„Neutrinos, Luxons, Preons, Quantons, Strangelets and Twistors Like a Dark matter and Dark energy, feat. Mr. NEUTRINO“

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Abstract: This article is focused on the most non–clarified situation of Particle Physics, like for example Neutrinos, Quantons, Preons, Luxons and subatomic and atomic scales microphenomenons Twistors and Strangelets.

The main part of this article is dedicated to dark matter and energy and flashback significance of Mr. Neutrino, respectively the outstanding atomic scientist Bruno Pontecorvo and his contribution to High Energy Particle Physics and Nuclear Physics, by his discoveries in scientific field, so called NEUTRINO OSCILLATIONS and other quantum phenomenas.

Although this article says about, for example – mixing angles θ [théta] of neutrinos, their "VIRTUAL TRANSMUTATION", DIRAC AND MAJORANA NEUTRINOS.

The most interesting part of the text is focused on infraparticles – goldstinos and preons– models of lepton, quarks and gauge bosons as composite objects.

Not in the ending part of this text is described, also, so called – The Suzuki Model (Lagrangian Based Suzuki's Ideas).

Included is also new concept of wave particle duality – wavicle and quanticle (including wave + particle).

The text involved the briefly biography of Mr. Neutrino respectively nuclear scientist Bruno Pontecorvo.

Keywords: neutrinos, quantons, preons, luxons, goldstinos, wavicle, quanticle, twistors, strangelets, oscillation, mixing angles θ, Pontecorvo, Suzuki, Dirac, Majorana.

Contents

1. Introduction and highlight's sketches of Author: Mgr. Imrich KRIŠTOF

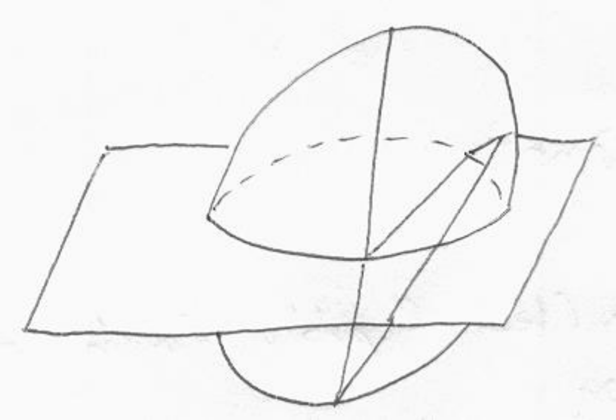

Fig. 1. Celestial (Riemann) 2–Sphere, that can be stereographically projected onto a complex plane.

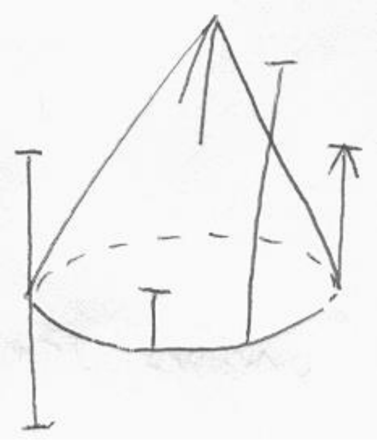

Fig. 2. Past and Null cone

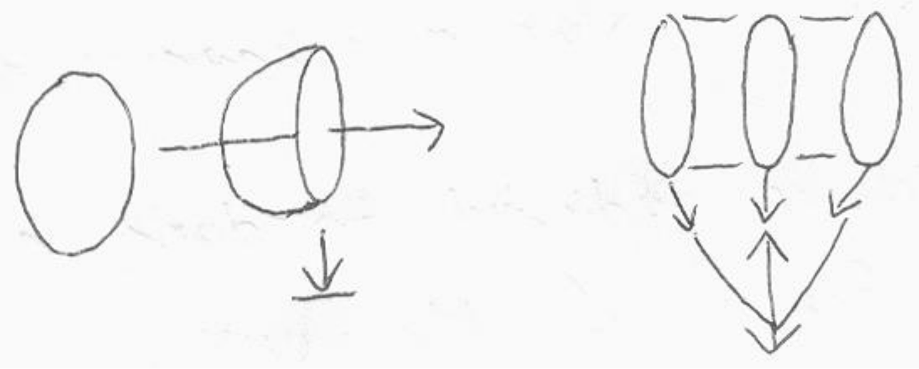

Fig. 3. MÖBIUS TRANSFORMATION OF THE PLANE, CORRESPOND TO LORENTZ TRANSFORMATION OF THE CELESTIAL SPHERE.

This "spinorial" point of view has an interesting application in finding the apparent shape of rapidly moving sphere.

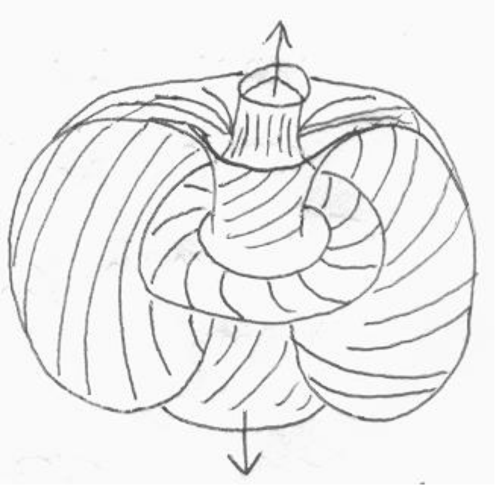

Fig. 4. Simplify scheme of TWISTOR, resp. TOROID OF TOKAMAK JET IN Culham [GB].

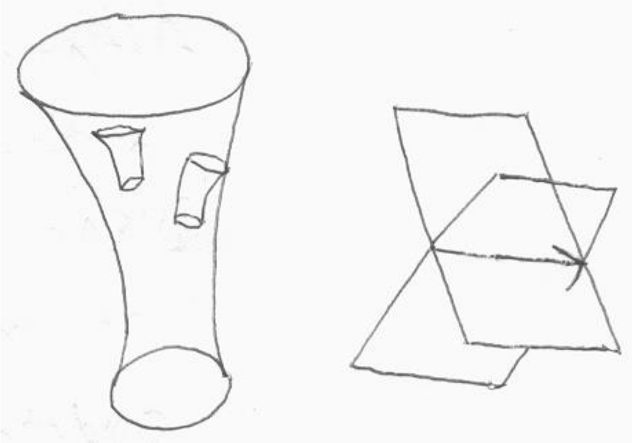

Fig. 5. Minkowski space.

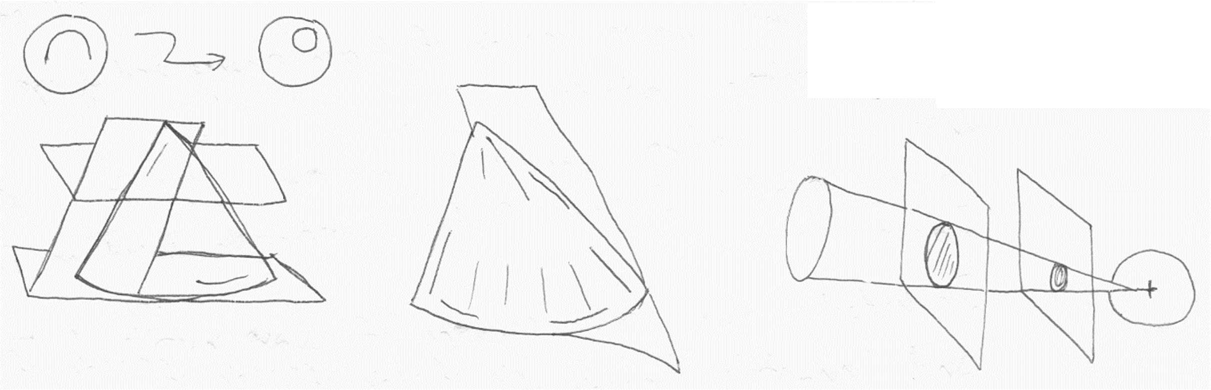

Fig. 6. Angular momentum of zero rest mass particle (Technical details can be found in the Twistor Principle).

1.1 TWISTORS

ONE OF THE EASIEST AND MOST STRAIGHTFORWARD WAYS OF DEFINING TWISTORS, USES THE TRANSFORMATION PROPERTIES OF LINEAR AND ANGULAR MOMENTUM OF A PARTICLE UNDER A SHIFT OF ORIGIN. CONSIDER A CHANGE OF ORIGIN FROM 0 TO POINT Q WITH COORDINATES q^a, WITH RESPECT TO THE NEW ORIGIN.

$$p^a(Q) = p^a(0)$$

$$M^{ab}(Q) = M^{ab}(0) - q^a p^b + q^b p^a$$

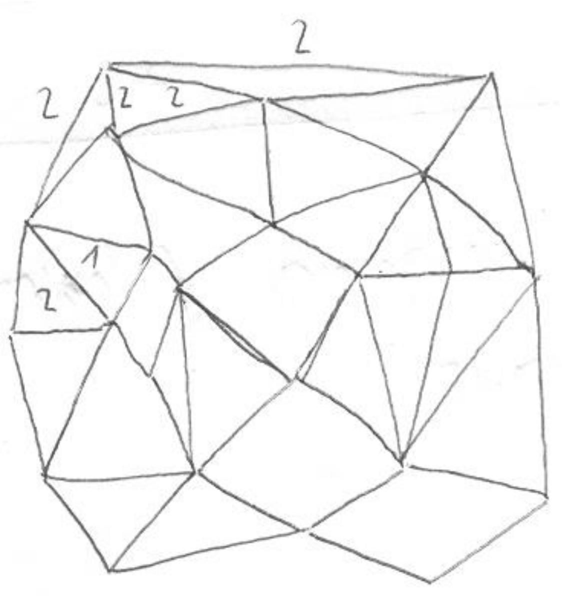

Fig. 7. SPIN NETWORK (Pauli–Lubanski spin vector)

1.2 TWISTOR GRAVITY

The whole power of the twistor program is contained within the complex analycity of the twistor functions called “contour integral”.

In space–time the massless particles are specified by their helicity (+ or – helicity denotes parallel and anti–parallel of the directions of spin and motion), they are now labelled by homogenity in twistor space.

Comment no. 1: Table no. 1 shows the helicity and homogenity for the massless particles. It shows that at the most fundamental, the twistor picture is not symmetrical.

Particle	Helicity	Homogenity
Graviton	+2	-6
Photon	+1	-4
Anti–neutrino	+1/2	-3
Unknown	0	-2
Neutrino	-1/2	-1
Photon	-1	0
Graviton	-2	+2

Weakly interacting or massive particles |wimps|: gravitino, photino, neutralino, axino, their non–zero mass (dark matter → dark energy).

Table 1. Helicity and Homogenity of hypothetical Massless Particle (“LUXONS”).

1.3 STRANGELETS

STRANGELET IS A HYPOTHETICAL PARTICLE CONSISTING OF THE DIFFERENT TYPES OF ATOMIC AND SUB–ATOMIC PARTICLES FOUND OR HYPOTHESIZED TO EXIST IN THE WHOLE OF THE CATEGORIZED BY TYPE.

A STRANGELET IS CONSISTING OF A BOUND STATE OF ROUGHLY EQUAL NUMBERS OF UP, DOWN AND STRANGE QUARKS. AN EQUIVALENT DESCRIPTION IS THAT A STRANGELET IS A SMALL FRAGMENT OF STRANGE MATTER, SMALL ENOUGH TO BE CONSIDERED A PARTICLE.

STRANGE MATTER IS A PARTICULAR FORM OF A S QUARK/MATTER, USUALLY THOUGHT OF AS A “LIQUID” OF UP, DOWN AND STRANGE QUARKS |S QUARK| IS THE THIRD LIGHTEST OF ALL QUARKS, A TYPE OF ELEMENTARY PARTICLES. STRANGE QUARKS ARE FOUND IN SUBATOMIC PARTICLES CALLED HADRONS.

EXAMPLE OF HADRONS CONTAINING STRANGE QUARKS INCLUDE KAONS (K MESONS), STRANGE D MESONS (D_S), SIGMA BARYONS |Σ| AND OTHER STRANGE PARTICLES.

1.4 THE DARK MATTER AND DARK ENERGY (THEIR FLUENCE TO WHOLE UNIVERSE)

The SCDM (COLD DARK MATTER) COSMOLOGY was inspired in part by growing interest in the idea of nobaryonic dark matter (NBDM).

In 1977, Ben Lee and Steve Weinberg considered the possibility of a new family of neutrinos with standard neutrino interactions and mass large enough, that annihilation of neutrino pairs could commence early enough at high enough density for significant reduction of the remnant number density.

The larger, the neutrino mass, the earlier the annihilation and the smaller the remnant density. Lee and Weinberg found, that for a neutrino mass of ~2 GeV, the remnant mass density could “provide a plausible mechanism for closing the Universe.”

Neutrinos (later known as WIMPS, for weakly interacting massive particles), would naturally drape themselves around galaxies. The lightest stable supersymmetric partner, or maybe axions, which “can cluster into galactic halos”.

The LHC is the largest operating particle collider in the world (diameter of this accelerator is ~27 km). It is located near Geneva, Switzerland – the four main experiments at LHC are ATLAS, ALICE, CMS, and LHC_b. The ATLAS and CMS experiments are multi–purpose experiments with similar physics goals: the measurement of “miracle” particle – HIGGS BOSON PROPERTIES and for physics beyond the Standard Model.

During its first data–taking period from March 2010 to February 2013, called RUN 1, the LHC delivered proton–proton collisions at centre–of–mass energies 7 and 8 teraelectronvolt (TeV). The LHC has restarted operation in summer 2015 (RUN 2), at centre–of–mass energies of 13 TeV.

Both the LHC collision energy and the ability to deliver and collect collision data have been increased significantly with respect to RUN 1.

As a consequence of this symmetry, IN SUSY (SUPERSYMMETRIC) MODELS, EACH OF THE SM PARTICLES HAS A SUPERSYMMETRIC PARTNER (R–PARITY) the lightest SUSY PARTICLE (LSP) is stable and can be identified with the WIMP DARK MATTER (DM) CANDIDATE.

COLLIDER SIGNALS OF SUSY ARE CHARACTERIZED BY CASCADE DECAYS OF SUPERPARTNER PARTICLE TERMINATING IN THE LSP. THESE SIGNALS PRODUCE A FINAL STATE SIGNATURE IN THE DETECTOR THAT IS RICH IN COLLIMATED SPRAYS OF PARTICLES (JETS) FROM QUARKS ANS GLUONS, IN SOME ACCOMPANIED BY LEPTONS AND PHOTONS, ALONGSIDE A SIGNICIANT AMOUNT OF MISSING TRANSVERSE MOMENTUM.

Experimental search strategies for SUSY searches discriminate signal and background events.

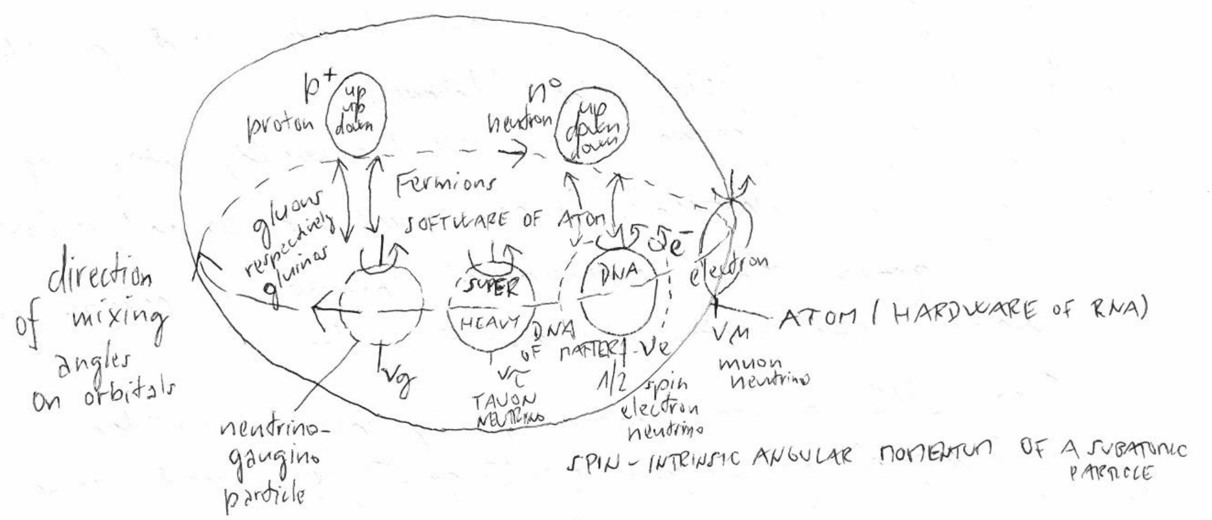

Fig. 8. Author sketch of Resonanza and oscillation of quarks and neutrinos/leptons and their biological application., like constituent of RNA and DNA.

Comment no. 2: Fermions – called according Enrico Fermi (spin 1/2, 3/2, 5/2) a cathegory of elementary particles. They are very small and very light. Fermions can be thought on the building blocks of matter.

Comment no. 3: Consequences of Interaction of neutrinos – elusive particle and matter. Continual Rotating Symmetry of oscillation of wave function. SPINORS WERE INTRODUCED IN 1913 IN GEOMETRY BY THE FRENCH MATHEMATICIAN, PROFESSOR OF MATHS AT SORBONNA ÉLIE JOSEPH CARTAN (9.4.1869 – 6.5.1951, Paris).

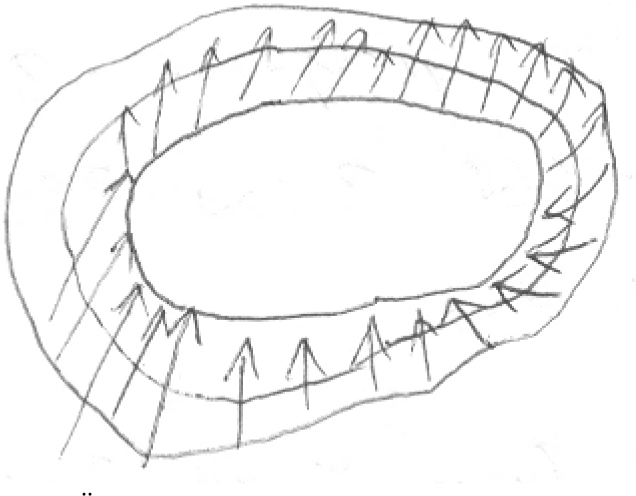

Fig. 9: MÖBIUS BAND rotating through a full turn of 360°.

1.5 PREONS

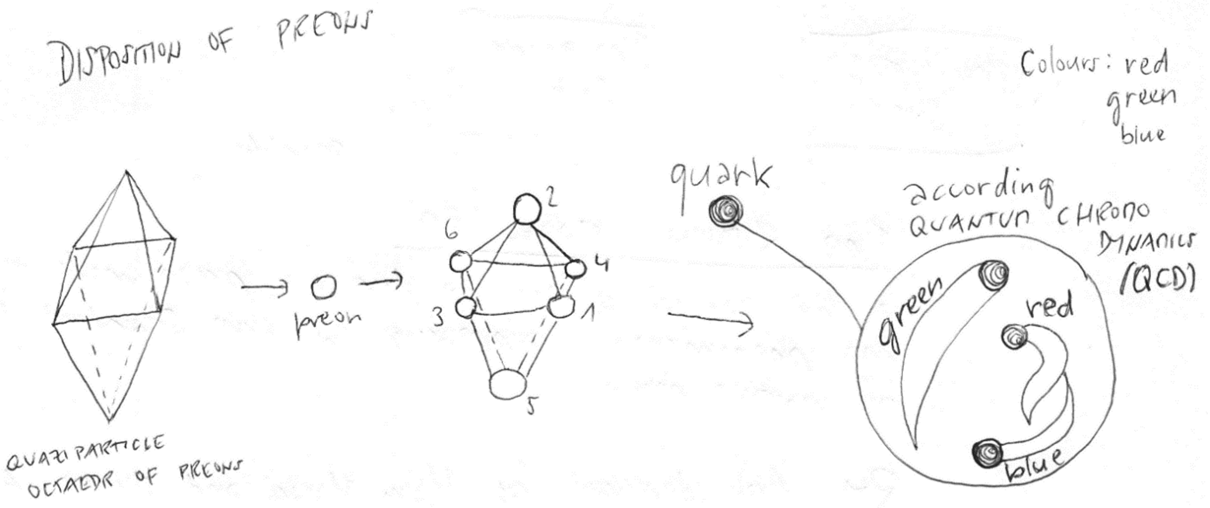

Fig. 10. Space conformation of PREONS according Author: Mgr. I. Krištof.

In particle physics, preon is a point particle, conceived of as subcomponents of quarks and leptons. The name was coined by Jogesh Pati and Abdus Salam in 1974. Principles of the Pati–Salam model are connected with proton decay, respectively an existence of right–(clockwise)–handed neutrinos (non–zero masses of neutrinos and neutrino oscillations). Preon models peaked in the 1980’s but has slowed as the Standard Model of particle physics. Almost all of these particles come in “left–handed” and “right–handed” versions (so called chirality). Quarks are not truly indestructible, since some can decay into other quarks.

Quarks are not themselves fundamental building blocks but must be composed of other, fundamental quanticles (quantities) – preons!

A model of STRONG INTERACTION AMONG NUCLEONS, MEDIATED BY PIONS (MESON π) IS AN EFFECTIVE THEORY FOR THE STRONG INTERACTION OF QUARKS MEDIATED BY COLOURED GLUONS.

The STANDARD MODEL (SM)

- The leptonic Sector,
- The quark Sector.

The RISHON MODEL (RM)

RM is the earliest effort to develop a preon model to explain the phenomenon appearing in the Standard Model (SM) of particle physics.

RM first developed by Haim Harari and Michael A. Shupe (independently of each other) and later expanded by Harari and his student Nathan Seiberg.

The model has involved two kinds of fundamental particles called rishons (which means “primary” in Hebrew). They are T (“Third”) since it has an electric charge of 1/3 e, or Tohu, which means “unformed” in Hebrew Genesis and V (“vanishes”), since it is electrically neutral, or Vohu [Bohu means “void” in the Hebrew Tanakh (The Old Testament)].

Though bohu may be pronounced as vohu by modern Israelis when the “b”is preceded by a vowel and thus lacks dagesh.

1.5 LUXONS

A massless particle, a particle traveling at the speed of light, elementary particle whose invariant mass is zero. The two known massless particles are both gauge bosons: the photon (carrier of electromagnetism) and the gluon (carrier of the strong force). Neutrinos were originally thought to be massless.

2. Composite Leptons and Quarks from Hexad Preons, Preons – models of leptons, quarks and gauge bosons as composite objects

- The Goldstone Phenomena (Superconductivity) – 2 DIMENSIONAL QUANTUM FIELD THEORY (t’Hooft Anomaly Matching Conditions) – [INFRAPARTICLES] – non-vacuum states with arbitrarily small energies. Take for example a chiral N = 1 super QCD (QUANTUM CHROMODYNAMICS) model a nonzero s quark VEV which is conformal in the IR. QCD goldstone bosons are infraparticles resp. NAMBU–GOLDSTONE FERMIONS (GOLDSTINOS). Vestigial bosonic superparticles of the goldstinos, called sgoldstinos, might also appear, but need not, as supermultiplets hwve been reduced to arrays.
- The Higgs Mechanism (Spontaneous Symmetry Breaking),
- The Higgs in The Standard Model,
- GRAND UNIFICATION THEORIES [GUT] by Pakistan Scientist Abdus Salam,
- UNSOLVED PROBLEMS OF THE STANDARD MODEL,
- COMPOSITE HIGGS BOSONS,
- MASS OF THE FERMIONS,
- COMPOSITE HIGGS MODEL,
- QUARK AND LEPTON SUB–STRUCTURE,
- MASSES OF BOUND STATE FERMIONS,
- CHIRAL PROTECTION, t’Hooft Anomaly MATCHING CONDITIONS,
- THE QUASI–GOLDSTONE FERMION MECHANISM,
- MASS GENERATION / FAMILY REPLICATION,
- QUARK AND LEPTON SUBSTRUCTURE MODELS,
- COMPOSITE WEAK BOSONS,
- THE SUZUKI MODEL (LAGRANGIAN BASED ON SUZUKI’S IDEAS),
- PROSPECTS OF W,Z COMPOSITENESS,
- MAGNETIC MOMENTS OF QUARKS AND LEPTONS,

These have spin 1/2 instead of 0, and carry all quantum numbers of the respective supersymmetry operators broken spontaneously. Goldstinos are spontaneous superpartners of all particles in the theory, of any spin, and the only superpartners, at that.

In theories where supersymmetry is a global symmetry, the goldstino is an ordinary particle (possibly the lightest supersymmetric particle, responsible for dark matter). In theories where supersymmetry is a local symmetry, the goldstino is absorbed by the gravitino, the gauge field it couples to, becoming its longitudinal component, and giving it nonvanishing mass. This mechanism is a close analog of the way the Higgs gives nonzero mass to W and Z bosons.

A Hexad Preon Model where, leptons, quarks and $W^{\pm}$ $Z;^{\pm}$ bosons are composite is proposed.

All salient features of the Standard Model (SM) can be obtained from the compositeness of leptons and quarks. There are exactly six quarks and six leptons with evident three families (generations); All quantum number of leptons and quarks can be given out of that preons, QED (QUANTUM ELECTRODYNAMICS) and QCD (QUANTUM CHROMODYNAMICS) are given by electro–strong interaction $U(1)_Q \otimes SU(3)_C$

The electro–weak interaction is represented by residual "Van der Waals" forces between preons and dipreons. It's shown that all processes in Standard Model (SM) are just reshuffle of preons. Also, a possible dark matter candidate is presented.

The other question like the electroweak symmetry breaking, the spin of fermions, lepton mixing and the origin and charge of quark.

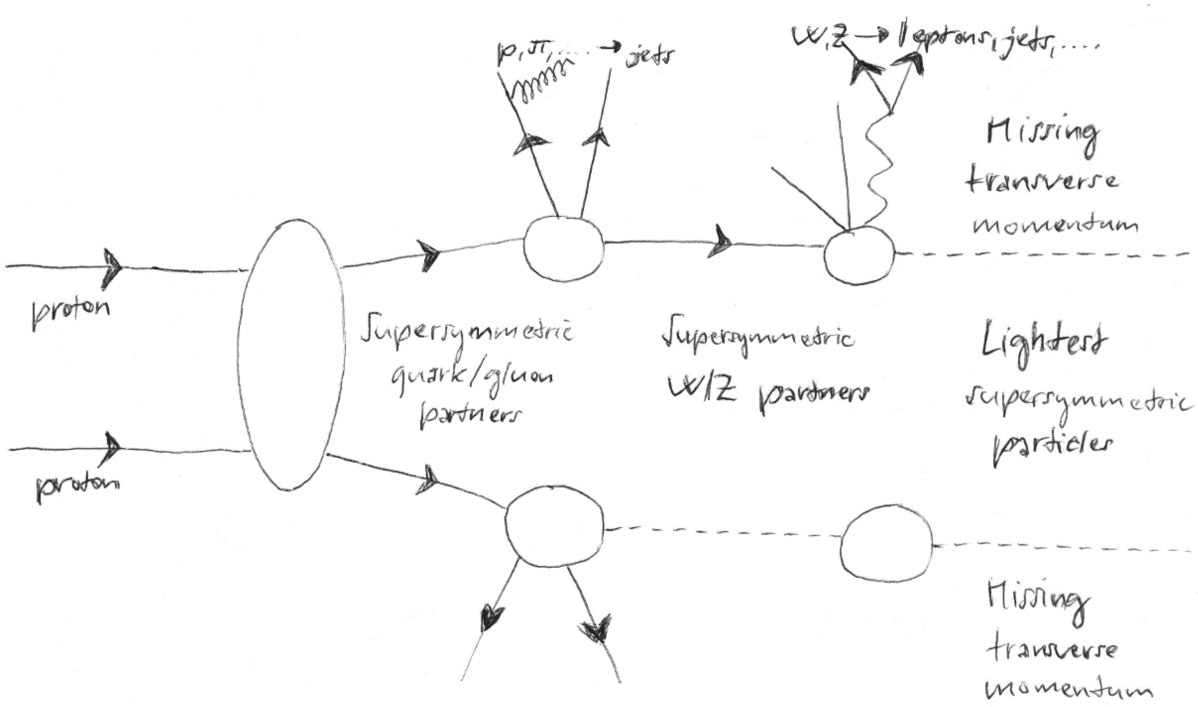

Fig. 11. A typical production and decay and resonace, chain involving SUSY particles. Dark matter (DM) is at the end of the decay chain, leading to mixing transverse momentum.

Microscopically

Weakly interacting massive particles (WIMP'S) with typical masses arround the electroweak symmetry breaking scale (~100 GeV/c^2) are a generic class of dark matter candidates favoured by many theories beyond the Standard Model (SM) of particle physics, such as supersymmetry (SUSY).

The production and annihilation of such particles in the early thermal Universe could naturally explain the abundance of regular matter observed nowdays – an appealing scenario known as the WIMP miracle.

For a WIMP mass between 1 and 1.000 GeV, the typical elastic recoil energy of an atomic nucleus ranges from 1 to 100 keV (for a large nucleus, the smaller the WIMP mass, the lower the mean recoil energy and vice versa), which is the primary signal in direct detection at about 3×10^{-26} cm^3.s^{-1}. Number of particles in the Standard Model (SM), provides such a particle, reffered to as neutralino.

The Super CDMS experiment located in the Soudan mine in Minnesota, U.S.A. uses cryogenic semiconductor detectors, armed with the so–called interleaved Z–sensitive ionization phonon (iZIP) technique to detect both the phonon and ionization signals at a low temperature of ~40–50 mK. The ionization signal into phonons, which reached an electron recoil threshold of 56 eV. With a 70kg–day exposure, the experiment set the leading limits published on low–mass WIMPS between 1.6 and 5.5 GeV/c^2.

The CDEX experiment located in CJPL used point–contact germanium detectors operating at liquid nitrogen temperature.

These detectors have also the advantage of a low threshold and a good rejection power to surface background, and hence are suitable for low–mass WIMP searches.

3. QUANTONS

Quanton – any quantum entity that shows the properties of both a particle and a wave.

Wavicle – synonyms, blend of wave+particle.

In quantum mechanics A wave–particle the same synonym is quanticle.

Wave particle duality: the concept applying to all matter and radiation, but most evident in light and particles such as the electron, that properties of waves and of particles are exhibited simultaneously…,

Example: de Broglie wavelength, $\lambda = {}^{h}\!/_{p}$, associated with a beam of particles of momentum p. (h being Planck's constant). The same formula gives the momentum of a photon γ or wavelength λ.

The results expect with wavelength λ_1 and λ_2

$$\lambda_1 = \frac{h}{p_1}, \lambda_2 = \frac{h}{p_2},$$

$$\lambda_2 - \lambda_1 = 2\lambda_C \left(\sin\frac{\theta}{2}\right)^2,$$

where θ is scattering angle of radiation,

where λ_C → Compton's wavelength

$$\lambda_C = \frac{h}{m_e c} = 2.4\,.\,10^{-12}\,m$$

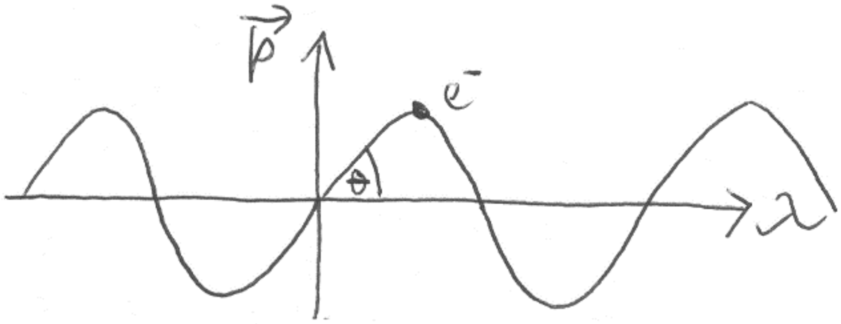

Fig. 12. Compton's wavelength.

RBS → Rutherford Backscattering (scattering optical phonon)

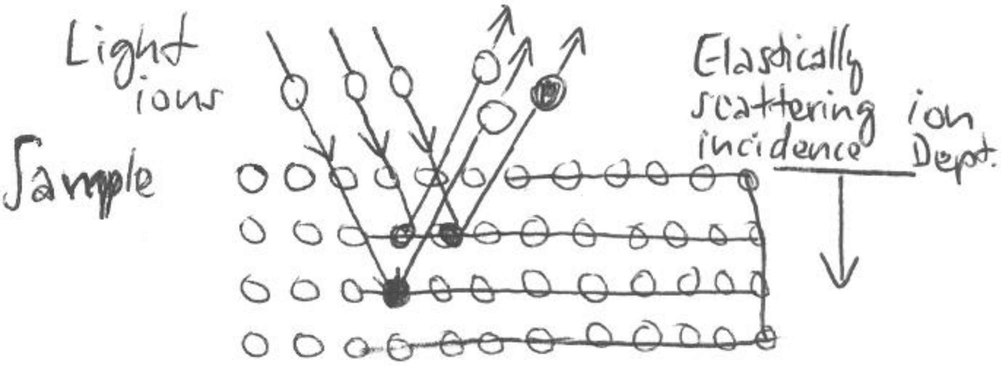

Fig. 13. RBS (Rutherford Backscattering Spectroscopy).

4. Indirect dark matter searches in cosmic radiation

Proposed particle candidates for dark matter span more than 60 orders of magnitude in cross–section (with Standard Model particles) and about 45 orders of magnitude in mass (Fig. 14). Weakly interacting, but much more massive than a neutrino (weakly interacting massive particle, or WIMP).

A very significant hypothesis for the production of dark matter is that it consists of thermal relics of the Big Bang (much like the photons of the cosmic microwave background radiation).

WIMPs ability to interact – expressed by the velocity–averaged annihilation cross–section <σv>, which for briefness we will simply refer to as annihilation cross–section – and the cosmologically relevant properties or observables. Sometimes this coincidence is popularized as the "WIMP miracle".

As the abundance is regulated by the already mentioned annihilation cross–section, requiring that the relics provide the entire observed dark matter provides a benchmark for indirect detection at about 3×10^{-26} cm^3s^{-1}.

An additional feature of WIMPs is that particle theories beyond the Standard Model (SM), invoked for a different reason than dark matter, often generically include a WIMP.

In particular, supersymmetry, which roughly doubles the number of particles in the Standard Model, provides such a particle, reffered to as neutralino.

The candidate most generically within reach of indirect detection belongs to the concept of weakly interacting massive particles (WIMPs), predicted by a variety of theories, most notably supersymmetry – that is, the neutralino.

KK stands for Kaluza–Klein, LTP refers to lightest–time–parity)–odd particle and CDM is cold dark matter (see fig. 14, Author Mgr. Imrich KRIŠTOF Sketch according Nature Physics).

Dominant part of WIMPs (for masses below 30 GeV) as being dominant of dark matter.

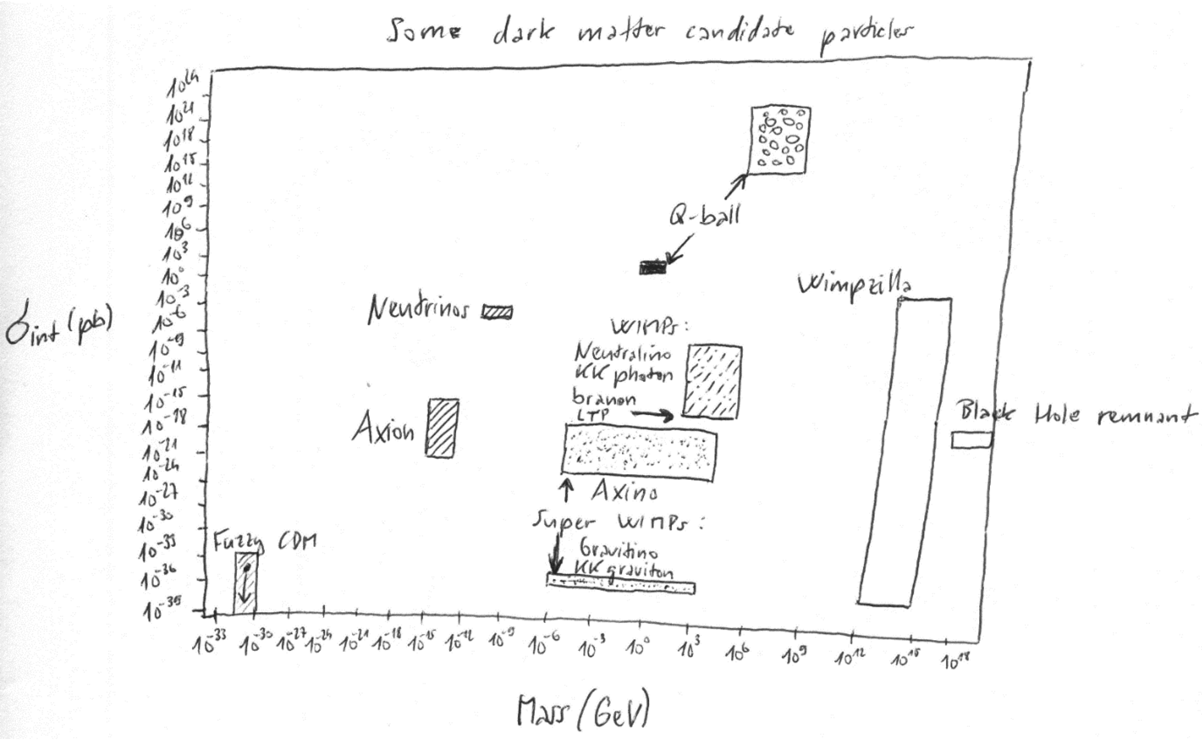

Fig. 14. Dark matter candidates indicating the interdependence of the interaction cross–section and particle mass.

5. High–energy neutrino particle astrophysics

Weakly interacting, chargeless neutrinos are ideal astronomical messengers as they travel through space without scattering, absorption or deflection. This weak interaction also makes them notoriously difficult to detect, leading to neutrino observatories requiring large–scale detectors.

A few years ago, the IceCube experiment discovered neutrino originating beyond the Sun with energies bracketed by those of the highest energy gamma rays and cosmic rays. The possibility of observing the so–called Greisen–Zatsepin–Kuzmin (GZK) neutrinos produced in the interactions of cosmic rays with microwave background photons was recognized by 1969. A consensus emerged that such sources could release a similar energy in cosmic rays, gamma rays, and neutrinos. This predicted neutrino flux was in fact discovered in 2013 by the IceCube experiment in Antarctica.

Even at a depth of 1.450 m, IceCube detects at a rate of 3.000 per second a background of atmospheric cosmic–ray muons originating in the Southern Hemisphere.

Two methods are used to identify neutrinos. Historically, neutrino searches focus on the observation of muon neutrinos that interact primarily outside the detector to produce kilometer–long muon tracks passing through the detection volume.

Although this allows for the observation of neutrinos that interact outside the detector, it is the necessary to use the Earth as a filter remove the huge background of cosmic–ray muons. This limits the neutrino view to a single flavour and to half the sky. The alternative method exclusively identifies neutrinos interacting inside the detector.

It divides the instrumented volume of ice into an outer veto shield and a ~500 megaton inner fiducial volume.

The advantage of focusing on neutrinos interacting inside the instrumented volume of ice it that the detector functions as a total absorption calorimeter measuring energy with a 10 – 15% resolution. Also, neutrinos from all directions in the sky can be identified, including both muon tracks, produced in muon neutrino charged – current interactions, and secondary showers, produced by electron and tau neutrinos as well as in neutral current interactions of neutrinos of all flavours.

The Cherenkov patterns initiated by an electron (or tau) neutrino of 1 PeV (petaelectronvolt, or 10^{15} eV) energy and a muon neutrino depositing 2.6 PeV energy while traversing the detector are contrasted.

In general, the particle's trajectory is determined from the arrival times of photons at the optical sensors.

For neutrino astronomy, the first challenge is to select sufficiently pure samples of neutrinos: roughly 100.000 per year in a background of ten billion cosmic–ray muons.

Analyses suggest that cosmic neutrino flux dominates the atmospheric background above an energy that may be as low as 30 TeV, with an energy spectrum that cannot be described as a single power, as was the case for the muon neutrino flux through the Earth for energies exceeding 220 TeV.

6. The King of Particles Bruno Pontecorvo – MR. NEUTRINO

The significance of Bruno Pontecorvo (MR. NEUTRINO), he proposed:

- the radiochemical method of detection of neutrinos,
- the μ–e universality of the electro–weak interaction,
- (the Brookhaven experiment), the accelerator neutrino experiment which allowed to prove that muon and electron neutrinos are different particles.

Development of idea by Pontecorvo pioneering work of neutrino masses, mixing, resp. mixing angles and oscillations.

6.1 Briefly biography of Mr. Neutrino – B. Pontecorvo

Comment no. 4: Bruno Pontecorvo – Nuclear Physicist (*22.8.1913 Marina Di Pisa, Italy – 24.9.1993 Dubna, Russia).

Pontecorvo started his scientific work in 1932 in Rome as a student of Enrico Fermi, with connections on brilliant scientist Ettore Majorana and distinctive Emilio Ségré. Later, he become a member of the Fermi Group on Project Manhattan.

He was the youngiest "ragazzo di Via Panisperna". Pontecorvo took part in many experiments in which the effect of slow neutrons was discovered.

From 1936 till 1940, Pontecorvo worked on the investigation of nuclear isomers in Paris in the Joliot–Curie group.

From 1940 till 1942, he worked in the U.S.A. (Project Manhattan). He also developed and realized a method of neutron well logging for oil prospecting. This was the first practical application of neutrons in geophysics.

From 1943 till 1948, Pontecorvo worked in Canada, first in the Montreal Research Laboratory and then in the Chalk River Laboratory.

He was the scientific leader of the project of the research nuclear reactor outside the U.S.A.

In Canada, Pontecorvo started research in elementary particles physics. For many years, the neutrino was considered as an “undetectable particle” respectively “ghost particle of atom”.

Soon after the famous 1934 E. Fermi paper on the theory of β–decay, Bethe and Peirels estimated the interaction cross section of neutrinos with atomic nuclei. They showed that the cross section was extremely small ($\sigma < 10^{-44}$ cm^2).

Pontecorvo was the first who challenged this opinion. In 1946, Pontecorvo proposed the radiochemical method of neutrino detection (South Dakota, Homestake).

The method realized with Raymond Davis, Jr. and John Bahcall was based on Pontecorvo’s observation of the decay, of the daughter nucleus produced in the reaction

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

Discussed in details the reaction

$$\nu + {}^{37}Cl \to e^- + {}^{37}Ar \tag{1}$$

Pontecorvo considered the method of neutrino detection based on the reaction as promising one for the following reasons:

(i) C_2Cl_4 is a cheap, nonflammable liquid,
(ii) ^{37}Ar nuclei are unstable (K–capture) with a convenient half–life (34.8 days),
(iii) A few atoms of ^{37}Ar (rare gas), produced during the exposition time, can be extracted from a large detector.

The Pontecorvo Cl–Ar method was used by Raymond Davis, Jr. In his pioneering experiment on the detection of solar neutrinos for which R. Davis, Jr. was awarded the Nobel Prize in 2002.

The radiochemical method of neutrino detection based on the observation of the reaction

$$\nu + {}^{71}Ga \to e^- + {}^{71}Ge \tag{2}$$

Reaction $\nu_e + {}^{71}Ga \to e^- + {}^{71}Ge$ (2) was used in the GALLEX-GNO and SAGE solar neutrino experiments in which ν_e’s from all thermonuclear reactions in the Sun including neutrinos from the main reaction $pp \to e^+ \nu_e np$ were detected. In Canada in 1948, Pontecorvo invented the low–background proportional counter that allowed to count very rare events. This counter was crucial for the detection of solar neutrinos in the Homestake, GALLEX, and SAGE experiments. B. Pontecorvo together with Hincks performed a series of brilliant pioneering experiments on the investigation of fundamental properties of the muon. In 1950, Pontecorvo moved to Russia. He started to work at Dubna where at that time the largest accelerator in the world was operating. In 1959, a project of a meson factory was under preparation in Dubna (for various reasons the project was not realized). In 1988, L. Ledermann, M. Schwartz, and J. Steinberger were awarded the Nobel Prize for “the discovery of the muon neutrino leading to classification of particles in families”. In 1957, Pontecorvo came to the idea of neutrino oscillations.

6.2 The First Ideas of Neutrino Oscillations (1957–1958)

We come now to the very bright idea of Bruno Pontecorvo, that of neutrino masses, mixing, and oscillations, which created a new field of neutrino research and a new era in neutrino physics. He proposed the idea of neutrino oscillation in 1957–1958 and pursued it over many years.

Pontecorvo was impressed by the possibility of $K^0 \rightleftharpoons \bar{K}^0$ oscillations suggested by Gell–Mann and Pais. This phenomenon was based on the following:

1. K^0 and $\bar{K}^0$ are particles with strangeness +1 and -1, respectively. Strangeness is conserved in the strong interaction.
2. Weak interaction, in which strangeness is not conserved, induces transitions between K^0 and $\bar{K}^0$.

Pontecorvo raised the question, "… whether there exist other "mixed" neutral particles (not necessarily elementary ones) which are not identical to their corresponding antiparticle and for which particle $\rightleftharpoons$ antiparticle transistions are not strictly forbidden."

He came to the conclusion that muonium (μ^+–e^-) and antimuonium (μ^-–e^+) could be such a system. At the time, it was not known that ν_e and ν_μ are different particles. Pontecorvo wrote that $\mu^+ - e^- \rightleftharpoons \mu^- - e^+$ transitions are allowed and "are induced by the same interaction which is responsible for μ–decay"

$$(\mu^+ - e^-) \to \nu + \bar{\nu} \to (\mu^- - e^+). \tag{3}$$

As it's well known according to the two–component neutrino theory, the neutrino is massless and for one neutrino type only a left–handed neutrino ν_L and a right–handed antineutrino $\bar{\nu}_R$ exist. The neutrino and antineutrino are mixed particles, that is, a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2. "And later in the paper he wrote," … the possibility became of some interest in connection with new investigations of inverse β–processes,"

Pontecorvo had in mind the following. In 1957, Davis performed a reactor experiment in which he searched for the production of ^{37}Ar in the process

$$\text{"reactor antineutrino"} + {}^{37}Cl \to e^- + {}^{37}Ar. \tag{4}$$

In 1957–1958, only one neutrino type was known. Pontecorvo assumed that the transition $\bar{\nu}_R \to \nu_R$ (and $\nu_L \to \bar{\nu}_L$) was possible. According to the two–component neutrino theory, which was confirmed by the experiment on the measurement of the neutrino helicity, only the field $\nu_L(x)$ enters in the weak interaction Lagrangian. Thus, from the point of view of this theory, ν_R and $\bar{\nu}_L$ are nointeracting "sterile" particles.

In the inclusive experiment of F. Reines and C. Cowan, Jr. due to neutrino oscillations a deficit of antineutrino events could be observed. Pontecorvo soon understood that ν_R and $\bar{\nu}_L$ are sterile particles. The terminology "sterile neutrino", which is standard nowdays, was introduced by him in the next publication on neutrino oscillations.

6.3 The Second Pontecorvo Paper on Neutrino Oscillations (1967)

The subsequent paper on neutrino oscillations was written by Bruno Pontecorvo in 1967.

Was well established, $K^0 \rightleftharpoons \bar{K}^0$ oscillations had been observed, and it has been proven that (at least) two types on neutrinos ν_e and ν_μ existed in nature.

In Pontecorvo wrote, "If the lepton charge is not an exactly conserved quantum number, and the neutrino mass is different from zero, oscillations similar to those in K^0 beams became possible in neutrino beams."

In the 1967 paper, Pontecorvo discussed the effect of neutrino oscillations for solar neutrinos. "From an observational point of view the ideal object is the Sun. If the oscillation length is smaller than the radius of the Sun region effectively producing neutrinos, direct oscillations will be smeared out and unobservable. The only effect on the earth's surface would be that the flux of observable Sun neutrinos must be two times smaller than the total (active and sterile) neutrino flux."

6.4 The Gribov–Pontecorvo Paper on Neutrino Oscillations (1969)

Gribov and Pontecorvo considered a scheme of neutrino mixing and oscillations with four neutrino and antineutrino states: left–handed neutrino ν_e, ν_μ and right–handed antineutrinos $\bar{\nu}_e, \bar{\nu}_\mu$, quanta of the left–handed neutrino fields $\nu_{eL}(x)$ and $\nu_{\mu L}(x)$. They assumed that there are no sterile neutrino states.

It was assumed in that in addition to the standard charged current V–A interaction with the lepton current

$$j^\alpha = 2\left(\bar{\nu}_{eL}\gamma^\alpha e_L + \bar{\nu}_{\mu L}\gamma^\alpha \mu_L\right) \tag{5}$$

In the total Lagrangian enters an effective Lagrangian of an interaction which violates L_e and L_μ. After diagonalization of the effective Lagrangian, the following mixing relations were found

$$\begin{gathered} \nu_{eL}(x) = \cos\theta\, x_{1L}(x) + \sin\theta x_{2L}(x)\ ; \\ \nu_{\mu L}(x) = -\sin\theta\, x_{1L}(x) + \cos\theta\, x_{2L}(x). \end{gathered} \tag{6}$$

Here, $x_{1,2}(x)$ are fields of the Majorana neutrinos with masses $m_{1,2}$, and θ is a mixing angle. All these parameters are determined by those of the effective Lagrangian.

The authors obtained the following expression for the $\nu_e \to \nu_e$ transition probability in vacuum (in modern notations):

$$p(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin\ ^2 2\theta\left(1 - \cos\frac{\Delta_{m^2}L}{2E}\right) \tag{7}$$

$\left|\Delta_{m^2} = \left|m_2^2 - m_1^2\right|\right|$ and applied the formalism developed to solar neutrino oscillations. They considered the possibility of the maximal mixing $\theta = {}^{\pi}/_{4}$ as the most simple and attractive one. In this case, the averaged observed flux of solar neutrinos is equal to 1/2 of that predicted.

6.5 The General Phenomenological Theory of Neutrino Mixing and Oscillations (Dubna, Russia, 1975–1987)

Idea of quark–lepton analogy, the charged current of quarks has the form (the case of four quarks)

$$J_\alpha^{CC(quark)}(x) = 2\left[\bar{\mu}_L(x)\gamma_\alpha d_L^C(x) + \bar{c}_L(x)\gamma_\alpha S_L^2(x)\right], \tag{8}$$

where

$$\begin{gathered} d_L^C(x) = \cos\theta_C d_L(x) + \sin\theta_C S_L(x)\,, \\ S_L^C(x) = -\sin\theta_C d_L(x) + \cos\theta_C\, S_L(x). \end{gathered} \tag{9}$$

are Cabibbo–GIM mixtures of d and s quarks and θ_C is the Cabibbo angle.

The lepton charged current

$$J_\alpha^{CC(lep)}(x) = 2\left[\bar{\nu}_{eL}(x)\gamma_\alpha e_L(x) + \bar{\nu}_{\mu L}(x)\gamma_\alpha \mu_L(x)\right] \tag{10}$$

has the same form as the quark charged current (same coefficients, left–handed components of the fields). Point of view to assume that $\nu_{eL}(x)$ and $\nu_{\mu L}(x)$ are also mixed fields:

$$\begin{gathered} \nu_{eL}(x) = \cos\theta\, \nu_{1L}(x) + \sin\theta\, \nu_{2L}(x)\ , \\ \nu_{\mu L}(x) = -\sin\theta\, \nu_{1L}(x) + \cos\theta\, \nu_{2L}(x). \end{gathered} \tag{11}$$

Here, $\nu_1(x)$ and $\nu_2(x)$ are Dirac fields of neutrinos with masses m_1 and m_2 and θ is the leptonic mixing angle.

The total lepton number $L = L_e + L_\mu$ is conserved and the neutrinos with definite masses ν_i $(i = 1{,}2)$ differ from the corresponding antineutrinos $\bar{\nu}_i$ by the lepton number $(L(\nu_i) = -L(\bar{\nu}_i) = 1)$.

In 1975, after the success of the two–component theory, there was still a general belief that neutrinos are massless particles.

A possible value of the mixing angle θ "it seems to us that the special values of the mixing angles $\theta = 0$ and $\theta = {}^{\pi}/_{4}$ (maximum mixing) are of the greatest interest."

6.6 Left–Handed Majorana Mass Term

Let us assume that in addition to the standard CC Lagrangian of the interaction of leptons and W–bosons (according author of this text and according the author's article. viXra: 1711:0337 Submitted on 2017–11–16, "Quantum Polyhedronic Concept of Gauge Particles and Gauge Fields in Correlations with Lepton–neutrino Particles Incorporated in Standard Model (SM)":

W-BOSONS (W-WION and WIINO):

$$\mathcal{L}_J^{cc}(x) = -\frac{g}{2\sqrt{2}}\, j_\alpha^{cc}(x)\, W^\alpha(x) + h.c.$$

$$j_\alpha^{cc}(x) = 2\sum_{l=e,\mu,\tau} \bar{\nu}_{lL}(x)\, \gamma_\alpha\, l_L(x) \qquad (12)$$

(and many other terms) in the total Lagrangian the following neutrino mass term enters

$$\mathcal{L}_L^{M} = -\frac{1}{2}\bar{\nu}_L M_L (\nu_L)^c + h.c. \qquad (13)$$

$$\text{Here,} \quad \nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \qquad (14)$$

$(\nu_L)^C = C(\bar{\nu}_L)^T$ is the conjugated field (right–handed component), (C is the matrix of the charge conjugation which satisfies the following relations $C_{\gamma_\alpha}^T C^{-1} = -\gamma_\alpha$, $C^T = -C$), and M_L is a 3x3 symmetrical, complex matrix ($M_L = M_L^T$).

After the standard diagonalization of the matrix M_L, we find the following mixing relations

$$\nu_{lL}(x) = \sum_{i=1}^{3} U_{li}\nu_{iL}(x), \quad l = e, \mu, \tau. \qquad (15)$$

the flavour neutrino field ν_{lL} $(l = e, \mu, \tau)$.

6.7 Dirac Mass Term

Standard CC Lagrangian of the interaction of leptons and W–bosons (WION, WIINO) in the total Lagrangian the following neutrino mass term enters

$$\mathcal{L}^{D} = -\bar{\nu}_L M^{D} \nu_R + h.c. \qquad (16)$$

Here,

$$\nu_R = \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix},$$

and ν_L is given by

$$\nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix},$$

And M^D is a complex 3x3 matrix.

After the standard diagonalization of the matrix M^D, we obtain the following mixing relations

$$\nu_{lL}(x) = \sum_{i=1}^{3} U_{li} \nu_{iL}(x), \quad l = e, \mu, \tau. \qquad (17)$$

Here, U is a unitary 3x3 mixing matrix, $\nu_i(x)$ is the field of the Dirac neutrinos with mass m_i.

The mass term $\mathcal{L}^{D}$ conserves the total lepton number L (which is the same for (ν_e, e), (ν_μ, μ), (ν_τ, τ). The Dirac neutrino ν_i and antineutrino $\bar{\nu}_i$ have the same mass m_i and differ by the lepton number $(L(\nu_i) = 1,\ L(\bar{\nu}_i) = -1)$.

6.8 Dirac and Majorana Mass Term

Let us assume that in addition to the standard CC Lagrangian of the interaction of leptons and w–bosons (WION, WIINO) in the total Lagrangian, the following neutrino mass term enters:

$$\mathcal{L}^{D+M} = \mathcal{L}_{L}^{M} + \mathcal{L}^{D} + \mathcal{L}_{R}^{M} . \qquad (18)$$

Fig. 15. Akademik Bruno Pontekorov resp. Mr. Neutrino excellent nuclear scientist Bruno Pontecorvo (22.8.1913 MARINA DI PISA, Italy – 24.9.1993 (Dubna, Russia)
https://alchetron.com/Bruno-Pontecorvo

Fig. 16. Distinctive physicist Ettore Majorana (5.8.1906 Catania – 25.3.1938 disappear? 1959?)
https://en.wikipedia.org/wiki/Ettore_Majorana

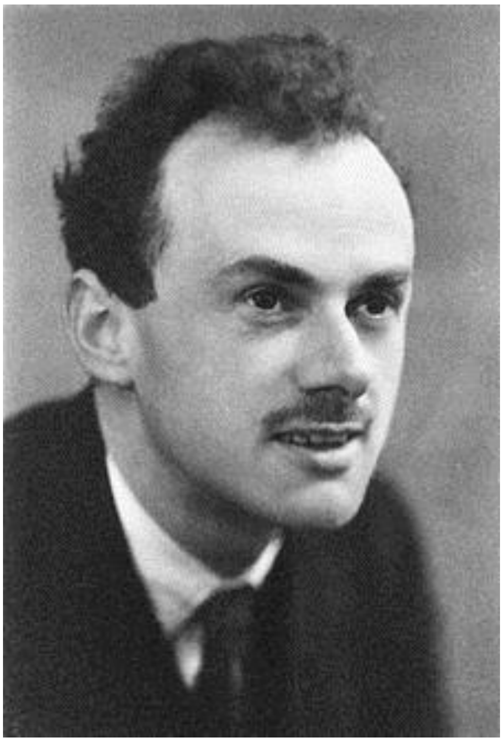

Fig. 17. Paul Adrien Maurice Dirac (8.8.1902 England, Bristol – 20.10.1984 Tallahassee, Florida)

Fig. 18. Paul Dirac with his wife in Copenhagen, July 1963 (Wikipedia)
Dirac married Margit Wigner (Eugene Wigner's sister). He adopted Margit's (Manci's Balazs) two children, Judith and Gabriel. Paul and Margit Dirac had two children together, both daughters, Mary Elizabeth and Florence Monica.

$$\mathcal{L}^{D+M} = \mathcal{L}^{M}_{L} + \mathcal{L}^{D} + \mathcal{L}^{M}_{R}. \qquad (18)$$

Here, $\mathcal{L}^{M}_{L}$ is the left–handed Majorana mass term, $\mathcal{L}^{D}$ is the Dirac mass term, and the right–handed Majorana mass term $\mathcal{L}^{M}_{R}$ is given by the expression

$$\mathcal{L}_R^M = -\frac{1}{2}\overline{(\nu_R)}^c M_R \nu_R + h.c., \qquad (19)$$

where M_R is 3x3 complex, symmetrical matrix.

After the diagonalization of the mass terms, we find the following mixing relations:

$$\nu_{lL}(x) = \sum_{i=1}^{6} U_{li}\nu_{iL}(x)\,, \qquad (20)$$

$$|\nu_{lR}|^C(x) = \sum_{i=1}^{6} U_{\bar{l}_i}\nu_{iL}(x)\ , \quad l = e, \mu, \tau. \qquad (21)$$

Here, U is a unitary 6x6 mixing matrix and $\nu_i(x)$ is the field of Majorana neutrino with mass m_i ($\nu_i(x) = \nu_i^C(x)$). The general case of the Dirac and Majorana mass term, the flavor neutrino fields $\nu_{lL}(x)$ are linear combinations of the left–handed components of six Majorana fields with definite masses. The same left–handed components of six Majorana fields with definite masses are connected with the conjugated right–handed sterile fields $(\nu_{lR})^C(x)$, which do not enter into Lagrangian of the Standard electroweak interaction.

In 1977, wrote a first review on neutrino oscillation in which he summarized the situation of neutrino masses, mixing and oscillations at the time when dedicated experiments on the search for neutrino oscillations had not started yet. This review attracted the attention of many physicists to the problem.

We assumed that neutrinos take part in the CC and NC (interactions). This assumption was based on the data of all existing experiments in which weak processes were investigated.

In the case of the neutrino mixing, $\nu_{eL}(x),\ \nu_{\mu L}(x)\ and\ \nu_{\tau L}(x)$ are not quantum fields but linear combinations of the fields of neutrinos with definite masses ν_{iL}.

The first question was, what are the QFT states of flavor neutrino $\nu_e,\ \nu_\mu\ and\ \nu_\tau$ (and flavor antineutrino $\bar{\nu}_e,\ \bar{\nu}_\mu\ and\ \bar{\nu}_\tau$) particles which are produced in weak decays, captured in neutrino processes, and so forth?

By definition, the muon neutrino ν_μ is a particle, which is produced together with μ^+ in the decay $\pi^+ \to \mu^+ + \nu_\mu$, the particle which produce e^+ in the process $\bar{\nu}_e + p \to e^+ + n$ is the electron antineutrino $\bar{\nu}_e$ and so forth.

Given by the standard model matrix element (with zero mass–squared differences) and independently on the production process the state of the flavor neutrino ν_l $(l = e,\ \mu, \tau\ )$ is given by:

$$|\nu_l\rangle = \sum U_{l_i}^{*}\,|\nu_i\rangle \qquad (22)$$

Here, $|\nu_i\rangle$ is the state of a neutrino with mass m_i, momentum $\vec{p}$, and energy (E = p is the energy of neutrino at $m_i \to 0$).

$$E_i = \sqrt{p^2 + m_i^2} \sim E + \frac{m_i^2}{2E} \qquad (23)$$

Thus, in the case of the mixing of neutrinos with small mass–squared differences, the state of a flavor neutrino is a coherent superposition of states of neutrinos (Dirac and Majorana) with definite masses.

In $\sin\theta_{12} \sim \frac{1}{\sqrt{3}},\ \ \sin\theta_{23} \sim \frac{1}{\sqrt{2}},\ \ \sin\theta_{13} = 0$, we formulated the following coherence condition

$$L_{ik} \gtrsim a.$$

Here, $L_{ik} = 4\pi\left(E/\left|\Delta_{m^2_{ik}}\right|\right)$ $(i \neq k)$ is the oscillation length $\left(\Delta_{m^2_{ik}} = m^2_k - m^2_i\right)$ and a is the QM size of a source. Notice that for mass–squared differences determined from the data of modern neutrino oscillation experiments

$$\Delta_{m^2_{12}} = (7.65^{+0.13}_{-0.20})\,.\,10^{-5}\; eV^2\,,$$
$$\Delta_{m^2_{23}} = (2.43 \pm 0.13)\,.\,10^{-3}\;\mathrm{e}V^2, \qquad (24)$$

and neutrino energies E > 1 MeV, the condition is obviously satisfied.

The relation $|\nu_l\rangle = \sum_i U^*_{l_i}\,|\nu_i\rangle$ is basic for the phenomenon of neutrino oscillations.

In accordance with QFT, we assume that the evolution of states is determined by the Schrödinger equation

$$i\frac{\partial\,|\psi\,(t)\rangle}{\partial t} = H\,|\psi\,(t)\rangle \qquad (25)$$

From this equation, it follows that if at t = 0 a flavor neutrino ν_l is produced at time t we have for the neutrino state

$$|\nu_l\rangle_t = e^{-iHt}\,|\nu_l\rangle = \sum_i |\nu_i\rangle\, e^{-iE_it} U^*_{l_i} \qquad (26)$$

Thus, if a flavor neutrino is produced, the neutrino state at a time t is a superposition of states with different energies, that is, nonstationary state.

Neutrinos are detected via the observation of weak processes

$$\nu_{l'} + N = l' + X, etc. \qquad (27)$$

Expanding the state $|\nu_l\rangle_t$ over the flavor neutrino states, we find

$$|\nu_l\rangle_t = \sum_{l'} |\nu_{l'}\rangle\left(\sum_i U_{l'i} e^{-iE_it} U^*_{l_i}\right) \qquad (28)$$

For probability of the transition $\nu_l \to \nu_{l'}$ during the time t is given by the expression, we find

$$P(\nu_l \to \nu_{l'}) = \left|\sum_i U_{l'i} e^{-iE_it} U^*_{li}\right|^2 \qquad (29)$$

The probability of transition $\bar{\nu}_l \to \bar{\nu}_i$ during the time, we find

$$P(\bar{\nu}_l \to \bar{\nu}_i) = \left|\sum_i U^*_{l'i}\, e^{-iE_it} U_{li}\right|^2 \qquad (30)$$

The expression (30) has a simple interpretation: U^*_{li} is the amplitude of the probability to find in the flavor state $|\nu_l\rangle$ the state $|\nu_i\rangle$; the factor e^{-iE_it} describes evolution of the state with energy E_i; $U_{l'i}$ is the amplitude of the probability to find in the state $|\nu_i\rangle$ the flavor state $|\nu_{l'}\rangle$; because of the coherence of the flavor states, the sum over i is performed.

$$t \sim L, \tag{31}$$

where L is the distance between the neutrino source and the detector.

The neutrino transition probabilities depend on two mass–squared differences $\Delta_{m_{12}^2}$ and $\Delta_{m_{23}^2}$ and on parameters which characterize 3x3 unitary mixing matrix (three angles and one phase).

From analyses of the experimental data that $\Delta_{m_{12}^2} \ll \left|\Delta_{m_{23}^2}\right|$ and one of the mixing angle (θ_{13}) is small.

7. Conclusions

The discovery of neutrino oscillations was a great triumph for Bruno Pontecorvo, who came to the idea of neutrino oscillations at a time when the common opinion favored massless neutrinos and no neutrino oscillations and who pursued this idea over decades.

Pioneering Pontecorvo neutrino oscillations papers and the development of the idea of neutrino masses, mixing, and oscillations in Dubna (Russia) at the end of the seventies.

In the LEP experiments, it was found that three flavor neutrinos $\nu_e, \nu_\mu,\ and\ \nu_\tau$ exist in nature, characterized by three mixing angles $\theta_{12}, \theta_{23},\ and\ \theta_{13}$ and CP phase δ.

Small neutrino masses cannot be naturally explained in the framework of the SM. Their explanation requires new physics beyond the Standard Model (SM).

From analyses of data of neutrino oscillations experiments, it was found that in the very first approximation

$$\sin\theta_{12} \sim \frac{1}{\sqrt{3}}, \quad \sin\theta_{23} \sim \frac{1}{\sqrt{2}}, \quad \sin\theta_{13} \sim 0. \tag{32}$$

The investigations of neutrino oscillations, driven by small neutrino masses and neutrino mixing, raised new questions which need further investigation.

The most outstanding and major problems are the following:

(1) Are neutrinos with definite masses ν_i Majorana or Dirac particles? This problem can be solved via observation of the lepton number violating neutrinoless double β–decay of some even–even nuclei.
(2) Is the neutrino mass spectrum normal or inverted?
    (i) Normal spectrum
    $m_1 < m_2 < m_3$,
    $\Delta_{m_{12}^2} \ll \Delta_{m_{23}^2}$,
    (ii) Inverted spectrum (IS)
    $m_3 < m_1 < m_2$,
    $\Delta_{m_{12}^2} \ll \left|\Delta_{m_{13}^2}\right|$.
(3) What is the value of the CP phase δ, the last unknown parameter of the neutrino mixing matrix?
(4) Are there transitions of flavor neutrinos $\nu_e, \nu_\mu,\ and\ \nu_\tau$ into sterile states?
(5) Independently from Pontecorvo in 1962, Maki et al. came to the idea of neutrino masses and mixing. Their arguments were based on the Nagoya model in which neutrinos were considered as constituents of baryons. In the possibility of the transitions ("VIRTUAL TRANSMUTATION") $\nu_\mu \to \nu_e$ was discussed.

PONTECORVO WAS VERY BRIGHT, WISE, EXCEPTIONALLY INTERESTING, AND A VERY FRIENDLY PERSONALITY. HIS CLEAR LACONIC QUESTIONS WERE VERY IMPORTANT FOR THE CLARIFICATION OF MANY PROBLEMS.

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