THE QCD VACUUM, HADRONS AND THE SUPERDENSE MATTER

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THE QCD VACUUM, HADRONS AND THE SUPERDENSE MATTER

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*To the memory of my first
teacher in physics,
Yu. B. Rumer.*

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Preface

Following tradition, let me start this book with a general outline of its contents. This preface is also an attempt to explain why this book is written and who its potential readers may be.

About 15 years ago it was discovered, that strong (or hadronic) interactions are governed by so called *Quantum Chromodynamics* (QCD), the theory of interacting quarks and gluons. As a theoretical construction QCD is very attractive, it is very economical and close in its foundations to Quantum Electrodynamics (QED). About a decade ago specialists in strong interactions were very optimistic about the rapid progress in this field: on one hand they had the fundamental theory and on the other, plenty of data. What more could be needed?

However, it was soon found that such optimism was rather naive. The Lagrangian written at the blackboard is not yet the theory, and the voluminous "Particle Data Tables" does not necessarily contain the information we really need. One has to decide which quantities are the most simple and the most fundamental ones, how to derive them from the theory and how to observe them in an experiment. In short, with the groundstones laid down one had a lot of physics to do. The present status of related studies and the nearest goals for the future is the subject of this book.

The smallness of the coupling constant at large momentum transfer (the so called "*asymptotic freedom*") makes it possible to consider "hard processes" using the familiar perturbative language. This so called "perturbative QCD" (below pQCD) has been born and successfully developed. Its applications have convinced us that QCD is really the true theory. It is more or less completed now, at least from the theoretical side.

However, *the most important strong interaction phenomena cannot be described by the perturbative methods*, and "nonperturbative QCD" (npQCD) is at the moment the greatest challenge to all of us. Opinions on its status and perspective differ drastically and I would like to mention one extreme case here.

Some people think that since the fundamental theory is known, the problem

is just a *computational* one. Therefore they use all the power of modern computers trying to solve it “from the first principles”. “QCD is nearly finished,” they say, “we just need more powerful computers and more efficient codes”. Another consequence of this viewpoint is that no more experiments in hadronic physics are needed: there are enough numbers to test the calculations.

This point of view is strongly opposed in this book. For example, we know from experiments that the proton mass is 938 MeV, and if some future computer experiments give the same value we will say that they are well done and that they demonstrate once more that QCD is indeed the right theory. But the real problem is to understand *why* the proton mass has this value. As it is shown below, the “battle for npQCD” is not only not won, but we have only started to realize what the reasonable strategy in this campaign may be.

In particular, we have realized that hadrons are not so simple and not so fundamental objects to start with: like the phonons in solids, they are elementary excitations in the complicated substance, *the QCD vacuum*. One may measure the phonon spectrum, their scattering cross sections at various angles, production and annihilation rates etc, but it is impossible to understand what phonons are without realizing that it is just the displacements of atoms. Similarly, *we also have to point out the main degrees of freedom* in terms of which the “vacuum structure” can be described. For doing this we need some simple empirical facts, for example, the equation of state of the matter (the solid state or the QCD vacuum). Therefore, we badly need quite different types of experiments!

There also exist some other hints showing that hadronic physics is now at a turning point in its development. Colliders have reached TeV energies, and whatever may be found at still higher ones will hardly contribute much to the understanding of strong interactions. Thus, this field of research is now decoupling from the frontier of the “high energy physics”. On the other hand, the gap separating hadronic and nuclear physics is now actively filled from both sides, so that the separation of these disciplines becomes purely conventional. (The heavy ion experiment just mentioned is a good example of this process.)

Why was this book written? The formal answer is that, after two review papers for Physics Reports, I have obtained a proposal from the World Scientific. The real explanation is that it is one more attempt to oppose the “entropy growth” and provide a kind of a guide for various activities connected with the npQCD, *explaining its ideas and established facts at the “general physics” level*. I have tried to keep to the lecture-type presentation (so the nickname of this book is “A hundred lectures on modern strong interaction physics”). If for some of the readers it turns out to be difficult to follow the presentation, they are encouraged to skip over such places, and to

return to them later, if it becomes clear that it is really necessary for them. The order of the presentation more or less follows the internal logic of the theory and partly its historical development, but it is not necessarily the best one for all the readers. This book is neither a mathematical textbook nor a detective story, so it is completely meaningful to try to read it from the middle.

I hope that this book can be useful for high energy or nuclear physicists (both the theorists and experimentalists) who are going to “look around” at topics not directly connected to their own work. It can also be useful for younger people who need some informal introduction before the more serious studies. The latter half of the book is probably most interesting for nuclear physicists, especially for experimentalists, because here we discuss a forthcoming experimental program with high energy heavy ion collisions, leading to highly excited matter.

Now, a word of warning is needed. Any judgement in such a rapidly developing field is risky and I am probably mistaken (or too subjective) in many places. Thus, following Bohr, let me say that my comments should not be taken as statements, but as questions.

The last point is the acknowledgements to my friends, from whom I have learned all this stuff. (If the meaning is not very clear, it is my fault, not theirs!). Let me name here some of them: V. L. Chernyak, D. I. Dyakonov, E. L. Feinberg, I. B. Khriplovich, V. A. Novikov, V. Yu. Petrov, M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, O. V. Zhirov and A. R. Zhitnitsky. Finally, I would not be able to handle such a voluminous book with hundreds of references and formulae, if I had not been aided by a computer. In this respect I am much indebted to B. Shuvalov who made it possible and so effective.