Physics – Uspekhi **49** (10) 1077 – 1078 (2006)

METHODOLOGICAL NOTES

PACS numbers: 12.15.Ff, 12.38.Aw, 14.80.Bn

The origin of mass and experiments on future high-energy accelerators

B L Ioffe

DOI: 10.1070/PU2006v049n10ABEH006030

Abstract. The observable world is the one consisting of nucleons and electrons. The mass of the nucleon arises from chiral symmetry breaking in quantum chromodynamics (QCD), so that high-energy accelerator experiments cannot give any clues to the nature of the mass of matter in the observable world. The origin of the mass of matter will be clarified when the mechanism of chiral symmetry breaking in QCD will be established.

The Large Hadron Collider (LHC), where two beams of protons, 7 × 7 TeV, will collide, is under construction at CERN. The plan is to make the LHC operational during 2007 and to begin experiments in 2008. The possibility of constructing other high-energy accelerators, namely, a linear accelerator for electrons and positrons with colliding e^+e^- beams with energies in the 0.5 – 1-TeV range, and muon and photon colliders, is also being discussed. The goal of the experiments on high-energy accelerators to come is to study physics beyond the Standard Model, i.e., to study physical processes at energies inaccessible with existing accelerators and to search for new heavy particles that are unknown but predicted theoretically, such as the Higgs boson and supersymmetric particles (to name just two). What is known as the Standard Model is the $SU(3) \times SU(2) \times U(1)$ gauge theory, where SU(3) corresponds to quantum chromodynamics (QCD) presenting the strong interaction theory, and $SU(2) \times U(1)$ to the electroweak theory which combines electromagnetic and weak interactions. The results of experiments involving operational (or operational in the past) high-energy accelerators agree with the predictions of the Standard Model and have produced no clues as to whether there is a new physics beyond the model. Experimental evidence on neutrino oscillations, the first data on the existence of the Majorana neutrino, and astrophysical data (the existence of dark matter) indicate that such a physics exists. Hence the great expectations related to experiments with the LHC and other future high-energy accelerators.

One of the most important problems that has remained unresolved in the verification of the Standard Model is the problem of the origin of the mass of particles that experiments with the LHC (and future accelerators) are supposed to solve. In their report [1] devoted to experiments with future accelerators, De Roeck, Ellis, and Gianotti suggest that "The most prominent areas where the Standard Model leaves unsolved problems include the origins of the particle masses..." In the joint suggestion of possible experiments on the LHC made by the ATLAS and CMS Collaborations [2] it is stated that "The $SU(3) \times SU(2) \times (1)$ gauge interactions in the Standard Model provide an elegant and tremendously successful description of existing data, but they give no explanation of the origin of particle masses." It is also believed [3] that the main problem of future studies on a linear e^+e^- collider is "the mechanism of electroweak symmetry breaking or, in other words, what is the origin of mass in particle physics." This problem is formulated in a similar way in other papers devoted to experiments on future accelerators (e.g., see Refs [4, 5]).

The above statements are based on the initial idea behind the Standard Model. In this model, the breaking of the gauge SU(2) symmetry, which is needed for the $W^\pm$ and Z intermediate bosons to acquire mass, is realized by the introduction of a scalar field φ, being the doublet in the SU(2) symmetry. The field φ interacts with the $W^\pm$ and Z fields, quarks, leptons, and itself. It is assumed that the self-action potential is such that its minimum emerges at a φ that is finite and constant in space and time, $\varphi = \varphi_0$. Thus, the field φ is represented as a series expansion near this potential minimum: $\varphi = \varphi_0 + \chi$, where χ is a quantum field whose quanta are Higgs bosons. It is because of the constant scalar field φ_0, i.e., the terms $g^2\varphi_0^2 W^2$, $g^2\varphi_0^2 Z^2$, $h_{li}\varphi_0 \bar{l}_i l_i$, and $h_{qi}\varphi_0 \bar{q}_i q_i$ in the interaction Lagrangian, that intermediate bosons, quarks, and leptons acquire their masses. (Here l_i and q_i are the lepton and quark fields, while h_{li} and h_{qi} are the coupling constants.) Therefore, the observation of the Higgs boson and of its interaction with quarks and leptons should explain the origin of lepton and quark masses. It is exactly this possibility that was expressed in the above statements.

The aim of the present note is to draw readers' attention to the fact that elucidation of the problem of the existence of the Higgs boson and of the structure of its interaction with quarks (and, more broadly, the study of interaction at high energies) is in no way related (more exactly, is related very little) to the problem of the origin of the masses of particles of the observable world. The observable world — the stars, the planets, the galaxies, and, in general, objects that surround us — consist of protons, nuclei, and electrons. Electrons contribute insignificantly to the mass of the Universe, less than 0.1%. Hence, to establish the origin of the mass of the observable world, we must establish the origin of the nucleon mass. (For the time being I will not mention the mass of dark matter.) A nucleon consists of u- and d-quarks, but these quarks have small masses: $m_u + m_d \approx 10$ MeV, i.e., their mass is only a small fraction ($\sim 1 - 2\%$) of the nucleon mass. It can be shown that in the formal limit $m_u, m_d \to 0$ the nucleon mass remains practically the same. The nucleon

---

B L Ioffe Russian Federation State Scientific Center
'A I Alikhanov Institute for Theoretical and Experimental Physics'
ul. B. Cheremushkinskaya 25, 119218 Moscow, Russian Federation
Tel. (+7 495) 123 31 93
Fax (+7 495) 883 96 01
E-mail: ioffe@itep.ru

Received 11 January 2006
Uspekhi Fizicheskikh Nauk **176** (10) 1103 – 1104 (2006)
Translated by E Yankovsky; edited by A Radzig

acquires mass because of spontaneous breaking of chiral symmetry in QCD, and this mass can be expressed in terms of vacuum condensates which break the chiral symmetry [6]. There is an approximate formula that expresses the nucleon mass in terms of the quark condensate [6–8]:

$$m = \left[-2(2\pi)^2 \langle 0 \mid \bar{q}q \mid 0 \rangle \right]^{1/3} . \tag{1}$$

Here, m is the nucleon mass, $\langle 0 \mid \bar{q}q \mid 0 \rangle$ is the quark condensate, and q is the field of u- or d-quarks. (Reviews of the current state of chiral symmetry in QCD, its breaking and the problem of proton mass can be found in Refs [9, 10].) From the chiral symmetry (conservation of the axial current, violated by the quark masses) there follows an expression for the quark condensate (the Gell-Mann – Oakes – Renner formula [11]):

$$\langle 0 \mid \bar{q}q \mid 0 \rangle = -\frac{1}{2} \frac{m_\pi^2 f_\pi^2}{m_\mathrm{u} + m_\mathrm{d}} , \tag{2}$$

where m_π and f_π are the mass and decay constants of the π-meson. As the quark masses tend to zero ($m_\mathrm{u}, m_\mathrm{d} \to 0$), so does m_π^2, with the result that $\langle 0 \mid \bar{q}q \mid 0 \rangle$ tends to a constant limit. The value of the quark condensate recently found from the data on τ-decay [10] is equal to

$$\langle 0 \mid \bar{q}q \mid 0 \rangle = -(254\ \mathrm{MeV})^3 \pm 10\,\% .$$

Substituting this value into formula (1) yields $m = 1.09$ GeV, while the experimental value of the nucleon mass is 0.94 GeV. Thus, to establish the reasons for the nucleon acquiring mass we must understand the mechanism of chiral symmetry breaking in QCD. The breaking of chiral symmetry occurs over large distances (~ 1 fermi $= 10^{-13}$ cm) and, in this way, is not related to experiments at high energies, which probe small interparticle distances of about 10^{-17} cm. (Chiral symmetry is not broken at small distances.) Clarification of the mechanism of chiral symmetry breaking in QCD constitutes a theoretical problem. Calculations on lattices could possibly help here, as well as experiments in collisions of heavy ions at high energies, from which data on phase transitions in QCD could be hopefully extracted. Incidentally, the baryon number density in such experiments is large, i.e., the chemical potential μ is high, while $\mu = 0$ in a vacuum. Phase transitions with μ finite and $\mu = 0$ can be quite different [12, 13].

In the Standard Model, the electron acquires its mass because of the interaction with the Higgs field. Consequently, the origins of the proton and electron masses are very different, so that their large difference is not surprising.

A brief remark concerning dark matter is in order. For the present, the nature of such matter remains unknown. Apparently, the particles of dark matter are extremely heavy and interact only weakly with ordinary matter. In this case, it is highly improbable that they acquire their mass because of the interaction with the Higgs field.

I would like to express my gratitude of A V Samsonov for his help in selecting the materials related to experiments on future accelerators. This work was made possible by the support of CRDF (Grant RUP2-2621-MO-04), the EC Fund within the “Research in Strongly Interacting Matter” Project, Contract 2004 No. R113-CT-2004-506078, and RFBR grant 06-2-16905a.

References

1. De Roeck A, Ellis J, Gianotti F “Physics motivations for future CERN accelerators”, Report CERN-TH/2001-23; hep-ex/0112004
2. Branson J G et al. (ATLAS Collab., CMS Collab.) *EPJdirect C* **4** (N1) 1 (2002); hep-ph/0110021
3. Richard F *Int. J. Mod. Phys. A* **19** 1240 (2004); hep-ph/0312020
4. Simmons E H, in *Flavor Physics for the Millennium, TASI 2000: Proc. of the Theoretical Advanced Study Institute in Elementary Particle Physics, Boulder, CO, USA, 2000* (Ed. J L Rosner) (Singapore: World Scientific, 2001); hep-ph/0011244
5. Froggatt C D “The origin of mass”, in *Proc. of the 6th Intern. Moscow School of Physics (XXXI ITEP Winter School of Physics), ITEP, February 18–26, 2003*; http://www.itep.ru/ws/2003/?proc; *Surv. High Energy Phys.* **18** 77 (2003); hep-ph/0307138
6. Ioffe B L *Nucl. Phys. B* **188** 317 (1981); **191** 591 (1981)
7. Belyaev V M, Ioffe B L *Zh. Eksp. Teor. Fiz.* **83** 876 (1982) [*Sov. Phys. JETP* **56** 493 (1982)]
8. Ioffe B L *Acta Phys. Polon. B* **16** 543 (1985)
9. Ioffe B L *Usp. Fiz. Nauk* **171** 1273 (2001) [*Phys. Usp.* **44** 1211 (2001)]
10. Ioffe B L *Prog. Part. Nucl. Phys.* **56** 232 (2006)
11. Gell-Mann M, Oakes R J, Renner B *Phys. Rev.* **175** 2195 (1968)
12. Rajagopal K, Wilczek F, in *At the Frontier of Particle Physics: Handbook of QCD: Boris Ioffe Festschrift* (Ed. M Shifman) Vol. 3 (Singapore: World Scientific, 2001) p. 2061
13. Chernodub M N, Ioffe B L *Pis'ma Zh. Eksp. Teor. Fiz.* **79** 742 (2004) [*JETP Lett.* **79** 606 (2004)]