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Work of the Tamm–Sakharov group on the first hydrogen bomb

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Abstract. This review is an extended version of a report delivered at a session of the Department of Physical Sciences, the Department of Energetics, Mechanical Engineering, Mechanics, and Control Processes, and the Coordination Council on Technical Sciences of the RAS devoted to the 60th anniversary of the first hydrogen bomb test. The significant physical ideas suggested by A D Sakharov and V L Ginzburg underlying our first hydrogen bomb, RDS-6s, and numerous concrete problems and difficulties that had to be solved and overcome in designing thermonuclear weapons are presented. The understanding of the country's leaders and the Atomic Project managers of the exceptional role of fundamental science in the appearance and implementation of our scientists' concrete ideas and suggestions is emphasized.

1. Organization of the Tamm special group

In 1948, a group of theoreticians led by I E Tamm was established at the Physical Institute of the USSR Academy of Sciences; by a special decree of the government, it was entrusted with the task of joining the research on thermonuclear detonation in a deuterium–tritium plasma — the governing process in the projected hydrogen 'tube' bomb. This research was carried out by Ya B Zel'dovich at the Institute of Chemical Physics, together with A S Kompaneets and S P D'yakov, and in KB-11 (Design Bureau No. 11) by D A Frank-Kamenetskii, G M Gandel'man, and A N Dmitriev.

The Tamm group included A D Sakharov, V L Ginzburg, S Z Belen'kii, and Yu A Romanov. Very soon, Sakharov and Ginzburg developed their own original ideas on creating a hydrogen 'sloika' bomb composed of spherical layers of solid lithium-6 deuteride and uranium-238, heated and ionizationally compressed by an explosion of a nuclear bomb at the center.

After a year of purely theoretical work by the group, some of its members had to move to KB-11. "This is needed for the success of the project," said B L Vannikov, the head of the First Main Directorate, the powerful organization in charge of the USSR Atomic Project, in a conversation with Tamm and Sakharov.

Although nobody was willing to be fully taken into the custody of top-secret physics, Sakharov and Romanov in May 1950 and Tamm a bit later moved to permanent positions at KB-11. I joined this group in May 1951, having graduated from the Physics Department of Moscow State University and being unexpectedly 'detached' from my postgraduate studies. This was a sharp turn in my life.

The work on RDS-6s progressed at full speed. Yu N Babaev, G A Goncharov, V G Zagrafov, B N Kozlov, and M P Shumaev joined the Tamm group in 1951–1953. The nuclear physics of matter under very high temperatures was i use.

2. Nuclear reactions and physical ideas of Sakharov and Ginzburg

The creation of a hydrogen bomb assumes, first and foremost, the use of the energy of a heavy hydrogen isotope, deuterium. On heating deuterium to very high temperatures of the order of 10 keV ($1\ \text{eV} = 1.16 \times 10^4$ degrees Kelvin times the Boltzmann constant $k = 1.38 \times 10^{-16}\ \text{erg K}^{-1}$) by an atomic bomb explosion, thermonuclear reactions

$$\mathrm{d} + \mathrm{d} \to \mathrm{p} + \mathrm{t} + 4\ \text{MeV}\,, \tag{1}$$

$$\mathrm{d} + \mathrm{d} \to \mathrm{n} + \mathrm{He}^3 + 3.3\ \text{MeV}\,, \tag{2}$$

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are initiated between the nuclei of deuterium (the deuterons) with the accompanying energy release (4 MeV and 3.3 MeV, respectively) in the form of kinetic energy of the reaction products. As a result, the energy released on burning 1 kg of deuterium is equal to the energy released on burning 1.3 kg of plutonium or U^{235}. The nuclei of tritium — tritons t — and the nuclei of helium He^3 forming in these reactions enter the thermonuclear reactions

$$\mathrm{t} + \mathrm{d} \to \mathrm{n} + \mathrm{He}^4 + 17.6\ \mathrm{MeV}\,, \tag{3}$$

$$\mathrm{He}^3 + \mathrm{d} \to \mathrm{p} + \mathrm{He}^4 + 18.34\ \mathrm{MeV} \tag{4}$$

with a substantially higher energy release. This is explained by the very strong coupling between nucleons (2p + 2n) in the nucleus of He^4 — the main isotope of helium. Taking secondary reactions into account results in the net energy release on burning 1 kg of deuterium being a factor of 4 larger.

Reactions (3) and (4) are very interesting theoretically, because the effective cross section of the first of them exhibits a resonant behavior if the energies of colliding particles are about 100 keV, related to the excitation of a level in the compound nuclei He^5 with the energy exceeding the mass of $n + He^4$ by 17.7 MeV; the cross section of the second reaction behaves similarly for energies of colliding particles of about 260 keV owing to the excitation of the level in a compound nuclei Li^5 with the energy exceeding the mass of $p + He^4$ by 18.6 MeV. Because of the large width of the resonance levels of He^5 and Li^5 nuclei, the cross sections of reactions (3) and (4) also increase substantially for small energies (~ 10 keV) of colliding particles. As a result, the cross section of the d – t reaction is greater than that of the d – d reaction by more than a factor of 100. The cross section of the He^3 – d reaction increases to a lesser degree because of a stronger Coulomb repulsion between a deuteron and doubly charged He^3.

The similarity in the properties of reactions (3) and (4), as well as (1) and (2), stems from the *mirror symmetry* of the participating nuclei, i.e., the symmetry under the exchange $n \rightleftarrows p$. In view of the isotopic invariance of nuclear forces, the masses of mirror nuclei differ from each other mainly because of the Coulomb energy of repulsion between protons and the mass difference between a neutron and a proton. The quark structure of neutrons and protons explains the ratio of their magnetic moments $\mu_n/\mu_p \approx -2/3$.

Working at KB-11, Tamm, notwithstanding his commitments to committee meetings, discussions of running and planned activities, and writing reports to higher authorities (Yu B Khariton, I V Kurchatov, A P Zavenyagin, B L Vannikov, and L P Beria), was interested in the important d – t reaction. To explain the experimental cross section [1], Tamm considered not only the permeability of the Coulomb barrier but also the above-mentioned resonance level of compound nuclei He^5, describing it with the help of the Breit–Wigner formula. In doing so, he was prompted to introduce the dependence of the width of the resonance level on the energy level of colliding particles. He similarly modified the cross section of another very important reaction, $Li^6 + n = He^4 + t$, which is discussed below. He frequently recalled the names of Bashkin and Peshkin, the US authors of Refs [2] and [3], in relation with these reactions. I am not aware of whether the corresponding Tamm's reports were preserved at KB-11. Fundamental works by Tamm and Sakharov on the theory of a magnetic thermonuclear reactor, carried out at KB-11, are published in Refs [4] and [5].

Theorists working with experimental cross sections of fusion reactions are most interested in the rates of these reactions, i.e., the number of reactions occurring per s in 1 cm^3 of a mixture of colliding particles heated to a temperature T. This rate is given by the formula

$$\langle \sigma(v) v \rangle n_1 n_2\,, \tag{5}$$

where $\sigma(v)$ is the reaction cross section, which depends on the relative velocity v of colliding particles, with n_1 and n_2 being their concentrations. The angular brackets denote averaging over the thermal (Maxwell) distribution of relative velocities:

$$\langle \sigma(v) v \rangle = \int \mathrm{d}^3 v \left(\frac{\mu}{2\pi T}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2T}\right) \sigma(v) v\,, \tag{6}$$

and $\mu = m_1 m_2/(m_1 + m_2)$ is the reduced mass of colliding particles.

Because the cross section $\sigma(v)$ contains the exponential Gamow factor,

$$\sigma(v) \sim \exp\left(-\frac{2\pi e^2}{\hbar v}\right) \ (\text{in the general case, } e^2 = e_1 e_2)\,, \tag{7}$$

strongly suppressing the cross section at small velocities of colliding charges of like sign, and because the Maxwell distribution decays exponentially at large velocities, integral (6) can in essence be computed via the steepest descent method and turns out to be proportional to an exponential function with the exponent defined by the cubic root of the inverse temperature:

$$\langle \sigma(v) v \rangle \sim \exp\left[-3\left(\frac{\pi^2 e^4 \mu}{2\hbar^2 T}\right)^{1/3}\right]. \tag{8}$$

For d – d reactions and temperatures of 10 and 20 keV, the values of the exponent are −8.73 and −6.93. The corresponding increase in temperature would increase the rate of d – d reactions 6-fold. But achieving this is very difficult. As a consequence, to increase the rate of a fusion reaction, one strives to increase the density of the thermonuclear fuel, i.e., the product of concentrations $n_1 n_2$.

It seems that for initiating fusion reactions (1) and (2), it suffices to place a layer of deuterium in an ordinary nuclear bomb between a fissionable material (a spherical shell of U^{235} or Pu^{239}) and conventional explosive surrounding it, the cumulative explosion of which would make the subcritical fissionable matter supercritical. However, it turned out that in this case deuterium cannot be heated and compressed sufficiently, and the fusion reaction is practically halted.

To essentially increase the rate of the fusion reaction, Sakharov proposed surrounding the deuterium layer in the construction described above with a shell made of ordinary natural uranium, which would slow down the scatter and, most importantly, essentially increase the concentration of deuterium.

Indeed, at temperatures achieved during the explosion of the initiator nuclear bomb, the surrounding matter is almost completely ionized. According to the Clayperon law, the pressure p in such a gas is nT, where n is the net concentration of nuclei and electrons and T is the temperature in energy units. Now, it is important to recall that the uranium nucleus is surrounded by 92 electrons, and that of deuterium by only one. From the equality of pressures and temperatures at the interface between deuterium and uranium, it follows that the concentration of nuclei of heated and compressed deuterium is

$$n_{\mathrm{D}} = \frac{Z_{\mathrm{U}}+1}{Z_{\mathrm{D}}+1}\, n_{\mathrm{U}} = \frac{Z_{\mathrm{U}}+1}{2A_{\mathrm{U}}M}\, \rho_{\mathrm{U}} \approx \frac{1}{5M}\, \rho_{\mathrm{U}} \sim 2.3\times 10^{24}\ \mathrm{cm}^{-3}\,, \tag{9}$$

i.e., it is proportional to the uranium density ρ_{U} with a coefficient weakly dependent on the shell material (Z is the material atomic number, A is the mass number, and M is the atomic mass unit equal to 1.66×10^{-24} g).

The increase in the rate of the d–d reaction leads to a perceptible production of tritium, which immediately interacts with deuterium via fusion reaction (3) with a cross section 100 times larger than that of the d–d reaction, and an energy release 5 times larger. Moreover, the nuclei of the uranium shell are easily fissionable under the action of 14 MeV neutrons appearing in the d–t reaction, and substantially increase the power of the explosion. Just this circumstance motivated the selection of uranium for the shell and not any other heavy material (for example, lead).

The power of the fusion process in deuterium could be substantially increased if part of the deuterium were initially replaced with tritium. But tritium is rather expensive and, moreover, radioactive. For this reason, Ginzburg proposed replacing it with Li^6, which decays to tritium under the action of neutrons in the reaction

$$\mathrm{Li}^6 + \mathrm{n} \to \mathrm{He}^4 + \mathrm{t} + 4.8\ \mathrm{MeV} \tag{10}$$

with a very large cross section proportional to the inverse velocity of neutrons and a resonance in the vicinity of 270 keV.

Indeed, the thermonuclear charge with deuteride of lithium-6 ($\mathrm{Li}^6\mathrm{D}$) led to a radical increase in the power of the fusion process and the energy release from the uranium shell in fission that was several times larger than the thermonuclear energy release.

Such are the 'first' and the 'second' physical ideas (according to Sakharov's terminology [6]) underlying the first variant of our thermonuclear weapon. Both ideas are laid out in reports by Sakharov and Ginzburg (see document Nos 52 and 59 in Ref. [7]).

3. Ways of increasing the concentration of deuterium and the rate of fusion reactions

We consider some quantitative aspects of both ideas in more detail.

If the carrier of deuterium is deuteride of lithium-6, the concentration of deuterium nuclei n_{D} is that of $\mathrm{Li}^6\mathrm{D}$ molecules, $n_{\mathrm{Li^6D}}$. Each of them contains 4 electrons and 2 nuclei. For this reason, we should replace $Z_{\mathrm{D}}+1=2$ with $Z_{\mathrm{Li^6D}}+2=6$ in (9), which reduces the right-hand side of (9) three-fold. In turn, the concentration of cold deuterium n_{D}^0 is determined by the density $\rho^0_{\mathrm{Li^6D}} = 0.82\ \mathrm{g\ cm^{-3}}$ of the inlaid deuteride of lithium-6: $n_{\mathrm{D}}^0 = n^0_{\mathrm{Li^6D}} = \rho^0_{\mathrm{Li^6D}}/8M$. Accordingly, the ionization implosion would increase the deuterium concentration by a factor of 12:

$$\frac{n_{\mathrm{D}}}{n_{\mathrm{D}}^0} \approx \frac{8\rho_{\mathrm{U}}}{15\rho^0_{\mathrm{Li^6D}}} \sim 12\,,$$

even without account for the increase in the uranium density.

If the carrier of deuterium is liquid molecular deuterium D_2, formula (9) for the maximum concentration of compressed D does not change, and the compression degree is

$$\frac{n_{\mathrm{D}}}{n_{\mathrm{D}}^0} = \frac{2\rho_{\mathrm{U}}}{5\rho^0_{\mathrm{D}_2}} = 54\,,$$

because $\rho^0_{\mathrm{D}_2} = 0.14\ \mathrm{g\,cm^{-3}}$. Although the absolute concentration is in this case three times larger than for deuteride of lithium-6, the advantages of a solid carrier with normal temperature against the liquid one with a temperature of −250 °C are obvious.

After successful tests of RDS-6s, Sakharov proposed using gaseous molecular deuterium D_2 compressed to 150 atm instead of $\mathrm{Li}^6\mathrm{D}$, in order to increase the concentration of ionizationally compressed deuterium. Everything said above for liquid deuterium D_2 is valid in this case, except for the density of the initially compressed gas of D_2, equal to $\rho^0_{\mathrm{D}_2} = 0.027\ \mathrm{g\ cm^{-3}}$.

It was proposed to place pieces or thin plates of lithium-6 into the layer of gaseous deuterium in order to gain tritium on irradiating them by neutrons after the explosion of the primer. The tritium nuclei, owing to their large mean free path, would leave thin pieces of lithium-6 and on entering the atmosphere of heated deuterium would interact with it via a fusion reaction (see document No. 40 in Ref. [8]).

I pay special attention to this variant of the 'device' because just it, under the name RDS-6SD, was approved by the Council of Ministers for development and testing in 1954. Another decision, as recalled by Sakharov [6], "obliged the missile scientists to develop an intercontinental ballistic rocket capable of carrying this charge. Importantly, the weight of the charge and hence the design of the missile were selected on the basis of my report. This predetermined the work of the gigantic design and production organization for many years. It was this rocket that launched the first man-made satellite orbiting Earth in 1957 and the spaceship with Yuri Gagarin aboard in 1961."

But detailed computations carried out in Moscow on the request of Sakharov showed that the energy yield of several variants of RDS-6SD was lower than expected. The 'exotic' construction did not live up to expectations and after numerous and dramatic discussion with high-ranking officials (V A Malyshev, B L Vannikov, A P Zavenyagin, I V Kurchatov) was abandoned.

At the same time, from the spring of 1954, a new, 'third' principal idea, that of imploding the thermonuclear fuel by *radiation* from an atomic bomb, started to be discussed in Sakharov's and Zel'dovich's theoretical divisions. This topic, however, is beyond the scope of this review.

4. Effective cross sections of the most important nuclear reactions

At the present time, it is known that material 713a delivered by K Fuchs (see document No. 31 in Ref. [7]) contained detailed information not only on the thermonuclear bomb, dubbed 'tube' by us, but also on the cross sections of the most important fusion reactions (1)–(4). At the beginning of May 1949, data on the cross section of the d–t reaction, without reference to the source, were made available to

Tamm and Sakharov, and also to Kompaneets from Zel'dovich's group.

It is curious that these cross section data were published in *Physical Review* [1] at that same time. The cross sections of d – d and d – He^3 reactions had been published in the same journal earlier, in 1947–1948.

Measurements of cross sections of fusion reactions and other nuclear characteristics were also carried out in a number of our laboratories. The most thorough research on the rate of the d – t reaction was carried out by the group of I Ya Barit (E M Balabanov, L N Katsaurov, V A Nefedov, I V Shtranikh) in I M Frank's laboratory (Lebedev Physical Institute, FIAN). The results obtained by this group essentially refined the data by Bretscher and French [1], convincingly confirming the 100-times difference in the rate of the d – t reaction over that of the dd-reaction.

The fission cross section of U^{238} by 14 MeV neutrons of the d – t reaction and the number of secondary neutrons appearing in this case were measured at FIAN, the Institute of Chemical Physics, the Laboratory of Measuring Instruments, the Hydrotechnical Laboratory, and KB-11. The cross section and the number of secondary neutrons turned out to be much larger than in the chain reaction.

The interaction of neutrons with Li^6 was studied at the Ukrainian Physical–Technical Institute and the Institute of Physical Problems. The cross section of reaction (10) was essentially refined with respect to the data in Ref. [9], as was the position of the resonance, shifted to the range of neutron energy around 250 keV.

Experimental data obtained in our laboratories and abroad were continuously collected by all members of the Tamm–Sakharov group, then analyzed and collected into a table of nuclear constants needed for the computation of the energy yield in RDS-6s.

In this respect, Romanov and I used to be frequent guests in the laboratory of Yu A Zysin, discussing with him and his collaborators the organization of nuclear physics research, in the range from measurements of elementary and effective constants to the integral measurement on the sloika model. This group — G P Antropov, P P Lebedev, A A Lbov, A I Pavlovskii, V N Polynov, O K Surskii, and Yu S Klintsov — achieved remarkable results, in particular owing to the accelerating tube of Pavlovskii, with the then record high yield of 14 MeV neutrons at 5×10^{10} per second.

The cross sections of fission of U^{235}, U^{238}, and Pu^{239} by neutrons with energies characteristic for the fission spectrum and also with energies of 2.5 and 14 MeV were measured, together with the mean number of secondary neutrons in fission by 14 MeV neutrons and the effective removal cross section of fast neutrons under the threshold of U^{238} fission.

The cross sections of reactions $(n, 2n)$ and other characteristics were measured for 15 elements. Finally, reactions on light nuclei were explored and the removal cross section was determined.

In the fall of 1951, Romanov and I visited the Hydrotechnical Laboratory (currently, the Joint Institute for Nuclear Research, Dubna), where a group led by V A Davidenko and M G Meshcheryakov, including I S Pogrebov, A I Saukov, V S Siksin, and Yu F Tuturov, measured the cross sections of d – d and d – t reactions and the 'utilization coefficient' of 14 MeV neutrons in a flat sloika model. We sent the results obtained by them to our Theoretical Section, and later M G Meshcheryakov — the director of the laboratory at that time — took us along a long corridor to the 250 MeV proton accelerator.

This huge construction weighing 7 thousand tons left an unforgettable impression. Built based on a proposal by S I Vavilov, I V Kurchatov, A I Alikhanov, D V Skobel'tsyn, and L A Artsimovich, the synchrocyclotron may serve as a monument to the insight of the leaders of our physical institutes. One can only marvel at the wisdom and foresight of the country's leaders who, just a year after the war, took the decision to build this accelerator at the Leningrad plant Electrosila, and the organization of its transportation by water ways to the region of the Ivan'kovo hydropower plant and the construction there of the future Center for Fundamental Nuclear Physics and the Physics of Elementary Particles.

During the tour, Romanov told me in secret that a collaborator of E Fermi, B Pontecorvo, who defected from Canada, was working at the accelerator.

Approximately at that time, Romanov proposed sending our report on the mean free path of neutrons with different energies in lithium deuteride, for varying concentrations of lithium-6, to O D Kazachkovskii from Laboratory B (Obninsk). The laboratory was studying the construction of nuclear reactors with enriched uranium. Many years later, my wife and I got acquainted with the Kazachkovskiis, and they almost immediately recalled the Romanov–Ritus formula. It proved to be useful. Kazachkovskii's section was exploring the interaction of neutrons with matter and other important issues pertaining to reactors with fast neutrons, which are more efficient for the production of plutonium-239 than thermal reactors.

5. Meeting on the problem of lithium-6 deuteride

Working together, Romanov and I co-authored about 10 reports. Although only a year older than me, Romanov had three years of practical experience working in the Tamm–Sakharov group and was keen to share both his knowledge and scientific methods with me as well as with other group members. I am very much indebted to him for that.

Our main involvement was the detailed exploration of the second idea, that of using Li^6D. We were looking at how the energy yield would increase if some amount of deuterium was replaced with tritium, the cross section of the d – t reaction being 100 times larger than that of the d – d reaction. Or what would happen if natural Li, containing 7.3% of Li^6, was not fully purified from the main, seventh, isotope, such that the concentration of Li^6D would become comparable to that of Li^7D? We were carrying out the related computations of the energy yield.

Somewhere at the end of 1951, a meeting devoted to the problem of Li^6D took place at the office of Khariton, attended by Kurchatov with all his suite. Among the invited heads of laboratories and sections of KB-11, Romanov and I turned out to be the youngest. It was there that I saw Kurchatov for the first time. Here, too, his nickname, 'The Beard', gradually became apparent. His beard, in reality, did not impress me in any particular way — it was rather sparse. But his handsome, intelligent face, his tall figure, and the absence of a big boss tone stay in my memory.

Needless to say, Romanov and I were delegated to this meeting by Sakharov, because we were closely involved in the problem of Li^6D; but Sakharov presented all our results himself. The auditorium was full, everyone was sitting in a semicircle, but the space at the center and behind the chairs remained free. Kurchatov was strolling alone through this free space. He first received a report from Khariton, then from Sakharov. And then, the following scene happened. Kurchatov stopped behind my chair and, leaning on my chair back, started talking about something. His beard touched my then still available hair. It seemed to me that everyone was looking at me and I felt lost.

No doubt this scene is kept in memory, but something else is kept too. Namely, the epilogue of the meeting, which was as follows. The arguments concerning Li^6D were very essential: Kurchatov acknowledged them and responded literally, "Well, then I will appeal to the government with a proposal on building a lithium factory." After these words, it became clear that lithium had been produced, by all probability, in laboratory conditions, and Li^6, even if separated, was available in a very small amount. The discussion immediately turned to the factory, which would deal not only with the production of lithium proper but also with the separation of its sixth isotope. In short, I left that meeting, and I think Romanov did too, with a feeling of being associated with an endeavor of immense national significance.

As follows from the documents of the USSR Atomic Project, the production of lithium-6 was planned much before the meeting with Khariton, but the decree of the Council of Ministers, alluded to by Kurchatov during the meeting, was signed by Stalin on 19 January 1952 (see document No. 173 in Ref. [7]). The implementation of two industrial methods of separating lithium isotopes, electromagnetic and electrolytic, was respectively led by L A Artsimovich and B P Konstantinov.

6. Problems of layer mixing, the equation of state, and the cumulative implosion of the 'sloika'

On exploding a thermonuclear charge, due to large accelerations, the boundaries of dense and light layers lose their stability. This may entail mixing of the layers and a reduction in the rate of the fusion reaction if the instability time scale is small or comparable to the time of the explosion.

In 1949–1950, S Z Belen'kii, not without consulting L D Landau, explored turbulent mixing and developed a method to estimate it based on experimental data obtained at KB-11 and LIPAN. In 1952, E S Fradkin (FIAN) analyzed three possible ways to reduce mixing.

At temperatures of the medium of the order of 10 keV, it is reasonable to use the equation of state

$$p = a\rho T + bT^4 \,, \tag{11}$$

in which the first term is the pressure of an ideal fully ionized gas and the second is the pressure of radiation.

In 1950, Fradkin took the incomplete ionization of uranium atoms into account, representing them with the Thomas–Fermi model. This barely changed the *pressure* in uranium for a given temperature and density, but did modify the relation between the *energy* of matter and radiation. The matter energy increased twofold compared with the value in the ideal gas model. This led to an increase in the total energy of 25% at the ignition stage and 10% at the stage of thermonuclear charge burning. It seems to me that Fradkin continued to explore the equation of state in 1955–1956.

I must mention the activity of E I Zababakhin and his collaborators pertaining to the problem of sloika implosion by a cumulative conventional explosion. When I entered his office for the first time, I saw a large sheet of Whatman paper on a Kuhlmann drawing board, with a sectional schematic of lenses of cumulative implosion. I was surprised that Zababakhin himself, and not the designers working in another building, was drawing this schematic at 1:1 scale, carrying out computations with the help of a slide rule 1 m long. Even more surprising was to hear his words that he had seen a similar schematic in a ready form far back in 1948 when, at the invitation of Zel'dovich, he had begun his work at KB-11. It seemed to me that I had heard something I was not supposed to hear. His collaborators N A Popov and V P Feodoritov were in attendance. Only later did I realize that for ethical reasons, Zababakhin could not hide from his young colleagues that he was not the author of the original schematic.

Now a similar implosion scheme had to be applied to a thermonuclear charge containing several spherical layers of light lithium deuteride and heavy U^{238} propagating from lenses of explosive to the plutonium charge being compressed. To achieve this, Zababakhin not only calculated the necessary power of the lenses but also separated the external uranium shell from the internal one by an open gap to ensure that the converging spherical detonation wave imparted the highest kinetic energy to the external shell on its way to the internal shell. Thus, the external shell and the gap play the roles of a projectile and a barrel in this cumulative gun. When the external shell hits the internal one, the forming shock wave compresses the inner heavy and light layers and shifts the plutonium charge into a supercritical state.

At the beginning of 1955, I used similar considerations in my proposal of double implosion of a basic thermonuclear charge by the *radiation* of an atomic bomb and a small thermonuclear charge (see document No. 140 in Ref. [8]). The sequential operation of two radiation sources strengthened and symmetrized the implosion and made it last longer.

As follows from the interesting paper by L V Al'tshuler [10], for an atomic bomb, the scheme of imploding the central plutonium core by hitting it with a converging spherical plutonium shell was developed theoretically by Zababakhin, and experimentally by Al'tshuler, K K Krupnikov, B N Ledenev, and S B Kormer beginning in 1948.

7. Task statement on the action of multi-layered charge for Landau's and Tikhonov's groups

After less than a year of my involvement, the time came to formulate the main mathematical task on detailed computations of the physical processes and energy yield in the sloika, which required solving a system of partial differential equations numerically.

Sakharov wrote the plan of this task in my work notebook and asked me to check it, augment it with the necessary detail, analyze possible variants of the initial data, and supply a table of cross sections for the $d-t$ and other reactions. I was immersed in this activity for several days. After Sakharov read my work and his remarks were taken into account, I rewrote the task with my fountain pen in greenish–blue ink on a quad-ruled sheet of paper specially given to me, using both sides. Its size would correspond to the current A3 format.

Now it is known from documents that the task was written on 5 April 1952 and entitled "Formulation of the problem on the action of the MC" and signed by Sakharov and myself (MC is the abbreviation of the multilayer charge) [11]. It was first sent to Landau's group, where it was the first task from the Tamm group, and then forwarded to Tikhonov's group.

For the first time, the confines of the 'object' were left by a document that contained the concise information on our first hydrogen bomb, based on the ideas and experimental results of our scientists. The preliminary work carried by the Tamm–Sakharov group set the optimal construction variant and the composition of thermonuclear fuel. The basic processes unfolding during the thermonuclear explosion were described by a system of partial differential equations, and solving them with the highest possible accuracy was the task of groups led by Landau and Tikhonov.

In several days, Tamm received a top-secret note from Landau with the following contents:

"Dear Igor' Evgen'evich,

The very insightful note you sent unfortunately lacks the values for velocities of particles for all groups. I would like to ask you to promptly send them to us.

Yours L Landau 11/IV 52."

It was admittedly my fault. In the task, the velocity of neutrons of three groups were featured simply as v_1, v_2, and v_3, without their numerical values.

But it was not my only fault. As it turned out, Sakharov and, following him, I missed the term with viscosity in the equations, which has to be artificially introduced to stabilize numerical computations. When I asked Sakharov to send corrections as soon as possible, he replied: "You know, they are experienced enough, they will guess this term, do not worry."

On the other hand, Sakharov was impatient to know the intermediate results pertaining to the burning out of lithium-6, and in two or three months he delegated me to visit both groups.

Landau, who I had never seen before, met me in the lobby of the Institute of Physical Problems and then accompanied me to the office of the institute director, A P Aleksandrov, who immediately signed the pass to the rooms of Landau's group. Leaving me alone in an empty room, Landau said: "I will introduce you to our lads." I was then 25 years old, and expected to meet someone my age. In two or three minutes, two rushed into the room — one completely bald and the other with still some remnant of hair on his head. But since Landau said 'lads', I quietly talked with them explaining the goal of my visit.

When one of my interlocutors brought a work notebook and unfolded it, it took up the entire table — so much larger was its horizontal length than the vertical one. I was startled and even somewhat confused to see that this notebook was evidently a foreign production and by all probability was specially intended for recording intermediate results of complex numerical computations. At that time, such computations were carried out by female technicians using electromechanical calculators made by Mercedes or Rheinmetall, delivered from Germany. Typographically ruled pages of this notebook contained columns of digits representing the values of various physical quantities as functions of time.

I wrote the numbers of interest to Sakharov and myself on a special sheet, which was dispatched to our object through the top-secret department.

My other impression is related to the interest in Sakharov evinced by my interlocutors (E M Lifshitz and I M Khalatnikov, and N N Meiman dropped in briefly several times; I learnt all these names when I was leaving and they signed my pass). I realized that they not only were unacquainted with Sakharov, but had never seen him. I therefore think that this was the first task for the Landau group coming from the Sakharov group (and this is confirmed by the documents of the USSR Atomic Project). Before this, the Landau group had worked on requests coming from the group of Zel'dovich pertaining to the atomic bomb and the 'tube'.

The Tikhonov group, which I visited the next day, was a different story. It was located in the building occupied by the laboratory of V I Veksler before FIAN moved from Miuss Square. Sakharov had had contact with this group already for several years. I, too, knew almost all of its members. Tikhonov gave lectures to my year, Samarskii led practical exercises and was my examiner, and Boris Rozhdestvenskii was my classmate. New to me were only V Ya Gol'din and N N Yanenko. However, Gol'din greeted me as if I we had known each other long before, and said: "Vladimir Ivanovich, you have so clearly formulated the task, do write for us always." In all probability, all preceding tasks were written by Sakharov and intended for 'supermen'. I knew that it was not easy to understand Sakharov.

Becoming familiar with the behavior of physical quantities of interest to me, I paid attention to some difference in the methods of carrying out numerical computations in Landau's and Tikhonov's groups.

For example, the most important quantity in computations was the rate of thermonuclear reactions, in particular, the $\mathrm{d-t}$ reaction. As we know, it is defined by the effective cross section of the reaction times the relative velocity of the colliding particles, averaged over the Maxwell velocity distribution [see formula (6)]. The groups were computing this integral as a function of temperature in their own way. In the Landau group, it was written as an exponential with exponent (8), computed by the steepest descent method, and the pre-exponential factor was a polynomial of the first or second degree in temperature, found as an interpolation of numerical values of the integral. In the Tikhonov group, the integral was written as a polynomial of a high degree (7th or 8th), with the coefficients found by interpolating the numerical values of the integral.

The differences in the implementation of the finite difference method used by both groups were discussed by a commission led by D I Blokhintsev at the end of January 1953. It found that the technique adopted by the Tikhonov group led to certain distortion of the time behavior of fusion reactions near shock waves that form at the layer boundaries. However, this distortion proved to be insignificant for the net energy release and other main parameters — burning out and regeneration of tritium and the energy yield for a 14 MeV neutron.

Both groups completed the computations by the end of December 1952, with the values for energy release of 250 and 220 kilotons of TNT equivalent.

The energy release of the sloika tested on 12 August 1953 turned out to be substantially larger — it reached 400 kilotons owing to a larger actual reaction cross section than assumed in computations and to using tritium in both the first and the second layer. This was a spectacular success of the Tamm group. Tamm and Sakharov became Heroes of Socialist Labor, were awarded very substantial Stalin Prizes, and got dachas and cars.

I do not know why Sakharov selected me to participate in formulating this important task. Possibly, he wanted to interest me in the higher level of the 'device' computational support and simultaneously introduce me to the elite of Soviet theoretical physics — Landau, Lifshitz, Khalatnikov, and Meiman.

Later, E M Lifshitz was a referee of my doctoral thesis, and at meetings in the editorial office of *JETP* during the difficult years for Sakharov, he used to take me to the institute (Institute of Physical Problems) garden and ask for details about Sakharov. G N Flerov had similar compassion for Sakharov, but I saw him much more seldom.

My participation in formulating the task spared Sakharov a premature estimate of his personality and his brainchild — the multi-layer charge — by the Landau group. I remember how thoroughly they questioned me about him, trying to assign him a 'star number' in Landau's ranking. Yes, they surely could not have seen him or read documents written by his hand.

I have learned about the further fate of this task from Sakharov's 'Memoirs' [6] and a book by Khalatnikov [12]. More precisely, it was passed to me by Gol'din, who later described it in his article dedicated to Tikhonov [13].

Approximately a year after the task was fulfilled, Rozhdestvenskii, for whatever reason, requested the original document, which should have been stored at the security department of the Institute of Applied Mathematics. It was missing there. Investigations into this extraordinary incident involved officers of the KGB. After scrutinizing all papers, it was found that four sheets intended to be destroyed were still in the file, but destroyed instead were the task sheets (as narrated by Gol'din [13], the correct reading should be 'the sheet' if it actually concerns the original). A horrible consequence of this incident was that the head of the security department, Vasily Sergeevich Nabokov, shot himself. He was an honest person, greatly respected at the institute.

8. Conversations with Kurchatov

In the second half of 1952, for a reason unknown to us, Romanov and I were summoned to Kurchatov. The meeting took place in the Laboratory of Measuring Instruments (presently, the Kurchatov Institute) in Kurchatov's huge office. I was most of all amazed to see that Kurchatov, who I had always considered to be only administering the science, this time gave us a concrete task of performing some computations aimed at some quantitative estimates.

I remember that he addressed us as 'lads', using 'you' in the informal form, which seemed to me impolite, compared with our conversations with Khariton.

I also remember that during our meeting L A Artsimovich entered the room, and they began quietly discussing something. Then suddenly they opened a hidden door, whose existence Romanov and I could not have suspected, passed into a room behind it, and stayed there for a while, talking.

Stored in my memory is also a large oil portrait of Stalin, in full height, in high boots.

As I think now, Kurchatov intended to check the validity of some data on energy release (why otherwise would he have summoned us?), possibly collected from abroad.

Having been given the task, Romanov and I went to some secret room supervised by the security department and performed our computations there. It is possible that our notes are still preserved somewhere.

To our surprise, when we returned and informed Kurchatov about our results, they left him dissatisfied, and he proposed that we come the next day to continue our computations.

On the next day, we once again carried out computations, talked with Kurchatov, and in the end managed to satisfy him somehow. I think that either our primary results were not up to his expectations or he wanted to be certain that there was no error. I am sure, however, that we were testing ideas not of his invention.

On the other hand, if the appearance of Artsimovich during the meeting was not accidental, then possibly the point was computing the amount of lithium-6 needed for a certain increase in the energy yield of the sloika or any similar 'device' unknown to us. It should be kept in mind that Artsimovich was the scientific head of lithium-6 production.

9. Tour of the Third Factory and preparations for the tests of RDS-6s

The immense respect enjoyed by the heads of theoretical departments Tamm, Sakharov, and Zel'dovich at KB-11 also translated to a considerable extent to their subordinates. This can explain the tour for theorists organized by Khariton to the 'sacred place' — the Third Factory, dealing with the assembly of prototypes of atomic bombs, where our sloika was also scheduled to be assembled.

The visit was begun not from the main entrance, but from the yard from which the ready output was delivered. My eyes were attracted by bright yellow hemispheres and blocks of TNT — the explosive used for implosion of fissile materials. As we walked further, we saw here and there black torpedoes for submarines lying on the floor. Apparently, low-power charges to be deployed in them were being assembled at that time. Periodically, we met marine officers wearing black tunics who were inspecting the production. Finally, we reached a large hall, where, on a high platform, our sloika was being assembled. Up to that point, only contours securing thin copper shells that would separate future layers of lithium deuteride and uranium had been installed. The shells were intended to divert heat released by radioactive tritium.

The visit was very enlightening for us, the theorists. We saw the design work of highly qualified personnel with an exclusive technical background. The developers of the main elements of RDS-6s and other bombs as well were V F Grechishnikov, S G Kocharyants, and N A Terletskii.

At the beginning of 1953, preparatory work to test RDS-6s was started at KB-11. At a very representative gathering of theoretical physicists and experimentalists, Sakharov informed everyone about the major questions to be solved during the tests.

First of all, it was necessary to measure the blast energy and learn about the robustness and the rate of the fusion reaction. To implement this, it was proposed that the following be measured:

— the time passing from the initiation to the beginning of the reaction in the device;

— fluxes of γ-rays and 14 MeV neutrons, the record of which allows assessing the rate of the reaction in the device over a hundred millionth fraction of second;

— the pressure and speed in the shock wave;

— the flux of γ-quanta from the radioactive cloud.

I was asked to relate the total energy release to the net flux of 14 MeV neutrons recorded by fluorine detectors using the reaction $F^{19} + n \to 2n + F^{18}$ with a threshold of 11 MeV. Several detectors, placed at various distances from the center of explosion, were intended to record the β^+-radioactivity of fluorine-18 with a half-life of 112 minutes.

The measurements on 12 August 1953 indicated that, on explosion, the yield was 6.3×10^{24} neutrons with an energy in excess of 11 MeV. This number turned out to be in good agreement with the expected total number of fast neutrons formed in a thermonuclear reaction of a charge with a power of 300–400 kt of TNT (see document Nos 22 and 34 in Ref. [8]). The relation between the energy release and net numbers of formed and leaving neutrons essentially relied on important experimental data obtained by Zysin's and Pogrebov's groups.

My other task was to estimate the influence of mixing between dense and light layers on the rate of fusion reactions based on values of the mixing indicator. As such, a γ-active Be^7 was used, forming in the reaction $Li^6 + d = n + Be^7$ and decaying through *K*-capture into Li^7 with the half-life of 53 days. Because 10% of the decay passes through the excited level of lithium-7,

$$Be^7 \to Li^{7*} \to Li^7 + \gamma\,, \tag{12}$$

with the radiation of the γ-quantum with an energy of 478 keV, the detection of Be^7 release after the explosion did not cause difficulties. The substantial release of Be^7 led to the conclusion that mixing insignificantly retarded the course of thermonuclear reactions.

Yet another of my tasks was to estimate the neutron flux in the light layers. Stable Co^{59}, specially deployed in the light layers as proposed by Sakharov, served as an indicator. Being hit during the explosion by neutrons, it transformed into β, γ-active Co^{60}:

$$\begin{aligned} &Co^{59}(n,\gamma)Co^{60} \to Ni^{60**} + \beta^- + \tilde{\nu}\,,\\ &Ni^{60**} \to Ni^{60} + \gamma_1 + \gamma_2\,, \end{aligned} \tag{13}$$

which, via β-decay (with a half-life of 5.3 years), converted into nickel-60 at its second exited level. From this level, nickel-60, through the almost instantaneous radiation of two γ-quanta with energies of 1.17 and 1.33 MeV, returned to its ground state.

Mysterious are the ways of the Lord. I successfully (and for the first time) measured the angular correlation of exactly these two cascade quanta in my graduate work of 1949–1950 in the laboratory of I M Frank. At that same time, one floor below, I Ya Barit, the supervisor of my work, was measuring the cross sections of $d-d$ and $d-t$ reactions.

The yield of Co^{60} recorded after the explosion by its β, γ-activity allowed judging the neutron flux density in the light layers and, accordingly, the rate of tritium formation there.

I may guess that this indicator, in addition to its relevance for mixing, was also dealt with at the test site by my friend and classmate E K Bonyushkin; unfortunately, I learned about it too late from his article devoted to Sakharov [14].

10. Ionization implosion as a step toward radiation implosion

The information dispatched by Fuchs in 1946 and 1948 contained two types of 'tube' ignition (see document Nos 11 and 31 in Ref. [7]). The second one assumed implosion by atomic bomb radiation of the intermediate two-liter primer composed of a deuterium–tritium mixture. On careful study, this variant could have become a setup of radiation implosion of a significantly larger amount of fuel.

Teller wrote in this respect in 1952 that the Teller–Ulam idea of radiation implosion "represents a comparatively small modification of the ideas known in a general form since 1946 (and used in the 'George' setup — *VR*). In essence, one needed only to add two elements: to explode a larger volume and to achieve stronger compression by preserving the explosive material cold as long as possible" [15].

Zel'dovich decided to consider the option from 1946, which appeared to be unworkable, and did not contain a promising setup for radiative implosion (see document Nos 95 and 123 in Ref. [7]).

Hence, even more precious was the elaboration in the Tamm group of other principles of the hydrogen bomb design proposed by Sakharov and Ginzburg, completely different from those used in the 'tube'. The ionization implosion of the nuclear fuel Li^6D and production of tritium were leading to a sharp increase in the rate of the fusion reaction. The computational task I recalled here fixed a substantial breakthrough made by our specialists in thermonuclear weapon development. The successful test on 12 August 1953 confirmed the correctness of the ideas and computations underlying its design.

The most valuable experience and firm understanding of the most complex questions pertaining to the thermonuclear explosion allowed our specialists to implement the 'floating in the air' and seemingly unfeasible idea of radiative implosion. The transition from ionization implosion to radiation implosion would be analogous to the American one, had they realized their 'Alarm Clock' design. But they failed to accomplish this, and thus granted us the priority in creating the first thermonuclear bomb.

The government recognized the construction of the hydrogen bomb as an immense success of Soviet science and industry. More than 400 members of scientific and scientific–technical staff became laureates of the Stalin Prize. For their exclusive service to the state, I E Tamm, A D Sakharov, V A Davidenko, E I Zababakhin, V K Bobolev, L D Landau, A P Aleksandrov, V F Grechishnikov, B P Konstantinov, A N Tikhonov, P Ya Antropov, V S Emel'yanov, and B S Pozdnyakov became Heroes of Socialist Labor. A A Bochvar, A P Zavenyagin, Ya B Zel'dovich, and E P Slavskii got the title twice, and B L Vannikov, N L Dukhov, I V Kurchatov, Yu B Khariton, and K I Shchelkin were awarded it thrice.[1]

This recognition demonstrated the major role of the USSR Academy of Sciences in creating the thermonuclear weapon.

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