

CONFERENCES AND SYMPOSIA

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Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (in commemoration of the 90th anniversary of Yakov B Zel'dovich's birth) (25 February 2004)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held in commemoration of the 90th anniversary of the birth of Yakov B Zel'dovich on February 25, 2004 in the conference hall of the P N Lebedev Physics Institute, RAS. The following reports were presented in the session:

(1) **V A Rubakov** (Institute for Nuclear Research, RAS, Moscow) *The problem of scale hierarchy in particle physics and cosmology*;

(2) **A A Starobinskiĭ** (L D Landau Institute of Theoretical Physics, RAS, Moscow) *The modern standard cosmological model and prospects for its development*;

(3) **R A Syunyaev** (Institute of Space Research, RAS, Moscow) *Cosmic background and the early universe*: *the first stars, the first galaxy clusters, and the secondary ionization of matter*;

(4) **V S Imshennik** (Institute of Theoretical and Experimental Physics, RAS, Moscow) *The neutrino corona of a protoneutrino star*;

(4) **S S Gershteĭn** (State Research Center 'Institute for High Energy Physics', Protvino) *Ya B Zel'dovich's contribution to modern particle physics*.

An abridged version of the last report is given below.

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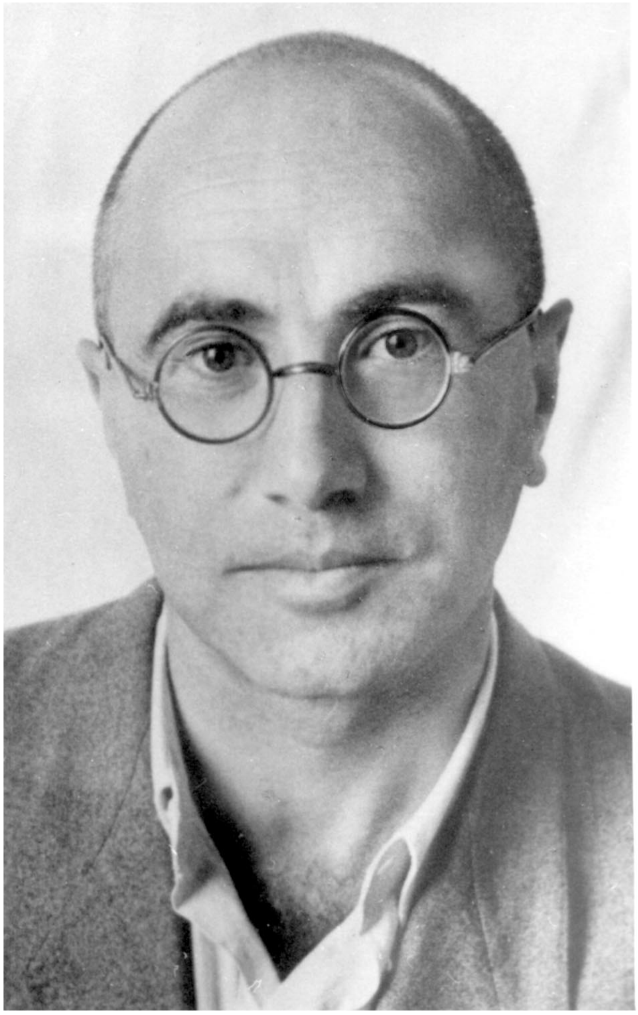
Ya B Zel'dovich's contribution to modern particle physics

S S Gershteĭn

1. Introduction

Yakov Borisovich Zel'dovich was perhaps one of the last versatile physicist of the previous 20th century, and his contributions to the various fields of science were fundamental. In the course of his life he changed his main areas of research several times, and each time he chose, demonstrating amazing intuition, the most interesting problems in which a scientific breakthrough could be expected.



Yakov Borisovich Zel'dovich
(08. 03.1914 – 02.12.1987)

In the early 1950s, elementary particle physics was just such an area. This was due, first, to the recent development of quantum electrodynamics (QED) and, second, to the discovery of a large number of new particles, pions, and many strange particles, whose classification had not yet been clarified. Zel'dovich's first works in elementary particle physics were devoted to the search for laws governing the production and decay of the newly discovered particles.

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2. Baryon and lepton numbers

After analyzing the decay of the lambda hyperon (at that time it was thought to belong to the V-particle class) into a proton and a pion, Zel'dovich in 1952 suggested the idea of a nuclear charge [1] corresponding to the law of conservation of heavy particles (nucleons and hyperons). In this way, he extended to hyperons the concept of a heavy charge, proposed in 1938 by E Stueckelberg for nucleons and later (in 1949 and 1952) discussed by E Wigner. (At that time Zel'dovich did not know about these works, since they were published in journals to which he had no access; the journals were *Helvetica Physica Acta* and *Proceedings of the American Philosophical Society*, respectively.) Roughly at the same time, A Pais extended the concept of a heavy charge to include hyperons and introduced what is today known as the 'baryon charge' (he also introduced the term 'baryons'). These ideas are fundamental to the modern classification of elementary particles.

In order to explain the absence of the $\mu^{\pm} \to e^{\pm}\gamma$ decay and neutrinoless double beta decay in experiments, Zel'dovich hypothesized (1953) that there must be a special conserved lepton number (or, as he called it, a 'neutrino charge') [2]. Contemporaneously with him, E Konopinsky and H Mahmoud, as well as D Marx, suggested using this concept. At that time only one type of neutrino (and its antineutrino) were known to exist. Hence, Zel'dovich suggested that the neutrino charges of the electron (e^-), the positively charged muon (μ^+), and the neutrino be assumed equal, and the same went for the neutrino charges of the positron (e^+), the negatively charged muon (μ^-), and the antineutrino, with the charges being opposite to those of the first group. In this case, the decay $\mu^{\pm} \to e^{\pm}\gamma$ and the double beta decay were found to be forbidden by the law of conservation of the 'neutrino charge', while the decays $\pi^- \to \mu^- + \nu$ and $\pi^- \to e^- + \tilde{\nu}$ were to be accompanied by the production of different particles: the neutrino and antineutrino, respectively. After publishing the results of L Lederman, J Steinberger, and M Schwartz experiments that proved the existence of two types of neutrinos, the electron neutrino and the muon neutrino, the 'neutrino charge' concept (or, to be precise, the concept of the 'lepton charge') was extended, and now we know of three families of leptons: (e^-, ν_e), (μ^-, ν_μ), and (τ^-, ν_τ), each of which has its own lepton charge (or lepton number).

What was most important then was that Zel'dovich stressed the profound difference between the nuclear (baryon) and neutrino (lepton) charges on the one hand, and the electric charge, on the other — the latter is the source of long-range (massless) electromagnetic fields [2]. What this means is that the *exact* conservation of electric charge corresponds to a local symmetry, thanks to which the electric charge being conserved becomes the source of a massless electromagnetic field. The absence of long-range fields generated by the baryon and lepton charges clearly indicates that conservation laws exhibit only approximate laws and are not exact. This problem interested Zel'dovich very much. Hence, he constantly stressed the importance of carrying out experiments on searching the neutrinoless double beta decay. Even today, this issue ranks among most important.

In 1957, B Pontecorvo [3] noted, then in connection with the single-neutrino scheme, that the most sensitive experiment that would verify the lepton number nonconservation amounts to searching for neutrino oscillations, because the distance over which oscillations caused by lepton number nonconservation occur is proportional to the amplitude rather than to the probability of the transition initiated by the 'superweak' interaction. (In the single-neutrino scheme, these oscillations had to transform into what is known as a sterile state: $\nu \to \tilde{\nu}_{st}$, which cannot be the cause of inverse beta decay.) Pontecorvo also noted that the presence of oscillations would have indicated that the neutrino has a nonzero rest mass. After the discovery of the muon neutrino and thereafter the tau neutrino, Pontecorvo's idea was extended to oscillations between neutrinos of different flavors. In the simplest variant, the $\nu_e \to \nu_\mu$ process was quantitatively examined in 1969 by Gribov and Pontecorvo [4] who predicted that, because of this process, a deficit of electron neutrinos in R Davis's experiments (having started shortly before) on recording solar neutrinos was to be observed, neutrinos that trigger the reaction $\nu_e + {}^{37}Cl \to {}^{37}A^* + e^-$. This deficit of solar (electron) neutrinos puzzled scientists for 30 years, but today we know why. This was one of the most remarkable discoveries of recent years. The discovery of oscillations of solar ν_e-neutrinos, $\nu_\mu \to \nu_\tau$-oscillations in atmospheric neutrinos, $\tilde{\nu}_e \to \tilde{\nu}_\mu$-oscillations in reactor neutrinos, and in accelerator experiments provided a consistent (within the experimental error) picture of oscillations between neutrinos of different flavors and made it possible to determine the absolute values of the difference of the squares of the masses of the neutrino eigenstates and the mixing angles. The sublepton charge nonconservation can be incorporated into the modern Standard Model. At the same time, refinement of the experimental data on neutrino oscillations and neutrinoless double beta decay may yield new information about lepton charge nonconservation, which in Grand Unified models is related to baryon charge nonconservation. All this confirms the fundamental importance for modern physics of the concepts of baryon and lepton charges introduced into particle physics by Zel'dovich.

3. Weak interaction. Baryonic lepton (leptoquark)

In the early 1950s, after the discovery of the decay $\pi \to \mu$, the decay of the muon, and the muon's capture by atomic nuclei, physics was confronted with a very intriguing question of whether the forces causing these processes are identical to the forces causing the beta decay of nuclei or, in other words, with the idea that weak interactions, whose only manifestation up to that point in time was beta decay, constitute a universal force. The idea was based on the fact that all processes mentioned above could be explained by a four-fermion interaction whose coupling constants coincided, by order of magnitude, with the coupling constant (G_F) of a similar interaction introduced by Enrico Fermi for explaining beta decay. The task in verifying this hypothesis was enormous, both theoretically and experimentally, all the more because by the beginning of the 1950s the very law of beta decay was not known. There were five variants of a four-fermion interaction leading to the $n \to p + e^- + \tilde{\nu}$ decay: the scalar (S), the vector (V), the tensor (T), the axial-vector (A), and the pseudoscalar (P). One of the variants (A or T) of the Gamow – Teller interaction was known to lead to allowed beta decay with the spin of the nucleus changing by 1. (Experiments in electron – neutral correlation erroneously pointed to the T variant.) There were also indications of an allowed $0 \to 0$ transition (${}^{14}O \to {}^{14}N^*$) for which a Fermi variant (S or V) was thought responsible. In this situation, Zel'dovich attempted to theoretically deduce the law of beta interaction. He said that the key idea in his reasoning was the requirement that the four-fermion interaction be renormalizable. (As is known, this idea later played a central role in building the electroweak theory.) Since the theory involving scalar mesons had been proved renormalizable, he assumed that these mesons could be the carriers of four-fermion interaction. (An important role in this assumption was also played by Zel'dovich's erroneous opinion that as a carrier of four-fermion interaction the vector meson cannot ensure that the allowed $0 \to 0$ transition comes about in beta decays.) Using the scheme proposed in 1936 by G Wentzel, whereby beta decay $n \to pe^- \tilde{\nu}$ proceeds according to the sequence of processes $n \to \tilde{\nu} + L$, $L \to p + e^-$ or $n \to e^+ + K$, $K \to p^+ + \tilde{\nu}$ (where L and K are the neutral and positively charged scalar bosons, respectively), Zel'dovich [5] pointed out that this scheme leads to the (V+T) law of beta decay (which at that time was believed to be the preferable one from the viewpoint of the existing experimental data). Soon, however, the experimenters, after analyzing the beta spectra in singly forbidden transitions, began to believe that the scalar (S) scheme rather than the vector (V) one was the Fermi variant in the law of beta decay. Only after parity nonconservation was discovered and the spiral neutrino hypothesis was proposed were Feynman and Gell-Mann [6] able in 1958 (the same was done independently by Sudarshan and Marshak [7]) to predict, on the basis of theoretical ideas, the correct (V−A) law of beta decay.

The paper [5] was Zel'dovich's first experience in the theory of beta decay. Today, it has been practically forgotten but still can be related to modern investigations. The point is that the L and K bosons in Zel'dovich's scheme carry baryon and lepton charges, i.e., are baryonic leptons (Zel'dovich used to call them nucleon isobars). The analogs of such particles in some Grand Unified theories are leptoquarks. According to Zel'dovich, such particles could manifest themselves in the form of resonances in ep scattering. Several years ago, in experiments with $e^{\pm}p$ scattering in the HERA collider, there were even indications of the existence of leptoquarks. However, further investigation did not corroborate these findings. But still it is possible to gather some information concerning the existence of leptoquarks (when the energy of the colliding particles is not sufficient to produce these particles directly) by studying experimentally (with high precision) the question of whether in the weak interaction laws, in addition to the (V, A) variants of the Standard Model, there are some others, say the T variant that emerges, according to Ref. [5], in the case of leptoquark exchange. Some indications of the admixture of the tensor variant were obtained in the experiments on radiative pion decay $\pi \to e\nu_e\gamma$ (V N Bolotov, V M Lobashev, et al.). This requires further substantiation, however. The modern limit on the scalar leptoquark mass comes out to $M_{LQ} > 113$ GeV c^{-2}.

4. Beta decay of the charged pion: $\pi^+ \to \pi^0 e^+ \nu$

The idea of the universal nature of weak interactions captured Zel'dovich's attention from the outset. Basing his reasoning on it, in 1954 he examined the earlier unknown process of beta decay of the charged pion: $\pi^+ \to \pi^0 e^+ \tilde{\nu}$ (or $\pi^- \to \pi^0 e^- \nu$) [8]. First of all, he pointed out that this decay can proceed only under the influence of the vector (V) variant of beta interaction and calculated the transition matrix element which proved to be equal to $\sqrt{2}$. The value in the $\pi^+ \to \pi^0$ transition amplitude corresponded to two possible routes of the transition, which are shown in Fig. 1. He also noted that this value can be obtained if, in accordance with the Fermi–Yang model, the isotopic triplet (π^+, π^0, π^-) consists of mirror nuclei comprised of nucleons and antinucleons. In this case, the wave functions for the nucleons and antinucleons in charged and neutral mesons must be the same and the matrix element for isotopic spin $T = 1$ is

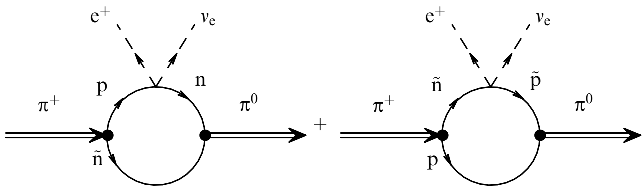


Figure 1. Beta decay of a charged pion: $\pi^+ \to \pi^0 + e^+ + \nu_e$.

$$M = \langle 1 \rangle = \sqrt{T(T+1) - T_3(T_3 - 1)} = \sqrt{2}.$$

(Obviously, such a result is also valid for the quark structure of pions, assuming the universal nature of weak interactions and isotopic invariance.)

The relative probability of the beta decay of the pion, calculated by Zel'dovich, proved to be very small: $\mathrm{Br}(\pi^+ \to \pi^0 e^+ \nu) \simeq 10^{-8}$, and in 1954 there was little hope of even recording this process in experiments. Measuring the probability of beta decay became especially important in connection with the verification of the law of conservation of vector current (the CVC law), which will be discussed later. This fact forced experimenters to find ways to record the process and to measure its probability. The first to record it in 1962 was Yu D Prokoshkin's group at the Laboratory of Nuclear Problems at JINR [9], and C Rubbia's group at CERN [10]. After a number of refinements (including the values of the mass difference of the charged and neutral pions, the π^+ lifetime, and the vector coupling constant taken from the $0 \to 0$ transitions in the beta decay of nuclei) were carried out and sufficient statistics on pion beta decay was gathered, it was found that the measured probability of the process coincided, to within 3%, with the theoretical value. At present, precision measurements of the probability of pion beta decay are of great interest since they open the possibility of refining the value of the matrix element V_{ud}, which determines the weak $u \to d$ transition in quarks. In the case of the pion beta decay, this process is not complicated by the strong interactions of the nucleon inside the nucleus, while refinement of V_{ud} can indicate whether contemporary experimental data has outgrown, so to say, the Standard Model. At present, the probability of pion beta decay has been measured in the Swiss meson factory at SIN to within 0.3%. Such an accuracy exceeds that required for isotopic invariance, if the latter is to be judged by the relative mass difference of the charged and neutral pions:

$$\frac{m_{\pi^\pm} - m_{\pi^0}}{m_\pi} \simeq 3\% .$$

But, as Zel'dovich noted in his earlier paper [11], this mass difference in the Fermi–Yang model is related to the additional Coulomb proton–antiproton interaction in the π^0 meson and reduces the meson's mass. (Zel'dovich's viewpoint on the origin of the mass difference in the pions remains valid in the quark model, since charged pions consist of quarks with like electric charges, while the neutral pion consists of quarks with unlike charges.) Since the Coulomb forces are long-range, creating the difference in mass of the charged and neutral pions, they are unable to substantially influence the identical nature of the wave functions of the particles comprising the pions because the latter are determined by the short-range strong interaction. (A similar situation occurs for the wave functions of the 'mirror nuclei' belonging to the same isotopic multiplet.) Hence, the data on pion beta decay can be used for obtaining the most exact information about the magnitude of the matrix element V_{ud}.

5. Meson corrections in the theory of beta decay and the CVC law

A characteristic feature of Zel'dovich's turn of mind was his belief in the beauty and symmetry of the fundamental laws of nature. He believed that the violation of this symmetry is due to certain side effects. Hence, when it was found that the ratio of the Gamow – Teller and Fermi beta decay constants is close to unity (precisely, $G_{G-T}/G_F \simeq 1.3$), Zel'dovich assumed that for a 'bare' nucleon this ratio is exactly unity, while all deviations from this figure are caused by pion corrections. Our calculations within the scope of the S and T variants of beta decay, known at that time, only corroborated this assumption. At the same time, for the vector variant it was found that with allowance for the pion beta decay earlier examined by Zel'dovich, all meson corrections cancel out and the vector coupling constant is not renormalized for strong interaction (in direct analogy with the electric charge of the proton). The beauty of this analogy appealed to Zel'dovich so much that, despite the existing erroneous idea that there could be no V variant of the beta interaction, in our joint paper [12] we concluded that, "While it is of no practical importance, it is methodically interesting that in the case of the vector (V) variant of the interaction one should expect that

$$g_V(\text{bare}) = g_V(\text{effective})$$

identically in any order in the meson–nucleon coupling constant.... Such a result could be predicted by analogy with the Ward theorem which refers to the interaction between a charged particle and an electromagnetic field; in this case, the virtual processes involving the particles do not lead to renormalization of the electric charge of the particle".

Later, after the discovery of the universal (V – A) interaction, Feynman and Gell-Mann arrived at the same conclusion. They noted that the vector constant of beta decay coincides to within 2% with the constant of muon decay [6]. (Today we understand that this difference is due basically to the Cabibbo angle: $G_V^{\beta} = G\cos\Theta_c$.) To justify their conclusion, they introduced, as a *hypothesis*, the coupling of the charged vector current isotopically of pions and the vector current of leptons, writing the first in the form of the vector part of electromagnetic current rotated in the isotopic space. Actually, this hypothesis was superfluous, since the presence of such a current followed directly from the beta decay of the charged pion examined by Zel'dovich. In 1958, L B Okun' described our work at an international conference, as a result of which Feynman and Gell-Mann at once chivalrously acknowledged our priority and thereafter always cited our paper [12].

At the Rochester Conference on High-Energy Physics, held in 1960, Feynman said, "The idea that, if there is a vector current in β-decay this current could be made to be conserved, was first suggested by Gershtein and Zeldovich. We were not familiar with that when Gell-Mann and I were working it out".

The discovery of the universal (V – A) interaction led to the hypothesis, expressed by O Klein in 1938, that the weak interaction between charged currents may be carried by vector $W^{\pm}$ bosons. Since electromagnetic interaction is also carried by vector particles (photons) there is the question of why vector fields are carriers of interactions. Actually, the answer was given in a work by Ch Yang and R Mills, according to which the conserved charges and their currents are necessarily sources of vector gauge fields. The discovery of the law of conservation of vector current (the CVC law) served as an indication that weak interactions must be described on the basis of the Yang – Mills gauge theory, while the analogy of weak and electromagnetic interactions almost immediately led to the idea of unifying these interactions (see Salam and Ward's article [13]). This approach eventually led to the elaboration of the gauge theory of electroweak interactions. Later on, the idea of gauge fields was also applied to strong interactions. In the simultaneous (and independent) works of N N Bogolyubov, A N Tavkhelidze, and B A Struminskiĭ, as well as M Hahn and Y Nambu, it was hypothesized that triplets of quarks of each flavor exist and they differ in a special conserved quantum number (called color). Hahn and Nambu assumed that this characteristic constitutes a conserved *charge* which takes on three values and generates eight gauge fields (gluons). The development of this idea led to the creation of quantum chromodynamics and the general principle of building gauge fields.

CVC also stimulated the development of such new fruitful areas of research as vector dominance, partial conservation of axial currents (PCAC), and current algebra. The new technique provided the means for a rigorous substantiation of Zel'dovich's hypothesis that deviations of the ratio G_A/G_V from unity are due precisely to pion corrections.

CVC is one of the main building blocks of the modern theory of electroweak interactions, which (among other things) makes it possible to determine the weak vector charge of quarks.

6. The hypothesis for the existence of neutral currents and the means to observe them

In 1959, even before the electroweak theory was postulated, Yakov B Zel'dovich named the effects in which weak neutral currents, which do not conserve parity, could manifest themselves [14]. One of these was the rotation of the plane of polarization of light in the scattering by atoms, and the other was the asymmetry that emerges in the scattering of longitudinally polarized $e^{\mp}$ (or $\mu^{\pm}$) by nuclei. Later on, both effects were used to verify the Salam – Weinberg theory of electroweak interactions. The first effect was observed thanks to the enhancement of the rotation of the plane of polarization in heavy atoms (pointed out by M A Bush'ya and I B Khriplovich) in the refined and ingenious experiments conducted by L M Barkov and M G Zolotarev in Novosibirsk, and the second was observed in experiments in electron scattering at SLAC and muon scattering at CERN.

It was Zel'dovich's work that prodded us in 1962 to search for effects caused by neutral currents in experiments with medium-energy neutrinos [15]. There was no doubt that neutral currents, if they exist, were to be discovered at high energies by muonless neutrino events in the neutrino experiments that were at that time being set up at CERN. (Neutral currents were indeed observed for the first time in high-energy neutrino experiments. But this happened only 11 years later, in 1973.) For the effect caused by neutral currents we selected the excitation of nuclear energy levels in neutrino (or antineutrino) scattering by nuclei. The selected example of neutrino excitation of the energy levels of a lithium nuclei proved to be unsuccessful from the experimental viewpoint. However, an effective way of recording the process of neutrino dissociation of a deuteron was established in later work by Yu V Gaponov and I V Tyutin. It was this process that played the crucial role in the experiments conducted at the Canadian SNO facility in order to verify the existence of oscillations of solar neutrinos and the validity of the standard model of the sun.

7. Electromagnetic interactions under parity violation

Examining the electromagnetic interactions of particles under breakdown of spatial parity, Zel'dovich discovered a new specific characteristic of particles that corresponded to the interaction $V \sim \mathbf{s}\,\mathbf{j} \sim \mathbf{s}\,\mathrm{rot}\,\mathbf{H}$, where $\mathbf{s}$ is the particle's spin, and $\mathbf{j}$ is the electromagnetic current [17]. By analogy with the monopole moment, he named this characteristic the 'anapole' moment and provided a pictorial model of an anapole. While the model of the monopole moment is a spherical capacitor whose electric field is detected when a charged particle lands into the area between the plates, the model of the anapole moment is a solenoid folded into a torus along whose surface an electric current flows, so that the magnetic field acts only on the current inside the solenoid. (Interestingly, there appears now indication that similar structures may be observed in some crystals.)

Using the example of a lambda hyperon, Zel'dovich produced a graphic explanation of why in the event of violation of P-parity (which leads to asymmetry in the decay) and conservation of CP-symmetry no electric dipole moment is generated in the particle, and pointed out that the discovery of an electric dipole moment may yield important information about the nature of CP-symmetry violation [18].

The most precise experiments currently limit the dipole moment of the neutron from above by the magnitude of $d < 0.63 \times 10^{-25} e$ cm (V M Lobashev et al.). These experiments were done based on the method of ultracold neutron confinement, proposed by Zel'dovich [19] and first implemented by F L Shapiro and his colleagues at JINR (Dubna). (The electromagnetic method of neutron confinement was suggested by V V Vladimirskiĭ.) The progress in the experimental detection of the electric dipole moment (or in substantially lowering the upper limit on its existence) is of great interest for establishing the nature of CP-symmetry violation. Hence the great importance of the experiments conducted at present.

8. Experiments in verifying QED at small distances

In 1955, Zel'dovich pointed out that important information about the limits of applicability of QED can be obtained from exact measurements of the magnetic moment of an electron [20]. A year later, V B Berestetskiĭ, O N Krokhin, and A K Khlebnikov [21] noted that with the same accuracy in measuring the magnetic moment of the muon one can achieve a 200-times larger limit on the QED cutoff limit (accordingly to the mass ratio m_{μ}/m_{e}). A recent $(g-2)$ experiment conducted at the Brookhaven National Laboratory in precision measurements of QED corrections to the magnetic moment of a muon became the center of attention because of the apparent deviations of its results from those that follow from the theory (which, true enough, uses the experimental data on the contribution of hadrons to vacuum polarization). At present, these deviations have been reduced and today do not exceed two standard errors, so that the alarm was probably false.

In the above-cited paper by Zel'dovich there was a remark that the best direct way to verify the validity of QED at small distances would be experiments with colliding electron beams, but he assumed that this was hardly possible because of low beam intensities. Later Gersh I Budker wrote that it was this remark that encouraged him to build a collider. One of the main goals of the experiments conducted in the first electron–electron collider built at the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences in Novosibirsk was to verify the validity of QED. Thus, the brief remark made by Zel'dovich contributed to the creation of modern collider techniques (at least in our country). [1]

9. Five-quark baryons

Zel'dovich became enthused when he found out about the quark hypothesis. His review, titled "Quarks for pedestrians" and published in *Uspekhi Fizicheskikh Nauk* in 1965 [23], contributed greatly to the popularization of this idea. In their joint paper [24] published in 1966, Zel'dovich and Andreĭ Sakharov discussed the possibility of the existence of five-quark baryons (recently there have been reports about the detection of such baryons, which are actively being discussed).

10. Exotic nuclei and neutron matter

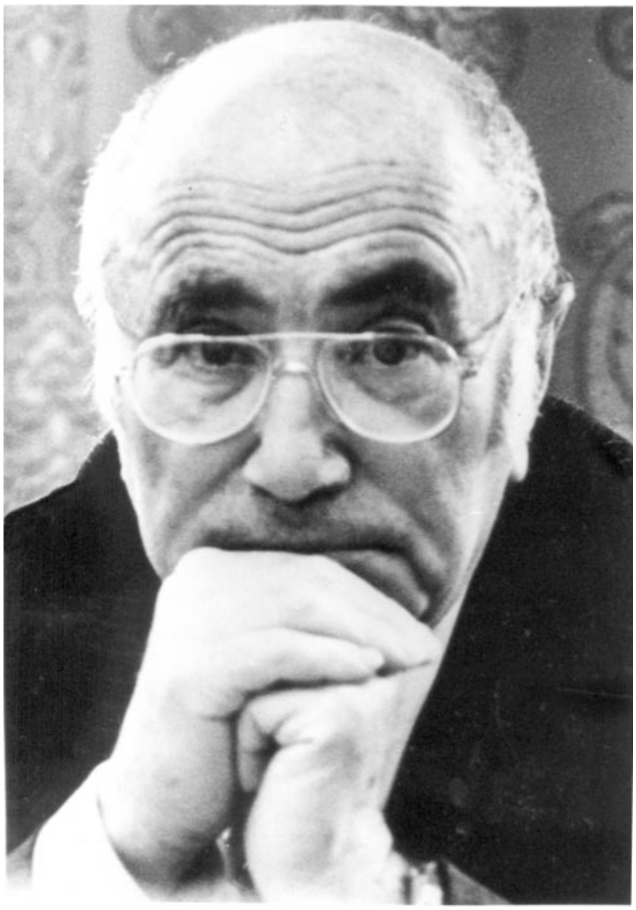
The work that Zel'dovich did in nuclear physics had a great impact on modern research. He predicted the existence of a number of neutron-enriched nuclei, i.e., ^{8}He nucleus. Many of the isotopes he predicted have been discovered, and beams of ^{8}He and other radioactive nuclei are already used in research in the KEK experiments in Japan and are planed for use at other scientific centers. Yakov Zel'dovich assumed that neutron matter, i.e., nuclei consisting only of neutrons or with a small admixture of protons, can exist. However, he was unable to prove his assumption by rigorous calculations. Nevertheless, the discovery of unstable nuclei, such as ^{10}He, ^{4}H and others (A A Korsheninnikov et al.) are, probably, proof of the validity of Zel'dovich's hypothesis. Another indication of this is that the unstable $Z = 108$ isotope containing the largest number of neutrons among nuclei with the same atomic number (discovered by Yu Ts Oganesyan's group at JINR) has the longest lifetime.

[1] One of the many examples of how Zel'dovich's remarks were implemented in carrying out experimental work of fundamental importance is his paper [22] on the possibility of measuring the circular polarization of gamma quanta by their reflection from a magnetized ferromagnet. The ingenious use of this method made it possible to determine the helicity of the electron antineutrino in the experiments by M Goldhaber et al. and to measure, with unique precision, the effects of parity violation in nuclear processes (V M Lobashev, V A Nazarenko et al.).

11. Muonic catalysis

Zel'dovich laid the ground for the theory of various mesomolecular phenomena in hydrogen and the muonic catalysis of nuclear fusion reactions. The first to express the idea of muonic catalysis was A D Sakharov (1948), and he did this immediately after the discovery of the muon. He pointed out that there must be a fusion reaction in the mesomolecular ddμ ion after its formation. However, in estimating the probability of mesomolecule production Sakharov made an error by assuming that in the process of collision of the dμ mesoatom with the deuterium nuclei, which leads to the formation of a mesomolecule, the binding energy of the mesomolecule is transferred to the emitted gamma quantum. In 1954, Zel'dovich, not knowing about Sakharov's classified work, noted that the main mechanism of mesomolecular production is the transfer of energy to the atomic electron (which occurs with a probability 100 to 1000 times higher than the radiative transition). Moreover, he made a very useful remark about the possibility of resonance formation of mesomolecules when they have an excited level with a low binding energy. This remark served as a clue for the temperature dependence of muonic catalysis in deuterium, discovered by V P Dzhelepov et al. at the Laboratory of Nuclear Problems (JINR) and led to the discovery of resonance synthesis of dtμ mesomolecules accompanied by the formation of a mesomolecular complex. Later on, when the calculations of L I Ponomarev and his colleagues revealed the existence of a loosely bound state in the deuterium – tritium mesomolecule dtμ, it became possible to predict that in the deuterium – tritium mixture one muon can perform more than 100 acts of nuclear fusion in the course of its lifetime (~ 2 μs) [25]. As a result, the study of muonic catalysis became the subject of many years' theoretical and experimental research at the accelerators of JINR and the Petersburg Nuclear Physics Institute with the participation of the Russian Scientific Center 'Research Institute of Experimental Physics' and at all meson factories worldwide (in Switzerland, Japan, the USA, and Canada). The results of this research make it already possible to design a source of 14-MeV neutrons with an intensity up to 10^{14} cm^{-2} s^{-1} on the basis of muonic catalysis.

After L Alvarez discovered (through experiments) muonic catalysis in 1957, Zel'dovich and Sakharov in their joint paper [26] estimated the effective cross section of the transfer of the muon from the proton to the deuteron, the rate of formation of pdμ mesomolecules, and the probability of nuclear fusion $p + d \to {}^3He$ in pdμ mesomolecules with energy transferred to the muon. (This process was actually used in the experimental discovery of muon catalysis.) In his next paper [27], Zel'dovich pointed out that the maximum efficiency of muonic catalysis is in any case limited by the effect of the muon attachment to helium (i.e., the capture of the muon on the mesoatomic orbit of the helium nucleus formed as a result of nuclear fusion). It is this limit that makes it impossible to obtained more than 200 acts of nuclear fusion per muon in muonic catalysis in a deuterium – tritium mixture.



One of the last pictures of Yakov Borisovich Zel'dovich.

12. Synthesis of particle physics and cosmology

In the mid-1960s, after the discovery of pulsars and the cosmic background, Yakov Zel'dovich's main scientific interests shifted to astrophysics and cosmology. Here too, having gained fundamental results in particle physics, he laid the ground for one of the main achievements of 20th century physics — that is, the synthesis of elementary particle physics and cosmology. Thanks to this synthesis, we can extract important information about elementary particles from cosmological data, and cosmology has become the 'proving ground' for verifying various Grand Unified models.

In 1965, in a paper written in collaboration with L B Okun' and S B Pikel'ner [28], Zel'dovich, basing his reasoning of the model of a hot universe, estimated the possible concentration of free quarks in the environment and initiated the experiments conducted by V B Braginskiĭ et al. in the search for such quarks (experiments in which Zel'dovich actively participated) [29]. The negative result of these experiments, which established the upper limit on the concentration of free quarks at a value smaller by several orders of magnitude than the predicted value, proved to be the main argument in favor of quark confinement. In 1966, Zel'dovich used cosmological data to estimate the upper limit on the total mass of stable neutrinos [30]. This estimate played an important role for many years, since it improved the limits on the muonic and tau neutrinos obtained in laboratory experiments by a factor of 1000 and almost 100,000, respectively. At present, since neutrino oscillations have been discovered and it has been found that the maximum difference in the masses of neutrinos of different flavors does not exceed 0.1 eV and that the limit on the mass of the electron neutrino found from the beta decay of tritium is smaller than 2.5 eV, this estimate is of historical interest only. This work [30] was one of the first that contributed to the synthesis of particle physics and cosmology. Of similar historical value are

Two of the main creators of Russia's nuclear shield, Yakov Borisovich Zel'dovich and Yuliĭ Borisovich Khariton. The picture was taken at the joint 150th anniversary: 70 years to Zel'dovich, and 80 years to Khariton (Institute of Chemical Physics of the USSR Academy of Sciences, Moscow, 1984).

the works of Zel'dovich and his colleagues on the subject of a neutrino universe, which were done immediately after the erroneous experimental indication that the neutrino mass $m_{\nu} \simeq 20$ eV. On the other hand, the estimate made by M Yu Khlopov and Ya B Zel'dovich [31] of the concentration of the relict magnetic monopoles at which the monopoles existed immediately after the Big Bang has not lost its importance even today. The fact that it was found that there are no monopoles with a concentration that is many orders of magnitude lower than the value provided by this estimate became one of the main arguments in favor of changing the scenario of the evolution of the early Universe.

Research in the field of particle physics and QED had prepared Zel'dovich for his important discoveries in cosmology. For instance, examining the creation of positrons in the field of supercritical nuclei ($Z > 137$) [32], he arrived at the idea (in his famous work done with A A Starobinskiĭ and L P Pitaevskiĭ) that particles and antiparticles can be created in a strong gravitational field — an effect that could fill the 'empty' early Universe with matter. Here I am unable, in view of the lack of space, to write about the triumph of many of Zel'dovich's ideas in astrophysics and cosmology, nor about the many candidates for 'black holes' discovered by his assumption that matter emits X-ray radiation in black hole accretion, nor about the confirmation of the spectrum of primary fluctuations by the data from observations of the large-scale structure of the Universe, nor about the Syunyaev–Zel'dovich effect which makes it possible to measure the peculiar velocities of distant galaxies, nor about many other topics. All this merits a special article. One can only marvel at how much Yakov Zel'dovich achieved in areas into which he stepped when he was already older than 50, when, in the opinion of many, the creative potential of theorists begins to die away. I would only like to mention the paper by Syunyaev and Zel'dovich [33], in which they noted that the results of measurement of the very small asymmetry of cosmic background radiation (angles smaller than 1°) yield unique information about the cosmological parameters. The sensational results of such measurements done recently at the Boomerang facility and especially in the WMAP experiment have shown that the density of the customary baryon matter amounts only to 4–5% of the average density of matter in the Universe. Together with the dark matter of unknown (nonbaryonic) origin concentrated in galaxies and galaxy clusters, it amounts to less than 30% of the average density, while about 70% is concentrated in the evenly distributed 'dark energy', whose origin is also unknown. Solving the 'dark-matter' and 'dark-energy' riddle constitutes a challenge for science in the 21st century. The answer to this riddle can be obtained only along the lines of the synthesis of the particle physics (both accelerator and non-accelerator) and cosmology, a synthesis whose foundation was laid by the work of Yakov Borisovich Zel'dovich.

Thus, most of the ideas expressed by Zel'dovich 30 to 50 years ago and the results of his research still occupy a central place in the theoretical and experimental work in modern particle physics and its crossroads with cosmology.

I would only like to add that many fundamental results were obtained by Ya B Zel'dovich at the time when he was almost entirely occupied by work at various secret facilities with great responsibilities attached to this work. He contributed greatly (and in many cases his contribution was crucial) to the effort of building a 'nuclear shield' for Russia (then the Soviet Union). His generosity in providing his pupils and colleagues with ideas, his support given to new areas of research in science, and the help he gave to young scientists only stresses how unique Yakov Borisovich Zel'dovich was.

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