Tribute to Bruno Pontecorvo and Samoil Bilenky

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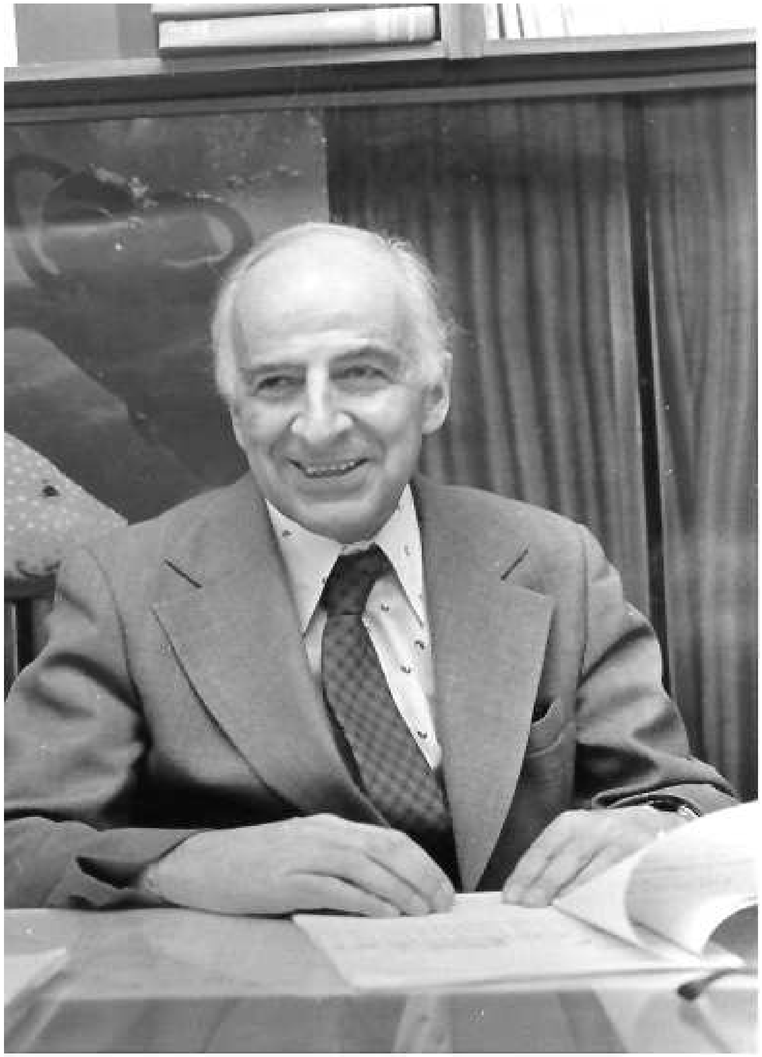
Bruno Pontecorvo was a brilliant experimental physicist. In the years 1931 - 1936 he wroked with Enrico Fermi in Rome, being the youngest member of Fermi's Group. Four of Pontercovo's ideas related to neutrinos led to Nobel Prizes in Physics.

Samoil Mihelevich Bilenky was eminent Russian theoretical physicist. Samoil Bilenky, as many friends and collaborators called him, was a teacher of a generation of particle physicists not only in Russia, but also in the former Eastern countries and later in Western Europe.

Bruno Pontecorvo and Samoil Bilenky were the founders of modern neutrino physics and played a leading role in its evolution to the present advanced state.

Bruno Pontecorvo (1913 - 1993)



At 70'th anniversary. (From the photo archive of JINR.)

Background

Bruno Pontecorvo was born on August 22, 1913, in Pisa (Marina di Pisa) in the family of an owner of a textile factory.
Currently and since many years now the Department of Physics (Edificio B) of University of Pisa is housed in the renovated building of Pontecorvo's factory (which was closed after the war and remained unused for a long time).
The square in front of the building is called "Largo Bruno Pontecorvo".

Bruno Pontecrvo had 4 brothers and 3 sisters. Three of the brothers became famous:
Guido (the eldest brother) - as a geneticist;
Bruno - as a physicist;
Gillo – as a movie director.

Pontecrvo enrolled and studied for two years at the Department of Engineering of University of Pisa. Then he decided to change to physics.
Under the advice of his elder brother Guido, he went to Rome with the hope of joining the Fermi Group. Pontecorvo passed successfully the exam that was taken by Fermi and Rasetti and was accepted as a 3rd year student of the Faculty of Physics and Mathematics of University of Rome (with the understanding that he will be involved in experimental research).

The Via Panisperna Boys (Rome, 1931-1936)

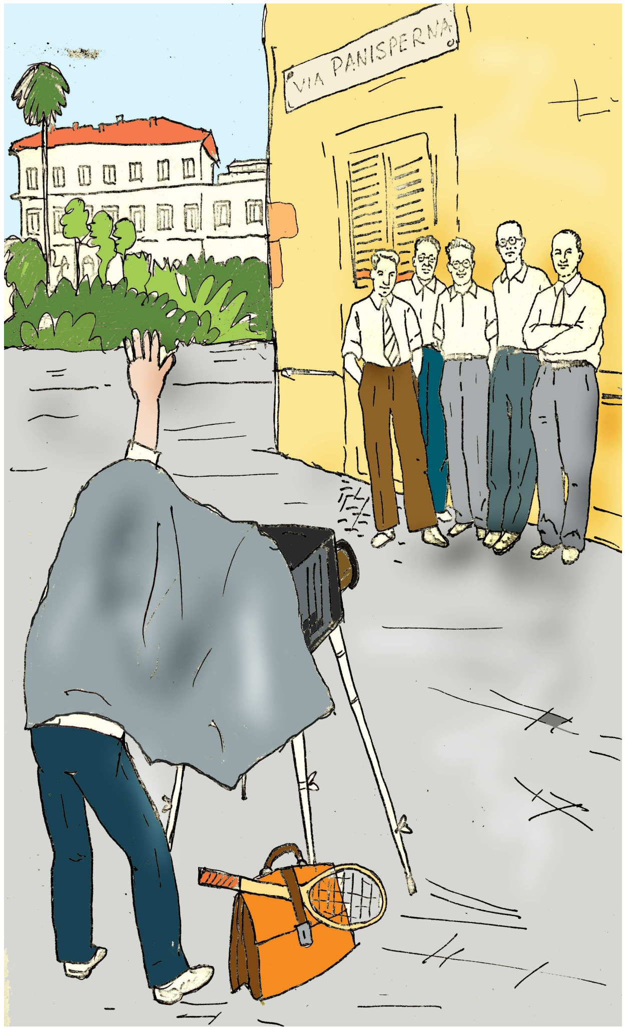
Pontecorvo worked in Fermi's Group from 1931 to 1936, first as a student and later as researcher, and was a member, together with Oscar D'Agostino, Emilio Segre, Edoardo Amaldi, Franco Rasetti and Ettore Majorana of "The Via Panisperna Boys" ("I Ragazi di via Panisperna"), as Enrico Fermi and his "team" were known.

An experimental study performed by Amaldi and Pontecorvo in 1934 lead to the discovery of the remarkable effectivness of slow neutrons in inducing radioactivity (nuclear reactions) – the most important discovery made by the Fermi's group.

The importance of Pontecorvo's contribution to this discovery is acknowledged by the fact that he was made co-author of the two publications describing the discovery. At that time Pontecorvo was 21.
For the... "discovery of nuclear reactions brought about by slow neutrons" Fermi was awarded the Nobel Prize for Physics in 1938.

This discovery opened the road to a plethora of applications of neutrons.

The Via Penisperna Boys



The Via Penisperna Boys including B. Pontecorvo

Drawings due to Misha Bilenky.

Paris (1936 - 1940): Nuclear Isomerism

In 1936 Pontecorvo received a premium of the Italian Ministry of Education; used it to visit College de France in Paris to work with F. Joliot-Curie.

At College de France he studied the phenomenon of “Nuclear Isomerism” - two atomic nuclei having the same values of the atomic and mass numbers Z and A and exhibiting different radioactive properties after being irradiated, e.g., with slow neutrons (corresponding to an isotop (Z,A) being in different metastable states with large orbital momentum).
At the time only a few isomers were known (Kurchatov: ^{80}Br, τ=18 min and 4.4 h).
Pontecorvo made pioneering experiments in which
i) conversion electrons in the decays of isomers were observed,
ii) beta-stable isomers were discovered (e.g., Cd irrdiated by neutrons),
iii) beta-stable isomers were produced by irradiation of nucleai by X-rays (with A. Lazard);
led to the discovery of the phenomenon of “nuclear phosphorenscence”.

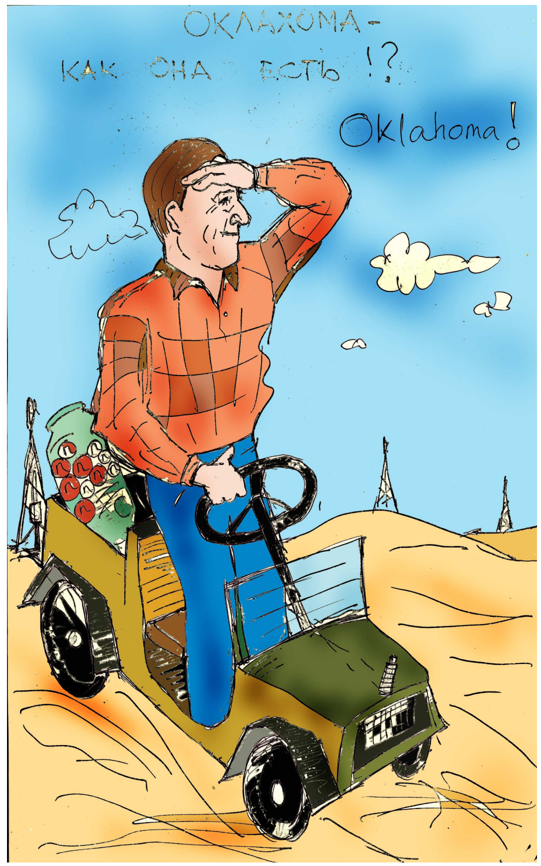
These studies were of crucial importance for development of the nuclear structure theory.

By 1980 there were known 550 isomeric pairs and about 25 isomeric triplets (with periods $>$ 1 sec).

For the studies of nuclear isomerism Pontecorvo was awarded the Curie-Carnegie Prize. F. Joliot-Curie and E. Fermi congratulated him on the excellent results. Pontecorvo was particularly happy to receive Fermi‘s congratulation (as he wrote in his autobiography, he thought that Fermi, who sometimes called him “great champion”, had respect for him only as an expert in tennis).

Tulsa, Oklahoma, USA (1940 - 1942): Neutron Well Logging

In 1940 just before the German troops occupied Paris, Pontecorvo with his wife and son escaped to the USA. In the period 1940 – 1942 Pontecorvo worked in a private oil searching company (Well Surveys, Inc.) in Tulsa, Oklahoma. He developed and used the method of neutron well logging for prospecting for oil (minerals and water).
This was the first practical application of slow neutrons.
The Pontecorvo's method of neutron well logging is widely used also today.



Pontecorvo in Oklahoma. (Drawing due to Misha Bilenky.)

Canada (1943 - 1949): Reactors, Neutrinos and Muons

In 1943 Pontecorvo was invited to take part in the Anglo-Canadian Uranium Project, as Scientific Leader of the Project, to build a research reactor in Canada.
Pontecorvo was 30 at the time.
Participated in the design of the two (heavy water) nuclear reactors, ZEEP and NRX, built at Chalk River, Ontario.
The ZEEP ("test" small) reactor went "critical" in 1945, the NRX reactor – in 1947 (had the largest neutron flux).
Pontecorvo worked at Chalk River Laboratories until the end of 1948; at the beginning of 1949 left for the U.K. (accepted an offer to work for AERE in Harwell).
At Chalk River he wrote 25 articles related to reactor design, of which only two were published.
Pontecorvo produced also two groundbreaking papers in the fields of neutrino and lepton (weak interaction) physics and studied the properties of the muon.

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF ATOMIC ENERGY

INVERSE β PROCESS

by

B. Pontecorvo

Chalk River, Ontario

20 November, 1946

PD-205

INVERSE β PROCESS

by

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Introduction

The Fermi theory of the β disintegration is not yet in a final stage; not only detailed problems are to be solved, but also the fundamental assumption - the neutrino hypothesis - has not yet been definitely proven. I will recall briefly the main experimental facts which have led Pauli to propose the neutrino hypothesis.

1. In a β disintegration, the atomic nucleus Z changes by one unit, while the mass number does not change.
2. The β spectrum is continuous, while the parent and the daughter states correspond to well defined energy values of the nuclei Z and Z ± 1.
3. The difference in energy between the initial and final states involved in a β transition is equal to the upper limit of the continuous spectrum.

We see that the fundamental facts can be reconciled only with one of the following alternative assumptions:

i. The law of the conservation of the energy does not hold in a single β process.

ii. The law of the conservation of the energy is valid, but a new hypothetical particle, undetectable in any calorimetric measurement - the neutrino - is emitted together with a β particle in a β transition, in such a way that the energy available in such transition is shared between the electron and the neutrino. This suggestion was made by Pauli and on

PD-205

This article contains two ideas that shaped the development of neutrino physics.

- Neutrinos can be detected by the inverse β-process $\nu + n \to p + e^-$.
- H. Bethe and R. Peierls, Nature 133 (1934) 689:

estimated $\sigma(\nu + n \to p + e^-)$ using Fermi's $\beta-$decay theory;
at $E_\nu \sim$ MeV, $\sigma \sim 10^{-44}\text{cm}^2$.
Concluded: "there is no practical possible way of observing the neutrino".

Pontecorvo: the nuclear reactors and the Sun are powerful sources of neutrinos; estimation of the fluxes lead to the conclusion:
neutrinos can be detected in experiments performed at reactors and possibly in experiments aiming to observe neutrinos emitted by the Sun.

Neutrinos were indeed observed first by F. Reines and C. Cowan in 1956 in an experiment performed at a nuclear reactor.
F. Reines received the Nobel Prize in Physics in 1995 for the neutrino observation.

- Pontecorvo proposed the radiochemical methods of neutrino detection.
- He proposed also the simplest concrete example - the Cl–Ar method, based on the reaction:

$$\nu_e + ^{37}\text{Cl} \to ^{37}\text{Ar} + \text{e}^-;$$

the produced ^{37}Ar undergoes a K–capture (half-life T $\cong$ 34 days),

$$^{37}\text{Ar} + \text{e}^- \to ^{37}\text{Cl}^* + \nu_e \ ,$$

the ^{37}Cl* thus formed emits (practically immediately) an Auger electron with E= 2.8 keV,

$$^{37}\text{Cl}^* \to ^{37}\text{Cl} + \text{e}^- \ .$$

Pontecorvo: a convenient compound of Cl to use in an experiment is CCl_4 (as suggested by J. Gueron).
CCl_4 was used as a target in the reactor experiment of R. Davis in 1955.
In the solar neutrino experiment of R. Davis et al. used perchlorethylene, C_2Cl_4.

Thus, the method proposed by B. Pontecorvo:
irradiate by neutrinos large volumes of a Cl compund for $\sim$ one month and extract the radioactive ^{37}Ar by a physical method (without complicated chemistry);
introduce then ^{37}Ar in a smaller counter having registration efficiency close to 100% (because of the high yield of Auger electrons).
It is important that there exist cheap, not too chemically active and not poisonous Cl compounds (e.g., CCl_4 or C_2Cl_4), and that the radioactivity of ^{37}Ar has a period T long enough to allow one to achieve a relatively effective separation and extraction.

Pontecorvo: the suppression of various beckgrounds – critical for the success in the use of Cl–Ar method for neutrino detection.

Performing tests with ^{37}Ar Pontecorvo (and independently S. Curran et al.) discovered "the high gain gas amplification regime" of the proportional (Geiger-Muller) counters, highly sensitive to β-radiation.
This regime permits one to reduce considerably the effective background of the counters by measurement of the pulse amplitude and the rise time of the pulse generated by the 2.8 keV Auger electron, emitted following the K–capture in ^{37}Ar.

Pontecorvo constructed already in 1949 a proportional counter with an extremely low effective background practically as low as in the counters used 20 years later by R. Davis et al. (and later in the SAGE and GALLEX experiments based on the Ga-Ge method).

The first results of the Cl–Ar solar neutrino experiment of R. Davis et al. published in 1968 – obtained by using a proportional counter of the type constructed by B. Pontecorvo in 1949 and the information about the amplitude of the pulses only.
In these first runs "^{37}Ar activity was not observed over a counter background ..." and only an upper limit on the ^{37}Ar production rate due to solar neutrinos was set.

A positive signal due to the solar neutrinos could be and was observed by R. Davis et al. only after the information about the pulse rise-time began to be used in 1970, which led to an additional considerable reduction of the background (by a factor of 10) in the proportional counter practically to its minimum possible level (due to cosmic rays) at the location of the detector.

1970 marked the beginning of the measurement of the "high" energy part (E $\geq$ 0.816 MeV) of the flux of neutrinos emitted by the Sun, performed by R. Davis using the Cl–Ar method of Pontecorvo with such remarkable success.
This also marked the beginning of the Solar Neutrino Astronomy.
The 1972 Davis et al. positive results announced at Nu'72:
the beginning of "solar neutrino deficit" saga;
resolved in 2001-2002 by SNO+SK and SNO data: the solar ν_e
undergo $\nu_e \rightarrow \nu_{\mu,\tau}$ transitions (oscillations) driven by $m_i^\nu \neq 0$ and $\theta^\nu \neq 0$!!!

For the observation of solar neutrinos R. Davis was awarded the Nobel Prize in Physics in 2002.

The Solar Neutrino Astronomy received strong impetus with the construction of Kamiokande, SAGE, GALLEX/GNO, SuperKamiokande, SNO and BOREXINO experiments, which provided unique data about the Sun and stellar evolution, and about neutrino properties.

The contributions of B. Pontecorvo to the foundation and the development of the Solar Neutrino Astronomy were fundamental.

Newton....

Drawing due to Misha Bilenky.

... and Pontecorvo inventing the Cl-Ar method.

Drawing due to Misha Bilenky.

the expression of the hyperfine structure splitting, $|\psi(0)|^2$ being proportional to a^{-3}. It is customary to eliminate the Bohr radius by introducing the Rydberg constant for infinite mass, together with the reduced mass of the electron. It then turns out that the hyperfine structure splitting is given by the expression

$$\nu = C\frac{2I+1}{I}\mu_N\left(\frac{m_r}{m_0}\right)^3. \qquad (2)$$

Here C contains universal constants and numbers, while m_r stands for the reduced mass of H or D, respectively. m_0 denotes the electronic mass. The ratio ν_H/ν_D is then given by

$$\nu_H/\nu_D = (4/3)(\mu_H/\mu_D)(m_H/m_D)^3,$$

and the numerical value for ν_H/ν_D as observed, is 4.3416 compared with a computed value of 4.3393.

Equation (1) is derived by neglecting the small components of the Dirac equation and replacing the large components by Schroedinger functions.

The discrepancy observed which, if the accuracy of observation is sufficient, in the case of the ratio at least, cannot be ascribed to inaccurate values of the universal constants, makes it advisable to re-examine the derivation of (1).

We have obtained a value for ν by consistently using Dirac's equation, retaining all four components through the perturbation calculation and using the rigorous Dirac functions in the evaluation of the matrix element for the perturbed energy. The hyperfine structure splitting apart from numerical factors is now given by

$$\nu = C'\frac{e\mu_N}{(h/mc)^2}[1-(E/mc^2)^2]^{\frac{3}{2}} = C'\frac{e\mu_N}{(h/mc)^2}(2R/mc^2)^{\frac{3}{2}}. \qquad (3)$$

The second equation in (3) is obtained by the somewhat arbitrary insertion of the empirical Rydberg constant in place of R_∞ which would, of course, follow from the Dirac equation.

This calculation leads, within the accuracy aimed at, to the same value as given by (2), with the one difference that the ratio of reduced to electronic mass appears in the three-halves rather than in the third power. This correction diminishes the discrepancies between the observed and calculated values of ν_H and ν_D, as follows. For H, the discrepancy is reduced to one part in 600; for D, to one part in 500; both deviations are obviously still large if one believes in the presently accepted values of the universal constants.

The ratio ν_H/ν_D, on the other hand, now differs from its calculated value by only one part in 8000; this is much smaller than the accuracy claimed for the earlier determinations of μ_H/μ_D, which enters as a factor into (3) and is assumed to be known to about 1 part in 3000.

In interpreting this result, several points must be kept in mind: The accuracy of the experimental determination of μ_H/μ_D and the calculated value which contains it as its most uncertain element, are not yet sufficiently good to exclude a different dependence on the ratio of the reduced masses.

The theory here used is obviously not consistent; we have carried out all calculations with the one-body Dirac equation and taken into account the two-body nature of the problem by the empirical introduction of R_H and R_D. This point will need further theoretical study.

We have also investigated the question of how the electronic magnetic moment may be expected to depend on the nuclear mass and have found different results depending on the physical interpretation given to the coordinates which enter into the Dirac equation.

A detailed paper will follow shortly.

[1] J. E. Nafe, E. B. Nelson, and I. I. Rabi, Phys. Rev. 71, 914 (1947). I am greatly indebted to the authors for telling me about their results before publication.

Nuclear Capture of Mesons and the Meson Decay

B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

THE experiment of Conversi, Pancini, and Piccioni[1] indicates that the probability of capture of a meson by nuclei is much smaller than would be expected on the basis of the Yukawa theory.[2,3] Gamow[4] has suggested that the nuclear forces are due exclusively to the exchange of neutral mesons, the processes involving charged mesons and the β-processes having probabilities which are smaller by a factor of about 10^{12}.

We notice that the probability ($\sim 10^6$ sec.$^{-1}$) of capture of a bound negative meson is of the order of the probability of ordinary K-capture processes, when allowance is made for the difference in the disintegration energy and the difference in the volumes of the K-shell and of the meson orbit. We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β-processes and processes of emission or absorption of charged mesons.

An immediate consequence of the experiments of the Rome group[1] is that the usual interpretation of the β-process as a "two-step" process ("probable" production of virtual meson and subsequent β-decay of the meson) completely loses its validity, since it would predict too long β-lifetimes: the meson is no longer the particle responsible for nuclear β-processes, which are to be described according to the original Fermi picture (without mesons). Consequently there is no need to assume that charged mesons have integral spin, as the Yukawa explanation of β-processes required. Once we believe that the ordinary β-process is not connected in any way with the meson, it is difficult to see strong reasons for the usual assumption that the meson decays with emission of a β-particle and a neutrino. We shall consider then the hypothesis that the meson has spin $\frac{1}{2}\hbar$ and that its instability is not a β-process, in the sense that it does not involve the emission of one neutrino. The meson decay must then be described in a different way: it might consist of the emission of an electron and a photon or of an electron and 2 neutrinos[5] or some other process.

On the $\mu-$Meson Properties and the Notion of the Weak Force

The Confusion

The $\mu-$meson (called "mesotron" untill 1947) was discovered by C. D. Anderson and S. Neddermeyer at Caltech in 1936, while studying cosmic rays.
Until 1947: mesotron$\equiv$particle introduced by Yukawa as a mediator of the nuclear force.

M. Conversi, E. Pancini and O. Piccioni (Phys. Rev. 71 (1947) 209):
the absorption rate of mesotrons in iron and carbon was relatively low, $\sim$ 10^{-6} sec^{-1}, with no visible tracks of particles after the mesotron was absorbed.

E. Fermi, E. Teller and V. Weiskopf (Phys. Rev. 71 (1947) 314):
the mesotron $\neq$ Yukawa particle, its absorption rate being $\sim 10^{10}$ times smaller.

The Solution

Pontecorvo found that $R(\mu^- + (A,Z)) \sim R(e^- + (A,Z))$, implying "the possibility of a fundamental analogy between the $\beta-$processes and the processes of emission or absorption of charged mesons" (i.e., of mesotrons).
The following set of suggestions was further made.
i) Since the mesotron$\neq$Yukawa particle it need not be a scalar particle;
ii) The mesotron has spin 1/2;
iii) The mesotron μ^- does not decay into $e^- + \bar{\nu}$;
it dacays into $e^- + \bar{\nu} + \nu$, or $e^- + \gamma$, or in some other way;
iv) In the process of $\mu-$capture a neutrino is emitted in the same way as in the process of electron K–capture,

$$e^- + (A,Z) \to (A,Z-1) + \nu, \quad \mu^- + (A,Z) \to (A,Z-1) + \nu$$

- $(e\nu)$ and $(\mu\nu)$ with the same coupling constants.

As we know now, all assumptions from the above list turned out to be correct.

From 1947 to 1949 Pontecorvo (together with E. Hincks):
– the first upper limit on $BR(\mu \to e + \gamma)$ ($\sim 10^{-5}$);
– the first evidence for the $\mu \to e + \nu + \bar{\nu}$ decay.

The significance of the article by Pontecorvo:
i) the true nature of the muon was recognized, and
ii) the idea of $\mu - e$ universality of the Fermi interaction was put forward.
This idea contained also the first hint of universal weak interaction.

Pontecorvo's was the first of a sequence of papers
(O. Klein (Nature 161 (1948) 897), G. Puppi (Nuovo Vimento 5 (1949) 567), T.D. Lee, M. Rosenbluth and C.N. Yang (Phys. Rev. 75 (1949) 905), and J. Tiomno and J.A. Wheeler (Rev. Mod. Phys. 21 (1949) 144)),
which led to the establishment of the notion of weak interaction as an independent fundamental interaction
(M. Gell Mann, Proc. of the Int. Conf. Elem. Part. Phys., Pisa, 1955, Suppl. Nuovo Cim. 4 (1956) 846).

By 1947 it was well understood that the $\beta-$decay and the electron capture were initiated by the same ($\beta-$decay) force, but no other manifestations of this force were known.

In the same volume of Phys. Rev.: V. Weisskopf, Phys. Rev. 72 (1947) 510.
R. Marshak and H. Bethe, Phys. Rev. 72 (1947) 506, "On the two meson hypothesis".
G. Lattes, G. Occhialini and C. Powell, Nature 160 (1947) 453.

Pontecorvo with family arrives in Dubna.

Drawing due to Misha Bilenky.

Dubna (1950 - 1993): Neutrinos

In 1950 Pontecorvo with family (wife and three sons) moved from England to Soviet Union.

He started to work in Dubna where the largest proton accelerator in the world (460 MeV later 680 MeV) at that time was operative.
Pontecorvo and his group performed experiments on the production of π^0 in neutron-proton and neutron-nuclei collisions, on pion-nucleon scattering and other experiments.

However, neutrinos were always on Pontecorvo's mind, since 1946 they have become his passion.

At the end of 1950'ies, independently of M.A. Markov and M. Schwarz, Pontecorvo realised:
experiments with accelerator neutrino beams are possible, can be used for studies of weak interactions and neutrino properties.

One fundamental unanswered question was:
are ν_e and ν_μ identical or different particles?

In 1959 Pontecorvo published a paper proposing how to test whether $\nu_e \equiv \nu_\mu$ or not with accelerator neutrinos: check whether $\nu_\mu + n \to p + e^-$.

Pontecorvo's proposal was realized in 1962 in the famous Brookhaven two-neutrino experiment, which proved that $\nu_e \neq \nu_\mu$.

In 1988 L. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize for the discovery of the muon neutrino. This discovery lead, in particular, to the notion of "families" of elementary particles.

Pontecorvo and the two-neutrino experiment.

Drawing due to Misha Bilenky.

Neutrino Masses, Mixing and Oscillations: Ahead of Time

Pontecorvo came to the idea of neutrino oscillations in 1957-1958: tried to find possible "lepton" analogs $K^0 - \bar{K}^0$ oscillations suggested by Gell-Mann and Pais.
In 1957 considered muonium $(\mu^+ - e^-)$ - anti-muonium $(\mu^- - e^+)$, mentioned neutrino.

In 1958 only one type of neutrino was known to exist.
The two-component neutrino theory was confirmed.
Pontecorvo considered (effectively) $\bar{\nu}_R \to \nu_{sR}$ ($\nu_L \to \bar{\nu}_{sL}$).
Assumed i) $L \neq$ const.;
ii) there exist ν_{sR} and $\bar{\nu}_{sL}$ ($\nu_R(x)$) in addition to ν_L and $\bar{\nu}_R$ ($\nu_L(x)$);
iii) understood that ν_{sR} and $\bar{\nu}_{sL}$ must be non-interacting.

Pontecorvo, 1958:

$$\bar{\nu}_R(x) = \frac{\chi_{1R} + \chi_{2R}}{\sqrt{2}}, \ \nu_R(x) = \frac{\chi_{1R} - \chi_{2R}}{\sqrt{2}}, \ m_1 \neq m_2 > 0;$$

$\chi_{1,2}$ - Majorana, $\eta_{1CP} = -\eta_{2CP}$, maximal mixing .

Pointed out: in reactor experiments a deficit of antineutrino events will be observed "due to the fact that the neutral lepton beam which at the source is capable of inducing the reaction $\bar{\nu} + p \to e^+ + n$ changes its composition on the way to the detector".

The Pontecorvo idea of neutrino oscillations created a new era in neutrino physics. This was a brave idea put forward at the time when the neutrinos were universally considered to be massless.

Maki, Nakagawa, Sakata, 1962:

$$\nu_{eL}(x) = \Psi_{1L} \cos\theta_C + \Psi_{2L} \sin\theta_C \,,$$

$$\nu_{\mu L}(x) = -\Psi_{1L} \sin\theta_C + \Psi_{2L} \cos\theta_C \,,$$

$\Psi_{1,2}$ - **Dirac,** θ_C- **the Cabbibo angle .**

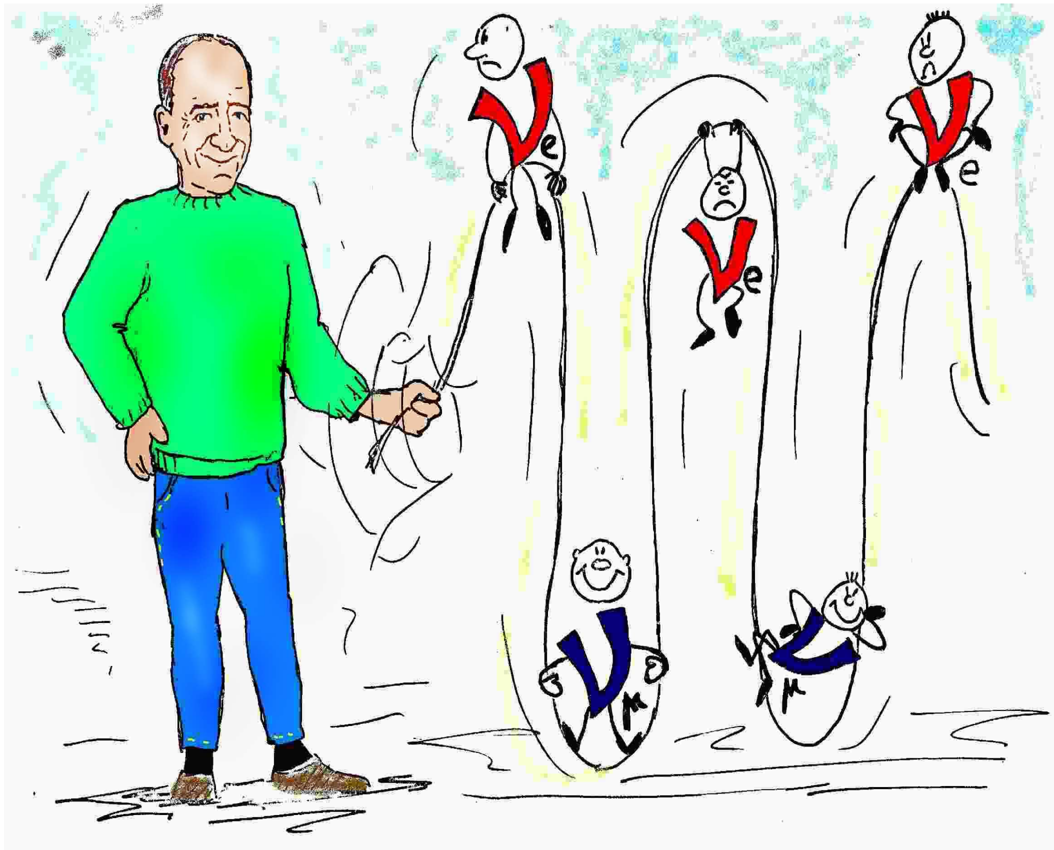
Pointed out that ν_μ **can undergo "virtual transmutations" into** ν_e**.**

1967: Pontecorvo considered $\nu_{e(\mu)} \to \nu_{\mu(e)}$ oscillations.
• He predicted that Davis et al. will observe a deficit of solar neutrinos due to oscillations.
• Considered also $\nu_{eL(\mu L)} \to \bar{\nu}_{sL}$, $\bar{\nu}_{eR(\mu R)} \to \nu_{sR}$, ν_{sR}, $\bar{\nu}_{sL}$ being "inactive" RH neutrino and LH antineutrino; introduced the term "sterile" neutrinos.

In a 1969 paper by V. Gribov and B. Pontecorvo, the Majorana mass term for the LH active neutrinos ν_{eL} and $\nu_{\mu L}$ was constructed,
$M^{(\nu)}_{l',l} = M^{(\nu)}_{l,l'}$, diagonalised, $m_{1,2}$ and $\tan 2\theta_\nu$ were derived in terms of $M^{(\nu)}_{l',l}$,
$\nu_{1,2}$ - Majorana particles.
In the same paper the expression for the 2-neutrino oscillations probability was first given.

At beginning of 1970ies Bilenky and Pontecorvo began to collaborate on problems related to oscillations of neutrinos.
This fruitful collaboration continued until the passing of Pontecorvo in 1993.

Pontecorvo was a member of the Soviet Academy of Sciences since 1958.
He was awarded the Lenin Prize in 1964 for his work on the weak interaction.



Pontecorvo and neutrino oscillations.

Drawing due to Misha Bilenky.

Samoil Mihelevich Bilenky (1928 - 2020)

At a seminar in 2018. (From the photo archive of JINR.)

Background

Bilenky was born on May 23, 1928, in Zmerinka, a town in Ukraine, in a family of an engineer.

He graduated in 1952 "cum laude" from the renowned Moscow Engineering and Physics Institute. His master thesis adviser was the famous Soviet theoretical Physicist I. Ya. Pomeranchuk.

The same year Bilenky got a permanent position at the Laboratory for Nuclear Problems (LNP) in Dubna, near Moscow, which became in 1956 the Joint Institute for Nuclear Research (JINR), and ever since was a staff member of JINR.

The Laboratory of Nuclear Problems was created in connection with the building of the first Soviet accelerator centre in the small town of Ivan'kovo (which was later "absorbed" by the newly built science town Dubna), about 120 km north of Moscow, on the banks of river Volga. This was a proton synchro-cyclotron with energy of the proton beam of 460 MeV. The accelerator was built in the record time of two years and became operational in 1948. Later (in the 1950s) a 10 GeV proton synchrotron was also built. The accelerator complex and LPN were classified until 1954; they were called "Hydro-Technical Laboratory" (not far there existed (and still exist) a dam with a hydro-electric power plant) and "Ploshchatka" ("The Plot"). At LNP a Theoretical Physics Section was formed under the leadership of Pomeranchuk, who was instrumental for the hiring of Bilenky.

In 1956 within JINR, the Laboratory of Theoretical Physics (LTP) was created. N. N. Bogoliubov was appointed Director of LTP and Bilenky became a staff member of this new theoretical physics unit. He remained a staff member of LTP ever since.

In 2006 Bilenky moved with his wife Sofa Isaevna to Vancouver, Canada, to be close to his son who after an unfortunate accident could move only on wheel-chair.

Research

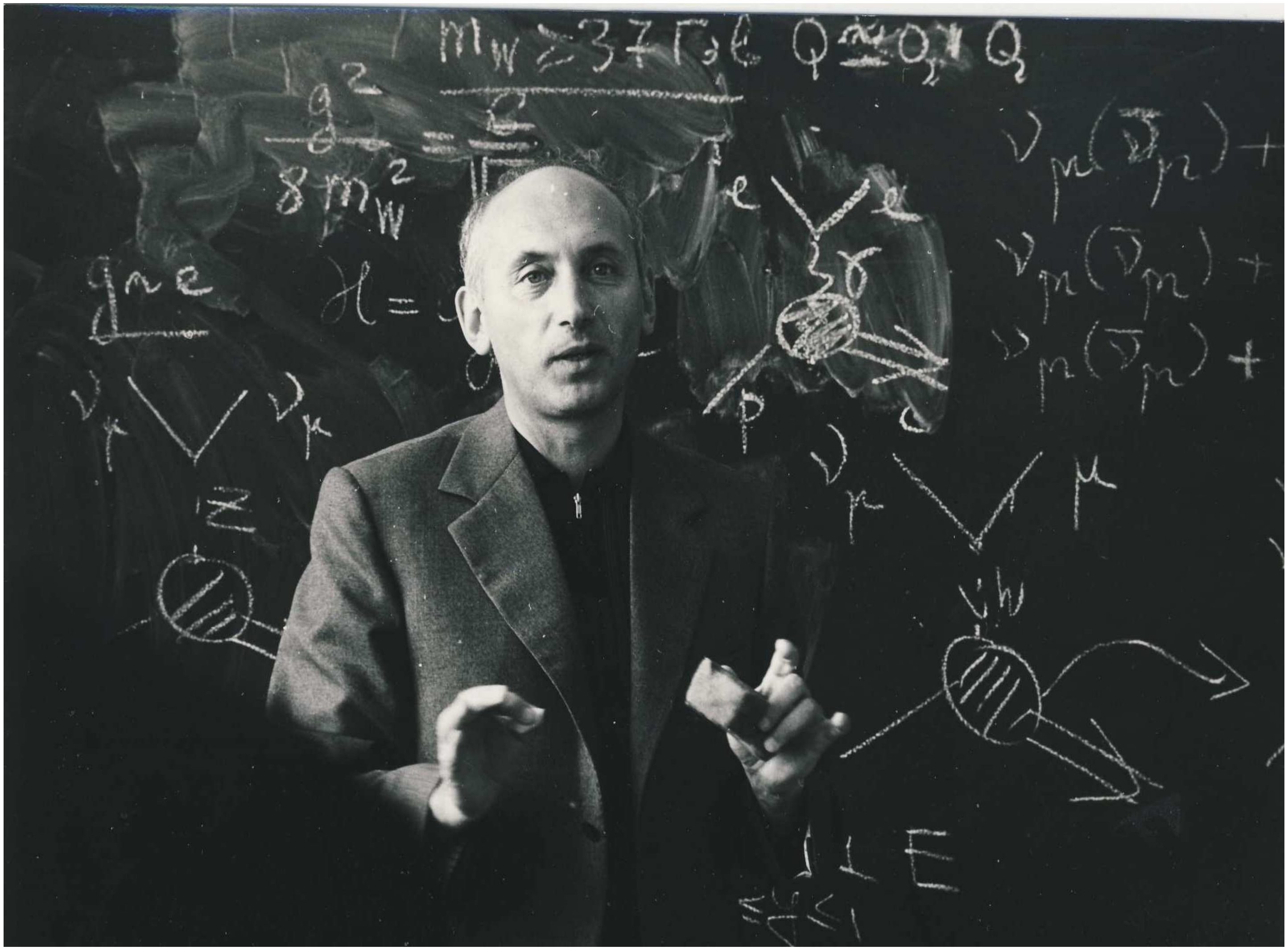
S.M. Bilenky is author and co-author of more than 250 scientific articles and 5 books.

Bilenky's scientific style is characterized by the striving to use model-independent approach to physical problems. In his works he built bridges between theory and experiment. He taught his students and junior collaborators to always see the physics behind the mathematical formulas.

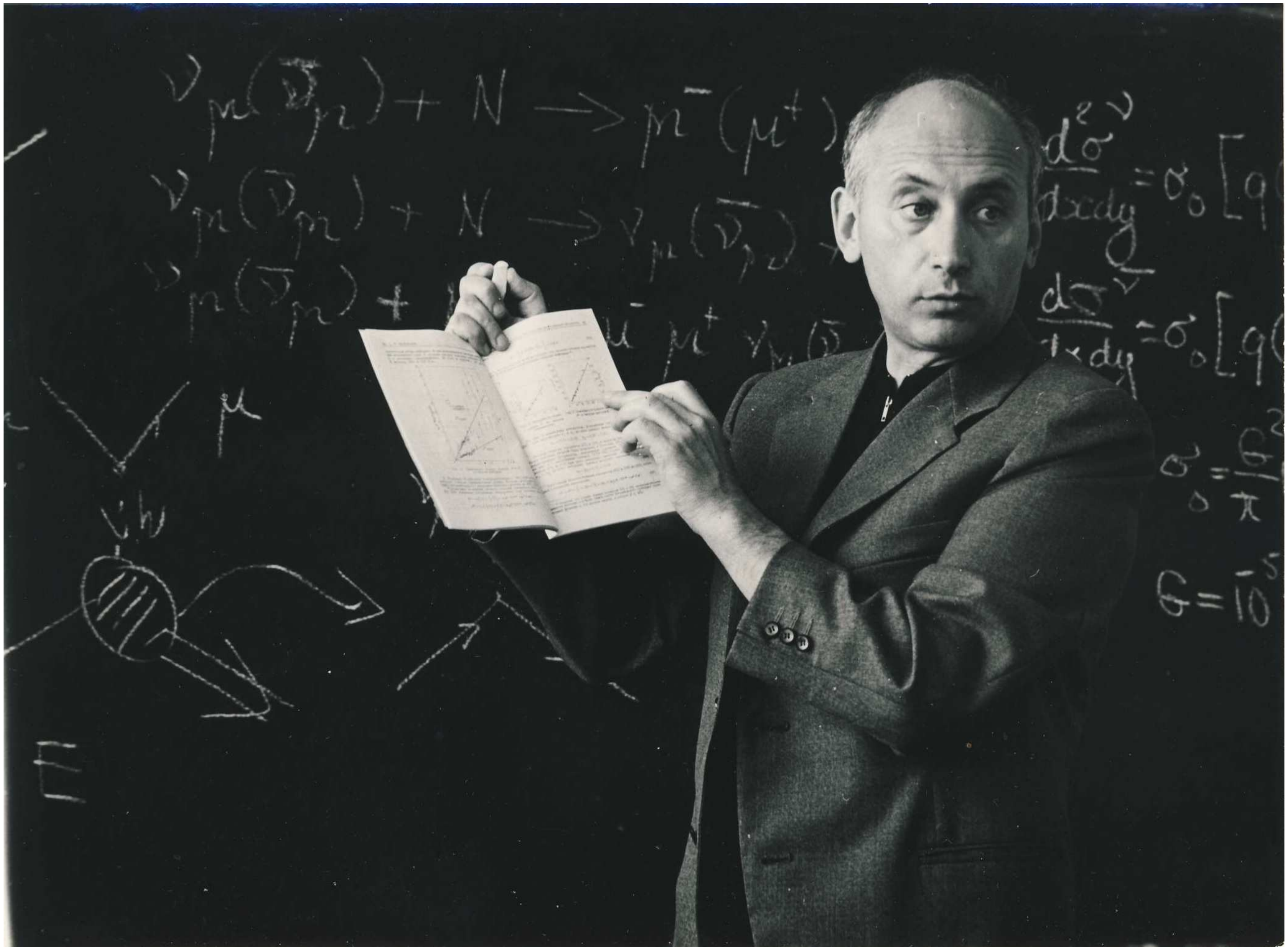
S.M. Bilenky obtained his Ph.D. degree in 1957 at LTP, JINR, for applications of the dispersion relation theory to weak interaction processes.

In a subsequent series of articles Bilenky discovered a general connection between polarisation effects and internal parities of particles in scattering processes and proposed a method of determination of parities of strange particles later used in experiments at LBL Berkeley and CERN. These articles also initiated the development of the polarised proton target technique in scattering experiments.

"Parity test for Omega$^-$ using polarized hydrogen target" S.M. Bilenky, R.M. Ryndin (Dubna, JINR). Sep 1965. 2 pp. Published in Phys.Lett. 18 (1965) 346-347



Giving a talk at JINR, Dubna (early 1970s). (From the photo archive of JINR.)

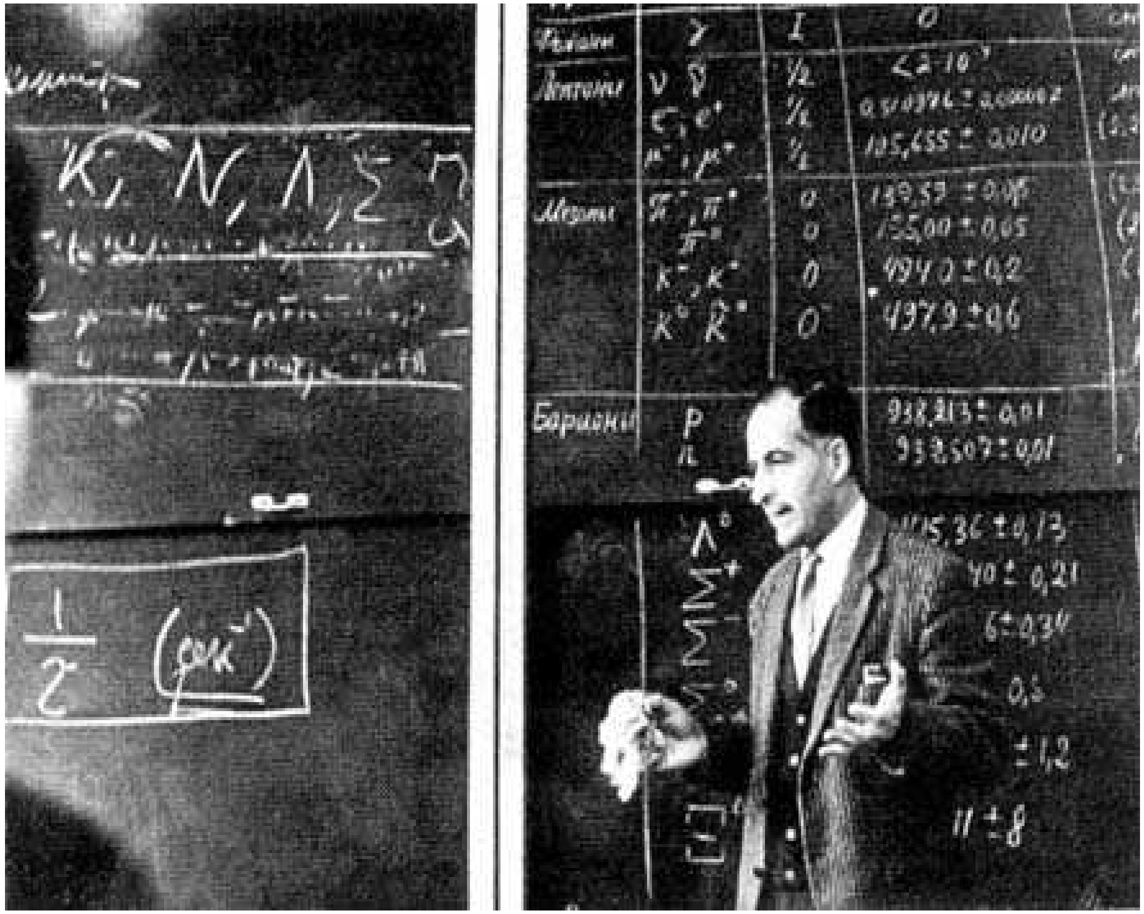


Giving a talk at JINR, Dubna (early 1970s). (From the photo archive of JINR.)

Contributions to Neutrino Physics

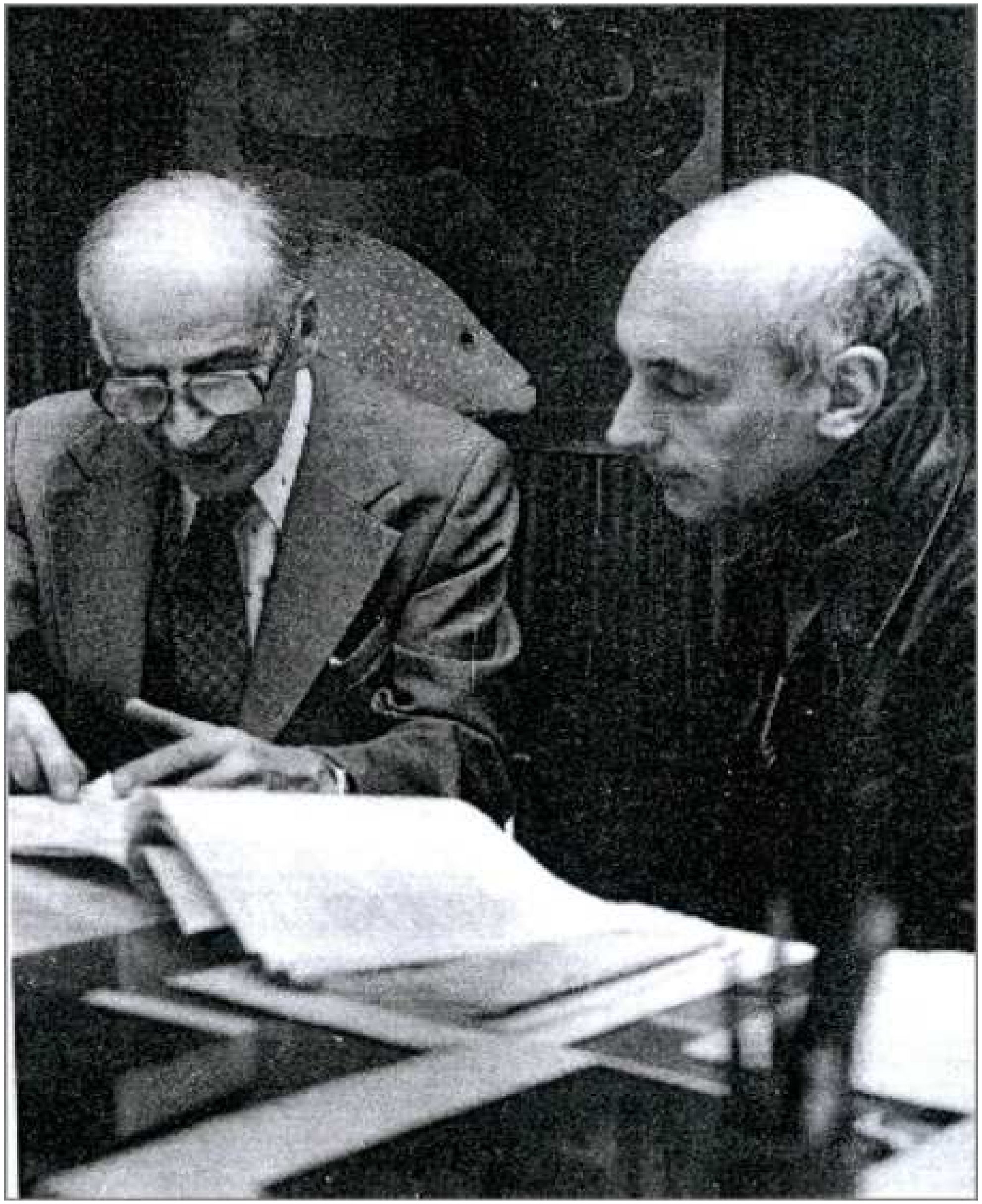
Collaboration with B. Pontecorvo

Bilenky's most prominent and well known contributions today are in the field of neutrino physics. In a fruitful collaboration and co-authorship with Bruno Pontecorvo, which started in the early 1970s, they developed the theory of neutrino oscillations in vacuum and laid the foundations of the phenomenological theory of neutrino mixing, on which every theoretical model of neutrino mass generation (including GUTs) is based.



B. Pontecorvo giving a talk at JINR, Dubna. (From the photo archive of JINR.)

B. Pontecorvo at a seminar at JINR, Dubna. (From the photo archive of JINR.)



With B. Pontecorvo at JINR in 1980s. (From the photo archive of JINR.)

S.M. Bilenky and B. Pontecorvo have written together 28 articles.

– "Quark-Lepton Analogy and Neutrino Oscillations", Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). Dec 1975. 3 pp., Phys. Lett. 61B (1976) 248.
– "The Quark-Lepton Analogy and the Muonic Charge (In Russian)", S. M. Bilenky, B. Pontecorvo (Dubna, JINR), 1976, 6 pp., Yad.Fiz. 24 (1976) 603 (ov.J.Nucl.Phys. 24 (1976) 316).
– "Again on Neutrino Oscillations", Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). May 1976. 11 pp., Lett. Nuovo Cim. 17 (1976) 569.
– "Lepton Mixing, $\mu \to e + \gamma$ Decay and Neutrino Oscillations", Samoil M. Bilenky, S.T. Petcov, B. Pontecorvo (Dubna, JINR). Jan 1977. 4 pp., Phys. Lett. 67B (1977) 309.
– "Lepton Mixing and Neutrino Oscillations" (review), Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). 1978. 37 pp., Phys. Rept. 41 (1978) 225.
– "Majorana and Dirac Masses, Neutrino Oscillations and the Number of Charged Leptons", Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). Jun 1980. 4 pp., Phys. Lett. 95B (1980) 233.
– "Neutrino Oscillations in New Mixing Schemes With Either Dirac or Majorana Masses", S.M. Bilenky, B. Pontecorvo (Dubna, JINR), Dec 1980. 3 pp., Phys. Lett. 102B (1981) 32.
– "Neutrino Oscillations With Large Oscillation Length in Spite of Large (Majorana) Neutrino Masses?", S.M. Bilenky, B. Pontecorvo (Dubna, JINR). Mar 1983. 7 pp., Yad.Fiz. 38 (1983) 415-419, Lett. Nuovo Cim. 37 (1983) 467.
– "Reactor Experiments And Solar Neutrino Problem". Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). Mar 1984. 6 pp., Lett. Nuovo Cim. 40 (1984) 161.

The style of the articles is extremely concise.

Bilenky and Pontecorvo, in particular, laid the foundations of the phenomenological theory of neutrino mixing, on which every theoretical model of neutrino mass generation is based. They were the first to understand in 1975-1976 that the properties of massive neutrinos (Dirac, Majorana) and of neutrino mixing in gauge theories of particle interactions are determined by the properties of the neutrino mass term, and more specifically, by the symmetries the neutrino mass term and the Lagrangian of the theory have. Later this idea found its natural realization in gauge theories of electroweak interactions and in GUTs.

They were the first to consider, e.g., the possibility of neutrinos having the so-called "Dirac + Majorana" mass term, which is at the basis of the seesaw mechanism of neutrino mass generation. This was done in 1976 on purely phenonemological grounds. Later it was used and is still being used in GUTs unifying the electroweak and strong interactions and in other non-GUT theories employing the seesaw mechanism. The seesaw mechanism not only provides a natural explanation of the smallness of neutrino masses, but via the leptogenesis theory relates the generation and smallness of neutrino masses to the generation of the matter-antimatter asymmetry of the Universe.

Again on Neutrino Oscillations.

S. M. BILENKY and B. PONTECORVO

Joint Institute for Nuclear Research,
Laboratory of Theoretical Physics - Dubna, U.S.S.R.
Laboratory of Nuclear Problems - Dubna, U.S.S.R.

(ricevuto il 19 Settembre 1976)

The question of oscillations in neutrino beams has been discussed for some time [1-7]. To start with we list below the various schemes which have been recently treated:

i) In ref [6] neutrino oscillations were considered on the basis of a theory [6,8] of the weak interaction of four leptons, which is fully analogous to the theory of the weak interaction of four quarks [9]. In this scheme the two neutrino fields ν and ν', describing particles with definite masses m and m' different from zero, enter the interaction through the two orthogonal combinations

$$\nu_e = \nu\cos\theta + \nu'\sin\theta\,,$$
$$\nu_\mu = -\nu\sin\theta + \nu'\cos\theta\,,$$

where θ is a mixing angle, which *a priori* has nothing to do with the hadron Cabibbo angle. In this scheme ν_e and ν_μ are not stationary states and the oscillations $\nu_e \rightleftarrows \nu_\mu$, $\bar\nu_e \rightleftarrows \bar\nu_\mu$ arise, the origin of which can be traced to the mass difference $|m-m'|$. Let us emphasize here that, first, in this scheme the overall number of neutral-lepton states is 8 (2 four-component neutrinos,) and that, second, in the case of maximum mixing ($\theta = \pi/4$), the properly averaged intensity of ν_e at large distances from a source of ν_e (let us say the Sun) is equal to $\frac{1}{2}$ of the intensity expected when oscillations are absent.

ii) In ref. [5,7] a scheme was considered which is a generalization of the preceding case to that of N four-component neutrinos with masses different from zero ($4N$-states). Here too oscillations will take place, as the particles entering the weak interaction will not be described by stationary states and will be orthogonal mixtures of the mass eigen-

(1) B. PONTECORVO: *Žurn. Èksp. Teor. Fiz.*, **33**, 549 (1957); **34**, 247 (1958); **53**, 1717 (1967).
(2) V. GRIBOV and B. PONTECORVO: *Phys. Lett.*, **28** B, 493 (1969).
(3) J. BAHCALL and S. FRAUTSCHI: *Phys. Lett.*, **29** B, 623 (1969).
(4) B. PONTECORVO: *Usp. Fiz. Nauk*, **104**, 3 (1971).
(5) B. PONTECORVO: *Žurn. Èksp. Teor. Fiz. Pis. Red.*, **13**, 281 (1971).
(6) S. M. BILENKY and B. PONTECORVO: *Phys. Lett.*, **61** B, 248 (1976).
(7) H. FRITZSCH and P. MINKOWSKY: preprint CALT-68-525.
(8) S. ELIEZER and D. A. ROSS: *Phys. Rev. D*, **10**, 3088 (1974).
(9) S. L. GLASHOW, J. I. ILIOPOULOS and L. MAIANI: *Phys. Rev. D*, **2**, 1285 (1970).

S.M. Bilenky, B. Pontecorvo, Lett. Nuovo Cim. 17 (1976) 569.

Dirac+Majorana mass term with $\nu_{\ell L}(x)$ and $\nu_{\ell R}(x)$; massive neutrinos: ν_j, j=1,2,...,6, $m_j \neq 0$ - Majorana particles.

$$\mathcal{L}^{\nu}_{D+M}(x) = -\overline{\nu_{l'R}}(\mathbf{x})\mathbf{M}_{Dl'l}\,\nu_{lL}(\mathbf{x}) + \frac{1}{2}\nu^{\mathsf{T}}_{l'L}(x)\mathbf{C}^{-1}\mathbf{M}^{LL}_{l'l}\,\nu_{lL}(\mathbf{x}) + \frac{1}{2}\nu^{\mathsf{T}}_{l'R}(\mathbf{x})\mathbf{C}^{-1}(\mathbf{M}^{RR})^{\dagger}_{l'l}\,\nu_{lR}(\mathbf{x}) + \mathrm{h.c.},$$

$(\mathbf{M}^{LL})^T = \mathbf{M}^{LL}$, $(\mathbf{M}^{RR})^T = \mathbf{M}^{RR}$

$$M = \begin{pmatrix} M^{LL} & M_D \\ M_D^T & M^{RR} \end{pmatrix} = M^T$$

If $\mathbf{M}_{Dl'l} \neq 0$ and $\mathbf{M}^{LL}_{l'l} \neq 0$ and/or $\mathbf{M}^{RR}_{l'l} \neq 0$:

$\mathbf{L}_l \neq$ *const.*, $\mathbf{L} \neq$ *const.*; n = 6 (>3)

$\mathbf{M} = \mathbf{M}^{\mathsf{T}}$, complex; $\mathbf{M}^{diag} = \mathbf{W}^{\mathsf{T}}\mathbf{M}\mathbf{W}$, W-unitary, 6×6; $\mathbf{W}^T \equiv (\mathbf{U}^T\ \ \mathbf{V}^T)$; $\mathbf{U} \equiv \mathbf{U}_{\mathrm{PMNS}}$: 3×6.

$\nu_{lL}(x) = \sum_{j=1}^{6} U_{lj}\chi_j(x)$, $\chi_j(\mathbf{x})$ - Majorana νs, $\mathbf{m}_j \neq 0$, l=e,μ,τ;

$\nu^C_{lL}(\mathbf{x}) \equiv \mathbf{C}(\overline{\nu_{lR}}(\mathbf{x}))^{\mathsf{T}} = \sum_{j=1}^{6} \mathbf{V}_{lj}\,\chi_j(\mathbf{x})$, $\nu^C_{lL}(\mathbf{x})$: sterile antineutrino

$\mathcal{L}^{\nu}_{D+M}(x)$ possible in the ST + ν_{lR}: $\mathbf{M}^{LL} = 0$; seesaw: $|M_D| << |M^{RR}|$.

Review article with B. Pontecorvo:
– "Lepton Mixing and Neutrino Oscillations", Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR). 1978. 37 pp, Published in Phys. Rept. 41 (1978) 225-261 (cited in 930 papers).

Was used universally for a long period as a reference article on the subject of neutrino mixing and neutrino oscillations.

PHYSICS REPORTS (Section C of Physics Letters) 41, No. 4 (1978) 225–261. NORTH-HOLLAND PUBLISHING COMPANY

LEPTON MIXING AND NEUTRINO OSCILLATIONS

S.M. BILENKY and B. PONTECORVO

Joint Institute for Nuclear Research, Dubna, USSR

Received 27 June 1977

Contents:

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PHYSICS REPORT (Section C of PHYSICS LETTERS) 41, No. 4 (1978) 225–261.

Copies of this issue may be obtained at the price given below. All orders should be sent directly to the Publisher. Orders must be accompanied by check.

Single issue price Dfl. 18.00, postage included.

B. Pontecorvo was on friendly terms with the whole Bilenky's family. Misha, Bilenky's son, made humorous sketches on the occasion of Pontecorvo's 75th birthday, which are now kept in Ponteorvo's office in LNP, JINR, Dubna.

B. Pontercorvo's office in LNP, JINR, Dubna.

Pontecorvo in Dubna.

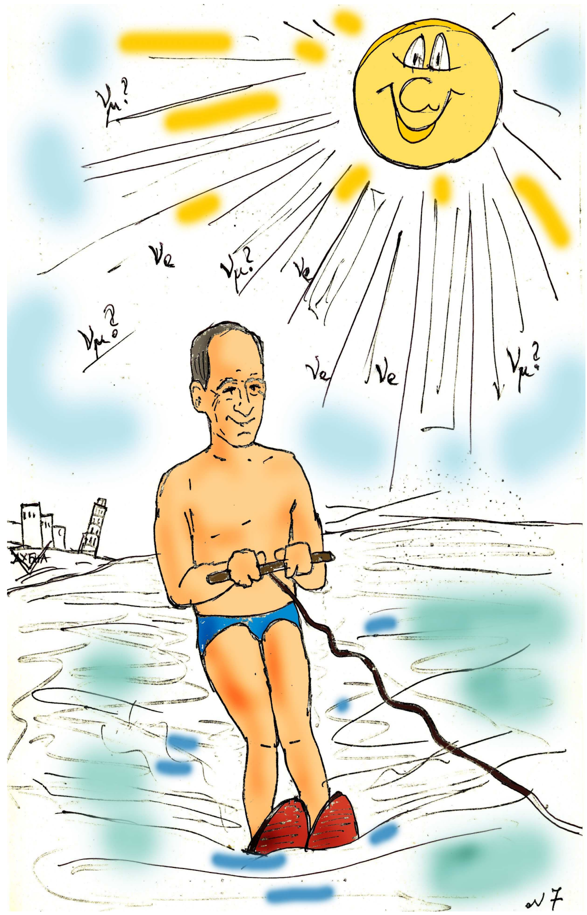
Drawing due to Misha Bilenky.

Pontecorvo in Dubna.

Drawing due to Misha Bilenky.

Pontecorvo in Dubna.

Drawing due to Misha Bilenky.



Pontecorvo in Dubna.

Drawing due to Misha Bilenky.

Pontecorvo in Dubna.

Drawing due to Misha Bilenky.

Дорогой Миша!

ещё до 75 лет у меня были 70, 60 и другие годы. Я храню в Москве сделанные по одному из этих случаев шутливые поздравительные транспаренса от друзей – профессиональных художников. Твои много лучше!

С благодарностью, любовью и наилучшими пожеланиями

Бруно Понтекорво

Дубна, 2 1988.

Dear Misha,

Before my 75th anniversary, I had 70's, 60's and other anniversaries. I keep in Moscow cartoons that I received once from my friends (professional artists) for my former anniversary. Your cartoons are much better!
With gratitude, love and best wishes.

Bruno Pontecorvo.
Dubna, 1988

Pontecorvo on Misha's drawings.

B. Pontecorvo liked practical jokes. His most famous one was played in 1954 together with Migdal on Landau.

In the early spring of 1976 Pontecorvo played one on Bilenky.
"The discovery of the $W^{\pm}-$ bosons at CERN..."

Pontecorvo passed on September 24, 1993.

In accordance with Pontecorvo's wishes, half of his ashes were buried in the Protestant Cemetery in Rome, and another half in Dubna in Russia.
In 1995, in recognition of his scientific merits, the prestigious Pontecorvo Prize has been instituted by the Joint Institute for Nuclear Research.

Samoil Bilenky wrote:
"Bruno Pontecorvo was one of the first who understood the importance of neutrinos for elementary particle physics and astrophysics.
He felt and understood neutrinos probably better than anybody else in the world.
Starting from his Canadian time he thought about neutrino for his whole life.
He was completely open-minded, without any prejudices, very courageous and with very good intuition and scientific taste.
The name of Bruno Pontecorvo will be forever connected with neutrino as the name of the founder and father of modern neutrino physics.
Bruno Pontecorvo was very bright, wise, exceptionally interesting and had a very friendly personality. People liked him and he had many friends in Italy, Russia, France, Canada and many other countries. He will remain with us in our memory and our hearts as a great outstanding physicist, as a man of great impact and humanity."

Very often Pontecorvo was much ahead of his time in his scientific ideas. This was the case, e.g.,, with the suggestion that neutrinos can be detected in experiments performed at reactors, and especially, with the radiochemical Cl–Ar method of neutrino detection, with the idea of $\mu - e$ universality, and with the neutrino mixing and oscillation hypothesis.
The scientific life of B. Pontecorvo was remarkably coherent: from 1946 on neutrinos became his scientific passion and our present understanding of their experimentally established and their possible properties, of how they can be "seen" and used for physics research, is primarily based on his ideas and his results.

Even during the period of collaboration with B. Pontecorvo, S.M. Bilenky made independent original and insightful contributions to the development of neutrino physics and continued to do so after the passing of B. Pontecorvo in 1993.

He was involved in studies devoted to all aspects of contemporary neutrino physics:
phenomenology of neutrino mixing and of neutrino oscillations,
neutrinoless double beta decay,
the problem of determination of neutrino mass ordering,
CP violation in neutrino oscillations,
tests of existence of sterile neutrinos at the eV scale,
the problem of determination of the absolute neutrino mass scale, etc.
Bilenky wrote also many review articles and lecture notes.

1980, Majorana Phases

S.M. Bilenky, J. Hosek, S.T.P., May 1980;

$\chi_k(x)$**-4 component (spin 1/2), Majorana, m**$_k \neq 0$**:**

C$(\bar{\chi}_k(x))^{\mathsf{T}} = \xi_k \chi_k(x)$**,** $|\xi_k|^2 = 1$**.**

U(1): χ_k**(x)** $\rightarrow e^{i\beta}\chi_k$**(x)- impossible!**
$\chi_k(x)$ **cannot absorb phases.**

j$_\alpha^{(lep)} = 2\,\bar{l}(x)\,\gamma_\alpha\, U_{lk}\, \chi_{kL}(x)$**, U = VP; n families,**

V: (n-1)(n-2)/2 Dirac CPV phases;

P = diag$(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}}, ..., e^{i\frac{\alpha_{n1}}{2}})$ **- (n-1) Majorana CPV phases;**
n=3, V: 1 Dirac CPV phase; P: 2 Majorana CPV phases.
n=2, V: CP conserving; P: 1 Majorana CPV phase.

In the same article:

$\mathbf{j}_{\alpha}^{(lep)} = 2\,\bar{l}(x)\,\gamma_{\alpha}\,U_{lk}\,\chi_{kL}(x)$, $\mathbf{U} = \mathbf{VP}$

$\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$, **not sensitive to the Majorana CPV phases and thus to the nature of** ν_j.

$A(\nu_l \leftrightarrow \nu_{l'}) = \sum_j U_{l'j} e^{-i(E_j t - p_j x)} U^{\dagger}_{jl}$,

$\mathbf{U} = \mathbf{VP}$: $\mathbf{P}_j e^{-i(E_j t - p_j x)} \mathbf{P}^*_j = e^{-i(E_j t - p_j x)}$

P - **diagonal matrix of Majorana phases.**

The result is valid also in the case of oscillations in matter (P. Langacker *et al.*, Nucl. Phys. B282 (1987) 589).

$\nu_l \leftrightarrow \nu_{l'}$ **oscillations are not sensitive to the nature of** ν_j.

S.M. Bilenky had collaborators in many countries mostly, but not only, in Europe. An incomplete list includes:
W. Alberico, C. Giunti, A. Bottino, V. Wataghin, S. Pascoli, F. Capozzi, A. Masiero, M. Fabbrichesi (Italy);
J. Bernabeu, A. Santamaria, J. Grifols, E. Masso, F. Botella, J. Segura (Spain);
M. Lindner, W. Winter, W. Potzel, F. von Feilitzsch, A. Faessler, G. Motz (Germany);
W. Grimus, Th. Schwetz (Austria);
T. Ohlsson (Sweden);
M. Mateev, E. Christova (Khristova), N. Nedelcheva (Bulgaria);
F. Simkovic (Slovakia);
C.W. Kim (S. Korea), B. Kayser (USA);
K.M. Graczyk (Poland).

For his devotion to the studies of neutrinos, which he called "exceptional particle, the most interesting among the elementary particles", and – in view of the fact that neutrino properties suggest the existence of New Physics Beyond the Standard Model – "a Gift of Nature", his long term friend and renowned particle physicist Jose Bernabeu proposed once jokingly that Bilenky should be called "Mister Neutrino".

Teacher and Mentor

Bilenky was an excellent teacher, mentor and inspiration for many young researchers in the field of elementary particle and neutrino physics. His lectures on different topics of theoretical particle physics at Moscow University, where he taught for 30 years, and on neutrino physics at various International Schools were always characterized by remarkable clarity. This made him a sought after speaker and he was invited and gave lectures at Universities all across Europe (Turin, Milan, Vienna, Prague, Valencia, Barcelona, Sofia, SISSA and ICTP in Trieste, Helsinki, among others) and in Israel (Technion).

Visiting SISSA in 2013 (with D. Amati, R. Iengo, SISSA students and postdocs).

Attending the Neutrino Telescopes Workshop in the 1990s. S.M. Bilenky attended several of the Workshops organised by Milla and enjoyed them immensely.

During one of the visits to SISSA and Trieste.

At NOW 2000 Bilenky chaired the "Sumarry Session".

Photo due to Eligio Lisi.

Bilenky is the author of 5 monographs in Russian and English, which have undergone several editions, appreciated by both theorists and experimenters.
"Introduction to the Feynman Diagram Technique",
"Introduction to the Physics of Electroweak Interaction",
"Introduction to the Scattering Theory"
have long become table books for generations of physicists. His many years of experience and achievements in neutrino physics are presented in
"Lectures on the Physics of Neutrino and Lepton-Nucleon Processes" and
"Introduction to the Physics of Massive and Mixed Neutrinos".

These books also helped and continue to help many young scientists enter professionally into the fascinating fields of modern particle and neutrino physics.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LECTURE NOTES IN PHYSICS 817
Introduction to the Physics of Massive and Mixed Neutrinos
Springer

Bilenky started in 1998 and was a tireless organiser of the well known Pontecorvo Neutrino Physics School. The School had eight editions so far (the last was in 2019) and was one of the reference international schools on neutrino physics in Europe.


VI International Pontecorvo
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Reactor ν experiments: Rupert Leitner (Charles U.)
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ν -oscillation phenomenology Boris Kayser (Fermilab)
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experiments - Yuri Shitov (JINR Dubna)
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0νββ–decay experiments Andrea Giuliani (CSNSM in Paris)
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Coherent scattering of ν's Henry Wong (Academia Sinica, Taipei)
ν nucleus interactions Jan Sobczyk (Univ. of Wroclaw)
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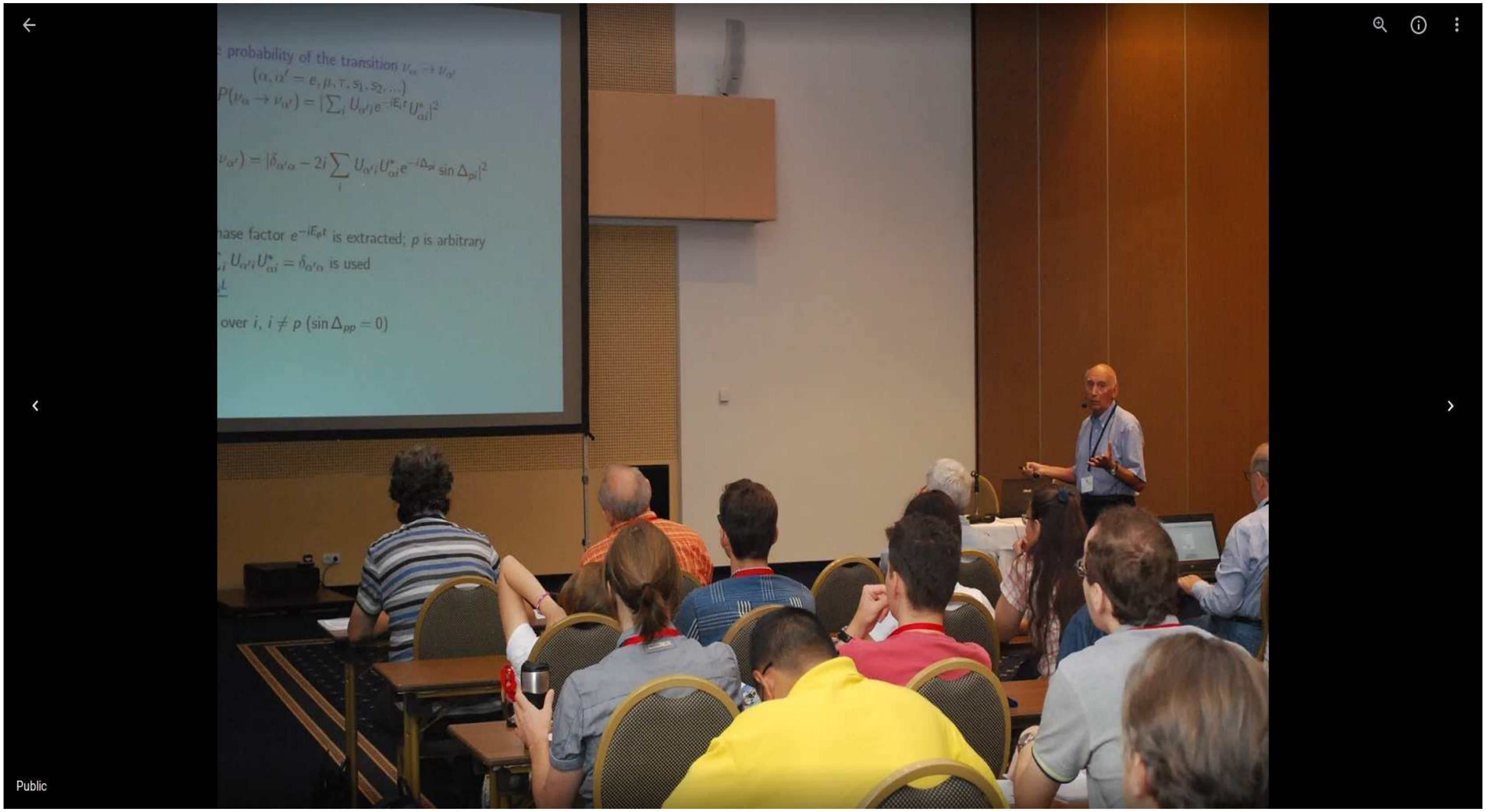
Everything about Higgs boson Guenakh Mitselmakher* (Univ. of Florida)
Statistics for ν-experiments Thomas Schwetz (KIT in Karlsruhe)



Lecturing at the Pontecorvo Neutrino Physics School in 2015 held in Slovakia.

For his research and teaching activities Bilenky received many recognitions: the Russian state medal "For distinguished service to the State", the International Bruno Pontecorvo Prize, the Humboldt Prize, the Medal of First Degree of the Faculty of Physics and Mathematics of Charles University in Prague, and other prizes.

I was lucky to be a student of Samoil Mihelevich at the Joint Institute of Nuclear Research (JINR) in Dubna in the 1970'ies when JINR was one of the leading world centers for studies in the field of elementary particle physics, and later to continue to collaborate with him. This collaborations was highly fruitful and valuable for me. We have co-authored altogether 22 articles. Our last joint article (with F. Capozzi) was published in 2017 and updated in June of 2020. Due to Samoil Mihelevich I was lucky to collaborate with both Bilenky and Pontecorvo on a study of the $\mu \to e + \gamma$ decay in gauge theories with heavy neutral (Majorana) leptons.

"Massive Neutrinos and Neutrino Oscillations", Samoil M. Bilenky, S.T. Petcov. Jul 1987. 84 pp. Published in Rev. Mod. Phys. 59 (1987) 671.

"On Oscillations of Neutrinos with Dirac and Majorana Masses", S.M. Bilenky, J. Hosek, S.T. Petcov (Dubna, JINR). May 1980. Phys. Lett. 94B (1980) 495.

"Lepton Mixing, $\mu \to e + \gamma$ Decay and Neutrino Oscillations", Samoil M. Bilenky, S.T. Petcov, B. Pontecorvo (Dubna, JINR), Jan. 1977, Phys. Lett. 67B (1977) 309.

"Majorana neutrinos, neutrino mass spectrum, CP violation and neutrinoless double beta decay. 1. "The Three neutrino mixing case", Samoil M. Bilenky (Dubna, JINR and SISSA, Trieste), S. Pascoli, S.T. Petcov (SISSA/INFN, Trieste). Feb 2001. 51 pp. Phys. Rev. D64 (2001) 053010.

"An alternative method of determining the neutrino mass ordering in reactor neutrino experiments", S.M. Bilenky (Dubna, JINR and TRIUMF), F. Capozzi (INFN, Padua), S.T. Petcov (SISSA/INFN, Trieste and Tokyo U., IPMU), Phys.Lett. B772 (2017) 179, Erratum: Phys.Lett. B809 (2020) 135765.

Bilenky attracted people with his kind and obliging character and had collaborators, students and friends in many countries. His human warmth and benevolent personality embodied the best humanistic and cultural traditions of the Russian Intelligentsia to which Samoil Mihelevich Bilenky belonged.

Bilenky loved his "job"– his research and teaching activities. His great interest in physics, the search for new ideas in science, did not diminish throughout his prolific life. He was constantly thinking and working on problems in neutrino physics, and more generally, in particle physics.

Bilenky's words are - for a theoretician there is no retirement. Of his more than 250 articles, about 40 have been published in recent years. And only a three weeks before he passed, he published a review on "Basics of the General Theory of Relativity for Beginners" – an area completely new to him.

Basics of General Theory of Relativity for Beginners

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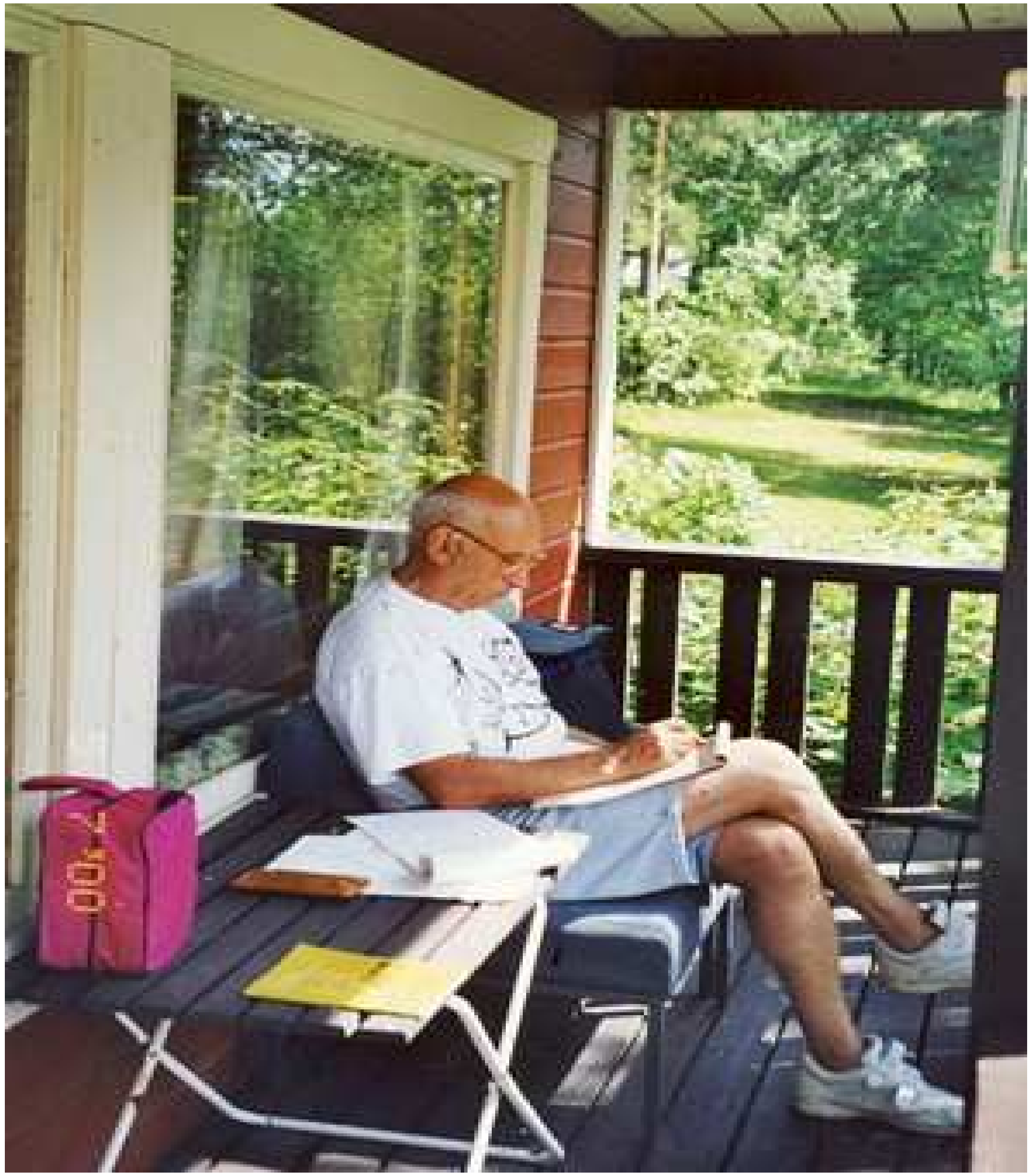
Abstract

We present a basics of the Einstein General Theory of Relativity. In the first part of this review we derive relations of Riemann geometry which are used in the General Relativity. In the second part we discuss Einstein Equations and some of its consequences (The Schwarzschild solution, gravitational waves, Friedman Equations etc). In the Appendix we briefly discuss a history of the discovery of the Einstein Equations.

1 Introduction

General Theory of Relativity is a great theory, confirmed by all existing data (see, for example, "Experimental Tests of Gravitational Theory" by T. Damour in PDG [1]) It is based on the requirement of invariance under the general transformations of coordinates in a curved Riemann space. The General Theory of Relativity, apparently, support a suggestion[1] that in a correct theory the simplest possibilities are realized. Recent discovery of the predicted by GTO gravitational waves opened a new and very powerful way of the investigation of the Universe. In the book "Classical Theory of Fields" L.D. Landau and E.M. Lifshitz wrote : "The General Theory of Relativity which was created by Einstein (and finally formulated by him in 1916) is, apparently, the most beautiful of all existing physical theories. It is remarkable that it was built by Einstein in a purely deductive way and only later was confirmed by astronomical observations" In this review I tried to present the basics of the General Theory of Relativity and some of its consequences in such a way that all derivations can be easily followed by a reader.

[1]"Simplicity is a guide to the theory choice" A. Einstein.



At a summer house near Helsinki, Finland, 2000.