EARLY YEARS OF HIGH-ENERGY NEUTRINO PHYSICS IN COSMIC RAYS AND NEUTRINO ASTRONOMY (1957-1962) *

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60th October Anniversary Prospect, 7A, Moscow 117312, Russia

Ideas of deep underground and deep underwater detection of high-energy cosmic neutrinos were firstly suggested by Moisey Markov in the end of 50^{th}. Frederic Reines was one of those who first detected high-energy atmospheric neutrinos in underground experiments in the middle of 60^{th} (as well as low energy reactor neutrinos 10 years earlier!). Markov and Reines closely collaborated in 70^{th} – 80^{th} in discussion of alternative techniques for large-scale neutrino telescopes. Some events of 50 – 80 years relating to the development of a new branch of Astronomy – the High-Energy Neutrino Astronomy, in which Markov and Reines took part, were described in my talk at ARENA Workshop. Below the first part of my talk at the Workshop is presented describing discussions and meetings the neutrino physics and astrophysics relating to the period 1957-1962 when I was Markov's student and later post-graduated student.

1. M.A. Markov and High-Energy Neutrino Physics

In the middle of 50^{th} M.A. Markov worked at the Joint Institute of Nuclear Research (Dubna) and also he was a lecturer at Physics Department of Moscow State University. In those years his interests concentrated on the Quantum Field Theory and Elementary Particle Physics. There was a couple of modern in that time problems which especially attracted Markov's attention:

- the classification of elementary particles.

I would mention in this respect Markov's paper, "On classification of elementary particles" (Report USSR Academy of Sciences, 1955). In this paper he suggested composite model based on proton, neutron, hyperons and their antiparticles. This model preceded more economic Sakata's model (1956) based on proton, neutron and Λ-hyperon;

- weak interactions of elementary particles.

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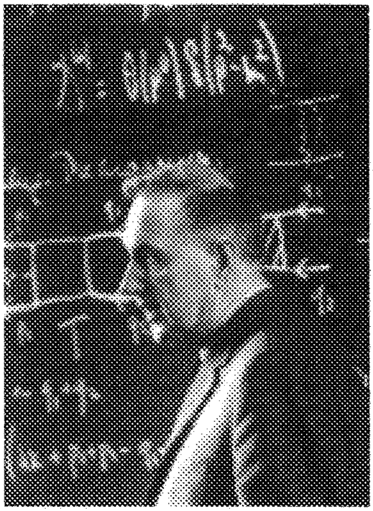
* This work is supported by grants 05-02-17410 and 05-02-26618 of the Russian Foundation of Basic Researches, grant 1782.2003.2 of the R.F. President, grant RUP2-2624-MO-04 of the U.S. Civilian Research and Development Foundation and by Program "Neutrino Physics" of the Presidium RAS.

I had a good luck to make my student work in Moscow University in 1957-1958 under Markov's leadership. Topic of my work suggested by Markov was: "interactions of the high-energy neutrinos with matter and detection of atmospheric neutrinos in underground experiments".

In fact Markov at that period initiated development of a new branch of the High-Energy Physics - the High-Energy Neutrino Physics – with aim to investigate fundamental problems of the weak interaction theory. These problems were in 1957 the following:



M.A. Markov, Seminar at JINR, Dubna in the middle of the 50^{th}

1. Are the weak interactions of the Fermi-type (four-fermion ones [1]) or Yukawa-type with intermediate bosons [2]?

2. How far the quadratic increase of the weak interaction cross-section with energy $\sigma = E_*^2$, where E_* is the energy in the center-of-mass system, continues to hold at very high energies?

This question was raised for the first time by W. Heisenberg in 1936 [3] who supposed that the four-fermion cross-sections could grow with energy up to $E_* \sim 1000$ GeV.

3. Possible existence of two kinds of neutrinos related to muon and electron. Idea of two neutrinos was first presented by S. Sakata in 1942 [4], but specific quantum numbers for muon and electron neutrinos were introduced by J. Schwinger [5] and K. Nishijima [6] in 1957.

2. Markov's suggestions of experiments with natural and artificial fluxes of high-energy neutrinos

2.1. Possibilities of underground (underwater) detection of atmospheric neutrinos

In September 1957 according to Markov suggestion as a first step I had to estimate a number of atmospheric neutrino interactions with nucleons and electrons in 1 cubic meter of Pb placed deep underground (in order to decrease background from atmospheric muons). So I had to evaluate fluxes of atmospheric neutrinos with energies higher than 1 GeV from the decays of π-mesons produced by cosmic rays in the Earth atmosphere and to calculate cross-sections of the neutrino-nucleon reactions

$$\nu + N \rightarrow N' + \mu(e) \qquad (1)$$

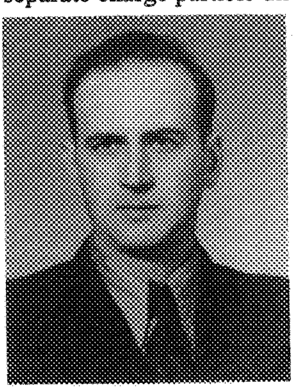
in the energy interval of 1-100 GeV for different variants (vector, axial vector, tensor, scalar and pseudoscalar ones) of the weak interaction theory (without and with nucleon formfactors) as well as neutrino-electron cross-sections

$$\nu + e \rightarrow \nu' + \mu(e) \qquad (2)$$

Our first results presented later in my diploma work [7] were the following:

- ν N – cross-sections for vector and axial vector variants were $\sigma_V(\nu N) = \sigma_A(\nu N) \sim 2\text{x}\ 10^{-38}\ \text{cm}^2$ at $E_\nu = 1$ GeV and grew linearly with energy, if this growth was not cut off by nucleon formfactors;
- $\sigma(\nu e) \sim m_e/M_N \text{ x } \sigma(\nu N)$ and its contribution could be neglected;
- if $\sigma(\nu N) \sim E_\nu$, the number of "internal" events produced by atmospheric neutrinos in an underground detector was ~3 times more than in a case, when $\sigma(\nu N)$ were constant above 1 GeV, for example due to nucleon formfactors; thus there appeared a chance to distinguish both alternatives;
- different numbers of muons and electron events induced by neutrino in a detector could give an evidence of the existence of two neutrino types;
- "several neutrino events (in $10^3\ m^3$ Pb target) per a month seemed to be a reasonable estimate"[7].

During a couple of years after 1958 the detection of the neutrino induced muon flux in the ground by "plane" detectors of ~1000 m^2 for which the number of "external" neutrino events is larger than "internal" ones was suggested [8,9, 10]. In [10] Markov reported his idea of deep underwater neutrino detection: "we propose setting up apparatus in an underwater lake or deep in the Ocean to separate charge particle direction by Cherenkov radiation".



G.T. Zatsepin in the 50th

In this period a number of theoretical papers on the weak interactions (V-A theory of Sudarshan and Marshak and Gell-Mann and Feynman), calculations of cross-sections of the neutrino reactions (T.D. Lee et al.) were published.

F. Reines [11] and K. Greisen [12] pointed out also that detectors of the size of kiloton or more sensitive volume were required to study interactions of cosmic ray neutrinos.

After detailed calculations of energy spectrum and angular distributions of the atmospheric neutrinos by G. Zatsepin and V. Kuzmin [13] possibilities of neutrino physics in cosmic rays were considered more carefully in [14].

2.2. *Why not high-energy neutrino experiments at accelerators?*

During carrying out my diploma work I used to visit Markov at his home every week to discuss results of my work. And I had a good opportunity to ask him various questions. Markov encouraged student's questions, even if they were naïve. One of my first questions in 1957 was related to possible use of an artificial source of high-energy neutrinos: "Why should we make calculations of atmospheric neutrino fluxes only? Why not to consider neutrino experiments at accelerators?" Markov looked at me carefully. As it turned out later Markov had discussed such possibility for the 10 GeV Dubna accelerator and results were pessimistic. My question probably stimulated Markov to come back to consideration of this problem. In a week Markov told me: "I had a talk with Bruno Pontecorvo. I told him that I would like to suggest neutrino experiments at accelerators. Pontecorvo liked such an idea very much".

Our estimations of possible neutrino fluxes and events in accelerator experiments had shown that high-energy neutrino experiments could be perspective for the future accelerators. Markov offered his student Docho Fakirov from Bulgaria to study this problem.

Fakirov defended his diploma work at Moscow University in 1958 [15]. In 1959 Markov had proposed report on the topic "On the High –Energy Neutrino Physics" to the International (Rochester) Conference on High-Energy Physics in Kiev. But after a negative reaction of some colleagues and the leader of the Weak Interactions Section ("Are you serious..?") withdrew the report from the agenda (see details in the Markov talk at 17th International Congress of History of Science [16]).

B. Pontecorvo had made a report "Electron and muon neutrinos" at Kiev Conference. To solve the problem of two neutrinos he suggested to investigate in an accelerator experiment production of electrons in reaction

$$\bar{\nu}_\mu + p \rightarrow n + e^+ \qquad (3)$$

which could be induced by low energy (~35 MeV) $\bar{\nu}_\mu$ from decays of μ^+ (stopped in a target after production in π^+-decays) if $\bar{\nu}_\mu = \bar{\nu}_e$ [17].

As M. Markov wrote in [16]:

"If our proposal of cosmic experiments was to some extent taken into consideration in realization of the neutrino experiments both in the South African mine (by Reines et al.) and in the Indian gold mine by the Indian-Japanese-English collaboration, our proposal concerning neutrino experiments at high energy accelerators (Fakirov et al.) remained practically unknown to wide scientific community. The note by Fakirov ("On spatial distribution of neutrino beam generated by high-energy neutrino collisions") was published in Sofia [18].

....The possibility of experimental separation of two types of neutrinos at high-energy accelerators in the process

$$\nu_\mu + n \rightarrow p + \mu(e) \qquad (4)$$

was discussed in a footnote in the proof of the book "Hyperonen und K-mesonen" made not later than in late 1959" [19].

2.3. Discussions about Neutrino-Nucleon Cross-Section Growth with Energy Higher than 1 GeV

It was noted by Markov [16] that in 50^{th} an idea of neutrino experiments was "met with strong opposition of the competent scientific community". One of the objections was that neutrino-nucleon cross-sections would grow with neutrino energy only up to 1 GeV, because of cutting role of nucleon formfactors, and detection of atmospheric neutrinos with energies in the region 10-100 GeV would not be possible.

Markov realized that, if somebody brings forward proposal to investigate neutrino-nucleon cross-section at high energies, he must try to find some arguments substantiating its possible growth above 1 GeV. I had a few discussions with Markov on this subject during 1958, in which he suggested some explanations. First of all contribution of different quasi-elastic processes was considered, but Markov stressed, that the important role of inelastic processes would be essential and their contribution into the total ν N-cross-section could be large.

So I was able to write in the end of 1958 in my diploma work [7]:
"It is possible that neutrino-nucleon cross-section increases at high energies because of appearance of the new channels in neutrino-nucleon reactions. ...It is possible to suggest that many new channels will arise due to the strong interaction in the intermediate states. But it is not clear now what their contribution is".

Markov had described the role of the inelastic channels (of deep inelastic processes, in fact!) in [18] (p.p. 292-293), but probably this Markov's idea had appeared too early: it was 10 years before quark-parton model became to be discussed for the neutrino-nucleon processes.

Later in 1964 I tried to come back to discussions of 1958 and speculated about the possible large contribution of the exclusive process in the ν N – collision, namely production of the nucleon isobar with 3/2 spin by neutrino, into the total ν N – cross-section [20]. But in fact only Markov's idea to take into account all inelastic (inclusive) processes turned out to be true.

It is worth reminding that the first evidence of the linear growth of ν N total cross-section with energy at E >> 1 GeV was obtained from the analysis of underground neutrino experiments [21].

3. High-Energy Neutrinos from Outer Space

3.1. From Radio to Neutrino and Gamma Observations of Astrophysical Sources of Cosmic Rays (Crab, Galactic Centre?)

After consideration of the possibilities of detection terrestrial neutrinos (atmospheric and accelerator ones) it became reasonable to consider opportunities of detecting high-energy neutrinos from extraterrestrial (astrophysical) sources. There was a chance, in my opinion, to find significant (higher than atmospheric) neutrino fluxes from some cosmic objects. I asked Markov's advice and he approved such investigation. My problem was to evaluate fluxes of cosmic neutrinos from the Crab nebula and from the galactic centre using energy arguments. Fortunately I was able to use the results of two recent papers of Vitaly L. Ginzburg (now Nobel prize laureate) on the origin of cosmic rays published in 1953 [22] and 1957 [23].

It had been written in [7] (see also [8-10]):

"With the isotropy of the sources and the isotropic distribution of cosmic rays in the galaxy, the neutrino flux in terrestrial conditions is bound to be determined by the flux of neutrinos produced in the atmosphere, as a probability of the meson production in the interstellar space... is very low. Yet observations seem to favor the theory of the production of cosmic particles in the shells of super new and of new stars [22]. According to radio-astronomical data there are many relativistic electrons in the expanding shells of these stars. It is not clear whether these electrons were accelerated or they were produced as a result of nuclear collisions. In [23] there are some arguments in favor of the secondary origin of these electrons. Then 2 antineutrinos (2 neutrinos) and 1 neutrino (antineutrino) have to be produced together with each electron (positron) in π-μ-decays. ...Besides π^0-mesons are produced as well as charged π-mesons. It means that 2 gammas are produced ...". Taking into account some data from [22] and [23] about the total number and energies of electrons and under some assumptions it was evaluated that "the neutrino flux from Crab could be equal to the atmospheric neutrino flux".

Some speculations were made in [7] about possible neutrino sources in the centre of our Galaxy. "Neutrinos can be produced not only in the shells of the super new stars, but at later stages after cosmic particles go out from the shells.

The cosmic protons are scattered by chance interstellar magnetic fields and disappear because of the collisions with interstellar substance." It was evaluated that, if the attenuation of the protons coming from the galactic centre is not essential the galactic neutrino flux is small. But in the case of strong proton attenuation, the neutrino flux could be large ("hidden" source).

It was also noted that "according to [24] gamma quanta of energy $\sim 10^{12}$ eV have to pass the Galaxy. ...In any case the presence of high energy photons beyond the atmosphere could be an argument in favour of the existence of, at least, the same fluxes of cosmic high-energy neutrinos"[7,9].

At the end of [7] the conclusion was made: "It is worth searching for high energy neutrinos from Outer Space, especially, if the high energy gammas beyond the atmosphere were found".

3.2. Atmospheric, extra-atmospheric neutrinos and a "scientific atmosphere " around of them.

At the period end of 50th - the beginning of 60th I, similarly to what Markov described in [16], encountered in many cases skeptical attitude to the ideas and possibilities of high-energy neutrino physics and astrophysics. Perhaps it was normal that later some critics began to work actively in this area. But at early stages of my work it was important for me to get any sign of support. Below I would like to recollect with gratitude these very first signs of support.

First of all I would like to recall discussions with my university-fellows: Vilik Arutyunyan, Vladimir Voronin, Igor Alekseev, Docho Fakirov. These discussions influenced in the inspiring way on preparation of my diploma work "On interactions of the cosmic ray high-energy neutrinos with substance ". This work was defended in the end of December 1958.

J.B. Zeldovich in the 50th

Next I would mention the talk with academician Jacob B. Zeldovich, which left deep impression on me. In September 1958 Zeldovich came to Moscow University to talk with the students of university chair "Theory of atomic nuclei" (on which I studied) to find young peoples for his research.

At that time Zeldovich worked in Arzamas Nuclear Center and was one of leading persons in Soviet A-and H-bombs project. I did not aspire then to get to Arzamas. When Zeldovich had asked me, what I was working on, I answered, that I was interested in the origin of cosmic rays and possibilities of investigating this problem by means of detecting high energy neutrinos from various astrophysical objects. I considered that these problems were hardly interesting to Zeldovich. In a second I understood, that it was mistaken: Zeldovich had become interested instantly. He asked me in detail on calculations of neutrino cross-sections, estimations of fluxes of cosmic neutrinos and suggested to work on this. His words were: " During the day time we shall work under the plan, and in the evenings we shall be engaged in neutrino astrophysics ". Fast reaction, energy, scientific enthusiasm of Zeldovich were unique and very attractive. But I wished to continue work with M.A. Markov and answered, that I had another plans.

In a couple of days Markov told me, that Zeldovich called him and said that he would like to take me for work. Several months passed and I became Markov's post-graduated student in the P.N. Lebedev Physical Institute of the USSR Academy of Sciences

My research work in Lebedev Institute under direction of Markov and in close contact with Markov's colleagues Aston A. Komar and Jury D. Usachev were supplemented by my participation in two regular seminars led by extremely vigorous persons Igor E. Tamm and Vitaly L. Ginzburg.

V.L. Ginzburg in the 50th

One discussion with V.L. Ginzburg at the end of 1959 was important for me. M.A. Markov and I met V.L. Ginzburg in his cabinet in the Theoretical department of Lebedev Institute and told him in detail about our estimations of the fluxes of high-energy neutrinos from astrophysical sources. I duly emphasized, that these estimations were stimulated by his works [22, 23]. After this talk prospects of high-energy neutrino astrophysics became one of the points of Ginzburg's permanent interest. In years that followed, Ginzburg meeting me often asked, what was new in the neutrino physics and astrophysics.

During this period I was engaged in calculations of cross-sections of various neutrino processes, including ones with an intermediate meson production. The neutrino experiments at accelerators became a branch of the experimental high-energy physics and many theorists all over the world took part in development of neutrino physics.

Discovery of the nonidentity of ν_e and ν_μ in experiments on accelerators took place [25]. Question of experimental search for intermediate mesons was moved forward on the agenda. An interesting opportunity of detecting charged intermediate meson in the resonant reaction

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (5)$$

had been noted by S. Glashow in 1960 [26]. However because of high value of resonant energy of neutrino in electron rest system ($E = M^2_W / 2m_e > 240$ GeV , if M_W larger than K-meson mass) this reaction could be observed in the planned underground neutrino experiments only at small M_W (~1 GeV). If masses of intermediate mesons are larger than two nucleon masses, it would be perspective in our opinion to search for the charged and neutral mesons at accelerator experiments with antiproton beams in the resonant reactions

$$\bar{p} + n \rightarrow W^- \rightarrow \bar{a} + b \quad (6)$$

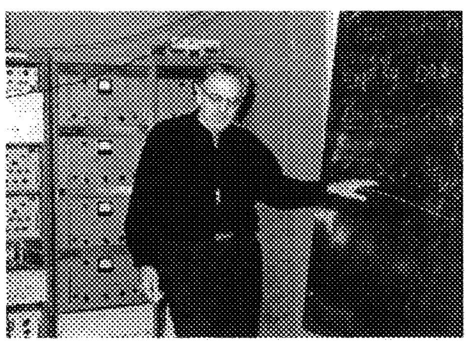
$$\bar{p} + p \rightarrow W^0 \rightarrow \bar{a} + a \quad (7)$$

In these proposals, later published in [27], there were no mentioning yet of resonant quark-antiquark processes, in which W- and Z-mesons were really discovered. But it was a step in the right direction.

3.3. Meeting Moisey Markov *with Frederic Reines - 1962*

I cite below the words in which Markov described the beginning of his long (thirty-year) dialogue with Reines during which warm friendly relations between them were established [28]:

" At Geneva conference 1962 I for the first time met Professor F. Rejnes. He approached me, holding in hands a reprint of some paper. It appeared, that it was the paper by I.M. Zheleznykh and me which had been published in 1961 in Journal "Nuclear Physics" under the title "On high-energy neutrino physics in cosmic rays" . The paper contained basically a material of diploma work of the student of Moscow State University I.M. Zheleznykh on the theme offered by me:



F. Reines, Seminar at the Baksan Neutrino Observatory, INR, 1977

" On interactions of high-energy neutrinos in cosmic rays with substance ". The result of the diploma work defended in 1958, was summarized in a phrase:

" Experiment with high-energy neutrinos born in an atmosphere, is difficult, but not hopeless. Anyway, discussion of opportunities of such experiment is meaningful. Favorable circumstance is that experiment could be performed at

any depths under the ground, sufficient for elimination of a background ... There is a sense to bring an attention to the question space neutrino detection ".
As I remember, Professor Reines has asked a question, whether there are in Soviet Union any attempts to organize the experiment offered by us? It is natural, that in the country the opportunity of realization of the given experiment was discussed..."

With this meeting the "prehistoric" stage of development of the high-energy neutrino physics in cosmic rays came to the end, race in underground experimental physics had begun and teams of the different countries prepared for start: a team of the USA (F. Reines, et al.), the joint team of the Great Britain, Japan and India (A. Wolfendale, S. Miyake, M.G.K. Menon, P.V. Ramana Murthy, V.S. Narasimham, B.V. Sreekantan, et al.) and a team of the Soviet Union (G.T. Zatsepin, A.E. Chudakov, et al.).

4. *Conclusion*

Reviewing my diploma work, M.A.. Markov, in particular, wrote: " The initiative belongs to Zheleznykh to consider a possible role of space neutrinos, i.e. a neutrino flux, arising not in an atmosphere of the Earth, ... but in specific processes in depths of the Universe. Here Zheleznykh has made a number of interesting estimations and proposals of experiments with high-energy gamma quanta, coming to an atmosphere of the Earth from Space, which could check the existing hypothesis of origin of cosmic rays. It is very probable, that such a possibility could be closed after more detailed analysis of this question, based on a larger amount of experimental data ". Review was signed on December 29th, 1958.

After more than 40 years of the theoretical studies of high-energy astrophysics problems and continuous development of alternative methods of detecting high-energy cosmic neutrinos V.L. Ginzburg was able to write in 2002 [29]: " At last, we are literally on the eve of the appearance of the high-energy neutrino astronomy with $E>10^{12}$ eV ".

And I am quite sure that ARENA. Workshop is an important stage for development of cooperation in this new branch of the Astronomy.

Acknowledgments

I am deeply indebted to Rolf Nahnhauer and other members of the Organizing Committee of ARENA Workshop for hospitality during my stay in Zeuthen and to Aston A. Komar for careful reading of this manuscript and valuable discussions.

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