INTRODUCTION TO THE BORIS IOFFE FESTSCHRIFT AT THE FRONTIER OF PARTICLE PHYSICS/HANDBOOK OF QCD[a]

M. SHIFMAN

Theoretical Physics Institute, University of Minnesota, Minneapolis, MN 55455

Handbook of QCD, Vols.1,2,3, 2200 pp., Ed. M. Shifman, is being published by World Scientific, Singapore. This book contains 33 reviews covering all aspects of (analytical) quantum chromodynamics, as we know it today. The articles have been written by recognized experts in this field, on the occasion of the 75$^{\text{th}}$ birthday of Professor Boris Ioffe. Combining features of a handbook and a textbook, this is the most comprehensive source of information on the current status of QCD. It is intended both, for students and advanced researchers. Each review is self-contained and pedagogically structured, providing the general formulation of the problem, telling where it stands with respect to other issues, why it is interesting and important, presenting the history of the subject, qualitative insights, and so on. The first part of the book is historical in nature. It includes, among other articles, Ioffe's and Orlov's memoirs on high energy physics in the 1950's, a note by Ludwig Faddeev, on the early work on the covariant quantization of the Yang-Mills theory, a note of Carlos Bollini on the discovery of dimensional regularization, and an essay on the discovery of asymptotic freedom written by David Gross.

The goal of this book is two-fold. First it was designed to present the full picture of the progress achieved in analytic quantum chromodynamics in the 1990's. QCD is *the* theory of hadrons which will stay with us forever, no matter what, unlike many recent theories whose relevance to Nature is still a big question mark. Every novel result in QCD, every new insight, has a special weight—it reflects our deepening understanding of the structure of matter.

QCD is a notoriously complicated theory, since the majority of interesting hadronic phenomena takes place at strong coupling. This explains why the progress was quite slow, and the final solution is not even in

[a]Preprint TPI-MINN-01/30, HEP-TH-2014. The work supported in part by DOE grant DE-FG02-94ER40823.

sight. The basic ideas and concepts which laid the foundation for this theory had been formulated in the 1970's: asymptotic freedom, infrared slavery, the dual Meissner effect as its possible explanation, topologically nontrivial vacuum structure and the θ angle, lattice formalism, and, finally, various approaches based on Wilson's operator product expansion. Not much has been added since then as far as the fundamental concepts are concerned (a possible exception is an insight obtained from supersymmetric gauge theories). Nevertheless, looking back, and comparing what was known to the QCD practitioners in the beginning of 1980's to the current state of affairs, it will immediately become clear that we have advanced rather far. A good intermediate reference point is provided by the collection *QCD – 20 Years Later*[b] which summarizes the status of theoretical research in QCD by the summer of 1992.

To name just a few topics characterized by the most dramatic developments let me mention the heavy quark theory, $1/N$ expansions for baryons, and the physics of hot and dense quark-gluon matter (including the color superconductivity). A breakthrough in the understanding of subtle qualitative aspects of the strong-coupling gauge dynamics occurred in the late 1990's when the previously existing nonperturbative methods in supersymmetric theories were drastically perfected. Although these latter results are only indirectly related to QCD *per se*, the general messages the superworld sends to the QCD practitioners are quite illuminating. Finally, I should mention that a gradual progress in lattice QCD in the 1980's and 90's has led to a "phase transition." The lattice calculations have acquired sufficient precision and reliability to replace, in many instances, experimental studies of the hadronic dynamics.

In short, the need for a comprehensive "encyclopedia" which would summarize modern understanding of the theory of hadrons, was quite obvious. This was one of the major motivations for this book, a joint effort of a large team of experts whose work was instrumental in making these developments happen. A glance at the list of participants shows that the project has attracted attention of the theorists most active

[b]Proceedings of the Aachen Workshop on QCD, Aachen, Germany, June 1992, Eds. P.M. Zerwas and H.A. Kastrup (World Scientific, Singapore, 1993), Vols. 1,2.

in this field. Each of them prepared a review on the topic of his/her choice, so that, combined together, they present the most comprehensive coverage of analytic QCD one can find in literature. I am deeply grateful to all participants of the project for their efforts which will, hopefully, bring lavish fruits—the book will be used in the community in the years to come.

This was not the only motivation, however. The second goal of this book – as important as its first goal – is to celebrate the 75-th birthday of Professor Boris Ioffe, whose contributions to the theory of hadrons and particle physics at large, are plentiful. The combination of these two tasks makes this book unique.

Ioffe published his first scientific paper in 1951. To give you a flavor of the time, let me remind you that at that time in America, the activities of the House Committee on Un-American Activities were in full swing. This was before satellites, before computers, and even before credit cards.[c] America was still in the age of black-and-white TV. (Who could believe this now? Commercial broadcasting in color started a few years later.)

People in the Soviet Union lived in a black-and-white world too, although they were still a few years away from the advent of television in Moscow. Soviet Union was at the peak of its power, communism sprawled all over Europe and Asia, and we were taught at school that it was the radiant future of all mankind. Those who showed even slightest doubts were very efficiently educated in the *gulag* camps. The atmosphere of these years is very vividly depicted in Ioffe's essay "A Top Secret Assignment" and in Orlov's article "Snapshots from the 1950's" which follows Ioffe's essay.

The Physical Review was not yet divided in sections. The issues appearing biweekly were dominated by nuclear physics; each issue would carry about a dozen papers of the type "Disintegration Scheme of Au^{199}," and one or two papers devoted to particle physics or field theory. To give you an idea, the September 15, 1951, issue which was unusually rich on particle physics and field theory, contained four papers on this subject:

[c]The first credit card, *Diners Club International*, had been just introduced in the US in 1950.

an experimental paper on the π^+ meson lifetime, Bethe's paper on the meson field theory, a paper discussing the fourth-order contribution to the electron self-energy, and, finally, Dyson's paper on the Schrödinger equation in QED.

The realm of strong interactions was limited to pion-nucleon physics which, in turn, was believed to be described by a pion-nucleon field theory. The understanding that the pion-nucleon field theories would not work, because the coupling constant was large, came as a shocking surprise. Ioffe recollects: "I demonstrated that the pion-nucleon constant was large and reported this result at a seminar in 1951. All participants, including Landau and Pomeranchuk, were stunned and shocked by this news. In the US a similar conclusion was reached by Robert Marshak, at approximately the same time. Until 1955, the Soviet particle physics community was completely isolated from the West. For about a year or so in the early 1950's the shipment of Physical Review and other physics journals to the USSR was banned by the American authorities. We were getting these journals illegally, through Sweden. Each issue delivered to ITEP would carry a thick black stamp "classified" on the cover page. This "classified" certainly did not refer to the contents but, rather, to the very fact of the appearance of these journals in Moscow. The first western physicist who came to Moscow was Källén, in 1955. He attracted huge crowds of physicists who came to listen to his talk at the Lebedev Institute. A few days later, he gave another talk at the Institute of Physical Problems, and their largest auditorium was jammed."

This is the past long gone. Since then everything changed—empires disintegrated, new technologies and new ideas blossomed, making our world truly global. A constant component which has not changed during all these 50 years has been Ioffe's dedication to particle physics, his leading role in the particle phenomenology. It would be fair to say that Ioffe's efforts were instrumental in shaping this area of research in the Soviet Union.

The golden age of QED after the discovery of the Feynman graphs, the discovery of strangeness, the Landau zero charge and the subsequent hibernation of field theory, the discovery of the $V - A$ theory of weak interactions, the proliferation of resonances, the Regge theory, Pomerons, the rise and fall of the S matrix methods, Gell-Mann's SU(3), Cabibbo's angle, partial conservation of the axial current, the quarks, the introduction of charm, the Bjorken scaling in deep inelastic scattering, Feynman's partons, the current algebra, the standard model, the proof of its renormalizability and the subsequent revival of field theory, the superextension of the Poincaré algebra and the advent of supersymmetry, asymptotic freedom, quantum chromodynamics, the November revolution of 1974 which began from the discovery of the J/ψ particles, the monopoles and instantons, the vacuum angle θ, axions, the color confinement, lattice QCD, hadronic jet physics and the detection of the gluons, the condensates and the development of the theory of hadrons, the large N expansions, the Skyrme model, canonization of the minimal supersymmetric standard model, hot and dense nuclear matter, the string revolutions, branes and brane worlds – these are just the most conspicuous stages high-energy physics went through since 1951. The 1st International Conference on High Energy Physics was held in Rochester, NY, in 1950. How many notions and ideas changed in high energy physics by the time of the current, 30th International Conference, which took place in the summer of 2000 in Osaka? Many of these changes carry a distinctive imprint of Ioffe's contributions, clearly visible in the background of those made by other researchers. You will read about Ioffe's lifelong achievements in more detail in Geshkenbein's article.

When I came to ITEP around 1970 to do my senior thesis project in particle theory, it happened so that I had to change my physics advisers three times in a relatively short time. Ioffe was my fourth adviser; he picked me up when I just started working on my PhD in 1972. At that time, he was mostly preoccupied with other activities—the physical design and start-up of the nuclear reactor for the first Czechoslovak nuclear power plant (you will read about this in Ioffe's essay). The lessons regarding physics I got from Ioffe were mostly of a general nature, but I remembered them once and for all.

The first lesson which Ioffe conveyed to me in more than one way was that in theoretical physics one should not narrow down one's interests to a single particular problem or a single topic. The scientific horizon of young people who are just starting to do independent research should be broad enough to allow them to choose topics belonging to various – and quite often, competing – directions, so that they can get a general perspective of what is going on in high energy physics. So, the first lesson was about broad horizons.

The second lesson was about attitude. Ioffe used to say that one chooses a career in physics not to get promotions, pay-raises and other "cookies" (he would say *pryaniki*, which is a special type of Russian cookies, something like donuts); not to get famous, but, rather, for sheer fun. Figuring out how things work and answering questions that nobody knew how to answer is fun, and this is the ultimate and the only motivation for devoting one's life to theoretical physics. It is not the fashion of the day that should dictate the topic of the next research project, but an intrinsic curiosity of the researcher which may lead him/her in unexpected directions. That's how the deepest discoveries are made.

I believe that both lessons remain as valid now, as they were almost 30 years ago. The string theory and its offsprings, the most fundamental theories of the day, left experiment far behind. In this environment, the objective criteria of what is important and what is less important are lost, to a large extent. The trends of the theoretical research are set up by personalities.

Way too often we see that fashion is a guiding principle for young people, while scientific curiosity becomes a marginal, rather than the primary motivation. Some complain that it is nerve-wrecking out there, in theoretical physics, and not too much fun.

Ioffe was the student of Landau, Pomeranchuk and Alikhanov. These were the "fathers" of Soviet particle physics, who established, back in the early 1950's, a unique atmosphere in the Moscow community of particle physicists. That's how Ioffe himself characterizes this atmosphere in one of his essays: "[Alikhanov] taught me many things: that one must develop a deep understanding of physics, going beyond the formal level; that one must work on a physics problem with absolute commitment, spare no effort, investing one's heart and mind to the fullest extent; that a true physicist must have a sense of responsibility and courage, integrity and decency; that his or her attitudes must always be genuinely democratic ... " Ioffe was absolutely instrumental in preserving these basic principles and traditions and in conveying them to younger generations of physicists. When I first appeared in ITEP in 1969, these traditions were very much alive. They provided us with the guiding principles that determined our life and work in the 1970's and the 80's, when Landau, Pomeranchuk, Berestetskii, and Alikhanov were no more ... The Theory Department of ITEP in those days was a unique phenomenon (it is described in some detail in my article published elsewhere[d]).

When Ioffe's career in theoretical physics began, the front-line fundamental research was much closer to the human scale than it is now. The impact some fundamental works of that time had on technology was almost immediate, of which the particle physicist of today can only dream. Ioffe spent much of his time working on the theory of nuclear reactors, and he excelled in this theory, much in the same way as in the theory of hadrons. Some people say that this was an unnecessary distraction. I do not think so. Rather, I am envious. What theoretical construction can be as solid as a nuclear power plant?

⋆ ⋆ ⋆

Now I have to say a few words about the structure of this book. First, the title of the book, "At the Frontier of Particle Physics," requires a comment. I want to explain why quantum chromodynamics remains a frontier science almost thirty years after its discovery.

Physics is a live organism; it grows like a tree – branches appear, grow, give rise to new branches, dry out ... Particle physics (later, high energy physics) split from nuclear physics in the 1950's, when it established itself as a separate discipline, with specific theoretical tools and experimental setups. Much in the same way, in the 1990's, string theory split from the rest of high energy physics. By now, its transformation to a separate science is complete. Professionals in this field call themselves string theorists rather than high energy theorists.

You may ask what remained in the realm of particle physics. I will

[d] M. Shifman, *ITEP Lectures on Particle Physics and Field Theory* (World Scientific, Singapore, 1999), pp. v – xi [hep-ph/9510397].

go as far as to say that QCD is its only heir. Supersymmetry-based phenomenology is not yet a competitor—after all, supersymmetry has yet to be discovered.

The first part of the book is historical. Apart from the above-mentioned Ioffe's and Orlov's memoirs, it contains notes by Geshkenbein and Khriplovich, on Ioffe's career in particle physics, an article by Ludwig Faddeev, on the early work on the covariant quantization of the Yang-Mills theory, and an essay on the discovery of asymptotic freedom written by David Gross. (The readers who would like to acquaint themselves with Frank Wilczek's perspective are referred to the collection *QCD – 20 Years Later* quoted in the beginning. Incidentally, it also contains illuminating memoirs of Murray Gell-Mann, one of the founding fathers of quantum chromodynamics.[e])

The second (and the larger) part of the book is a collection of reviews on all aspects of the modern theory of hadrons, and Yang-Mills theory at large, written specifically for this publication. The phenomena, regularities and dynamical regimes discussed in these reviews are extremely diverse – from nuclear physics to high-energy scattering, to color superconductivity – nevertheless, they all are described by QCD. In fact, the present book can be considered as a testimony to the exceptional wealth of the dynamical phenomena taking place in the hadronic world. Given this richness, can one hope to find in the future a single analytic solution, the holy grail of two generation of theorists, which would be applicable to all these regimes?

It was up to the individual contributor to choose the topic closest to his/her heart. My task was to make sure that the team would be representative enough, so that all relevant topics would be covered. Working on this book turned out to be a very exciting endeavor. I hope you will find it just as exciting to read.

August 29, 2000.

[e]It was M. Gell-Mann who coined the name *quantum chromodynamics*, QCD for short. I clearly remember that Valya Zakharov, who was ITEP's ambassador at the 1972 Rochester Conference, upon return from FERMILAB told us that Gell-Mann had been preaching color octet gluons as the strong force mediators, and we ought to do something. Unfortunately, it took me about a year to get started.

General acknowledgments

The editor would like to express his sincere gratitude to all participants of the project. I am grateful to Alex Roitman who was responsible for typesetting this book in LaTeX, and to Eric Barrett for expert advice on the English grammar. I would like to thank Prof. Jan Fischer for his consultations regarding the spelling of the Czech names mentioned in Ioffe's essay and the Czech history.

Special thanks go to Forrest Rhoads, Milla Grin and Mort Hamermesh, for translating Ioffe's essay from Russian, and to Mrs. Poline Tylevich for creating several successive versions of the cover jacket and illustrations.

List of participants

P. van Baal, I. Balitsky, S. Beane, P. Bedaque, M. Beneke, Z. Bern, C. Bollini, V. Braun, S. Brodsky, K. Chetyrkin, P. Colangelo, F. De Fazio, D. Diakonov, H.G. Dosch, L. Faddeev, B. Geshkenbein, D. Gross, W. Haxton, K. Holland, B. Ioffe, A. Kaidalov, A. Khodjamirian, V. Khoze, I. Khriplovich, A. Kovner, H. Leutwyler, F. Lenz, A. Manohar, L. McLerran, U.-G. Meißner, S. Nussinov, W. Ochs, Yuri Orlov, V. Petrov, D. Phillips, A. Radyushkin, K. Rajagopal, M. Savage, V. Schön, M. Shifman, E. Shuryak, A. Smilga, M. Strassler, M. Thies, Wu-Ki Tung, N. Uraltsev, A. Vainshtein, U.-J. Wiese, F. Wilczek, S. Wörlen, J. Wosiek, A. Yung.