YAKOV BORISOVICH ZELDOVICH

Selected Works of Yakov Borisovich Zeldovich, Volume I

Chemical Physics and Hydrodynamics

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SELECTED WORKS
OF
YAKOV BORISOVICH ZELDOVICH

Ya. B. Zeldovich, ca. 1946

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Preface to the English Edition of the Selected Works of Ya. B. Zeldovich

There has been no physical scientist in the second half of the twentieth century whose work shows the scope and depth of the late Yakov Borisovich Zeldovich. Born in Minsk in 1914, he was the author of over 20 books and over 500 scientific articles on subjects ranging from chemical catalysis to large-scale cosmic structure, with major contributions to the theory of combustion and hydrodynamics of explosive phenomena. His passing in Moscow in December of 1987 was mourned by scientists everywhere. To quote Professor John Bahcall of the Institute for Advanced Study: "We were enriched in Princeton as in the rest of the world by his insightful mastery of physical phenomena on all scales. All of us were his students, even those of us who never met him." In his range and productivity, Zeldovich was the modern equivalent of the English physicist Raleigh (1842-1919) whose name is associated with phenomena ranging from optics to engineering.

The breadth of Zeldovich's genius (characterized as "probably unique" by the Soviet physicist Andrei Sakharov) was alternately intimidating or enthralling to other scientists. A letter sent to Zeldovich by the Cambridge physicist Steven Hawking, after a first meeting in Moscow, compares Zeldovich to a famous school of pre-war mathematicians who wrote under a single fictitious pseudonym: "Now I know that you are a real person, and not a group of scientists like Bourbaki."

No selection from an opus of such scope can capture its full range and vigor. While basing ourselves primarily on the Russian edition, published by the Soviet Academy of Sciences in 1984–1985, we were delayed repeatedly as important and hitherto untranslated (but frequently cited) papers were brought to our attention as clearly warranting inclusion. Zeldovich played a major role in re-editing the Russian edition before translation and in choosing additional material for the present work. All told, this edition is approximately 15% longer than the Russian edition and the second volume contains one largely new section: *Physics, Personalia*, including impressions of Einstein and Landau, and ending with *An Autobiographical Afterword.*

Because he wrote in Russian during a period when relations between that culture and the western world were at an historically low ebb, international recognition for Zeldovich's achievements were slower to arrive than merited. Within the Soviet Union his accomplishments were very well recognized, in part, due to his major contributions to secret wartime work. As the world's leading expert on combustion and detonation, he had naturally been drafted early into the effort for national survival. He had written entirely prescient papers in 1939 and 1940 (included in this volume) on the theoretical possibility of chain reactions among certain isotopes of uranium. The physicist Andrei Sakharov wrote that "from the very beginning of Soviet work on the atomic (and later the thermonuclear) problem, Zeldovich was at the very epicenter of events. His role there was completely exceptional." Zeldovich was intensely proud of his contributions to the wartime Soviet scientific effort and was the most decorated Soviet scientist. His awards include the Lenin Prize, four State Prizes, and three Gold Stars.

As a corollary to internal recognition, of course, Zeldovich's scientific work was burdened by the enormous handicaps of isolation, secrecy and bureaucracy in a closed society, made more extreme for him by restrictions due to defense work. He was not permitted to attend conferences outside of the Soviet Block until August 1982 at age 68, when he delivered an invited discourse "Remarks on the Structure of the Universe" to the International Astronomical Union in Patras, Greece. When asked then by this Editor when he was last out of the Soviet Union, he answered without hesitation "sixty eight years ago," i.e., only in a prior life. Previous to that meeting, his access to preprints, normal correspondence, all of the human interchange of normal scientific life, were severely circumscribed with contacts increasing as he moved out of defense work. Then, as international relations improved, international acclaim followed. Elected in 1979 as a foreign associate of the U. S. National Academy of Sciences, he had already been made a member of the Royal Society of London and other national scientific academies. Despite having turned relatively late in his scientific career to astrophysics, his accumulated achievements in that area, rewarded with the Robertson Prize of the U. S. National Academy of Sciences for advances in cosmology, put him among the world's leading theoretical astrophysicists.

The science is of course more interesting than the honors it wins for the scientist. Let me note just two items from astrophysics, my own specialty, where Zeldovich showed extraordinary vision and imagination. He argued shortly after their discovery that quasars were accreting black holes, and that the universe was likely to have a large-scale porous structure, anticipating in both cases the standard paradigms for interpreting these cosmic phenomena. In addition, he was among the first to realize that the early universe could be used as our laboratory for very high energy physics, leaving as fossils strange particles and cosmic microwave background fluctuations.

If the matter is more important than the recognition, it was also true, for Zeldovich in particular, that the manner was as significant as the matter. He always proceeded by a direct intuitive *physical* approach to problems. Even in areas where his ultimate accomplishment was a mathematical formulation adopted by others such as the "Zeldovich number" in combustion theory or the "Zeldovich spectrum" and the "Zeldovich approximation" to linear perturbations in cosmology, the reasoning and approach are initially and ultimately physical and intuitive. His view was that if you cannot explain an idea to a bright high school student, then you do not understand it. He backed up this conviction, and his interest in the education of young scientists, with the book *Higher Mathematics for Beginners*, which presented in a clear and intuitive way the elementary mathematical tools needed for modern science. Here again Zeldovich was in good company; from Einstein to Feynman, the greatest physicists have felt that they could and *should* make clear to anyone who cared to listen, the excitement of modern science.

The value of Zeldovich's papers, unlike those of most scientists, has outlived the novelty of his results. But, inevitably, one must question the logic of republishing scientific papers. Is not all valid scientific work included in and superseded by later work. Of course there is a value in collecting, for the record, in one place the major works of a truly great scientist. The fact that we include with each paper, commentaries (often revised from the Soviet edition) by the author on the significance of these papers will further enhance their value to historians and philosophers of science. But Zeldovich was almost above all else the teacher, the founder of a school of today's world famous scientists and author of widely read texts at all levels. He had strong views on *how* science should be done and how it should be taught. To him, the "how" of the scientific method, of his own scientific method, was central; it was what he most wanted to communicate in making his work available to a broader audience.

We are happy to be able to provide a complete enlarged edition of the works of this great scientist for the English-speaking world. We would like to thank the Academy of Sciences of the USSR for permission to utilize (a) *Izbrannye Trudy: I. Khimicheskaĭa Fizika i Gidrodinamika* and (b) *II. Chastitsy, Iadra, Vselennaĭa*, but especially offer our thanks to Professors G. I. Barenblatt and R. A. Sunyaev for their dedication and expertise in closely reading (Volumes One and Two, respectively) the entire manuscript in its English edition.

J. P. Ostriker
19 January 1990

Я. Б. ЗЕЛЬДОВИЧ

Избранные труды

ХИМИЧЕСКАЯ ФИЗИКА И ГИДРОДИНАМИКА

Под редакцией
академика Ю. Б. ХАРИТОНА

ИЗДАТЕЛЬСТВО «НАУКА»
МОСКВА
1984

The Scientific and Creative Career of Yakov Borisovich Zeldovich

1. Introduction

The Editors feel that this volume of selected works by Ya.B. Zeldovich, *Chemical Physics and Hydrodynamics*, as well as a second volume, *Particles, Nuclei, and the Universe*, will be of great scientific interest to the reader, be he a chemist, physicist, or astronomer.

The present edition, undertaken in connection with the seventieth birthday of Academician Yakov Borisovich Zeldovich, is an original exposition of the now-classical results of a scientist, results which remain actual even today. Some were obtained by Ya.B.[1] as early as the thirties, before World War II, while many papers were published between 1947–1986. Some have already become bibliographical rarities, as, for example, "The Theory of Combustion and Detonation of Gases," published in 1944 and included in this volume. In spite of the fact that a significant part of the results presented here is widely known, having been incorporated into textbooks and monographs, we can heartily recommend these collected works to scientists, graduate and undergraduate students; the material offered here has not become obsolete not only because we have included some of Ya.B.'s most recent papers. In this introductory article and in the commentaries to individual papers the present state of each problem is briefly described and references are made to the most important later works.

However, most important for the reader, especially the young reader, is the style of presentation in these original articles by Ya.B. By studying these papers one may not only obtain specific information about a particular question, but also learn about the formulation of scientific problems and the creative scientific process. In the original papers the "scaffolding" used by the author during the "construction of the building" is still there. One may see just which questions were left unclear or solved erroneously by his predecessors, and what obstacles, psychological and scientific, the author, Ya.B., had to overcome to produce new results. One can even see his emotions as he wrote a paper or a monograph. In textbooks and modern monographs, as a rule, there predominates a natural tendency to "straighten up" the actual course of development of science, to show rather how, in retrospect, it should have proceeded. The original publications, and in particular the papers by Ya.B. collected here, show how science is actually built.

In terms of their subject matter the two volumes are basically independent, and so one may envision a physical chemist interested only in this first part or an astronomer interested only in *Particles, Nuclei, and the Universe*. A certain connection between the two volumes does, however, exist. The present volume

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[1] In this book we will use the abbreviation Ya.B., as he is often referred to in conversation by his friends and colleagues.

contains a biographical outline describing all of Ya.B.'s creative life, including general characterizations of papers which, in terms of content, are related to the next volume. The second book also includes several articles by Ya.B. on general subjects and his scientific autobiography.

This introductory article has turned out much longer than those in many other anniversary editions. Even if this is not justified, then at least it is explained by the unusual breadth of Ya.B.'s scientific interests. Indeed, where else can one find a scientist who, having begun with problems of adsorption, catalysis, and chemical kinetics, moves on to ignition and combustion of gases and powders and detonation, then to nuclear chain reactions, critical mass, and nuclear power, then immerses himself in questions of elementary particle physics, and, finally, plunges into cosmological structure and the first moments of the creation of the universe ... and in each area brings about a fundamental breakthrough and leaves several generations of thankful students and colleagues to continue to develop the results from the heights already achieved ... participates in experiments to verify predictions he has made and often waits many years for someone to discover the predicted phenomenon ... and takes an active part in the technological realization of possibilities revealed in his theoretical calculations, participating in the direction of a large collective of theorists and experimentalists ... and generalizes the results of his work in numerous monographs.

The Editors of this book felt obliged to do everything possible to help the reader, especially the younger reader, to extract a maximum of useful information from Ya.B.'s works. We felt we could best do this by describing in detail the creative course of Ya.B.'s life and work.

Ya.B. was born on March 8, 1914, at the home of his grandfather in Minsk, but after mid-1914 the family lived in Petrograd. Ya.B. began his scientific career when he was seventeen years old. After graduating from high school at fifteen, he entered a school for laboratory assistants associated with the Leningrad Institute, "Mekhanobr."[†] The students were paid stipends, and to repay them they had to spend at least three years on assigned jobs. It so happened that the students were taken on an excursion to the Physico-Technical Institute. Ya.B. liked it there, and he in turn was liked.

The head of one of the Institute departments, S. Z. Roginskiĭ (later a Corresponding Member[‡] of the USSR Academy of Sciences), became interested in the serious questions asked by the youth. They agreed that Ya.B. would work at the Institute for a couple of hours after classes. The date that this work began is recorded as March 15, 1931. The head of the chemical physics section, N. N. Semenov, assigned Ya.B. a report to present at a seminar: "Transformations of Ortho–Para-Hydrogen in the works of the German physical chemist Bonhöffer." Ya.B. showed both enthusiasm and understanding. First impressions had been confirmed and soon the influ-

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[†] An institute of mechanical, as opposed to thermal, processing of solids.

[‡] Members of the USSR Academy of Sciences (AS USSR) fall into two categories: full members (academicians) and corresponding members.

ential director of the Physico-Technical Institute, Academician A. F. Ioffe, signed a letter to "Mekhanobr" requesting that they "release Ya.B. to science." The transfer (*via* the unemployment office, which still existed in the USSR!) was effected, and on May 15, 1931, Ya.B. began his work in the chemical physics section which, by that time, had become an independent institution, the AS USSR Institute of Chemical Physics.

Ya.B. was assigned to S. Z. Roginskiĭ's department of heterogeneous reactions. However, he was immediately spotted by the theorists of the chemical physics section (the theoretical department in this section was headed by AS USSR Corresponding Member Ya. I. Frenkel). They helped Ya.B. to grasp the foundations of theoretical physics. They taught him constantly, persistently, and patiently, and thus Ya.B. received a higher education without entering a university or institute. He had little choice: studies at a university would have required him to abandon his own work for 4–5 years. Such a loss of time did not seem reasonable, and this was understood by all his colleagues at the Institute. The absence of a university degree did not bother anyone.

Ya.B. himself considers his teachers to be L. D. Landau, S. Z. Roginskiĭ, N. N. Semenov, and Yu. B. Khariton. Nonetheless, Ya.B. is an exceptionally original person in science. He does not repeat anyone, yet at the same time, from his first steps in science, he was accustomed to learning from everyone with whom life brought him together. And even now, famous and renowned as few are, he continues to learn from anyone who can offer anything new.

The variety of problems in chemistry, classical physics, nuclear physics, and cosmology to which Ya.B. has made fundamental contributions is so great that it is hard to believe that it has all been done by a single person.

After meeting and talking to Ya.B., the famous English physicist and mathematician S. Hawking wrote to him: "Now I know that you are a real person and not a group of scientists like the Bourbaki."

In a first approximation the 70 years of Ya.B.'s life can be divided into four periods: 1914–1930 — childhood and high school; 1931–1947 — the Institute of Chemical Physics, the study of adsorption, catalysis, phase transitions, hydrodynamics, and, most importantly, the theory of combustion and detonation with application to rocket ballistics, and the first papers on nuclear chain reactions; 1947–1963 — work on the creation of a new technology, nuclear physics and elementary particle physics, and a textbook, *Higher Mathematics for Beginners*; 1964–1987 — astronomy, including application of the general theory of relativity, and cosmology.

We move now to a description of basic directions in the scientific work of Academician Ya.B. Zeldovich.

2. Adsorption and Catalysis[2]

Ya.B. began his work at the Institute of Chemical Physics as a laboratory assistant in the catalysis laboratory. He stayed in this laboratory for four years. While there he began postgraduate work and defended his thesis for the Candidate of Sciences (Ph.D) degree, "Problems of Adsorption," in February, 1936.

Together with his colleagues in the laboratory he studied problems of the crystallization of nitroglycerin, oxidation of hydrogen on a platinum catalyst, and oxidation of CO on manganese catalysts. The first and the third problems were of practical significance.

The most fundamental results, presented in three articles (**1**, **2**, **3**),[†] are related to the *theory* of adsorption and catalysis. However, the simultaneous experimental work left its imprint on these theoretical papers by aiding in the selection of the most relevant problems and providing concreteness in the approach.

The interconnection between theory and experiment was realized in this research in the most direct fashion. In subsequent work as well his own experimental work helped Ya.B. to better understand a problem and influenced the entire style of his work as a theorist.

Let us turn to the theory of the adsorption isotherm, i.e., the dependence of the quantity q of a substance adsorbed on the surface of an adsorbent on the gas pressure p or on the concentration of the substance being adsorbed (the "adsorbate") in a solution. This dependence is studied at constant temperature, whence the name "isotherm."

At the beginning of the thirties there was a deep, puzzling contradiction between numerous experiments and theory. The simple theory developed by Irving Langmuir (USA) led to the expression $q = ap/(p + b)$, which at low pressure gives $q = ap/b = kp$, where $k = a/b$. Thus, for $p \ll b$, $q \ll a$, a linear dependence (direct proportionality) between q and p at low pressure and sparse surface coverage is a general feature of the theory. Meanwhile, in a very large number of cases and over a broad range of variation of p and q, a fractional dependence was observed—the so-called Freundlich isotherm,

$$q = Cp^{1/n},$$

where $n > 1$, i.e., the exponent is less than one, which corresponds to stronger binding of the first portions of the adsorbate.

Ya.B. advanced an essentially new idea: the adsorbent surface is composed of sectors with differing levels of adsorption activity, and each surface may be characterized by a specific distribution function of the sectors according to their activity level. He found an effective method of determining

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[2] Professor O. V. Krylov took part in the writing of this section.

[†] Here and below, numbers in boldface type refer to papers in the present volume.

this distribution function using the known (measured) adsorption isotherm. It may be noted here that I. Langmuir had earlier considered adsorption on a surface with two or three different types of sectors, but he did not provide an explanation of the Freundlich isotherm.

In essence, I. Langmuir had in mind an aggregate of monocrystals with several kinds of faces. The linear law of adsorption on each face (at low pressures) could yield nothing more than a linear law for the whole aggregate.

Ya.B. considered that the most important adsorbents—porous coal, silica gel, and the powdered manganese dioxide which he had studied experimentally—are amorphous substances, i.e., they do not have clearly articulated crystalline structure. Only thus is it possible to obtain a large developed surface—the most important feature of an adsorbent. In this case, it is natural to consider all the possible values of adsorption activity and a smooth distribution function of surface sectors according to their level of activity.

How may we check this conception? The adsorption activity reflects the adsorption energy, i.e., the bonding energy between an adsorbed atom or molecule and the corresponding surface sector. More precisely, this activity depends on the ratio of the bonding energy to the energy of thermal motion, i.e., to the temperature at which the adsorption is measured. Knowing the activity distribution function of the sectors, we may proceed to a function of distribution according to the heat of adsorption. But this means that, from the adsorption isotherm measured at one temperature, we may calculate the isotherm for any other temperature.

When applied to the Freundlich isotherm, $q = Cp^{1/n}$, Ya.B.'s conception leads to an unusually simple conclusion: the exponent is directly proportional to the absolute temperature,

$$1/n = T/T_1,$$

where T_1 has a particular value for each adsorbent–adsorbate pair.

Experiments (including those of Ya.B. himself) provided excellent confirmation of this conclusion.

Let us note that this dependence of n or $1/n$ on T is valid only for $T < T_1$, when $1/n < 1$, so that the isotherm has the form of an upwardly convex curve.

Ya.B. elegantly showed that an integral of a certain form yields different kinds of expressions (exponential with a fractional power or linear) for different parameter values.

Ya.B.'s paper (**1**) remains a model of precise macroscopic analysis of a complicated situation.

However, Ya.B. goes further. Analysis of the Freundlich isotherm leads to exponential dependence of the number of sectors with a given value, α, of the adsorption heat on Q, namely, $\rho(Q) = \text{const} \cdot \exp(-\alpha Q)$. A natural explanation of this dependence lies in the fact that the adsorption heat, Q, is linearly related to the energy, U, necessary to create an area of a given type, $Q = \beta U$. In this case, the distribution law found for Q is transformed into an analogous law, $\rho(U) = \text{const} \cdot \exp(-\alpha\beta U)$. Now it acquires the clear physical meaning of the Boltzmann distribution.

The quantity $(\alpha\beta)^{-1}$ acquires the meaning of effective temperature, which characterizes the energy properties of the surface. It is assumed that, when the catalyst is prepared, fluctuations occur in the distribution of atoms on the surface which in fact lead to its inhomogeneity; later the fluctuations "freeze," and the experimenter works with a well-defined, inhomogeneous, but immutable surface.

Significantly later, foreign scientists reached a similar conclusion regarding the Freundlich isotherm. In the USSR, a theory of adsorption on an inhomogeneous surface was developed independently by M. I. Temkin of the Karpov Physico-Chemical Institute in connection with electrochemical research by Academician A. N. Frumkin. M. I. Temkin's work on a logarithmic isotherm was cited in [74] and published in [75]. The theory of adsorption and catalysis on an inhomogeneous surface was especially extensively developed by S. Z. Roginskiĭ.

In his next paper (**2**), Ya.B. posed a theoretical question which did not arise from experiments known at that time.

If fluctuations and restructuring of the surface are possible during the preparation of an adsorbent, then might not this process occur *during* the process of adsorption and desorption as well? There arises a new concept of a "homogeneous-in-the-mean" surface: at each moment this surface consists of different sectors, but over the course of the fluctuations every sector passes through all possible states. For each sector the probability of a given state (or the amount of time that the sector is in a given state) is the same as for any other sector.

This is a new, more complicated, yet also more realistic and fruitful concept of statistical homogeneity, as opposed to the simple "static" homogeneity of a fixed monocrystal face. Together with statistical homogeneity, the concepts of fluctuations and of the characteristic time of these fluctuations are introduced.

The next point of fundamental significance is that the very presence of the adsorbate on the surface must change the equilibrium distribution of the surface sectors according to their structure and energy of formation U, since the adsorption energy Q partially compensates for the energy used to form a sector of a given type.

Now the kinetic concept of surface fluctuations and relaxation enters into the theory of adsorption. A nontrivial dependence is predicted between the adsorbed quantity and the rate of pressure or concentration change of the adsorbent. Also predicted is the phenomenon of hysteresis during adsorption and desorption over a time comparable to the relaxation time of the surface.

It is shown that for very rapid relaxation the surface once again behaves as a homogeneous surface. This explains why Langmuir's isotherm is rigorously applicable, not only to an ideal homogeneous fixed monocrystal face, but to a rapidly fluctuating fluid surface as well. The significance of this work goes beyond the boundaries of adsorption problems.

Adsorption of a reagent is a necessary stage of catalysis, and of enzymatic catalysis in particular, i.e., the assembly of protein or transport RNA on a DNA matrix.

Enzyme or DNA mutations may be likened to the fluctuations of a surface. In principle, therefore, in developing upon this work of Ya.B., one might consider a natural, physical explanation of directed mutations and of the influence of the environment (an adsorbate entering a reaction) on the mutations.

Ya.B. expressed these thoughts in a presentation in 1960 on the occasion of S. Z. Roginskiĭ's sixtieth birthday, but he never published them, realizing that they were too raw and that their scientific realization would require a deep understanding of biological processes.

Since then some progress has been made in this direction (completely independently of Ya.B.!): in violation of the "central dogma" of molecular genetics, influence of transport RNA on DNA was discovered. It is possible that the ideas of how reacting substances influence enzymes will prove significant in the study of the prebiological stage of evolution.

All these considerations are given here simply to emphasize the depth and potential significance of what Ya.B. actually did in this paper.

We should note that this article by Ya.B. apparently remained little noticed in its time. In any case, we are unaware of any reference to it in the works of other authors. This is explained by the fact that its ideas were far ahead of their time. Only in recent years, due to the wide application of physical methods in studies of adsorption and catalysis, have the changes in the surface (and volume) structure of a solid body during adsorption and catalysis been proved. Critical phenomena have been discovered, phenomena of hysteresis and auto-oscillation related to the slowness of restructuring processes in a solid body compared to processes on its surface. Relaxation times of processes in adsorbents and catalysts and comparison with chemical process times on a surface were considered in papers by O. V. Krylov in 1981 and 1982 [1] (see references at end of Introduction).

Finally, paper **3** is devoted to the specifics of chemical reactions on porous catalysts. Catalysts in the form of porous granules with highly developed inner surfaces are precisely those most frequently used in industry.

Ya.B. analyzes the problem of penetration of reacting substances into the granules. He shows that, together with the well-known extreme cases of reaction throughout the entire volume of the granule and reaction restricted to the granule's surface, there is an important intermediate region of parameters where the reaction occurs inside the granule, but only in a layer adjacent to its surface. The thickness of this layer depends in turn on the concentration of the reacting substances and on the temperature. Therefore the observed effective activation heat and order of the reaction are variable with respect to the actual characteristics of elementary events on the surface.

For the first time a graph of the logarithm of the reaction rate as a function of the inverse temperature is given in which the slope of the curve decreases by a factor of two as the temperature increases in the transition to the internal diffusion region, and falls almost to zero in the external diffusion region. This graph is now reproduced in almost all textbooks.

Let us mention Ya.B.'s contribution to the theory of multi-stage adsorption, reflected in his Candidate of Sciences thesis.

Let us also touch on some experimental papers by Ya.B. on adsorption and catalysis which are not included in the present book.

Together with S. Z. Roginskiĭ, he studied adsorption and catalytic oxidation of CO on MnO_2 [2]. He obtained the equation of the adsorption isotherm. He showed that the kinetics of activated adsorption of CO on MnO_2 obey an exponential law of decrease of the adsorption rate as a function of the quantity of adsorbed substance. This fact was interpreted as "self-poisoning" of the surface by the bicarbonate acid which forms. It was later explained by the inhomogeneity of the surface with a uniform distribution of adsorption centers according to their activation energies. Subsequent studies [3] showed the wide applicability of this equation. In the literature it was called the Roginskiĭ-Zeldovich equation, and sometimes the Elovich equation (after one of S. Z. Roginskiĭ's collaborators who was also studying problems of adsorption).

It was further found that strong chemosorption of CO on MnO_2 and oxidation of CO to CO_2 have a common intermediate stage—the so-called weak adsorption of CO:

$$\mathrm{MnO_2 + CO \rightarrow MnO_2(CO)} \left[\begin{array}{l} \longrightarrow \mathrm{MnO(CO_2)} \\ \xrightarrow{O_2} \mathrm{MnO_2 + CO_2}. \end{array} \right.$$

A system in the weak adsorption stage may possess an increased level of activity. The fruitfulness of this concept was recently confirmed in studies of the initial stages of adsorption (see, for example, [4, 5]). Particles in a presorption state can have an increased energy level; they may, for example, be in an oscillatory- or electron-excited state. Ya.B. also studied the catalytic oxidation of hydrogen [6].

3. Hydrodynamics. Magnetohydrodynamics. Heat Transfer. Self-Similarity

Problems of how chemical reactions (including catalytic reactions and combustion) run under real conditions naturally led Ya.B. to hydrodynamics, heat transfer and problems of turbulence. Another significant factor was his contact with the prominent scientist D. A. Frank-Kamenetskiĭ, who joined the Institute of Chemical Physics in 1935 with broad interests in these areas and in similarity theory.

Ya.B.'s early works (**4**, **5**) were strikingly deep and far ahead of their time. It is difficult to imagine that their author was a young man of 23. In the first of these papers (**4**) he established the extremum property of heat transfer in a fluid at rest, analogous to the well-known extremum property of dissipation for viscous fluid flows. But what is remarkable here is not only the classically simple result. In this paper a very important physical quantity appeared for the first time—"the rate of decay of temperature inhomogeneities"—which plays for the temperature field exactly the same role as does the rate of energy dissipation for the velocity field in a viscous fluid.

A few years later, A. N. Kolmogorov and A. M. Obukhov constructed a remarkable theory of local structure of developed turbulent flows which became one of the greatest achievements of classical physics in the twentieth century. Here the dissipation rate turned out to be the basic governing parameter of this theory in the inertial interval of turbulence scales, and this then yielded the famous Kolmogorov-Obukhov "two thirds law". In 1949, A. M. Obukhov developed a corresponding theory for temperature fields which proved to be of exceptional practical importance since temperature fluctuations determine the dispersion of light in the atmosphere. The governing parameter in this theory turned out to be the same decay rate of temperature inhomogeneities first introduced by Ya.B.

In the second paper (**5**) Ya.B. obtained the now classical similarity laws of ascending convective flow development (for both laminar and turbulent flows). These laws are now widely used by geophysicists in studies of atmospheric and oceanic convection. In 1953–1954 A. S. Monin and A. M. Obukhov independently used the same fruitful ideas for other conditions and obtained similarity laws for shear flow in a density stratified medium in a gravity field.

We note that later too—even in recent years—Ya.B. has turned his attention to this sphere of problems: we have here a paper by Ya.B. devoted to diffusion in a one-dimensional fluid flow (**6**), papers on hydrodynamics and thermal processes in shock waves which are reviewed in the next section, and on the hydrodynamics of the Universe in the next volume in the section devoted to astrophysics and cosmology. Here we consider only Ya.B.'s papers on magnetohydrodynamics or, more precisely, on the problem of magnetic field generation in the motion of a conducting fluid.

The paper "A Magnetic Field in the Two-Dimensional Motion of a Conducting Turbulent Fluid" (**7**) began a series of studies on magnetohydrodynamics. The reader can see that this is not a long paper, however, very important results are obtained in it. To correctly appraise it we must recall that at the time of its publication it seemed almost self-evident that turbulent motion of a sufficiently well-conducting fluid is unstable with respect to spontaneous generation of a magnetic field. In other words, any initial value of the magnetic field, however small, must grow with time. Indeed, a magnetic field is frozen into an ideally conducting fluid. Chaotic turbulent motion of such a fluid therefore "entangles" the magnetic field lines and stretches them, which leads, it would seem, to growth of the field. Ya.B. was the first to find that such reasoning is, in any case, not conclusive.

In the special case of two-dimensional flow considered in the paper, the initial field does in fact increase, but only by a finite factor which increases with the magnetic Reynolds number. Subsequently this increase is replaced by exponential decay. The proof is based on the fact that the vector potential equation for a magnetic field in the two-dimensional case has the character of the diffusion equation in a moving medium which naturally describes perturbation decay. The error in the "naive" argument above is that, during entanglement of the magnetic field lines, there occurs not only an increase of the field, but also a decrease in its characteristic spatial scale, which in the two-dimensional case yields energy flux into the small-scale region of the field where dissipation related to finite conductivity necessarily occurs.

Another, no less important result obtained in this paper is the calculation of the diamagnetic susceptibility of a turbulent conducting fluid. Because magnetic field lines are frozen into a chaotically moving, ideally conducting fluid, the average of the field (not the mean square of the field!) in such a fluid in steady state after a sufficiently long time is zero, so that the ideally conducting turbulent region "expels" the external magnetic field. For finite conductivity, because the field lines slip by the fluid, this expulsion is incomplete, and the turbulent fluid acts like a diamagnetic with finite, but small, magnetic permeability. In the paper an estimate is made of this permeability. The result is not specific to the two-dimensional case—in the three-dimensional case as well the magnetic permeability decreases without limit as the so-called magnetic Reynolds number increases.

These results were further generalized in a joint paper by Ya.B. and A. A. Ruzmaikin, "The Magnetic Field in a Conducting Fluid Moving in Two Dimensions" (**8**). It is shown that the proof of the statement regarding decay of the magnetic field can be carried out even without assuming that the velocity field of the fluid is a function of only two coordinates. It is essential only that the motion itself be two-dimensional, i.e., that the velocity component normal to the surface be zero everywhere. In the simplest case the velocity lies in the x,y-plane, with $v_x = v_x(x, y, z, t)$, $v_y = v_y(x, y, z, t)$, and the only condition is that $v_z \equiv 0$.

It is quite interesting that exponential growth of the field is impossible in the case of motion along plane surfaces and along the surfaces of spheres enclosed within one another. In motion along other surface systems, for example, cylinders or ellipsoids, exponential growth of the field is possible, however, it is specific and slow for low magnetic viscosity. Thus, the concept of a "slow dynamo" was introduced as an intermediate case between absence of field generation and rapid generation independent of the magnetic viscosity. This question, as well as Ya.B.'s own concrete realization of a fast dynamo in three-dimensional non-steady motion, is considered in more detail in the section "Mathematics in the Works of Ya.B. Zeldovich."

Subsequently Ya.B.'s colleagues and students substantially advanced both the general theory of magnetic field generation and its practical applications to the Sun, galaxies, and other astrophysical objects.

Along with the methods of similarity theory, Ya.B. extensively used and enriched the important concept of self-similarity. Ya.B. discovered the property of self-similarity in many problems which he studied, beginning with his hydrodynamic papers in 1937 and his first papers on nitrogen oxidation (**25**, **26**). Let us mention his joint work with A. S. Kompaneets [7] on self-similar solutions of nonlinear thermal conduction problems. A remarkable property of strong thermal waves before whose front the thermal conduction is zero was discovered here for the first time: their finite propagation velocity. Independently, but somewhat later, similar results were obtained by G. I. Barenblatt in another physical problem, the filtration of gas and underground water. But these were classical self-similarities; the exponents in the self-similar variables were obtained in these problems from dimensional analysis and the conservation laws.

In 1956, Ya.B. encountered a different problem, the problem of a short-duration impulse (**9**), in which the self-similarity proved to be completely different. This problem was studied independently by a West German physicist, K. von Weizsäcker, who published very similar results somewhat earlier. The problem, which has various technological and astrophysical applications, may be outlined as follows: a half-space filled with gas is adjacent to a vacuum. The boundary of the half-space is impacted so that the boundary for some time penetrates into the gas and is then withdrawn. The motion then proceeds as follows: a strong shock wave propagates in the gas, and at the same time the gas on the opposite side expands into the vacuum. It turns out that the motion quickly enters a self-similar regime, just as in the problem of strong thermal waves. This problem also involves conservation laws—those of energy and momentum. However, the exponents in the similarity variables, and in particular in the law of the shock wave propagation, cannot be determined from the conservation laws. The reason for this is deep and non-trivial: the transition to the self-similar regime occurs non-uniformly in space. The exponents of the self-similar variables, as it works out, are determined not from the conservation laws and dimensional analysis, but rather from the global condition of existence of the self-similar solution, in full analogy with the propagation velocity of a travelling wave of flame in the combustion problem; this analogy, as subsequently became clear, is of a very deep nature. Problems of this kind were also studied before Ya.B. in the works of the German physicist K. Guderley, and of the Soviet scientists L. D. Landau and K. P. Staniukovich (1942–1944) on convergent strong shock waves. However, it was precisely in the aforementioned paper by Ya.B. in 1956 that the essential difference between these problems and the classical self-similarities was emphasized. Such self-similarities were separated into a special class and called self-similarities of the second kind.

4. Phase Transitions. Molecular Physics

The problems of phase transition always deeply interested Ya.B. The first work carried out by him consisted in experimentally determining the nature of "memory" in nitroglycerin crystallization [8]. In the course of this work, questions of the sharpness of phase transition, the possibility of existence of monocrystals in a fluid at temperatures above the melting point, and the kinetics of phase transition were discussed. It is no accident, therefore, that 10 years later a fundamental theoretical study was published by Ya.B. (**10**) which played an enormous role in the development of physical and chemical kinetics. The paper is devoted to calculation of the rate of formation of embryos—vapor bubbles—in a fluid which is in a metastable (superheated or even stretched, $p < 0$) state. Ya.B. assumed the fluid to be far from the boundary of absolute instability, so that only embryos of sufficiently large (macroscopic) size were thermodynamically efficient, and calculated the probability of their formation. The paper generated extensive literature even though the problem to this day cannot be considered solved with accuracy satisfying the needs of experimentalists. Particular difficulties arise when one attempts to calculate the preexponential coefficient.

The significance of this research, however, is by no means exhausted by this particular, though important, problem. It turned out that the technique developed here may be transferred almost without change to a large number of kinetics problems in which the slow decay of non-equilibrium systems of widely varying physical nature is considered. We may speak here not only of the kinetics of other phase transitions of the first kind (the generality of the work in this respect was indicated by Ya.B. himself), but also of such outwardly dissimilar phenomena as, say, formation of vortex rings in the supercritical motion of liquid helium, "three-particle" recombination of electrons in a gas, and formation of a stream of "escaping" electrons in a plasma. In all cases the governing factor is precisely the slowness of the process, which allows application of the Fokker-Planck equation or the diffusion equation for the appropriate variable (the meaning of these variables, of course, is different in different problems). Further, in all cases it turns out, just as in Ya.B.'s basic paper, that the process rate is determined by the "bottleneck," i.e., by a comparatively small region of parameter values where the process occurs most slowly. The diffusion coefficient varies little in this region and may be determined outside of the region, where it has a direct macroscopic meaning. Further, the boundary condition imposed on the distribution function downstream from the "bottleneck" turns out to be insignificant, which allows one to obtain a closed-form solution even when the form of this condition cannot be established exactly.

In the problem of bubble production the size of the embryo is the independent variable in the diffusion equation. The value of the diffusion coefficient itself is determined by solving the hydrodynamic equations describing the growth of a bubble in a viscous fluid.

By way of illustration, we note that in the recombination problem mentioned above the energies of the electrons are the variables in the diffusion equation, the bottleneck is the region of energies near the boundary of the continuous spectrum, and the slowness of the process is related to the small amount of energy transfer from an electron to a heavy particle in one collision. In the problem of "escaping" electrons in a plasma, slowness is ensured by the weakness of the electric field, the independent variable in the diffusion equation is the momentum component along the field, and the bottleneck is determined, as in the kinetics of new phase formation, by the saddle point of the integral.

Turning to molecular physics, we note first papers by Ya.B. which are close to the problem of phase transition. We begin with the theory of interaction of an atom with a metal (**11**). By applying quantum-mechanical perturbation theory to the interaction of the virtual dipole moment of an atom with conducting electrons of the metal, the dependence on distance of the attractive force of the atom to the surface is obtained. The calculation led to a slow, $\sim l^{-2}$, law for the potential energy decay with distance. This paper was published in 1935, and for many years remained essentially the only one devoted to the subject.

Later, considering the problem from a macroscopic point of view, H. Casimir and D. Polder (Netherlands, 1948), and E. M. Lifshitz (1954), obtained a different, more rapid law of interaction decay. Only recently L. P. Pitaevskiĭ showed that the contradiction does not indicate an error: Ya.B. studied an extreme case of large Debye radius, and this case is realizable in principle.

Of particular value, especially in stimulating related experimental research, was a joint paper by Ya.B. and L. D. Landau, "On the Relation Between Liquid and Gaseous States of Metals" (**13**), in which the authors discuss the form of the phase equilibrium curve between the dielectric and conducting phases of liquid metals. Because transition between the metallic and dielectric phases at absolute zero may occur only as a transition of the first kind, the P,T-plane must have a line of transition of the first kind between the metal and dielectric, terminated by a critical point. There are then two fundamentally different possibilities. Either this critical point coincides with the critical point of fluid–vapor transition (in this case the entire transition curve coincides), or the fluid–vapor and metal–dielectric transition curves branch at some triple point, and each transition has its own critical point. The experimental situation, due to difficulties related to the necessity of working at high temperatures and pressures, long remained unclear. Only recently has it become apparent that, in fact, both variants are feasible: the first in cesium and the second in mercury.

In a paper in 1938 (**12**), "Proof of the Uniqueness of the Solution of the Equations of the Law of Mass Action," Ya.B. showed by means of an elegant mathematical investigation that the equations of thermodynamic equilibrium in a mixture of chemically reacting ideal gases (or in ideal solutions) always have a solution and that this solution is unique. The significance of this result has grown in recent years as systems with several stable states or nondecaying oscillations have begun to attract a great deal of attention, and a new field has emerged—synergetics—which studies such situations. Thanks to Ya.B.'s work, we are certain that the non-trivial character of synergetic systems is due either to the non-ideal nature of the system (in the sense of molecular interactions and phase transitions), or to the fact that the system is open. The steady state equations describing an ideal system with chemical reactions, influx of reagents, and outflow of reaction products, at first glance resemble the equilibrium equation. Therefore, it is especially interesting to establish a very general property of the equilibrium equations which distinguishes them from the equations for an open steady state system.

A number of Ya.B.'s papers were devoted to the properties of states close to the fluid–vapor critical point, to periodic crystallization, and to the limiting chemical kinetic laws of bimolecular and chain reactions. We will not, however, attempt to take the place of the bibliography at the end of the book which provides a complete list of Ya.B.'s papers on the subjects of this volume.

Let us mention several papers by Ya.B. on various problems of molecular physics and quantum mechanics which have not been included in this volume. Among the problems considered are the peculiar distribution of molecules according to their oscillatory modes when the overall number of oscillatory quanta does not correspond to the temperature of translation [9], the influence of the nuclear magnetic moment on the diffusion coefficient [10] and on absorption of light by prohibited spectral lines [11].

The study of electron interaction with a chaotic radiation field is essentially similar to problems in molecular physics. However, because of its significance for cosmology, the papers on this subject have been placed in the next volume (see also Ya.B.'s review [12]).

The study of quantum systems in a periodic field and the introduction of the concept of quasi-energy are also of much interest; a brief article on this subject is placed in the next volume. Here we restrict ourselves to a reference to the review paper [13].

Ya.B.'s contribution to the theory of unstable states is systematized in his monograph *Scattering, Reactions and Fission in Non-Relativistic Quantum Mechanics* [14], and one of his papers will be included in the book *Particles, Nuclei, and the Universe.*

5. Theory of Shock Waves*

Ya.B.'s work on shock waves was of immense practical and theoretical importance. The monographs he wrote received worldwide recognition. The publication in 1946 of a small book, *Theory of Shock Waves and Introduction to Gasdynamics* [15] was a major event in the literature on fluid mechanics. The problem was that gasdynamics was usually presented as a mathematical science, one aimed at mathematicians and theoreticians. In Ya.B.'s book, for the first time, the same basic material was presented by a physicist with the deep penetration into the physical essence of phenomena characteristic of Ya.B., with his own, original vision of the physical world, and with simplicity and accessibility. One is astounded by the insight of individual remarks, findings, and associations which allow one to see a phenomenon from an unusual angle, to understand something which went unnoticed before.

Generations of physicists entering the field of gasdynamics and using it for the solution of both practical and theoretical problems learned it from the book *Theory of Shock Waves and Introduction to Gasdynamics.*

In 1963 an extensive monograph written by Ya.B. and Yu. P. Raizer, "The Physics of Shock Waves and High Temperature Hydrodynamic Phenomena," was published. A second, expanded edition of the monograph came out in 1966 [16]. Simultaneously, in 1966, an English translation of the second edition was published in the USA. In this book, besides the authors' papers on shock waves, explosions, high temperature phenomena and related problems, all the experience gained in the use of physical concepts in gasdynamics was generalized and systematized. The book has become a reference for anyone who works in the fields of high temperatures, plasma, explosions, and high-speed flows. According to the Science Citation Index, for many years the book has been one of the most frequently cited.

Let us mention several specific papers by Ya.B. on shock waves. In a

*Professor Yu. P. Raizer took part in the writing of this section.

paper written in 1946 (**15**) the problem of the structure of a shock wave in a gas with retarded excitation of some degrees of freedom was considered for the first time. Earlier, A. Einstein [18] and others had studied the influence of processes with slow relaxation (dissociation and excitation of the internal degrees of freedom) on sound propagation. In Ya.B.'s paper these ideas are carried over to the nonlinear process of shock wave propagation. Different compression regimes are feasible—smooth or with a pressure discontinuity—depending on the wave amplitude.

Several years later the process analyzed in Ya.B.'s article became the basis for the most powerful method for experimental study of physico-chemical kinetics in gases at high temperatures—shock tubes. For two decades practically all measurements of the probabilities of excitation of molecular oscillations and of dissociation of molecules, i.e., everything that was needed for calculations of the motion of space vehicles through the atmosphere, were performed in shock tubes by recording current parameters in the relaxation layer. We may note that even in the experimental study of ignition in a shock tube, the first work was done by Ya.B. with Ya. T. Gershanik and A. I. Rozlovskiĭ [19].

Since as far back as the time of the classical works on gasdynamics only compression shock waves were known, while rarefaction occurred without discontinuities. Rarefaction waves are continuous in space. This is stated by Zemplen's theorem and is related to the fact that in a rarefaction discontinuity the entropy would decrease, which is impossible. But this is so only if the adiabate in the pressure-volume diagram is convex down. This fact was also known. The thermodynamic properties of practically all substances satisfy this condition.

In 1946 Ya.B. pointed out (**14**) a possible case where the opposite situation occurs. This happens near the critical point where the differences between a vapor and a fluid are obliterated. In a substance under near-critical conditions rarefaction should propagate as a discontinuity, and compression—as a continuous process. Many years later, at the end of the seventies, this prediction of Ya.B. was confirmed experimentally in Novosibirsk by a group working under Academician S. S. Kutateladze. At present, only two cases are known when rarefaction shocks occur: in solid bodies in the region of polymorphous transformations (this had been observed long ago), and near the critical point, as Ya.B. predicted.

At the end of the fifties, Ya.B. gave a qualitative picture of the structure of shock waves with radiation transfer taken into account [20]. In front of a compression shock there is a layer heated by radiation from the compressed gas. Behind the discontinuity there is a temperature peak. The simultaneously developed quantitative theory of these effects allowed detailed explanation of the experimentally observed patterns of luminescence of the front in strong shock waves and of the radiation in the early stage of a fire ball in a strong explosion [21]. These and a few other works on shock waves were presented in the first review paper on the physics of strong shock waves by Ya.B. and Yu. P. Raizer [22].

In 1963 the remarkable phenomenon of gas breakdown by laser radiation was discovered in experiments, which laid the ground for broad new directions in plasma physics and the physics of the interaction of laser radiation with a substance. Soon Ya.B. and Yu. P. Raizer developed the cascade theory of laser breakdown [23]. Hardly a single article of the great number devoted to optical breakdown manages without a reference to this work.

Ya.B. is a theoretical physicist. However, a characteristic peculiarity of his scientific style is his interest primarily in those problems in theoretical physics which allow immediate experimental verification by one method or another, and his interest in the methodology and feasibility of real physical experiments. Therefore the reader should not be surprised at the presence of a number of experimental works in his bibliography. The most interesting of these from a methodological standpoint is his new method for studying substances at high pressures by reflection and refraction of light on the surface of a shock wave propagating in a transparent substance [24–26]. Study of the dependence of the reflection and polarization coefficients of reflected light on the incident angle allows, in principle, determination of the complex refraction coefficient of a medium at pressures up to hundreds of thousands of atmospheres. It turns out, in particular, that water stays transparent up to a pressure of 144 thousand atm, with significant deviations from the Lorenz-Lorentz formula observed.

6. Theory of Combustion and Detonation

Ya.B.'s papers on combustion and detonation initiated a new stage in the development of this science in which the ideas and methods of gasdynamics, gas-kinetic theory, and the effects of molecular transport and the actual kinetics of high-temperature chemical reactions were brought together logically and consistently. A Soviet school of specialists on combustion was formed and received worldwide recognition; one of its recognized founders was Ya.B.* It was no accident that this school emerged at the end of the thirties at the Institute of Chemical Physics. It was here that Academician N. N. Semenov developed the chain theory of chemical reactions and the theory of thermal explosion.

The combustion theory could not have been created without a clear understanding of the kinetics of chemical reactions and without the creative atmosphere, initiated by A. F. Ioffe, which N. N. Semenov fostered and expanded. Under these conditions, Ya.B. introduced clarity into the deep

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*The formation of this stage is excellently characterized by collections of papers from the period 1920–1950 [27–30].

understanding of processes of heat transfer and hydrodynamics and developed mathematical methods adequate to the problems of combustion theory (see section 7 below regarding these methods).

Ya.B.'s studies of combustion and detonation are diverse and multidirectional. They include the chemical thermodynamics of combustion, propagation of exothermic chemical transformation fronts, deflagration and detonation theory, thermo-diffusion and chemo-kinetic processes in combustion and at high temperatures in general, and gasdynamics of flows in the propagation of non-uniform flame fronts and in detonation.

Among Ya.B.'s interests were: the combustion of gases and solid rocket fuels, of condensed liquid explosives and powders, the combustion of premixed fuel compounds, and diffusive combustion. In every one of his lines of inquiry he obtained fundamental results which served as starting points for numerous theoretical and experimental studies in the USSR and worldwide.

The scope of the modern science of combustion is significantly broader than it was a few decades ago. Together with the traditional application of combustion in energy installations—to obtain mechanical work, heat, electrical energy, and to maintain transportation systems, etc.—new applications have been developed such as the production of new materials through combustion, use as a source of information about chemical kinetics at high temperatures and pressures, and the production of a high-temperature, laser-active medium.

In the present collection of Ya.B.'s papers we have included primarily his first articles which formulate the basic ideas and concepts that were then worked out mathematically and thoroughly verified both in later papers by Ya.B. and in the papers of his many students. Moreover, the modern science of combustion all over the world is developing now along the paths outlined in Ya.B.'s papers.

Indicative in this respect is the monograph, "Theory of Combustion and Detonation of Gases," published in 1944 (**16**). In it the basic concepts of flames and detonation waves in gases, their characteristic properties and possibilities, and the interaction within them of gasdynamic, molecular and kinetic processes, are presented in concise form;[3] explanations are given for previously inadequately understood phenomena of propagation limits, thermodiffusive flame instability, and the peculiar influence of small chemical admixtures. The style of presentation is appealing for its deep argumentation; theoretical reasoning is supported by numerous experimental studies both in the Soviet Union and abroad, with many of them performed in the combustion laboratory of the AS USSR Institute of Chemical

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[3] Detailed and rigorous study of the most important problems is done mainly in subsequent articles in the second part of this book, and in a series of monographs and papers (see the bibliography at the end of this volume). However, this does not diminish the significance of the monograph included here, which presents the main aspects in the clearest and most concise form.

Physics, which Ya.B. headed until 1947. Close interaction between theorists and experimentalists ensured extraordinarily rapid progress in the science of combustion during this period. Among those involved in collaboration and in all the discussions with Ya.B. were N. N. Semenov, Yu. B. Khariton, A. F. Belyaev, D. A. Frank-Kamenetskiĭ, K. I. Schelkin, O. I. Leipunskiĭ, S. M. Kogarko, P. Ya. Sadovnikov, G. A. Barskiĭ, V. V. Voevodskiĭ and other well-known representatives of the Soviet school of combustion.

Despite the diversity of the studies being carried out, they had a single ideological and methodological platform: at their foundation was the strong dependence of the chemical reaction rate on temperature, and various related threshold phenomena. To obtain the basic laws of combustion, asymptotic methods were used, complemented by an explicitly physical interpretation.

Ya.B. showed that exothermic chemical reactions in a flow which arise due to the strong dependence of their rates on the temperature lead to a discontinuous, jump-like transition from one reaction regime to another, despite the fact that the chemical reaction rate itself is a smooth, continuous function of the temperature, pressure, reagent composition, and other parameters. The reason lies in the nonlinearity of the basic equations of combustion theory, which generally have several solutions, some stable and some not. For an exothermic reaction in a jet with intensive mixing (an ideal mixing reactor) there are stable low- and high-temperature regimes, and an unstable transient regime. The transitions between the first two correspond to ignition and extinction (experimentally they are recorded, for example, by a sudden change in luminosity).

An important feature of combustion phenomena is their hysteretic character: for example, extinguishing a high-temperature chemical reaction turns out to be possible only when conditions are provided such that the cold system is far from the threshold of ignition. Realization of a particular combustion regime depends on the history of the process, i.e., whether the initial gas temperature was high or low.

The present volume contains a paper by Ya.B. (**17**) and a joint article with Yu. A. Zysin (**17a**) which are devoted to the study of a reactor with complete mixing. In the section where ignition is considered Ya.B.'s results essentially reproduce Academician N. N. Semenov's theory of thermal explosion (1928), which relates to a single reaction event involving a given portion of a substance in a closed vessel. It is interesting, however, that when one takes reagent consumption into account, the transition from slow reaction to explosion in a closed vessel is not, rigorously speaking, discontinuous. In a reactor with ideal mixing, as the time approaches infinity, we obtain an absolutely sharp discontinuity. The theory of extinction in a reactor has no precursors, and for energy science this extreme case is no less interesting than that of thermal explosion.

In the second paper (**17a**), by taking into account the heat transfer to the vessel walls, a stable reaction regime is discovered which cannot be obtained by continuous variation of the external conditions. These features of the equations of combustion theory and the basic patterns of exothermic reaction in a jet studied by Ya.B. have recently been used widely in, for example, the modern theory of chemical reactors.

However, most important and complicated are those processes in which the chemical combustion reaction occurs in space and time. Let us note a brief paper by Ya.B. on the theory of gas ignition by a heated surface (**18**). This work may be considered a generalization of D. A. Frank-Kamenetskiĭ's theory of thermal explosion. However, when part of the surface has a high temperature, Ya.B. was able to formulate a general principle of ignition which is applicable under the broadest variety of geometric and gasdynamic conditions.

Nevertheless, the most typical general feature of a reaction is the existence of fronts of chemical transformation which are able to propagate, without being extinguished, in a hot mixture with a constant velocity: at subsonic speed for a laminar flame (or deflagration front), at supersonic speed for a detonation wave (see below for a more detailed discussion of this paper).

The strong dependence of the chemical reaction rate on the temperature allowed Ya.B., in his work with D. A. Frank-Kamenetskiĭ (**19**), to find the structure of a laminar flame: he isolated in the flame a narrow zone of chemical transformation adjacent to the region of maximum combustion temperature, and a wider zone of heating in which the chemical reaction can be neglected. In each of these zones simplifications of the basic equations of the theory are possible which allow them to be integrated, i.e., allow one to find the temperature and concentration distributions; the integration results to a simple analytical formula for the velocity of flame propagation, known in world literature as the Zeldovich–Frank-Kamenetskiĭ formula (ZFK-model of thermal flame propagation).

The Zeldovich–Frank-Kamenetskiĭ formula related the velocity of flame propagation to real, Arrhenius-type chemical kinetics, and thus raised flame experiments to the rank of kinetic experiments which allow one to obtain important information (activation energy, reaction order, pressure dependence, etc.) about the process of chemical reaction at high temperatures and pressures in a broad range of variation of the composition of the combustible mixture. In the combustion of energy fuels more than half of the energy is supplied by the reaction $CO + \frac{1}{2}O_2 = CO_2$. On the initiative of N. N. Semenov a detailed kinetic study of this reaction was carried out at high temperatures by measurement of the flame velocity [31, 32]. In the absence of hydrogen admixtures, water vapors, or other hydrogenous compounds, the flame propagates quite slowly. The rate of the reaction between CO and oxygen turned out to be proportional to the concentration of hydrogen, which plays the role of a necessary catalyst. We should also mention experiments on the influence of various flegmatizers on the flame velocity in near-threshold mixtures. These experiments form the basis of modern methods of accident prevention in work with combustible mixtures. Thanks to the work of Ya.B., combustion theory has become a part of chemical physics.

Initially developed for simple, single-stage schemes of chemical transformation and for the case of similar temperature and concentration distributions, the theory of normal flame propagation was generalized by Ya.B. and his followers to complex chemical transformations with branching and non-branching chain reactions, with sequential and parallel stages and several separate reaction zones, and with a large concentration of intermediate active centers.

At the basis of analytic solutions with complex chemical transformation mechanisms in flames there remained the fundamental assumption of the narrowness of the chemical reaction zones compared to the heating and diffusion zones; this assumption is valid for large reaction activation energies, which correspond to realistic situations. Considering the importance of this basic assumption, at the Ninth International Colloquium on the dynamics of explosions and reacting systems (France, 1983) specialists from different countries working in the field of combustion decided to introduce the use of the dimensionless Zeldovich number, $\mathrm{Ze} = E(T_B - T_0)/RT_B^2$ (E is the activation energy, T_B and T_0 are the maximum temperature in the reaction zone and the initial temperature, respectively, and R is the universal gas constant). In the asymptotic method developed by Ya.B., Ze is a substantially large quantity.

In 1980 Ya.B., together with G. I. Barenblatt, V.B. Librovich, and G. M. Makhviladze, published a fundamental monograph, "The Mathematical Theory of Combustion and Explosion" [33].

The ideas and methods of combustion theory have found wide application in various areas of physics, biology, and mechanics. We note such phenomena as the propagation of an impulse along a nerve, the formation of a neck (a characteristic wavelike narrowing) in polymer extension, the propagation of laser breakdown and discharge, the zones of ionization of a gas by ultra-high-frequency radiation, and the structure and propagation of cracks in elastic materials.

Let us turn to detonation theory. By the turn of the century the rule for calculating the velocity of a detonation wave and other parameters using only thermodynamic data and the conservation laws was known. It appeared that the chemical kinetics of the transformation of the original explosive substance or mixture into the final reaction products did not play any role, and that it was enough to consider only the initial and final states.

Despite good agreement between this rule and experiment, a certain inconsistency remained in its justification. The laws of conservation and thermodynamics allowed a solution with increased detonation velocity and pressure (compared with those calculated according to the Chapman-Jouguet "rule"), but this solution proved incompatible with the condition of expansion of the explosion products after detonation. One half of the rule was thus justified: the pressure may not be higher than that allowed by the Chapman-Jouguet rule. However, no mechanical or thermodynamic considerations prohibited detonation with an increased velocity, but decreased pressure.

It was necessary to consider the kinetics of the chemical reaction, and this was first done by Ya.B. Previously, the kinetics had been considered in connection with the detonation capacity of combustible materials. Yu. B. Khariton in 1939 had formulated a general principle: a substance reacts in a detonation wave, but at the same time it also flies apart under the influence of high pressure. The ability of a charge to detonate depends on the relation between these two processes. In a paper by Ya.B. published in May, 1940 (**27**), an idealized process without any losses is considered. The conservation equations are valid; however, it turns out that not all states satisfying the conservation laws occur during the reaction. Ya.B. succeeded in providing a logically flawless justification of the Chapman-Jouguet rule. The problem had been ripe. Apparently independently, in 1942 W. Doering in Germany arrived at an analogous result, and in 1943 J. von Neumann in the USA did as well. We should also note that in 1940 a Soviet scientist, A. A. Grib (a student of Academician S. A. Khristianovich), had been working on detonation theory. Because of the war he was not able to publish his results (which provided a less complete analysis of the chemical reaction, but a more detailed picture of the hydrodynamics of the expansion of the explosion products) until 1944.

Ya.B.'s research on detonation waves received worldwide recognition. In the literature outside the USSR the term "ZND-theory," after Zeldovich, von Neumann, and Doering, is widely accepted.

The most important new conclusion of the theory turned out to be the fact that in front of the zone of reaction products, whose state is determined by the Chapman-Jouguet rule, there is a certain amount of initial combustible material compressed by the shock wave. In this compressed material the pressure is approximately twice as high as the final pressure. The significance of the existence of a zone of such increased pressure is obvious not only for the theory, but also for accident prevention. Many studies are devoted to experimental proof of the existence of this zone. Perhaps still the most convincing and practically useful is a paper written by Ya.B. in collaboration with S. M. Kogarko which confirmed the conception of an increased pressure zone (**28**). Concrete perceptions of the conditions of the chemical reaction have changed substantially (see the commentary to **28**). However, Ya.B.'s basic conclusions—the principle of velocity selection and the existence of this increased pressure zone—remain valid even today.

Ya.B. performed interesting research on the limits of propagation of deflagration and detonation waves in channels, and on the concentration limits of combustion in gases (**20**). The strong sensitivity of the chemical reaction rate to temperature variation in the wave caused by heat transfer to the channel walls produces an avalanche-like process: the heat transfer decreases the reaction rate and, thus, the wave velocity, and this in turn promotes even greater heat transfer. At the limit the wave propagation velocity turns out to be only one and a half to two times less than the adiabatic velocity. Modelling of this phenomenon for different combustible mixtures and for channels of different sizes is determined by the Peclet number, which is constructed from the adiabatic propagation velocity. This number was introduced into practice in papers by Ya.B. Modern calculations for various fire-retarding devices are based on concepts developed by him.

The concentration limits of flame propagation in large vessels, when thermal losses due to heat transfer are small, are explained by Ya.B. from the standpoint of thermal losses by radiation. The flame velocity at the concentration limits also turned out to differ significantly from zero.

Combustion is extraordinarily rich with a variety of instabilities. Bending of the flame front causes redistribution of the thermal and diffusion fluxes within it: flame sectors which are convex with respect to the combustible mixture end up in a different temperature-concentration regime than concave sectors, and therefore propagate through the combustible mixture with a different velocity. Ya.B.'s paper with N. P. Drozdov (**21**) shows that in combustible mixtures in which the diffusion coefficient of the deficient reagent exceeds the coefficient of thermal conductivity the plane flame front ceases to exist—it disintegrates into individual islands enriched by the easily diffused component and possessing an increased temperature. These islands are able to move independently in the combustible mixture with a velocity which exceeds the planar flame velocity. Thermodiffusion phenomena are the reason for the formation of flames with complex structures (cellular, polyhedral, pulsating, etc.) which presently attract the attention of numerous researchers. (Regarding this and, in particular, subsequent papers by Ya.B. see the commentary to **21**, cited above.)

Thermal expansion of a gas in a curved flame front leads to the formation of gasdynamic vorticity in the combustion products and is the cause of a flame instability discovered by L. D. Landau, and also by G. Darriet (France), in 1944. It turned out, however, that this instability was very reluctant to exhibit itself in experiments! The first explanation of such a phenomenon—using the example of a spherical flame—was given by A. G. Istratov and V. B. Librovich. Ya.B. and his coauthors [34] proposed a method for calculating rapid combustion in a tube containing an elongated flame front (stabilized combustion in a flow), and also spontaneous flame propagation in a tube. The evolution of the surface of a curved flame front in time, as well as the presence of a tangential component of the flow velocity along the flame, makes the flame front more stable with respect to hydrodynamic perturbations and explains the observed deviation of experimental facts from the results of the hydrodynamic instability theory proposed by L. D. Landau.

In diffusion combustion of unmixed gases the combustion intensity is limited by the supply of fuel and oxidizer to the reaction zone. The basic task of a theory of diffusion combustion is the determination of the location of the reaction zone and of the flow of fuel and oxidizer into it for a given gas flow field. Following V. A. Schvab, Ya.B. considered (**22**) the diffusion equation for an appropriately selected linear combination of fuel and oxidizer concentrations such that the chemical reaction rate is excluded from the equation, so that it may be solved throughout the desired region. The location of the reaction zone and the combustion intensity are determined using simple algebraic relations. This convenient method, which is universally used for calculations of diffusion flames, has been named the Schvab-Zeldovich method.

However, in this paper Ya.B. went further and considered the chemical kinetics. He determined the limit of intensification of diffusion combustion, which is related to the finite chemical reaction rate and the cooling of the reaction zone, for an excessive increase of the supply of fuel and oxidizer. If the temperature in the reaction zone decreases in comparison with the maximum possible value by an amount approximately equal to the characteristic temperature interval (calculated from the activation energy of the reaction), then the diffusion flame is extinguished. The maximum intensity of diffusion combustion, as Ya.B. showed, corresponds to the combustion intensity in a laminar flame of a premixed stoichiometric combustible mixture.

With Ya.B.'s active participation Soviet science achieved great success in the theory of combustion and in the practical use of solid rocket fuels (powders). This volume contains Ya.B.'s basic ground-laying paper (**24**).

As in the theory of detonation, specialists on internal ballistics were working on thermodynamic and hydrodynamic theories. Conceptions of the mechanism of combustion in the thirties were quite primitive.

Meanwhile, in 1938 at the AS USSR Institute of Chemical Physics A. F. Belyaev showed that the combustion of liquid explosives occurs in the gas phase after their evaporation. In analogy with this, Ya.B. proposed a theory of combustion of a solid powder (**24**) according to which the powder is heated in the solid phase and then decomposes, transforming into a gas; it is only in the gas phase, at some distance from the surface, that the bulk of the chemical energy is released. Ya.B. also pointed out the peculiar effects of non-steady combustion of a powder.

The heated layer in a condensed powder substance plays the role of an inertial heat accumulator: the heat stored in the layer during slow (low-pressure) combustion goes for additional heating of the combustion products at increased pressure and increases the combustion rate compared to the rate of the steady process. In contrast, as the pressure is decreased part of the heat from the reaction zone is spent on the creation of a wider heated layer; the reaction zone is cooled and combustion may cease. Ya.B. developed a theory for the combustion rate of a powder with small pressure variations, and determined the conditions under which undesirable high frequency oscillations occur in a powder combustion chamber. Discovered at the AS USSR Institute of Chemical Physics by O. I. Leipunskiĭ, the increase in the combustion rate of a powder when a gas flow is blown over its surface (the blowing or erosion effect), was given a clear gasdynamic interpretation in a paper by Ya.B. [35] (written in 1943, published in 1971). Of extraordinary importance for the internal ballistics of solid propellant rockets is the possibility of extinguishing the powder by a rapid decrease in pressure; a theory of powder extinction by a sharp, jump-like drop in pressure, or by a smooth, but sufficiently deep change in pressure, was developed by Ya.B. in the 1940s. It has found extensive application in modern industrial equipment which uses a powder as a working agent.

A special place among kinetic studies in combustion is occupied by work on nitrogen oxidation. Begun at the AS USSR Institute of Chemical Physics in the mid-thirties on the initiative of N. N. Semenov, research to determine the feasibility of fixation of atmospheric nitrogen for the production of mineral fertilizers has today found application in the development of environmental protection measures for toxic components of combustion products, including nitrogen oxide. In December, 1939, Ya.B. defended his doctoral dissertation on "The Oxidation of Nitrogen in Combustion and Explosions." It was precisely these studies, in which D. A. Frank-Kamenetskiĭ, P. Ya. Sadovnikov, A. A. Rudoy, A. A. Kovalskiĭ, and others actively participated, that led Ya.B. to the problems of combustion and detonation.

The publication of papers on nitrogen oxidation was delayed (**26** and a monograph, "The Oxidation of Nitrogen in Combustion," written together with P. Ya. Sadovnikov and D. A. Frank-Kamenetskiĭ). In these works Ya.B. studied in detail the kinetics of nitrogen oxidation; having proved that oxidation occurs *via* a non-branching chain reaction with an equilibrium concentration of active centers, he calculated the formation of nitrogen oxide in a closed vessel and during the sudden "hardening" of a reacting, rapidly expanding gas. The kinetic scheme of nitrogen oxidation which Ya.B. demonstrated is a central one in the internationally accepted practice of calculating environmental pollution by the exhaust products of internal combustion engines, by coal power stations, and by chemical factories, and rightfully bears Zeldovich's name.

The restricted space of this introductory article does not allow us to give further attention to Ya.B.'s papers on the physical chemistry of combustion and detonation.[4] In Ya.B.'s own words, the science of combustion and detonation is dear to him because it provided him, at the beginning of his life and career, with a wide-open field of activity both as a theorist and as a bold experimenter. Important problems of a fundamental nature were being solved, problems which were related to important technological applications. The tremendous contribution which Ya.B. made to this science is the pride and showpiece of the Soviet school of combustion. Ya.B.'s work on the theory of detonation and combustion was recognized by awarding him the State Prize of the USSR in 1943.

The science of detonation and combustion developed actively after World War II. A significant role in this development was played by the work of scientists at the AS USSR Institute of Chemical Physics, particularly that of A. G. Merzhanov and his colleagues in the field of combustion, including condensed systems, the work of AS USSR Corresponding Member K. I. Schelkin, Y. K. Troshin, A. N. Driemin, B. V. Novoshilov and G. B. Manelis, and also of scientists at the AS USSR Siberian Branch—AS USSR Corresponding Member R. I. Soloukhin and his colleagues—in the field of detonation, and the work of scientists at the AS USSR Institute of Problems of Mechanics—Y. B. Librovich and his colleagues. New concepts appeared, especially in problems of the stability of solutions found earlier. Let us emphasize, however, that the work of Ya.B. was not refuted; rather it was built upon, and it served as a starting point for the future development of combustion science. In 1984, the International Institute of Combustion awarded Ya.B. the Lewis gold medal for his brilliant accomplishments in research on combustion processes.

7. Mathematical Aspects of the Combustion Theory

The phenomena of ignition and extinction of a flame are typical examples of discontinuous change in a system under smooth variation of parameters. It is natural that they have played a substantial role in the formation of one of the branches of modern mathematics—catastrophe theory. In Ya.B.'s work it is clearly shown that steady, time-independent solutions which arise asymptotically from non-steady solutions as the time goes to infinity are discontinuous. It is further shown that transition from one type of solution to the other occurs when the first ceases to exist. The interest which this set of problems stirred among mathematicians is illustrated by I. M. Gel'fand's

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[4] The next section, which deals with the mathematical aspects of this group of papers, is something of a supplement to this one.

well-known programmatic paper [36].

Even greater interest among mathematicians was stimulated by problems of state propagation. As is known, in 1937 the fundamental paper by A. N. Kolmogorov, I. G. Petrovskiĭ, and N. S. Piskunov (KPP) appeared, and, independently, a paper by R. A. Fisher (USA), regarding the propagation of a biologically predominant species. In 1938, the aforementioned paper by Ya.B. and D. A. Frank-Kamenetskiĭ (ZFK) on flame propagation (**19**) was published.

At issue in both cases were solutions describing propagation with constant velocity. The velocity itself here should be defined as the eigenvalue of the parameter for which the equation has a solution. Such a statement of the problem was unusual for mathematicians. Evidence of the interest it caused may be found, in addition to I. M. Gel'fand's article, in review articles by the American scientists D. Aronson and H. Weynberger (1975 and 1978 [37,38]), and many others.

The difference in the results of KPP and ZFK is characteristic. In the KPP problem the velocity has a continuous spectrum, bounded from below by the condition of a non-negative solution. The ZFK method, meanwhile, yields in the typical case one definite value for the propagation velocity. The difference is completely explained by the fact that, unlike the biological problem of KPP, the chemical reaction rate at and near the initial temperature is typically negligible. In practice, the problem reduced to construction of a travelling-wave-type solution for a set of coupled diffusion and heat transfer equations (of a combustible gas or for the combustion products). It was rigorously proved that, allowing for a shift in the direction of propagation, the solution of the problem exists and is unique.

This work had a happy fate; it was continued and developed by scientists around the world. It is enough to say that the first generalization of Ya.B.'s work on flame propagation to multi-component mixtures was done by the famous American hydrodynamicist T. von Kármán. Later, many hundreds of papers were devoted to problems of the mathematical theory of combustion, considering both theoretical problems of flame propagation, even questions of existence and uniqueness, and purely practical problems, including calculations of the flame propagation velocity in specific gas mixtures. A review of these papers, albeit far from complete, may be found in monograph [33].

We note also research by Ya.B. performed together with G. I. Barenblatt in 1957 [39], which has proved to be a key to understanding not only the problems of stability and flame propagation to which it was directed, but a far wider range of phenomena as well. This is the problem of the stability of invariant solutions to problems in mathematical physics. The question was posed thus: what is flame stability? Let us perturb the temperature and concentration distribution in a flame. Which flame shall we call stable? We recall that the solution of the problem of a flame as a travelling wave was determined with accuracy to within translation. In the later paper, it was noted that the definition of flame stability should also be translation-invariant: a situation in which the perturbed distribution of temperature and concentration tends to the translated, rather than the original, distribution should not be considered unstable. As it turned out, gas flames are stable in this sense under fairly general assumptions. One may also speak of the zeroth (time-independent) perturbation mode, which has now been found in many problems of theoretical physics.

Finally, comparatively recently, Ya.B., A. P. Aldushin, and S. I. Khudyaev (**23**) completed a theory of flame propagation which considers the most general case of a mixture in which the chemical reaction occurs at a finite rate at the initial temperature as well. In this work the basic idea is followed through with extraordinary clarity: flame propagation represents an intermediate asymptote of the general problem of a chemical reaction occurring in space and time. At the same time, the relation between the two types of solutions (KPP and ZFK) is completely clarified.

Let us turn to Ya.B.'s paper on ignition of a combustible gas mixture by a heated wall (**18**). By the time this paper was written, N. N. Semenov and D. A. Frank-Kamenetskiĭ had already done work on gas ignition in closed vessels under a variety of assumptions. In N. N. Semenov's work the gas was assumed to be ideally mixed and the temperature of the gas in the vessel to be constant. D. A. Frank-Kamenetskiĭ considered a gas at rest, so that heat transfer occurred only through molecular thermal conduction.

Ya.B.'s paper was the first to consider the external problem: ignition of a reacting gas mixture by a heated body. It was clear that he had to begin with the simplest case of a heated wall; problems of ignition by a wire or ball were solved later. Here again a basic, classically simple result was obtained: at the limit of ignition of the mixture the thermal flux from the heated wall vanishes. An expression for the minimum rate of heat transfer far from the body sufficient to prevent ignition was also obtained. However something else was significant as well: just as in the problem of calculating the flame propagation velocity, this problem had all the distinctive features of asymptotic analysis. Certain terms which arose only a decade and a half later were not used in the paper; otherwise the paper (**18**) consistently applied a technique which took final shape in the mid-fifties in the works of S. Kaplun, P. Lagerstrom, M. Van-Dyke, J. Cole, and others—the method of matched asymptotic expansions—which now plays a very important role in fluid and gas mechanics. Furthermore, group-theoretical methods, a great rarity at the time, also played a significant role in this paper and were decisive in the solution of a difficult nonlinear problem of mathematical physics.

8. *Chain Fission of Uranium*[5]

The discovery in 1938–1939 of nuclear fission of uranium, which led ultimately to the discovery of nuclear power, heralded a new, extraordinarily fruitful stage in Ya.B.'s scientific activity. His interests were concentrated on the study of the mechanism of fission of heavy nuclei and, what proved particularly important, on the development of a theory of the chain fission reaction of uranium. During 1939–1943 Ya.B. wrote several papers which laid the foundation for this subject and were of fundamental value. We note that four of these papers, written in collaboration with Yu. B. Khariton, were done practically in two years before the war. The papers of this series form the foundation of modern physics of reactors and nuclear power; they are widely known and do not require special commentary—a short review of the basic physical results is eloquent enough.

The paper of 1939 [1*], "On the Chain Decay of the Main Uranium Isotope," studies the effects of elastic and non-elastic neutron moderation and concludes that chain fission reactions by fast neutrons in pure metallic natural uranium are impossible. The 1940 paper, "On the Chain Decay of Uranium under the Influence of Slow Neutrons" [2*], is classic in the best sense of this word; its value is difficult to overestimate. The theoretical study performed showed clearly that the effect of resonance absorption of neutrons by nuclei of ^{238}U is a governing factor in the calculation of the coefficient of neutron breeding in an unbounded medium; it was concluded that a self-sustained chain reaction in a homogeneous "natural uranium–light water" system is impossible.

The second paper of 1940 [3*], entitled "Kinetics of Uranium Chain Decay," is no less significant than the first. This pioneering work yielded a whole series of brilliant results: for the first time, the need to take into account the role of delayed neutrons in the kinetics of chain nuclear reactions was shown (it is precisely the delayed neutrons which ensure easy control of nuclear reactors), the influence of heating on the kinetics of a chain process was considered in detail, and a number of conclusions were reached which are of much importance for the theory of reactor control. This same paper predicted the formation in the process of chain fission of new, previously unknown, nuclei which strongly absorb neutrons, a prediction which was later fully confirmed.

In the 1941 paper with Yu. B. Khariton [40], the problem of the critical size of a sample of ^{235}U in the fission of nuclei by fast neutrons was considered. The calculations showed that, in order to sustain a chain fission reaction by fast neutrons in a sample of ^{235}U surrounded by a heavy neutron reflector, it is sufficient to have only ten kilograms of pure ^{235}U isotope. Here also a theory is given which allows calculation of the critical mass of

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[5] Here and below we denote by * references to articles by Ya. B. Zeldovich which may be found in the second volume of his selected works, *Particles, Nuclei, and the Universe.*

^{235}U dissolved in light water.

Ya.B.'s unpublished 1943 paper, "The Age Theory of Neutron Moderation," is closely related to his studies of the war period. The age theory, developed independently of E. Fermi, forms the basis for calculation of a reactor by slow neutrons. It was in this paper that the famous "age equation" was obtained.

Ya.B.'s work on the problem of the chain fission of nuclei, together with his work on detonation and shock waves, were the scientific foundation of Ya.B.'s practical activity in a collective which was carrying out a very important state assignment. This activity was acknowledged by awarding Ya.B. the highest decorations of the USSR.

At the same time, the study of uranium fission guided Ya.B. toward problems of microphysics, the theory of elementary particles and the nucleus. Thus, the work of 1939–1941 became a decisive turning point in Ya.B.'s life and career.

9. *The Theory of Elementary Particles*

Ya.B.'s contribution to the theory of elementary particles came primarily during 1950–1960. Therefore it does not seem superfluous to provide a brief description of the situation during that time.

The 1950s saw the beginning and flowering of research on elementary particles in accelerators built specially for this purpose. Beginning with the study of pions, discovered not long before in cosmic radiation, the decade was marked by the discoveries of most of the strange particles, and was crowned by the discovery and study of hadron resonances in accelerators. In the theory of strong interactions the decade began with construction of an isotopic classification of the hadrons and ended with the discovery of $SU(3)$-symmetry. At the same time, the dispersion approach in the theory of strong interactions was formed.

In the mid-fifties the violation of parity was discovered, and a universal theory of weak interactions—the $(V\text{-}A)$–theory—was created. Construction of composite hadron models was begun. The first non-abelian gauge theory was developed.

During these years Ya.B. made important contributions to a whole series of the above trends. In 1952 he formulated the law of nuclear (baryon) charge conservation [4*], extending it to the unstable particles recently discovered in cosmic radiation and subsequently called strange particles.

In 1953 Ya.B. introduced the law of conservation of lepton (neutrino) charge [5*] as one of the basic rigorous laws of nature. Both of these laws are important for the classification of elementary particles and the processes in which they participate.

Thorough testing of these conservation laws has so far revealed no violations. Thus, recent (1983) experiments demonstrated that the lifetime of a proton exceeds 10^{31} years (these experiments sought the decay of a proton into a positron and neutral pion predicted by the Grand Unification Theory). Modern theoretical predictions regarding baryon instability and nonconservation of baryon charge do not change the practical applicability of this conservation law throughout laboratory physics.

In 1954 Ya.B. was the first [6*] to direct attention to the importance of measuring the β-decay of a charged π-meson. He proved that for the scalar variant of the weak interaction this decay is prohibited if the pion is a composite one, while for the vector variant the decay is allowed and the square of its matrix element is twice that of the vector matrix element in neutron decay. Continuing the theoretical investigation of this decay in a 1955 paper [7*], Ya.B. and S. S. Gershtein concluded that the constant of the vector interaction of nucleons is not modified by strong interactions, just as the electric charge of strongly interacting particles is not modified by virtual particles. This observation by Ya.B. and S. S. Gershtein, made at a time when it was generally accepted that a scalar, rather than vector interaction occurs in β-decay, played an important role in the creation of a universal theory of weak interactions.

In 1957, formulating within the framework of this theory the idea of conserved vector current, M. Gell-Mann and R. Feynman (USA) revived the hypothesis of Ya.B. and S. S. Gershtein. In a report at the Rockberk conference in 1960, R. Feynman said, "The idea that if there is a vector current in β-decay then it can be made a conserved one was first proposed by S. S. Gershtein and Ya. B. Zeldovich. M. Gell-Mann and I were not aware of this when working on the idea." Experimental discovery of the decay, $\pi^+ = \pi^0 + e^+ + v$, was made in 1962. Subsequent measurements of the probability of this decay in laboratories at the Joint Institute for Nuclear Research, CERN, and at research centers in the USA, showed that it satisfies the relation predicted by Ya.B. with a high degree of accuracy.

In 1955 Ya.B. and G. M. Gandelman [8*] indicated that exact measurement of the magnetic moment of an electron is a promising method of determining the limits of applicability of quantum electrodynamics at small distances. In 1956 V. B. Berestetskiĭ, O. N. Krokhin, and A. K. Khlebnikov noticed that measurement of the magnetic moment of a muon allowed even smaller distances to be probed. Since then, study of the magnetic moments of the muon and electron has become a classical method for finding the limits of applicability of quantum electrodynamics. Today, theoretical and experimental values of the magnetic moment agree with an accuracy of order 10^{-9} for an electron and 10^{-8} for a muon. Recently it has become customary to interpret this agreement as an indication of the fact that the dimensions of the internal structure of leptons do not exceed 10^{-16} cm.

In 1958 Ya.B. proposed a technique for finding neutral resonances using the method of deficient mass [9*]. The search for resonances by this method, when a peak is observed in the spectrum of deficient masses, was later used successfully in the discovery of a series of unstable particles. The authors of these experimental papers arrived at this method apparently without knowing of Ya.B.'s work, but this does not diminish his priority.

Far ahead of the physics of its time, Ya.B.'s paper of 1959 [10*] presents arguments in favor of the existence of a weak interaction of neutral currents which does not preserve parity (electron–electron and proton–proton) and proposes experiments to seek this interaction. It is remarkable that Ya.B.'s considerations were based on the hypothesis that a neutrino and electron form an isotopic doublet, and that the weak interaction must be isotopically invariant. This idea, proposed independently by Ya.B. and not long before by S. A. Bloodman (USA), was very bold. After all, at the time it was assumed that the concept of isotopic spin did not apply to leptons. The experiments proposed by Ya.B. were performed two decades later when, in 1978 in Novosibirsk, the rotation of a polarization plane of a laser beam passing through bismuth vapor was found, and at Stanford the difference between cross-sections of nucleon interactions with left- and right-polarized electrons was demonstrated. This latter effect was predicted by Ya.B. for muons as well, and was recently observed in an experiment at CERN. It should be emphasized that the scheme proposed by Ya.B. in 1959 contained only diagonal neutral currents, in complete agreement with the later theory of electro-weak interaction and with experiment. Ya.B. turned to the question of the possible role of weak interactions in explaining left-right asymmetry in biology later, following other researchers (see his paper with D. B. Saakyan [41]).

Also in 1959, Ya.B. proposed an experiment on the transformation, $K_2^0 \to K_1^0$ on electrons and offered a theory for this phenomenon [42]. The experiment was later carried out at the Serpukhov accelerator.

When we speak of the papers of the 1950s, we must not fail to mention articles published in 1954–1960 on muon catalysis (for a review with complete bibliography, see [43]). Various aspects of cold muon catalysis in nuclear reactions of hydrogen, deuterium, and tritium were considered. In recent years the ideas which lay at the foundation of these papers have been further developed and verified. In particular, it was Ya.B. [40] who noted the decisive role of muon adhesion to the helium nucleus which is formed in the reaction: this process restricts the number of reaction steps, and the future for applying this process in energy engineering depends on it.

In giving an overall evaluation of the series of papers on elementary particle theory published by Ya.B. in the 1950s, it must be noted that it was performed during a period when Ya.B.'s primary and very important activity was the creation of a new technology. In the almost complete absence of personal interaction and contacts with leading physicists during this period, his choice of timely problems and his ability to obtain important results appears even more surprising.

Let us turn to papers on the theory of elementary particles published by Ya.B. in the 1960s and 1970s. The 1960s brought into the physics of elementary particles the quark hypothesis. Theorists were on the verge of creating a quantum chromodynamics, a theory of quark–gluon interaction.

During these years Ya.B.'s unremitting attention was directed to quarks. He organized a true offensive all along the front, studying various quark models, analyzing possible physico-chemical methods for seeking free quarks, and elucidating the possible behavior of quarks in the early stages of the evolution of the Universe. He not only initiated, but even personally participated in an experiment seeking free quarks [44]. In 1965 he published a brief review, "Quarks and the Classification of Elementary Particles for Pedestrians" [45], remarkable for its simplicity and enthusiasm, and a detailed study, "Quarks: Astrophysical and Physico-Chemical Aspects" [11*], [46] (in collaboration with L. B. Okun and S. B. Pikelner).

Taken together, these works gave rise to a contradiction which led theorists to the idea of quarks confinement. At the same time, these papers gave birth to a new direction which Ya.B. began to develop in the 1960s, a bridge between cosmology and elementary particle physics.

In 1961 the first paper on this subject came out—"On the Upper Density Limit of Neutrinos, Gravitons and Baryons in the Universe" written with Ya. A. Smorodinskiĭ [47]. In 1966 Ya.B. and S. S. Gershtein [12*] established an upper cosmological limit for the mass of a muonic neutrino. This limit, about $100\,eV$, is four orders more accurate than that given by the best laboratory measurements. The point is that for any larger neutrino mass their combined mass in the Universe would be so large that it would be incompatible with the limits established by the known age of the Universe. This paper had great influence both on the development of elementary particle physics and on the development of cosmology; it has entered into textbooks of both disciplines. In connection with this paper, we should also mention the research of one of Ya.B.'s students, V. F. Schvartsman [48], in which a theoretical limit is established for the number of different types of neutrinos ($n < 10$) by their influence on the relation between the rates of occurrence of hydrogen and helium in the Universe. All of modern "cosmological elementary particle physics" is very much indebted to these two works.

Beginning in the mid-sixties, Ya.B. repeatedly tried to evaluate the energy density of a vacuum, to find the magnitude of the so-called cosmological constant [13*]. His interest in the physics of vacuum grew in the 1970s when, while exploring an idea of D. A. Kirzhnitz and A. D. Linde on phase transition, Ya.B., I. Yu. Kobzarev and L. B. Okun [49] constructed the theory of the domain structure of a vacuum and its possible influence on the cosmological expansion of the Universe.

Vacuum domains should appear during the cooling of the Universe if spontaneous violation of SP-symmetry occurs in nature. In addition, contiguous domains should differ from one another by the sign of the SP violation. The domains should be separated by very thin and very heavy walls, the theory of whose motion was developed by Ya.B. and his coauthors.

This work initiated a whole new line of research at the intersection of elementary particle theory and cosmology (the theory of unstable vacuum, vacuum bubbles, vacuum strings, etc.).

An interim summary of much of the research of Ya.B. and his students was given in a review by Ya.B. and A. D. Dolgov [50] which gained worldwide recognition and has become a standard reference in practically all the papers on this subject both in the USSR and abroad.

Let us also note Ya.B.'s analysis of how well the conservation of electric charge has been verified (his paper together with L. B. Okun on the stability of an electron [51]), and his paper investigating the possibility of gravitational annihilation of the baryon charge [52].

We note several very general formulations of the problem. A striking example of this is Ya.B.'s 1967 paper [14*], in which he considers the possibility of a theory in which the bare photon field is absent, while the observed electromagnetic field is created entirely by quantum fluctuations of a vacuum. This bold idea, which extends to electrodynamics an earlier idea about gravitational interaction (in part, under the influence of Ya.B.'s papers on the cosmological constant), has not yet been either proved or disproved. However, both ideas have elicited lively discussion in the scientific literature.

As an example of Ya.B.'s role in the development of particle physics we quote from an article by G. I. Budker on colliding beams, "The idea of antiparallel particles is not new; it is a trivial consequence of the theory of relativity. As far as I know, it was first expressed by Academician Zeldovich, though in a very pessimistic context. His pessimism is quite understandable" [53]. As is well known, G. I. Budker and his collaborators and their foreign colleagues were able to overcome the enormous difficulties which caused this pessimism. The role of colliding beams in particle physics is impossible to overestimate.

10. Nuclear Physics

Forming a natural group with Ya.B.'s papers on uranium fission and elementary particles are a small, but fundamentally important group of papers on nuclear physics which have had major repercussions.

The first was a brief note in 1956 on the possibility of cold neutron storage [15*]. It is known that a neutron moving with sufficiently small velocity experiences complete internal reflection in its fall from a vacuum to a wall made, for example, of graphite. According to Ya.B., this phenomenon may be used for long-term "storage" of neutrons. The idea was experimentally realized, first in the USSR by AS USSR Corresponding Member L. F. Shapiro and his colleagues, and later abroad as well. Thanks to this idea it became possible to measure with high accuracy the electric dipole moment and life span of a neutron.

The storage of cold neutrons (the idea and the experiment) was registered officially* as a discovery in 1958. Ya.B. was awarded the Kurchatov gold medal for this work.

The second paper, in 1960, discusses the existence of nuclei at the threshold of stability having excessive numbers of neutrons [16*]. Its most remarkable result was the prediction of a new helium isotope, Helium-8. This isotope was soon discovered experimentally and the decay chain was traced (due to the weak interaction $^8\mathrm{He} \rightarrow {}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be}$ with subsequent $^8\mathrm{Be} \rightarrow 2^4\mathrm{Be}$).

After this article there followed a series of other publications, reviews and monographs by Ya.B. in collaboration with A. I. Baz, V. I. Goldanskiĭ and V. Z. Goldberg [54], listed in the commentary. Overall, the study of nuclei at the threshold of stability has now become a broad field of inquiry in nuclear physics.

Let us note, finally, two ideas of Ya.B. which have not yet found experimental confirmation. We refer to the possibility of the existence of excited states of nuclei with an anomalously long life span—with a large angular momentum [17*] or with an anomalously large value of the isotopic spin [18*]. Perhaps their publication in this edition will help to experimentally verify the nontrivial ideas of Ya.B.

11. Astrophysics and Cosmology

Ya.B. actively entered astrophysics and cosmology at the beginning of the sixties. Today, twenty years later, few people in the world can rival his influence on the development of astrophysics and cosmology. His ideas inspire new work not only among theoreticians. The largest radiotelescopes, optical devices, orbital x-ray observatories list among their experimental and observational accomplishments the discovery of effects predicted by Ya.B. These include gigantic voids in the Universe, surrounded by clusters of galaxies, and x-ray sources which gain energy by accretion to black holes and neutron stars, and the decrease in relic radiation intensity in the directions of clusters of galaxies surrounded by hot intergalactic gas.

The chief problem (and one suited to the scale of his talent), which Ya.B. has set himself and toward whose solution he has persistently moved the last twenty years, is the question of the properties and origin of the large-scale

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*There exists in the USSR a practice of official registration of scientific discoveries. *Translator's note.*

structure of the Universe, of the reasons for the appearance of the original density perturbations, of the law of their growth in the course of the cosmological expansion, of the peculiarities of compression of matter in the nonlinear stage of growth, and, finally, of observable manifestations of all these stages. The resulting picture is often called the theory of galaxy formation, although it would be more correct to call it the theory of formation of the large-scale structure of the Universe.

Ya.B.'s entry into astrophysics coincided with the second revolution in astronomy, which was marked by rapid development of experimental research methods in radioastronomy and the launching into space of instruments which are sensitive in the x-ray and ultraviolet ranges of the spectrum. During the period from 1964 to 1972, discoveries were made of quasars, relic radiation, radiopulsars, and compact x-ray sources emitting radiation due to accretion, i.e., the collapse of matter onto neutron stars and black holes. Ya.B. actively began work in this, for him, new field several years before the most important new observations appeared. His papers during these years were devoted mainly to the application of general relativity theory to astrophysical objects and to the Universe as a whole. He was among the founders of a new field of science—relativistic astrophysics—which addresses such problems as the last catastrophic stages of the evolution of stars, the discovery of black holes, the physics of the early stages of the expansion of the Universe, and the theory of supermassive stars, with masses ranging from hundreds of thousands up to billions of solar masses. He studied in detail the properties of black holes and the processes which occur in their vicinity. Earlier, black holes had been considered only as a possible product of the evolution of sufficiently massive stars. Ya.B. showed in 1962 [19*] that even a small mass can collapse if its density is sufficiently high. From this followed a paradoxical conclusion, that the equilibrium of any mass is always metastable with respect to gravitational collapse.

Cosmology is based on the assumption that matter in the early stage of evolution of the Universe was of extraordinarily high density. From this, in 1966, Ya.B. and I. D. Novikov came to the conclusion that the generation of small black holes was possible in the early stages of evolution. Finally, it was shown in a very general form that the collapse of any nonsymmetrical object leads to the creation of an external observable metric which is wholly determined by conserved quantities [55] (with A. G. Doroshkevich and I. D. Novikov).

In 1964 Ya.B. [20*], and independently of him E. Salpiter (USA), showed that a black hole may be found by its influence on the surrounding gas. The heating of the gas produces radiation which may then be detected. It was only after the publication of these papers that astronomers realized that black holes could be observed. It was, in fact, the papers of Ya.B. and his students that pointed out the very important role of accretion of matter