The scientific works of A.D. Sakharov

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Just prior to the sixtieth anniversary of the birth of A.D. Sakharov everything was quite different than it is now; the question of issuing a special issue of UFN wasn't even raised. Andreĭ Dmitrievich has died, and it is bitter to realize this, but I confess there is not today such a feeling of the anomaly of what is occurring as existed ten years ago when he was "buried alive." However I must note that in that initial period of exile the isolation was not yet as absolute as in subsequent years.

As a gift for his sixtieth birthday Sakharov's friends in Moscow prepared an anniversary collection of articles which contains a chapter "Sakharov–the scientist." The section on Sakharov's articles on fundamental problems of physics was written by Yu. A. Gol'fand, whereas my share was the controlled thermonuclear reaction (CTR) and magnetoimplosive generators. I well remember the joy which I experienced when, working on the article for this collection, I discovered in the book by I. N. Golovin about Kurchatov[2] the following passage with which I shall begin this introductory article to the scientific papers of A. D. Sakharov being published here. So, here is the conversation of I. V. Kurchatov with his deputy (who was not named in Ref. 2) on New Year's Eve of 31 December 1950:

"Deputy: "Igor Vasil'evich! CTR—this is the greatest problem in releasing the energy within the nucleus! You have successfully solved the first problem. Now nobody doubts anymore that an atomic electric power station will work utilizing the fission of uranium. Sakharov has called upon us to work on solving the second, no less grandiose atomic problem of the twentieth century—obtaining limitless energy by burning ocean water! This is a problem to the solution of which one would not begrudge devoting one's entire life"...Kurchatov...related with enthusiasm how Sakharov proposed to create plasma by the induction method having mounted on a toroidal chamber an iron core with a primary winding... . Already after several months a laboratory headed by Artsimovich was in operation which was created by Kurchatov and involved up to a hundred staff members. The theoretical investigations were headed by M. A. Leontovich" (Ref. 2, pp. 81–82); in later editions of the book after 1972 there is no longer any mention of Sakharov. It was, of course, an obvious oversight that in March 1981 I was given free access in the Lenin library to the book with such a text glorifying Sakharov.

I shall briefly recount some aspects of the scientific career of Andreĭ Dmitrievich.

1. Controlled thermonuclear reaction. As a commentary on the problem of the CTR I shall reproduce several excerpts from my article in Ref. 1:

"In 1950 A.D. Sakharov together with I. E. Tamm put forward the idea which, probably, is his principal scientific and inventive accomplishment. This is the proposal of realizing a controlled thermonuclear reaction for purposes of producing energy by using the principle of magnetic thermal insulation of plasma (cf.: the Great Soviet Encyclopedia, articles about Sakharov and Tamm). A controlled thermonuclear reaction, just as the reaction occurring in the hydrogen bomb, is a fusion of the nuclei of isotopes of hydrogen—deuterium and tritium—with the formation (by fusion) of nuclei of helium and release of energy, not in an explosion, but under conditions of an industrial device—a thermonuclear reactor. In contrast to the chain reaction of the fission of uranium and plutonium nuclei in an atomic bomb and in the reactors of atomic electric power producing stations, a thermonuclear reaction is possible only at a temperature of tens or even hundreds of millions of degrees.

Sakharov and Tamm showed that in the motion of charged particles—nuclei and electrons—in a magnetic field of special configuration the removal of heat is reduced to such an extent that in principle it becomes possible to heat the plasma to the required temperature and to sustain it for a time sufficient for the thermonuclear reaction to take place. I. V. Kurchatov reported this work on 25 April 1956 in his famous lecture at the English atomic center in Harwell[3] at the time of his visit to England with Khrushchev and Bulganin; it was published in the proceedings of the Geneva conference on peaceful utilization of atomic energy, and also in the collection of papers of Ref. 4 under the general title "The theory of a magnetic thermonuclear reactor" (MTR). Parts 1 and 3 are papers by I. E. Tamm, Part 2 is the paper by A. D. Sakharov... ((A. D. Sakharov, (10, 13, 28)); cf., the list of papers by A. D. Sakharov following the present article)[1)]. These papers by Sakharov and Tamm are acknowledged to be pioneering investigations. Subsequent investigations were continued under the guidance of L.A. Artsimovich...

...One of the results of efforts over many years of a large group of Soviet scientists was the system known as "tokamak." This system is very close to the initial ideas of Sakharov and Tamm who have investigated, in particular, a toroidal configuration both in a steady-state and a non-steady-state variants. Today it is regarded as one of the most promising ones.

"At present the prospects appear to be better than ever before: several years ago Russian experimenters invented a device called "tokamak." This device has been reproduced comparatively successfully in the USA,"—wrote in 1976 Hans A. Bethe.[5]

"The most ingenious and promising method was the so-called "tokamak" proposed in the USSR,"—P. L. Kapitza (Nobel Lecture in 1978).[6]

Quite a complete picture of the then current state of the problem of controlled thermonuclear fusion has been given by the Associate Director of the Division of Thermonuclear Research of the USA Department of Energy, J. F. Clarke, in a review written in December 1979 for the journal Fizika Plazmy.[7] Here are some quotations from this review:

"The latest results of experiments carried out in the USA, USSR, Europe and Japan show that the "tokamak,"

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which is one of the possible approaches to fusion can retain sufficiently well the thermonuclear plasma needed for energy release."

"There are no fundamental technical obstacles for a practical production of energy by the controlled thermonuclear fusion on the basis of the scientific successes of "tokamaks..."

...We approve the joint planning of research on the largest "tokamaks" of the world which are under construction at present: T-15 in the USSR, JT-60 in Japan, JET in Europe and TFTR in the USA. These efforts must prepare the foundation for the next step—the transfer of the thermonuclear program to the stage of engineering development."

... Sakharov was also engaged in a line of investigations associated with the use of lasers which was a method different in principle and an alternative to the approach of magnetic insulation and confinement of plasma. In his brief autobiography A. D Sakharov writes: "In 1961 I proposed for the same purpose (obtaining a controlled thermonuclear reaction–B.A.) heating of deuterium by a beam of a pulsed laser" ("Sakharov about himself," New York, 1974). This idea arose independently in different countries and is at present being intensively developed both in the USSR and abroad...

...At the present time in the scientific laboratories of many countries broad-based investigations are being carried out of different variants of the solution of the problem of a controlled thermonuclear reaction. After the lecture by I. V. Kurchatov in Harwell, which left a tremendous impression all over the world, investigations on controlled thermonuclear reactions were carried out openly and in close international collaboration. They were an example of the entire system of international collaboration which grew up in the 50's–70's and which was placed in jeopardy by the well-known events of recent years, including the conviction of Yu. F. Orlov and the exile of A. D. Sakharov.

On 14 September 1981 the *X* European Conference on Plasma Physics and controlled Thermonuclear Fusion will be open in Moscow. Is such a conference possible without the participation of the founder of the entire field—Academician Sakharov? The illegal confinement of Sakharov endows this question with exceptional poignancy." (End of quotation from Ref. 1, pp., 121–126).

In addition to the collection of articles of Ref. 1 in connection with the sixtieth birthday of A. D. Sakharov there was published a collection of his scientific works[8] with comments by leading foreign specialists, and also with the synopsis by Sakharov himself, in which concerning his work on CTR he writes as follows:

Controlled Thermonuclear Reactions

1. Reports during 1950–1951 (in collaboration with I. E. Tamm). Here we proposed the principle of magnetic thermalization, determined the transport coefficients of a "magnetized" plasma (thermal conductivity, diffusion, and thermal diffusion), and proposed a toroidal configuration in a stationary and a nonstationary variant; the latter is discussed in connection with the problems of plasma instability.

2. A report of 1951. I proposed a thermonuclear breeder in which neutrons from the thermonuclear D + T reaction are used to accumulate plutonium or uranium 233 and tritium. Plutonium and uranium 233 are burned in relatively simple (nonbreeder) reactors, producing energy, tritium, and fissile materials. Evidently it is in this direction that a controlled thermonuclear reaction can for the first time achieve practical significance. The papers of 1 and 2 were presented by I. V. Kurchatov during his visit to the Harwell Laboratory in 1956 (during the visit of Khrushchev and Bulganin to Great Britian) and were then published in the *Proceedings of the Geneva Conference on the Peaceful Uses of Atomic Energy* ["Theory of the magnetic nuclear reactor"; Paper 2].

In P. T. Astashenkov's book *Achievements of Academician Kurchatov*, which was published in 1979 and begins

FIG. 1. A. D. Sakhrov and I. V. Kurchatov in a grove of trees next to the house where I. V. Kurchatov lived at the time on the territory on the Institute of Atomic Energy, 1958. (Photo by D. S. Pereverzev)

with an account of Kurchatov's visit to Harwell, the names of Tamm and myself are not mentioned. I. N. Golovin's biography of Kurchatov, published several years earlier, gives our names.

3. In a seminar in 1960 (perhaps 1961, I do not recall), I discussed the possibility of realizing a controlled thermonuclear reaction by means of a laser.

4. In connection with the idea of "explosive breeding" proposed by a number of authors, I have made a number of additional suggestions in various seminars, proposing in particular the use of a subterranean "corrugated" chamber. In this variant, the soil plays the part of the strong walls needed to withstand the pressure of the explosion products, and hermetic sealing is achieved by a thin-walled chamber. The entire project carries the danger of radioactive contamination, and it should perhaps be carried out on the moon, and the fuel transported to the Earth by spacecraft. (That was the end of the quotation of A. D. Sakharov from Ref. 8, pp., 3–4.)

In this brief introductory article I do not aim to give a review of the scientific activity of Sakharov nor to describe the state of affairs as of today; particularly since I am not a specialist in the majority of those fields of physics in which Andreĭ Dmitrievich busied himself at different periods of his life. This spectrum is, as is well known, quite broad: CTR, obtaining ultraintense magnetic fields by the implosion method (A. D. Sakharov (19,21)), μ-catalysis (A. D. Sakharov (7, 12)), an attempt on the basis of a "naive" quark model to guess the mass spectrum of mesons and baryons (A. D. Sakharov (22, 44, 48)), quantum field theory and gravitation, cosmology, and in one of the last papers (A. D. Sakharov (52))—quantum cosmology. A popular account of this can be found in the memoirs of A. D. Sakharov[9] (below I make extensive use of quotations from these memoirs since in my opinion it is very valuable to hear the voice of Andreĭ Dmitrievich himself), and in the special issue of the journal Priroda.[10] Comments by specialists can be found in Ref. 8 and in the collection of scientific works of A. D. Sakharov at present being prepared for publication.[11] The article by R. Dalitz published in this issue of Soviet Physics-Uspekhi is a commentary, written for Ref. 11, on the dissertation of A. D. Sakharov for the degree of candidate of science (A. D. Sakharov (2)), a part of which is the paper "Interaction of the electron and the positron in pair production" (A. D. Sakharov (6)).

FIG. 2. A. D. Sakharov in the 1950's.

2. Fundamental physics was the principal passion of Andreĭ Dmitrievich throughout his entire life; unfortunately he was able to devote to it relatively not too much time.

In 1947 A. D. Sakharov made an attempt, although an unsuccessful one, to overcome the ultraviolet divergences in quantum electrodynamics and to calculate the famous Lamb splitting of levels in the hydrogen atom. This is how he recalls this:

"...The dissertation was finished and I was thinking of further scientific work...I remembered that in the literature there was a discussion of the presence in the optical spectrum of the hydrogen atom of a certain anomaly which contradicted a formula following from theory. Specifically, there were indications (not very definite ones because of the extreme smallness of the effect lying at the limit of accuracy of optical methods of measuring the levels), that of the two levels of the hydrogen atom, which according to theory should coincide very closely, one lies somewhat higher than the other..." (Ref. 9, p. 114 in Russian text, p. 82 in English version).

And later, in connection with the attempt to calculate the effect the following comments on the problem of UV divergences:

"This was a great difficulty of the theory throwing a shadow on the entire development of the physics of quantum fields in the course of many decades. I assumed that one should investigate the difference of the effects for a bound and a free electron. Since the effect of binding manifests itself, as I correctly suppose, only in the case of not very great frequencies of the zero-point oscillations, there was a hope that the difference effect would turn out to be finite. In order to give a correct meaning to the subtraction of two infinite quantities in calculations, at first one can restrict oneself to the interaction with oscillations with a frequency lower than some limiting "cut-off" frequency sufficiently high that for it the effect of binding is already not very significant, and then formally to go to the limit of an infinite cut-off frequency. I, of course, understood that the significance of this idea goes far beyond the framework of the particular problem of the anomaly in the hydrogen atom and, in particular, must extend to scattering processes. I was very excited. With all this I came to Igor' Evgen'evich (in the summer or fall of 1947). Unfortunately, he did not support or approve my idea, rather–the reverse. First, he said, that these ideas are not very new, and in one form or another have been expressed many times. This was indeed so, but by itself it could not have stopped me,—I was already sufficiently enthusiastic and interested that I was not too concerned with such things as priority, I was interested in the heart of the matter. Second, he said, that the idea apparently, "does not carry through," a finite result is not obtained. I. E. made reference to a recently published paper by the American theoretician Dancoff who calculated the radiation corrections to the scattering process by a method which in principle was very close to the one which I proposed to use to calculate the difference in the energy of levels in the hydrogen atom. I found Dancoff's paper in the library: indeed he did not obtain a finite result on subtraction (i.e., one tending to a constant value as the "cut-off" energy was made to go to infinity). Dancoff's calculations were very complicated and involved—since all this occurred before Feynman's work who invented a much more compact and transparent general method of calculations (Feynman "diagrams"). Dancoff simply made a mistake, but, of course, neither Igor' Evgen'evich nor I could discover it on casual perusal. If intuition had not deserted us, we should have doubted Dancoff's work as many times as would have been necessary to discover the error or, what would have been even more sensible, temporarily to ignore the contradiction that had arisen and to seek simpler problems for calculation the results of which could have been compared with experiment. As is well known it is in exactly this way that more astute and bolder persons proceeded who achieved success. But not we. Thus I lost the possibility of carrying out the most outstanding investigation of that time (and the most important one by a long shot in my life). Of course this was not accidental. Paraphrasing a well known dictum, everyone carries out those tasks of which he is deserving"...(Ref. 9, pp. 115–116 in Russian text, pp. 82–83 in English).

"...Recalling that summer of 1947 I feel that I never, neither earlier nor later, approached so close to great science, to its cutting edge. Of course I am somewhat disappointed that I personally did not measure up (no objective circumstances are significant here). But from a broader point of view I can not help but exult in the forward march of science and had I not myself come in contact with it I could not experience this feeling with such intensity!" (Ref. 9, p. 119 in Russian text, p. 85 in English).

I think that Andrei Dmitrievich is not quite correct when he speaks here that whenever again approached so close to great science, to its frontier edge. However, very likely here there is no objective criterion. This is what he felt when he wrote these lines at the beginning of the eighties.

Within the field of theoretical physics the middle sixties are perhaps the most fruitful period of Sakharov's scientific activity. Cosmology, quantum field theory and gravitation, quarks, mesons and baryons—such is the circle of his interests.

3. Induced gravitation (A. D. Sakharov (29, 30, 38, 43)). The quantum vacuum of material fields "responds" to external fields (electromagnetic, gravitational, etc.), and this leads to a renormalization of the Maxwell or Einstein action term. One can suppose that the starting gravitational action is equal to zero, while the observable gravitational phenomena are entirely and completely determined by quantum corrections. This is the famous idea of A. D. Sakharov which he called the "theory of zero Lagrangian of the gravitational field" and which has entered the textbooks (cf., for example, Ref. 12, V.2, pp. 56–57). Mathematically the problem reduces to an investigation of the restructuring of the spectra of the D'Alembert and Dirac operators in external fields, physically the effect of quantum-induced origin of gravitational attraction is similar to the well-known (and experimentally confirmed) Casimir effect in quantum electrodynamics (cf., the comments by D. A. Kirzhnits in (Ref. 10, p. 65)). In Ref. 9 Andreĭ Dmitrievich presents this set of ideas in the following manner:

"I decided to examine those changes in the energy of zero-point oscillations of fields of elementary particles which occur in the transition from a plane four-dimensional space-time to a curved one, and to associate these changes in energy with expressions appearing in the equation of Einstein's gravitation theory. Einstein and (independently from him) David Hilbert *postulated* these expressions, while the coefficient entering into them which is inversely proportional to the gravitational constant they took from experiment. According to my idea the functional form of the equation of gravitational theory (i.e., the general theory of relativity), and also the numerical value of the gravitational constant should follow from the theory of elementary particles "by themselves," without any special hypotheses.

Zel'dovich met my idea with delight and soon himself wrote an article initiated by it.

I called my theory "the theory of zero Lagrangian." This terminology is associated with the fact that for theoreticians it is often convenient to deal not with energy and pressure but with another quantity associated with them—the so-called Lagrangian function: which is the difference between the kinetic and the potential energy (in quantum language–with the Lagrangian). In a portion of my work I made use of this apparatus.

For a graphical image of my idea I invented a picturesque term—"metrical elasticity of vacuum." In introducing into the vacuum material bodies possessing a certain amount of energy they tend to distort it, i.e., to change its metric (geometry). But the vacuum "resists" such a change since, due to the quantum motions occurring in it, it possesses an "elasticity." A graphical example is a hose in which water is flowing. In this case, however, elasticity is of opposite sign, an instability exists. The greater is the elasticity of vacuum the less is its geometry changed by bodies of a given mass, and the less is the gravitational curvature of the trajectories. On the scale of the microworld the elasticity of vacuum is very great, i.e., gravitational interactions for particles of the microworld are weak..." (Ref. 9, pp. 46-47 in Russian text, pp. 260–261 in English).

Concerning the paper (A. D. Sakharov (43)) in "Memoirs":

"In 1974 I completed and in 1975 I published an article in which I developed the idea of a zero Lagrangian of the gravitational field, and also those methods of calculation which I used in preceding papers. In doing so it turned out that I arrived at a method which was proposed many years ago by Vladimir Aleksandrovich Fock, and later by Julian Schwinger. However, my conclusion and the very path of constructing it and the methods were quite different. Unfortunately I did not have a chance to send my paper to Fock—it so happened that he died just then.

"Subsequently I discovered in my article some errors. In it the question that remained without a final answer was: does "induced gravitation" (the present-day term used in

FIG. 3. A. D. Sakharov, Ya. B. Zel'dovich, and L. A. Khalfin (International Seminar "Quantum Gravitation," Moscow, May 1987). (Photo by A. I. Zel'nikov)

place of the term "zero Lagrangian") give the correct sign of the gravitational constant in any of the variants which I examined" (Ref. 9, pp. 780–781 in Russian text, pp. 540–541 in English).

The problem of evaluating the induced gravitational constant (G_{ind}) is still awaiting its solution. In his commentary on these papers of Sakharov in the book of Ref. 8 S. Adler asserts (cf., also his article in Ref. 10 and the review of Ref. 13), that one can expect that a finite G_{ind} can be calculated only in an initially conformally-invariant theory, in the multiplet of the initial fields of which there are no scalar fields. In this case the gravitational constant, as well as the nonzero masses of particles, must arise not as a result of an "external" Higgs mechanism, but due to the so-called dynamical spontaneous violation of scale invariance. Sakharov frequently returned to a discussion of the variants of a conformally-invariant, massless initial theory. In this connection an important, from my point of view, idea was expressed by him (A. D. Sakharov (52)) in the context of "high-dimensional" physics. But this will be dealt with below.

The string theory which appeared in the eighties ("the theory of everything"—TOE), and the revival of interest in the old ideas of Kaluza and Klein concerning the existence of supplementary dimensions of space-time Sakharov referred to as the "great events of our time." In the book of Ref. 14 he writes about his involvement in science in 1986 as follows:

"I set myself the aim to study string theory and adjoining theories, and also to study theoretical papers on the interface between cosmology and high energy physics. I do not have very much hope of personal creative success, but to understand the essence of what possibly is the current revolution in physics—one must strive!!!...".

"String theory is, at a new level, the realization of my old ideas concerning induced gravitation! I cannot refrain from feeling proud on this point" (Ref. 14, pp. 14-15).

4. The Baryon Asymmetry of the Universe. The explanation of this macroscopic phenomenon is possibly Sakharov's principle result in fundamental physics. From the synopsis by A. D. Sakharov written by him in 1980 for Ref. 8 we quote:

"This paper (A. D. Sakharov (26, also S7)) makes a suggestion concerning the origin of the observed baryon asymmetry $A = N_B/N_\gamma \sim 10^{-9}$ of the universe from an initial charge-symmetric state as a result of nonequilibrium processes in the early stages in the expansion of a "hot" universe with violation of *CP* invariance and nonconservation of baryon charge. Violation of *CP* invariance had been discovered experimentally not long before the paper was written. Nonconservation of baryon charge was postulated in the paper and a definite mechanism was proposed to ensure conservation of the "combined charge" $3B + L$ (in the paper, L_μ).

It was pointed out that, because of *CPT* symmetry, baryon asymmetry cannot arise under stationary conditions, so that departures from equilibrium due to the cosmological expansion are important. The combined law of conservation for the baryons (with allowed quark-lepton transformations) leads to much longer proton lifetimes at the same mass of the quark-lepton boson than is predicted in the SU_5,

O_{10}, etc., grand unification schemes. Therefore, if it is found that the proton decays with a lifetime of the order of 10^{30} years, my hypothesis of a combined conservation law must be abandoned.

The paper also puts forward the idea of cosmological *CPT* symmetry with respect to the Friedmann singularity. Such a symmetry includes a change in the direction of the flow of entropy time. The "reversal of the arrow of time" eliminates the paradox of irreversibility known since the end of the nineteenth century. For $t<0$, the time derivatives occur in the statistical equations with the opposite sign, while for $t>0$ they occur with the usual sign, i.e., in the cosmological theory the symmetry between the two directions of time inherent in the equations of motion is also recovered for nonequilibrium processes (including life processes).

Concerning the present state of the problem of baryon asymmetry refer to the review paper by A. D. Sakharov at the Friedmann conference in Leningrad in June 1988 (A. D. Sakharov (54)). A. D. Sakharov said (from an interview at the time of the Friedmann conference):

"At the present time we have rather an excess of scenarios of the origin of baryon asymmetry. They all have both definite advantages, and also essential defects. It seems to me that to choose any one of them as the preferred one is not at present possible. Apparently, this is a task for the future, but there are no difficulties of principle here.

All the existing schemes for the origin of baryon asymmetry are based on three well known assumptions: the absence of a law of conservation of baryon charge, a result of which is proton decay; the difference between particles and antiparticles manifesting itself in violation of *CP* invariance; the non-steady-state of the Universe. While the last two assumptions do not raise doubts, the instability of the proton is a more complicated matter. Twenty years ago the only argument in favor of this hypothesis was the fact of baryon asymmetry of the Universe. Since then theories of Grand Unification have appeared in which the nonconservation of baryon charge arises naturally. However, so far no one has succeeded in experimentally demonstrating proton decay (Ref. 15, p. 8).

5. Multisheet (pulsating, oscillating) models of the Universe (A. D. Sakharov (37, 46, 50, 51)). Sakharov wrote that such models (cf., A. D. Sakharov (Ref. 51)) described naturally the exceedingly small value of the mean spatial curvature of the Universe divided by the entropy density to the 2/3 power." In each succeeding cycle the entropy is greater than in the preceding one and the present small ($\sim 10^{-58}$) value of the dimensionless parameter indicated above is due to the fact that from the initial moment of minimum entropy quite a few cycles have occurred. The inflationary models with their "production of entropy" in the decay of the "vacuum" of the scalar field, obviously provide an alternative explanation of this large (raised to the minus first power) number. In a letter which I received from Gor'kiĭ in May 1982 Andrei Dmitrievich, in particular, wrote:

"...Regarding cosmological ideas of an exponential initial phase. (With the Linde improvement or without it.) So far my attitude to them is a wary one (perhaps this is due to old age?). I cannot understand how starting with a gigantic cosmological constant one can obtain zero in the present vacuum. And mainly—I would hate to turn my back on the multisheet model. Well, never mind, we'll wait. The future will show who is right... ."

In the interview mentioned above at the time of the Friedmann conference Sakharov says the following concerning inflationary models based on the concept of an initial vacuum-like state of matter (first introduced by E. B. Gliner in 1965 (Ref. 16); Sakharov also examined (A. D. Sakharov (20)) the vacuum-like equation of the state of matter as one of the possibilities in the superdense region near a singularity):

"Turning to the past of the Universe can we say with complete confidence that at first it was very dense and hot? If one speaks of times ~ 1 s after the initial moment then it certainly was very hot. But if we are dealing with a time such as 10^{-44} s, then here for the time being we still do not know anything definite. Possibly at this moment there was an absolute vacuum, and an absolute void, i.e., conversely, it was very cold. However, one should not forget that this is not a simple void with all its properties of isotropy and zero temperature, but this is a vacuum which possesses an energy and a negative pressure.

At present this is only one of those branches, variants on our tree of knowledge, which perhaps corresponds to reality, and perhaps we must "grow" quite different branches moving back in time, and leave these particular branches on this tree. It is a beautiful idea, but unfortunately, nature does not always tend to such elementary beauty, sometimes it finds an even higher beauty, the existence of which we did not even suspect. But in general I like the idea of an initial vacuum (Ref. 15, p. 10).

The first moments of the existence of our Universe, the subsequent stages of its evolution over a period of $\sim 10^{10}$ years as a result of which the picture being observed today arose—it is on these problems that the attention of cosmologists and astrophysicists is primarily concentrated. In his articles on a multisheet Universe A. D. Sakharov examines not only the past, but also the future and even a very distant one. (What is the evolution of the Universe after all the protons have decayed, $t>10^{30}$ years? What is the final state in compression and what will happen after passage through a singularity?) Can one combine the ideas of an oscillating Universe and an exponential behavior of the scale factor near its minimum value? Models of this kind have a number of advantages (Ref. 17), but contradict the second law of thermodynamics: the vacuum-like state which is stable in course of expansion cannot be a final state in the case of collapse. In an attempt to surmount this difficulty and thereby to solve the previously mentioned "multisheet-inflationary" dilemma Sakharov examined some exotic theories in which the "vacuum-like" state arising in the high energy region possesses not only energy but also entropy (Ref. 18).

6. Reversal of Time's Arrow (RTA). From the hypothesis of CPT-symmetry of the Universe (not of the dynamical equations, but of the *state* of the Universe) follows the vanishing of the average density of any conserved charge. It is precisely from it, if one takes into account the observed baryon asymmetry of the Universe, that the "mad" idea concerning the nonconservation of baryon charge followed with necessity (obvious to Sakharov). But the observed world is not only C-asymmetric but also T-asymmetric ("one cannot twice step into the same stream"). Sakharov always associated the irreversible flow of time exclusively with the sec-

FIG. 4. S. Hawking and A. D. Sakharov. International Seminar "Quantum Gravitation." Moscow, May 1987. (Photo by A. I. Zel'nikov).

ond law of thermodynamics, with the increase in entropy. How can one reconcile this macroscopic T-asymmetry with the hypothesis of CPT-symmetry of the Universe? And another question related to this one. If entropy is increasing then it means that earlier it was less than it is now, and still earlier it was at a minimum (or equal to zero). And still earlier? If time's arrow is defined by the increase in entropy, then the word "earlier" in the last question has no meaning. From the instant of minimum entropy (the point Φ (A. D. Sakharov (37, 50))) "in both directions" in time one can have only "later". Sakharov named this phenomenon "reversal of time's arrow." At the moment of RTA one does not assume a violation of the dynamical laws of physics. This moment is distinguished only by the fact that this is a state (defined on a singular or a nonsingular hypersurface) in which *T*-noninvariant statistical correlations are absent" (A. D. Sakharov (46)). The hypothesis of CPT-symmetry of the Universe is a special case of the RTA hypothesis since the former necessarily requires that the point Φ be singular (under PT reflection components of the gravitational standard change sign, and that means that they must vanish at the symmetry point (A. D. Sakharov (50)). But generally speaking RTA can also occur at the moment of maximum expansion. One has in mind that the Universe is at that moment empty, the entropy is a minimum, and the "filling" occurred in subsequent cycles (cf., the diagram in the article (A. D. Sakharov (51))). The idea of RTA was also expressed by Hawking whom Sakharov met at the time of the international seminar "Quantum Gravitation" (Moscow, May 1987). This is how Andreĭ Dmitrievich describes this meeting:

"The spiritual strength of this man is astounding, he has preserved friendliness towards people, a sense of humor and an inexhaustible curiosity, a tremendous scientific activity...I had several conversations with Hawking when he with the aid of his mechanical wheelchair came out of the hall of the meetings...In the course of the first conversation Hawking gave me reprints of his latest papers—on the loss of coherence in complex topological structures, on the direction of time's arrow, etc. The first paper he presented at the seminar and said, paraphrasing Einstein: "God not only plays with dice, but throws them so far that they become inaccessible." On the next day I said to Stephen that I had read his lecture on time's arrow and am very pleased that he has now accepted the validity of the criticism by Page (his collaborator) concerning the erroneous assumption of the reversal of time's arrow at the instant of maximum expansion of the Universe and of *maximum* entropy. The reversal of time's arrow is possible only in the state of *minimum* entropy. Due to shyness I did not mention the simplest and clearest example—that of a closed Universe in the state of false vacuum with positive energy and entropy equal to zero. At this moment Hawking made a motion with his fingers and the computer dispassionately said: "Yes!". Unfortunately I did not say that I first expressed the idea of the reversal of time's arrow (in the state of minimum entropy) already in 1966 and several times returned to this subject" (Ref. 14, pp. 65–66).

In Ref. 9 A. D. Sakharov writes in great detail concerning this set of questions and, in particular, on the very posing of the problem:

"In the "standard" (single-sheet) cosmology there exists a problem: what existed prior to the moment of maximum density? In multisheet cosmologies (with the exception of the case of the spatially-flat model) one cannot escape this problem—the question is brought back to the moment of the beginning of expansion of the first cycle. One can adopt the point of view that the beginning of the expansion of the first cycle or, in the case of the standard model, of the single cycle is the Moment of the Creation of the World—and therefore the question of what existed prior to that lies beyond the limits of scientific investigation. However, perhaps to the same extent—or according to me to a greater extent—that approach is justified and fruitful which admits an unrestricted scientific investigation of the material world and space-time. Apparently in connection with this there is no place for an Act of Creation, but the basic religious conception of the divine meaning of existence is not touched upon by science, but lies beyond its limits.

I know of two alternative hypotheses that refer to the problem under discussion. One of them, it seems to me, was first expressed by me in 1966 and was subjected to a number of refinements in subsequent papers. This is the hypothesis of the "reversal of time's arrow." It is closely associated with the so called problem of reversibility...

...The alternative hypothesis on the prehistory of the Universe consists of the fact that in reality there exists not one Universe, and not two (as—in a certain sense of the word—in the hypothesis of the reversal of time's arrow), but a multiplicity of Universes that differ cardinally from each other and that arose from a certain "primary" space (or from parts of which it is composed; possibly this is simply another method of expression). Other Universes and the primary space, if there is any sense to speak about it, can, in particular, have in comparison with our Universe a different number of "macroscopic" space and time dimensions—coordinates (in our Universe—three space and one time dimensions; in other Universes everything can be different!). I ask that no special attention be paid to the adjective "macroscopic" enclosed in quotation marks. It is associated with the "compactification" hypothesis according to which the majority of the dimensions has been compactified, i.e., closed in on itself on a very small scale.

It is assumed that between different Universe there is no causal connection. It is specifically this point that justifies their being treated as individual Universes. I refer to this grandiose structure as a "Mega-Universe." Some authors have discussed variants of such hypotheses. In particular, the hypothesis of multiple creation of closed (approximately hyperspheric) Universes is defended in one of his papers by Ya. B. Zel'dovich.

The ideas of a "Mega-Universe" are very interesting. Possibly, truth lies specifically in this direction. However, for me in some of these constructions there is one unclear point of a somewhat technical nature. It is quite acceptable to assume that the conditions in different regions of space are quite different. But laws of nature must necessarily be everywhere and at all times the same. Nature cannot be like the Queen in Carrol's tale "Alice in Wonderland," who arbitrarily changed the rules of the game of croquet. Existence is not a game. My doubts refer to those hypotheses which admit a breakdown of the continuity of space-time. Are such processes admissible? Are they not a violation at the points of breakdown specifically of the laws of nature, and not of the "conditions of existence"? I repeat, I am not sure that these are well-founded apprehensions; perhaps, I once again, as in the problem of the conservation of the number of fermions, start from a too narrow point of view. Moreover, hypotheses are quite conceivable in which the creation of the Universes occurs without violation of continuity.

The assumption that spontaneous creation occurs of many, and perhaps an infinite number, of Universes that differ in their parameters, and that the Universe surrounding us has been distinguished among the multiplicity of worlds specifically by the condition of appearance of life and mind, has acquired the name of the "*anthropic principle*" (Ref. 9, pp. 784–787 in the Russian text, p. 546 in English).

7. Cosmological transitions with change in the signature of the metric. The quotations presented above are from one of the latest, the 29th chapter of "Memoirs", written (or rewritten anew after one of the recurrent thefts of the manuscript of the book in October 1982) in 1983. During the same period Sakharov wrote an article the title of which is used as the heading of this section. The anthropic principle (cf., regarding it in Refs. 19, 20), the Mega-Universe, the "additional" dimensions of space-time-concerning all this, among other things, refer to the article (A. D. Sakharov (Ref. 52)) submitted to Zh. Eksp. Ter. Fiz. in April 1984 and published in August, when Andreĭ Dmitrievich had already been confined for more than three months in the Semashko hospital of the Gor'kiĭ region with all the consequences arising from this (cf., Ref. 21).

A few words concerning the time when the article (A. D. Sakharov (52)) was being written. The year 1983: The fateful article "The danger of thermonuclear war. Reply to Sidney Drell"; in April the infarction suffered by E. G. Bonner who brought this article from Gor'kiĭ (May) and transmitted abroad for publication (June); the anti-Sakharov letter by academicians A. A. Dorodnitsyn, A. M. Prokhorov, G. K. Skryabin, and A. N. Tikhonov which was followed by an unprecedented persecution of Elena Georgievna. Andreĭ Dmitrievich realized that this was a life-and-death matter and wishing to cut this knot demanded that his wife should be allowed to leave for medical treatment abroad. In doing so he, as I interpreted it, expected to be successful, but, of course, only in the case if a sufficiently intensive support would be forthcoming. Figuratively speaking, in order to have success an "implosion" is required, the combination of effort directed simultaneously from all sides *into one point*. The effectiveness of the idea of such a cumulative compression was well known to him: the construction of the bomb, magnetic cumulation, laser compression, and in social affairs: the victory in 1980 when due to the combination of efforts of the division of theoretical physics (DTP) of the Physics Institute of the Academy of Sciences and of colleagues from abroad he was allowed to continue working in the Physics Institute of the Academy of Sciences; the victory concerning the departure abroad of the daughter-in-law Liza Alekseeva in December 1981. Unfortunately, the "insane" idea concerning the trip of Elena Georgievna was received in approximately the same way as in 1967 the idea of proton decay—at best with bewilderment. In this case "implosion" did not occur, and Andreĭ Dmitrievich was forced to solve the problem himself, depending only on himself. On the manuscript, and also on the author's copies of the article "Cosmological transitions with changes in the signature of the metric" preserved in the DTP there is an inscription in Sakharov's hand: "Dedicated to Lyusya" (i.e., to Bonner). In the journal the dedication is absent, just as earlier in the article "Many-sheeted models of the Universe" (A. D. Sakharov (51)) the dedication "To the memory of the President of the National Academy of Sciences of the USA Dr. Phillip Handler" had been deleted.

The principal idea of the paper (A. D. Sakharov (52))[2)] is as follows: in quantum gravitation (and more widely—in quantum cosmology) one should take into account not only the small fluctuations of the gravitational field (gravitons) and not only fluctuations which lead to a change in the topology (for example, the daughter Universes in the space with signature $(-++ + ...)$), but also the quantum transitions with a change in the number of time axes. In all of this the entire discussion is carried out not in four dimensions, but in a space of a higher, generally speaking a very great, number of dimensions. (The large number of additional coordinates, and also the complex topology of the compact spaces, apparently, as Sakharov wrote in section 4, are necessary to explain the smallness of the observed cosmological constant within the framework of the "anthropological" approach to this problem.) Thus, the signs of the components of the metric tensor in the case of quantization must be not constraints, but dynamical variables; into the Feynman path integral (1) of the paper (A. D. Sakharov (52)) terms both with an imaginary, as well as with a real index of the exponential enter on an equal basis, and this is automatically taken into account by the factor $\sqrt{g}$ in (1).

The cardinal problem is the choice of the Lagrangian L which describes gravitational theory in Q-dimensional space.

Sakharov's suggestion is: the action in Q-dimensions must be conformally invariant, i.e., (symbolically) $L \sim C^{Q/2}$, where C is the Weyl tensor. Such a Lagrangian can arise within the framework of the concept "induced gravitation" as a polarization effect due to the "elasticity of the vacuum" of massless matter fields conformally-invariant in Q-space. It does not contain dimensional parameters and, in principle, is calculable (if, of course, one succeeds to deal by a conformally-invariant method with the ultraviolet divergences). The standard Einstein–Hilbert Lagrangian in four dimensions, as well as the entire series in terms of the curvature of "our" space-time, is reestablished at the next stage: as a result of the compactification of "extra" dimensions. *The fact that the Einstein action can be induced by compactification is an essential and nontrivial extension of the idea of quantum-induced gravitation which was first proposed by Sakharov in 1967.*

In string theory, and in supersymmetric theories with "flat potentials," and in "scaleless" models of the Kaluza–Klein type, the spectrum of the fields of a four-dimensional effective theory includes massless scalar fields (dilaton, the scale of the compactification), on which the Newtonian constant, the fine structure constant, etc. depend in a multiplicative manner. This leads to the well-known difficulty of "floating" cosmologically varying constants, which is excluded by observations with a great degree of accuracy. As far as I know, this problem so far has not been solved; hopes here rest on low-energy quantum radiative corrections as a result of which in the initially flat potential a minimum must arise, which fixes the vacuum average of the scalar zero-modes. However, the entire low-energy region ($E \ll M_{\rm Pl}$, $E \sim \lesssim 10^2$ GeV, $M_{PL} \sim 10^{19}$ GeV) is terra incognita of modern unified theories. Sakharov's idea concerning the primary conformally-invariant gravitational theory in Q dimensions proposes an entirely different solution of the problem of "floating" constants. In such a theory the dependence of the radius of compactification on macroscopic coordinates of the four-dimensional space-time can always be brought to a different gauge by a scale transformation. (The situation is completely analogous to the case of Brans-Dicke theory with $\omega = -3/2$ in which the variability of the Newtonian constant is fictitious; (cf., A. D. Sakharov (41))). As a result gravitation in four-dimensional space is described by the standard Einstein theory (and not the Brans-Dicke theory) while the dimensionless constants of the interaction of gauge fields are numbers which do not depend on the scale of compactification ρ.

To illustrate this set of Sakharov's ideas I calculated the "four-dimensional" gauge and Newtonian constants for the compactification model $M^Q = R^4 \times S^K$ (R^4 is the Minkowskiĭ space, S^K is a K-dimensional sphere, $Q = K + 4$) in the theory with an initial conformally-invariant supersymmetrizable, so-called "geometric" action (cf., in the review of Ref. 22) which is a "chain" product of Weyl tensors:

$$S^{(Q)} = \gamma \int (\mathrm{Tr}\, C^{Q/2} \sqrt{|g|}\, d^Q x; \qquad \text{(a)}$$

$\mathrm{Tr}\, C^m = C^{kl}_{ij} C^{pq}_{kl} ... C^{ij}_{rs}$ $- m$ factors, γ is a dimensionless constant.

The first terms of the effective Lagrangian arising as a result of compactification are:

$$L^{(4)} = \Lambda + \frac{1}{16\pi G} R - \frac{1}{4\alpha^2} F^2; \qquad \text{(b)}$$

Λ is the cosmological term, G is the Newtonian constant, α is the interaction constant of the gauge Young–Mills field of the group of motions of the sphere S^K, which parametrizes in accordance with the standard Kaluza–Klein procedure the nondiagonal components of the metric tensor of Q-space. Using in (a) the general formulas of the paper of Ref. 23 we obtain in this case ($Q = K + 4$, $K = 2d$, ρ is the compactification radius, $\Omega^{(K)}$ is the volume of a K-dimensional sphere of unit radius):

$$\frac{1}{16\pi G} = \gamma c d A \frac{1}{\rho^2}, \qquad \text{(c)}$$

$$\frac{1}{\alpha^2} = \gamma c \frac{d+1}{2d+1} [6A + 4(d+1)^2 (2d+3)^2 B], \qquad \text{(d)}$$

where

$$c = \Omega^{(2d)} (d+2)(2d-1) [(d+1)(2d+3)]^{-(d+2)},$$

$$A = (-1)^{d+2} \{12^{d+1} + [2d(2d-1)]^{d+1}\} + 2[3(2d-1)]^{d+1},$$

$$B = (-1)^{d+1} \{12^d + [2d(2d-1)]^d\} - [3(2d-1)]^d.$$

The fundamental difference of Sakharov's conformally-invariant approach from the "classical" Kaluza–Klein theory in which the gauge interaction constant is determined by the

FIG. 5. A. D. Sakharov after the end of a six-month hunger strike. Gor'kii (Nizhniĭ Novgorod), October 1985.

ratio l_{Pl}/ρ ($l_{Pl} = 10^{-33}$ cm is the Planck length) consists of the fact that here, as be can be seen from (d), σ does not depend on ρ and is determined only by the dimensionality and geometry of the compact space of the "additional" dimensions, and also by the constant γ in the primary action (a). The latter, as we have already said, is in principle calculable if (a) is a quantum-induced action.

The compactification model that we have considered is nonphysical, since in it the Λ-term in (b) differs from zero, and also, as can be seen from (c) and (d), it is not possible to have simultaneously $G>0$ and $\alpha^2>0$. I have examined this toy model for purely illustrative purposes because Sakharov's idea concerning a conformally-invariant theory of gravitation in a space of many dimensions seems to me to be promising, and I wanted to show a concrete example how this works. The paper (A. D. Sakharov (52)) is rich in ideas, which is surprising if one remembers under what conditions it was being written.

8. During the next two years (1984, 1985) Andreĭ Dmitrievich could practically do no science at all. In the hospital he could not even think about science because, as he related later, he was not left alone even for a minute by agents disguised as patients. In 1986 Sakharov wrote and published in Zh. Exp. Teor. Fiz. the article "Evaporation of black miniholes and high-energy physics" (A. D. Sakharov (53)). Can one observe the "shadow world", the particles of which interact extremely weakly with the elementary particles of our world? Sakharov shows that this is in principle possible through the universal interaction—gravitation, and shows that there exist very subtle effects when the properties of the "shadow" particles affect the behavior of black holes.

After Chernobyl, Andreĭ Dmitrievich made a radical proposal concerning ensuring the safety of reactors of atomic energy stations—placing them underground. In subsequent years, already in Moscow, he, in spite of being heavily involved in social matters, investigated and developed this question, had meetings with specialists, including the Director of the Mining Institute of the Kola scientific Center of the Academy of Sciences of the USSR, Professor N. N. Mel'nikov, whose article on the problem of underground placing is being published in Ref. 11. A. D. Sakharov proposed the adoption of an international law forbidding the construction of above-ground atomic energy stations. It is interesting that in this question his position coincides with the position of the "father" of the American hydrogen bomb, Edward Teller.

Already in 1986 Andreĭ Dmitrievich put forward a proposal on preventing major loss of people as a result of catastrophic earthquakes. In October 1988 he reported on this subject in Leningrad at the Soviet-American seminar "Nonlinear systems in earthquake prediction." Sakharov expressed his opinion that one can artificially induce earthquakes by using as a trigger mechanism a nuclear explosion at great depth...The object of this action is to release the stored energy before it becomes critical and thus to avoid large losses"—wrote G. I. Barenblatt (Ref. 10, p. 120). On

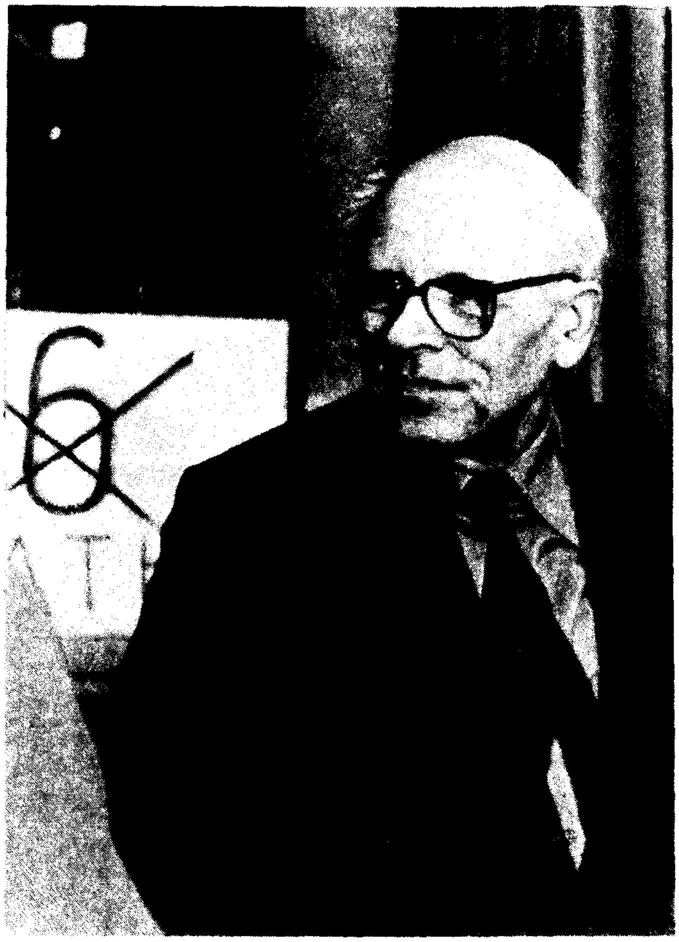

FIG. 6. A. D. Sakharov. At the Physics Institute of the Academy of Sciences, 11 December 1989, at a meeting (a two-hour warning strike demanding the withdrawal of the 6th clause of the Constitution of the USSR).

this subject also see the article by V. I. Keilis–Borok in Ref. 11.

At the same time, as I have already mentioned, fundamental physics was, and remained until the end, the main passion of Andreĭ Dmitrievich. He was well informed concerning the main events in this field, although himself, of course, could not take part in it, particularly after having been elected in 1989 a People's Deputy of the USSR. Once I addressed to him this banal and, essentially, absurd question: when will you occupy yourself with science?" "When they again exile me to Gor'kiĭ," replied Andreĭ Dmitrievich. Nevertheless, in June 1988 at the international conference dedicated to the centenary of A. A. Friedmann, Sakharov presented a long review paper "Baryon asymmetry of the Universe" (A. D. Sakharov (54)). After Ya. B. Zel'dovich died in December 1987 Sakharov became the head of the Council on Cosmomicrophysics associated with the Presidium of the Academy of Sciences of the USSR.

On 29 November 1989, two weeks before he died, he participated in a meeting of the Council at the P.K. Shternberg State Astronomical Institute at the Moscow State University, and participated very actively (cf., the article by M. Yu. Khlopov on this subject in Ref. 10).

As I have already said, these notes are not a review of the scientific activity of A. D. Sakharov, and I shall not summarize. There is no point to repeat what is generally well known concerning such doubtless achievements as a magnetic thermonuclear reactor, magnetic cumulation or an explanation of the baryon asymmetry of the Universe. Some of these ideas and results have been firmly imbedded in science, others are still in the incubation stage.

In August 1989, completing his second (and last) book of Memoirs, Andreĭ Dmitrievich wrote on its last page:

"Of course the end of the work on this book creates a feeling of a boundary, a summary. Paraphrasing a line of A. S. Pushkin: "Why does an incomprehensible sadness trouble me secretly?" And at the same time—a feeling of the powerful flow of life, which began before us and will continue after us. *This is the miracle of science.* And although I do not believe in the possibility of a rapid creation (or creation generally?) of an all-encompassing theory, nevertheless I see gigantic, fantastic achievements in the course of even only my own life and expect that this flow will not dry up, but, quite the reverse, will expand and branch out..." (Ref. 14, p. 220).

The author is grateful to L. B. Okun' who read the manuscript of the article and made valuable comments.

[1)] (A. D. Sakharov (10),...) refers to the number of reference in the list of scientific articles, popular science articles, general articles and statements of A. D. Sakharov which follows the present article.

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