The last of the Mohicans...

L. I. Urutskoev [1)], Yu. P. Rybakov [2)], N. V. Samsonenko [2)]

1) Sukhumi Institute of Physics and Technology, Sukhumi (Abkhazia)
2) Peoples' Friendship University of Russia, Moscow

Dedicated to the blessed memory of Georges Lochak

It is very difficult to write in the past tense about such a bright personality, which, of course, was Georges Lochak. And although a serious illness pulled him out of active life several years before his death, and it would seem that there was enough time to come to terms with the inevitable, but, nevertheless, the sad news of February 4, 2021 painfully echoed in the hearts of those who were intimately familiar with him. Georges Lochak was a multifaceted personality who surprisingly combined: the talent of a theoretical physicist with the gift of a writer and popularizer of science, and his love for art and history with a subtle flair of a crystallographer for various manifestations of the symmetry of Nature. He was a prominent representative of the scientific school of Louis de Broglie, who consistently defended and promoted the ideas of his great Teacher. Georges Lochak fruitfully worked for many years in the field of theoretical physics and published over a hundred scientific articles. But perhaps his most famous scientific achievement is the theory of the lepton magnetic monopole. This truly unexpected result was first published by him in 1983 [1].

Pierre Curie was the first to draw attention to the fact that if a magnetic charge exists, then it must obey a different type of symmetry than an electric charge [2]. His reasoning was simple. The electric charge is a scalar and produces a field that is described by the polar vector $\boldsymbol{E}$. Since the magnetic field vector $\boldsymbol{H}$ is a pseudovector, the reason that generates it (that is, the magnetic charge) must have the same symmetry, which means that the magnetic charge is pseudoscalar. And it was on this basis that Lochak liked to say: "There is no real symmetry between electricity and magnetism, but there are two slopes of the same peak: vector and pseudovector."

In physics, Dirac's theory of the magnetic monopole is widely known [3]. In this theory, Dirac succeeded in linking the non-integrability of the phase of the wave function with the singularity arising in the description of the interaction of an electron with a magnetic pole. Based on the idea of local gauge invariance, the laws of electromagnetism and quantum mechanics, he deduced the possibility of the existence of such a particle, which is called: ad hoc. Dirac's monopole is not a solution to the basic equation of quantum electrodynamics that bears his name, and although more than one hundred theoretical works are devoted to this topic, it still stands somewhat apart from the place where the main road of development of theoretical physics passes.

Georges Lochak said that in 1957, when he came to Louis de Broglie at the Poincaré Institute, all the staff of the institute, with the exception of the concierge, were busy solving the Dirac equation. But there was no concierge on the staff of the institute, and Lochak added, laughing. As a young theorist, he wrote Dirac's theory in algebraic language, representing the Dirac spinor in terms of a pseudoscalar, a pseudo-angle, and six Euler angles: three representing rotation in three-dimensional space and three others that represent imaginary rotations in Minkowski space. Lochak presented the Dirac equation in terms of rotation, relying on the immutable fact that everything rotates in the world of quantum mechanics (everything is based on spin). This approach led him to a rather complex representation of the Dirac equation, which contained two remarkable formulas: one related the electric current to the rotation of the spin; while the other linked two unknown objects. One of these objects is a pseudo-angle, the other is a strange value, the fourth component of the rotation of the spin vector. These two formulas were remarkably similar and very simple, although they were the result of very complex calculations. Any theoretician intuitively understands that if simple connections are obtained as a result of long and complex calculations, then they contain some kind of secret meaning. For many years, the meaning of the quantities included in the formulas obtained remained incomprehensible to Lochak.

The understanding of the physical meaning of the values he obtained came only in 1982 during a colloquium in honor of Rene Thom. Georges

Lochak chose "the geometrization of physics"[1] as the subject of his speech. During his speech, he suddenly realized: the first equation says that there is a connection between the conservation of an electric charge and a certain rotation, the second expresses the conservation of a magnetic charge associated with a different angle of rotation. He told us that from that moment he plunged into calculations, right during the colloquium. It took him some time to create a rigorous theory, and as a result, what we now call the Lochak theory of the magnetic monopole appeared [4, 5]. It seems to us that in this memorial essay it makes no sense to give detailed calculations of Lochak theory, since it was published by the author in all details in *Annales de la Fondation Louis de Broglie*. We will only try to emphasize its difference from other theories of the magnetic monopole.

Initially, we will look at Lochak's theory through the eyes of an experimenter, and since experimenters believe in complex formulas (no less than theorists in experimental results), we will write the basic Lochak equation. In relativistic units, it will look like:

$$\gamma^{\mu}\nabla_{\mu}\Psi \equiv \gamma^{\mu}\left(\partial_{\mu} + ig\gamma^{5}B_{\mu}\right)\Psi = 0, \tag{1}$$

in which the charge is not a scalar, but a pseudoscalar operator $G = g\gamma^5$. Equation (1) can be interpreted as an equation describing just a magnetic charge, because its solutions satisfy the Curie symmetry rules for a magnetic charge.

But due to the pseudoscalar nature of the operator G, the scalar g does not change sign during spatial inversion, which, of course, cannot but "warm the soul of the experimenters". In fact, in Lochak's theory, the chirality of the magnetic one does not lie in the change in the sign of the magnetic charge during spatial inversion, but in the transition to another eigenvalue corresponding to the eigenvalue of the other sign of the matrix $g\gamma^5$.

The linear mass term in (1) is absent, since it does not correspond to the gauge transformation with the matrix γ^5. Thus, equation (1) is divided into two independent equations in the well-known Weyl representation (spiral representation), which is usually used to describe neutrinos. This is an important point of the entire Lochak's theory, since at zero

[1] This topic was very close to him, and in 1994 Georges Lochak published in France a wonderful book "La Géométrisation de la Physique", and in 2005 it was published in Russian.

magnetic charge g, his equation (1) coincides with the neutrino equation. This allows the Lochak monopole to be interpreted as a magnetically excited state of a neutrino, which is very important for experimenters in at least several aspects.

First, it has zero (or almost zero)[2] rest mass, which means that no significant energies are needed to create a monopole-antimonopoly pair, and experimenters do not need powerful linear accelerators or colliders, but rather small installations. But, on the other hand, it is for this reason that it is not so easy to detect it, since given its "neutrino origin", one can a priori assume that its interaction cross section with matter will not be high. Unfortunately, Lochak's theory does not answer the question: how effectively a magnetic monopole will interact with electric charges. Apparently, only future experiments can answer this question.

Second, the Lochak's magnetic monopole is a lepton and, therefore, a participant in weak interactions. That is, its presence should affect the probabilities of weak nuclear processes: k-capture, β^- and β^+ decays. The last circumstance is very important, since it is, as it were, the "calling card" of the Lochak's monopole. Another of its "calling card" is the fact that it has chiral symmetry, which means that it changes the sign of its charge upon spatial reflection. To this it should be added that equation (1) admits tachyon solutions, which can also happen by the direction of the search for the Lochak's magnetic monopole.

When the experimenter gets a truly unexpected and qualitatively new result, the first thing he starts to do is to check and double-check the results of his diagnostics and to carry out validation experiments. If it is not possible to achieve success on this path (in other words, to get rid of an unexpected result), then he begins to study similar experiments of other researchers, trying to understand: why other researchers did not find this result? And if he comes to the conclusion that either his installation is unique, or he used diagnostics that other researchers did not use in similar experiments, then confidence gradually grows in him: the registered effect is not an experimental error, but a real experimental fact. Then he completely "falls in spirit" and, out of complete despair, begins to study the works of theorists, hoping to find a theory that would predict, at least something similar to the effect he registered. And if he succeeds, then he is seized by a feeling of unrestrained joy, since he

[2]It should be borne in mind that when Georges Lochak created his theory, neutrino oscillations had not yet been experimentally detected and the neutrino was considered a massless particle.

instantly realizes that he can share responsibility with the theoretician "for what he has done."

In 1998, quite unexpectedly, it was discovered that the initiation of nuclear reactions is observed during a multichannel high-current electric explosion of metal foils in a liquid. The experiments were carried out by the Institute of Atomic Energy named after I.V. Kurchatov and many specialists from the institute were involved in the study of this phenomenon. It was quickly established that the course of these exotic nuclear reactions is not accompanied by any known type of nuclear radiation (neutrons, γ-quanta), as well as residual radioactivity. All types of detectors available at the Institute for recording any type of nuclear radiation were used. But they were all "silent". This circumstance gave rise to deep doubts about the reliability of the result.

Out of complete despair, it was decided to use the "old-fashioned" methods of detecting radiation: nuclear emulsions. And, as it turned out, it was this "old-fashioned" technique that gave the result. After the manifestation of nuclear emulsions, very strange traces were found on their surface, reminiscent of the track of a caterpillar crawling along the sand. These tracks did not look like any of the known types of radiation. But, of course, these were traces of penetrating radiation, since the plates with nuclear emulsions deposited on them were wrapped in two layers of photographic paper, and were located at least a meter from the place of the electric explosion. Thus, an electrically charged particle could not reach the nuclear emulsion; moreover, the type of tracks from ions of any energy was well known. It seemed to all the participants in the experiment that we were at a dead end, since a neutral particle does not leave traces in a nuclear emulsion, and an electrically charged one does not reach.

A ray of hope flashed when a magnetic field was applied to the installation. The strange tracks changed their topology, the "caterpillar" tracks turned into something that looked like a comet. A black core and a tail with a variable degree of blackening were clearly visible, which gradually merged with the light part of the emulsion. This meant that the detected radiation interacts with a magnetic field. It was then that the intuitive hypothesis that we observe a magnetic monopole was born for the first time. After that, the first targeted pilot experiments on the registration of a magnetic monopole began.

The idea was taken from work [6], in which it was proposed to use the domains of a ferromagnet as a trap for a magnetic monopole. In accordance with the calculations of the authors of the work, the magnetic monopole trapped in the trap should change the magnetic field on the nuclei of the atoms of the ferromagnet, due to the large value of its charge. It was proposed to use ^{57}Fe as a ferromagnet, so that after the capture of magnetic charges, one could observe a slight broadening of the lines of the Mössbauer spectrum. Foils of ^{57}Fe were installed near the place of the electric explosion in such a way that one of them was in the field of the north pole of the magnet, and the other - in the south pole. Based on the assumption that magnetic monopoles should be produced in pairs with different charges (north-south), it was necessary to select them. The experiment showed that the Mössbauer spectrum did not broaden, as expected, but shifted as a whole: to the left from the initial position on one magnet and to the right on the other. The effect was not great, but it surely went beyond three measurement errors. This was the first powerful argument in favor of the magnetic monopole hypothesis. Several years later, Nikolai Ivoilov repeated these measurements using the Mössbauer conversion spectrometry method and obtained the same result [7].

But the hypothesis of magnetic monopoles led to a catastrophic contradiction with the conservation law. From mass spectrometric measurements, we quite accurately knew the number of nuclei that underwent nuclear transformations. It was quite reasonable to assume that the number of emerging pairs of monopoles should be comparable to the number of acts of nuclear reactions that have occurred. The Dirac monopole was the least massive of all magnetic monopoles that we knew about at the time. But a simple multiplication of the required number of monopoles by the mass of one Dirac monopole led to an amount of energy significantly exceeding that which was originally stored in our capacitor bank. We were again at a dead end. By that time, more than 400 experiments had already been carried out, and we decided to publish the results obtained, calling the radiation we detected: "strange" [8]. In the published article, only a "timid" hypothesis was expressed that the possibly "strange" radiation is magnetic monopoles.

In order to try to understand the mechanism of nuclear transformations, experiments on the electric explosion of titanium foils in a uranium solution were started in 2000. Radioactive U nuclei served as detectors in these experiments. Experiments have shown that an electric explosion does not affect nuclear processes occurring due to strong nuclear interactions, but it significantly initiates processes involving weak nuclear interactions (it was mainly β^- decay). This was somewhat unexpected, but quite understandable, simply based on the values of the constants of the strong nuclear, electromagnetic and weak nuclear interactions. It was around this time that one of our colleagues from the Nuclear Center in Dubna told us about Lochak's theory. And when we got acquainted with it, we were simply delighted. This is not to say that we immediately realized the subtleties of this theory, but we understood the main thing. The theory of the lepton magnetic monopole completely removed the contradiction with the law of conservation of energy and shed light on new current results, simply because the Lochak monopole is a lepton.

Soon Georges Lochak flew to Moscow and visited our laboratory. It was a very useful and pleasant acquaintance for all members of the experimental group. He spoke at a seminar at our institute, and his theory became much clearer for us. We, in turn, shared with him in detail our latest results. He listened attentively and bitterly complained that he had devoted so little space in his theory to the lepton character of his monopole. After this trip, he quickly eliminated his shortcoming and very soon published his article on the influence of a lepton magnetic monopole on the course of weak nuclear processes [9]. So not only the theory helped the experiment, but the experiment also helped the theory.

Several years later, Nikolai Ivoilov, using double-sided X-ray films, registered chiral radiation traces [10]. This was a strong additional argument for the "strange radiation" being Lochack's magnetic monopole. But the entire sum of the experimental results obtained did not yet make it possible to make the statement that the Lochak magnetic monopole was discovered. Additional research was required. And first of all it was necessary to develop an analogue of the "Geiger counter" for a magnetic monopole. Because, as is well known, science begins when metrology appears. And although some progress in this direction is observed, but so far, unfortunately, such a device has not been developed to this day.

The experimentally observed phenomenon of nuclear transformation of atoms, which occurs in a dense, weakly ionized plasma at low energies (~ 1 eV), remained outside the framework of the predictions of the theory created by G. Lochak. Experimental results [11, 12] and numerical simulation [13] have shown that the phenomenon of nuclear transformation is a fundamentally new type of reactions in nuclear physics and is of an essentially collective (many-particle) nature. For this reason, it cannot be described by the single-particle equation (1). For a theoretical description of these types of nuclear reactions, some fundamentally different approaches must be developed. Georges Lochak understood this perfectly, but was convinced that the lepton magnetic monopole in this phenomenon can play the role of a kind of "catalyst" of nuclear processes [14].

Lochak's theory of the lepton magnetic monopole is in no way connected with the Standard Model, and therefore was "on the sidelines" of the mainstream development of theoretical physics. Since any new elementary particle must have its own cell ("registration") in the Standard Model. Harold Stumpf succeeded in rectifying the situation and solving this problem [15–17]. By introducing magnetic symmetry into the lepton sector, he showed that the lepton magnetic monopole can be consistently included in the Standard Model by expanding it. In 2015, G. Lochak and H. Stumpf published a joint book dedicated to the magnetic monopole, as if summing up their activities over the last decade of their lives [18].

In addition to the theory of the magnetic monopole, Georges Lochak was fruitfully engaged in other topical issues of theoretical physics. It should be mentioned the active participation of G. Lochak in the discussion of a number of topical results of quantum theory. In particular, his works on the interpretation of quantum mechanics in connection with J. Bell's theorem on nonlocal hidden parameters are well known. Thus, in his article, he poses the question of whether Bell's inequality is of general importance for theories with hidden parameters, and answers this question in the negative [19].

The argumentation of G. Lochak is based on a very important remark about an additional assumption made by Bell in the proof of his theorem. As is well known for the Einstein - Podolsky - Rosen paradox, when formulated in the version of D. Bohm, two successive measurements of the projection of the particle spin on different directions were considered. At the same time, Bell additionally assumed that the distributions of hypothetical hidden parameters are the same for the first and second measurements. G. Lochak emphasized that such an assumption cannot be true, since during measurement there is always a change in state, and hence a change in distribution .

The conclusion made by G. Lochak is very important for the further development of quantum theory. In particular, in the theory of de Broglie's double solution, measurement is associated with the interaction of particles, that is, with nonlinear terms in the equations of motion describing the influence of the so-called "singular" part of the de Broglie wave.

In one of the last visits of G. Lochak to Russia, one of the authors [3)] of this article asked him the question:

"What achievement of de Broglie is, in your opinion, the most important among all scientific directions developed by your Teacher during his long life?"

Without hesitation for a second, he instantly replied:

"Well, of course, the de Broglie wave, which is possessed by all elementary particles without exception (and there are already several hundred of them!). It follows from this that the wave functions of all elementary particles without exception (even not yet discovered) automatically satisfy the second-order wave equation, which in this sense is more general and more universal than any first-order equation (Maxwell, Dirac ...) used for descriptions of particular cases of individual classes of particles".

We would like to pay tribute to the insight of G. Lochak, who thought very outside the box and deeply understood Physics, like his great teacher Louis de Broglie. Georges Lochak was an extremely charming person, communication with whom always brought true intellectual and emotional pleasure.

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