducting facilities constructed during the last decade, which are smaller in size than JET and JT-60U, are intended for the realization and investigation of stationary discharges, rather than the attainment of high P_{fus}^{max} values. The further increase in P_{fus}^{max} (by a factor of 30–50 in comparison with the values attained in JET and TFTR) should occur when ITER reaches its design objectives, i.e. about 2027.

Important tasks during the last 20 years have comprised the improvement and analysis of experimental databases in different areas of tokamak's physics and derivation on their basis of empirical scalings employed to calibrate theoretical

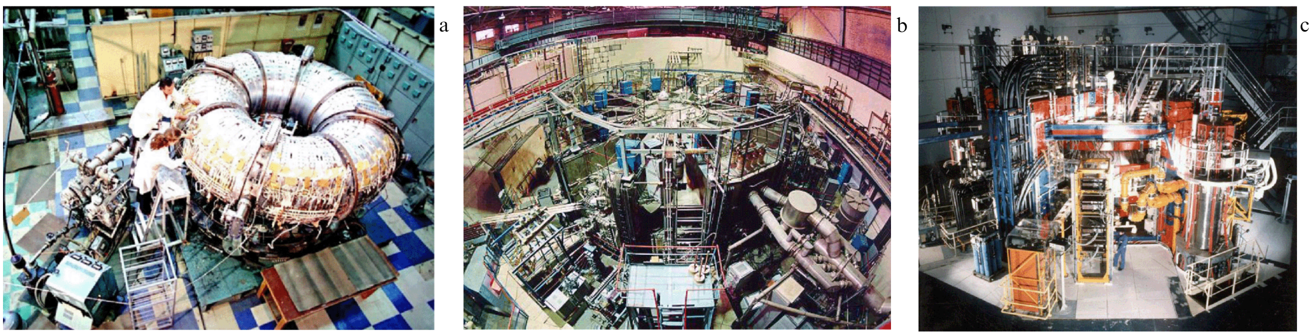


Figure 5. Tokamaks with superconducting coils: (a) assembly of the superconducting coils of T-7, (b) T-15, and (c) Tore Supra [23].

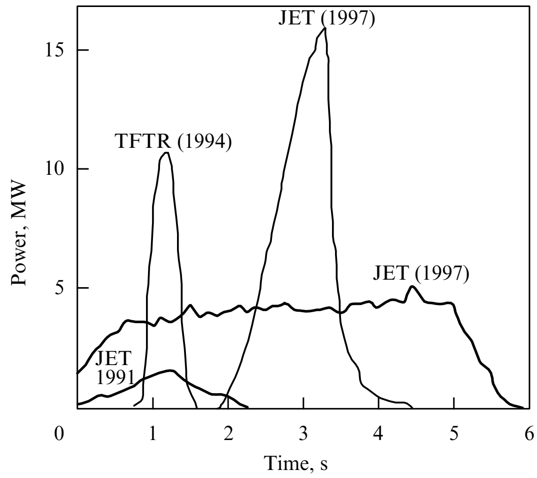


Figure 6. Thermonuclear power produced in DT experiments at the TFTR (Princeton, USA) and JET (Culham, England) facilities [40].

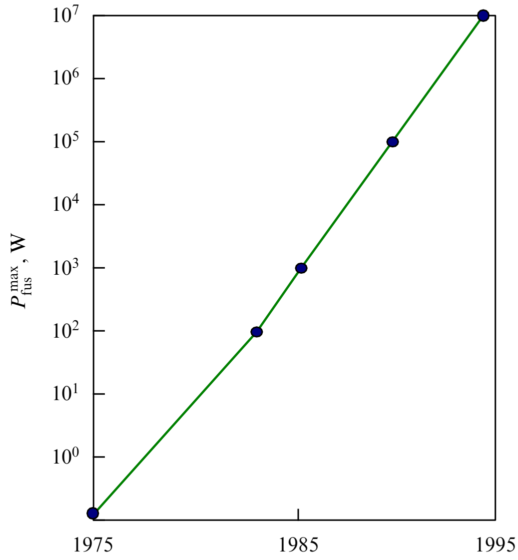


Figure 8. Growth dynamics of fusion power generated in different experimental facilities over a period of 20 years (1975–1995) [19].

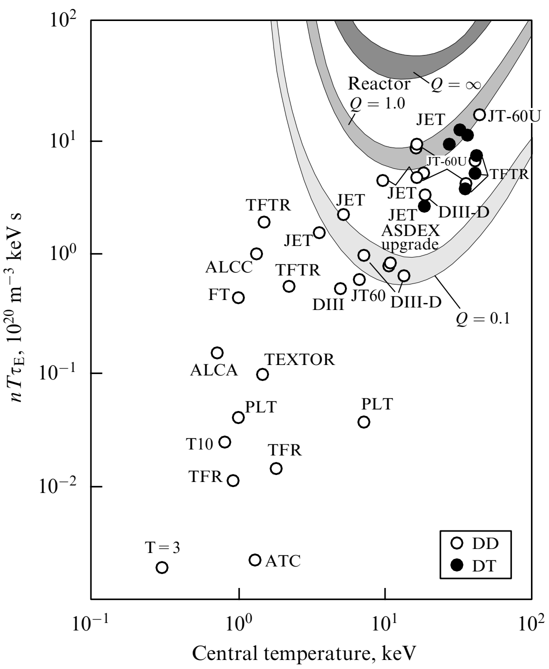


Figure 7. Experimental values of $nT\tau_E$ as a function of central ion temperature. Shown are the zones with the values of $Q \equiv P_{fus}/P_{aux} = 0.1$, 1.0, and ∞ [42].

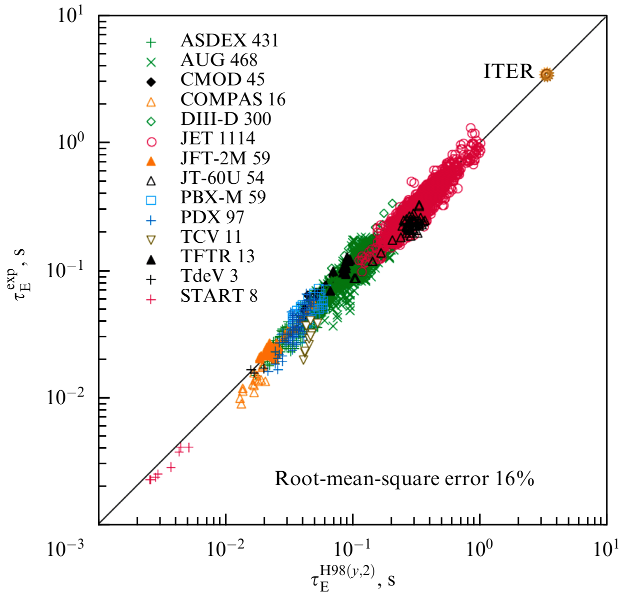


Figure 9. Comparison of the thermal plasma energy confinement time τ_E^{exp} in the H-mode for 14 tokamaks (indicated in the drawing) with empirical scaling $\tau_E^{H98(y,2)}$.

models and predict plasma parameters of future nuclear fusion machines.

By way of example, Fig. 9 demonstrates the plasma energy lifetime τ_E^{exp} for H-modes at 14 different facilities as a function of lifetime predicted by the empirical scaling IPBH98(y,2), which is based on the analysis of data from eight facilities [40]:

$$\tau_E^{H98(y,2)} = 0.0562 I^{0.93} B^{0.15} n^{0.41} P^{-0.69} R^{1.97} \kappa^{0.78} \varepsilon^{0.58} M_i^{0.19} ,$$

where $\kappa = V/2\pi^2 R a^2$, $\varepsilon = a/R$, τ_E is measured in seconds, the units of measurement for I — [MA], B — [T], n — [10^{19} m^{-3}], P — [MW], and M_i — [amu].

One can see a relatively good agreement between experimental τ_E^{exp} values and the scaling predictions as τ_E^{exp} is changed approximately 400-fold. Also shown is the value of $\tau_E = 3.4$ s required to obtain $Q \sim 10$ in the ITER in inductive mode for a plasma current of 15 MA and a thermonuclear power of ≈ 500 MW.

The construction of new experimental facilities was being continued. In 1991, an ASDEX Upgrade tokamak ($R = 1.6$ m, $a = 0.5-0.8$ m, $B_t = 3.9$ T, $I = 2$ MA) was built in Garching (Germany), which had a D-shaped cross section and a single-null divertor. An improved H-mode with an internal transport barrier was obtained at this facility for the first time. In 2009, it was possible to demonstrate at this facility the feasibility of producing plasma with high parameters in a chamber with a tungsten wall, with plasma heating by fast neutral atomic beams [43]. Difficulties were encountered in obtaining stable discharges in this chamber due to the high inflow of tungsten atoms with the use of ion-cyclotron plasma heating.

In 1991, a small START tokamak ($R = 0.3$ m, $R/a = 1.25$, $B_t = 0.5$ T, $I = 0.3$ MA) with a rather high-power injection heating (≈ 1 MW) was commissioned in Culham (UK) [44]. A record value of $\beta = 8\pi\langle p\rangle/B_t^2 \approx 40\%$ was attained in this tokamak. This facility belongs to the class of so-called spherical tokamaks. Three spherical tokamaks of larger size were launched in 1999: MAST ($R/a = 1.4$, $R = 0.85$ m, $B_t = 0.4$ T, $I = 1.4$ MA) in England (Culham), NSTX ($R/a = 1.4$, $R = 0.85$ m, $B_t = 0.38$ T, $I = 1.4$ MA) in the USA (Princeton), and Globus-M ($R/a = 1.5$, $R = 0.36$ m, $B_t = 0.38$ T, $I = 0.25$ MA, b/a up to 1.8) at the PTI (St. Petersburg) [45].

The main parameter which distinguishes spherical tokamaks from ordinary ones is a substantially smaller aspect ratio ($R/a = 1.3-1.8$). This underlies the main attractive features of spherical tokamaks: their compactness, a higher limit in β, and a softer disruption instability. However, lowering the aspect ratio encounters additional technical difficulties in comparison with ordinary tokamaks. Among them is the absence of free space for accommodating the neutron shield in the central zone of the facility and, therefore, the impossibility of using superconductors for the toroidal solenoid and the central poloidal circuit in the operation with a DT plasma. Due to a small reserve of volt-seconds in the central solenoid, problems emerge with inductive discharge ignition.

At the present time, the feasibility of a noninductive discharge ignition and stationary current drive in spherical tokamaks are under investigation; in particular, under analysis are the prospects of closing toroidal solenoid coil currents along the vertical axis of the system with the employment of a liquid metal jet or a plasma column produced by a Z-pinch. Investigations of the plasma behavior in spherical tokamaks are being pursued, and the merits and demerits of their employment as fusion reactors or as fusion neutron sources are being discussed.

Three superconducting tokamaks with a D-shaped plasma cross section and a divertor have been constructed during the last decade, which were intended for studying discharges up to 300–1000 s in duration: Experimental Advanced Superconducting Tokamak (EAST) ($R = 1.7$ m, $a = 0.4$ m, $B_t = 3.5$ T, $I = 1$ MA) in Hefei (China) [46]; Korea Superconducting Tokamak Advanced Research (KSTAR) ($R = 1.8$ m, $a = 0.5$ m, $B_t = 3.5$ T, $I = 2$ MA) in Daejeon (South Korea) [47], and SST-1 ($R = 1.1$ m, $a = 0.2$ m, $B_t = 3$ T, $I = 0.22$ MA) in Gandhinagar, India [48]. Under construction in Naka (Japan) is a large superconducting JT-60SA tokamak ($R = 3.16$ m, $a = 1.02$ m, $B_t = 2.7$ T, $I = 5.5$ MA) with a double-null divertor and a ~ 100-s-long plasma current plateau (an EU–Japan collaboration project) [49]. Experiments executed at these facilities will be aimed at obtaining the physical and technological information required to optimize and monitor stationary discharges at ITER and the DEMOnstration Power Plant (DEMO).

Other important results obtained in recent decades are as follows:

(i) Discovery of a 'hybrid' regime with improved energy retention in comparison with that in the standard H-mode for which the ITER pulsed operating mode is designed. The improved hybrid mode, if realized successfully in the ITER, will make it possible to obtain the design parameters for a lower plasma current and sustain them for several thousand seconds.

(ii) Raising the limiting plasma pressure and, consequently, the limiting fusion power in the reactor due to stabilization of the neoclassical tearing instability with the help of a focused microwave radiation beam correcting the profile of the plasma current, and due to suppression of the instability that bears a relation to the finite wall resistance by compensating the scattered magnetic fields and producing a variable magnetic field of a given configuration controlled by a feedback system.

(iii) Discovery of systems with a peripheral transport barrier free from instability bursts at the plasma boundary (ELM [4]-free quiescent H-mode) and demonstration of the suppression of this instability by dint of resonance magnetic field perturbations and its attenuation by injection of hydrogen pellets.

(iv) Significant progress in the development of methods of early warning about disruption instability development in tokamaks and methods for mitigating its consequences.

Over the past 10–15 years, the experiments in Russia have been performed on six tokamaks: T-10 at the Kurchatov Institute, T-11M at TRINITI, and Globus-M, TUMAN-3M, FT-1 (until 2006), and FT-2 at the PTI. The biggest Russian tokamak T-15, which was constructed in 1988, was taken out of service in 1995 because of insufficient financing.

6. Development of tokamak plasma theory

Since 1951, theoretical investigations on controlled nuclear fusion at LIPAN have been supervised by M A Leontovich. The theoretical school he founded became a leader in the theory of high-temperature plasma for years to come.

Russian scientists constructed the theories of equilibrium, transfer processes, magnetohydrodynamic and kinetic plasma instabilities, plasma turbulence, and atomic processes and radiation, and laid the theoretical foundations for the methods of plasma heating and current generation. B B Kadomtsev laid the groundwork for the theory of transport phenomena (diffusion and thermal conduction) in turbulent plasmas. V D Shafranov is the author of papers on the theory of equilibrium and stability of plasma in the tokamak magnetic fields. He derived the equation for plasma equilibrium in two-fluid plasmastatics (the Grad–Shafranov equation), which underlies the theory of plasma equilibrium in axisymmetric magnetic configurations, and deduced the stability criterion for a plasma current column in a magnetic field, which is known as the Kruskal–Shafranov criterion.

In 1967, A A Galeev and R Z Sagdeev [8] constructed the so-call neoclassical transport theory which takes into account the presence of a special group of plasma particles trapped between the portions of force lines with a magnetic field enhanced owing to its toroidicity. They showed that the particles trapped in a rarefied high-temperature plasma play a decisive part in collisional processes of a heat and particle transport.

The results of theoretical investigations were published in collected articles entitled *Voprosy Teorii Plazmy* (*Reviews of Plasma Physics*). Beginning from 1963, 24 volumes in all have been published up to the present. The first 18 volumes were published in Russian and English, and the latest 5 volumes only in English. Recently, a decision was taken to republish volumes 19–24 in Russian at the National Research Centre 'Kurchatov Institute' and to publish the future volumes in

[4] Edge localized mode (ELM) — *Translator's comment.*

Russian with subsequent translation into English under Academician E P Velikhov's supervision.

At present, elaboration of the theory and numerical simulations are being carried out in all key areas of tokamak physics, including research in support of the ITER program. These areas comprise:

— the initial stage of discharge;
— confinement and transport processes;
— stability (MHD, turbulence);
— disruption instability, development of methods for its suppression and minimization of its detrimental consequences;
— the physics of near-wall plasma;
— controlled discharge physics (integrated scenarios, multiparametric plasma control, the physics of high-energy particles, etc.);
— methods of plasma heating and plasma current drive;
— integrated discharge simulation.

7. T-20 and INTOR projects

By 1975, a conceptional design of a T-20 reactor-scale facility ($R=5.0$ m, $a=2$ m, $B_{\rm t}=3.5$ T, $I=6$ MA, $n=0.5\times10^{20}$ m^{-3}, $T=10$ keV, $P_{\rm fus}=0.5$ GW, $q=2.3$) was prepared. Its commissioning was planned for 1985. It was conceived that T-20 would be sited in the town of Sosnovyi Bor, near the Leningrad atomic power plant, in a new center for testing experimental thermonuclear reactors (the State Nuclear Fusion Reactor Test Center, SNFRTC) [10]. An amount equivalent to US \$2 billions was to be allocated for setting up the T-20 and construction of the SNFRTC. However, more recently these plans were revised, and instead of T-20 and the SNFRTC it was decided to build about ten less ambitious projects like T-15 and TSP tokamaks, as well as a long open trap (LOT) and a rippled open trap (ROT).

In 1979, on the initiative of Soviet scientists, the IAEA established an international workgroup with the aim of exploring the feasibility of a nuclear fusion reactor based on a tokamak system. The workgroup was to determine the program, technical objectives, and facility parameters, and to appraise the existing scientific and technical basis for making a fusion reactor on an international ground, which was to demonstrate the technical feasibility of energy production from thermonuclear fusion and be the most reasonable step after the building of the T-15 (USSR), JT-60 (Japan), JET (Europe), and TFTR (USA) facilities. Workgroup participants from the USSR, the USA, Japan, and the European Community prepared a report on the scientific and technical basis and arrived at the conclusion that this basis is sufficient for designing and constructing an INternational TOkamak Reactor (INTOR) in a decade. The main characteristics of this reactor are as follows: $R=5.2$ m, $a=1.3$ m, $b/a=1.6$, $B_{\rm t}\leqslant5.5$ T, $I\leqslant6$ MA, $\langle n_{\rm e}\rangle=1.4\times10^{14}$ cm^{-3}, and $T=10$ keV. Unlike T-20, the INTOR was supposed to have a divertor and a vertically elongated plasma cross section.

The INTOR project was never implemented, but the results of the almost 10-year-long work of the project participants have played an important role in the development of the ITER project.

8. ITER and DEMO

In November 1985, in the name of the USSR E P Velikhov came up with a proposal to make a new-generation tokamak with the participation of the USSR, Europe, the USA, and Japan. In 1986, an agreement was reached in Geneva about the collaborative design of a facility which was to demonstrate the scientific and technological feasibility of harnessing thermonuclear reactions for peaceful purposes. During a three-year period, from 1988 to 1990, the combined effort of Soviet, American, Japanese, and European scientists and engineers resulted in the development of the conceptual project of a fusion reactor, which received the name ITER (Fig. 10). The project was aimed at attaining a self-sustained nuclear fusion reaction ($Q=\infty$) in a DT plasma with $P_{\rm fus}\approx1$ GW in the inductive mode, and obtaining $Q\approx7$ at $P_{\rm fus}\approx0.75$ GW in the stationary mode [50].

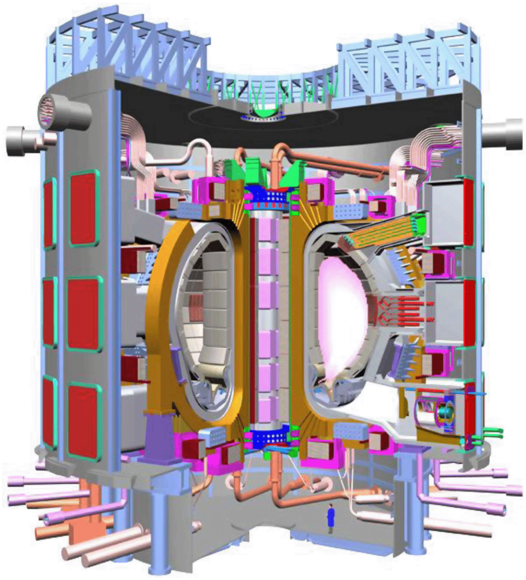


Figure 10. Poloidal section view of ITER. To estimate the ITER dimensions, a human silhouette is depicted at the bottom of the drawing.

In July 1992, the EC, Russia, the USA, and Japan signed a quadrilateral agreement on the development of an engineering design of ITER. The engineering design was completed in 1998. In the course of work on the design, several facility parameters were changed in comparison with those accepted in the conceptual project. In particular, the double-null divertor was replaced with a single-null one, the plasma volume and the thermonuclear power in the inductive mode were increased by factors of 2 and 1.4, respectively, while the magnitudes of magnetic field and plasma current were hardly changed.

In January 1999, the USA withdrew from the ITER project due to a decision by Congress. The US Congress justified this decision by the high cost of the project [10]. The EC, Russia, and Japan continued their work on the project to reduce its cost. In 2001, a second, smaller version of the technical design that was approximately two times less expensive was completed. In 2003, the USA resumed its participation in the project. China and South Korea also joined the project, and India did so in 2005. In May 2006, the consortium participants signed in Brussels an agreement about the beginning of practical implementation of the project in 2007. The first stage of construction should be completed by 2018. The first plasma production is planned for late 2019. Commencement of full-scale DT-plasma experiments is planned for 2027.

Table 2. Comparison of the design parameters of ITER [51] and one of the DEMO versions [52].

Parameter	ITER		DEMO Stationary mode ($\geqslant 10^6$ s)
	Inductive mode	Stationary mode ($\geqslant 3 \times 10^3$ s)	
Plasma current I, MA	15	9	15
Magnetic field B_t on plasma axis, T	5.3	5.18	6.8
Maximum field B_{max} on superconductor, T	11.8	11.8	14.6
Minor plasma radius a, m	2	1.85	2.1
Major plasma radius R, m	6.2	6.35	6.5
Ion temperature $T_i(0)$ on plasma axis, keV	23	25	45
MHD stability margin q_{95} at radius $r = 0.95a$	3.0	5.2	5.3
Ratio of $\langle n_e \rangle$ to Greenwald limit, $\langle n_e \rangle / n_G$	0.85	0.75	1.0
Confinement improvement factor $H_{H98(y,2)}$	1.0	1.4	1.3
$\beta_N = \beta(100aB/I)$	1.8	3.0	3.9
Bootstrap current fraction f_{BS}	0.15	0.5	0.79
Noninductive current fraction f_{NI}	0.21	1	1
Fusion power P_{fus}, MW	400	350	3000
Plasma heating power $P_{heat} = P_\alpha + P_{aux}$, MW	120	140	654
Thermal plasma energy W_{th}, MJ	320	290	1215
Fraction of radiative energy loss $f_{rad} = P_{rad}/P_{heat}$	0.5	0.57	0.86
$Q = P_{fus}/P_{aux}$	10	5	54
Disruption frequency $f_{disruption}$	~ 0.1 (per pulse)	~ 0.1 (per pulse)	$\leqslant 1$ (per year)

The final ITER version is intended for DT plasma production with $P_{fus} = 400-500$ MW and $Q \geqslant 10$ in inductive mode with a pulse duration of about 500 s. The feasibility of 'controllable burning' of the DT plasma, i.e. modes with $Q > 30$, should also be explored. Among important ITER tasks remain experiments with noninductive current drive in the quasistationary mode with a pulse duration of ≈ 3000 s for $Q \geqslant 5$, which are of immediate interest in designing the first experimental fusion power plant — DEMO. Another important ITER task is the execution of nuclear technological tests required for designing DEMO. ITER should demonstrate the combined operation of all technological systems required for DEMO and test the tritium recovery modules. The inductive and stationary mode parameters of ITER and of one of DEMO's versions with $P_{fus} = 3$ GW are collected in Table 2 [51, 52].

The surprising thing is that the plasma volume (950 m^3) and the longitudinal magnetic field intensity (5 T) in Sakharov's project (see Table 1) are practically the same as the corresponding parameters of the ITER project (831 m^3 and 5.3 T). At the same time, other parameters of these projects are markedly different. For instance, the magnitude of longitudinal current in Sakharov's project is 75 times lower than in the ITER project. Today we know that the magnitude of current in Sakharov's project could be raised to ≈ 2.8 MA without violating the hydromagnetic plasma stability for a safety margin factor $q_a = 5B_t a^2/(IR) \approx 3$ accepted for the ITER project. To avoid disruption instability with respect to the limiting density, the average plasma density should satisfy the empirical Greenwald scaling n $[10^{20}$ m$^{-3}] < I\,[\mathrm{MA}]/(\pi a^2)$ [m^2], from which it follows that the plasma density must be approximately one order of magnitude lower than in Sakharov's project, even for the corrected current $I = 2.8$ MA. Accordingly, the fusion power release at the same temperature would be lower by about two orders of magnitude. Therefore, a self-sustained DD fusion reaction is out of the question in this system; however, this system would hold considerable interest with the use of a DT mixture, although not as great as ITER because of the nonoptimal shape of the plasma cross section and the absence of a divertor. This commentary serves to illustrate the exercise of knowledge gained by the nuclear fusion community on the thorny path pointed out by A D Sakharov and I E Tamm 60 years ago.

9. New stage of tokamak research in Russia

Losing the leading place in the physics and technology of tokamaks significantly lowers Russia's capabilities in mastering fusion power production. The plan of making an up-to-date divertor tokamak by upgrading the T-15 complex (Table 3), adopted in the framework of a Federal dedicated program, will serve to restore this place. Putting into operation the new tokamak in 2015 not only will permit carrying out topical studies in support of the ITER program, but will also be a major step towards the development of a fusion neutron source for hybrid systems.

Table 3. Main parameters of the modernized T-15 tokamak.

Aspect ratio	2.2
Plasma current I_P, MA	2.0
Major torus radius R, m	1.48
Elongation of plasma cross section, κ	1.9
Plasma triangularity δ	0.3 – 0.5
Plasma configuration	SN
Discharge duration, s	5 – 10
Toroidal field B_t on plasma axis, T	2.0
Flux content in solenoid $\Delta\Psi_{CS}$, Wb	6
Neutral injection power, MW	9
Microwave heating power, MW	6
Ion-cyclotron heating power, MW	6
Lower hybrid heating power, MW	4

The experimental program of the new tokamak will cover a wide range of research, including the solution to the following problems.

• Physical and technological substantiation of the demonstration thermonuclear neutron source (TNS).

• Attainment of high β_N values as a way to reducing the cost of fusion reactors and simultaneously ensuring a high density and a high temperature.

• Control of current and pressure profiles as a way to increase β_N and the confinement time τ_E.

• Implementation of improved confinement modes with inner and outer transport barriers.

• Feasibility study of modes with high β and n_e values in a stationary discharge with an all-noninductive current drive.

• Divertor optimization and investigation of the peripheral plasma effect on the global plasma discharge characteristics.

• Exerting real-time control over the stability, equilibrium, heating, and confinement of high-temperature plasma.

• Exploration of plasma interactions with various materials, including graphite, tungsten, and lithium.

• Employment of the new tokamak as a test site for trying out systems like stationary neutral injectors, and stationary high-frequency, microwave, and lower hybrid plasma heating devices, as well as for testing first-wall and divertor materials and technologies, etc.

The design of the new tokamak based on the upgraded version of the T-15 complex has already been made, and its construction will begin in 2012 (Fig. 11).

It is well known that Andrei D Sakharov and I E Tamm considered the MTR as a high-power neutron source for the production of artificial fissionable material. This idea revived in the 1970s in the form of so-called hybrid reactors, whose conception was elaborated under the supervision of E P Velikhov, I N Golovin, and V V Orlov. For various reasons, however, the work on hybrid reactors was suspended in the USSR and the USA.

At the present time, the interest in hybrid systems, including those based on tokamaks, has been rekindled. In accordance with the work plans on CNF elaborated and adopted in Russia, apart from participation in the ITER project, an industrial tokamak-based fusion neutron source should be designed and built with the objective of fuel production and transmutation of highly active nuclear reaction products for scientific and technological purposes. The new tokamak at the Kurchatov Institute may be regarded as a hydrogen prototype of the neutron source.

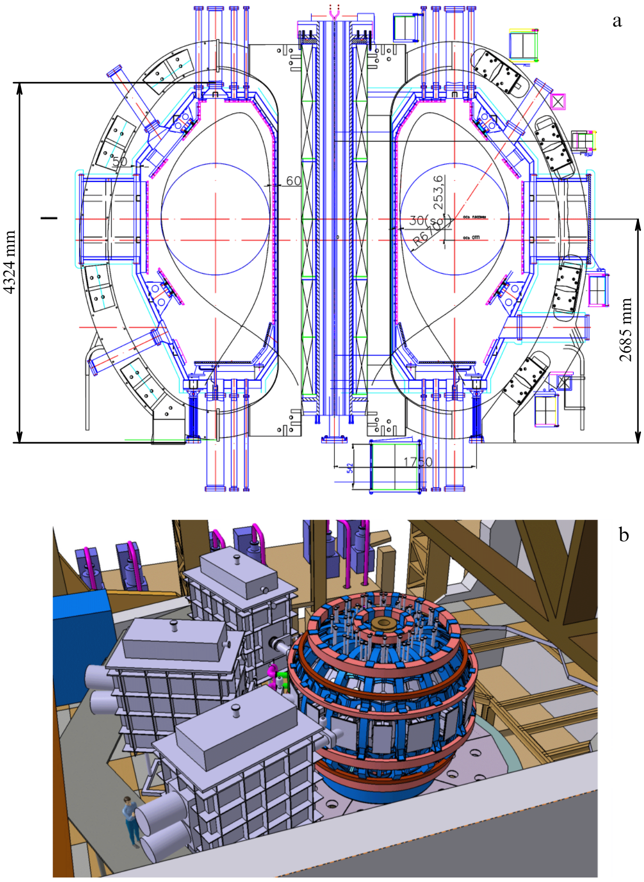


Figure 11. Cross section (a) and accommodation of modernized T-15 tokamak in experiment room (b).

Therefore, proceeding from the great body of findings made in the course of experimental and theoretical tokamak research and related technological developments, Russian physicists and engineers come back to Sakharov's original ideas.

10. Conclusions

Investigations into the magnetic thermal insulation of plasma initiated by A D Sakharov and I E Tamm 60 years ago [5] have reached the stage which allows designing in 1990–2010 and making a start on the construction of the tokamak-based International Thermonuclear Experimental Reactor (ITER). ITER is supposed to reach the design objectives in the inductive mode with $P_{fus} = 0.4-0.5$ GW and $Q \geqslant 10$ in 2027. Next, this should be followed by the attainment and study of long-duration modes ($\geqslant 3000$ s) with $Q \geqslant 5$, which hold great interest to extrapolations towards DEMO.

[5] The Early history of research into a controlled nuclear fusion (CNF) was presented in reviews [53, 54, 56 – 61] and a scientific literary composition [55].

The Russian Federation is among the seven member countries of the international agreement on the construction of ITER. It participates in designing and making the components and units of the facility, in developing and producing diagnostic systems and control systems, in developing discharge scenarios, and in simulating the physical processes in the ITER plasma.

The construction at the NRC 'Kurchatov Institute' of a modern tokamak equipped with a divertor and based on the modernized T-15 complex will enable carrying out extensive research in support of ITER, developing hydrogen prototypes of a fusion neutron source, and preparing personnel in the area of controlled thermonuclear fusion.

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References

1. Sakharov A D *Vospominaniya* (Recollections) Vol. 1 (Moscow: Al'fa-Kniga, 2011) Ch. 9
2. Sakharov A D, in *Fizika Plazmy i Problema Upravlyaemykh Termoyadernykh Reaktsii* (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) Vol. 1 (Exec. Ed. M A Leontovich) (Moscow: Izd. AN SSSR, 1958) p. 20 [Translated into English (New York: Pergamon Press, 1961)]; *Usp. Fiz. Nauk* **93** 564 (1967)
3. Tamm I E, in *Fizika Plazmy i Problema Upravlyaemykh Termoyadernykh Reaktsii* (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) Vol. 1 (Exec. Ed. M A Leontovich) (Moscow: Izd. AN SSSR, 1958) p. 3 [Translated into English (New York: Pergamon Press, 1961)]
4. Tamm I E, in *Fizika Plazmy i Problema Upravlyaemykh Termoyadernykh Reaktsii* (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) Vol. 1 (Exec. Ed. M A Leontovich) (Moscow: Izd. AN SSSR, 1958) p. 31 [Translated into English (New York: Pergamon Press, 1961)]
5. Budker G I, in *Fizika Plazmy i Problema Upravlyaemykh Termoyadernykh Reaktsii* (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) Vol. 1 (Exec. Ed. M A Leontovich) (Moscow: Izd. AN SSSR, 1958) p. 68 [Translated into English (New York: Pergamon Press, 1961)]
6. Pfirsch D, Schlüter A, Report PI/PA/7/62 (Münich: Max-Planck Institute, 1962)
7. Shafranov V D *Atom. Energ.* **19** (2) 120 (1965) [*Atom. Energy* **19** 1008 (1965)]
8. Galeev A A, Sagdeev R Z *Zh. Eksp. Teor. Fiz.* **53** 348 (1967) [*Sov. Phys. JETP* **26** 233 (1968)]
9. Bezbatchenko A L et al., in *Fizika Plazmy i Problema Upravlyaemykh Termoyadernykh Reaktsii* (Plasma Physics and the Problem of Controlled Thermonuclear Reactions) Vol. 4 (Exec. Ed. M A Leontovich) (Moscow: Izd. AN SSSR, 1958) p. 116 [Translated into English (New York: Pergamon Press, 1961)]
10. Golubchikov L G *ITER. Reshayushchii Shag* (ITER. The Decisive Step) (Moscow: MIFI, 2004)
11. Dolgov-Savel'ev G G et al., in *Trudy 2-i Mezhdunarod. Konf. po Mirnomu Ispol'zovaniyu Atomnoi Energii, Zheneva, 1958. Doklady Sovetskikh Uchenykh* (Proc. 2nd Intern. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1958. Reports of Soviet Scientists) (Moscow: Atomizdat, 1959) p. 85
12. Vasilevskii V S et al. *Zh. Tekh. Fiz.* **30** 1137 (1960)
13. Dolgov-Savel'ev G G et al. *Zh. Eksp. Teor. Fiz.* **38** 394 (1960) [*Sov. Phys. JETP* **11** 287 (1960)]
14. Gorbunov E P, Razumova K A *Atom. Energ.* **15** (5) 363 (1963) [*Atom. Energy* **15** 1105 (1964)]
15. Gorbunov E P, Mirnov S V, Strelkov V S *Nucl. Fusion* **10** 43 (1970)
16. Artsimovich L A, in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 2nd Intern. Conf. Culham, 1965* Vol. 2 (Vienna: IAEA, 1966) p. 595
17. Artsimovich L A et al. *Atom. Energ.* **22** 259 (1967) [*Atom. Energy* **22** 325 (1967)]
18. Artsimovich L A, in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 2nd Intern. Conf. Culham, 1965* Vol. 1 (Vienna: IAEA, 1969) p. 157
19. Mirnov S V *Energiya iz Vody* (Energy from Water) (Moscow: Trovant, 2008); http://www.triniti.ru/Art/Mirnov1.pdf
20. Peacock N J et al. *Nature* **224** 488 (1969)
21. Anashin A M et al. *Zh. Eksp. Teor. Fiz.* **60** 2092 (1971) [*Sov. Phys. JETP* **33** 1127 (1971)]
22. Artsimovich L A et al. *Zh. Eksp. Teor. Fiz.* **61** 575 (1971) [*Sov. Phys. JETP* **34** 306 (1972)]
23. All-the-World's Tokamaks, http://www.tokamak.info
24. Vlasenkov V S et al., in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 5th Intern. Conf., Tokyo, 1974* Vol. 1 (Vienna: IAEA, 1975) p. 33
25. Vlasenkov V S et al. *Nucl. Fusion* **13** 509 (1973)
26. Alikaev V V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **15** 41 (1972) [*JETP Lett.* **15** 27 (1972)]
27. Artemenkov L I et al., in *6th Eur. Conf. on Controlled Fusion and Plasma Physics, Moscow, USSR, July 30 – August 4, 1973* Vol. 1 (Dubna: JINR, 1973) p. 153
28. Artsimovich L A, Shafranov V D *Pis'ma Zh. Eksp. Teor. Fiz.* **15** 72 (1972) [*JETP Lett.* **15** 51 (1972)]
29. Dobrokhotov E I et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **31** 663 (1980) [*JETP Lett.* **31** 625 (1980)]
30. Bortnikov A V et al., in *6th Eur. Conf. on Controlled Fusion and Plasma Physics, Moscow, USSR, July 30 – August 4, 1973* Vol. 1 (Dubna: JINR, 1973) p. 165
31. Vlasenkov V S et al., in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 7th Intern. Conf., Innsbruck, 1978* Vol. 1 (Vienna: IAEA, 1979) p. 211
32. Mirnov S V et al. *Nucl. Fusion* **51** 073043 (2011)
33. Berlizov A V et al., in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 6th Intern. Conf., Berchtesgaden, 1976* Vol. 1 (Vienna: IAEA, 1977) p. 3
34. Grove D et al., in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 6th Intern. Conf., Berchtesgaden, 1976* Vol. 1 (Vienna: IAEA, 1977) p. 21
35. Apgar E et al., in *Plasma Physics and Controlled Nuclear Fusion Research, Proc. 6th Intern. Conf., Berchtesgaden, 1976* Vol. 1 (Vienna: IAEA, 1977) p. 247
36. Dobrokhotov E J et al., in *11th Eur. Conf. on Controlled Fusion and Plasma Physics, Aachen, 5 – 9 September 1983* Vol. 1 (Geneva: European Physical Society, Plasma Physics Division, 1983) p. 369
37. Wagner F et al. *Phys. Rev. Lett.* **49** 1408 (1982)
38. Doyle E J et al. *Nucl. Fusion* **50** 075005 (2010)
39. Andrejko M V et al. *Plasma Phys. Control. Fusion* **36** A165 (1994)
40. ITER Physics Basis Editors *Nucl. Fusion* **39** 2137 (1999) p. 2143
41. Kamada Y et al. *Fusion Sci. Technol.* **42** 185 (2002)
42. Unterberg B, Samm U *Trans. Fusion Sci. Technol.* **41** 415 (2006)
43. Gruber O et al. *Nucl. Fusion* **49** 115014 (2009)
44. Sykes A et al. *Plasma Phys. Control. Fusion* **39** B247 (1997)
45. Gusev V K et al. *Zh. Tekh. Fiz.* **69** (9) 58 (1999) [*Tech. Phys.* **44** 1054 (1999)]
46. Wan B et al. (for the EAST and HT-7 Teams and Intern. Collab.) *Nucl. Fusion* **49** 104011 (2009)
47. Park Y S et al. *Nucl. Fusion* **51** 053001 (2011)
48. Pradhan S and SST-1 Team *20th IAEA Fusion Energy Conf.* (1 – 6) FT3-4Rb (2004)
49. Kamada Y et al. *Nucl. Fusion* **51** 073011 (2011)
50. ITER Physics, ITER Documentation Series No. 21 (Vienna: IAEA, 1991)
51. Mukhovatov V et al. *Nucl. Fusion* **47** S404 (2007)
52. Tobita K et al. *Fusion Eng. Design* **81** 1151 (2006)
53. Kadomtsev B B "Ot MTR do ITER" *Usp. Fiz. Nauk* **166** 449 (1996) ["From MTR to ITER" *Phys. Usp.* **39** 419 (1996)]
54. Shafranov V D "Pervyi period istorii termoyadernykh issledovanii v Kurchatovskom institute" *Usp. Fiz. Nauk* **171** 877 (2001) ["The initial period in the history of nuclear fusion research at the Kurchatov Institute" *Phys. Usp.* **44** 835 (2001)]
55. Shafranov V D *Nenauchnye Trudy* (Nonscientific Works) (Moscow: RNTs "Kurchatovskii Institut"; Trovant, 2009)
56. Bondarenko B D "Rol' O.A. Lavrent'eva v postanovke voprosa initsiirovaniya issledovanii po upravlyaemomu termoyadernomu

sintezu v SSSR'' *Usp. Fiz. Nauk* **171** 886 (2001) [''Role played by O A Lavrent'ev in the formulation of the problem and the initiation of research into controlled nuclear fusion in the USSR'' *Phys. Usp.* **44** 844 (2001)]

57. Goncharov G A ''K pyatidesyatiletiyu nachala issledovanii v SSSR vozmozhnosti sozdaniya termoyadernogo reaktora'' *Usp. Fiz. Nauk* **171** 894 (2001) [''The 50th anniversary of the beginning of research in the USSR on the potential creation of a nuclear fusion reactor'' *Phys. Usp.* **44** 851 (2001)]
58. Goncharov G A ''Iz Arkhiva Prezidenta Rossiiskoi Federatsii'' *Usp. Fiz. Nauk* **171** 902 (2001) [''From the Archive of the President, Russian Federation (USSR Council of Ministers Resolution)'' *Phys. Usp.* **44** 859 (2001)]
59. Sakharov A D ''Otzyv A.D. Sakharova na rabotu O.A. Lavrent'eva'' *Usp. Fiz. Nauk* **171** 908 (2001) [''A D Sakharov's referee report on O A Lavrent'ev's paper'' *Phys. Usp.* **44** 865 (2001)]
60. Mirnov S V ''Akademik B.B. Kadomtsev i Internatsional'nyi termoyadernyi eksperimental'nyi reaktor ITER'' *Usp. Fiz. Nauk* **179** 767 (2009) [''Academician B B Kadomtsev and the International Thermonuclear Experimental Reactor (ITER)'' *Phys. Usp.* **52** 725 (2009)]
61. Putvinskii S V ''Vozmozhna li budushchaya mirovaya energeticheskaya sistema bez yadernogo sinteza?'' *Usp. Fiz. Nauk* **168** 1235 (1998) [''Can the future world energy system be free of nuclear fusion?'' *Phys. Usp.* **41** 1127 (1998)]

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

From the Cosmological Model to the generation of the Hubble flow

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Contents

Abstract. **This paper reviews various approaches to the question (pioneered by Sakharov) of how the observed Hubble flow forms. By extrapolating the Cosmological Standard Model to the past, the geometrical properties of and conditions in the early Universe are determined. A new cosmogenesis paradigm based on geodesically complete black/white hole geometries with an integrable singularity is discussed.**

1. Introduction

In his papers (see, for example, Refs [1, 2]), Andrei Dmitrievich Sakharov repeatedly expressed the idea that cosmological flows may build up from superdense singular states of matter as a result of quantum transitions accompanied by changes in the world constants, signature, time arrow, and other geometrical characteristics of space-time and matter. The way gravitating systems or their parts get into such special states and how they leave them have spawned discussions over a long period of time, which continue even now.

Large curvatures and densities arise in a natural way in separated space-time domains during the collapse of compact astrophysical objects, leading to the formation of black holes. Yet the question of how the collapse passes into expansion still awaits a solution. The concept of the multisheeted universe proposed in Sakharov's works, as well as the paradigm of multiple universes (Multiverse) (see, for example, book [3]), widely accepted today, requires the existence of an explicit and simple physical mechanism generating multiple flows of expanding matter. However, the mechanism of *cosmogenesis* — the formation of cosmological flows of matter — remains vague thus far. To explore it, we need to know the initial structure of our material flow, which we call the early Universe, with sufficient accuracy.

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The task of determining the geometrical properties of the early Universe was successfully solved at the turn of this century with the appearance of the Cosmological Standard Model (CSM) which describes all the totality of experimental and observational data in the energy range $10^{-3} - 10^{12}$ eV. With the creation of the CSM, it has become possible to recover the initial state of the Universe through the direct extrapolation in the past, having made only the assumption that the general relativity (GR) is valid for energies up to that of Grand Unification ($\sim 10^{25}$ eV). The subsequent direct extrapolation (toward even larger energies) faces difficulties because of the inflationary stage of the Big Bang (BB) during which the Hubble radius goes beyond the light horizon of the past, where the prevailing part of the information on the pre-inflationary flow geometry is confined (Fig. 1) [4]. The deviations from the quasi-Friedmann model increase at the inflationary stage (for the extrapolation in the past); therefore, the structure of cosmological flow at the beginning of inflation could be substantially different from the Friedmann one and have another symmetry and topology.

Owing to the appearance of the CSM, the problem of generation of the initial state of expanding flow (the cosmogenesis problem) has acquired a rigorous scientific formulation in the framework of GR, since energies do not exceed the Planck value. Additionally, because the gravitating system passes through its ultrahigh energy and curvature phases very fast, in considering models with the transition of collapse into expansion it is sufficient to use only local conservation laws which can be represented in the general geometric form of the Bianchi identities. For doing so, it is convenient to move all kinds of gravity modifications and quantum-gravity corrections to the mean Einstein tensor to the right-hand side of gravity equations, associating all these terms with the *effective* energy–momentum tensor which now

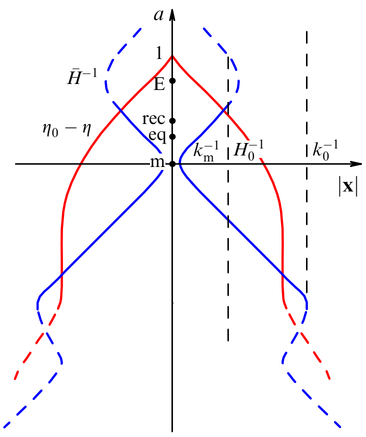

Figure 1. The ordinate is the scale factor a, and the abscissa is the comoving coordinate $|\mathbf{x}|$ (observers's world line is $\mathbf{x} = 0$). The line $\bar{H}^{-1}$ corresponds to the Hubble radius ($\bar{H} = aH$), $\eta_0 - \eta$ is the light cone of the past. The k_m^{-1}, H_0^{-1}, and k_0^{-1} scales correspond to some fractions of a millimeter, the value of 4.3 Gpc, and the size of the Friedmann world. The time moments labelled as m, eq, E, and rec mark the end of the inflationary stage of the BB and the origins of DM, DE, and recombination epochs.

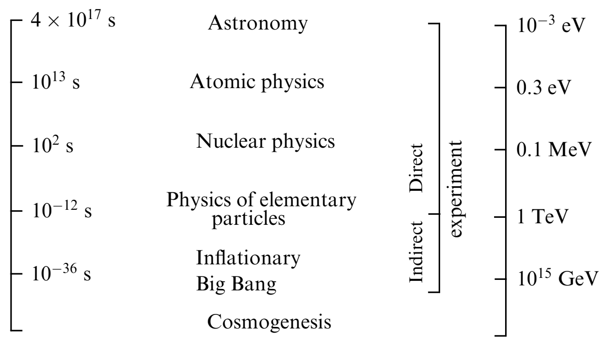

Figure 2. Experimental basis of the early Universe. The left scale corresponds to the Universe curvature radius expressed in seconds, and the right one shows characteristic energies.

includes not only material but also space-time degrees of freedom. Such an approach enables us to keep the notion of mean metric space-time (independently of values of density and curvature components) and stay in the class of geometries with *integrable* singularities [5], which facilitates the construction of full maps of black (white) holes on radial geodesics and the understanding of physics behind the gravitational transformation of the internal T-region in a black hole to the anticollapse of created matter in the white hole (cosmological expansion).

In what follows, we consider the lessons from the extrapolation, determine the initial conditions in the early Universe, discuss the physical nature of the multisheet universe, and present models for the formation of cosmological flows of matter in the framework of the cosmogenesis concept proposed by us.

2. Lessons of extrapolation

The Cosmological Standard Model rests on extensive observational and experimental bases in the energy range spanning 15 orders of magnitude — from the current cosmological density ($\sim 10^{-3}$ eV) to energies of electroweak transition ($\sim 10^{12}$ eV) explored with the Large Hadron Collider and corresponding to the age of the Universe of several picoseconds (Fig. 2). No extrapolation is involved here — this is the available scientific knowledge, well studied and tested on Earth. Extrapolation begins further, in advancing over the next 13 orders of magnitude in energy, up to that of Grand Unification.

The most important outcome of this knowledge is our ideas about the geometry of the early Universe, which is identified in GR with the structure of the metric tensor and the energy–momentum tensor. The empirically derived model contains a small parameter — the amplitude of cosmological inhomogeneities of the metrics ($\sim 10^{-5}$) — which allows the perturbation theory to be applied to its description. In the zeroth order, we deal with the spatially flat Friedmann model described by a single function of time — the scale factor $a(t)$ depending on the physical composition of matter. In the first order, the structure of tensors proves to be more complex — it can be reduced to three irreducible forms [6]: scalar (density perturbations), tensor (gravitational waves), and vector (for example, magnetic fields), each represented by its power spectrum: $S(k)$, $T(k)$, and $V(k)$, where k is the wave number (inverse perturbation scale). For a random spatial phase of perturbation, the second and third orders do not introduce new free functions.

We conclude that the initial cosmological flow of matter is fully deterministic and possesses a laminar, quasi-Hubble character (a weakly inhomogeneous, or quasi-Friedmann universe). Having specified the initial conditions and matter composition, we obtain as the result of evolution the whole palette of physical processes and events in the current world. Of the four functions mentioned above, we know only the first two in the domains of definition accessible for observational cosmology. The ongoing Planck experiment will unveil the spectrum of cosmological gravitational waves, assuming it is successful. The detection of the vector mode lies beyond the present-day experimental possibilities.

The explanation of the initial properties of cosmological flow is the main task of cosmogenesis. The statement of physical problems follows from the lessons of extrapolation [4], of which seven are considered below.

1. *The Universe is large*. This fact can be explained by the presence of a short inflationary stage of the BB preceding the radiation-dominated period of expansion.

The current Hubble radius (4-curvature radius) equals $H_0^{-1} \simeq 4.3$ Gpc which, on the time scale, lies 60 orders of magnitude away from the Planck value. According to the CSM, the scale factor could have changed by only 30 orders of magnitude over this period, as follows from the Friedmann equations describing the events in the principal order of the perturbation theory:

$$H \equiv \frac{\dot{a}}{a} = H_0 \sqrt{\frac{10^{-4}}{a^4} + \frac{0.3}{a^3} + 0.7} \;\to\; \frac{H_0}{100a^2}\,, \tag{1}$$

$$\gamma \equiv -\frac{\dot{H}}{H^2} = \frac{2 \times 10^{-4} + 0.4a}{10^{-4} + 0.3a + 0.7a^4} \in (2,\, 0.4)$$

(the three terms under the root sign correspond to the radiation, nonrelativistic matter, and dark energy; the scale factor is normalized to unity at the present time). By performing extrapolation in the past, we recover the dominance of radiation at the early times and a value of several millimeters for the initial size of the Universe, which is a very large magnitude exceeding the Planck value by 30 orders of magnitude. To explain such a size, a preceding inflationary stage is needed with a value of $\gamma < 1$ and the number of Hubble epochs not less than 70 ($\sim$ 30 ln 10).

2. *The causality principle*, witnessing independently the existence of the inflationary phase of the BB. According to formulas (1), the galactic scales turn out to be outside the causal zone in the radiation-dominated period of expansion (see Fig. 1). They could have got into this zone from the causally connected domain provided that a short inflationary stage of the BB exists.

3. *The smallness of tensor mode,* also pointing to the inflationary stage of the BB, and the Gaussian character of density perturbations.

While the zeroth order of the perturbation theory is described by the Friedmann equations, the first order corresponds to oscillators (see the Appendix). The *S*- and *T*-modes evolve as massless scalar fields $q = (q_S, q_T)$ experiencing external gravitational action of the nonstationary Hubble flow, which leads to the parametric amplification of fields q in the course of cosmological expansion [4, 7, 8]. Under sufficiently general assumptions about the expansion rate, the equations for elementary oscillators admit a general solution; however, their excitation amplitudes depend on the initial data. For oscillators residing initially in their ground (nonexcited) state, the power spectra of the generated perturbations have the form

$$T(k) \simeq \frac{H^2}{M_{\mathrm{P}}^2} < 10^{13}\ \mathrm{GeV}, \qquad \frac{T}{S} \simeq 4\gamma < 0.1\,, \tag{2}$$

where $\langle q_{S,T}^2 \rangle = \int (S, T)\, \mathrm{d}k/k$, $\langle \ldots \rangle$ implies averaging over the state, and $M_{\mathrm{P}} \equiv G^{-1/2} \simeq 10^{19}$ GeV is the Planck mass. As we can see, the tensor mode is on equal footing with the scalar one in the theory, whereas their ratio depends on the magnitude of γ during the parametric generation epoch. The inequalities (2) reflect the present-day observational limitations on cosmological gravitational waves. From the second inequality, it follows that the quantity γ was below unity in the early Universe, which indirectly points to the inflationary character of the early Hubble flow. A rigorous proof of the primary inflation will become possible in the case of direct detection of the tensor mode by exploring the relic radiation and confirming the theoretically predicted relationship between the slope of the exponent of the *T*-spectrum and the ratio between perturbation mode amplitudes ($n_T \equiv \mathrm{d} \ln T / \mathrm{d} \ln k \simeq -2\gamma \simeq -0.5 T/S$).

We stress that this assertion rests on the hypothesis that the early Hubble flow is ideal, as expressed by the vacuum initial condition for the fields q. This assumption is supported by the observed *Gaussian* random spatial distribution of large-scale density perturbations (the property of quantum fluctuations linearly transferred to the field of inhomogeneities) and a pronounced temporal phase of acoustical oscillations that corresponds to a *growing* adiabatic evolution branch (the implication of the parametric amplification effect).

4. *The presence of dark matter*. Nonlinear halos 'inhabited' by galaxies inside them are composed of nonrelativistic particles of dark matter (DM) that do not interact with baryons and radiation. The nature of DM particles is currently unknown, but there are observational arguments favoring the assertion that the origin of DM is rooted in the baryon asymmetry of the Universe. Here are two of them: the cosmological mass densities of DM and baryons are close to each other (their ratio equals 5), and their large-scale distribution scales in space coincide (the cosmological horizon at the instant of equal densities of relativistic and nonrelativistic components of matter is identical to the acoustical horizon at the instant of hydrogen recombination). If we take into account that the ratio between densities for two nonrelativistic media stays constant with time, we are led to conclude that the reasons for the appearance of DM and baryon asymmetry are interconnected. One can suppose that both the particles of DM and excessive baryons have been formed in nonequilibrium processes of particle transformation in a hot radiative plasma of the Hubble flow. In this case, their origin is not related to the pre-inflatory history of the BB.

5. *Indications in favor of the existence of dark energy*. The matter forming the structure of the Universe is measured by gradients of gravitational potential, derived from dynamical observations of galaxies and gas, as well as with the help of gravitational lensing. Its share does not exceed 30% of the critical density. The remaining 70% constitute a uniformly distributed subsystem that does not interact with light or baryons. This is the so-called dark energy (DE) possessing a negative effective pressure comparable in absolute value to its energy density. By all probability, here we are dealing with a relic superweak field 'conserved' at the stage dominated by radiation and particles that came into motion (in the slow-roll state) under the action of self-gravity 3.5 billion years ago. If it is indeed so, we are witnessing the relaxation of a massive field, which suggests a different view of the Hubble flow history.

6. *The history of the Universe's evolution*. We see that evolution passed through the periods of accelerated ($\gamma < 1$) and decelerated ($\gamma > 1$) expansion. The first case includes the inflationary stages of the BB and DE, and the second one covers the stages dominated by radiation and matter. We know that small perturbations fade away for $\gamma < 1$ but grow for $\gamma > 1$. Hence, it follows that the history of the Universe has seen periods of both *build-up* (recovery) of the Hubble flow and phases of its *destruction* (and then we are talking about structure formation). This is a manifestation of the dual character of long-range gravity, capable of creating strongly ordered systems from rather general initial distributions and states of matter. It is the anticollapse, or inflation (the build-up of an ideal Hubble flow), and its inverse, the process of collapse (the formation of gravitationally bound halos and black holes). Thus, we can view the dynamical history of the flow as a process, covering 14 billion years, of relaxation of massive fields to the minimum energy state. Here, we come close to the seventh and last lesson from the extrapolation of the CSM toward a pre-inflationary universe. It is how to create the conditions necessary for the occurrence of an expanding material flow, taken over by inflation and transformed into the observed Hubble flow.

3. Conditions of cosmogenesis

Thus, solving the cosmogenesis problem means answering three questions.

- How do large densities form?
- Where does the expansion come from?
- What is the origin of cosmological symmetry?

Inflation leaves these questions unanswered. In its different variants (e.g., Refs [9, 10]), new physical fields are introduced, which from the very beginning are in a superdense state. The birth of the Universe from 'nothing' [11] again leads to the idea of 'false' vacuum with a high density, whereas in bouncing models, having been developed for already more than 40 years, the question about the initial state no longer makes sense (owing to modifications of the equation of state), and the Friedmann symmetry is introduced axiomatically.

The fundamental principle in the natural sciences, stating that all measurable quantities should remain finite in a solution that describes Nature, allows us to advance in solving the cosmogenesis problem. Indeed (see Ref. [5]), if we consider realistic models of black/white holes with *smoothed* metric singularities, it becomes possible to constrain tidal forces (despite the divergence of some curvature components) and recover a geodesically complete metric space-time based on dynamic solutions stemming from the energy–momentum conservation laws. In the vicinity of a singularity forming around a collapsed object, there is the effective matter which we model in a broad class of equations of state. Radial geodesics now do not end at the singular hypersurface, but continue in the T-domain of a white hole. Hence, we arrive at the conclusion that the T-domain of a black/white hole originated from the collapse of a compact astrophysical system may spawn a new (daughter, or astrogenic) universe that is in the absolute future with the respect to the maternal black hole. In that case, the answers to the posed questions are almost obvious:

- The ultrahigh curvatures and densities at the initial stages of cosmological evolution arise because of extremely strong rapidly varying gravitational fields existing inside the black/white hole and generating matter belonging to the daughter universe;
- The initial push to the cosmological flow of effective matter comes from the expanding T-domain of the white hole that was formed as a result of the collapse of a compact object in the maternal universe. Relatedly, the BB phenomenon is of a purely gravitational nature and is, in essence, the manifestation of gravitational (tidal) instability;
- The symmetry of the inner domain of the black/white hole outside the body of a collapsed system is that of a homogeneous cosmology, in which the material flow in the white hole can be isotropized through the known inflation mechanisms, and in this way the white hole will transform into the Friedmann world.

4. Black/white holes with integrable singularity

The application of the aforementioned principle to the general type spherically symmetric metrics implies the finiteness of real-valued functions N and Φ in $\mathbb{R}^2 \in (r, t)$:

$$\mathrm{d}s^2 = N^2(1 + 2\Phi)\,\mathrm{d}t^2 - \frac{\mathrm{d}r^2}{1 + 2\Phi} - r^2\,\mathrm{d}\Omega\,, \qquad (3)$$

where r and t are the radial and temporal Eulerian coordinates in the R-domains of space-time ($\Phi > -1/2$) and, accordingly, the temporal and radial coordinates of the same solution in the T-domain ($\Phi < -1/2$ (see Ref. [12])), and $\mathrm{d}\Omega$ is the interval squared on the surface of a 2-sphere.

According to the equations of GR, we have

$$\Phi = -\frac{Gm}{r}\,, \qquad (4)$$

where the everywhere continuous function of mass

$$m = m(r, t) = 4\pi \int_0 T_t^t r^2\,\mathrm{d}r \qquad (5)$$

becomes zero in the inversion line $t = 0$ because of the requirement that Φ be finite, with T_t^t being the tt component of the energy–momentum tensor. The integrability of the function $T_t^t r^2$ at a zero point (for a finite black-hole mass) leads us to the notion of the *integrable* singularity $r = 0$ surrounded by the effective matter.[1] In the absence of spatial flows in the T-domain, the energy–momentum tensor takes the form $T_\mu^\nu = \mathrm{diag}\,(-p,\, \varepsilon, -p_\perp, -p_\perp)$. In Section 5, we shall give examples of models in which the energy density is generated by variations of transverse pressure $p_\perp$ changing in a triggered manner at certain time instants r. In these models, the tidal forces for radial geodesic lines are everywhere finite, and world lines of test particles continue from the T-domain of the black hole into the white one (see Ref. [5] for more details). Thus, the tidal gravitational interaction in the vicinity of integrable singularity attains the form of time oscillation connecting the inner regions of the black and white holes. We call this effect collapse *inversion*.

5. Astrogenic universes

The matter in T-domains of spherically symmetric vacuum geometries can be generated with the help of time variations of the function $p_\perp(r)$, for example, jumps of the first kind, because the equations of motion do not contain its derivatives (the energy is supplied by the gravitational field, and the metric is automatically adjusted in accordance with GR). The longitudinal pressure can conveniently be chosen 'vacuum-like' ($p = -\varepsilon$) for the sake of simplicity, then $N = 1$ everywhere in $\mathbb{R}^2$ and the reference frame (3) is comoving with matter, and the energy density follows from the Bianchi identity

$$\frac{\mathrm{d}(\varepsilon r^2)}{r\,\mathrm{d}r} = -2p_\perp\,. \qquad (6)$$

Consider two simple variants of the behavior of function $p_\perp$ (Fig. 3 and 4):

A) Asymmetric step, $p_\perp^{(\mathrm{A})} = p_0\theta\big(r(r_0 - r)\big) - p_1\theta(-r)$;

B) Symmetric step, $p_\perp^{(\mathrm{B})} = p_0\theta(r_0^2 - r^2)$, where $r_0 \leqslant 2GM$ and p_1 are real-valued positive constants, and $M \equiv 8\pi r_0^3 p_0/3$ is the black-hole mass. Integration of Eqn (6) subject to the initial condition $\varepsilon(r \geqslant r_0) = 0$ gives the following continuous $\varepsilon(r)$ functions:

$$\varepsilon^{(\mathrm{A})} = -p_\perp^{(\mathrm{A})} + p_0\,\frac{r_0^2}{r^2}\,\theta(r_0 - r)\,, \quad \varepsilon^{(\mathrm{B})} = p_\perp^{(\mathrm{B})}\left(\frac{r_0^2}{r^2} - 1\right). \qquad (7)$$

Accordingly, A is the model of the astrogenic universe ($\varepsilon^{(\mathrm{A})} \to p_1$ for $r \to -\infty$), while B offers an example of an

[1] We assume that this matter can be induced by an intense rapidly varying gravitational field (because of quantum-gravity processes of vacuum polarization and matter creation) existing outside the collapsed object in the T-domain of the black/white hole. In that case, the symmetry of the full solution preserves the global Killing t-vector contained in the original Schwarzschild metric in a vacuum, and all the physical variables considered here are functions of r only (we suppose that $r > 0$ in the maternal black hole, and that $r < 0$ in the metric continuation into the T-domain through the $r = 0$ line).

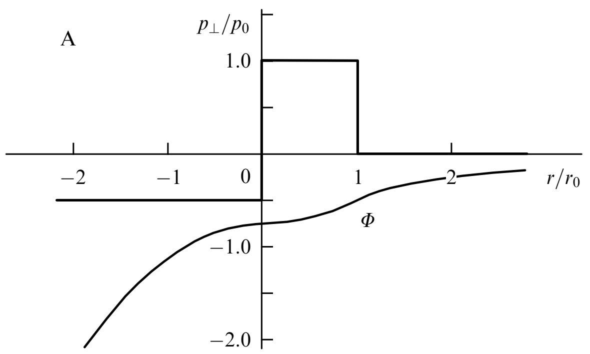

Figure 3. An asymmetric profile of transverse pressure (bold broken line), leading to the transformation of collapse into the cosmological expansion that asymptotically tends to the de Sitter solution. The curve depicts the evolution of gravitational potential in a model in which matter fills the entire T-domain of a black hole ($r_0 = 2GM$). Additionally, as an example, it is assumed that $p_1/p_0 = 0.5$.

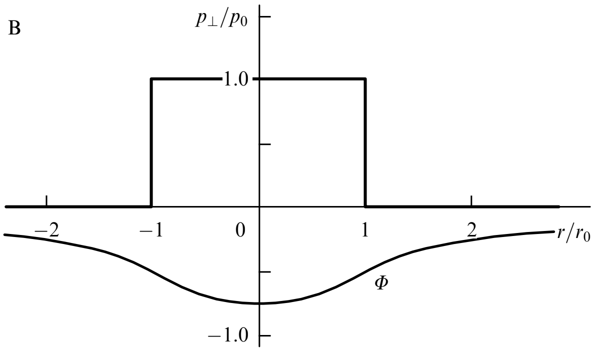

Figure 4. A symmetric profile of transverse pressure (bold broken line) leading to the transformation of a black hole into a white hole of the same mass. The curve plots the evolution of gravitational potential in a model in which matter fills the T-domains of black and white holes completely ($r_0 = 2GM$).

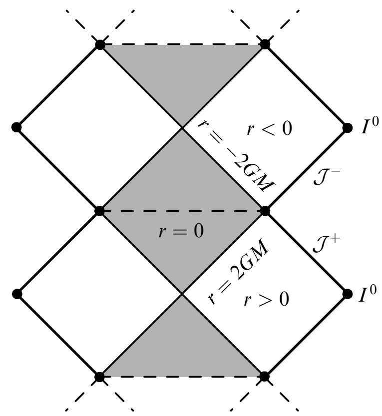

Figure 5. The Penrose diagram of a pulsating flow with a symmetric function $p_\perp(r)$ (see Fig. 4). The shaded domain is occupied with matter. $\mathcal{J}^+$ is the light infinity of the future for observers in the domain $r > 0$; $\mathcal{J}^-$ is the light infinity of the past for observers in the domain $r < 0$, and I^0 are spatial infinities of the R-domains.

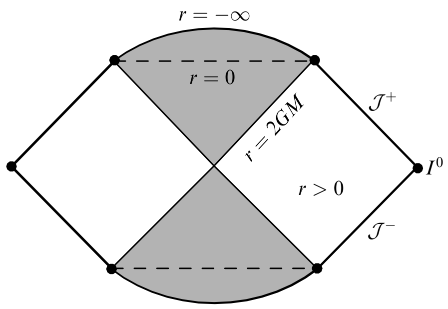

Figure 6. The Penrose diagram of the astrogenic universe with an asymmetric function $p_\perp(r)$ (see Fig. 3).

oscillating (eternal) black/white hole. The potential $\Phi(r)$ belongs to the class of C^1 functions [see Eqns (4) and (5), and Figs 3 and 4].

Consider the limiting cases of option B. As $r_0 \to 0$, we have an eternal black/white hole maximally continued into a vacuum, with a δ-shaped source localized in the region $r = 0$ [5]:

$$\varepsilon = 2p_\perp = M\,\frac{\delta(r)}{2\pi r^2}\,. \tag{8}$$

For the limiting extension, $r_0 = 2GM$, we obtain a stationary hole with an oscillating flow of matter in the T-domain, where $r = -2GM\sin(H\tau)$, $H^{-1} \equiv 2\sqrt{2}GM$, τ is the oscillation frequency and the proper time of the flow:

$$\varepsilon = \frac{3H^2}{8\pi G}\cot^2(H\tau)\,, \tag{9}$$

$$\mathrm{d}s^2 = \mathrm{d}\tau^2 - \frac{1}{2}\left(\cos^2(H\tau)\,\mathrm{d}t^2 + \frac{\sin^2(H\tau)}{H^2}\,\mathrm{d}\Omega\right).$$

Here, we are dealing with a spatially homogeneous, anisotropic and pulsating flow of matter, the full Penrose diagram of which is plotted in Fig. 5. Phase transitions in matter at the stage of its volume expansion can lead to inflation and isotropization of the flow, establishing in this manner the Friedmann symmetry in an arbitrarily large volume.

A simple example of such a scenario is illustrated by case A. Indeed, for $\tau \geqslant 0$ from Eqn (7) we get a solution that asymptotically tends to the de Sitter one (Fig. 6):

$$r = -\frac{\sinh(H_1\tau)}{\sqrt{2}H_1}\,, \qquad \varepsilon = \frac{3H_1^2}{8\pi G}\coth^2(H_1\tau)\,, \tag{10}$$

$$\mathrm{d}s^2 = \mathrm{d}\tau^2 - \frac{1}{2}\left(\cosh^2(H_1\tau)\,\mathrm{d}t^2 + \frac{\sinh^2(H_1\tau)}{H_1^2}\,\mathrm{d}\Omega\right),$$

where the constant $H_1 = (8\pi G p_1/3)^{1/2}$ can take any values, independent of the value of external mass of the maternal black hole. This elementary example of the astrogenic universe allows easy generalization to more complex models, with inclusion of massive scalar fields, radiation, and other elements of the modern 'kitchen'of the CSM.

6. Conclusions

Extrapolation of the CSM in the past implies the expanding initial Hubble flow of matter with ultralarge curvatures and densities. In models of black/white holes with integrable singularities, cosmological flows may arise in the expanding T-domains of these geometries (white holes) lying in the absolute future with respect to the maternal black hole. In the framework of the proposed concept, we arrive at the notion of *astrogenic cosmology* — the cosmology obtained through the inversion of the collapse of some astrophysical compact system into the expanding flow of effective matter outside the maternal body of the collapsed object proper. Speaking figuratively, black holes in such models play a role of matches igniting other worlds.

It is conceivable that the multisheet universes with complex topology, anticipated and discussed by Sakharov, owe their existence to collapsed systems that completed their evolution in the maternal Universe. Scientific theories have predictive skills and have to be tested against experiments and observations. These questions inspire us to new studies of riddles and problems of cosmogenesis.

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7. Appendix

It should be kept in mind [4] that $q_S = \delta a/a + Hv$ and v are the perturbations of a comoving scale factor and the matter velocity potential, respectively, and $q_T = (q_\lambda)$ are the amplitudes of gravitational waves with the polarization $\lambda = \oplus, \otimes$. The conformal fields $\tilde{q} = \tilde{\alpha} q/\sqrt{8\pi G}$ behave like classical harmonic oscillators with variable frequencies in the Minkowski space:

$$\tilde{q}'' + (\omega^2 - U)\,\tilde{q} = 0\,, \qquad (11)$$

where the prime denotes a derivative with respect to the Minkowski time $\eta = \int \mathrm{d}t/a$, and

$$U \equiv \frac{\tilde{\alpha}''}{\tilde{\alpha}}\,, \quad U_T = (2-\gamma)\,a^2 H^2\,, \quad \tilde{\alpha}_S = \frac{a\sqrt{2\gamma}}{\beta}\,, \quad \tilde{\alpha}_T = a\,,$$

where $\omega = \beta k$, β_S is the speed of sound in the light speed units, and $\beta_T = 1$. For two or more media, a term describing the action of isometric perturbations has to be added to the right-hand side of equations for S-oscillators.

The dependence of the effective frequency $(\omega^2 - U)$ on time leads to the parametric excitation of elementary oscillators in the course of the Universe's evolution. Assuming the initial vacuum state of fields in the wave zone $(\omega^2 > |U|)$, which transforms with time into the parametric one $(|U| > \omega^2)$, we get the required solution (11) (for more details, see Ref. [4]):

$$\frac{\exp\left(-\mathrm{i}\int \omega\,\mathrm{d}\eta\right)}{\tilde{\alpha}\sqrt{2\omega}} \to \frac{\boldsymbol{c} - \mathrm{i}}{C\sqrt{2k}} \to \frac{M_{\mathrm{P}}\sqrt{\pi}}{2k^{3/2}}\,q_k\,, \qquad (12)$$

where C is the matching constant in the region $|U| \simeq \omega$, and the function $\boldsymbol{c} = -kC^2 \int \tilde{\alpha}^{-2}\,\mathrm{d}\eta \to \mathrm{const}$ converges on the upper limit for $\gamma < 3$. The 'frozen' fields q_k correspond to the growing branch of the general solution, their phase is random, and the module defines spectral amplitudes $S = |q_{kS}|^2$ and $T = |q_{k\oplus}|^2 + |q_{k\otimes}|^2$. For $\beta = 1$ and $\gamma \simeq \mathrm{const}$, equations (11) become identical for all modes and $T/S = 2\tilde{\alpha}_S^2/\tilde{\alpha}_T^2 = 4\gamma$; for $\gamma < 1$, we get the T-spectrum (2) up to a factor of order unity.

References

1. Sakharov A D *Zh. Eksp. Teor. Fiz.* **83** 1233 (1982) [*Sov. Phys. JETP* **56** 705 (1982)]
2. Sakharov A D *Zh. Eksp. Teor. Fiz.* **87** 375 (1984) [*Sov. Phys. JETP* **60** 214 (1984)]
3. Carr B (Ed.) *Universe or Multiverse*? (Cambridge: Cambridge Univ. Press, 2007)
4. Lukash V N, Mikheeva E V *Fizicheskaya Kosmologiya* (Physical Cosmology) (Moscow: Fizmatlit, 2010)
5. Lukash V N, Strokov V N, arXiv:1109.2796
6. Lifshitz E M *Zh. Eksp. Teor. Fiz.* **16** 587 (1946)
7. Lukash V N *Pis'ma Zh. Eksp. Teor. Fiz.* **31** 631 (1980) [*JETP Lett.* **31** 596 (1980)]
8. Lukash V N *Zh. Eksp. Teor. Fiz.* **79** 1601 (1980) [*Sov. Phys. JETP* **52** 807 (1980)]
9. Guth A H *Phys. Rev. D* **23** 347 (1981)
10. Linde A D *Phys. Lett. B* **108** 389 (1982)
11. Dolgov A D, Zel'dovich Ya B, Sazhin M V *Kosmologiya Rannei Vselennoi* (Moscow: Izd. MGU, 1988) [Translated into English: Dolgov A D, Sazhin M V, Zeldovich Ya B *Basics of Modern Cosmology* (Gif-sur-Yvette: Editions Frontières, 1990)]
12. Novikov I D *Astron. Zh.* **38** 564 (1961) [*Sov. Astron.* **5** 423 (1961)]

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A D SAKHAROV'S 90TH BIRTHDAY COMMEMORATION

Cosmological Sakharov oscillations and quantum mechanics of the early Universe

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Contents

Abstract. **This is a brief summary of a talk delivered at the Special Session of the Physical Sciences Division of the Russian Academy of Sciences, Moscow, 25 May 2011. The meeting was devoted to the 90th anniversary of the birth of A D Sakharov. The focus of this contribution is on the standing-wave pattern of quantum-mechanically generated metric (gravitational field) perturbations as the origin of subsequent Sakharov oscillations in the matter power spectrum. Other related phenomena, particularly in the area of gravitational waves, and their observational significance are also discussed.**

1. Sakharov's first cosmological paper

The ideas and results of Andrei Sakharov's remarkable paper [1] have influenced the course of cosmological research and are still at the center of theoretical and observational studies. The title of his paper was "The initial stage of an expanding universe and the appearance of a nonuniform distribution of matter." The paper was submitted to JETP on 2 March 1965, that is, in the days when not only the existence of the cosmic microwave background radiation (CMB) was not yet established, but even the nonstationarity of the Universe was still debated. The second sentence of the abstract says: "It is assumed that the initial inhomogeneities arise as a result of quantum fluctuations of cold baryon–lepton matter at densities of the order of 10^{98} baryons/cm^3. It is suggested that at such densities gravitational effects are of decisive importance in the equation of state...."

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In what follows, we discuss recent attempts to explain the appearance of cosmological perturbations (density inhomogeneities, gravitational waves, and possibly rotational perturbations) as a result of quantum processes. In our approach, the perturbations arise as a consequence of superadiabatic (parametric) amplification of quantum mechanical fluctuations of the appropriate degrees of freedom of the gravitational field itself. For us, therefore, gravity is of decisive importance not so much because of its contribution to the equation of state of primeval matter but because the gravitational field (metric) perturbations are the primary object of quantization. Nevertheless, it must be stressed that the mind-boggling idea suggesting that something microscopic and quantum mechanical can be responsible for the emergence of fields and observed structures at astronomical scales was first formulated and partially explored in Sakharov's paper.

A considerable part of paper [1] is devoted to the evolution of small density perturbations, rather than to their origin. The spatial Fourier component of the relative density perturbation is denoted as $z_\kappa(t)$, where κ is the wavenumber. The function $z_\kappa(t)$ satisfies a second-order differential equation, numbered in the paper as Eqn (15), which follows from the perturbed Einstein equations. The calculation leading to the phenomenon that was later named Sakharov oscillations is introduced by the following words [1, p. 350]:

Yu.M. Shustov and V. A. Tarasov have at our request solved Eqn (15)*, with the aid of an electronic computer, for different values of* κ*. The calculations were made for the simplest equation of state, satisfying* $\varepsilon = nM$ *with* $n^{1/3} \ll M$ *and* $\varepsilon = An^{4/3}$ *with* $n^{1/3} \gg M$ *(A is a constant* ~ 1)

$$\varepsilon = n(M^2 + A^2 n^{2/3})^{1/2} \qquad (16).$$

In [1], the quantity, $n = 1/a^3(t)$ is the particle number density, ε is the energy density in the rest frame of matter, and $p = n\,\mathrm{d}\varepsilon/\mathrm{d}n - \varepsilon$ is the pressure. Obviously, interpolating formula (16) describes the transition from the relativistic equation of state $p = \varepsilon/3$, applicable at early times of evolution and relatively large n, to the nonrelativistic equation of state $p = 0$, valid at small n and late times. During the transition, the speed of sound decreases from $c_s = c/\sqrt{3}$ to $c_s = 0$.

It is important to realize that the physical nature of the discussed transition from $p = \varepsilon/3$ to $p = 0$ can be quite general. Being guided by the physical assumptions of his time, Sakharov speaks about cold baryon–lepton matter, the degenerate Fermi gas of relativistic noninteracting particles, and so on. But it is important to remember that the perturbed Einstein equations, such as Eqn (15), do not require knowledge of the microscopic causes of elasticity and the associated speed of sound. Gravitational equations operate with the energy–momentum tensor of matter and its bulk mechanical properties, such as the energy density, pressure, and the link between them, the equation of state. These are postulated by Eqn (16), and we can now think of the results of the performed calculation as a qualitative model of what can occur in other transitions, for example, in the transition from a fluid dominated by a photon gas with the equation of state $p = \varepsilon/3$ to a fluid dominated by cold dark matter (CDM) with the equation of state $p = 0$.

For simple models of matter, such as $\varepsilon = n^{\gamma}$ and $p = (\gamma - 1)\varepsilon$, Eqn (15) can be solved in elementary functions. Sakharov writes:

When $\gamma =$ const, the solution of this equation is expressed in terms of Bessel functions; for example, when $\gamma = 4/3$ we have increasing and decreasing solutions of the form $(\theta \sim t^{1/2}\kappa)$

$$z \propto \begin{cases} \cos\theta - \theta^{-1}\sin\theta\,, \\ \sin\theta + \theta^{-1}\cos\theta\,. \end{cases}$$

Indeed, these are the well-known solutions for $z_\kappa(t)$ in the $p = \varepsilon/3$ medium. The general solution of Eqn (15) is a linear combination of these two branches with arbitrary (in general, complex) coefficients. The first solution can be called increasing and the second decreasing because they respectively behave as θ^2 and θ^{-1} at very small θ. At later times, not long before the transition to the $p = 0$ stage, the functions $z_\kappa(t)$ represent ordinary acoustic waves with the oscillatory time dependence $\cos\theta$ and $\sin\theta$. We do not learn anything new from matching the increasing/decreasing part of the solution to the oscillatory part of the same solution; the general solution is already given by the formula above. At the $p = 0$ stage, the solutions for $z_\kappa(t)$ do not oscillate as functions of time; they are power-law functions of t.

The crucial observation in Sakharov's paper is contained in the following quotation:

The function $a(t)$ can be obtained in the case of Eqn (16) *analytically* (*Shustov*). *Shustov and Tarasov find, by integrating* (15)*, the limiting value as $t \to \infty$ of the auxiliary variable*

$$\zeta = z\left(1 + \frac{a^2 M^2}{A^2}\right)^{-1/2},$$

putting $\mathrm{d}\zeta/\mathrm{d}t = \mathrm{d}z/\mathrm{d}t \sim z_0$ *as* $t \to 0$. *It is obvious that* $\zeta(\infty) \propto z_0 B$.

In accordance with the results of the sections that follow, we put $z_0 \sim \kappa$. $\zeta(\infty)$ is a function of the parameter $A^{1/2}\kappa$. This function is oscillating and sign-alternating, but attenuates rapidly with increasing κ.

The last sentence of this quotation is a surprising statement of incredible importance. It says that well after the transition to the $p = 0$ stage ($t \to \infty$), the density fluctuation $z_\kappa(t)$ becomes an oscillating and sign-alternating function of the wavenumber κ. The square of this function is what can be called the power spectrum. Sakharov uses $z_\kappa(t) = z_{0\kappa}/\dot{a}^2$ at the very early times and takes $z_{0\kappa}$ as $z_0 \sim \kappa$ from his quantum mechanical considerations. It is therefore stated that the initial smooth power spectrum $z_{0\kappa}^2$ transforms into an oscillatory final power spectrum that has a series of zeros and maxima at some specific wavenumbers κ. If we imagine that in the era before the transition to the $p = 0$ stage, the field of sound waves was represented by a set of harmonic oscillators with different frequencies, then the claim is that well after the transition, some oscillators find themselves 'lucky', in the sense that they occur at the maxima of the resulting power spectrum, while others are 'unlucky', because they are at the zeros of the resulting power spectrum.

Certainly, such a striking conclusion cannot be unconditionally true. After all, a computer can be asked to make a similar calculation, but backwards in time. In this calculation, we can postulate a smooth power spectrum at the late $p = 0$ stage and evolve the spectrum back in time to derive the functions $z_\kappa(t)$ at the early $p = \varepsilon/3$ stage. The derived functions do not coincide with what was taken as the initial conditions in the original calculation [1], but such new initial conditions are possible in principle. By construction, these new initial conditions would not lead to the final power-spectrum oscillations. On the other hand, if the oscillations do arise from physically justified initial conditions, then this is an extremely important phenomenon. It dictates the appearance of a periodic structure in the Fourier space (a 'standard ruler' with characteristic spatial scales), which can be recognized in observations and can be used as a tool for other measurements.

The point of this remark is to stress that, as is argued below in more detail, the initial conditions leading to the Sakharov oscillations are inevitable if the primordial cosmological perturbations were indeed generated quantum mechanically.

The oscillatory transfer function $B(\kappa)$ participates in further calculations in [1], but it plays quite a modest role there. Sakharov himself did not elaborate on the discovered phenomenon in later publications. However, it seems to me that he was perfectly well aware of the importance of his observation, and he attentively followed subsequent developments. Some evidence for this is given in Section 4.

It was Ya B Zeldovich who assigned significant value to the discovered oscillations and named them the Sakharov oscillations. In conversations, at seminars, in papers with R A Sunyaev and A G Doroshkevich, and in a book with I D Novikov, Zeldovich discussed the physics of the phenomenon and its possible observational applications. Zeldovich and coauthors deserve credit for seeing the relevance of Sakharov's work for their own studies and for mentioning his paper. For example, one of the first papers on the subject in the context of a 'hot' model of the Universe [2] remarks: "at a later stage of expansion the amplitude of density perturbations turns out to be a periodic function of a wavelength (mass). Such a picture was previously obtained by Sakharov (1965) for a cold model of the Universe." And further [2]: "The picture presented above is only a rough approximation since the phase relations between density and velocity perturbations in standing waves in an ionized plasma were not considered. As mentioned in the introduction, Sakharov (1965) showed that the amplitude of perturbations of matter at a later stage when pressure does not play a role (in our case after recombination) turns out to be a periodic function of wavelength." Zeldovich and Novikov [3] discuss the phenomenon at some length and note that "The distribution of astronomical objects with respect to mass will thus reflect the Sakharov oscillations in a very smoothed-out form only. It is possible that they may not be noticed in a study of the mass spectrum." Fortunately, as we see below, there was significant observational progress in revealing Sakharov oscillations.

In the more detailed paper by Peebles and Yu [4], which paralleled [2], a modulated spectrum, with maxima and zeros, is explicitly presented in Fig. 5 and the relevance of the "first big peak in Fig. 5" for future experimental searches for irregularities in the microwave background radiation is noted. The spectral modulation was derived as a result of numerical calculations. Later private correspondence on the physical interpretation of oscillations inevitably ended up with lucky and unlucky oscillators [5]: "The Sakharov oscillations you mention also were considered by Jer Yu and me (a few years after Sakharov)..... Here there truly are modes that are unlucky, in the sense that they carry negligible energy."

To better understand the Sakharov oscillations, as well as other closely related phenomena, we have to make some formalization of the problem. We do this in the next section. Before that, it is interesting to note as a side remark that in his quantum mechanical considerations, Sakharov discusses the "initial stage of the expansion of the universe," and in particular with the scale factor $a = \exp(\lambda t)$ as $t \to -\infty$. He found this evolution in two cases, c and d, out of the four considered. A scale factor of this type is now advertized as inflation. However, Sakharov himself was sceptical about cases c and d. He finds arguments against them and concludes: "For these reasons we turn to curves a and b." (Criticism of contemporary inflationary claims can be found in [6, 7].)

2. Wave fields of different natures in time-dependent environments

The main physical reason behind Sakharov oscillations, and indeed behind many other similar phenomena, is the time dependence of the parameters characterizing the environment in which a wave field is given. This can be a changing speed of sound, or a changing background gravitational field, or all such factors together. In cosmology, the central object is the gravitational field (metric) perturbations. Other quantities, such as fluctuations of the density and velocity of matter (if they are present; we recall that they are absent in the case of gravitational waves), are calculable from the metric perturbations via the perturbed Einstein equations. Only in special conditions and for relatively short-scale variations can the gravitational field perturbations be neglected.

The gravitational field perturbation h_{ij} is defined by

$$\begin{aligned} ds^2 &= -c^2\,dt^2 + a^2(t)(\delta_{ij} + h_{ij})\,dx^i\,dx^j \\ &= a^2(\eta)\left[-\,d\eta^2 + (\delta_{ij} + h_{ij})\,dx^i\,dx^j\right]. \qquad (1) \end{aligned}$$

For each of the three types of cosmological perturbations (density perturbations, gravitational waves, and rotational perturbations), the field h_{ij} can be expanded in spatial Fourier modes with wave vectors $\mathbf{n}$:

$$\begin{aligned} h_{ij}(\eta, \mathbf{x}) = \frac{\mathcal{C}}{(2\pi)^{3/2}} \int_{-\infty}^{\infty} d^3\mathbf{n} \sum_{s=1,2} p_{ij}^s(\mathbf{n})\, \frac{1}{\sqrt{2n}} \\ \times \left[h_n^s(\eta)\exp(i\mathbf{n}\mathbf{x})\, c_{\mathbf{n}}^s + h_n^{s*}(\eta)\exp(-i\mathbf{n}\mathbf{x})\, c_{\mathbf{n}}^{s\dagger}\right]. \qquad (2) \end{aligned}$$

The power spectrum (variance) of a given field is a quadratic combination of the field averaged over space, or over the known classical probability density function, or over the known quantum mechanical state. In all cases, we arrive at an expression of the structure

$$\langle 0|\, h_{ij}(\eta, \mathbf{x})\, h^{ij}(\eta, \mathbf{x})|0\rangle = \frac{\mathcal{C}^2}{2\pi^2} \int_0^{\infty} n^2 \sum_{s=1,2} \left|\, h_n^s(\eta)\right|^2 \frac{dn}{n}. \quad (3)$$

The quantity

$$h^2(n, \eta) = \frac{\mathcal{C}^2}{2\pi^2}\, n^2 \sum_{s=1,2} \left|h_n^s(\eta)\right|^2 \qquad (4)$$

is called the metric power spectrum. At each instant of time, the metric power spectrum is determined by the absolute value of the gravitational mode functions $h_n^s(\eta)$ (in general, complex). (We often suppress the index $s = 1, 2$, which marks two polarization states present in metric perturbations of each type of cosmological perturbations.) To calculate power spectra of other quantities participating in the problem, we have to expand these quantities as in Eqn (2) and then use their mode functions in expressions for their power spectra, similar to Eqn (4).

The gravitational mode functions $h_n^s(\eta)$, as well as mode functions of other quantities participating in our problem, satisfy one version or another of the second-order differential 'master equation' [8]

$$f'' + f\left[n^2\, \frac{c_s^2}{c^2} - W(\eta)\right] = 0\,, \qquad (5)$$

where the 'speed of sound' c_s and the 'potential' $W(\eta)$ are functions of time in general. In particular, the Sakharov mode functions $z_\kappa(t)$ for density perturbations obey a specific equation of this kind (written in the t time). And the above-quoted Sakharov solution, for $\gamma = 4/3$, expressed in terms of Bessel functions with the argument θ, is a particular case where $c_s = c/\sqrt{3}$, whereas $W(\eta)$ is a simple function of the scale factor $a(\eta)$. Gravitational wave equations are also equations of this form with $c_s = c$.

Two linearly independent high-frequency solutions (i.e., solutions of master equation (5) without $W(\eta)$ and with $c_s = \text{const}$) are usually taken as $f_n(\eta) = \exp\left[\pm in(c_s/c)\,\eta\right]$. If these mode functions $f_n(\eta)$ represent sound waves not long before the transition to the $p = 0$ stage, then using them for calculating the power spectrum would lead to $|f_n|^2 = 1$ and hence to the absence of oscillations in the power spectrum of density perturbations. Therefore, we do not expect any segregation into lucky and unlucky oscillators in the post-transition era. The general decomposition (2) should be considered more thoroughly.

The general high-frequency solution of Eqn (5) (for simplicity, we temporarily set $c_s/c = 1$) is given by $f_n(\eta) = A_n \exp(-in\eta) + B_n \exp(in\eta)$, where complex coefficients A_n and B_n are in general arbitrary functions of n. The $\mathbf{n}$-mode of the field

$$h_{\mathbf{n}}(\eta, \mathbf{x}) = f_n(\eta)\exp(i\mathbf{n}\mathbf{x}) + f_n^*(\eta)\exp(-i\mathbf{n}\mathbf{x})$$

is a sum of two waves traveling in opposite directions with arbitrary amplitudes and arbitrary phases. One particular traveling wave is chosen by setting $|A_n| = 0$ or $|B_n| = 0$. By contrast, the choice $|A_n| = |B_n|$ makes the field a standing wave, that is, the product of a function of η and a function of $\mathbf{nx}$:

$$h_{\mathbf{n}}(\eta, \mathbf{x}) = 4\rho_A \cos\left(n\eta + \frac{\phi_B - \phi_A}{2}\right) \cos\left(\mathbf{nx} + \frac{\phi_B + \phi_A}{2}\right),$$

where we use $A_n = \rho_{A_n} \exp(\mathrm{i}\phi_{A_n})$, $B_n = \rho_{B_n} \exp(\mathrm{i}\phi_{B_n})$ without the label n.

The power spectrum of the general solution is

$$|f_n|^2 = \rho_A^2 + \rho_B^2 + 2\rho_A \rho_B \cos(2n\eta + \phi_B - \phi_A)\,.$$

Clearly, for a given time instant η, the spectrum is a modulated function of n. For the modulation to take the form of strictly periodic oscillations, the phase $\phi_B - \phi_A$ must be a linear function of n. The oscillations vanish for traveling waves and have the maximal depth, up to the appearance of zeros, for standing waves. In principle, ρ_A and ρ_B could themselves be complicated functions of n, but for the moment we do not consider this possibility.

In Fig. 1, for illustration, we show a model spectrum $h^2(n,\eta) = \sin^2[n(\eta - \eta_e)]$ ($\eta_e = \mathrm{const}$) plotted for a discrete set of wavenumbers n. The zeros in the spectrum, marked by blue stars, move and proliferate in the course of time, in the sense that they gradually arise at new frequencies, and the distance between them decreases. The moving zeros and moving maxima are inherited and fixed (possibly with a phase shift) in the spectrum at the $p = 0$ stage after the transition.

Indeed, the general solution of Eqn (5) after the transition is $f_n(\eta) = C_n + D_n\eta$. The coefficients C_n and D_n then become oscillating functions of n. The moving features become fixed features at some particular wavenumbers, thus defining the lucky and unlucky oscillators. If the transition can be approximated as a sharp event occurring at some η_{eq}, then by matching the general solutions for the function $f_n(\eta)$ and its first time derivative $f_n'(\eta)$ at $\eta = \eta_{\mathrm{eq}}$, we find the coefficient in the increasing solution as

$$|D_n|^2 = n^2\left(\frac{c_s}{c}\right)^2 \times \left[\rho_A^2 + \rho_B^2 - 2\rho_A\rho_B \cos\left(2n\left(\frac{c_s}{c}\right)\eta_{\mathrm{eq}} + \phi_B - \phi_A\right)\right].$$

Obviously, there are no final spectrum modulations if the incoming field consists of traveling waves ($\rho_A = 0$ or $\rho_B = 0$), and the modulations have maximal depth if the waves are standing ($\rho_A = \rho_B$). The relevant set of maxima is determined by the set of n where the function $\sin^2[(c_s/c)\,n\eta_{\mathrm{eq}} + (\phi_B - \phi_A)/2]$ has a maximum, starting from $(c_s/c)\,n\eta_{\mathrm{eq}} + (\phi_B - \phi_A)/2 = \pi/2$. The smallest n and hence the largest spatial scale $\lambda = 2\pi a(\eta)/n$ is expected to be the most pronounced observationally. For such long wavelengths, metric perturbations cannot be neglected in general. We note that if the $p = 0$ post-transition medium is CDM, then there must be oscillations in the CDM power spectrum.

It follows that only a very high degree of organization of the field before the transition — standing waves with phases proportional to n — can lead to the emergence of periodic Sakharov oscillations in the post-transition pressureless matter and in the associated metric perturbations.

The power spectra of cosmological fields in the recombination era determined the angular power spectrum of the cosmic microwave background anisotropies observed today. The CMB spectra differ greatly depending on whether the perturbations are realized as traveling or standing waves. This is best illustrated with the help of gravitational waves, in which case only gravity is involved, and hence we should not worry about the 'acoustic physics' and the role of various matter components. The decoupling of photons from baryons at the last-scattering surface $\eta = \eta_{\mathrm{dec}}$ has no effect on gravitational waves themselves, but for the photons it is very important in which gravitational field they start their journey and propagate.

In Fig. 2, we show two power spectra of gravitational waves given at $\eta = \eta_{\mathrm{dec}}$ and two corresponding CMB temperature spectra caused by them (more details are given in [8]). The red (wavy) line describes the physical spectrum

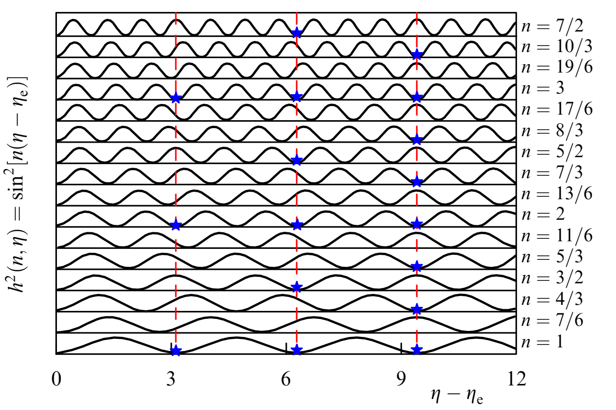

Figure 1. A model spectrum of the pre-transition wave field with moving (proliferating) zeros.

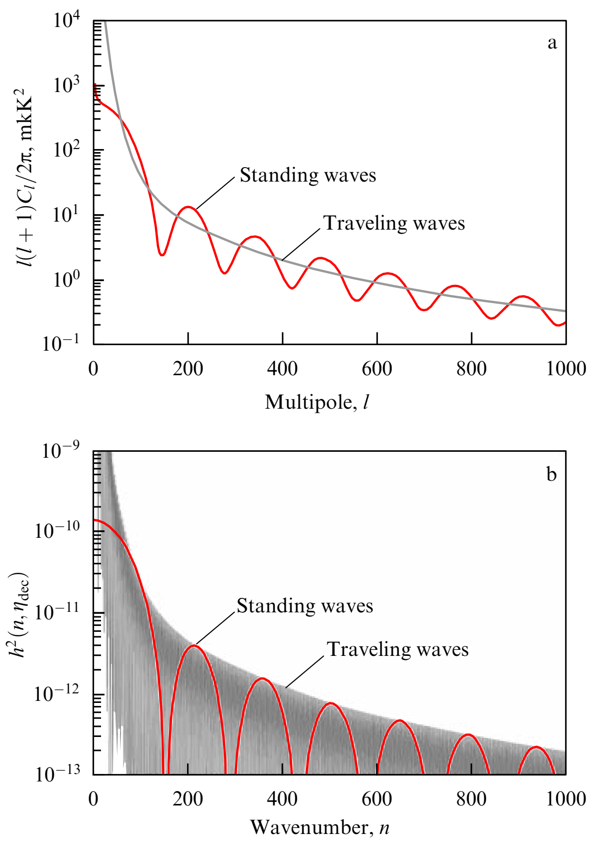

Figure 2. Angular power spectra of CMB temperature anisotropies (upper graph) generated by power spectra of standing or traveling gravitational waves (lower graph).

formed by (quantum-mechanically generated) standing waves, whereas the grey (smooth) line shows the alternative background formed by traveling waves. The power spectrum of the alternative background was chosen to be an envelope of the physical one, and therefore the broad-band powers in the two spectra are approximately equal, except at very small n. The CMB spectra are placed right above the underlying gravitational wave spectra in order to demonstrate the almost one-to-one correspondence between their features in n-space and l-space. A similar correspondence holds for the power spectrum of the first time derivative of the h_{ij} field and the CMB polarization spectra for which it is responsible [9]. It is important to note that the planned new sensitive measurements of CMB polarization and temperature (see, e.g., [10]) may be capable of identifying the first cycle of oscillations in the physical gravitational wave background.

3. Current observations of oscillations in the power spectra of matter and CMB

It should be clear from the discussion above that the Sakharov oscillations are not trivial acoustic waves in relativistic plasma. Waves such as variability in space and time always exist, in the sense that they are the general solution of the density fluctuation equation. The Sakharov oscillations are something much more subtle. They are the variability in the post-transition power spectrum, that is, oscillations in Fourier space. At late times, the oscillatory shape of the matter power spectrum remains fixed. The oscillations define the preferred wavenumbers and spatial scales, in agreement with the standing-wave pattern of the pre-transition field.

Oscillations in the final power spectrum do not arise simply as a result of a 'snapshot' of oscillations in the baryon–photon fluid or as an 'impression' of acoustic waves in the hot plasma of the early universe onto the matter distribution. And they are neither the result of the propagation of spherical sound waves up to the 'sound horizon' before recombination, nor the result of the 'freezing out' of traveling sound waves at decoupling. The event when the plasma becomes transparent can make the Sakharov oscillations visible, but this is not the reason why they exist. Periodic structures in the final power spectrum arise only if sound waves in relativistic plasma (as well as the associated metric perturbations) are standing waves with special phases. The oscillations in the power spectrum do not arise at all if the sound waves are propagating. It is also clear from the discussion above that the phenomenon of oscillations is not specific to baryons. The oscillations are present, for example, in the power spectrum of metric perturbations accompanying matter fluctuations and in gravitational waves.

It appears that actual observations have revealed convincing traces of Sakharov oscillations in the distribution of galaxies. Existing and planned surveys concentrate on the distribution of luminous matter (baryons), and the spectral features are therefore called baryon acoustic oscillations (BAOs). The structures in the power spectrum are Fourier-related to the spikes in the two-point spatial correlation function. Both characteristics have been measured in galaxy surveys (see, e.g., [11 – 14]; the last citation contains many references to previous work).

Of course, the ideal picture of standing waves in the early plasma is blurred by the multicomponent nature of cosmic fluid and by the variety of astrophysical processes occurring on the way to the observed spatial distribution of nonrelativistic matter. This makes the oscillatory features much smoother and much more difficult to identify. Moreover, the measurement of our own particular realization of the inherently random field is only an estimate of the theoretical, statistically averaged, power spectrum, such as Eqn (4). Nevertheless, the impressive observations of recent years have given significant evidence of the existence of Sakharov oscillations.

A similar situation occurs in the study of the CMB temperature and polarization. The difference between smooth and oscillatory underlying spectra for the ensuing CMB anisotropies was illustrated by gravitational waves in Fig. 2. Density perturbations are more complicated because they include the individual power spectra of fluctuations in matter components, the velocity of the fluid that emits and scatters CMB photons (the velocity and the associated Doppler terms require careful definitions), and gravitational field perturbations. Surely, the observed peaks and dips in the CMB temperature angular spectrum C_l^{TT}, now measured up to high multipoles l [15], are a reflection of oscillations in the underlying power spectra at the time of decoupling $\eta_{\rm dec}$. (A link with the phenomenon of Sakharov oscillations, in some generalized sense, was mentioned in [16, 8].) It is very likely that the oscillations in C_l^{TT} at relatively high l are a direct reflection of the standing-wave pattern of density variations in the baryon–electron–photon plasma itself, and are therefore 'acoustic' signatures. By contrast, the structures at the lowest multipoles l probably have a considerable contribution from the pre-transition metric perturbations, which were inherited at the time of transition $\eta_{\rm eq}$, mostly by the gravitationally dominant cold dark matter, and hence the structures are more like 'gravitational' peaks and dips [8]. (The current cosmological literature emphasizing the 'acoustic' side of the problem incorrectly claims that there should not be oscillations in the power spectrum of CDM.)

It should be remembered, however, that the decomposition of the total CMB signal into different contributions is not unambiguous, and the interpretation may depend on the coordinate system (gauge) chosen for the description of fluctuations. The decomposition of the total signal in the so-called Newtonian gauge is presented in Fig. 3, taken from [17]. The dominating Sachs–Wolfe contribution is a combination of variations of the metric and photon density.

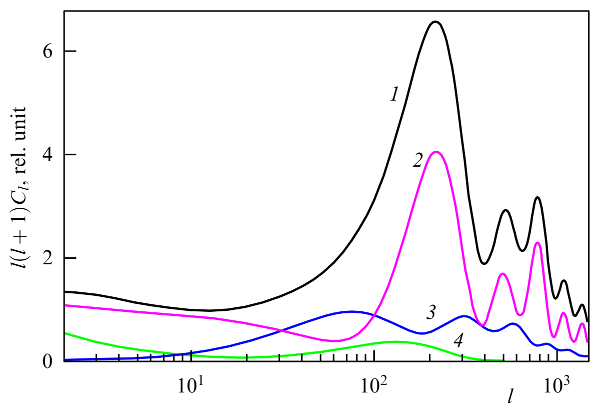

Figure 3. Various contributions to CMB temperature anisotropies [17]. Curve *2*, the contribution due to the Sachs – Wolfe effect; curve *3*, the Doppler contribution; curve *4*, the contribution of the integral Sachs–Wolfe effect.

We can make the following intermediate conclusions. First, for the Sakharov oscillations to appear in the final matter power spectrum, they must the encoded from the very beginning in the power spectrum of primordial cosmological perturbations as a consequence of standing waves. Therefore, the Sakharov oscillations must have a truly primordial origin (quantum mechanical, as we argue below). Second, the very existence of periodic structures in power spectra of matter and CMB gives us no less information about the Universe than do those discoveries that will hopefully be made with the help of these 'standard rulers'. In particular, in the case of data from galaxy surveys, it is important to be sure that we are dealing with manifestations of Sakharov oscillations, and not with something else. If they are Sakharov oscillations, then the phases were remembered for 13 billion years. Third, at some elementary level, the Sakharov oscillations can be tested in laboratory conditions. This is a difference in the fates of traveling and standing waves in a medium in which the speed of sound changes from large values to zero. It would be useful to perform this experimental demonstration.

4. Quantum mechanics of the very early Universe

It is appropriate to start this section with one of the last photographs of Sakharov (see Fig. 4). It shows an intermission in the meeting chaired by Sakharov at which the present author (among other enthusiastic speakers) argued that if primordial cosmological perturbations were generated quantum mechanically, then the result would be not just something but very specific quantum states known as squeezed vacuum states, and why this should be important observationally. The notions of the vacuum, a squeezed vacuum, and a displaced vacuum (coherent states) sounded suspicious to the audience, but Sakharov remained silent. At some crucial point he astonished me by the question "which variable specifically is squeezed?" Such a question can be asked only by someone who is perfectly well familiar with the subject and deeply understands its implications.

Indeed, from the sketch in Fig. 5, we can see that simple quantum states of a harmonic oscillator can greatly differ in the mean values and variances of conjugate variables. For example, squeezed coherent states can be squeezed, i.e., have very small uncertainties, either in the number of quanta or in the phase. This leads to different observational results. I was glad to answer Sakharov's question, because a squeezed vacuum state can be squeezed only in phase. The arising correlation of the $\mathbf{n}$ and $-\mathbf{n}$ modes is equivalent to the generation of a standing wave (a two-mode squeezed vacuum state; more details are given in [18] and [6]). The appearance of a standing-wave pattern is not surprising if we think of the generation process as the creation of pairs of particles with equal energies and oppositely directed momenta. Moreover, the phase, almost free of uncertainties in strongly squeezed vacuum states, smoothly depends on n, as the oscillators with different frequencies n start free evolution (rotation of a highly squeezed ellipse in the X_1, X_2 plane) after the completion of the generation process (squeezing of the vacuum circle into an ellipse). This provides the prerequisites for the future Sakharov oscillations.

The generation of excitations in physically different degrees of freedom — relic gravitational waves and primordial density perturbations — is described by essentially the same equations. The equation for gravitational wave mode

Figure 4. One of the last photographs of Sakharov.

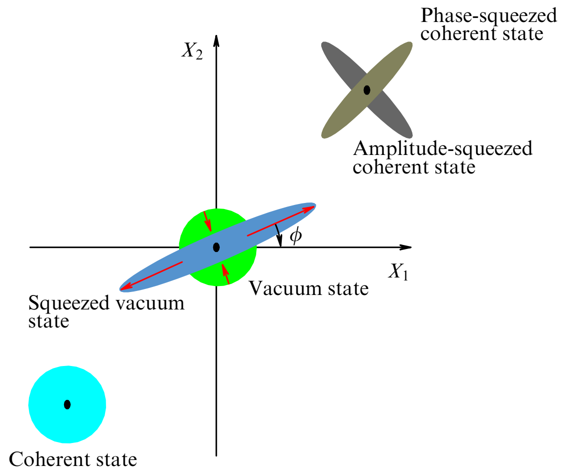

Figure 5. Some quantum states of a harmonic oscillator.

functions is

$$h'' + 2\,\frac{a'}{a}\,h' + n^2 h = 0\,, \tag{6}$$

while the equation for metric perturbations describing the density perturbation degree of freedom is

$$\zeta'' + 2\,\frac{(a\sqrt{\gamma})'}{a\sqrt{\gamma}}\,\zeta' + n^2\zeta = 0\,, \tag{7}$$

where the variable $\zeta(\eta)$ is also known as the curvature perturbation. Surely, Eqns (6) and (7) can also be written in the form of the master equation, Eqn (5). The function $\gamma(\eta) \equiv 1 + (a/a')'$ in Eqn (7) is not the constant γ that Sakharov [1] uses in the equation of state, but the scale factor $a(\eta)$ is a power-law function for simple equations of state, and $\gamma(\eta)$ is then a constant. In this case, Eqns (6) and (7) are identical, and they have general solutions in terms of the Bessel functions.

The two-mode Hamiltonian

$$H = n c_{\mathbf{n}}^{\dagger} c_{\mathbf{n}} + n c_{-\mathbf{n}}^{\dagger} c_{-\mathbf{n}} + 2\sigma(\eta)\, c_{\mathbf{n}}^{\dagger} c_{-\mathbf{n}}^{\dagger} + 2\sigma^*(\eta)\, c_{\mathbf{n}} c_{-\mathbf{n}} \tag{8}$$

is common for these two degrees of freedom, with the coupling function $\sigma(\eta) = (\mathrm{i}/2)[a'/a]$ for gravitational waves and $\sigma(\eta) = (\mathrm{i}/2)[(a\sqrt{\gamma})'/(a\sqrt{\gamma})]$ for density perturbations. The coupling functions coincide if $\gamma(\eta) = \mathrm{const}$. As a result of the Schrödinger evolution, the initial vacuum state of cosmological perturbations (ground state of the corresponding time-dependent Hamiltonian) evolves into a two-mode squeezed vacuum (multiparticle) state. In other words, cosmological perturbations are quantum mechanically generated as standing waves [6, 18].

The simplest models of the initial stage of expansion of the Universe are described by power-law scale factors $a(\eta)$. (The four cases of the initial stage considered by Sakharov [1] also belong to this category.) Such gravitational pump fields $a(\eta) \propto |\eta|^{1+\beta}$ generate gravitational waves (t) and density perturbations (s) with approximately power-law primordial spectra:

$$P_{\mathrm{t}}(k) = A_{\mathrm{t}}\left(\frac{k}{k_0}\right)^{n_{\mathrm{t}}}, \qquad P_{\mathrm{s}}(k) = A_{\mathrm{s}}\left(\frac{k}{k_0}\right)^{n_{\mathrm{s}}-1}, \tag{9}$$

where $n_{\mathrm{s}} - 1 = n_{\mathrm{t}} = 2(\beta + 2)$, and we use $k_0 = 0.002$ Mpc^{-1}. The amplitudes $(A_{\mathrm{t}})^{1/2}$ and $(A_{\mathrm{s}})^{1/2}$ are independent unknowns, but according to the theory based on Eqns (6)–(8), they should be of the same order of magnitude: $A_{\mathrm{s}}^{1/2} \sim A_{\mathrm{t}}^{1/2} \sim H/H_{\mathrm{Pl}}$, where H is the Hubble parameter at the initial stage of expansion. [The inflation theory also uses the same superadiabatic (parametric) amplification mechanism, which was originally worked out for gravitational waves [19, 6]. However, after blind wanderings between variables and gauges, inflationists arrived at what they call the 'standard', or even 'classic', result of the inflation theory. Namely, the prediction of arbitrarily large A_{s} in the limit of the Harrison–Zeldovich–Peebles spectrum $n_{\mathrm{s}} = 1$ and, moreover, for any strength of the generating gravitational field, i.e., for any value of the Hubble parameter H of the inflationary de Sitter expansion $\dot{H} = 0$.] It is common to characterize the contribution of gravitational waves to the CMB by the ratio $r \equiv A_{\mathrm{t}}(k_0)/A_{\mathrm{s}}(k_0)$.

Our analysis [20] of the 7-year Wilkinson Microwave Anisotropy Probe data (WMAP7) has resulted in $r = 0.285$ and $r = 0.2$ as the respective maximum likelihood values in 3-parameter and marginalized 1-parameter searches. The uncertainties are still large, and therefore these numbers can only be regarded as indications of a possible real signal. The relic gravitational waves are very difficult to register, but they are the cleanest probe of the very early Universe [19, 21, 6]. This is why they are in the center of several programs aimed at their identification. The Sakharov oscillations are an element of the whole picture of quantum-mechanically generated cosmological perturbations, and hence the detection of relic gravitational waves would be a huge support for the entire theoretical framework.

5. Expected results of the ongoing observations. Conclusions

The prospects of measuring relic gravitational waves with the help of data from the currently operating Planck mission appear to be good. In Fig. 6, taken from [20], we show the expected signal-to-noise ratio with which the signal will be observed assuming that the indications found in WMAP7 data are real. A big obstacle is the foreground contamination, which should be carefully dealt with. The ability, ranging from excellent to none, of removing contamination is parameterized by the parameter $\sigma^{\mathrm{fg}} = 10^{-2}$, 10^{-1}, 10^0. We also work with the pessimistic case, in which $\sigma^{\mathrm{fg}} = 1$ and the nominal instrumental noise in the BB polarization channel at each frequency is increased by a factor of 4. We see from the figure that the S/N ratio can be as large as S/N ≈ 6, and even in the pessimistic scenario, it remains at the interesting level S/N > 2.

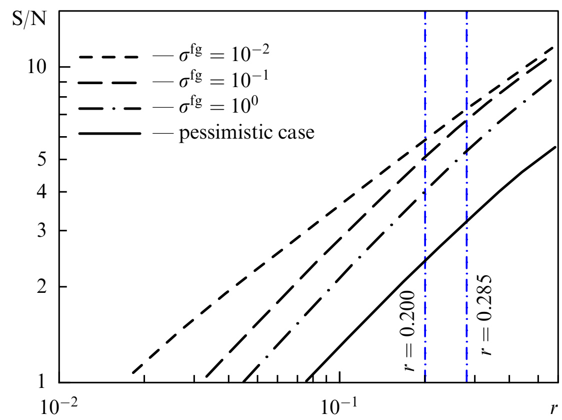

Figure 6. The expected S/N ratio in the detection of relic gravitational waves by the Planck mission.

As was already mentioned above, the planned dedicated observations [10] may even be able to outline the first cycle in the oscillatory power spectrum of the gravitational wave background.

In general, we can conclude that the originally proposed Sakharov oscillations, as well as related phenomena whose existence can be traced back to the earliest moments of our Universe, are right in the focus of current fundamental research.

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References

1. Sakharov A D *Zh. Eksp. Teor. Fiz.* **49** 345 (1965) [*Sov. Phys. JETP* **22** 241 (1966)]
2. Sunyaev R A, Zeldovich Ya B *Astrophys. Space Sci.* **7** 3 (1970)
3. Zeldovich Ya B, Novikov I D *Relyativistskaya Astrofizika* (Relativistic Astrophysics) Vol. 2 [Translated into English (Chicago: Univ. of Chicago Press, 1983)]
4. Peebles P J E, Yu J T *Astrophys. J.* **162** 815 (1970)
5. Peebles P J E, Letter of May 30, 1990
6. Grishchuk L P, in *General Relativity and John Archibald Wheeler* (Astrophysics and Space Science Library, Vol. 367, Eds I Ciufolini, R Matzner) (New York: Springer, 2010) pp. 151 – 199; arXiv:0707.3319
7. Grishchuk L P, arXiv:1012.0743
8. Bose S, Grishchuk L P *Phys. Rev. D* **66** 043529 (2002)
9. Baskaran D, Grishchuk L P, Polnarev A G *Phys. Rev. D* **74** 083008 (2006)
10. Fraisse A A et al., arXiv:1106.3087
11. Cole S et al. *Mon. Not. R. Astron. Soc.* **362** 505 (2005)
12. Eisenstein D J et al. *Astrophys. J.* **633** 560 (2005)
13. Percival W J et al. *Astrophys. J.* **657** 645 (2007)
14. Beutler F et al., arXiv:1106.3366
15. Hlozek R et al., arXiv:1105.4887
16. Jorgensen H E et al. *Astron. Astrophys.* **294** 639 (1995)
17. Challinor A *Lecture Notes Phys.* **653** 71 (2004); astro-ph/0403344
18. Grishchuk L P, in *Quantum Fluctuations: Les Houches Session LXIII, June 27 – July 28, 1995* (Eds S Reynaud, E Giacobino, J Zinn-Justin) (Amsterdam: Elsevier, 1997) pp. 541 – 561
19. Grishchuk L P *Zh. Eksp. Teor. Fiz.* **67** 825 (1974) [*Sov. Phys. JETP* **40** 409 (1975)]
20. Zhao W, Grishchuk L P *Phys. Rev. D* **82** 123008 (2010)
21. Grishchuk L P *Pis'ma Zh. Eksp. Teor. Fiz.* **23** 326 (1976) [*Sov. Phys. JETP Lett.* **23** 293 (1976); http: www.jetpletters.ac.ru/ps/1801/article_27514.pdf]